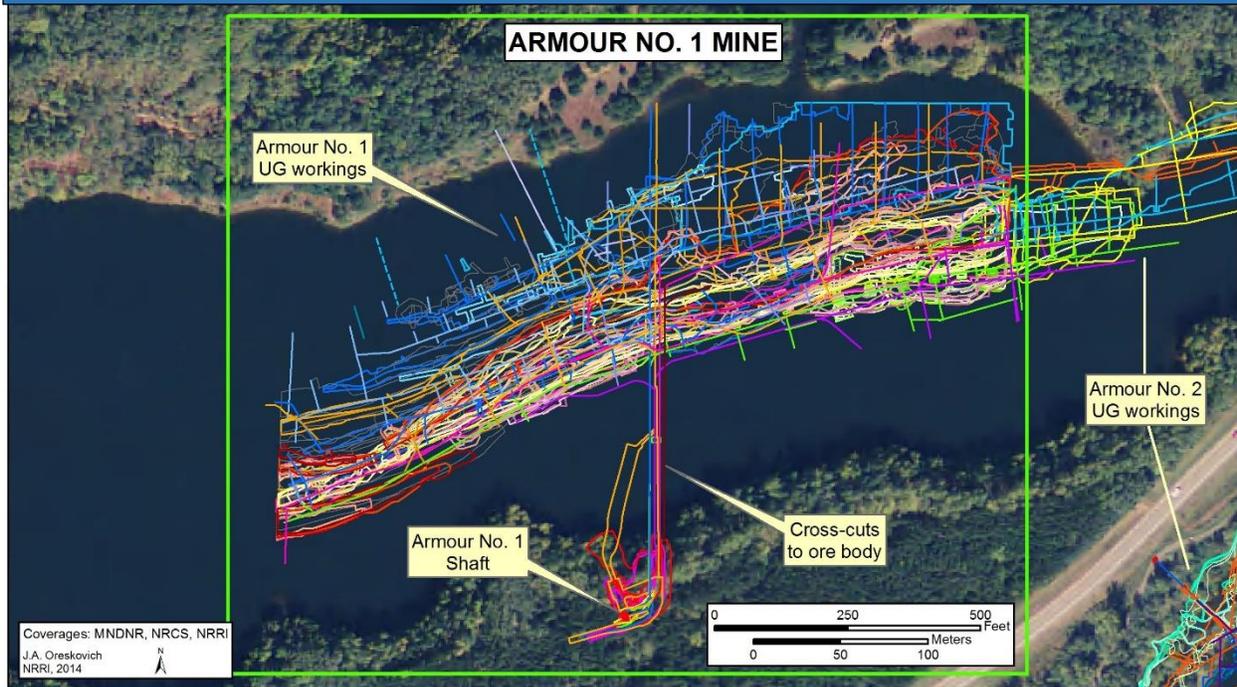


# COMPRESSED AIR ENERGY STORAGE (CAES) IN NORTHERN MINNESOTA USING UNDERGROUND MINE WORKINGS AND ABOVE GROUND FEATURES

by

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*Cover Photo*

A series of mines north of Ironton and Crosby presents an opportunity for linked CAES storage.

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## **EXECUTIVE SUMMARY**

Currently, the only viable means of storing energy on a large scale are through: 1) Pumped Hydro Energy Storage (PHES); 2) Compressed Air Energy Storage systems (CAES); or 3) Liquid sodium sulfide battery systems. Pumped Hydro Energy Storage potential of Minnesota was addressed in a previous study by Fosnacht et al. (2011). Briefly, with CAES, air is compressed during times of low electric energy demand. Later, when the electric demand is greater, the stored compressed air is expanded to drive electric generators. This bulk energy storage technique has energy capacities that range from 10-1,000 MW-hrs. Conventional or diabatic CAES combines mechanical energy storage with combustion turbine technology. The second class of CAES technologies, called Advanced CAES, does not utilize fossil fuel in combustors. These are not hybrid systems, but pure energy systems that are different from Conventional CAES. One advantage of Advanced CAES is that facilities are not dependent on the economic uncertainty of natural gas price volatility and potential carbon dioxide (CO<sub>2</sub>) emission charges. Advanced CAES technologies are emerging technologies, and at the present time no full-scale facilities are in operation.

The goal of this research project is to determine the potential viability, environmental sustainability, and societal benefits of CAES, as a vital, enabling technology for wind turbine-based power generation. The intent of this research is to provide a clear roadmap for CAES development in Minnesota.

This project is multifaceted and draws resources across the University System and from key industrial partners: Great River Energy and Minnesota Power. The results from the project will provide vital information to decision makers on the potential of CAES and give guidance on how the technology can be implemented using the unique assets of the Minnesota' various Iron Ranges (Mesabi and Cuyuna) or in other areas, so that renewable mandates and greenhouse gas reduction can be effectively accomplished.

The results show that the topography and water resources exist at various sites that could allow a 100 to 200 MW facility to be constructed if the overall economic, mineral rights, and environmental issues associated with a given site can be properly managed. This report delves into the possibilities and outlines selection criteria that can be used for site selection. Other information is developed to compare the potential economic impact of implementation of the project within the constraints of the factors that can be monetized using the current policy environment. Finally, potential life cycle, regulatory, environmental, and permitting issues that are associated with implementation of the concept are discussed.

Electric utilities often operate in service areas of substantial size and are impacted by and have impact on the distribution and transmission systems. As a utility seeks to balance generation and load within its system, it may identify energy storage as an opportunity. Privately owned electrical energy storage (EES) by utilities is a major area of development (Byrne et al., 2012). CAES facilities on the order of 10 MW with less than ~10 hours of storage will not impact the operation of the electric transmission system or offer ancillary services to the system. Therefore, the value of such systems may be realized in the environmental value of the technology (carbon-free) or the ability of the technology to provide back-up to intermittent sources when no other back-ups exist.

Large scale industries and communities may have need for energy storage. For example, communities located in remote or isolated regions may benefit from having local storage to ensure electricity is available and affordable in times of need.

The location of the cavern, and therefore, the location of the surface facility, is set by the near surface geology. In all cases of published facility design, the identification and engineering verification, and design of underground storage is the critical first step of the project.

For example, Minnesota has two mining districts, i.e., the Mesabi Iron Range (currently producing iron ore pellets) and the Cuyuna District in central Minnesota that was mined for manganese in the past. Both of these areas have pre-existing surface and underground mining facilities that may be able to provide, with further development, potential to host a CAES facility and/or if underground mining on the Mesabi Range occurs in the future, the new underground workings may be applicable for a CAES facility.

### Facilities and Basic Operational Characteristics

- Compressed Air Energy Storage (CAES) plants compress air when there is an excess of electric energy production and generate electric energy using a turbine when the demand exceeds the production. The storage of compressed air to produce energy in this way is typically done in underground chambers, which could be existing cavities, e.g., mining rooms, drifts, and shafts, or cavities created with this specific purpose, e.g., in salt formations or similar to the underground propane storage facilities, like at the mined Solar Gas storage facility near Erskine in Polk County, northwestern MN. There are three types of CAES facilities:
  - Conventional or Diabatic CAES combines mechanical energy storage with combustion turbine technology. There are only two commercial-scale CAES plants in operation today, one in Huntorf, Germany and one in McIntosh, Alabama. Both facilities are in solution-mined salt domes. There are three types: 1) Low Temperature Adiabatic; 2) High-Temperature Adiabatic; and 3) Isothermal CAES.
  - Advanced CAES Technologies are emerging technologies, and at the present time no full-scale facilities are in operation. Several facilities are planned, and at least three commercially viable systems are in development and expected to be deployed within the next decade.
  - Second Generation Adiabatic CAES consists of an off-the-shelf combustion turbine that produces typically 40% of the total plant output. The other 60% is derived from a conventional CAES system that uses waste heat from the combustion turbine to heat the stored air before expansion.
- CAES facilities participate in financial markets with the ability to participate in the wholesale energy and reliability services markets.

## Location Analyses

- Preliminary estimation of underground air storage requirements for a CAES plant in central and northern Minnesota shows that existing (abandoned) mining shafts and drifts alone on the Cuyuna and Mesabi Ranges would not provide enough air storage capacity for the initially envisioned energy production of 100 MW sustained for 10 hours. The compressed air storage capacity would need to be complemented with new caverns built for this expressed purpose.
- A potential new technology, Hydrostor, appears to have promise in both using mining features (pit lakes) and in reducing the capital and operating costs associated with compressed air energy storage. Many locations both on the Mesabi and Cuyuna iron ranges have been identified which have the characteristics (water depth, closeness to transmission facilities, substations, etc.) that make this technology concept worthy of more detailed study for potential applicability to renewable energy storage in Minnesota. The repurposing of deep pit lakes with minimal environmental impact and with great reduction in capital costs likely make this the most viable option considered, in that cavern creation costs are eliminated and most of the work to bring the air to the storage site can be done by piping without significant rock drilling and land disturbance.
- This study investigated a conceptual design and feasibility evaluation for three CAES facilities: 1) Taconite Ridge; 2) United Taconite CAES; and 3) Cuyuna Range: Armour 1 and 2, as well as other pre-existing underground mines on the Cuyuna and Mesabi Ranges. As noted above, various pit lake locations were also investigated for the Hydrostor technology concept.

## Environmental and Permitting

- The groundwater modeling results are sensitive to values of hydraulic conductivity. Also, boundary conditions must be characterized including: local geology, surrounding water table depth, operating pressures, and how the air will be contained in the projected cavern (lining or a water curtain). The geometry and layout of the cavern are also important parameters for the model and finally, existing groundwater data must be used to calibrate the model. The use of pit lakes for the air storage accumulator may avoid or lower hydraulic conductivity issues.
- New caverns for CAES can be constructed with, steel plates, concrete, or plastic, liners or without a liner, i.e., in unlined caverns, a water curtain can be employed to prevent leakage by choosing a depth such that the hydrostatic pressure of the water surrounding the cavern is equal or greater than the pressure at which the gas is to be stored. Lined caverns can be emplaced at shallow depths provided the balance between the force generated by the internal pressure and downward force associated with the weight of the rock above the cavern is such that the uplift is prevented. A second way to prevent leakage, when no phreatic surface exists or when smaller depths than dictated by a phreatic surface under hydrostatic conditions is desired for the cavern is to use water curtains, i.e., water is injected under pressure (equal to or greater than the pressure at

which the gas is to be stored) in water galleries that surround the cavity. This system requires constant pumping of water during operation and is more expensive.

### Policy, Economics, and Past Attempts

- At the state level, renewable portfolio standards require generation from renewable sources of electricity, but the role of energy storage in renewable portfolio standards is varied, but most focus on generation technologies, not storage capabilities.
- In Minnesota, there has not been specific legislation promoting storage. However, if a CAES project were to be developed in conjunction with wind development, applicable policies related with renewable energy would also be important. In Minnesota, the Renewable Energy Production Incentive (Minn. Statute 216C.41 Subdivision 1-Definitions): “Qualified wind energy conversion facility” is 1.0 cent per kw-h until December 31, 2018, the Renewable Energy Standard (Minn.Stat.216B.1691) and the Energy Policy Goal (Minn. Statute 216C.05 Subd.2): 25% of total energy used in the state should be derived from renewable energy resources by 2025.
- Federal Energy Regulatory Commission (FERC) orders regarding CAES:
  - FERC Order 755 for storage technology requires regional transmission organizations and independent system operators to adopt a two-part market-based compensation method for frequency regulation services—a capacity payment reflecting opportunity costs and a market-based performance payment—rewarding faster-ramping resources, such as batteries and flywheels.
  - FERC Order 784 requires high-voltage interstate transmission operators to recognize the value of energy storage systems that can quickly and precisely dampen potentially dangerous disturbances in electrical frequencies.
  - FERC Order 792 added energy storage to the category of resources eligible to interconnect with the electric grid. Thus, energy storage can receive rates, terms and conditions for interconnection with public utilities that are just and reasonable and not unduly discriminatory.
  - FERC Order 890 requires ISOs to develop tariffs, market rules, and control algorithms, to open markets for non-generation energy storage technologies to provide ancillary services.
- CAES projects are affected by government protocols shaping facility siting. Environmental permitting and approvals by state and federal entities will shape how CAES technologies are developed and deployed. Repurposing of pit lakes for an energy storage facility without the need for two reservoirs using the Hydrostor concept is an interesting variant compared to the other more conventional concepts evaluated in this study.
- As CAES plants store compressed air in subsurface rock formations, the geologic characteristics of the site are paramount for facility operation. This is avoided using the Hydrostor concepts.
- Site selection will affect economic characteristics that will impact facility costs and the cost of electricity. Infrastructure costs, such as access to the high-voltage electric

transmission network and easy delivery of natural gas, will affect the financial viability of CAES.

- The ability of CAES projects to be constructed on the Cuyuna or Mesabi Ranges remain dependent on access to land and mineral rights for cavern based systems. Earlier work on the viability of the PHES project in Mesabi and Cuyuna Ranges (Fosnacht et al., 2011) addressed this issue, “The largest mineral rights owner and a major landowner is the State of the Minnesota. Purchasing the land to build a CAES facility is complicated by the fact that property rights may be severed, which means that landowner may not hold the mineral rights.” These issues remain important for any CAES development. Repurposing of pit lakes for accumulators will require smaller land disturbance for the compressor and turbine generator and auxiliary facilities, but will not require below ground or above ground disturbance for the air accumulators.
- The Minnesota Public Utilities Commission (MPUC) is the permitting authority for any future CAES plant. However, MPUC does not provide a specific guideline for CAES facility because this authority is still investigating the CAES technologies and their implications. Instead, they provide general guidelines for any large energy facility proposed. The general process of permitting is explained in Section 2 of this report.
- Despite CAES technologies having the potential to create benefits for the power system, there are currently numerous barriers to their deployment. Price is clearly a barrier, with CAES technologies significantly more expensive than the alternatives that are currently in use, but there are also regulatory barriers that could be addressed to incentivize deployment of compressed air energy storage. Some of these potential regulatory changes, such as creating electricity markets where price is a function of power quality, as well as power quantity, are longer term issues, but there are other regulatory barriers to storage that could be addressed now. CAES coupled with a wind farm could be made eligible to receive renewable energy credits under Minnesota’s Renewable Energy Standard, similar to its treatment in Michigan. Operating costs may be reduced with the Hydrostor concept due to reduced initial capital and financing charges associated with this hybrid of PHES and CAES.
- At the present, high market entry barriers prevent CAES from seeking additional revenue in the market even though CAES has ability to provide various ancillary services. Some systems can be operated as floating reserves to provide ancillary services and this could aid market penetration.
- The future viability of CAES will depend on the extent to which public utility commissions and electricity market operators establish rules that internalize system-wide costs, looking at CAES as a part of a resource portfolio that serves a range of valuable functions.
- Potential CAES projects will need to not only show that their project has value but also be able to show that value in a way that can be inputted into the models used by the appropriate regulating body for that area.
- There are a range of energy planning models looking at very short time frames to decades-long time frames. The long-range models are assessing generation capacity expansion needs for 15 to 30 plus years out. Some examples of this type of model are EGEAS from EPRI, and System Optimizer or Strategist from Ventyx. When looking at shorter time frames, models such as PSS\E are used to assess power flow and dynamic conditions of

the grid in static snapshots and evaluate for operational robustness. Other short-term models evaluate economically how a specified portfolio of generation resources will perform. The complexity of these models, such as PROMOD or PLEXOS, requires long run times (50-plus hours) to examine individual scenarios.

- When a CAES facility is coupled with a wind farm, the CAES facility qualifies to get renewable energy production incentive (Minn. Statute 216C.41). Interestingly, the storage facility does not have to be at the wind farm location to effectively store wind or solar generated energy. There is a debate on the best location for storage facilities (near generation or near the consumers of the electricity).
- Compatibility with present and future mining is a key objective in siting and designing compressed air storage energy (CASE) project in the northern Minnesota. This area offers many advantages for a CAES project, including preexisting mining space that could be used as a cavern, the hard rock structural features that facilitates stable cavern creation, or the repurposing of mining created pit lakes for underwater accumulators.
- This report outlines a framework for assessing the compatibility of potential CAES sites with present and future mining. The premise is that: 1) CAES plants would need to be insulated from the effects of current and future mining; 2) engineering techniques are available that could achieve this insulation in many cases; and 3) building a CAES project that can coexist with mining will require additional land and engineering beyond what's needed for power production for total land based solutions. Use of pit lakes for accumulators is a new concept that could reduce compatibility issues.
- Nearby mining could harm a CAES project primarily through blasting and the possibility of leakage. This is avoided with accumulators located deep underwater in an existing pit lake.
- Using a mine as a CAES reservoir adds significant financial risk due the possibility of leakage that takes considerable time and money to correct. Permitting processes will likely require that these types of potential impacts be addressed. Should such damages occur, legal remedies could be sought, but lawsuits are costly and holders of mineral rights typically have precedence. Selecting a site that would never fall within the area of influence of current or future mining would be ideal, but this is only realistic in northern Minnesota using the pit lake option because mineral deposits are widespread. A more feasible and secure approach is to site and design the plant so it is insulated from nearby mining or uses non-land features that insulate the CAES facility from mining disturbance.
- Minimizing blast vibration damage might be achieved through inclusion of a blast buffer (size according to the geologic properties of the site). Blast buffers on the range of 2,000 to 3,000 feet are reported in the LVP (Laurentian Vision Partnership, 2002). Where active mining or future mining could approach closer than the necessary buffer, techniques such as pre-splitting could be utilized. The pit lake option will use the deep water to reduce blast vibration impacts.
- For CAES projects to coexist with mining in northern Minnesota further detailed evaluation of mining plans must be undertaken. Two categories of additional costs must be estimated, both based on the preferred geotechnical options to minimize impacts from blasting and dewatering: 1) the costs of additional design and construction work (described above); and 2) the costs of additional property acquisition. CAES projects in

northern Minnesota will need to buy or lease surface and mineral rights for both for the project footprint, encompassing the reservoirs and surface facilities, and for a buffer zone needed to insulate the project from current or future mining. If the pit lake option is considered, it may be possible to lower accumulator construction costs by temporarily pumping the water to an adjacent lake to store the water during construction of the accumulators and to then backfill the reservoir. This would require careful assessment of impacts even though they would be of a temporary nature.

- The methods for implementing CAES will vary depending on whether it is an independent CAES or it is coupled with a wind farm. In addition, the difference of on-peak price and off-peak price, the price of natural gas, location, and ownership all affect the value of CAES. Not only arbitrage revenue; revenue from ancillary service market will also improve the profitability of CAES.
- The economic and policy literature on CAES can be divided into two classes. The first class focuses on the value of independent CAES. The second class deals with the value of CAES with wind integration.
- The difference between on-peak price and off-peak price and the volatility of price for natural gas and electricity have raised interest in the potential economic value for electricity storage. Some of the storage options uncovered in this study need further detailed evaluation with the use of pit lakes as the most promising option.
- Potential benefits from CAES would be congestion relief, deferred transmission, and better grid and asset utilization.
- Compared with pure storage devices, the CAES device purchases 44% less energy, choosing from lower cost hours. Drury et al. (2011) estimated the value of CAES, considering both operating reserves revenue and arbitrage revenue, in several U.S. markets. They found that conventional CAES systems could earn an additional \$23±10/Kw-yr by providing operating reserves, and adiabatic CAES systems could earn an additional \$28 ±13/Kw-yr. They also found that arbitrage-only revenues are unlikely to support a CAES investment in most market locations, but the addition of reserve revenues could support a conventional CAES investment in several markets. Adiabatic CAES revenues are not likely to support an investment in most regions studied.
- Most studies on CAES with wind integration suggested that the CAES plant is likely to be unprofitable. More detailed study on the pit lake option with its reduced capital costs needs to be undertaken to fully appreciated the cost reductions associated with this option.
- For various price scenarios, most CAES plants are unprofitable, considering CAES has a relatively high operation cost per kW installed and the major revenue of CAES are from arbitrage and ancillary service revenues. Major key issues affecting the value of CAES plants are the following: 1) natural gas price; 2) the type of plant – Independent CAES plant or coupling CAES plant with a wind farm; and 3) uncertainties in the price of electricity. Technical factors affecting the value of CAES are heat rate, energy ratio (energy efficiency factor), power ratio (power efficiency factor), ramp rate, response time, and storage duration period. Financing factors affecting the value of CAES are capital costs, real estate and taxes, construction, and permitting period. Some systems have heat recuperations systems that greatly impact round trip energy efficiency. Efficiencies

approaching 85% can be possible with the heat capture technology. This efficiency, coupled with the lower costs capital charges for creating underground storage facilities, may allow better profitability to be attained with the pit lake accumulator concept than the fully land based options.

- Within the system as a whole, the impact of energy storage technologies like CAES will depend on the value of the energy services they provide compared to alternatives.
- In some states, such as California, energy storage is mandated as more and more renewable energy is brought on stream. There are no such mandates in Minnesota or with the Midwest System Operator Area at the current time. Development of future mandates may be a key facilitation step for allowing adoption of this technology.
- Future planning between power companies and mining operators also can potentially facilitate the use of CAES in the future. As in the PHES study, sites exist that may favor the use of underground mining to recover iron ore and manganese resources on the Mesabi Range or the Cuyuna Range, respectively. The recovery of ore from these sites may help lower the cost of cavern creation for a future CAES facility after the mining has completed mineral extraction. Significant cooperation is required from a long term perspective to allow this secondary use of the mined facility to be considered. The use of existing features such as the myriad of deep pit lakes that exist on both iron ranges is a unique situation for Minnesota and warrants further consideration because it eases the need for close coordination between the mining and power companies.

### **Final Conclusions of this Study**

The overall results of this study have shed new light on what would be involved in adopting compressed air energy storage in Minnesota. Equally important, the study informs various topics that clearly must be considered for any site on a regional basis that must be considered for future adoption of this type of storage capacity. As noted, policy, permitting, geology, facility types, and facility advancements will impact future adoption strategies.

Compressed Air Energy Storage is a major energy storage technology that has been in discussion for several decades, but only a small number of conventional systems exist today. CAES is a promising technology that offers scalable, clean, and flexible electrical energy storage but has market barriers resulting from gaps in technology, policy, and energy economics. The need for underground storage caverns compounds the complexity of a project because it severely limits sites to specific locations and engineering of underground structures is expensive for larger facilities. The repurposing of already existent pit lakes to hold air accumulators at deep water depths is a promising concept that could facilitate adoption of CAES in Minnesota. Smaller-scale systems may find easier siting and application depending on local needs for secure energy availability for both land and pit lakes locations.

Advanced CAES technologies are still in the development phase. Adiabatic CAES is developing by incorporating both standard and novel methods for storing and using the heat of compression. Isothermal CAES is advancing through the development of new heat transfer technologies. Technology leaders are working on scalable above ground compressed air storage systems that would free CAES from geographical restriction. These advances will open up new possibilities for

CAES. The new concept of Hydrostor is a hybrid concept that couples water pressure in facilitating storage of high volumes of air for power generation and is one that can use locations that likely could give Minnesota a unique position for facilitating renewable energy growth in the Midwest region as an electricity storage center for the Midwest region.

The energy economics of CAES must be considered from local, regional, and national perspectives. CAES plants seek to have financial models that are sustainable. The selection of the type of CAES platform (i.e., conventional versus advanced) is an iterative process that must consider engineering design, electrical transmission system, plant dispatch model and economics, as well as the environmental resource impacts of the facility. The participation of the CAES facility in energy markets is very dependent on the local and regional location of the facility. Basic questions that need to be considered include: 1) Does the electric utility operating the transmission systems in the area have a need for energy storage, and what services are needed? and 2) What are the specific markets and market rules available to the facility via the Independent System Operator? Understanding the energy storage needs of a region and understanding the market opportunities for specific energy and ancillary services are key factors to establishing the primary design and operational goals of the CAES facility.

Four hypothetical CAES facilities were examined. The three sites were selected to illustrate the range of CAES application. Site 1 is the Taconite Ridge CAES facility and is a small facility with capacity of 7.5 MW for five hours using a near-isothermal CAES technology. Site 2 is the UTAC CAES facility with a capacity of 136 MW for eight hours using conventional CAES. The underground cavern for the site will be co-developed during the mining of a large ore body located ~1,200 ft. below the surface. Site 3 is the Cuyuna CAES facility utilizing an existing, but abandoned, mine works located at 800 ft. below the surface. Site 4 is the use of the many pit lakes that were created by past mining activities. The first two sites demonstrate possible feasibilities and the range of complexities involved in CAES design. The third situation was not found to be feasible with the complex nature of the shafts and drifts involved in the two mines considered. The fourth site(s) appears to have the best possibilities for energy storage at any of the capacities noted. Many compatible pit lake sites have been identified for potential further evaluation. Specific capital cost estimates were made for the first two sites on a broad range basis based on literature estimates. The capital costs of the fourth site option (pit lakes) was not done in detail, but the above-ground facilities will be similar to options one and two; however, the accumulator and air transmission costs to the accumulator will be greatly reduced using the deep water option.

At this point in time, it does not appear that a large-scale, land based (including cavern creation) CAES facility is viable in northern Minnesota. The use of the hybrid option incorporating a pit lake to hold the air accumulator may be the most practical option. This option needs a more detailed engineering study to fully determine its applicability. Minnesota Power has developed transmission infrastructure and balancing capabilities to meet their current and future needs. There are no obvious existing underground caverns available, and the co-development of a cavern along with ore-mining is possible but will be a challenging endeavor that will involve active cooperation between the power developer and the mining company. Advanced CAES technologies are still developing, and because of their scalability (small to large) and use of above ground storage, they remain a possible future technology for very site-specific applications. For example, a community or industry that has very localized energy surplus or deficit could take

advantage of a small CAES plant. Presently, no commercially available Advanced CAES facilities exist, and stakeholders will need to continue to monitor this area of high technology. Northern Minnesota does possess competent rock strata that could allow creation of an underground compressed air storage system, but economics and policy considerations need to become more favorable and renewable energy portfolios for the state likely have to reach much higher levels than the current 25% target that is set for the state.

The pit lake option, as noted, needs to be investigated more fully. Fortunately, this concept is under demonstration by Ontario Power at the 1 MW level off Toronto Island using Lake Ontario as the deep water accumulator site. Discussions with the developer of this facility and with Ontario Power should be a follow-up discussion for the future as the technology experience is fully elucidated.

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**CHAPTER 1:****INVESTIGATION INTO COUPLING LEGACY AND FUTURE  
UNDERGROUND MINING ACTIVITIES IN MINNESOTA WITH CAES****Geology Team**

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**Synopsis**

The purpose of this study was to investigate whether Minnesota’s mining activities, past, present, and future, could be coupled with compressed air energy storage (CAES) to meet today’s need for energy alternatives and on-demand energy production. To this end, legacy underground mine workings on the Cuyuna Range in central Minnesota and the Mesabi Iron Range in northeastern Minnesota were evaluated for suitability as CAES storage caverns, as were sites for CAES cavern development in concert with mining ore. Three potential site-specific mining-related CAES scenarios in Minnesota were selected for in-depth investigation by the full project team. The three scenarios are: (1) Above-ground CAES storage (low volume storage); (2) Mining a mineral resource to produce a CAES storage cavern (high volume storage); and (3) Use of legacy underground mining features for CAES storage (medium volume storage).

**Section 1.0:  
Executive Summary**

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## EXECUTIVE SUMMARY

Minnesota has been the largest producer of iron ore in the United States for more than a century. From the opening of the Soudan Mine in 1884 to the taconite mines of today, iron ore mines have been carved into and under vast tracts of the Minnesota countryside. Ore production comes from three distinct ranges, the Cuyuna, Mesabi, and Vermilion, located in central and northeastern Minnesota. Each range has been mined by both open pit and underground mining methods.

The purpose of this study was to investigate whether Minnesota's mining activities, past, present, and future, could be coupled with compressed air energy storage (CAES) to meet today's need for energy alternatives and on-demand energy production. To this end, legacy underground mine workings were evaluated for suitability as CAES storage caverns, as were sites for CAES cavern development in concert with mining ore. Three potential site-specific mining-related CAES scenarios in Minnesota were selected for in-depth investigation by the full project team. The three scenarios are:

1. Above-ground CAES storage (low volume storage);
2. Mining a mineral resource to produce a CAES storage cavern (high volume storage); and
3. Use of legacy underground mining features for CAES storage (medium volume storage).

Above-ground storage has been linked with a small wind farm located on mining company property on the Mesabi Range. Also on the Mesabi Range, drill hole data was used to site a potential underground mine/CAES storage cavern based on ore units found at depth down dip from current open pit mining activities. Other select caverns in/near Minnesota are also discussed. Features of underground mines on the Cuyuna Range, documented in GIS format for this study, were selected for closer evaluation of their suitability for CAES storage.

The above scenarios/sites are presented herein, together with the main body of work performed as this part of the study, the mapping of the underground features of the Cuyuna Range to provide a basis for assessment. While much work has been done to document the underground workings of the Mesabi Range, comparable work had not been undertaken for the Cuyuna and Vermilion ranges. To do so entailed locating and retrieving historical maps and documents, converting the maps to digital format via scanning, geo-referencing the maps, and digitizing the underground mining features. Pertinent structural information was researched to accompany the mapped workings. Mine mapping was restricted to the Cuyuna Range for this project due to central location and proximity to major power transmission lines; however, historical data regarding Vermilion Range underground mines was also acquired so that the underground features of all three iron ranges could be presented.

**Section 1.1:  
Potential Scenarios for CAES in Minnesota**

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## INTRODUCTION

Energy storage is a necessary part any equation allowing alternative energy sources (wind, hydro, etc.) to actively compete with hydrocarbon fuels in their ability to produce on-demand electrical power. As part of an initiative seeking ways to increase the use of alternative energy sources in Minnesota by the year 2025, NRRI looked into the potential of using legacy mining features on the Mesabi Iron Range for Pumped Hydro Energy Storage (PHES) (Fosnacht et al., 2011). A similar course of investigation into the use of legacy mining features for Compressed Air Energy Storage (CAES) was pursued for this project.

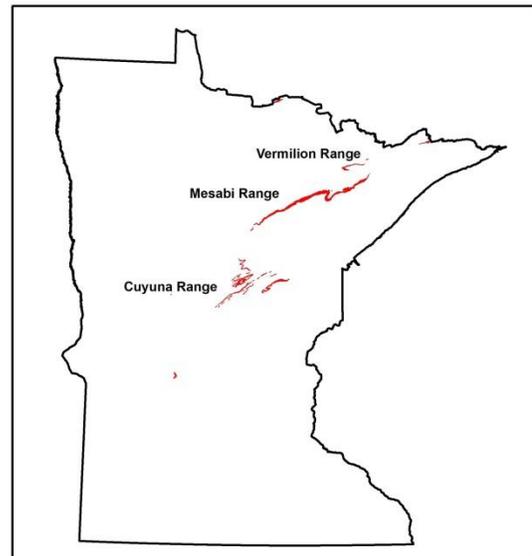
## PURPOSE AND SCOPE

Similar to the PHES study, the purpose of this study is to identify those legacy mining features that hold potential for use in a CAES system. A Geographic Information System (GIS) approach was used to capture, study, and display the available data. In addition to legacy features, current and potential future mining and mineral-related activities were also looked at for CAES potential.

The scope of this project encompasses Minnesota's three iron ranges located in central and northeastern Minnesota. Initially designed for the Mesabi Range, the project area was expanded to include the Cuyuna and Vermilion ranges (Fig. 1.1-1). Mine workings of the Cuyuna Range, like those of the Mesabi Range, lie in relatively close proximity to major electrical transmission lines, an important economic consideration for CAES. These lines can transport excess energy from any source (fossil fuel, wind, hydro, etc.) and any distance to a CAES storage facility and deliver on-demand energy from it. Vermilion Range mines are more remotely located from major transmission lines.

Beyond legacy features, this study also takes a look at current and future opportunities to couple CAES storage with mining activity in the state. There are several advantages to doing so:

1. The mining industry is a major power consumer and therefore, has a vested interest in power supply and uninterrupted power delivery;
2. Mines control large tracts of lands, not all of which are purposed to actual mining. Land is required for processing activities, stockpiles, settling basins, tailings basins, buffers and more. These lands undergo a thorough environmental review prior to the issuance of permits; and
3. Mining an underground orebody to create a CAES cavern to spec would offset the cost of cavern excavation as a saleable commodity is produced in the process.



**Figure 1.1-1.** Minnesota's iron ranges.

## **PROJECT WORK**

The bulk of this project was devoted to creating a digital GIS framework of underground mining activity on the Cuyuna Range of East-Central Minnesota. This work entailed locating, retrieving and scanning mine maps, geo-rectifying these maps, digitizing mine features, documenting feature attributes, researching structural details, and generating 3-D models for more detailed evaluation, where applicable. Comparable work has already been done for over two-thirds of the Mesabi Range. Together these studies provide a basis for CAES site determinations.

CAES scenarios and representative sites were selected for in-depth study by the full project team. These scenarios will be presented at the forefront of this report, prior to delving into details of the study itself.

## **PROJECT DELIVERABLES**

Project deliverables are detailed at the beginning of Section 1.2. Deliverables include a database of Cuyuna Range underground mines, GIS coverages of Cuyuna Range underground mines in shape file and geodatabase format, mine maps in PDF and JP2 or Tiff format, and a selected bibliography for the Cuyuna Range.

## **DISCLAIMER**

It must be noted by users of the data herein that the coverages produced are only as good as the maps that were found. While they represent a fair view of the mining activity that took place, they should not be assumed to be complete. Ground-truthing by GPS, geophysical means, and borehole drilling are a necessary part of any site evaluation.

The University of Minnesota does not warrant or guarantee that there are no errors. Users may wish to verify critical information. In addition, every effort has been made to ensure that the interpretation conforms to sound geologic and cartographic principles; however, no claim is made that the interpretation is rigorously correct.

## **ACKNOWLEDGEMENTS**

The author would like to gratefully acknowledge the assistance of Peter Clevestine, Dale Cartwright, and Jim Sellner of the Minnesota Department of Natural Resources Division of Lands and Minerals (MN DNR-LAM) in Hibbing, MN; Bob Wagstrom of the Minnesota Department of Revenue (MDOR) Minerals Tax Office in Eveleth, MN; Roger Johnson and Gary Liubakka of Great Northern Iron Ore Properties (GNIOP); Greg Lindahl and Beth Hooper of Superior Mineral Resources LLC; Christopher Welter, Archivist, and Claude Clarke, Archives Assistant, of the Iron Range Research Center (IRRC) at the Minnesota Discovery Center in Chisholm, MN; Steve Weber, Minnesota Department of Natural Resources (MN DNR), Manager, Cuyuna Country State

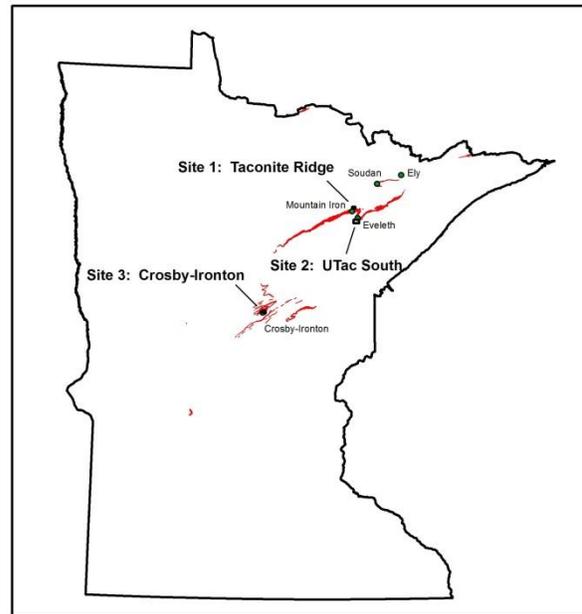
Recreation Area (CCSRA) in Ironton, MN; and Paul R. Coyle of the U.S. Department of the Interior Office of Surface Mining Reclamation and Enforcement (OSMRE), National Mine Map Repository (NMMR) in Pittsburgh, PA. In particular, the author would like to acknowledge the contributions of Richard (Flippo) Valentino of Black River Falls, WI and formerly of Crosby-Ironton, MN and Frank Oreskovich (deceased), formerly of Black River Falls, WI and Crosby-Ironton, MN toward understanding the mining methods and activities at the Armour No. 1 and Armour No. 2 underground mines in Crosby-Ironton, MN where both worked many years as miners.

## POTENTIAL SCENARIOS FOR CAES IN MINNESOTA

Based on the underground mine mapping results and on findings from the various project teams, three scenarios for CAES in Minnesota were selected for in-depth study. These scenarios offer opportunities for low, medium, and high volume compressed air storage while embracing the “green” concepts of alternative energy, repurposing, and recycling. Each scenario has been partnered with a specific site locality to enable detailed study from a geotechnical and facilities aspect. Each site is within reasonable proximity to existing major electrical transmission lines to facilitate energy delivery and uptake. The selected sites are presented here in detail. Additional sites and concepts are presented as well.

The three scenarios and their selected evaluation sites (Fig. 1.1-2) are as follows:

1. Above Ground CAES Storage – Taconite Ridge Wind Farm, Mesabi Range;
2. Excavated Cavern By Mining a Mineral Resource – United Taconite South property, Mesabi Range; and
3. Use of Legacy Mining Features:
  - a. Mine shafts and drifts – Armour No. 1 and Armour No. 2 underground mines, Cuyuna Range; and
  - b. Mine shafts in series – Armour No. 1, Armour No. 2, Thompson, Meacham, and Croft mine shafts, Cuyuna Range.



**Figure 1.1-2.** Potential CAES scenario location map.

## SCENARIO 1: ABOVE-GROUND CAES STORAGE (LOW VOLUME STORAGE FACILITY)

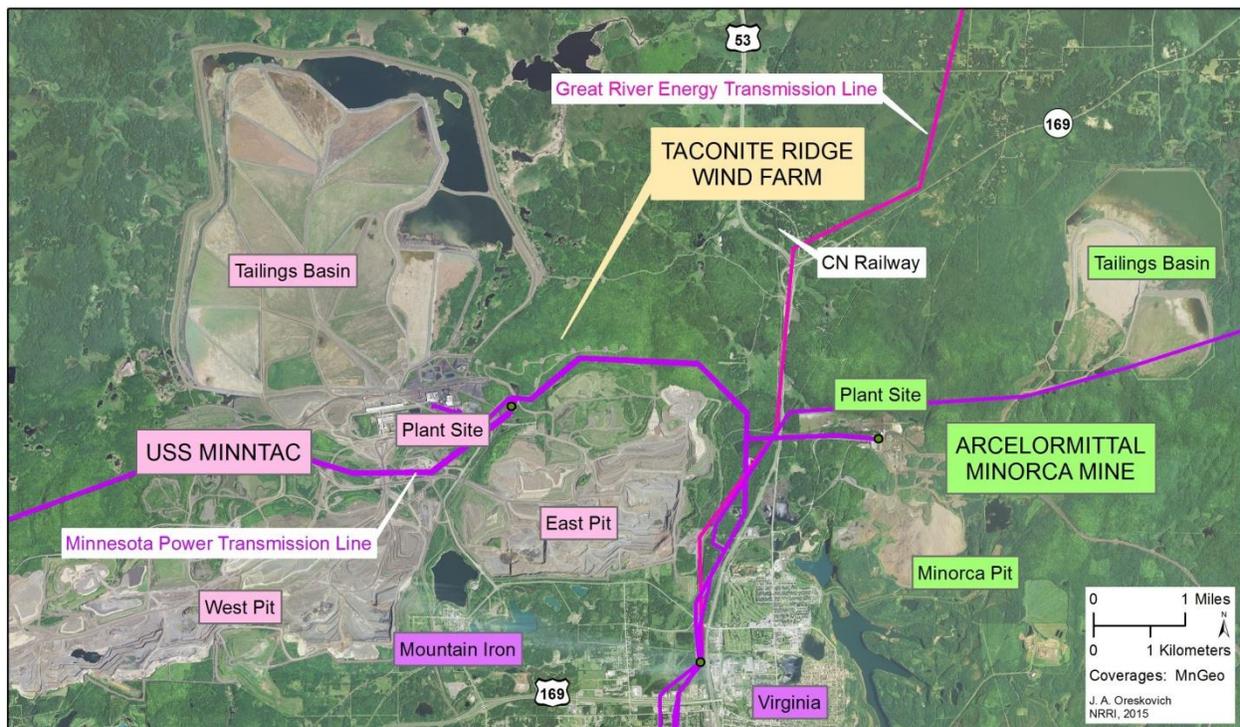
### Taconite Ridge Site

The Taconite Ridge Wind Farm (Fig. 1.1-3, Fig. 1.1-4) is located on U.S. Steel’s Minntac Mine property on the Mesabi Range in northeastern Minnesota. This site offers the opportunity to investigate the use of small, above-ground, CAES units coupled with wind generation. Taconite Ridge Wind Farm was developed and is owned by Minnesota Power. U.S. Steel is Minnesota Power’s largest power customer (Allete, 2008).

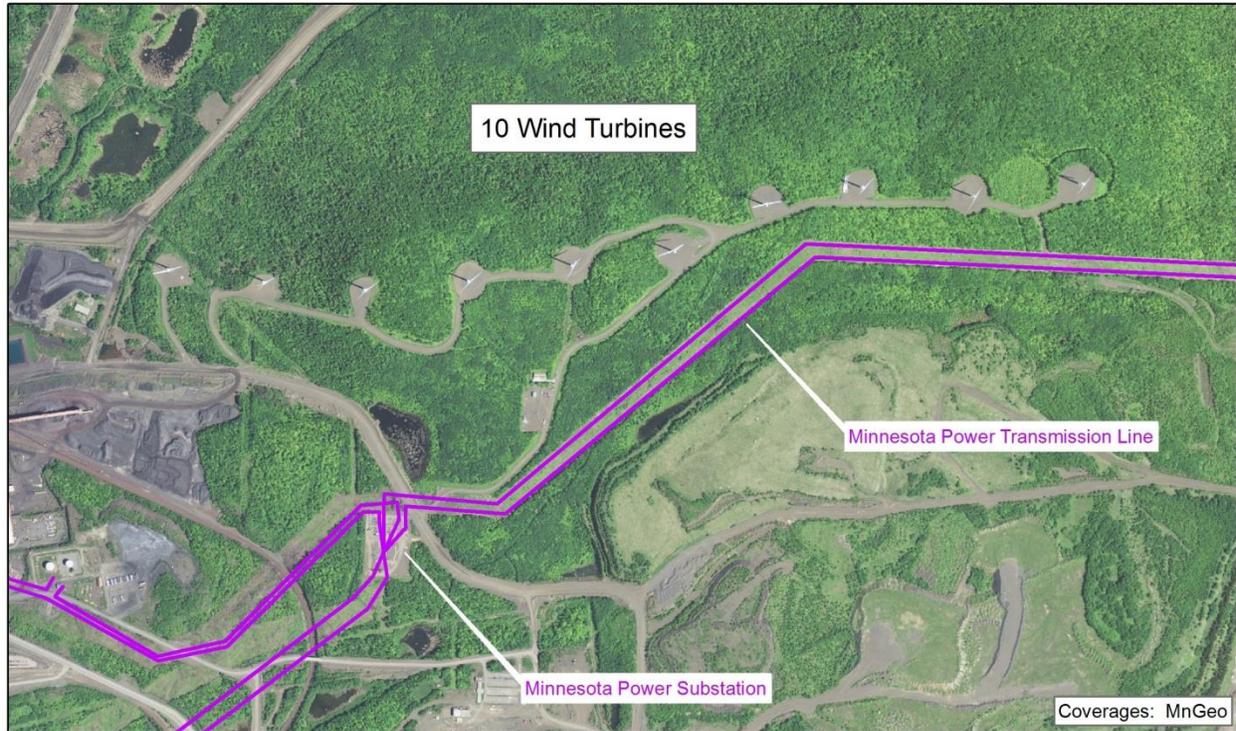
Situated on the Laurentian Divide, just north of the cities of Mountain Iron and Virginia, Taconite Ridge hosts ten 2.5 megawatt (MW) wind turbines for up to 25-MW generating capacity (Minnesota Power, 2007). The turbines stand 265 feet (80 meters) tall (Allete, 2008). Each turbine has three 140-foot-long blades (Ramsay, 2008).

The Taconite Ridge site has been evaluated for up to 10 MW for 1-3 hours, roughly one-third the generating capacity of the turbines (see Facilities Team study, Chapter 3, this report). This scenario allows for direct on-site coupling with wind generation.

Minntac is the largest taconite mine and production facility on the Mesabi Range. Its property straddles the Laurentian Divide, which in this locale separates waters flowing north to Hudson Bay from those flowing east to the Great Lakes and St. Lawrence River. The pit and plant operations lie south of the divide, while the tailings basin resides north of the divide.



**Figure 1.1-3.** Location map of the Taconite Ridge Wind Farm.

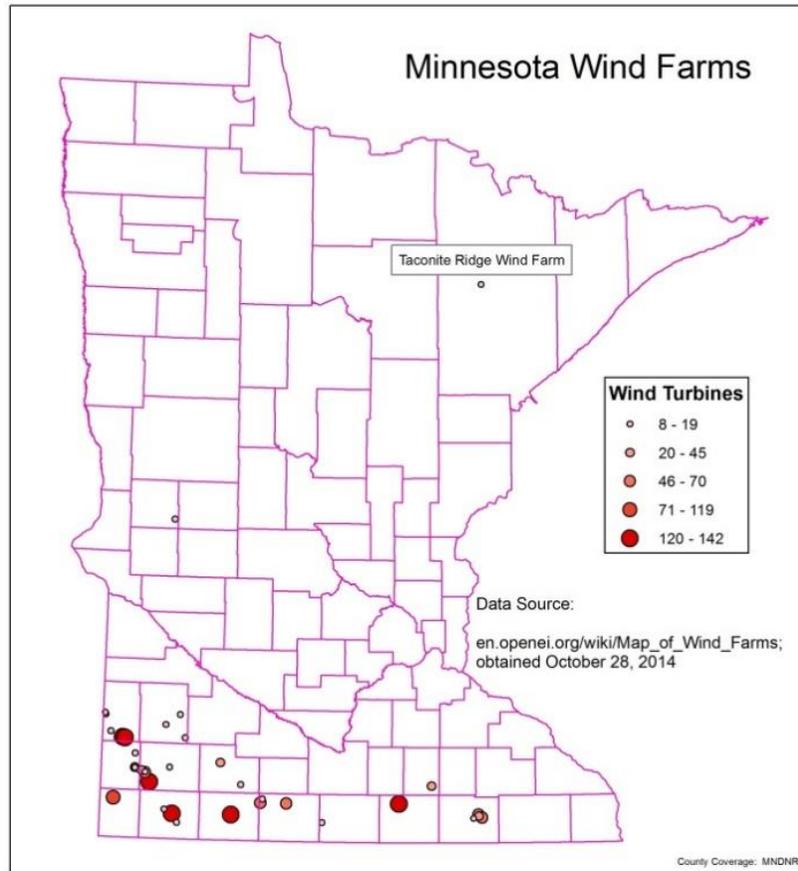


**Figure 1.1-4.** Closer view of the 10 wind turbines on Taconite Ridge.

### **Minnesota Wind Farms**

Wind farms (classified here as those with eight or more turbines) in Minnesota are found almost entirely in the very southern part of the state (Fig 1.1-5). Geographic factors easily play into this with wide-open expanses and unobstructed wind flow from out of the Plains. Taconite Ridge is an aberration in the forested northern part of the state. Its existence is owed to the continental Laurentian Divide that forms the backbone of the Mesabi Range.

Taconite Ridge is among the smaller wind farms in Minnesota at ten turbines. According to the website [http://www.thewindpower.net/zones\\_en\\_4\\_minnesota.php](http://www.thewindpower.net/zones_en_4_minnesota.php) (2015), there are 50 wind farm sites in Minnesota with 8 or more turbines. The largest wind farms have from 134 to 142 turbines and can generate up to 205.5 MW.



**Figure 1.1-5.** Location of wind farms (eight or more turbines) in Minnesota.

## **SCENARIO 2: EXCAVATED CAVERN BY MINING A MINERAL RESOURCE (HIGH VOLUME STORAGE FACILITY)**

The second CAES scenario investigated is the potential to mine a Minnesota orebody by underground methods to create a compressed air energy storage cavern. A similar scenario was looked at during the PHES study, where the underground cavern would become the lower reservoir of a pumped hydro system. Ideally, mining an orebody would generate revenue from a saleable commodity that, in turn, would off-set the cost of producing the energy storage cavern. Also, in eco-friendly terminology, an underground mine would be repurposed into an energy storage facility.

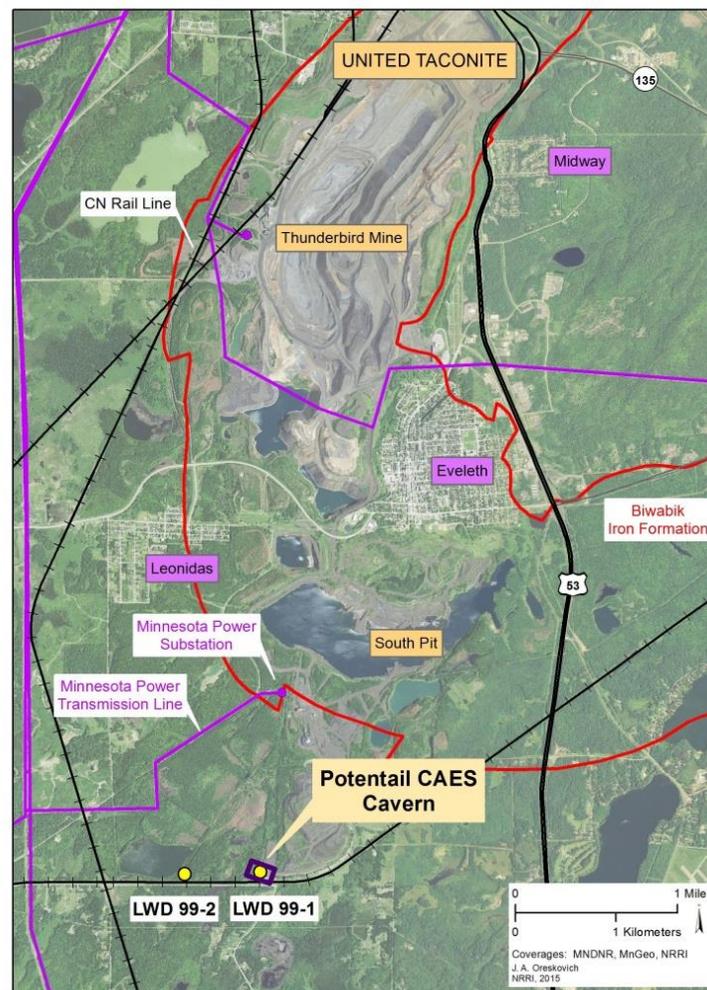
### **United Taconite South Site**

Findings by the Facilities Team determined that a 486,000 m<sup>3</sup> cavern at a minimum depth of 1,000 feet be employed for an industry standard CAES facility with a capacity of 136 MW for 10

hours. Said depth would allow a cavern to better contain and withstand the internal and external stresses of compressed air storage and release.

Based on drill holes LWD 99-1 and LWD 99-2, a site meeting the 1,000-foot-depth criterion while hosting a potential orebody was identified. It lies south of United Taconite's open pit mining operation near Eveleth (Fig. 1.1-6). This same site was looked at during the PHES study (Severson, 2011). Under a similar scenario, the ore would be mined underground to generate a lower water reservoir. In a pumped hydro system, it could be paired with United Taconite's water-filled South Pit, a potential upper reservoir (Fosnacht et al., 2011). Depth to the potential orebody would yield a generous head (elevation difference between the upper and lower reservoir) to drive on-demand electrical power as needed.

LWD 99-1 and LWD 99-2 are deep holes that were re-logged by NRRI geologists as part of a study investigating the geologic and stratigraphic controls of the Biwabik Iron Formation (BIF) (Severson et al., 2009). LWD 99-1 had been drilled to a depth of 1,350 feet; LWD 99-2 to over 1,380 feet.



**Figure 1.1-6.** Location map of investigated site for CAES cavern excavation.

Located down-dip from United Taconite's pit, these holes encounter BIF units at depth that were/are mined as ore within the pit. Severson et al. (2009) identified these same ore units within the drill core. The term "ore" implies economic viability of the rock resource. Whether or not these units at depth actually prove to be of ore grade remains to be determined.

Drill hole LWD 99-1 contains three potential taconite ore units:

1. Upper Cherty (UC) from 673-791 feet (118-foot thickness);
2. Uppermost Interbedded Chert (IBC) from 852-906 feet (54-foot thickness); and
3. Lower Cherty (LC) from 1,064-1,257 feet (193-foot thickness).

Neighboring drill hole LWD 99-2, located approximately 2,470 feet (753 m) to the west, also contains three potential ore units:

1. UC from 748-798 feet (50-foot thickness);
2. Middle IBC from 954-1,004 feet (50-foot thickness); and
3. LC from 1,136-1,381 feet (245-foot thickness) (Severson, 2011).

The BIF generally dips 7°-15° to the southeast (Severson, 2010). However, the location of LWD 99-1 and LWD 99-2 on the southern axis of the broad regional fold known as the Virginia Horn appears to skew the dip direction to the southwest and possibly even to the west for LWD 99-2 (Jirsa et al., 1998; Fig. 1.1-7). The two drill holes also appear to reside in different blocks of thrust rock that are separated by the Dorr Fault. If the Dorr Fault is inferred to continue southward at the shown trend, it would pass to the west of LWD 99-1. Determining whether the fault extends this far south and how deep it penetrates will require further drilling.

A CAES cavern design for the United Taconite South site was provided by Dr. C. Carranza-Torres (Geotechnical Engineering Team, pers. comm., April, 2015). The design calls for room and pillar construction at a depth of 1,200 feet (366 m). To attain the Facilities Team's proposed volume of 486,000 m<sup>3</sup>, four main storage caverns would be excavated in the taconite ore, each 810 feet long x 50 feet wide x 100 feet high. Separating the four caverns are three unmined rock pillars, each 100 feet wide. Through the center of each rock pillar, a cross-cut storage drift measuring 50 feet wide x 100 feet high would be excavated.

For simplicity, and because there are no deep drill holes located immediately to the east, the proposed cavern has been centered on drill hole LWD 99-1. The long direction of the proposed cavern in the accompanying figures has been aligned with the trend of the orebody in the fault block within which LWD 99-1 presumably resides (Fig. 1.1-7, View A). Centering the cavern on LWD 99-1 precludes taking into account the likely proximity of a fault zone. Pending further geological investigation, the facility could be shifted eastward and/or up- or down-dip.

### *Positive site attributes*

Figure 1.1-8 illustrates positive factors for placing a CAES facility in this vicinity. This site is served by a major Minnesota Power electrical transmission line and substation within 1.25 miles

of the proposed facility. There is road access to the site from County Hwy. 7 to the west and U.S. Hwy. 53 to the east.

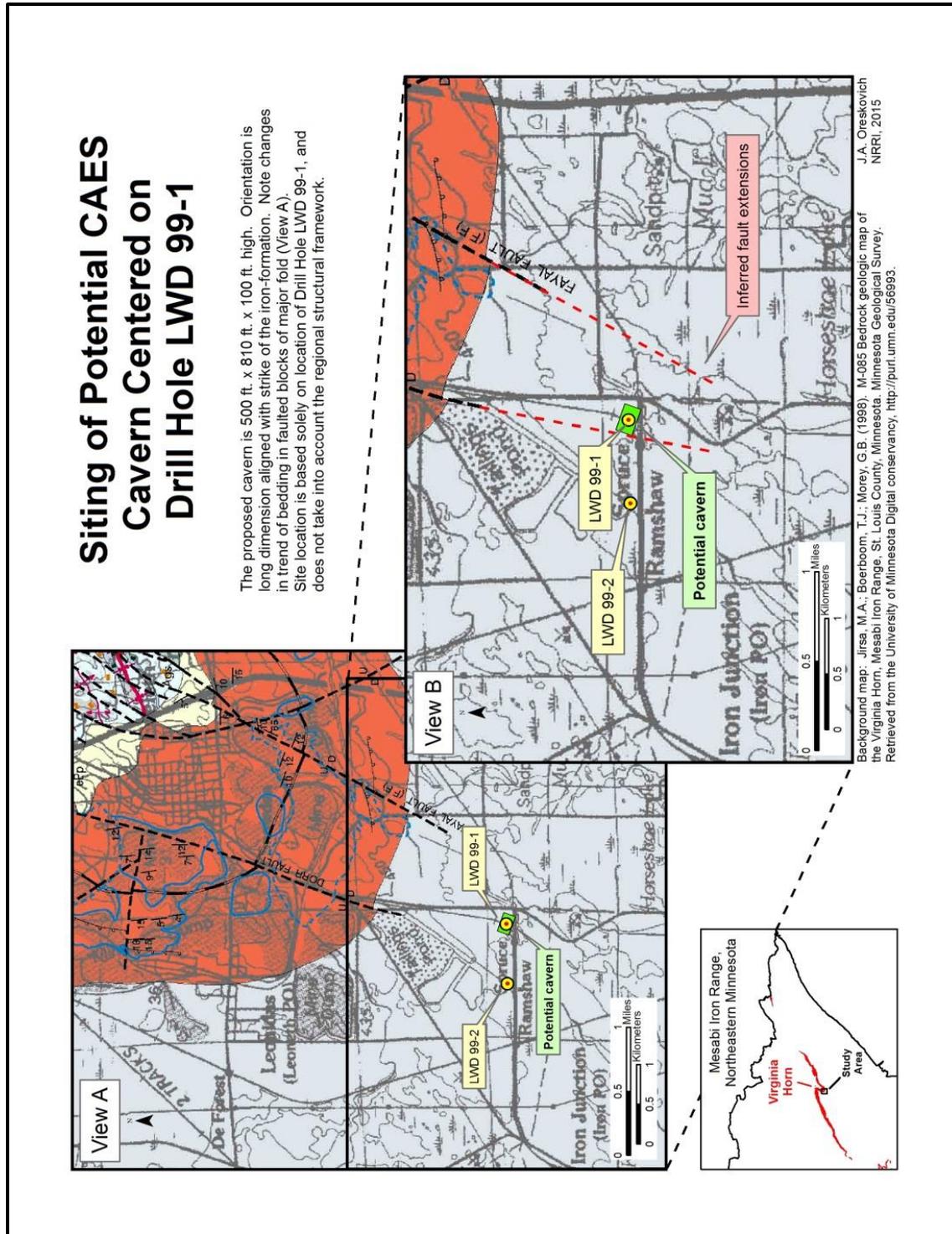


Figure 1.1-7. Geological map of the proposed CAES cavern site.

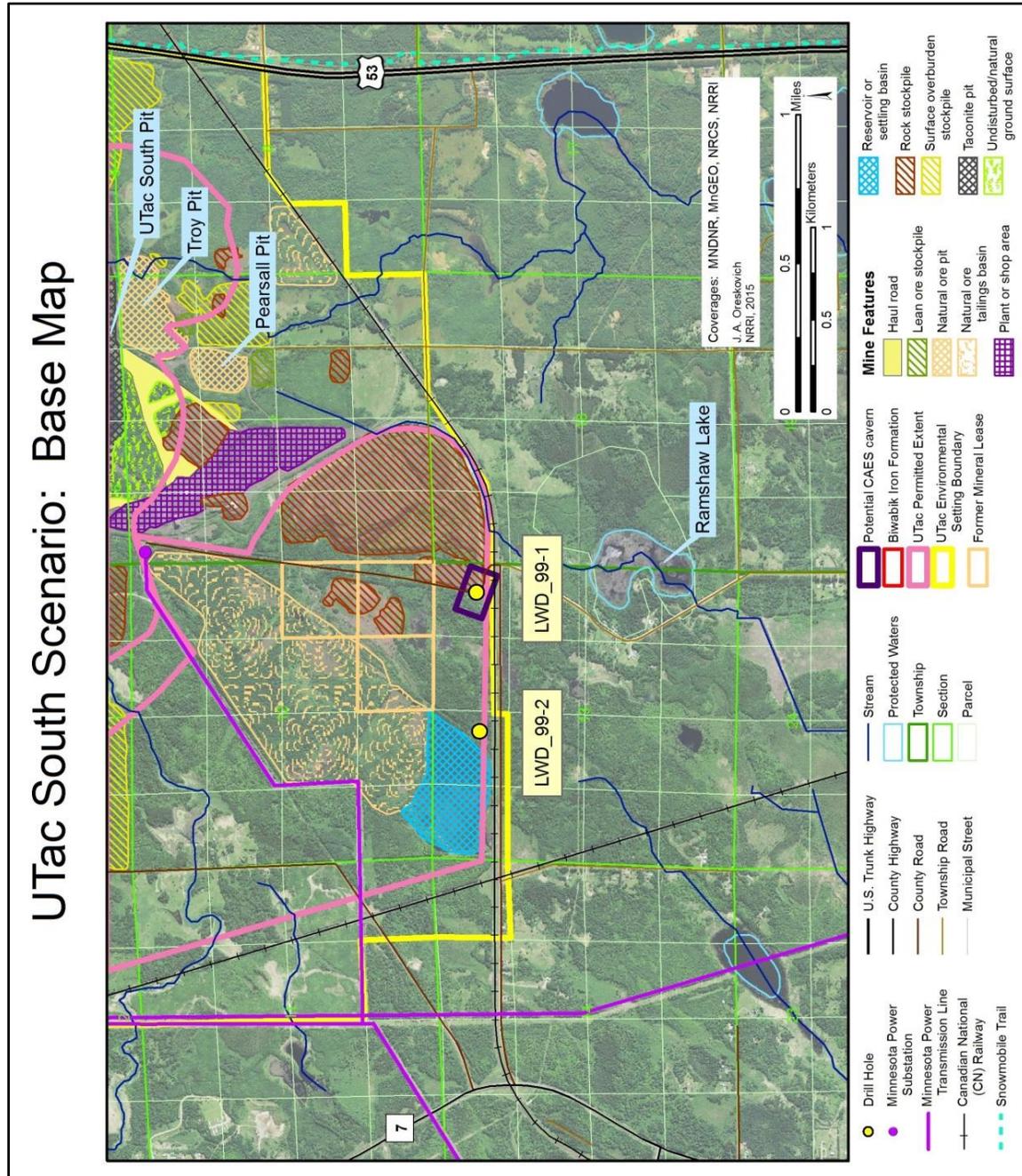


Figure 1.1-8. Base map coverages of the proposed CAES cavern site.

A settling basin located approximately 0.5 miles to the west of LWD 99-1 could serve as a water source should a water curtain be part of the facility design. The Pearsall and Troy natural ore pits, as well as United Taconite's South Pit, all of which are water-filled, are within 1.1-1.3 miles to the NE, while Ramshaw Lake to the south is within 0.5 miles.

The site resides within an area that has already been permitted, specifically for stockpile emplacement in this case. This location also places it within the environmental setting boundaries used in the permitting process, meaning that a detailed environmental review had been conducted prior to issuance of permits. Baseline data for a significant portion of the environmental review area that would necessarily be required for a CAES facility has already been established.

Of note are the three former mineral lease parcels shown immediately north of LWD 99-1 (Fig. 1.1-8). Included in the MN DNR mineral lease file, they are listed as miscellaneous leases issued to Eveleth Taconite Company and Eveleth Expansion Company on July 1, 1981. The leases were terminated two years later on June 30, 1983.

Location of an old rock stockpile on-site would likely impede potential future open pit mining of the immediate area, while not interfering with a potential underground CAES facility. LiDAR elevation data places the stockpile height at 100 feet (Fig. 1.1-9).

As seen in Figure 1.1-10, United Taconite has surface ownership of multiple parcels in the vicinity of LWD 99-1 and LWD 99-2. These locations were determined from the plat coverage made available by St. Louis County, Minnesota, for use in Google Earth. United Taconite parcel ownership extends south of its currently permitted boundaries, expanding the potential area for situating a CAES.

United Taconite is a major producer of taconite pellets. As such, it is a potential consumer for the ore that would be mined to generate the CAES cavern. United Taconite is also a major industrial consumer of electrical power. Working in concert with such an entity would likely facilitate development of a CAES facility.

### *Negative site attributes*

The proposed site is in close proximity (300 feet) to the Canadian National (CN) rail line. This rail line would likely drive the facility up-dip to the north. This new location may or may not impact desirable depth.

Another possible negative for this site is the potential future resumption of mining by United Taconite in its South Pit. Even if mining were to proceed eastward from the South Pit rather than down dip to the south, the effects of blasting would be felt.

Currently, United Taconite is mining the north end of the Thunderbird Mine, the large pit seen in Figure 1.1-6 to the north of the city of Eveleth. The Minnesota Department of Transportation (Mn/DOT) is in the final planning stages for relocating U.S. Hwy 53 so that United Taconite can continue to mine northeastward through the existing roadway. This area is illustrated at the top of Figure 1.1-6, where U.S. Hwy. 53 curves to the northwest. U.S. Hwy. 53 is the major arterial north-south route from Duluth to International Falls at the Canadian border.

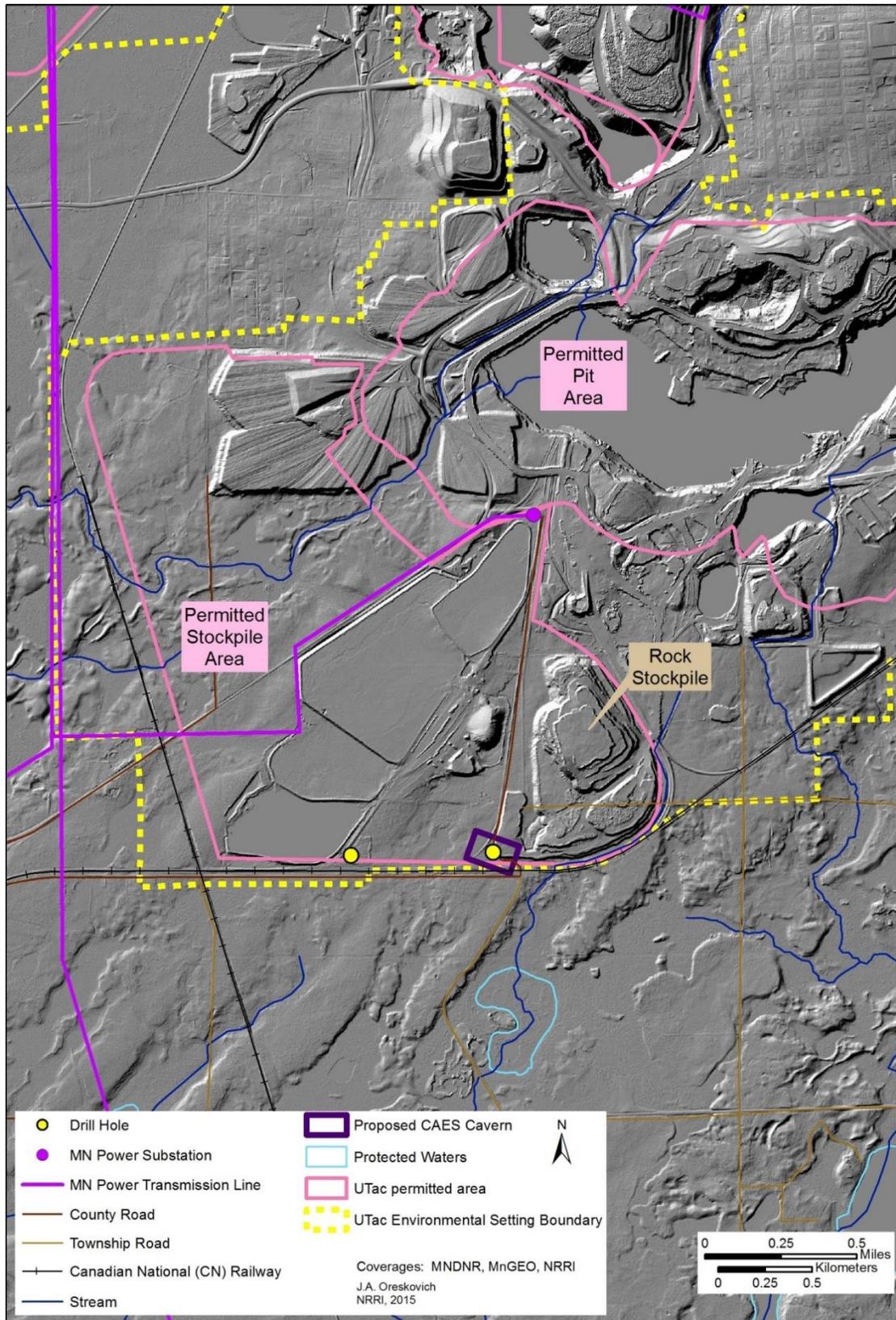
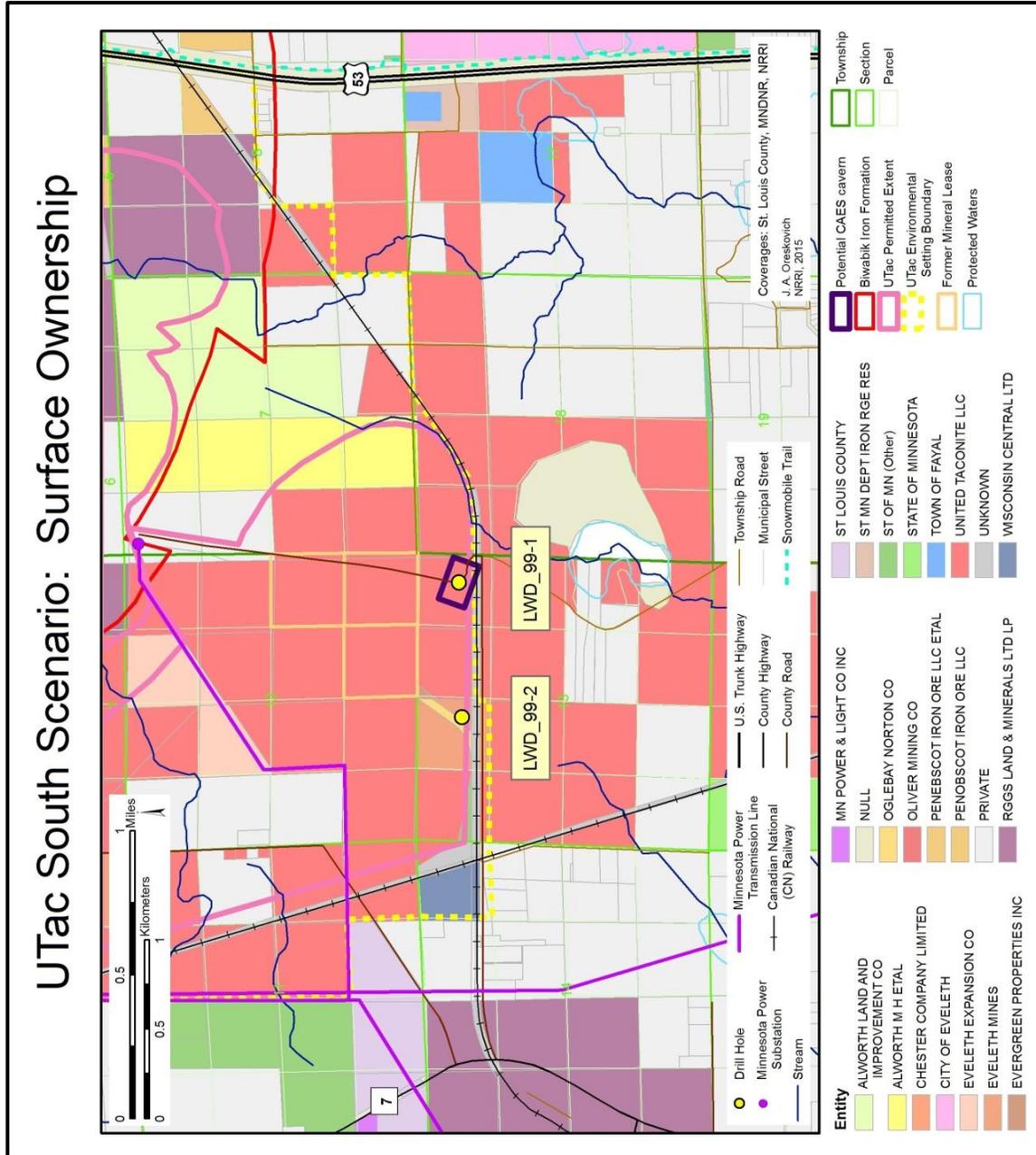


Figure 1.1-9. Hillshade map of study area.



**Figure 1.1-10.** Plat map displaying surface ownership of the proposed CAES cavern site.

### **Summary of United Taconite South Site Attributes**

A summary of the United Taconite South site attributes relative to an excavated (mined) cavern CAES facility is presented here:

#### *Positive site attributes*

- Potential orebody at depth > 1,000 feet;
- Potential ore determinations in drill holes made as part of prior in-depth study characterizing geologic and stratigraphic controls of the Biwabik Iron Formation (Severson et al., 2009);
- Close proximity to major power transmission line and substation;
- Road access to site from County Hwy. 7 (west) and U.S. Hwy. 53 (east);
- Close proximity to settling basin for water curtain draw;
- Residence in mine-permitted area (for stockpile);
- Residence within mine environmental setting boundary (baseline data for future EIS);
- Mine surface control of extensive surrounding parcels; and
- Proximity to potential consumer for mined product/also major power consumer.

#### *Questionably positive site attributes*

- Swift relinquishment of acquired mineral leases in immediate area; and
- Presence of ~120 A 100-foot high rock stockpile on-site (mining deterrent).

#### *Potentially negative site attribute*

- Close proximity to rail line (300 ft.); and
- Potential for resumption of open pit taconite mining to east.

### **ADDITIONAL CAVERN INVESTIGATIONS**

Several other types of caverns were reviewed over the course of this study. These include excavation by solution boring at Emily, MN to mine manganese, an underground LP gas storage cavern at Erskine, and potential use of abandoned cold war era missile silos for CAES.

### **Emily Borehole Manganese Mining**

Manganese has been identified as a critical and strategic mineral for the United States. It is critical to steel production; there is no satisfactory substitute (U.S. Geological Survey, 2015), and steel cannot be made without it. The U.S. is 100% reliant on foreign imports for domestic manganese consumption (Cannon, 2014). In addition to steel production, manganese is used in batteries, electronics, fertilizers, animal feed, and brick/tile colorants.

## *History*

Minnesota was a large producer of manganese from the Cuyuna Range during the first half of the 20<sup>th</sup> century. While its higher grade resources have been depleted, the Cuyuna Range, particularly the Emily District, holds the largest manganese resource in the country, albeit of low grade. Figure 1.1-11 displays a large portion of the Emily District with named mining properties and an unmined ore reserve that date back to the earlier era of mining in the district.

When foreign interests began looking into the Emily area in recent years, Crow Wing Power, the regional non-profit electric cooperative, stepped in. Looking to preserve the economic opportunity for Minnesota and ensure that the local resource would benefit Emily and the surrounding community, Crow Wing Power acquired the mineral leases on 180 acres of land. In 2008, 80 acres of land was purchased by the newly formed entity, Cooperative Mineral Resources (CMR) (Fig. 1.1-9), a wholly-owned subsidiary of Crow Wing Power (Cooperative Mineral Resources, 2015).

In mid-November, 2010, bulk sampling of the ore deposit was initiated via a novel mining technology, borehole mining. Borehole mining uses high-pressure water jets inserted into a borehole to break up the rock and flush it out in slurry form. In the process, an underground cavern is created (Fig. 1.1-12). Particles up to approximately 2.6 inches (~6.6 cm) in size can be recovered by the borehole mining tool (Minnesota Department of Natural Resources, 2005). Difficulties encountered with the procedure delayed completion of the bulk sampling process until early August, 2011 (Cooperative Mineral Resources, 2015).

CMR's website reports that mineralogical testing and subsequent bench scale processing of the bulk sample and collected drill cores have led to successful upgrading of the Emily manganese to in-demand Electrolytic Manganese metal (EMM) and Electrolytic Manganese Dioxide (EMD). CMR signed a Memorandum of Understanding (MOU) with Star Minerals Group Ltd. of Saskatoon, Saskatchewan and Octopus Technologies Inc. of Vancouver, British Columbia on Dec. 3, 2014 for the purpose of cooperatively developing "a mine to market, manganese-based battery technology" (Cooperative Mineral Resources, 2015).

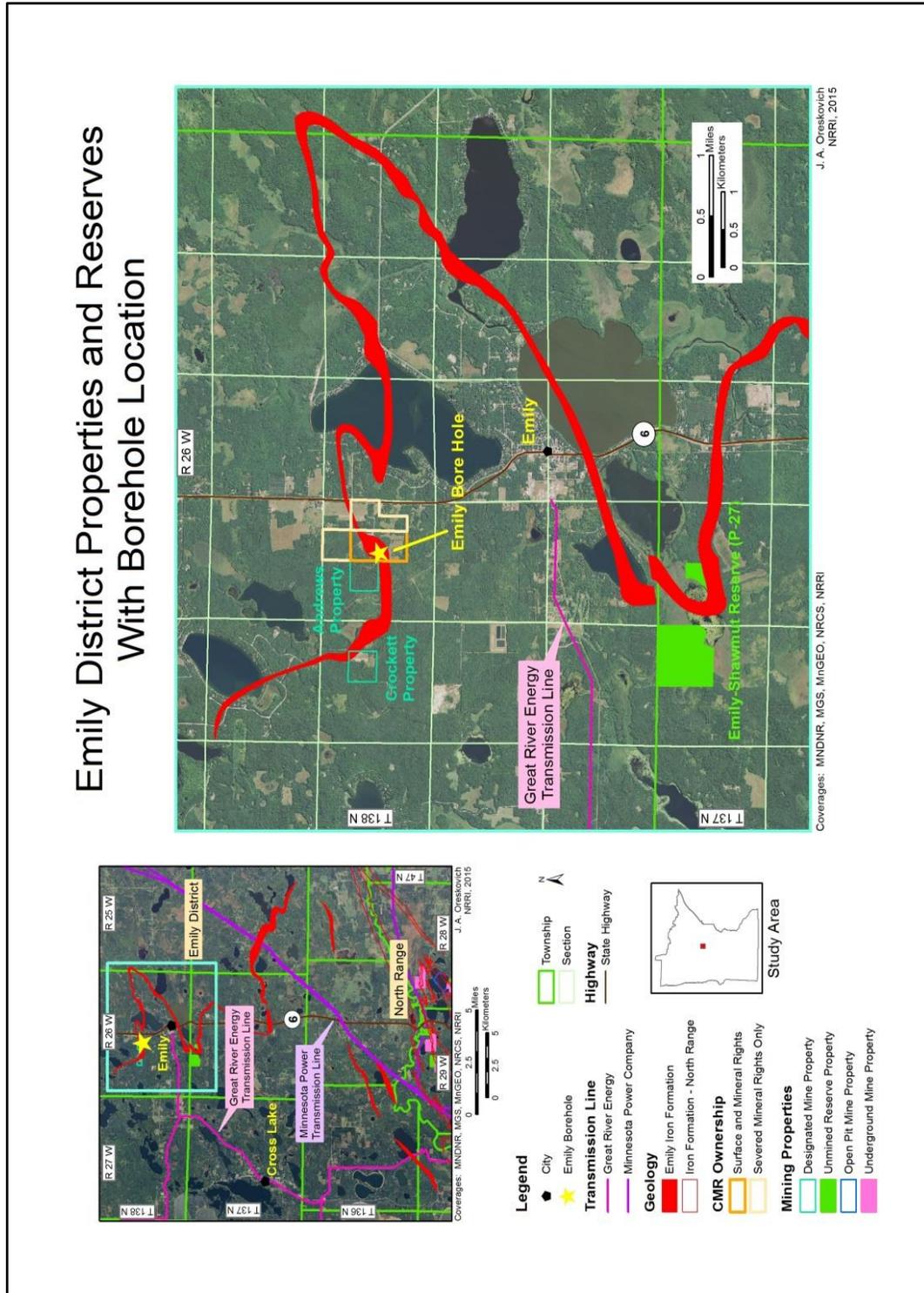


Figure 1.1-11. Location map of Emily area resources.



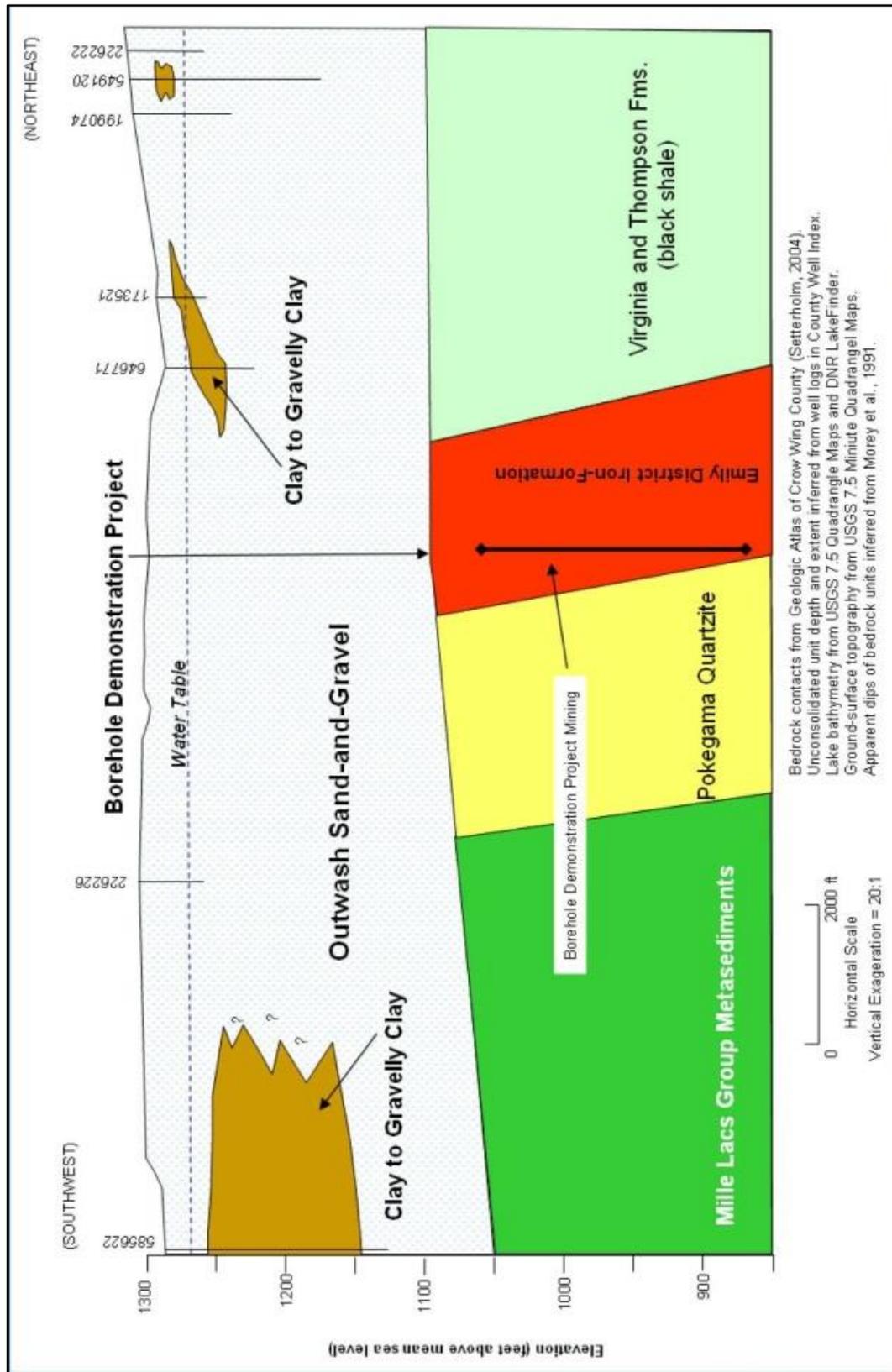


Figure 1.1-13. Geological section through the Emily borehole site (Liljegren, 2010).

Enriched manganese was detected in two zones within the iron-formation: from 200-225 feet in depth and from 295-410 feet in depth. The lower interval is underlain by “clayey” iron-formation (Barr, 2009b).

Overall, iron-formation retrieved from the borehole and geotechnical hole was very heterogeneous. It ranged from soil-like to hard rock, with most ranging in-between: “generally a weak, friable rock or a highly fractured rock often with silty infilling” that was variable in material type and color (Barr, 2009b).

#### *Method not suitable for CAES at Emily site*

Review of geotechnical and subsidence studies conducted on the Emily borehole site by Barr Engineering (Barr 2009a,b; 2010) indicate that, in this circumstance, the borehole technology would not provide a suitable cavity for CAES. Fig. 1.1-14 illustrates the typical progression of cavity development generated by the borehole method of mining. In friable material, the cavity would not be sustained. Barr’s studies predict that the cavity would collapse on itself concurrent with or shortly after boring.

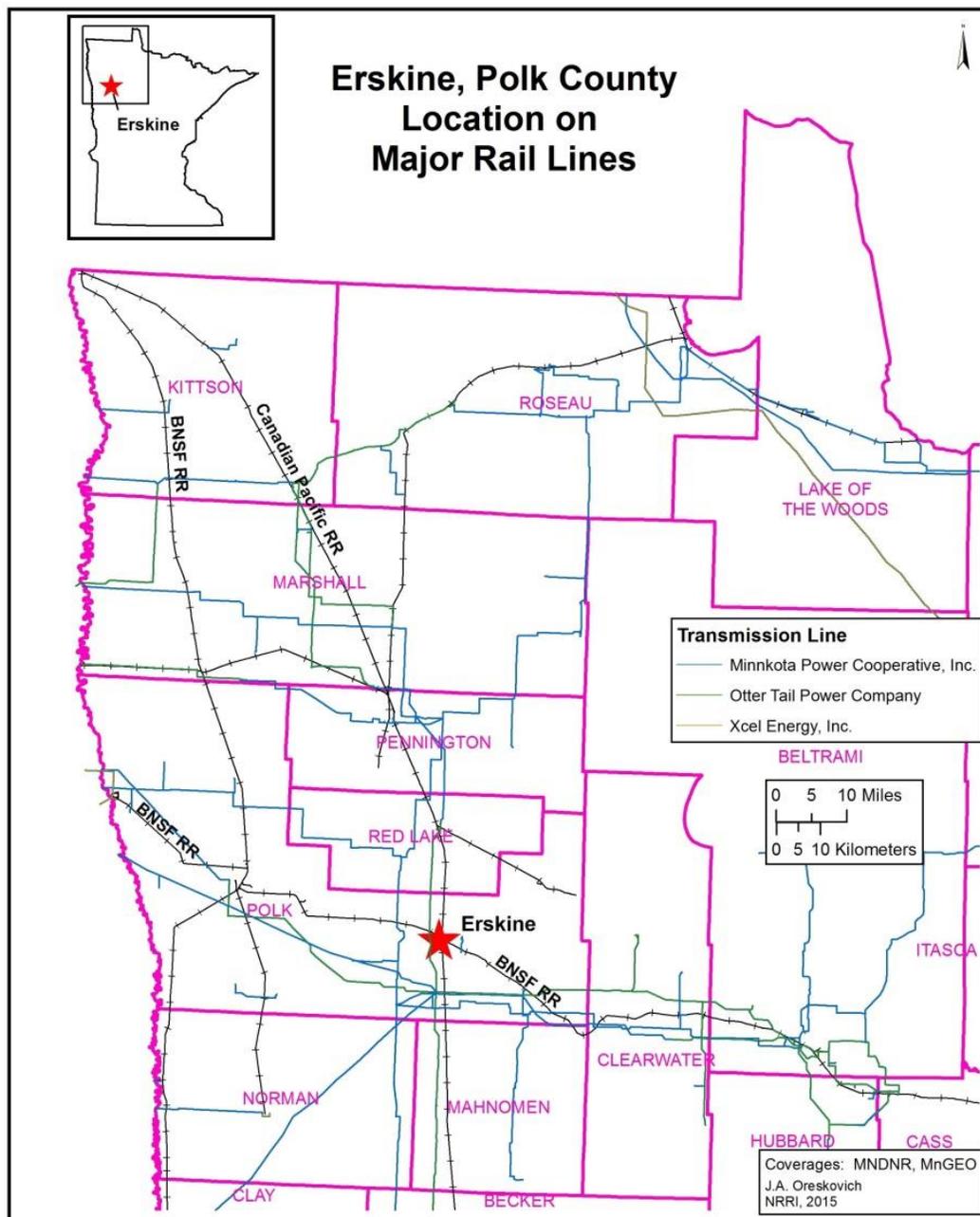
Residence of an often friable orebody at shallow depth beneath a fractured brittle discontinuous caprock topped by 175+ feet of unconsolidated glacial material makes location of a CAES facility at this site unfeasible. This determination is based on lack of drilling down dip into the orebody. CMR is currently evaluating the best method of ore extraction to use on its deposit.

#### **Erskine LP Gas Cavern**

An underground LP gas storage cavern is located in northwestern Minnesota, west of the city of Erskine in Polk County (Fig. 1.1-15). The Erskine LP gas cavern is presented here as an example of a Minnesota hard rock underground storage cavern. It has been in use for over half a century. While this and comparable sites could not be mined for a metallic ore, at least a portion of the construction costs could be offset by aggregate production and sale. Good aggregate for road construction is at a premium in some parts of Minnesota, such as Kittson County in the far northwestern corner of the state. Note the city of Erskine’s (and Polk County’s) location on two major rail lines, Burlington Northern Santa Fe and Canadian Pacific (Fig. 1.1-15). There are also major electrical transmission lines running through the area.



**Figure 1.1-14.** Depiction of the cavity typically created by borehole mining (Liljegren, 2010).



**Figure 1.1-15.** Erskine, Polk County location map with rail and transmission lines.

Excavated from March 1961 to May 1962, the cavern is 350 feet long by 285 feet high, with a ceiling height of 25 feet. The cavern floor resides at a depth of 530 feet. The excavated rock totaled 17 million tons. LP storage volume in the cavern is 14 million gallons (Mofjeld, 2003).

A feasibility study of the site by Fenix & Scisson, Inc. (1960) provides geological and testing data, along with a recommended design approach. The scope of the study included detailed site exploration with core drilling, formation pressure tests, and laboratory testing on rock samples,

preliminary cost estimates, discussion/outline of construction plans, and recommended construction methods.

The cavern host rock is a hard, dense, finely crystalline gray metamorphic rock called "Erskinite." It is a Precambrian rock believed to have originally been a siliceous carbonate sediment, possibly a dolomitic sandstone (Fenix and Scisson, Inc., 1960). Properties of the rock are presented in Table 1.1-1.

The feasibility report advised use of conventional room and pillar mining, with maximum drift dimensions of 30 feet wide by a maximum of 30 feet high. Supporting pillars were recommended to be a minimum size of 40 feet square (Fenix and Scisson, Inc., 1960).

**Table 1.1-1.** Mineral composition of "Erskinite," the host rock of the LP Gas storage cavern at Erskine, MN (Fenix and Scisson, Inc., 1960).

ERSKINITE			
Mineral	Composition	Hardness	Estimated %
Zoisite	$\text{HCa}_2\text{Al}_3\text{Si}_3\text{O}_{13}$	6-7	50%
Epidote	$\text{HCa}_2(\text{Al,Fe})_3\text{Si}_3\text{O}_{13}$	6-7	
Serpentine	$\text{H}_4\text{Mg}_3\text{Si}_2\text{O}_9$	2-4	20%
Chlorite	Variable, H,Mg,Fe,Al,SiO <sub>2</sub>	2-3	20%
Talc	$\text{H}_2\text{Mg}_3(\text{SiO}_3)_4$	1	
Quartz	$\text{SiO}_2$	7	5%
Magnetite	$\text{Fe}_3\text{O}_4$		3%
Pyrite	$\text{FeS}_2$		
Calcite	$\text{CaCO}_3$		Minor

### Missile Silos

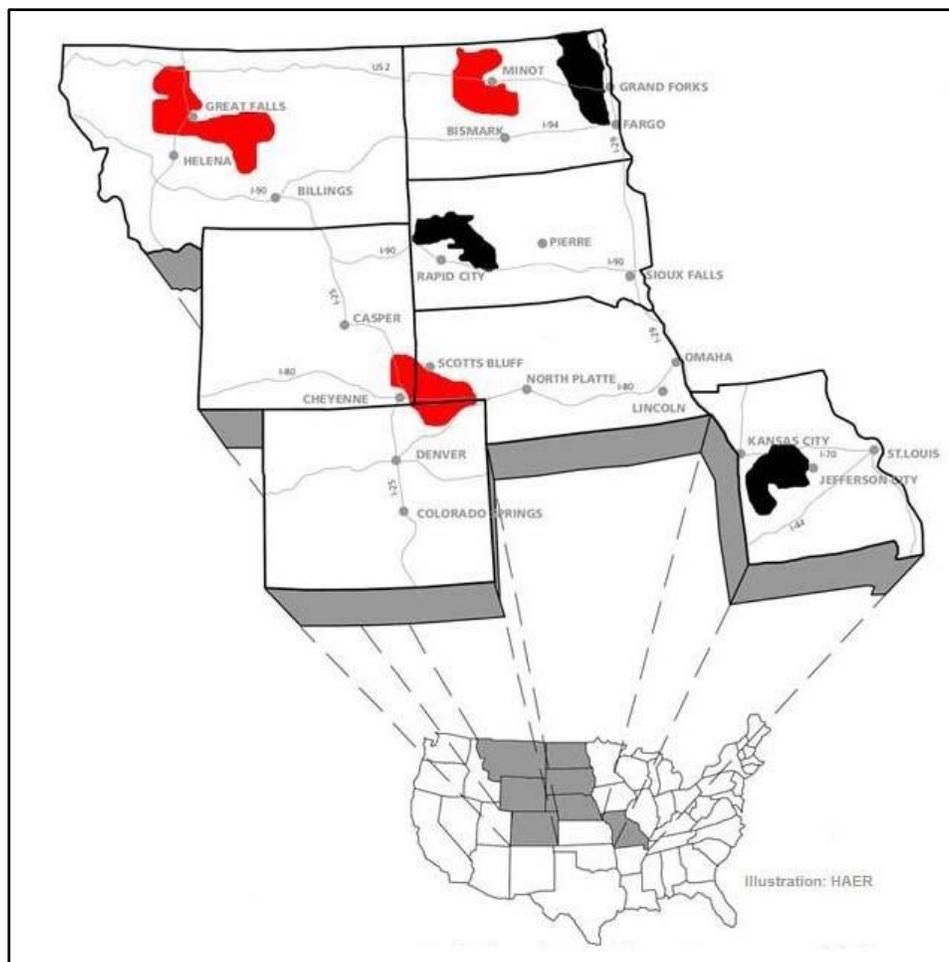
Abandoned missile silos were looked at as another potential underground cavern for compressed air energy storage. The nearest missile silos to Minnesota are those of the Minuteman missiles of North Dakota (Fig. 1.1-16). There were six Minuteman missile wings located in the Upper Great Plains Region of the United States. Wings comprised multiple squadrons that were made up of five flights. Each flight had a central control facility surrounded by ten launch facilities/missile silos that were located from 3 to 15 miles away and distant from each other (National Park Service, 2014).

The minuteman missile silos are 80 feet deep and 12 feet in diameter. They are topped with a 100-ton blast door (Strategic Air Command, 2003). The silos were constructed of reinforced concrete 14 inches thick. The inside was lined by ¼-inch steel plate (Techbastard.com, 2014). Volume of a minuteman missile silo is almost 9,050 ft<sup>3</sup>.

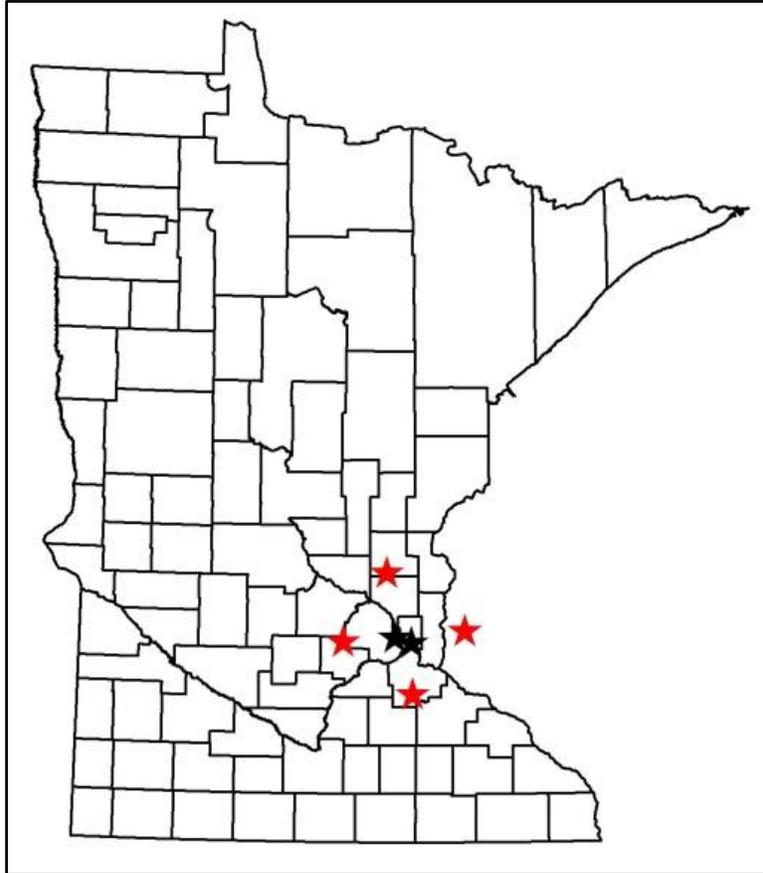
Minnesota's underground missile-related structures consisted of magazines and control bunkers, rather than actual silos. During the cold war era, four NIKE missile silos were placed

outside the metro area to defend Minneapolis-St. Paul from air strikes. Three of these sites are located in Minnesota; the fourth site is in Roberts, WI (Fig. 1.1-17). The Minnesota sites are located near the cities of Bethel to the north, St. Bonifacius to the west, and Castle Rock to the south.

NIKE sites typically have three side-by-side missile magazines that are roughly 22 feet below ground. Magazine dimensions are approximately 60 feet by 70 feet with a ceiling clearance height of 11-12 feet beneath massive ceiling support beams. Some additional rooms are located on one end (20<sup>th</sup> Century Castles, LLC, 2015). Construction materials and wall/ceilings thicknesses were not obtained. Shallow depth would preclude use of the NIKE missile magazines for CAES purposes.



**Figure 1.1-16.** Location map of the six Minuteman missile wings in the Upper Great Plains Region (National Park Service, 2014).



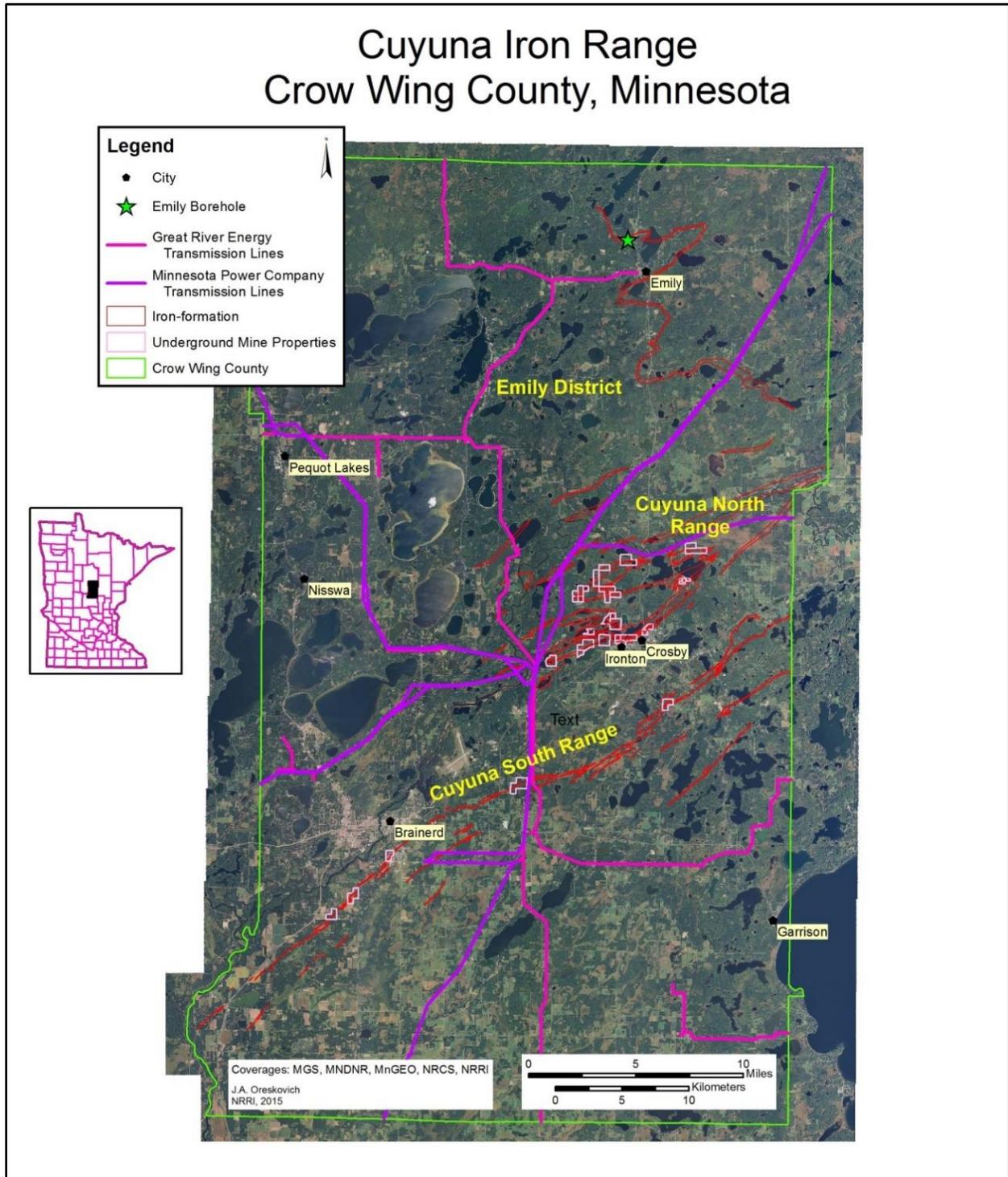
**Figure 1.1-17.** NIKE missiles surrounding the Minneapolis-St. Paul metro area.

### **SCENARIO 3: USE OF LEGACY MINING FEATURES (MEDIUM VOLUME STORAGE FACILITY)**

The site selected for Scenario 3 is located on the Cuyuna Range in east-central Minnesota (Fig. 1.1-18). Most of the Cuyuna Range lies within Crow Wing County, but it does extend eastward into Aitkin County and to the southwest into Morrison County (coverages in Fig. 1.1-9 have been clipped to the Crow Wing County boundary). Note the distribution of major transmission lines through the Cuyuna Range.

Three mining districts comprise the Cuyuna Range: the Emily District, a broad unmined region to the north currently drawing interest for its manganese resources; the Cuyuna North Range, a compact densely-mined region in the center, located near the cities of Ironton and Crosby; and the Cuyuna South Range, a long, narrow strip running southwest-northeast to the south of Ironton and Crosby that experienced limited mining during the first decade of production on the Cuyuna Range (Fig. 1.1-19).

Based on knowledge obtained through the underground mine mapping portion of this project, maps produced, mine depth, and proximity to major transmission lines, the Armour No. 1 and Armour No. 2 mines located at Ironton and Crosby on the Cuyuna North Range were selected for closer inspection (Fig. 1.1-19).



**Figure 1.1-18.** Map of Cuyuna Range, Crow Wing County, Minnesota displaying mining districts, underground mine properties, and major power transmission lines.

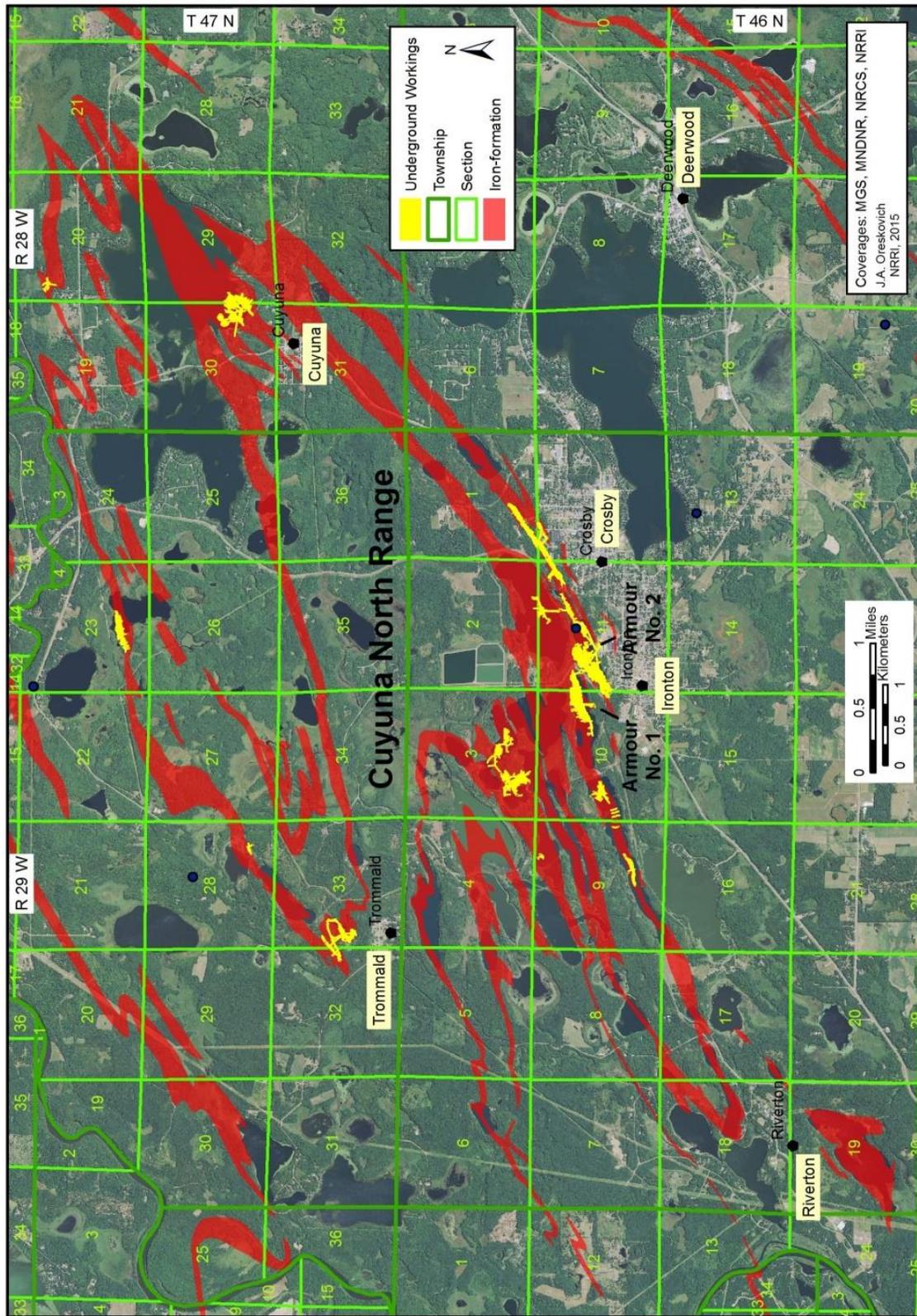


Figure 1.1-19. Iron-formation of the Cuyuna North Range with underground mine workings.

The Armour mines, together with the Croft mine located approximately 1 mile to the northeast, comprise the deepest underground mines on the Cuyuna Range. The Armour No. 1 mine shipped over 6.8 million long tons of natural iron ore over a span of nearly 50 years (Skillings Mining Review, 2005). Most of this was from underground workings.

Surpassing the Armour No. 1 mine, the Armour No. 2 mine produced over 9.1 million long tons (Skillings Mining Review, 2005). Mining was both underground and open pit. This production was despite the mine being idled between 1933 and 1949 (Aulie and Johnson, 2002).

The Armour mines' production placed them in the fourth and fifth spots, respectively, for all-time ore production on the Cuyuna Range, right behind the largest open pit mines (the Portsmouth, Mahnomen, and Sagamore). Final shipments were made in 1960 for the Armour No. 1 and in 1968 for the Armour No. 2 (Skillings Mining Review, 2005). Underground operations ceased in the Armour No. 2 mine at 1:00 a.m. on June 1, 1967 (Pettersen, 2006), making it the last underground mine to operate in Minnesota.

The Armour No. 1 and Armour No. 2 shafts at 800-foot and 582-foot depths, respectively, and the Croft shaft with a depth of 630 feet, are deeper than any of the mine shafts on the Mesabi Range. Deeper shafts occur on the Vermilion Range: the Soudan Mine at 2,700 feet; the Chandler Mine at 920 feet; the Pioneer, Savoy, Sibley, and Zenith mines in Ely all exceed 1,000 feet in depth (Crowell & Murray, 1920).

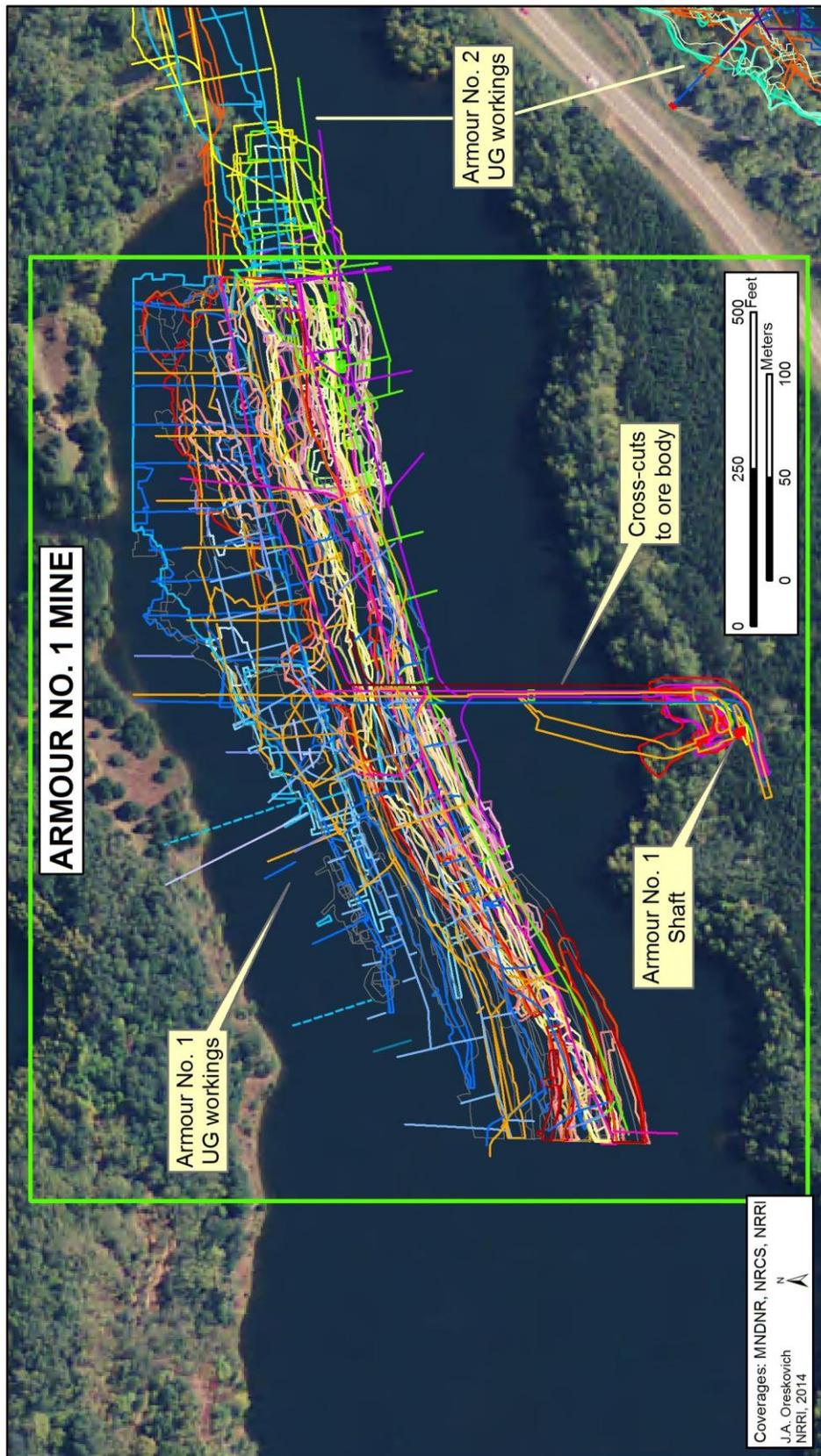
### **Scenario 3a: Mine shafts and drifts – Armour No. 1 and Armour No. 2 underground mines, Cuyuna Range**

The Armour No. 1 and Armour No. 2 mines are described in detail below. These mines are typical of many of the underground mines in Minnesota, whether on the Cuyuna, Mesabi, or Vermilion ranges, in terms of mining methods used, resulting structure, and what, if any, role they may play in CAES development.

#### *Armour No. 1 Mine*

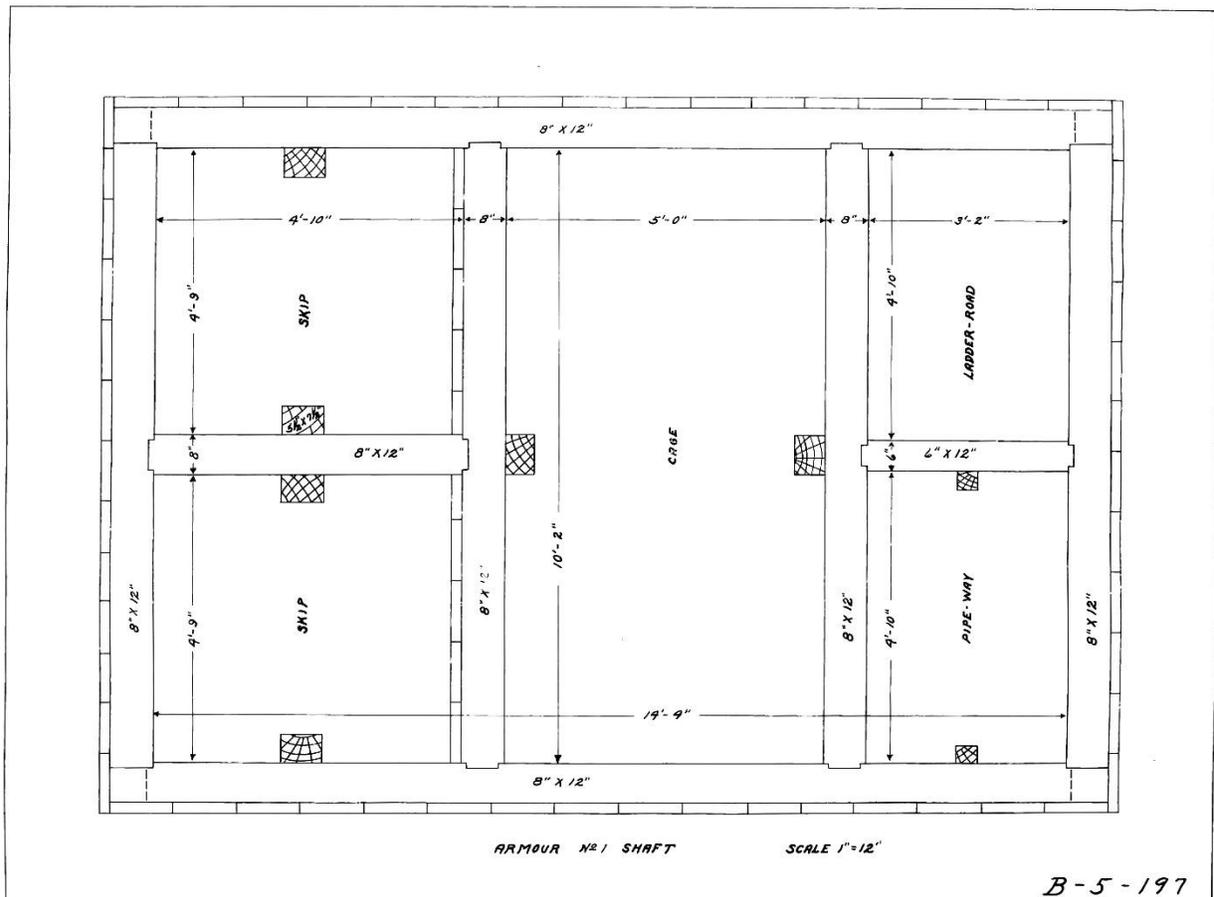
The Armour No. 1 mine resides in the SE  $\frac{1}{4}$  of the NE  $\frac{1}{4}$  of Section 10, Township 46 N., Range 29 W. (Skillings Mining Review, 2005). Within the Armour No. 1 mine, the entire iron-formation is oxidized, comprising a tabular ore body that extends to a mined depth of 800 feet (Schmidt, 1963). Schmidt (1963) reports that shaft sinking for the mine began in 1910. The shaft was located well off the ore body in chlorite schist to the south.

Figure 1.1-20 illustrates the drifts and outlines of mined extents on many (but not all) levels and sub-levels of the Armour No. 1 mine. Each level and sub-level is represented by a different color. The distance from the shaft to the ore body via the underground cross-cut drifts shown exceeds 500 feet. Like the shaft, the cross-cuts were driven through schist, described by a former Armour miner as “green rock” that didn't require timbering (R. Valentino, pers. comm., 2013).



**Figure 1.1-20.** Armour No. 1 mine showing mapped shaft, cross-cuts, drifts, and mined extents.

Overburden thickness at the shaft site was 65 feet and a circular concrete shaft was used to penetrate it (Zapffe, 1915). The hoisting shaft itself was a five-compartment shaft (Fig. 1.1-21), consisting of a 10' 2" x 5' 0" central man cage, two 4' 9" x 4' 10" skip ways for hoisting ore, a 4' 10" x 3' 2" ladder-way and a 4' 10" x 3' 2" pipe-way (schematic from National Mine Map Repository collection). Outside dimensions, as shown, are 16 feet by slightly less than 12 feet (assuming the shaft is framed by 2 x 4 lumber).



**Figure 1.1-21.** Schematic of the Armour No. 1 shaft (National Mine Map Repository collection).

Initially, the shaft was sunk to 300+ feet, with the main haulage level at 300 feet and the main sub-level at 200 feet (Zapffe, 1915). Maps obtained for this study illustrate cross-cut drifts from the shaft to the orebody on the 200- and 300-foot levels. Shaft level plats for the 450-, 700-, and 800-foot levels indicate that the cross-cuts at these levels were driven in 1940 (450-foot level) and in 1953 (700- and 800-foot levels). There are no dates on the 525- and 600-foot levels to mark when these cross-cuts were driven.

The orebody was mined by the top-slicing method (Schmidt, 1963). This procedure is borne out by maps circa 1926 that show areas mined in 1913 on the 110-, 120-, 130-, and 140-foot sub-levels. The mine was idled from mid-1913 until Inland Steel picked it up in 1915, at which time it

was reopened as an open pit operation on the western side of the property (Harder and Johnston, 1918).

Underground mining apparently resumed in 1926, as indicated by notations in mining rooms on the maps listed above, and also on a map of the 100-foot level. Yearly progression can be traced downward through maps of each succeeding level, until what appears to be June, 1959 (“6-59”) written in several small rooms on the 770-foot sub-level. Below, on the 784-foot sub-level, Contract 67 (“C-67”) miners had driven up a raise from the 800-foot main haulage drift in February, 1959. They mined rooms/slices in succeeding radial fashion around the raise/chute, mining in a counterclockwise direction. The rooms are dated from February 1959 through June 1959.

Mining from the 784-foot sub-level may constitute the deepest extent that the Armour No. 1 orebody was mined. Shipments from the mine ceased in 1960. While the eastern haulage drift on the 800-foot level extended 250 feet into the Armour No. 2 property, and the orebody was outlined on the map, no map indicating actual mining of the orebody from the 800-foot level was found.

### *Armour No. 2 Mine*

The Armour No. 2 mine resides in the SW  $\frac{1}{4}$  of the NE  $\frac{1}{4}$  and the S  $\frac{1}{2}$  of the NW  $\frac{1}{4}$  of Section 11, Township 46 N., Range 29 W. (Skillings Mining Review, 2005). Three orebodies comprise this mine as seen in Figure 1.1-22: 1) the extension of the Armour No. 1 orebody into the northwest corner of the property; 2) the main orebody running from southwest to northeast through all three parcels; and 3) “Orebody A,” located to the southeast of the main orebody, running from southwest to northeast across the boundary of the two easternmost parcels. Different colors are used in Figure 1.1-22 to represent the drifts and mined extents of the various Armour No. 2 levels and sub-levels portrayed. Not all of the levels and sub-levels were mapped. Workings shown in yellow belong to other mines (Armour No. 1, Bonnie Belle, Ironton, and Thompson).

Schmidt’s Plate 3 (1963), part of which is shown in Figure 1.1-23, illustrates how the belts of iron-formation containing the first two orebodies listed above merge together to the east along with that containing the Mangan No. 2 orebody to the north to form one broad expanse of iron-formation containing the orebody mined as the Portsmouth open pit. The Portsmouth mine was the largest producer on the Cuyuna Range at 12,370,260 long tons of ore shipped. Like the Armour No. 1 mine, the Portsmouth mine made its last shipment in 1960 (Skillings Mining Review, 2005).

As the Armour No. 1 and Portsmouth mines were winding down, the Armour No. 2 was sinking a new shaft to serve the eastern side of the property, particularly Orebody A. Orebody A was worked subsequent to the open pit operation. The map of the shaft and cross-cut drifts on the 378-foot level do not have any dates but must have been in place by the end of 1960, since sub-level 253 of Orebody A, its top level, was worked from January to April 1961. The new shaft level plat at the 582-foot level is dated 1960. Cross-cuts at that level to both the middle orebody and Orebody A bear dates from 1961, but they are subsequent to the mining on sub-level 253. The last mining occurred on sub-level 558 in 1967.

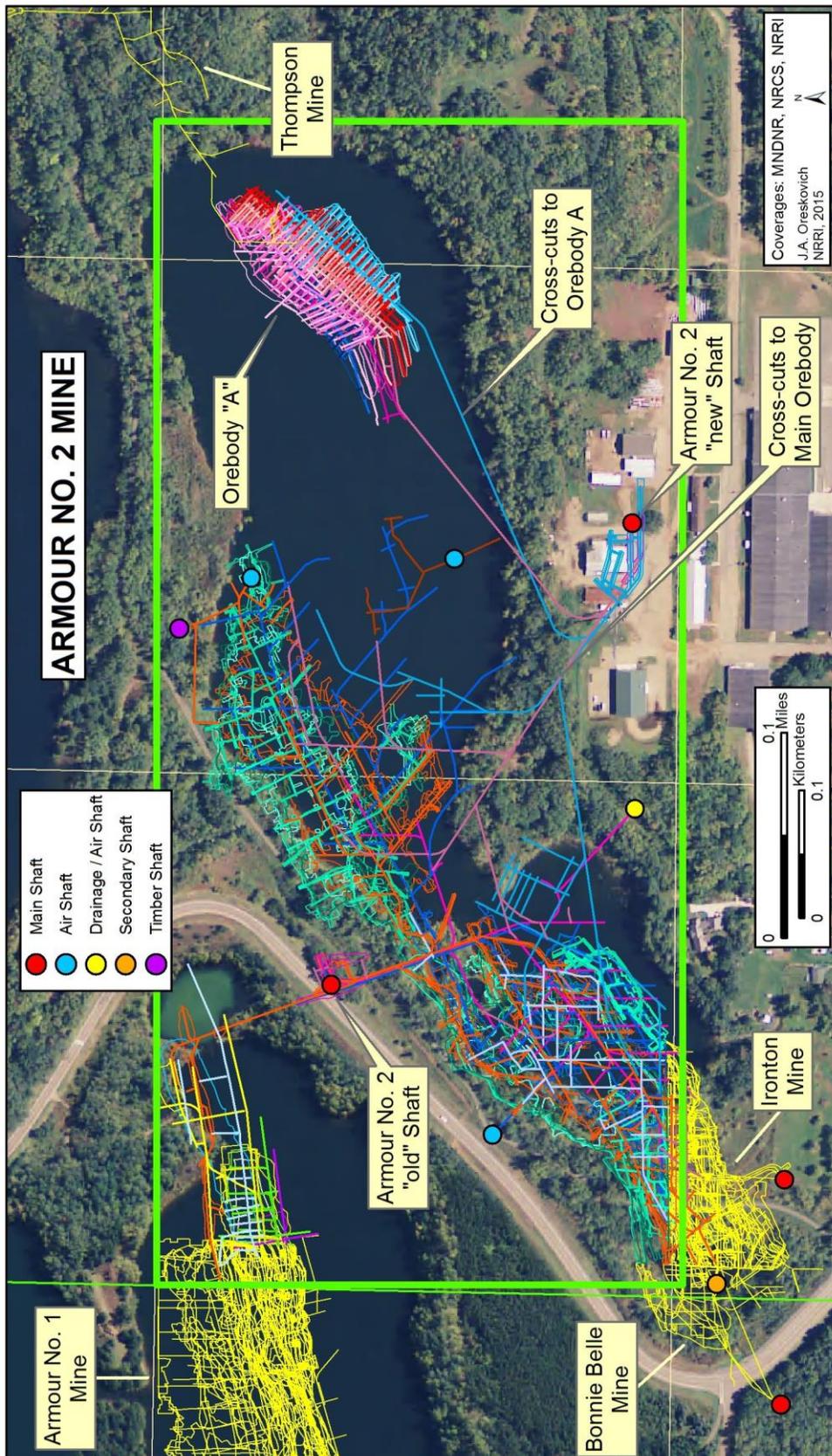


Figure 1.1-22. Armour No. 2 mine showing shafts, cross-cut drifts and mined extents.

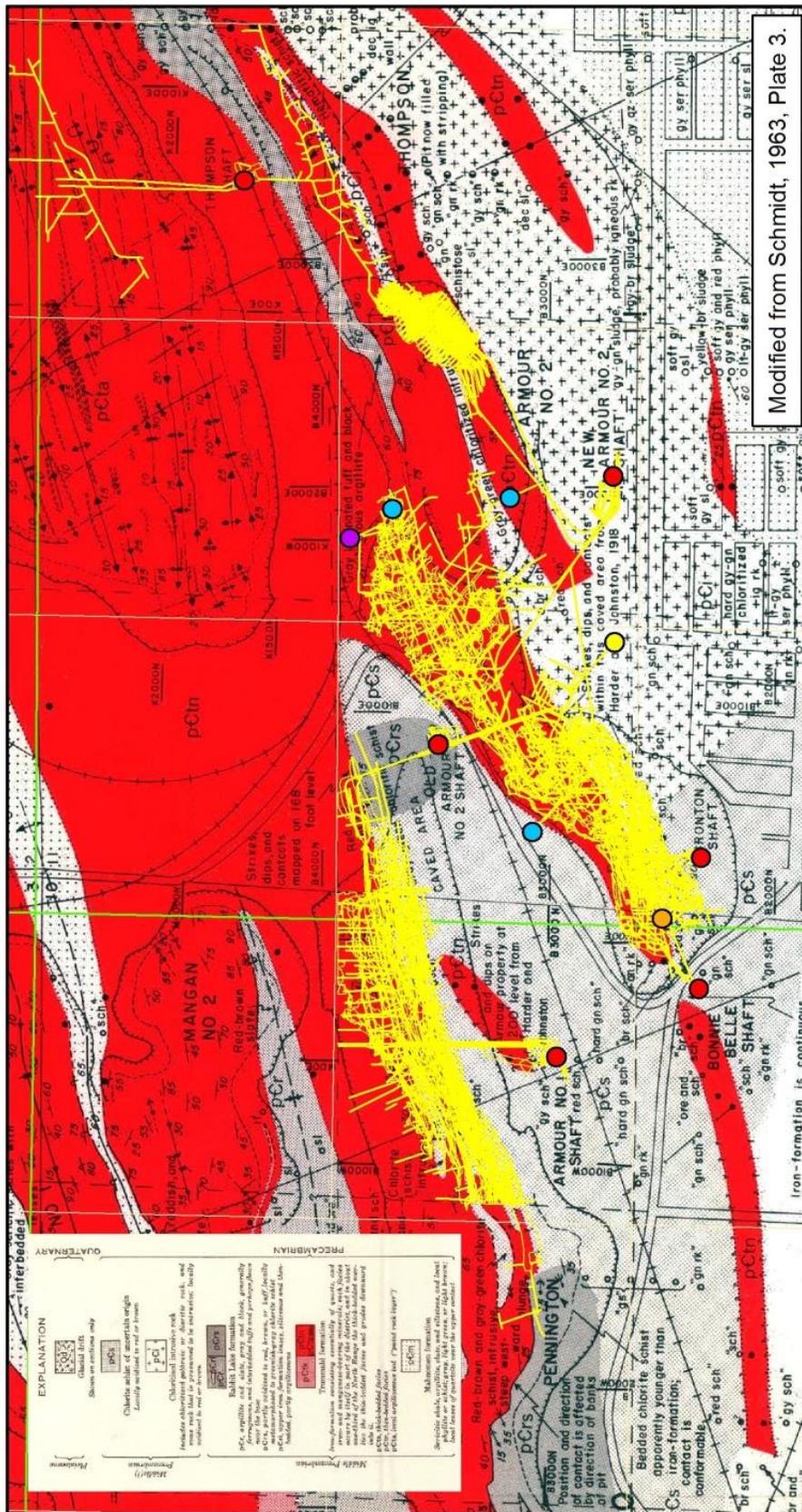


Figure 1.1-23. Armour Nos. 1 and 2 and Thompson mine workings overlaid on Schmidt's Plate 3 (1963).

The first Armour No. 2 shaft was sunk in January of 1911 (Aulie and Johnson, 2002). As with Armour No. 1, a circular concrete shaft was put down through 65 feet of overburden into green chloritic schist. The cross-cut from the shaft leading northwest to the Armour No. 1 orebody is also entirely in chloritic schist (Harder and Johnston, 1918). This information can be seen on Schmidt's Plate 3 in Figure 1.1-23.

The main haulage level was at 168 feet, connecting with both the 200-foot level of the Armour No. 1 mine and the central main orebody on the Armour No. 2 property (Harder and Johnson, 1918). The two mines were tied together so that each could serve as an air shaft for the other (Edwards, 1913).

The Armour No. 2 shaft was a five-compartment shaft, like that at Armour No. 1. It was down 358 feet by 1917 (Crowell & Murray, 1917), its greatest depth. This shaft was used until at least 1930, the latest year noted in mining rooms on any of the level/sub-level maps obtained. It was about this time, during the Depression years, that Inland Steel gave up its leases on the Armour No. 2, Ironton, and Wearne properties, keeping only the Armour No. 1 (Aulie and Johnson, 2002). The book reports that the Armour No. 2 was operated by Inland Steel from 1915 to 1933.

No information has been found on when the open pit mine on the Armour No. 2 property was opened and operated, but in 1949 the underground operations resumed. Ore from both the Armour No. 1 and Armour No. 2 mines was hauled out through the Armour No. 1 shaft. This work continued until the Armour No. 1 lease expired in 1959 (Johnson, 2004). Production shifted to the new shaft on the Armour No. 2 property and underground mining continued until 1967.

A new five-compartment shaft for the Armour No. 2 mine was sunk in the later part of the 1950s. This shaft served the older workings to the west and the new Orebody A deposit on the east side of the properties that was worked in the 1960s. According to Schmidt's (1963) Plate 3 (Fig. 1.1-23), the shaft was sunk in chloritized intrusive rock. Its location places it today in the Crosby Industrial Park, which makes it very accessible.

Details of that shaft can be seen in the schematic in Figure 1.1-24, which carries a date of 1956. Outside dimensions are 16 ft. 4 in. x 11 ft. 8 in. Inside dimensions for the compartments are 5 ft. 1 in. x 3 ft. 6 in. (2); 5 ft. 1 in. x 5 ft. 1 in. (2); and 10 ft. 8 in. x 5 ft. 3 in. (1). The shaft appears to be of steel beam construction.

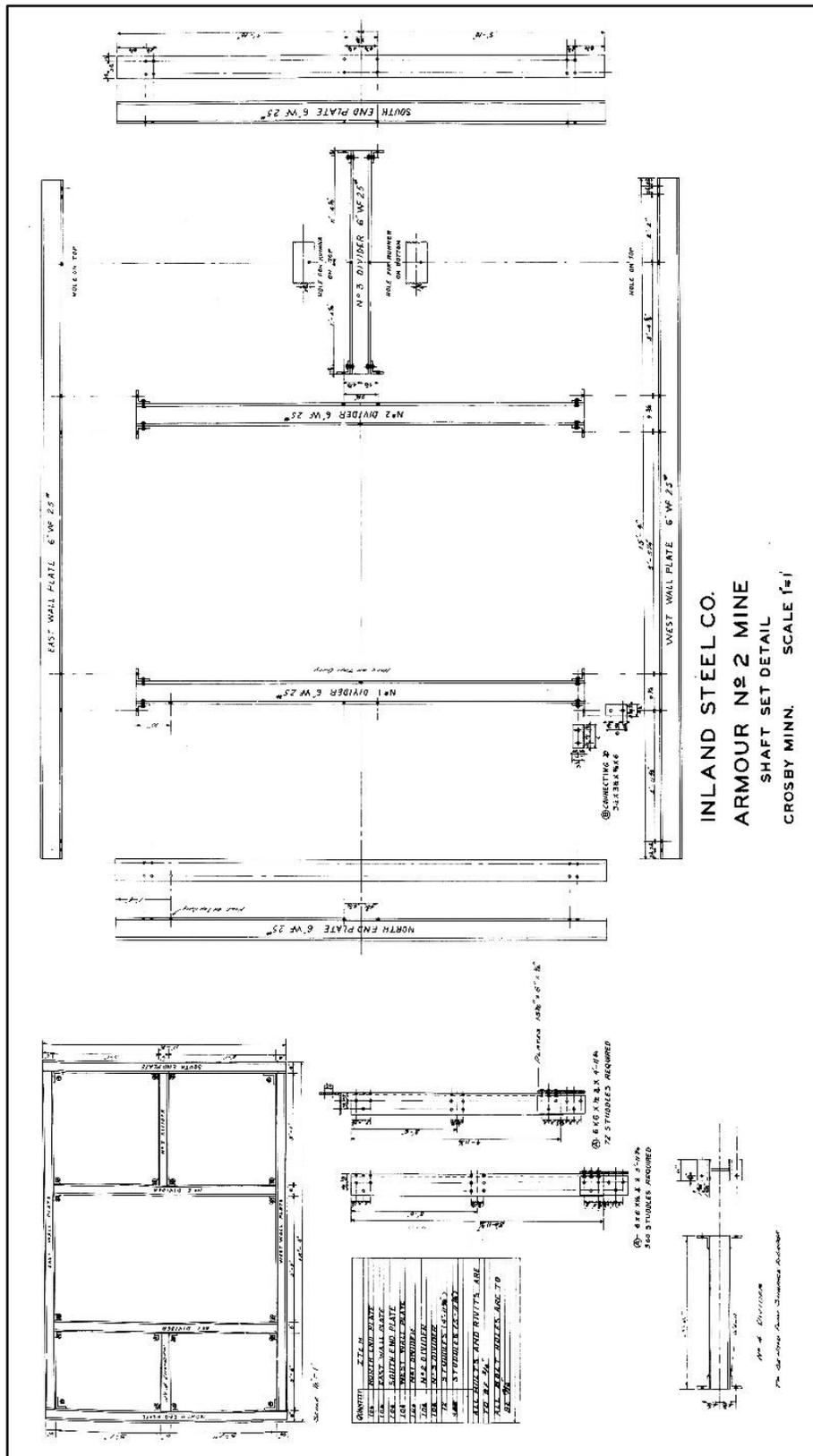


Figure 1.1-24. Schematic of the "new" Armour No. 2 main shaft.

### *Armour Mine Workings*

The Armour No. 1 and Armour No. 2 mines together produced nearly 16 million long tons of ore for shipment (Skillings Mining Review, 2005). No numbers were found that gave any indication of the amount of waste rock that accompanied production.

A listing of the mined levels and sub-levels in the Armour mines is provided in Table 1.1-2. This listing is based on mine maps acquired. While the listing for the Armour No. 1 mine appears to be complete, the completeness of the listing for the Armour No. 2 mine is questionable. Of note is that the Armour No. 2 mine 600-, 650-, and 800-foot level maps and the 700- and 730-foot sub-level maps indicate that these areas were mined from the Armour No. 1 mine. All of the maps acquired for the Armour No. 1 mine (95) and the majority of the maps acquired for the Armour No. 2 mine (64) came in digital format upon request from the U.S. Department of the Interior Office of Surface Mining Reclamation and Enforcement, National Mine Map Repository in Pittsburgh, PA. An additional 16 maps were acquired for the Armour No. 2 mine from the MDOR Minerals Tax Office in Eveleth, MN (7) and from Superior Mineral Resources LLC in Hibbing, MN (9).

The map sets were reviewed for those displaying the greatest and most recent extent of mine workings on each level/sub-level. The selected maps were geo-rectified, and mine workings were digitized from the geo-rectified maps. Mine workings were digitized for all of the main levels. A sufficient number of sub-level maps were selected for digitizing to generate a good picture of the orebody.

Attributes such as drift width, drift height, the height of the mined extents, and the elevation were recorded at the time of digitization for the purpose of generating 3-D models of the mining activity. Drift widths were scaled from the maps. Drift height was assumed to be eight feet unless otherwise noted on the map or the drifts were less than eight feet wide. Height of mined extents was determined by the difference in elevation between each level/sub-level and the preceding one above.

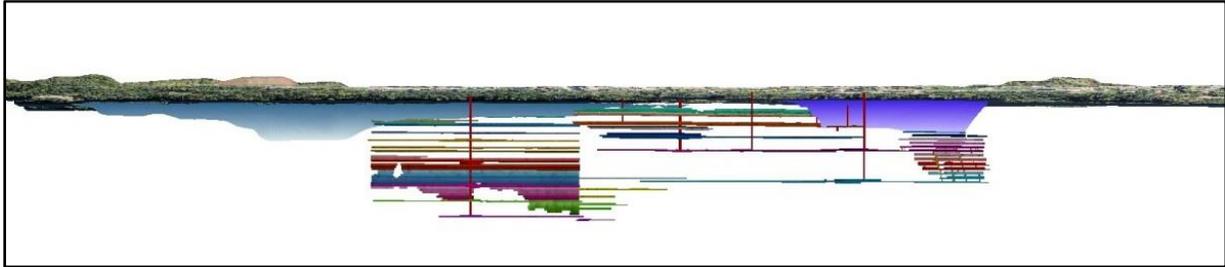
**Table 1.1-2.** A listing of the levels and sub-levels mined in Armour No. 1 and Armour No. 2, based on maps acquired.

<b>LEVELS / SUB-LEVELS MINED</b>			
<b>Armour No. 1 Mine</b>		<b>Armour No. 2 Mine</b>	
100 Ft Sub	424 Ft Sub	77 Ft Sub	353 Ft Sub E End
110 Ft Sub	437 Ft Sub	87 Ft Sub	378 Ft Level E End
120 Ft Sub	450 Ft Level	97 Ft Sub	408 Ft Sub E End
130 Ft Sub	464 Ft Sub	107 Ft Sub	438 Ft Sub E End
140 Ft Sub	478 Ft Sub	117 Ft Sub	450 Ft Sub
150 Ft Sub	492 Ft Sub	127 Ft Sub	468 Ft Sub E End
160 Ft Sub	506 Ft Sub	137 Ft Sub	489 Ft Sub
170 Ft Sub	518 Ft Sub	147 Ft Sub	498 Ft Sub E End
180 Ft Sub	525 Ft Level	157 Ft Sub	525 Ft Level
190 Ft Sub	530 Ft Sub	168 Ft Sub	528 Ft Sub E End
200 Ft Level	544 Ft Sub	178 Ft Sub	558 Ft Sub E End
210 Ft Sub	558 Ft Sub	188 Ft Sub	582 Ft Level
220 Ft Sub	572 Ft Sub	198 Ft Sub	600 Ft Level
230 Ft Sub	586 Ft Sub	208 Ft Sub	650 Ft Level
240 Ft Sub	600 Ft Level	218 Ft Sub	700 Ft Sub
250 Ft Sub	602 Ft Sub	228 Ft Sub	730 Ft Sub
260 Ft Sub	616 Ft Sub	238 Ft Sub	800 Ft Level
270 Ft Sub	630 Ft Sub	248 Ft Sub	
280 Ft Sub	644 Ft Sub	253 Ft Sub E End	
290 Ft Sub	658 Ft Sub	258 Ft Sub	
300 Ft Level	672 Ft Sub	268 Ft Sub	
312 Ft Sub	686 Ft Sub	278 Ft Sub	
324 Ft Sub	700 Ft Level	288 Ft Sub	
336 Ft Sub	714 Ft Sub	298 Ft Sub W End	
348 Ft Sub	728 Ft Sub	303 Ft Sub W End	
360 Ft Sub	742 Ft Sub	308 Ft Sub	
372 Ft Sub	756 Ft Sub	318 Ft Sub	
385 Ft Sub	770 Ft Sub	328 Ft Sub W End	
398 Ft Sub	784 Ft Sub	338 Ft Sub W End	
411 Ft Sub	800 Ft Level	348 Ft Level	

Figure 1.1-25 provides a surface view of the Armour No. 1 and Armour No. 2 mines as a reference for the ensuing 3-D images. It is evident from this view that both the Armour No. 1 and Armour No. 2 underground mines lie beneath pit lakes at this time. Note that the workings of Orebody A in the Armour No. 2 mine are directly connected to the underground workings of the South Thompson Mine to the east. Orebody A workings on the 278-foot sub-level connect with the 250-foot level drift of the South Thompson mine. Both are at an elevation of 974 feet. The collar elevation of the Thompson shaft is nearly 30 feet below that of the Armour No. 2 shaft, explaining the level/sub-level variation. The Armour No. 1 pit is an extension of the Pennington mine pit to the west.

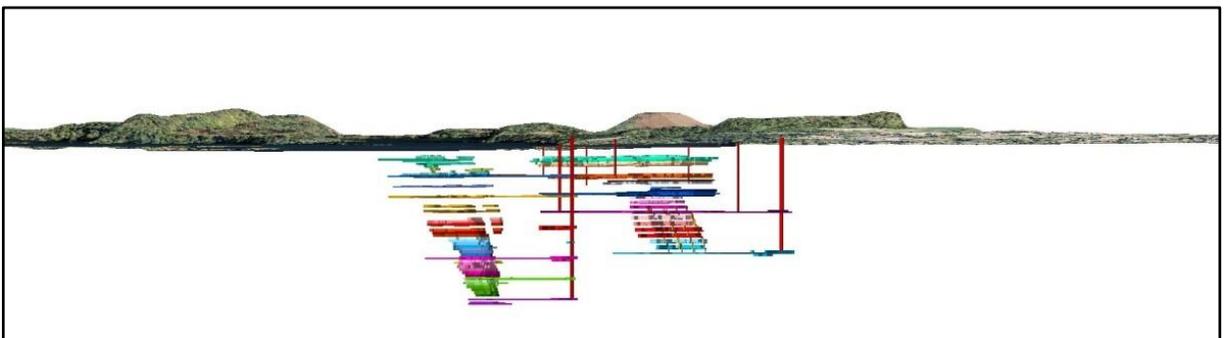


and the Armour No. 2 mine pit lake to the east (right, purple). Bathymetry for the Pennington-Armour No. 1 pit lake is derived from a 1986 MN DNR Ecological Services Section contour map of area pit lake depths. Bathymetry for the Armour No. 2 pit lake is derived from an Inland Steel map of the pit itself. The Armour No. 1 orebody would appear as a solid mass if all of the sub-levels had been digitized.



**Figure 1.1-26.** Depiction of water-filled mine pits and underground mined extents below surface. Orientation is identical to Fig. 1.1-25.

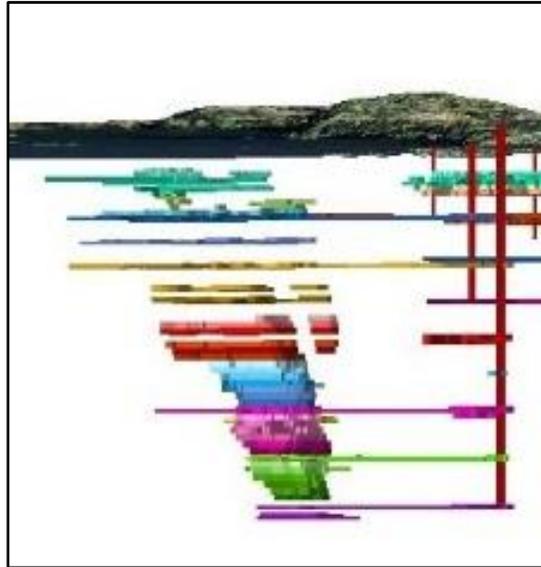
Figure 1.1-27 is rotated 90° to the west (left) and the pit lakes have been removed. Mining on the uppermost levels of the Armour No. 1 mine took place both prior to and subsequent to mining of the open pit on the western end of the Armour No. 1 property, as discussed previously. The pit map indicates where underground workings were encountered during the open pit mining.



**Figure 1.1-27.** Side-on view (north to the left) of the underground mined extents with the water removed.

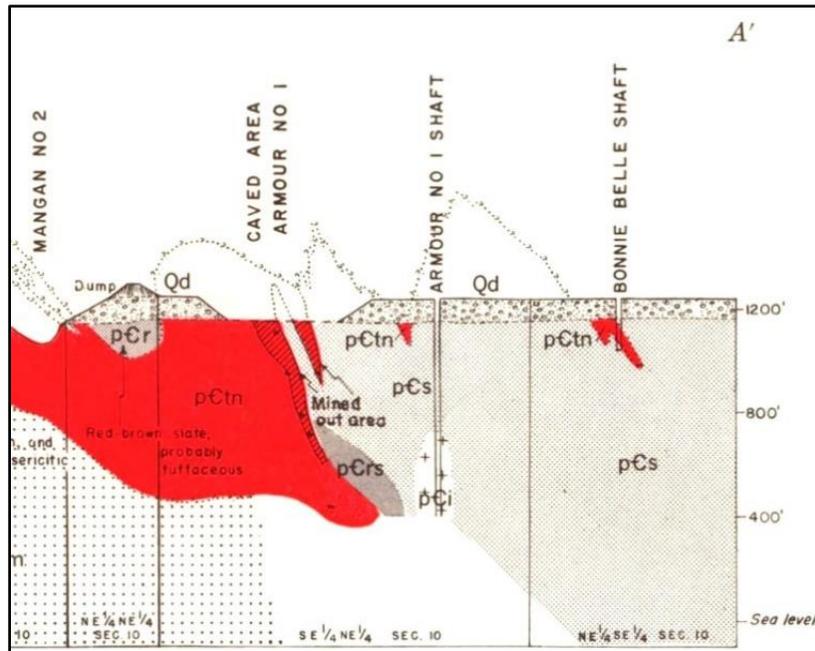
The pit is shallow above the underground workings. Water would have been pumped out of the pit while the underground mine was in operation. The Pennington open pit mine and the Armour No. 1 mine closed about the same time. Final shipments for both mines occurred in 1960 (Skillings Mining Review, 2005). Since that time water has been allowed to flood the former pits.

A closer view of the Armour No. 1 orebody is seen in Figure 1.1-28. The tabular steeply-dipping nature of the orebody can be seen here. Again, this would appear as a solid mass if all of the sub-levels had been digitized.

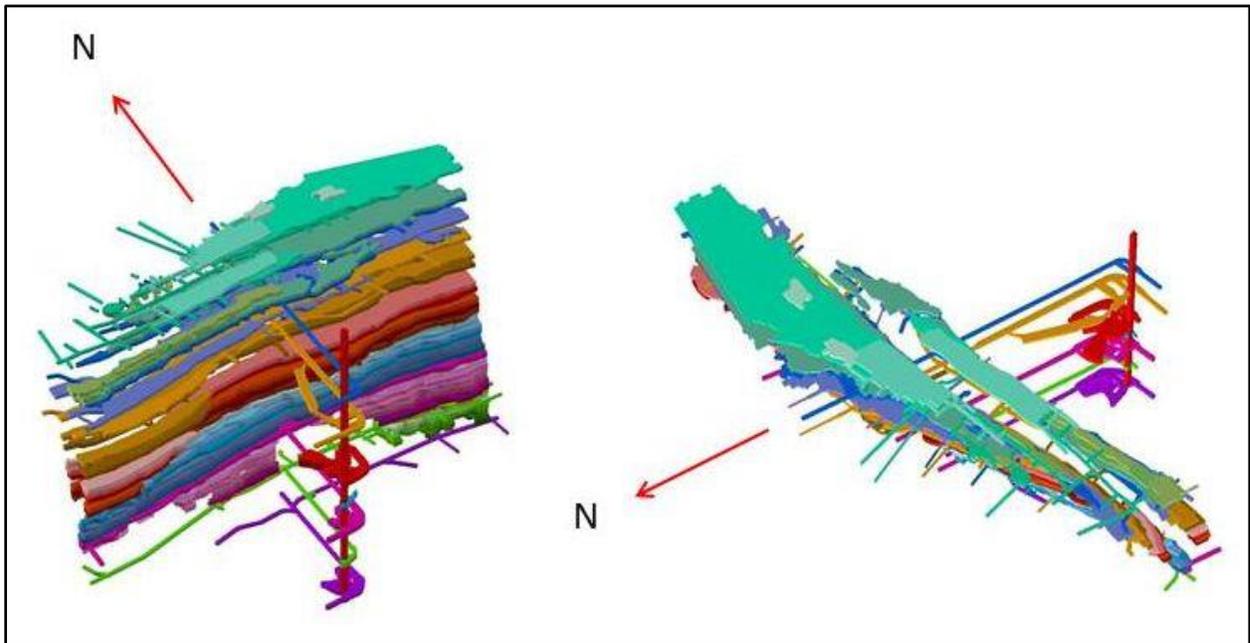


**Figure 1.1-28.** Closer side-on view (north to left) of the Armour No. 1 orebody. Note the separate “leg” to the right (south) of the main orebody.

Mining commenced at the top, 90 feet below the surface, and proceeded downward through the entire 800-foot depth of the orebody. A shorter appendage can be seen to the right (south) of the main orebody. This is due to its separation from the main orebody by a lens of hematitic schist (Schmidt, 1963). Figure 1.1-29 presents part of a cross-section from Schmidt (1963) Plate 3. The orebody and its appendage appear as the “mined out area” on the cross-section. A fuller representation of the tabular Armour No. 1 orebody is seen in Figure 1.1-30, as well as a rotated top-down view that clearly shows the isolated appendage to the south.

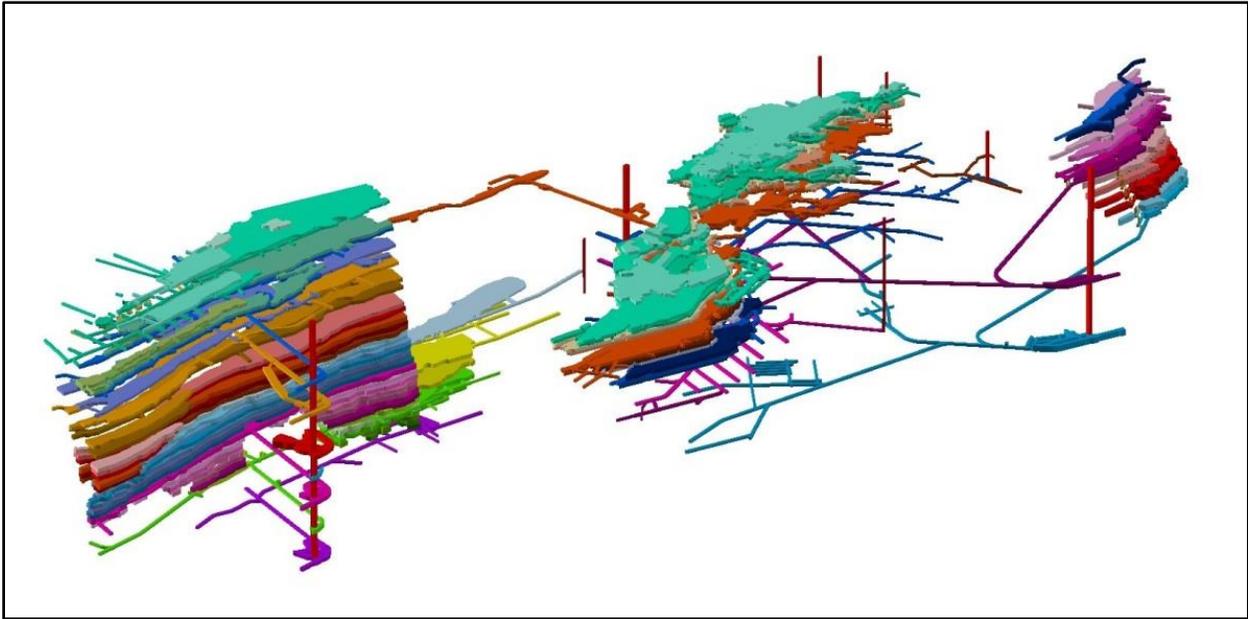


**Figure 1.1-29.** Image from cross-section on Schmidt (1963) Plate 3. Note correspondence of the Armour No. 1 orebody shown in Figure 1.1-28 to the mined out area denoted here. A hematitic schist lens separates the two parts of the orebody (Schmidt, 1963).



**Figure 1.1-30.** More rotated views of the Armour No. 1 orebody.

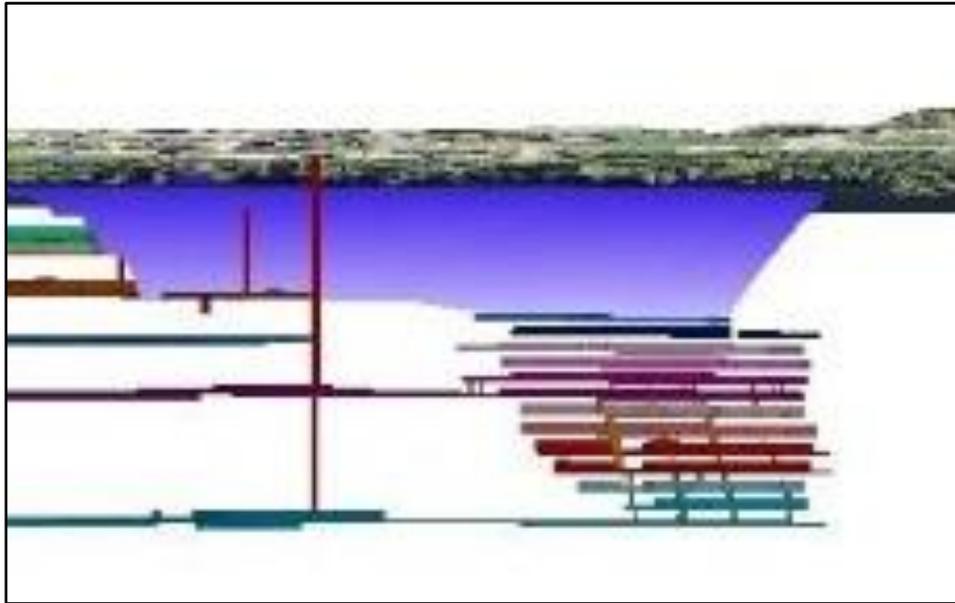




**Figure 1.1-32.** Rotated view of the Armour No. 1 and Armour No. 2 underground mine workings. North aligns with the Armour No. 1 cross-cut drifts (northwest).

Maps indicate that only the lower part of the northwest orebody was mined. This makes sense in that entry was gained through the Armour No. 1 shaft, and this was where Armour No. 1 was operating at the time. The upper levels would have been caved, rendering them inaccessible.

Orebody A was mined by the stoping method from the 253- through 558-foot sub-levels. Initially it was thought that this may be an isolated orebody, hence its consideration for CAES potential. Only maps from the 348-foot level down had been found. Subsequently the remaining maps were found that brought the orebody up to the level of the pit bottom, although not directly beneath it (Fig. 1.1-33). Mined subsequent to the open pit, the pit would have likely been maintained dry for the remaining life of the mine.



**Figure 1.1-33.** Armour No. 2 pit and Orebody A.

#### *Armour Mine Workings and CAES*

The preceding pages have presented a picture of the mining activity that occurred at the Armour No. 1 and Armour No. 2 mines during their time of operation. At the present time all of the shafts should have been filled with some kind of material and sealed off as safety precautions. The pits have been allowed to fill with water, and all void spaces within the shafts, cross-cuts, and mined extents would be filled with water as well.

Since the condition of the mined extents make containment of compressed air unlikely, attention was focused on the shafts and cross-cuts. These are contained outside of the iron-formation in the schist rock. The cross-cuts, which apparently were not timbered, should have remained opened.

Volume determinations were made for the available void space within the shafts and cross-cuts of both mines. Cross-cut drift lengths were stopped approximately 100 feet from the orebody for buffering purposes in the Armour No. 1 mine (Fig. 1.1-34).

Cross-cut drifting was more extensive in the Armour No. 2 mine. Cross-cuts on the 378-foot level run from the shaft to Orebody A and also to the main orebody. Similarly, on the 582-foot level, cross-cuts run from the shaft to Orebody A and also toward, but below, the main orebody, branching off toward both its northern and southern lobes. Raises have been driven from the cross-cuts on both levels to workings above. For volume calculation purposes, the cross-cuts were stopped approximately 100 feet short of Orebody A and 100 feet short of the first raises encountered toward the main orebody (Fig. 1.1-35).

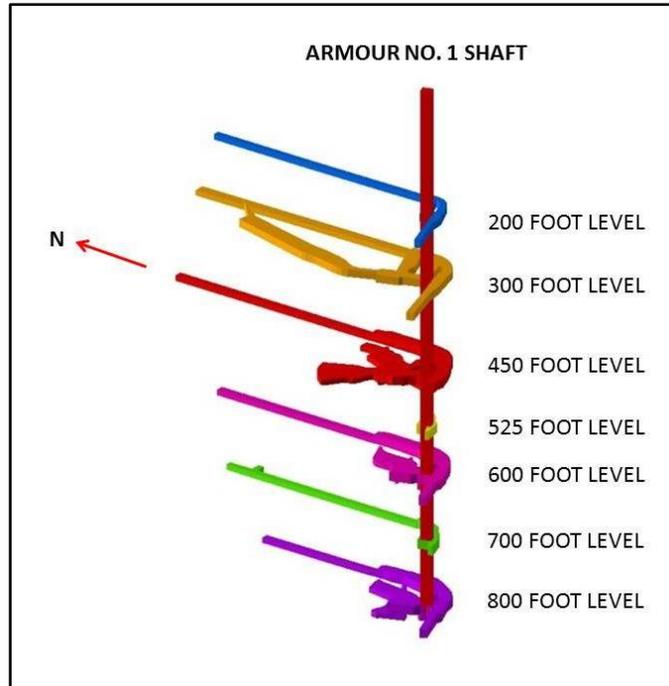


Figure 1.1-34. 3-D view of Armour No. 1 shaft and cross-cuts for volume calculation.

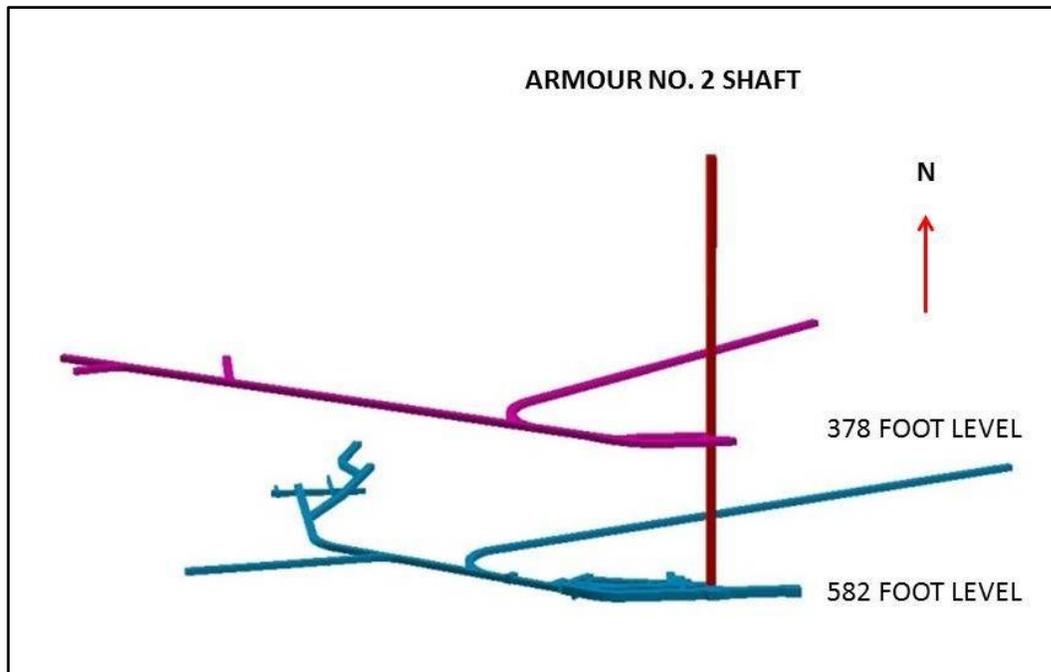


Figure 1.1-35. 3-D view of Armour No. 2 shaft and cross-cuts for volume calculation.

As shown in Table 1.1-3, potential area for compressed storage in Armour No. 1 is 929,184 ft<sup>3</sup> (26,311 m<sup>3</sup>). Potential area for compressed air storage in Armour No. 2 is 641,588 ft<sup>3</sup> (18,167 m<sup>3</sup>).

**Table 1.1-3.** Volume calculations for Armour No. 1 and Armour No. 2 mine features.

	MINE FEATURE	VOLUME_FT <sup>3</sup>	VOLUME_M <sup>3</sup>
<b>Armour No. 1</b>	SHAFT	153,600.0000	4,349.4676
	CROSS-CUT DRIFTS	174,417.5032	4,938.9617
	MINED EXTENT AT SHAFT	601,166.9628	17,023.1525
	<b>TOTAL:</b>	929,184.4660	26,311.5818
	MINE FEATURE	VOLUME_FT <sup>3</sup>	VOLUME_M <sup>3</sup>
<b>Armour No. 2</b>	SHAFT	111,744.0000	3,164.2377
	CROSS-CUT DRIFTS	330,924.7584	9,370.7644
	MINED EXTENT AT SHAFT	198,920.1994	5,632.7929
	<b>TOTAL:</b>	641,588.9578	18,167.7950

### **Scenario 3b: Mine shafts in series – Armour No. 1, Armour No. 2, Thompson, Meacham, and Croft mine shafts, Cuyuna Range**

The second scenario investigated for potential CAES storage relative to legacy mining features is that of using a series of mine shafts in tandem. Such a scenario presents itself on the Cuyuna North Range north of the cities of Ironton and Crosby (Fig. 1.1-36).

Three additional mines lie along the same north-east trending orebody as Armour No. 2's Orebody A. These are the South Thompson, the Meacham, and Croft. The Thompson Mine was an original Inland Steel property. Inland Steel was sinking the Thompson shaft in 1911 at the same time that the Iroquois Steel Company (a subsidiary of the Rogers-Brown Ore Company) was sinking the Armour No. 1 and Armour No. 2 shafts. The Meacham shaft was sunk the previous year, 1910, by the Rogers-Brown Company. The Croft mine shaft came a little later, in 1914, sunk by the Merrimac Mining Company (Aulie and Johnson, 2002).

Two mines lie on the southwestern end of the Armour No. 2 main orebody, the Ironton mine and the Bonnie Belle mine. The Ironton mine was originally called the Cuyuna-Duluth mine. Its shaft was sunk in 1912 by the Cuyuna-Duluth Company. The Bonnie Belle mine was initially called the Liberty mine. Its shaft was sunk in 1918 by Liberty Mining (Aulie and Johnson, 2002). The Bonnie Belle and Ironton mines are directly connected to the Armour No. 2 mine workings.

Shaft sized has been determined by the number of compartments comprising each. Generally this is indicated in how the shafts are drawn on mine maps. The Armour No. 1, Armour No. 2, and Thompson shafts are five-compartment shafts. The Ironton, Meacham, and Croft shafts are three-compartment shafts. The Bonnie Belle shaft appears to be a two-compartment shaft.

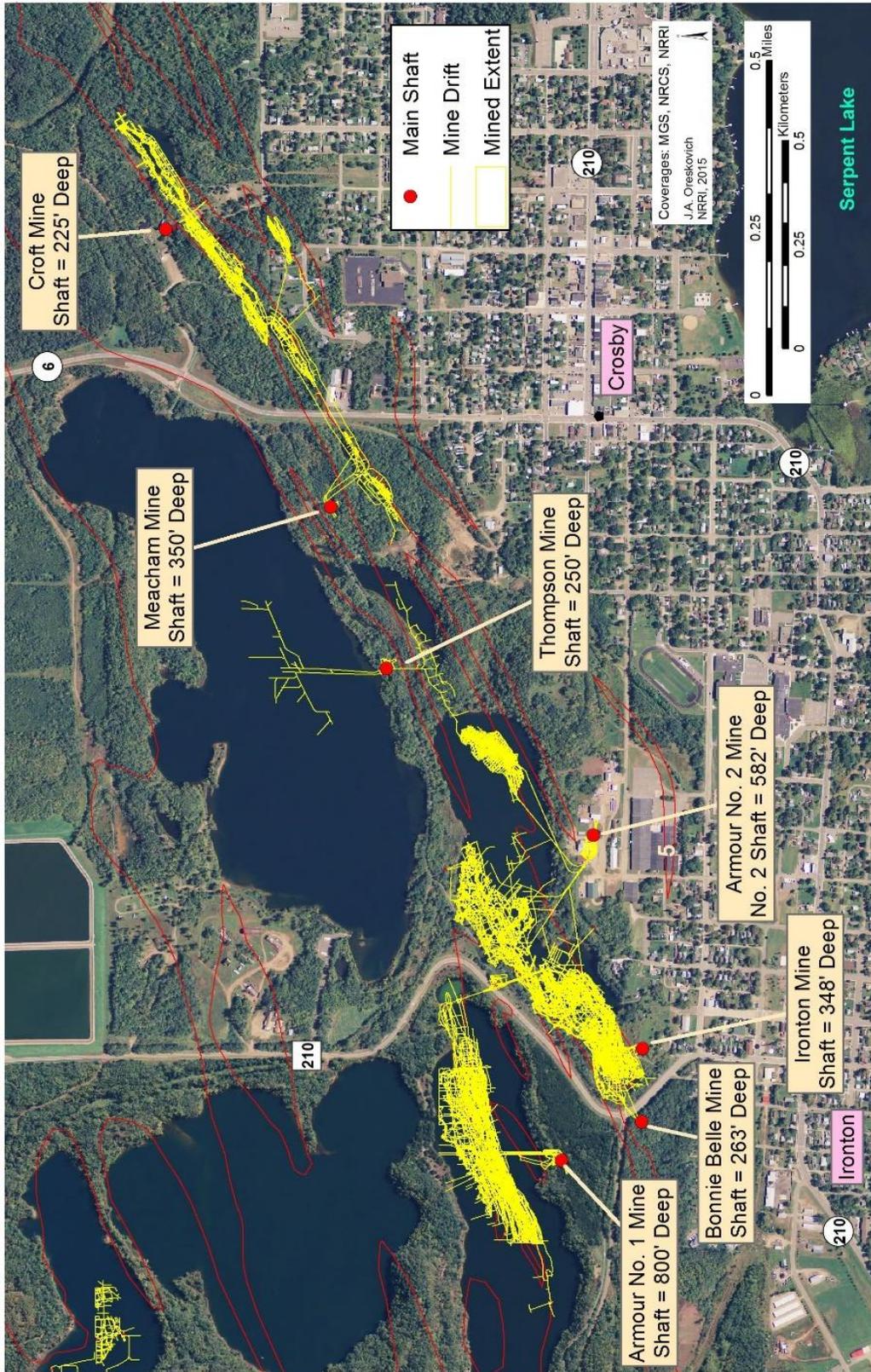


Figure 1.1-36. A series of mines north of Ironton and Crosby presents an opportunity for linked CAES storage.

Outside dimensions used for the shafts were as follows:

- five-compartment shafts – 16 feet x 12 feet;
- three-compartment shafts – 18 feet x 6 feet; and
- two-compartment shaft – 12 feet x 8 feet.

Shaft depth was taken as the lowest level of workings found for each shaft.

Table 1.1-4 summarizes the volume of space potentially available for CAES storage by linking together the seven aforementioned shafts. It should be noted that the original main shaft for the Armour No. 2 mine was not included in this calculation due to its roadside location on the narrow isthmus of land between the Pennington-Armour No. 1 pit and the Armour No. 2 pit. The calculated volume of void space available by linking the seven shafts is 482,016 ft<sup>3</sup> (13,649 m<sup>3</sup>).

**Table 1.1-4.** Volume calculation for seven mine shafts in a series.

Linked Shafts in Series						
MINE SHAFT	SHAFT TYPE	DEPTH	LENGTH	WIDTH	VOLUME_FT3	VOLUME_M3
Armour No. 1	5-compartment	800	16	12	153,600	4,349.47
Armour No. 2	5-compartment	582	16	12	111,744	3,164.24
Bonnie Belle	2-compartment	263	12	8	25,248	714.94
Croft	3-compartment	630	18	6	68,040	1,926.68
Ironton	3-compartment	348	18	6	37,584	1,064.26
Meacham	3-compartment	350	18	6	37,800	1,070.38
Thompson	5-compartment	250	16	12	48,000	1,359.21
				<b>TOTAL:</b>	482,016	13,649.17

## FACTORS AFFECTING USAGE OF THE ARMOUR NO. 1 AND ARMOUR NO. 2 MINE FEATURES AND THE CUYUNA SHAFTS IN SERIES FOR CAES STORAGE

### Post-mining condition of legacy underground mine features

It should be expected that most shafts have been caved or otherwise filled with materials such as surface overburden, rock, scrap, construction debris, recovered road materials (asphalt and concrete chunks), or poured concrete. Excavation of shaft fill would likely be required in most cases for CAES shaft evaluation.

Underground mine drifts and workings, and shafts, to the extent that they are open, should be expected to be water-filled. Figure 1.1-37 exhibits the large number of water bodies in the vicinity of the Cuyuna North Range. This area is a geographic region of low relief that lacks rock outcrops and is underlain by a blanket of glacial sediments. Overburden in the Armour No. 1, Ironton, original Armour No. 2, Thompson, and Meacham shafts held consistently at 65 feet in thickness, increasing to 110 feet in the Croft shaft to the east.



In a region geographically dotted with lakes, mining has only compounded the number. Twenty-six mine pit lakes are indicated on the map of the Cuyuna North Range in Figure 1.1-37 (beige text boxes). Cessation of mining activities results in deactivation of pumps used to maintain dry working conditions in both underground and open pit operations. Underground workings flood with unimpeded ground and surface water inflow. Mine pits experience years of rising water levels due to precipitation, as well as ground and surface water inflow, until equilibrium is established when outflow elevations are attained. Where waters bridge adjacent pit boundaries they coalesce to form even larger pit lakes.

Many underground mine names (red text) are seen duplicated as pit lakes in Figure 1.1-37. These mines typically originated as underground mines and at a later date were worked by open pit methods. Some mine shafts in Figure 1.1-37 appear in unnamed water bodies (ex. Merritt No. 1). This can be attributed to water ponding in depressions created by surface subsidence. Subsidence was incurred by caving during or subsequent to underground mining activities.

Underground drifts, blasting fractures, joint planes or permeable strata can act as conduits to link water bodies that appear isolated on the surface. Dewatering any one water body could conceivably have a regional impact well beyond the immediate target. This is a common occurrence with mine pits on the Mesabi Range. Conversely, isolating a shaft and series of cross-drifts for CAES purposes could prove a significant challenge.

### **Post-mining use of legacy mine features**

Mining features offer a unique opportunity for repurposing industrial lands into recreational lands and Minnesota has often led the way in this effort. Mineland reclamation became state law in 1969. Enforcement of that law came in 1977 with the establishment of the Mineland Reclamation Division of the Iron Range Resources and Rehabilitation Board (IRRRB). Under Minnesota State Statute 298.223, the IRRRB Mineland Reclamation program was tasked to “provide for the reclamation, restoration or reforestation of minelands not otherwise provided for by the state law for the purpose of reclaiming and enhancing those areas of northeastern Minnesota adversely affected by mining taconite and iron ore” (<http://mn.gov/irrrb/miningtimber/mineland-reclamation/>). Mineland Reclamation was responsible for reclaiming lands that were mined prior to 1980. Reclamation of lands mined from 1980 forward became the responsibility of the mines themselves, with oversight from MN DNR (Kurth, 1913).

The scope of Mineland Reclamation’s directive covers all three of Minnesota’s iron ranges. Programs include mine shaft capping, pit wall stabilization and re-sloping, revegetation of disturbed ground, habitat restoration, mitigation of impacted wetlands and environmental education. Repurposing mine pits for recreational purposes has been an ongoing endeavor of the program.

Surface waters form the basis of a large tourism economy in east-central and northeastern Minnesota where sport fishing is a year-round pursuit. IRRRB, in conjunction with MN DNR, has been stocking mine pit lakes with several species of game fish, particularly trout, since the late 1970s. Boat access to pit lakes has been established, as well as swimming beaches and other amenities.

### **Cuyuna Country State Recreation Area**

On the Cuyuna Range, the greatest obstacle to development of a CAES facility based on the Armour mines and the associated Bonnie Belle, Ironton, Thompson, Meacham, and Croft mine shafts is directly attributable to the success of the Mineland Recreation programs. Working in conjunction with MN DNR and local units of government, IRRRB has helped transform the Cuyuna Range into a prime recreation area. Today it is the site of the Cuyuna Country State Recreation Area (CCSRA). The northern portion of the CCSRA covers much of the Cuyuna North Range (Fig. 1.1-38) where it encompasses natural lakes, mine pit lakes, and acres of mine stockpiles.

Created in 1993, the CCSRA was Minnesota's first established State Recreation Area. A State Recreation Area is designed to allow more intensive recreational use than a state park (Minnesota Department of Natural Resources, 1995). In addition to boating, fishing, and hiking, the CCSRA has developed a national and international reputation among mountain bike enthusiasts. The first mountain biking trail, a half-mile demonstration trail, was built in 2007. Construction of a 30-route mountain bike trail network took place in 2010 (International Mountain Bicycling Association (US), 2011). This network comprises 25 miles of mountain biking trails within the CCSRA that incorporate use of the stockpiles left behind from the Cuyuna era of mining.

### **Provision for future mining within the CCSRA**

Provision was made from CCSRA's establishment that mining could one day return to the CCSRA. Several references to this were found:

1. MN DNR Cuyuna Lakes State Trail Master Plan contains the following pursuant to the Laws of Minnesota for 1993, Chapter 172, Section 34, subd 3:  
"MINING. The commissioner shall recognize the possibility that mining may be conducted in the future within the Cuyuna Country State Recreation Area, and that use of portions of the surface estate and control of the flowage of water may be necessary for future mining operations." (Minnesota Department of Natural Resources, 2004)
2. MN DNR Record of Decision on Environmental Assessment Worksheet for the CCSRA Mountain Bike Trail System Section 12g identified iron and manganese mineral deposits as potential environmental effects; proposed mitigation: "A goal for the area is that the land surface shall remain relatively unencumbered so that future mineral evaluations can take place. The proposed trails are not a large encumbrance, and can be easily relocated for mining activities." (Minnesota Department of Natural Resources, 2008)

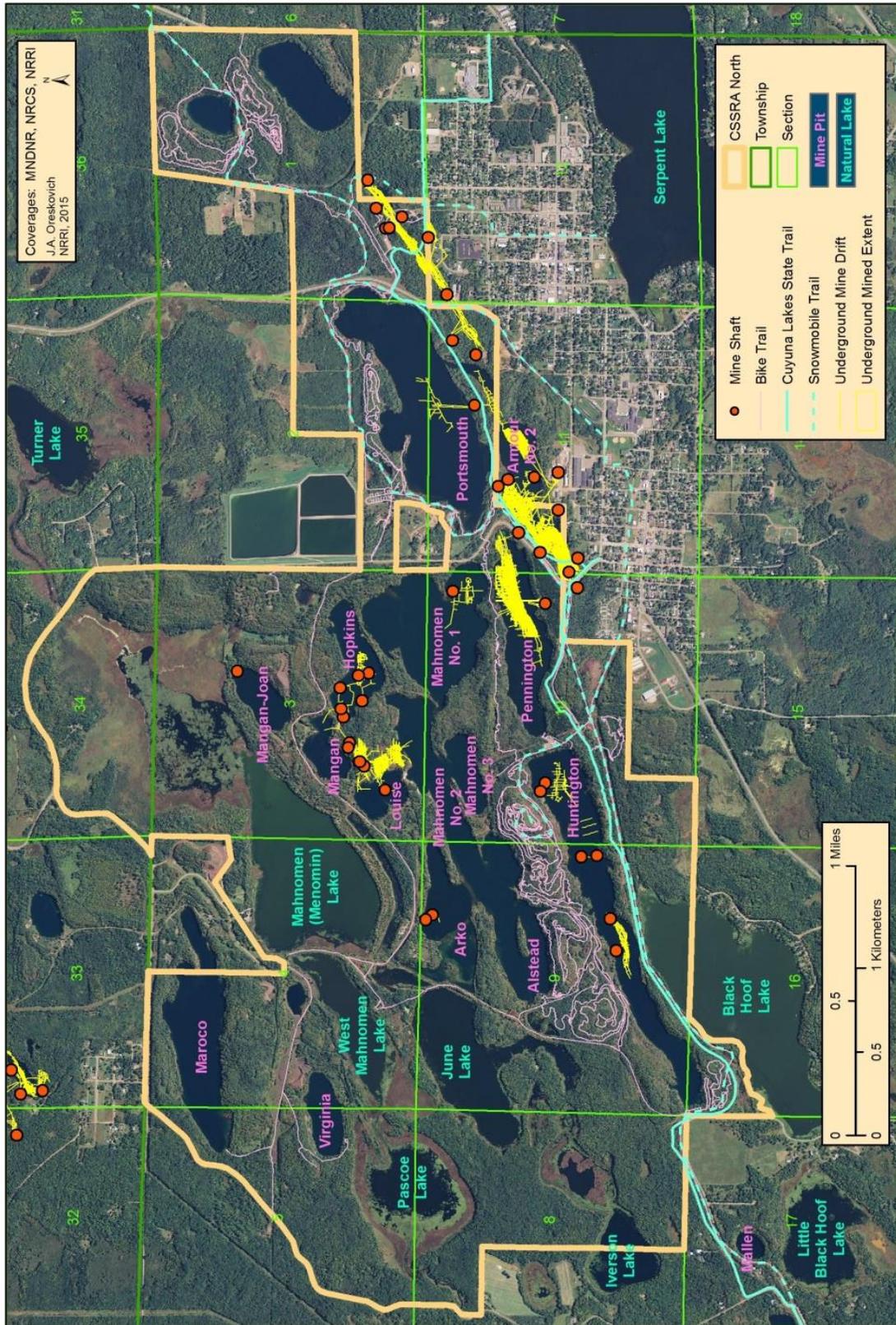


Figure 1.1-38. Northern portion of the Cuyuna Country State Recreation Area (CSSRA) depicting hiking, biking and snowmobile trails.

3. MN DNR Recommendations for Land Use Screening Criteria For Public Metallic Minerals Lease Sales Post 2013 contains the following wording under the heading “Exclusion of lands from public lease sales”:

“The following types of lands and features are always excluded from non-ferrous metallic mineral leases, and the recommendation is to continue to exclude these lands from leasing...

- 2) State parks and state recreation areas

All lands within the statutory boundaries of state parks and state recreation areas are excluded from leasing, *provided that exceptions may be made as to the Hill Annex State Park and the Cuyuna Country State Recreation Area, where the establishment of these two management units specifically recognized that mining may occur in the park/SRA.* (author’s emphasis; Minnesota Department of Natural Resources, 2013.)

### **CAES study legacy underground mine features and the CCSRA**

A closer inspection of the CAES study area reveals that the Armour No. 1, Thompson, Meacham and Croft main shafts reside within the CCSRA (Fig. 1.1-39). The Bonnie Belle and Ironton shafts lie outside of the CCSRA but are situated less than 150 ft. and 100 ft., respectively, from the Cuyuna Lakes State Trail, as well as biking and snowmobile trails for the Bonnie Belle.

Within the CCSRA, the Thompson and Meacham shafts lie less than 150 ft. from the Cuyuna Lakes State Trail as shown. This area is a paved, multi-use trail extending from Crosby southwest to Riverton that spans the study area shown in Figure 1.1-39. Eventually this trail will tie Aitkin and Brainerd to the Cuyuna Range cities via a paved trail.

The Croft shaft not only resides within the CCSRA, but the mine itself is the site of the Croft Mine Historic Park. Bike trails surround the facility and there is access from the Cuyuna Lakes State Trail. The main shaft resides near the entrance to a structure that houses a simulated underground mine. According to Schmidt (1963), the shaft is 630 ft. deep. The Croft underground workings depicted in Figure 1.1-39 reflect maps obtained to date that extend down to the 333-ft. level.

While located within the CCSRA, the Armour No. 1 mine shaft and cross-cuts, discussed in detail earlier, reside slightly more distant from trails and County Road 30 that runs between the Armour No. 1 mine and the main orebody of the Armour No. 2 mine. The site is accessible from County Road 30 to the east as well as from North Road to the south of the property that is followed by the bike and snowmobile trails. The Armour No. 1 mine resides on State property owned by the MN DNR.

The “new” Armour No. 2 shaft, Orebody A, and the cross-cuts discussed previously reside outside of the CCSRA. The shaft is located within a fenced-off clump of trees in the Crosby Industrial Park (Fig. 1.1-40). Plat maps on the Crow Wing County website indicate that the shaft lies on property owned by the City of Crosby.

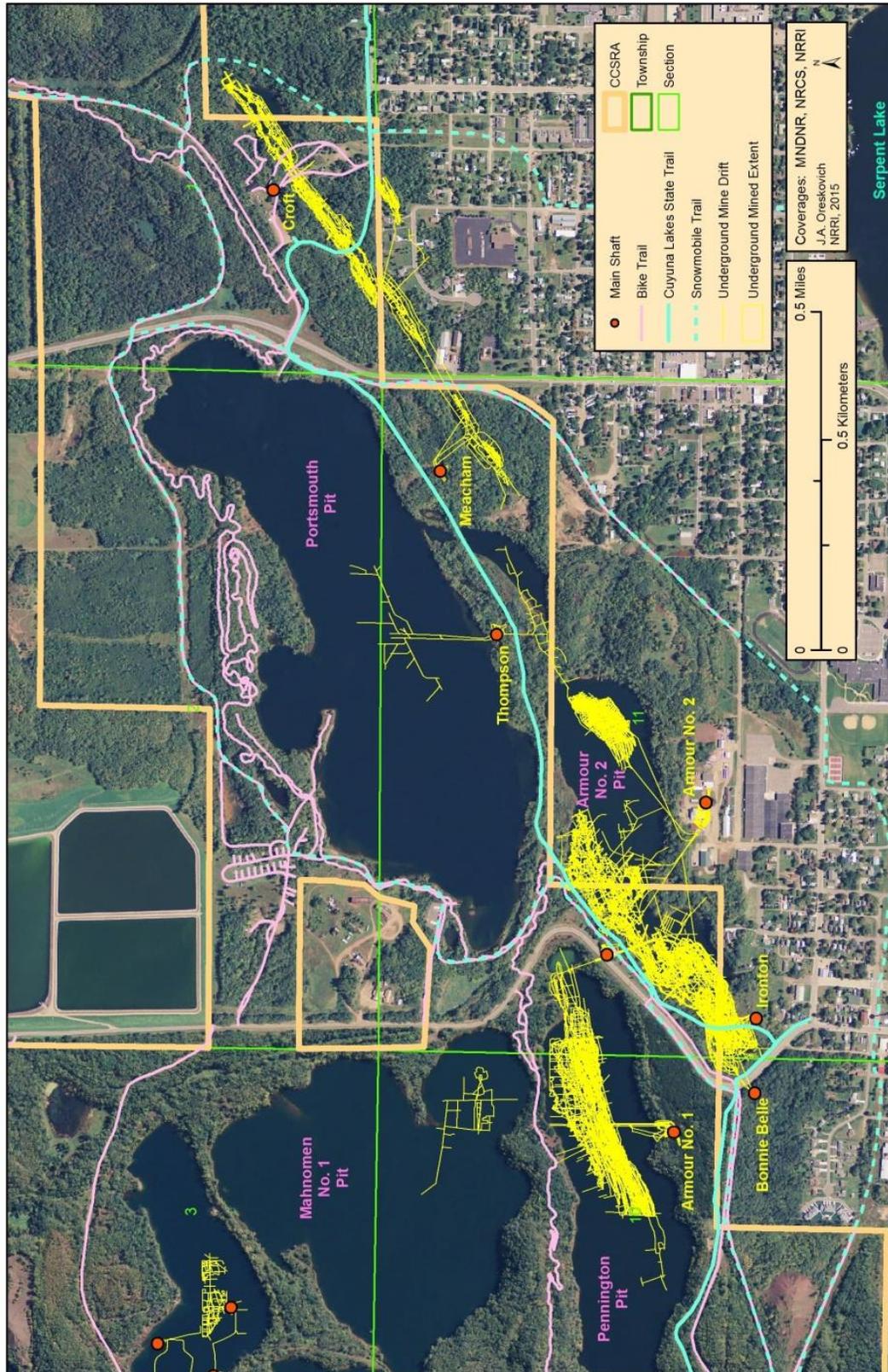


Figure 1.1-39. Closer view of the CAES study area within the CCSRA showing proximity of main shafts to trails.



**Figure 1.1-40.** Location of "new" Armour No. 2 main shaft in the Crosby Industrial Park.

## DISCUSSION

While worthwhile for study purposes, the prospect of using the series of mine shafts (Armour No. 1, Bonnie Belle, Ironton, Armour No. 2, Thompson, Meacham, and Croft) located along the southern end of the Cuyuna North Range in tandem for CAES purposes is unlikely. Location within the CCSRA and/or directly alongside of the Cuyuna Lakes State Trail would preclude such activity. In addition, the Croft mine is a historic park site.

Use of the shafts and cross-cut drifts of the Armour No. 1 and Armour No. 2 mines present greater, yet slim, opportunity for CAES. While located within the CCSRA, the Armour No. 1 shaft and cross-cuts are situated to the south and directed away from the land surface activity of the recreation area. Consideration of water use in the Pennington Pit is not taken into account in this discussion.

North Road, the Cuyuna Lakes State Trail, and the bike and snowmobile trails are in relatively close proximity to the shaft on its south. There is some room to swing this infrastructure further to the south away from the shaft. The Armour No. 1 parcel is owned by MN DNR, while the wooded parcel to the south of that is owned by the City of Ironton. There is a 30-foot-deep ravine

to be contended with on the City of Ironton property between the trails and the subdivision to the south. MN DNR-Lands and Minerals Division (LAM) owns the parcel to the west of the City of Ironton parcel.

The Armour No. 2 shaft has direct access but is closely surrounded by buildings in the industrial park. Surface area is restricted.

The Armour No. 1 shaft has the full head of the Pennington and possibly the Mahnomen No. 1 pit lakes to contend with for dewatering. While dewatering of the Armour No. 2 shaft may have to contend only with the head of the smaller Armour No. 2 pit lake, there are likely conduits to the Portsmouth pit lake in addition to the direct connection to the Pennington pit lake via the cross-cut in schist from the old Armour No. 2 shaft to the Armour No. 1 workings.

In terms of location, the potential for CAES development using the legacy mine features in the immediate study area at this time appears slim due to the CCSRA and site constraints. The prospect that mining can resume at a later date within the CCSRA could change that assessment. Legacy underground mine features for the remainder of the Cuyuna Range, as well as for the Mesabi and Vermilion ranges, will be presented in the following section.

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**Section 1.2:  
Review of Underground Workings on Minnesota's Iron Ranges for CAES Potential**

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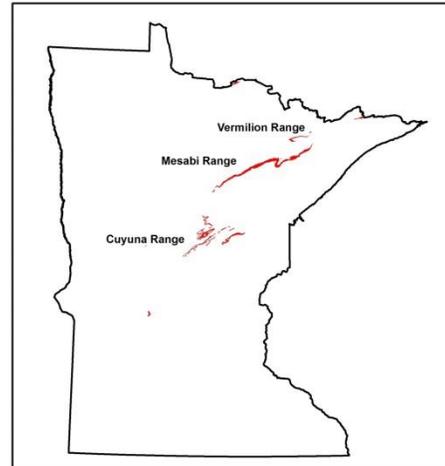
## INTRODUCTION

The state of Minnesota has been endowed with a wealth of mineral resources ranging from both ferrous and non-ferrous metallic mineral deposits to industrial sand, clay, and aggregate deposits. Of particular interest to this study are the iron deposits.

Minnesota hosts three distinct regional geological occurrences of economically-significant iron-bearing strata (Fig. 1.2-1). Known as the Mesabi Range, the Cuyuna Range, and the Vermilion Range, these iron-bearing strata (iron- and manganese-bearing strata on the Cuyuna Range) have historically been feeding U.S. steel mills for more than 130 years. Underground mining in Minnesota occurred during the first 80 years of this period, generating voids that could potentially host compressed air energy storage (CAES).

Underground mining took place on all three ranges, beginning in 1884 on the Vermilion Range, 1892 on the Mesabi Range, and 1909 on the Cuyuna Range. It was used to extract natural (oxidized, non-magnetic) iron ores. There has been no underground mining to date of the unoxidized magnetic taconite iron ores on the Mesabi Range. The potential to do so in order to produce a custom-made cavern for CAES was addressed earlier in this report (Section 1.1, Scenario 2: Excavated Cavern by Mining a Mineral Resource (High Volume Storage Facility)).

It is the legacy features of underground mining – shafts, drifts, and voids created by employment of stoping, top-slicing and caving, sub-level caving, and square-setting mining techniques – that hold potential for CAES. Stopping and sub-level caving were used in the harder ores, particularly on the Vermilion Range and in various orebodies on the Cuyuna Range. Square-setting (used in the earlier years) and top-slicing and caving were used to extract the generally softer ores of the Mesabi and Cuyuna ranges. Timbering was used in all but the stoping (open room) method.



**Figure 1.2-1.** Iron ranges of Minnesota.

## PROCEDURE

### Rationale

The majority of the work on this project has centered on the underground mines of the Cuyuna Range, although each of the three Minnesota iron ranges will be addressed. The rationale for this is threefold:

1. The underground mines of the central, eastern, and part of the western Mesabi Range were previously digitally mapped through the Minnesota Department of Natural Resources Division of Lands and Minerals (MN DNR-LAM). Underground mining

features, including shafts, drifts, and mined extents, were mapped from 2006 to 2011 by this author (through NRRI) and MN DNR-LAM colleagues Dale Cartwright and Matt Oberhelman. This large body of work is available to the public at [http://www.dnr.state.mn.us/lands\\_minerals/underground/index.html](http://www.dnr.state.mn.us/lands_minerals/underground/index.html) and upon request from the MN DNR-LAM office in Hibbing, MN. Remaining to be mapped are those mines toward the western end of the Mesabi Range.

2. The Vermilion Range, which hosts very deep mines (the Soudan Mine is 2,707 feet deep, the Ely mines are around 1,000-1,500 feet deep), lacks major power transmission lines to and within the vicinity. The Soudan Mine is the site of a Minnesota State Park as well as a deep underground physics laboratory. The Ely mines (Chandler, Pioneer, Savoy, Sibley and Zenith) are interconnected, lying adjacent to the city of Ely. Pioneer Lake on the city's northern edge formed from the subsidence of the underground workings. The Soudan Mine workings were digitized in 2003 by this author (Peterson and Patelke, 2003).
3. The Cuyuna Range, like the Mesabi Range, saw intensive underground as well as open pit mining of natural iron ore. Little, if any, previous work has been done to digitally map the depth and extents of these mines. Digitization of the surface and underground extent of the mine workings was a necessary first step in evaluating their suitability for CAES.

## **Method**

Digitally mapping the underground mines of the Cuyuna Range followed procedures established during the mapping of Mesabi Range underground mines at MN DNR-LAM. The author has made every attempt to produce a comparable body of work for the Cuyuna Range within the constraints of this study.

### *Mine Search*

Skilling's Mining Review's Minnesota Mining Directory (2005) was used to establish a basis from which to initiate searches for underground mine maps. The mining directory contains the following information pertinent to this work: mine names for each iron range; a reference to former mine names; mine locations in parcel, section, township and range; beginning and ending years of natural ore shipments; number of long tons shipped; most recent mine operator; last known mine fee owners or representatives; and maps illustrating the mine tracts.

### *Data Sources*

Mine operator and fee owner/representative data were used to direct searches for maps of underground mine workings during the course of the MN DNR-LAM Mesabi Range mine mapping projects. Providing additional invaluable assistance was the St. Louis County Mine Inspector's

office located in Virginia, MN and the Minnesota Department of Revenue (MDOR) Minerals Tax Office located in Eveleth, MN as well as the general public.

Map sources for the Mesabi Range mine mapping project included current taconite mining operations (Arcelor-Mittal Minorca Mine, Hibbing Taconite Company, United Taconite, U.S. Steel Keewatin Taconite, and U.S. Steel Minntac), fee holders (Eveleth Fee Office, Great Northern Iron Ore Properties (GNIOP), Meriden Engineering, and RGGGS Lands and Minerals), MN DNR, the Iron Range Research Center (IRRC) located at Minnesota Discovery Center in Chisholm, MN, the MDOR, and the National Mine Map Repository, Office of Surface Mining Reclamation and Enforcement (OSMRE), located in Pittsburgh, PA. For the CAES project, underground mine maps for the Cuyuna Range and Mesabi Range were obtained from MDOR, IRRC, MN DNR, OSMRE, GNIOP, and Superior Mineral Resources LLC (SMR) of Hibbing, MN.

A total of 1,464 digital map images received from OSMRE for the CAES project were reviewed for relevance, with over 700 applicable to the project. Digital images were also acquired from MN DNR-LAM. Seventy-three paper/mylar maps from the IRRC archival collection were selected for scanning and use. Paper maps were obtained from MDOR, GNIOP, and SMR.

Mylar and paper underground mine maps were taken to the MN DNR-LAM office in Hibbing for scanning via a large format scanner. Digital image files of the scanned maps were provided to MN DNR-LAM to be added to the Minnesota underground mine map collection. Once scanned, the map images were digitally geo-rectified in Esri® ArcMap™ 10.1.

### *Geo-rectification*

This GIS project is based on shapefile, geodatabase, and imagery data obtained online from MN DNR, the Minnesota Geological Survey (MGS), the Minnesota Geospatial Information Office (MnGEO) and the U.S. Department of Agriculture (USDA) Natural Resources Conservation Service (NRCS) Geospatial Data Gateway. These data included the Public Land Survey (PLS) data (township, section, and parcel) used as the overall basis for geo-rectification. GPS coordinates for mapped features (including mine shafts) were unavailable. In addition to PLS data, geo-rectification was made on the basis of current and past imagery photography from the National Agriculture Imagery Program (NAIP) of the USDA Farm Service Agency (FSA), acquired online from NRCS, and on current and historic topo maps (circa 1912-1915 and 1950s).

Unlike the large taconite mines operating today in Minnesota that can extend for miles, mines of the Cuyuna Range underground era typically reside within one or two 40-acre parcels. Mine workings are mapped to the parcel or part parcel, making accuracy in geo-rectification difficult. Parcel lines dating from the time of initial underground mining often do not correspond to current PLS GIS coverages. In addition, if paper rather than mylar maps were the source of the digital images used, error is introduced due to paper's tendency to stretch over time with handling.

Surface imagery was employed for alignment purposes; however, surface features such as roads, railroad tracks, buildings, and even stockpiles from the time the maps were produced have been obliterated by succeeding open pit mining in the vicinity. Today's landscape is very different from that at the time most of the underground mines operated on the Cuyuna Range.

Digital plat maps for the cities of Ironton and Crosby were used as the basis of alignment for the Armour No. 1 and Armour No. 2 mines discussed previously in the report. Ironton was platted

in 1910 (<http://cuyunalakes.com/cities/index.htm>). Crosby was platted within a year or two of Ironton. Digital plat maps for these cities from the 1913 Standard Atlas of Crow Wing County and early topographic maps from Brainerd (1915), Cuyuna (1913), and Deerwood (1912) were used to aid in the alignment of the Armour and other Cuyuna North Range mines.

Mining operations are typically designed and mapped on a grid at 100 foot or 200 foot spacing aligned to north or to the trend of the orebody. Mine grid starting points (coordinate 0,0) relative to PLS corners vary from mining company to mining company and from mine to mine. Because of their fixed spacing, mine grids were used as the overriding factor in the orientation and geo-rectification of the individual mines for digitization. As a result, the integral relationship of the workings within an individual mine have been maintained, even as the mine may be skewed or offset from its actual physical location. Error of offset is likely within 100 feet (30.5 meters). Future acquisition of GPS coordinates for shaft locations should make corrections a simple matter of shifting and/or rotation.

### *Digitization*

Mining features (including shafts, drifts, mined extents, and caved extents) were digitized from the geo-rectified images, building point, polyline, and polygon GIS coverages. It was not within the scope of this project to digitize every mined level and sub-level for each mine as was done previously for the Mesabi Range mapping projects. Where a mine comprised a large number of levels and sub-levels, features from a sufficient number of these were digitized to establish the mine's areal and depth footprint.

An additional GIS coverage was built to show the parcel footprints of underground mine and ore reserve properties on the Cuyuna Range. Property descriptions were pulled from Beltrame (1977), Skillings Mining Review (2005), and MDOR data files. Parcel outlines were digitized to MN DNR PLS coverages.

### **Project Deliverables**

Project deliverables are as follows:

1. Database of Cuyuna Range underground mine workings compiled from multiple source documents and provided in spreadsheet format: CuyunaRange\_Underground MineWorkings.xlsx (Appendix 1.2-B);
2. Underground mine workings of the Cuyuna Range in shapefile and geodatabase format (Appendix 1.2-C – This information is not included in this report at this time, but it is available at NRRI and will be made available on the NRRI website);
3. Mine maps of Cuyuna Range underground mines in PDF format (Appendix 1.2-D – This information is not included in this report at this time, but it is available at NRRI and will be made available on the NRRI website);

4. Geo-rectified mine maps of Cuyuna Range underground mines in JP2 or TIFF format (Appendix 1.2-E – This information is not included in this report at this time, but it is available at NRRI and will be made available on the NRRI website); and
5. Cuyuna Range selected bibliography (Appendix 1.2-F).

### *Database*

Literature searches yielded multiple sources of information on the various mines of the Cuyuna Range, from which a database was built. The project database, CuyunaRange\_UndergroundMineWorkings.xlsx, is provided in Microsoft® Excel® 2010 spreadsheet format in Appendix 1.2-B. The database contains mine names, former mine names, locations, mining methods, dates of operations, shaft information, ore types, and mine-specific narrative details, along with the data sources. Databases of mine-specific data for the Mesabi Range were created during the course of the MN DNR mine mapping projects (Phase 1 Central Mesabi Range Mine\_History\_Database and Phase 2 Eastern Mesabi Range Mine\_History\_Database). These databases can be obtained from MN DNR as directed in the earlier paragraphs on rationale.

### *GIS Coverages*

GIS coverages of the Cuyuna Range underground mining features and related mining and ore reserve parcels are provided in Appendix 1.2-C<sup>1</sup> in both shape file and file geodatabase format. The coverages, developed in Esri® ArcMap™ 10.1, include:

#### Shape Files:

1. cuyuna\_underground\_driftsln.shp (mine drifts as polylines);
2. cuyuna\_underground\_minedextentspy.shp (mined extents as polygons);
3. cuyuna\_underground\_shaftspt.shp (mine shafts as points);
4. cuyuna\_underground\_minespy.shp (all shafts, drifts and mined extents as polygons);  
and
5. cuyuna\_underground\_minepropertiespy.shp (mine and ore reserve parcels as polygons).

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<sup>1</sup>This information is not included in this report at this time, but it is available at NRRI and will be made available on the NRRI website.

File Geodatabase fgdb\_cuyuna\_undergroundmines (cuyuna\_undergroundmines.gdb) with feature classes:

1. drifts (mine drifts as polylines);
2. minedextents (mined extents as polygons);
3. shafts (mine shafts as points);
4. mines (all shafts, drifts and mined extents as polygons); and
5. mineproperties (mine and ore reserve parcels as polygons).

### *Mine Maps in PDF format*

Maps acquired for the CAES study that show underground mine workings on the Cuyuna Range have been assembled into booklets for each mine. The booklets are not included in this report as Appendix 1.2-D at this time, but they are available at NRRI and will be made available on the NRRI website. The maps include surface, mine level, mine sub-level, shaft, pit, and exploration views. No claim is made that the maps used in this study and provided herein are a complete representation of the workings of any given underground mine. Likewise, no claim is made that the maps found and used in this study represent the most recent or complete extent of any given mine level or sub-level.

### *Geo-rectified Mine Maps*

Maps showing Cuyuna Range underground mine workings that were geo-rectified and used in the digitization of the underground workings include surface, mine level, mine sub-level, and pit views. This maps are not included in this report as Appendix 1.2-E at this time, but they are available at NRRI and will be made available on the NRRI website.

### *Bibliography*

A Selected Bibliography of Cuyuna Range Mining and Geology has been created for this project and is included as Appendix 1.2-F. Subjects and citations range from mining developments and conditions dating as far back as 1911 to recent geologic studies on the manganese resources of the Cuyuna Range and the potential for SEDEX (sedimentary exhalative) mineralization in the region.

### *Caveat*

The mapping and data presentations prepared for this project are solely dependent upon maps and literature that were found during the course of this project. This information in no way presumes or precludes that more recent (or other) maps and articles exist that may alter the

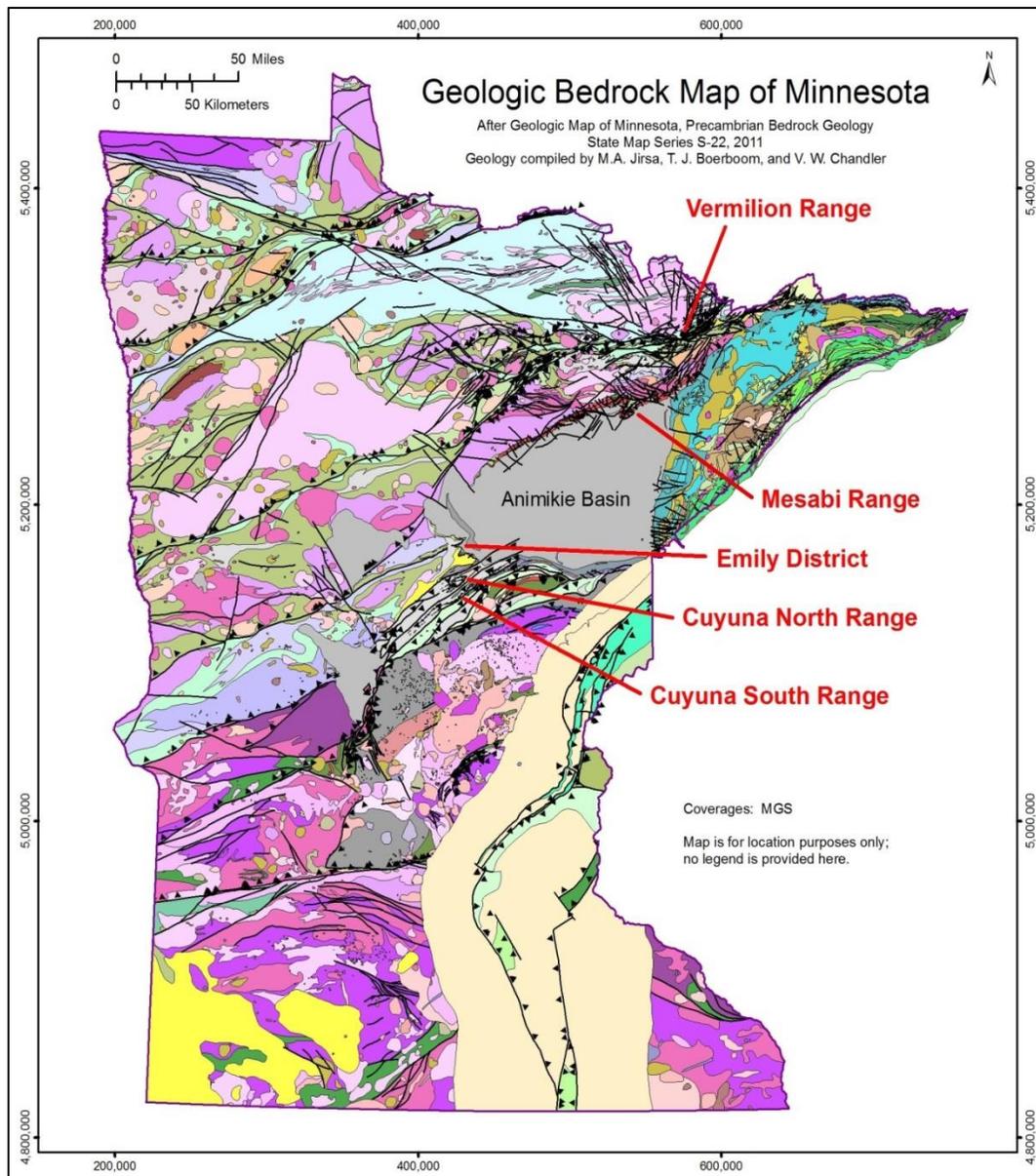
appearance or extent of mining activities as shown herein. The mapped locations of the underground workings were derived without the benefit of GPS coordinates. The data user assumes responsibility for ground truthing prior to use in strategic applications.

#### *University Disclaimer*

The University of Minnesota does not warrant or guarantee that there are no errors in the GIS data sets included with this report. Users may wish to verify critical information. Every effort has been made to ensure that the interpretation conforms to sound geologic and cartographic principles; however, no claim is made that the interpretation is rigorously correct.

## Presentation Order

The following pages present the underground workings of Minnesota's Cuyuna, Mesabi, and Vermilion iron ranges, noting depth, where available, and potential for CAES. Areas with mineral-related potential for CAES cavern construction coupled with ore extraction are also noted. While open pit operations are not discussed here, unmined properties designated as ore reserves are included.



**Figure 1.2-2.** Location map of the Vermilion, Mesabi, and Cuyuna (North and South Ranges and Emily District) iron ranges relative to Minnesota's bedrock geology terrain (Source: Minnesota Geological Survey State Map Series S-22, 2011).

As geologic bedrock features, the locations of Minnesota’s three iron ranges are shown in Figure 1.2-2 against the backdrop of the state geologic bedrock map (Jirsa et al., 2013). The Cuyuna North and South Ranges and the Emily District comprise the Cuyuna Range. The three iron ranges will be presented from south (Cuyuna) to north (Vermilion).

The underground mines of the Cuyuna Range will be addressed first, as they were the focus of this study. Since the bulk of mining activity took place on the Cuyuna North Range, it will be presented first. Following the Cuyuna North Range will be the Cuyuna South Range, which saw relatively minimal mining activity but which hosts multiple identified, but unmined, natural iron ore reserves that may hold potential for CAES. The Emily District, which has yet to see a mining operation, will then be addressed.

Underground workings of the Cuyuna Range will be followed by those of the Mesabi Range, presented here in small scale map format. Mesabi Range underground mine workings can be viewed in closer detail relative to base map, hydrographic, elevation, ownership, and geologic features in Section 2.5 (PHES Host Sites, Scenarios and GIS Coverage Map Sets) of Fosnacht et al. (2011), available online at <http://d-commons.d.umn.edu/handle/10792/2895>. Mesabi Range underground workings can also be viewed via MN DNR-LAM’s underground mine mapping interactive website at [http://www.dnr.state.mn.us/lands\\_minerals/underground/interactive.html](http://www.dnr.state.mn.us/lands_minerals/underground/interactive.html). Animated 3-D models of individual Mesabi Range underground mines can be viewed at [http://www.dnr.state.mn.us/lands\\_minerals/underground/mines/index.html](http://www.dnr.state.mn.us/lands_minerals/underground/mines/index.html).

Finally, a brief presentation of the underground mines of the Vermilion Range will be addressed. Only the Soudan Underground Mine has been mapped in digital format.

## **Map Coverages**

A GIS approach was used to present the underground mine workings in this report and to determine CAES potential. Maps were built using coverages obtained from MGS, MN DNR, MnGEO, and NRCS, as well as coverages generated at the Natural Resources Research Institute (NRRI), University of Minnesota Duluth (UMD). A listing of the coverages used and their source is provided in Table 1.2-1.

## **Header tables and data sources**

A header table is provided for each underground mining operation and ore reserve on the Cuyuna Range. Data in the header tables was drawn from multiple sources. The reader is directed to the CuyunaRange\_UndergroundMineWorkings.xlsx database (Appendix 1.2-B) for the specific source relative to any given item in the table.

Surface ownership of ore reserve properties was determined in most cases from the MN DNR GIS coverage own\_mnstwdpy2 (2008), obtained from the former MN DNR Data Deli. In select cases, as noted, surface ownership was looked at more closely via parcel data found online using Crow Wing County’s GIS Public Mapping Service Interactive Maps (<https://mn-crowwingcounty2.civicplus.com/85/Interactive-Maps>).

**Table 1.2-1-1.** A listing of GIS coverages and sources used in Chapter 1.2 of the CAES study.

CAES STUDY GIS COVERAGES USED (Shape File)					
Coverage	Feature Type	Title	Source	Currentness	
adm_minowpy3	Polygon	State Owned/Controlled Mineral Interests	MN DNR-LAM (St. Paul)	07162010	
adm_tawindpy3	Polygon	State Lands by Administrator – Trails and Waterways	MN DNR-Data Deli	1999	
bdry_adwma2py3	Polygon	State Wildlife Management Area Boundaries – Publicly Accessible	MN DNR-Data Deli	022006	
bdry_countpy2	Polygon	County Boundary	MN DNR-Data Deli	1996	
bdry_munip3	Polygon	Municipal Boundaries	MN DNR-Data Deli	2001	
bdry_natrpy3	Polygon	Native American Treaty Boundaries in Minnesota	MN DNR-Data Deli	2006	
bdry_statpy2	Polygon	Minnesota State Boundary	MN DNR-Data Deli	2007	
bdry_sforpy3	Polygon	State Forest Boundaries	MN DNR-Data Deli	2005	
bedrock_geology_polygons	Polygon	Precambrian Bedrock Geology (State Map Series S-22, 2011)	MGS	2011	
cent_popplpt1	Point	Populated Places	MN DNR-Data Deli	2006	
contact_faults	Polyline	Contacts and Faults; Precambrian Bedrock Geology (State Map Series S-22, 2011)	MGS	2011	
cuyuna_underground_driftsin	Polyline	Cuyuna Underground Mine Drifts	NRRI	2015	
cuyuna_underground_minedextentspy	Polygon	Cuyuna Underground Mined Extents	NRRI	2015	
cuyuna_underground_shaftspt	Point	Cuyuna Underground Mine Shafts	NRRI	2015	
cuyuna_underground_minespy	Polygon	Cuyuna Underground Mines (Composite)	NRRI	2015	
cuyuna_underground_mineproperties	Polygon	Cuyuna Underground Mine Properties	NRRI	2015	
electLine07s	Polyline	Electrical Transmission Lines	MNGEO	2007	
elecSubs07s	Point	Electrical Substations	MNGEO	2007	
form_lines	Polyline	Features primarily inferred from geophysical data, Precambrian Bedrock Geology (State Map Series S-22, 2011)	MGS	2011	
form_ins	Polyline	Linear Features in the Precambrian Bedrock (OFR10_02, 2010)	MGS	2010	
lake_openwpy3	Polygon	DNR 24K Lakes	MN DNR-Data Deli	1990	
M-Logged	Point	NRRI-Logged Drill Holes	NRRI	2010	
mine features	Polygon	Mining Features (Mesabi Range)	MN DNR-LAM (Hibbing)	2013	
mnforty	Polygon	Control Point Generated PLS to 40-A & Gov. Lot	MN DNR-Data Deli	2006	
naip13_crow wing	MrSID	2013 Natl. Ag. Imagery Program Mosaic – Crow Wing County	NRCS	2013	
naip13_itasca	MrSID	2013 Natl. Ag. Imagery Program Mosaic – Itasca County	NRCS	2013	
naip13_st louis	MrSID	2013 Natl. Ag. Imagery Program Mosaic – St. Louis County	NRCS	2013	

Table 1.2-1 (Continued).

CAES STUDY GIS COVERAGES USED (Shape File)					
Coverage	Feature Type	Title	Source	Currentness	
own_mnstdwp2	Polygon	GAP Stewardship 2008 – All Ownership Types	MN DNR-Data Deli	2008	
parcels	Polygon	PLS Parcels (Mesabi Range)	MN DNR-LAM (Hibbing)	1991	
parcsec	Polygon	PLS Section Boundaries (Mesabi Range)	MN DNR-LAM (Hibbing)	1996	
parctwp	Polygon	PLS Township-Range Boundaries (Mesabi Range)	MN DNR-LAM (Hibbing)	1993	
Pc_contacts_faults	Polyline	Precambrian Contacts and Faults (OFR10_02, 2010)	MGS	2010	
Pc_glg_polys	Polygon	Precambrian Bedrock Geology (OFR10_02, 2010)	MGS	2010	
permit_setting_bndrys	Polygon	Environmental Setting Boundaries	MN DNR-LAM (Hibbing)	09072010	
pls_sectpy3	Polygon	Section Level Public Land Survey	MN DNR-Data Deli	1996	
pls_twpshpy3	Polygon	PLS Town-Range Boundaries	MN DNR-Data Deli	1993	
protected_waters_inventory	Polygon	Protected Waters Inventory	MN DNR-Waters	2004	
rail_linesln3	Polyline	DOT Basemap Railroads	MN DNR-Data Deli	2002	
road_dotln	Polyline	DOT Basemap Roads – All Types	MN DNR-Data Deli	2001	
STREETS_LOAD	Polyline	Roads, Minnesota	MnGEO	2012	
strm_baseIn3	Polyline	DNR 24K Streams	MN DNR-Data Deli	2010	
strm_troutln3	Polyline	Minnesota Trout Streams	MN DNR-Data Deli	2009	
trl_snombIn3	Polyline	Minnesota Snowmobile Trails	MN DNR-Data Deli	2011	
trl_stateIn3	Polyline	Minnesota State Trails	MN DNR-Data Deli	2010	
trl_stpln3	Polyline	Minnesota State Park Trails and Roads	MN DNR-Data Deli	2010	
Utac_ultimate	Polygon	United Taconite Ultimate Boundaries	MN DNR-LAM (Hibbing)	2010	
watr_dnrpy2	Polygon	DNR 100 K Hydrography	MN DNR-Data Deli	2008	
wet_nwipy3	Polygon	National Wetlands Inventory Program	MN DNR-Data Deli	1994	
wshd_lev04py3	Polygon	DNR Watersheds - DNR Level 04 - HUC 08 - Majors	MN DNR-Data Deli	2009	
CAES STUDY GIS COVERAGES USED (File Geodatabase)					
Feature Class	Feature Type	File Geodatabase	Source	Currentness	
dnr_hydro_features_all	Polyline	water_dnr_hydrography.gdb	MnGEO	2014	
dnr_rivers_and_streams	Polyline	water_dnr_hydrography.gdb	MnGEO	2014	
National_wetlands_inventory_polygons	Polygon	Water_nat_wetlands_inventory.gdb	MnGEO	1994	
STREETS_LOAD	Polyline	trans_roads_mndot_tis.gdb	MnGEO	2012	

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## **Mining terminology**

Listed below are several terms and definitions as used in this report:

- Bessemer Ore<sup>2</sup> (B): ore with phosphorus (P) content low enough to make Bessemer iron ( $P \leq 0.060 \%$ );
- Crosscut: a drift perpendicular to (and through) the orebody, used herein as a drift extending from the shaft to the ore body, typically a main haulage drift;
- Drift: a horizontal or inclined passageway below ground;
- Dry analysis<sup>1</sup>: chemical analysis performed on an ore sample dried at 100° C (212° F) to remove all but chemically combined water in order to attain a uniform physical state;
- Haulage drift: a drift used for the movement of workers, machinery and materials between the shaft and working areas;
- Level: a horizontal layer from which ore is mined;
- Mangan Ore: manganiferous iron ore;
- Merch Ore (MO): merchantable ore; ore that could be shipped “as mined” from the ground;
- Mine workings: composite of the shafts, drifts, and excavated openings within the mine;
- Natural analysis<sup>1</sup>: a calculated value derived from the dry analysis ( $(100\% - \text{moisture } \%) \times \text{dry analysis } \%$ ) that represents the element in the condition of the ore as sampled;
- Non-Bessemer Ore<sup>1</sup> (NB): ore with phosphorus (P) content too high to make Bessemer iron ( $P > 0.060 \%$ )
- Shaft: a vertical or inclined passage from the surface to the underground workings;
- Sub-level: layer(s) mined above a main (haulage) level, with ore dropped through chutes for conveyance on the haulage level to the shaft for hoisting;
- UG: underground mining – mining method used in ore reserve estimates to indicate basis upon which taxable tonnage was derived;
- Wash Ore (WO): ore requiring beneficiation to remove unwanted materials (i.e., sand, etc.) prior to shipping; and
- Wash Ore Concentrate (WOC): ore that has been beneficiated to remove unwanted materials.

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<sup>2</sup>Source: Crowell & Murray (1920).

## CUYUNA RANGE

### Geology

The major focus of this study has been the Cuyuna Range. Location of the Cuyuna Range near the geographical center of the state positions it well for the incoming and outgoing power collection and dispersal necessary to CAES. Central Crow Wing County, in the vicinity of the North and South ranges, serves as a virtual hub of power distribution via Great River Energy and Minnesota Power transmission lines (Fig. 1.2-3).

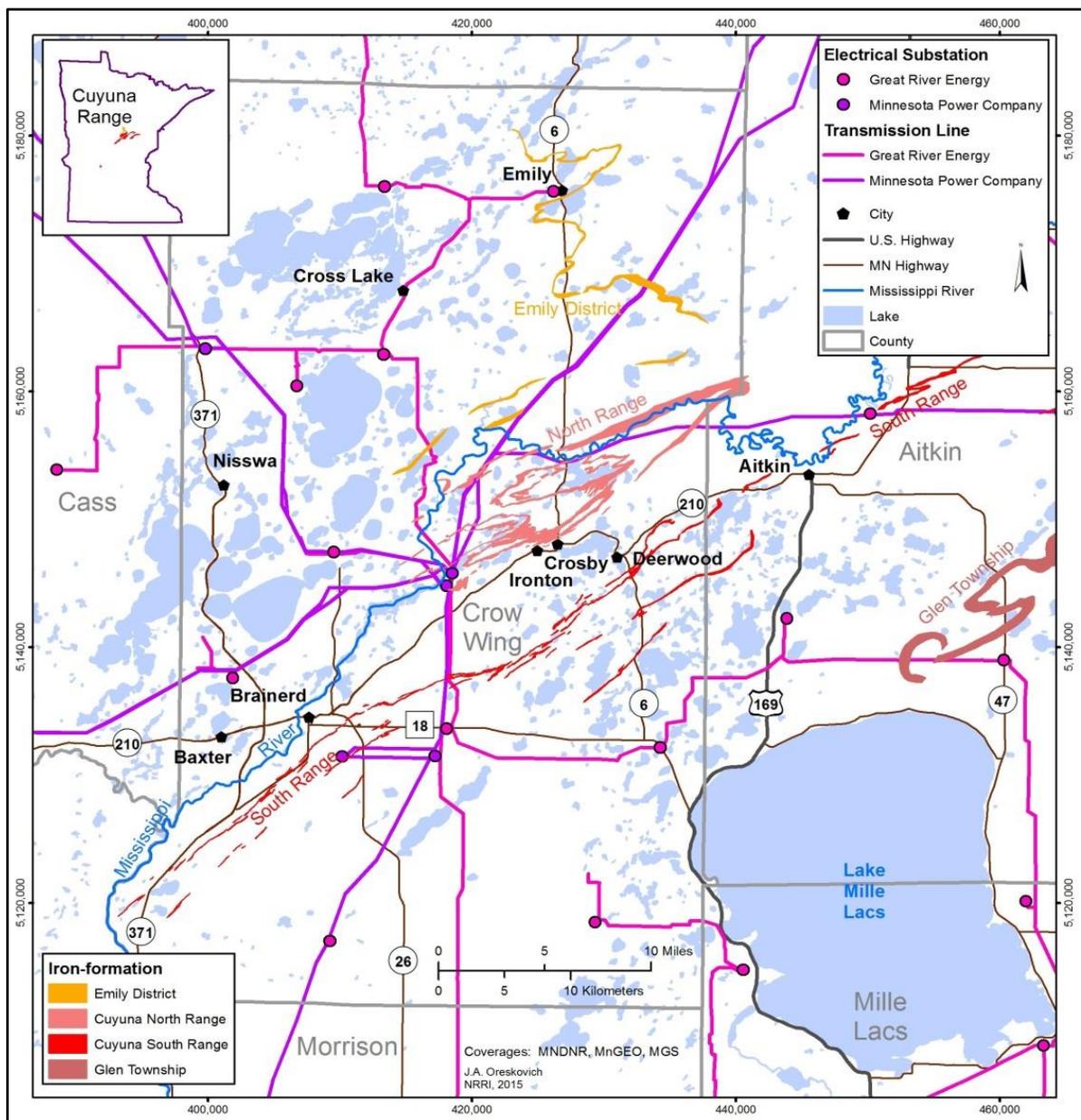


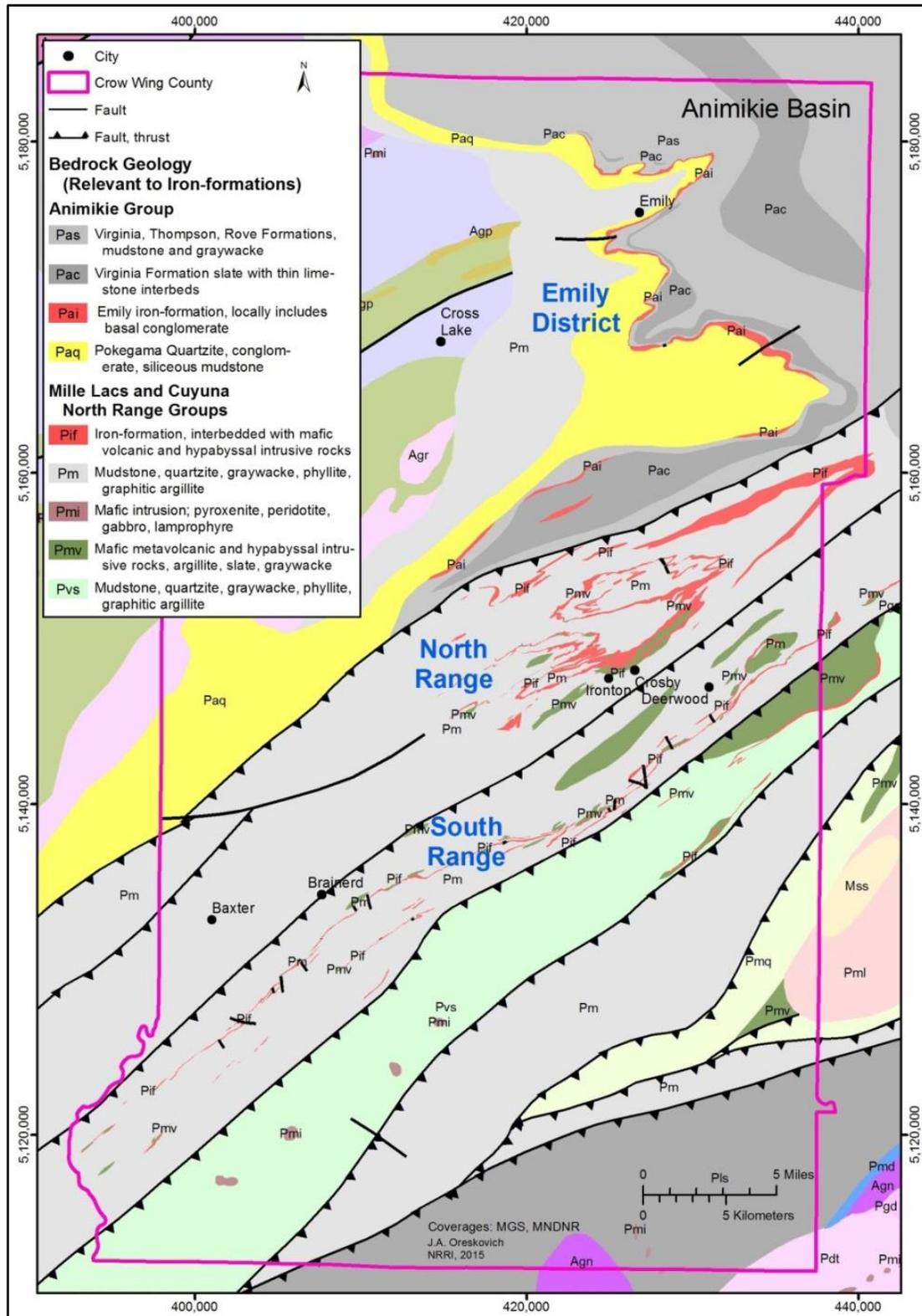
Figure 1.2-3. Major power transmission lines and substations in proximity to the Cuyuna Range.

For purposes of this report, the Cuyuna Range includes the North Range, South Range and Emily District within the boundaries of Crow Wing County. While the South Range extends northeastward into Aitkin County and southwestward into Morrison County, iron ore mining, with one exception, was historically confined to Crow Wing County. The exception is the Gorman open pit mine, located in Morrison County, which operated briefly in the early 1950s (Skillings Mining Review, 2005).

The iron-formations of the North Range, South Range, and Emily District are separate geologic units containing “distinctively different stratigraphic rock packages of presumably different ages” (Severson et al., 2003). Severson further suggests that the Emily District could be subdivided into two potentially distinct units. Figure 1.2-4 displays the Precambrian bedrock geology of the Cuyuna Range in Crow Wing County.

The Emily Iron Formation is the oldest of the three Cuyuna Range iron-formations. It lies on the southern edge of the Animikie Basin, opposite the Mesabi Range that resides on the northern perimeter of the basin (Fig. 1.2-2). To its south lies the North and South Range iron-formations on separate panels of a fold and thrust belt derived from tectonic activity to their southeast.

In subcrop, the North Range iron-formation, the Trommald Formation, presents as a continuous—but folded and distorted—unit, while that of the South Range presents as a thin line or lines of discontinuous lenses. The North Range is relatively broad and short, roughly 18 miles in length along strike by 5 miles wide. In contrast, the South Range is nearly 54 miles in length along strike just within Crow Wing County and averages around 1.5 miles in width. The northern portion of the Emily Iron Formation, seen outlining the tips of three broad folds in Figure 1.2-4, covers an area of approximately 14 miles by 7 miles. The southern, northeast-trending, portion of the Emily Iron Formation extends 15 miles along strike and is 1.3 miles in width.

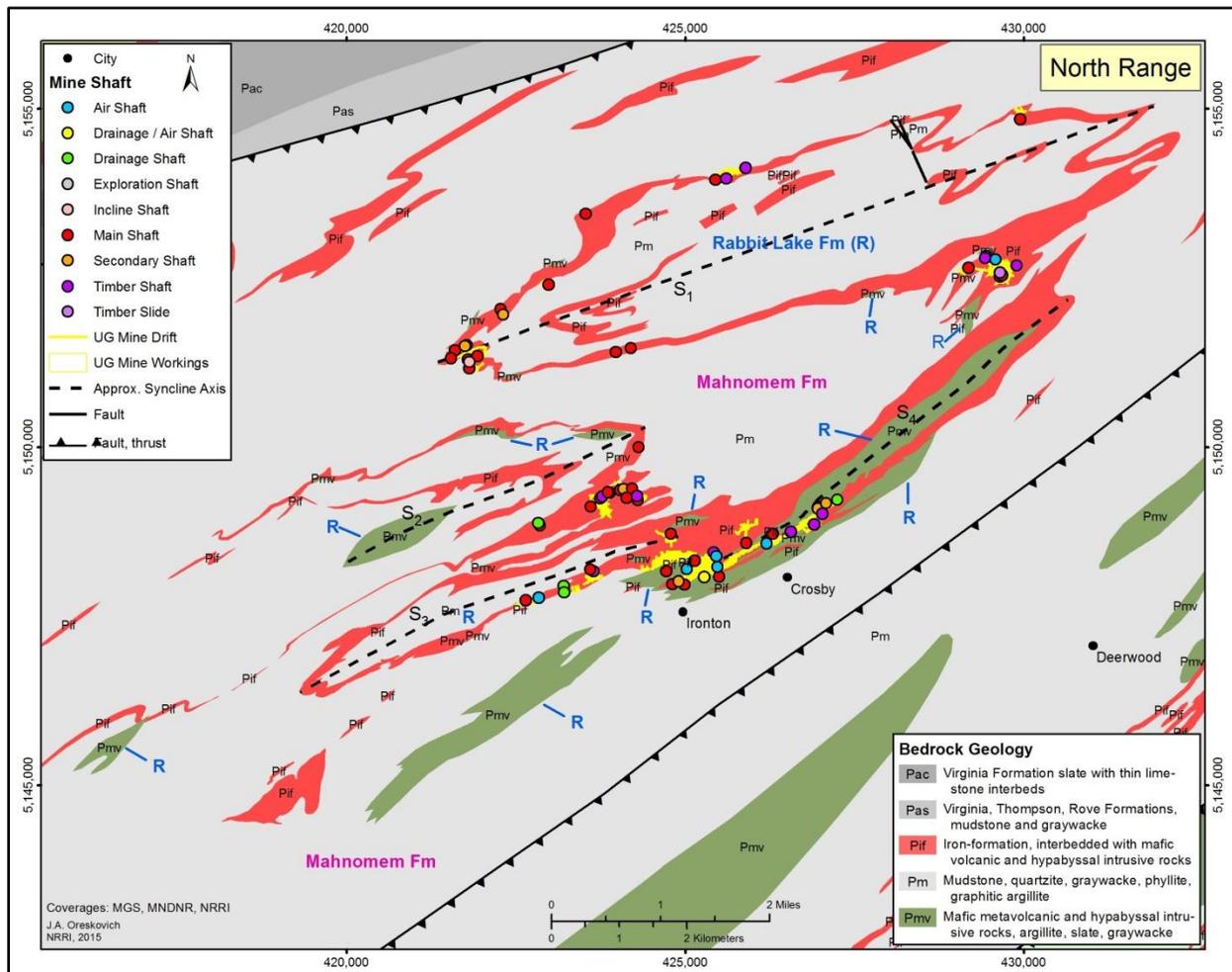


**Figure 1.2-4.** Bedrock geology of the Cuyuna Iron Range, Crow Wing County, Minnesota (Source: Minnesota Geological Survey State Map Series S-22 (2011)).

**Cuyuna North Range**

The Trommald Iron Formation, seen in red in Figure 1.2-5, is the source of nearly all the iron and manganese iron ores produced on the North Range. It conformably overlies the Mahnomem Formation with a sharp contact (Schmidt, 1963) and underlies the Rabbit Lake Formation. Together, these three stratigraphic units comprise Schmidt’s North Range Group. The Mahnomem Formation is a quartz-rich sandstone-siltstone sequence while black shale and graywacke comprise the Rabbit Lake Formation (McSwiggen et al., 1995).

Grout and Wolff (1955, p. 56-57) produced a geologic column for the Cuyuna North Range that contains formations and beds along with unit thicknesses and resident mines/ore bodies. The column was based on the Biwabik Iron Formation of the Mesabi Range, assuming similarity at that time. While this is no longer strictly correlated, the column provides a sense of where in the iron-formation a particular mine resides relative to others, and the nature of the ore found in that mine. Grout and Wolff’s (1955) geologic column, with slight modification, is presented in Appendix 1.2-A.



**Figure 1.2-5.** Bedrock geology map of the Cuyuna North Range (Source: Minnesota Geological Survey State Map Series S-22 (2011)).

Cuyuna North Range underground mines are distributed in the Trommald Formation, for the most part, along the flanks of four northeast-trending synclines (Fig. 1.2-5) that resulted from folding due to tectonism to the southeast. Approximate syncline axes are indicated by the black dashed lines. Additional distortion is evidenced by the prevalent drag folds shown.

Prior to recognition of the synclinal nature of the North Cuyuna deposits, Ostrand (1918) described the ore deposits of the North and South Cuyuna ranges as occurring in a series of northeast-trending seven or eight belts. He designated the five northern-most belts the “producing belts,” as this is where there were working mines at the time. Ostrand’s five northernmost belts, with resident mines (Figs. 1.2-6 and 1.1-37) and corresponding ore types, as of his writing in 1918, are as follows:

1. Ferro, Algoma, Gloria and Milford – mined for manganese only;
2. Merritt (manganese) and Kennedy (iron);
3. Louise, Sultana, Mangan No. 1, Hopkins, and Joan No. 1 – all mined for manganese (Hopkins is partly iron);
4. Mahnomen, Mangan No. 2, Evergreen (Portsmouth), North Thompson, Armour No. 1, Armour No. 2, Pennington, Feigh, Hill Crest, and Rowe – commercial quantities of both iron and manganese, usually sold on a combined basis; most or all of the ore was produced by open-pit methods; and
5. Ironton, Armour No. 2, South Thompson, Meacham, and Croft – all solely iron mines.

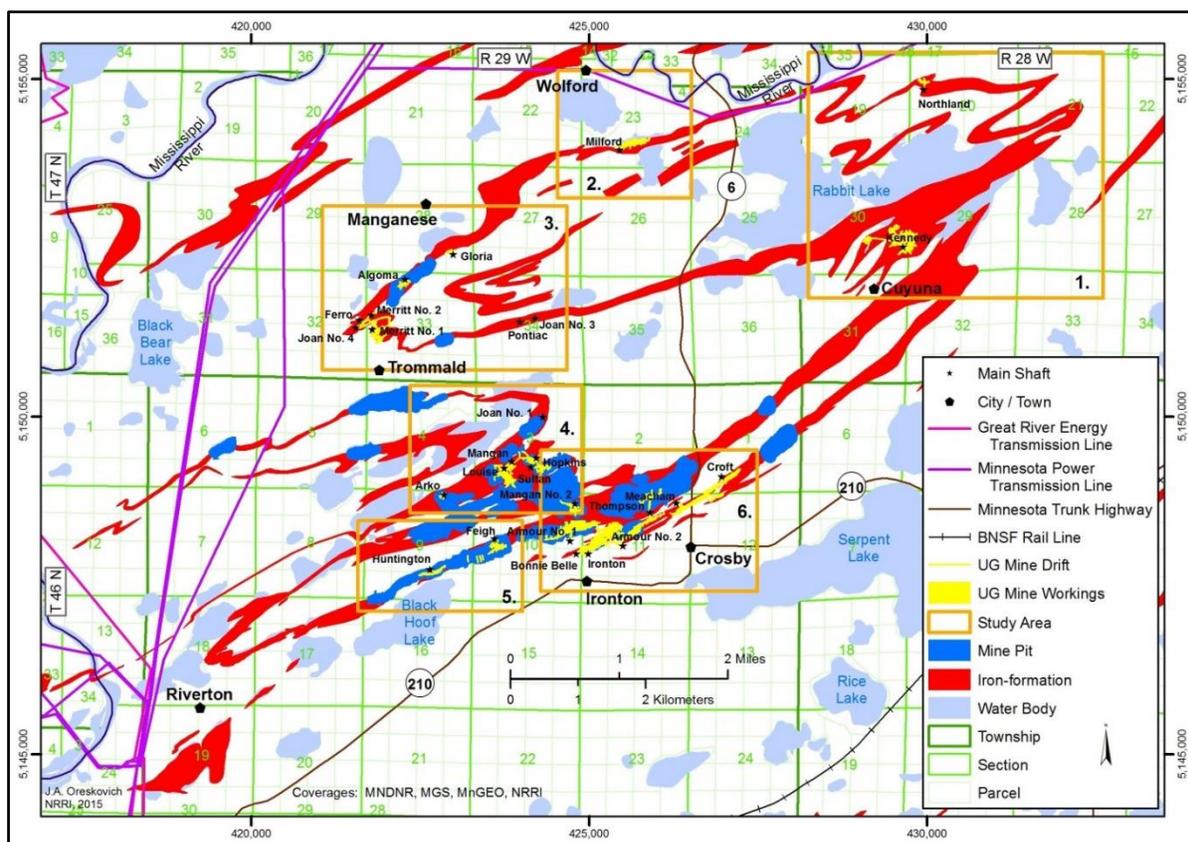


Figure 1.2-6. Cuyuna North Range study areas.

Ostrand's fifth belt, together with the Armour No. 1 and the portion of the Armour No. 2 and Thompson mines located in the fourth belt, produced the greatest amount of, and deepest, underground workings on the Cuyuna Range. Most of the mines in Ostrand's fourth belt, with the exception of the Armour No. 1, were worked entirely or primarily as open pit mines.

Morey (1990) reports that all but two of the mines on the Cuyuna North Range produced ore from the Trommald Iron Formation. The exceptions are the Snowshoe and Virginia mines, both of which operated in iron-formation that occurred in the lower part of the overlying Rabbit Lake Formation. These mines, both of which were worked by open pit methods, can be seen in Figure 1.1-37.

Maps and other data were found that showed the location and verified the existence of twenty-eight underground mining operations on the Cuyuna North Range (Fig. 1.2-6). While most of these operations produced ore that was shipped, a few consisted only of a shaft that was sunk and then abandoned, with little or no mine development. A summary listing of the Cuyuna North Range underground mines is provided in Table 1.2-2.

This study also acquired data for properties designated as having unmined taxable ore reserves. Unmined ore reserves serve as potential sites for CAES as described in Section 1.1, Scenario 2: Excavated Cavern by Mining a Mineral Resource (High Volume Storage Facility).

Identity and location of the ore reserve properties was obtained from Beltrame (1977) and from the data file collection at the MDOR office in Eveleth, MN. Ore reserve estimates, assay data, and related information was retrieved from MDOR data files. A summary listing of the Cuyuna North Range ore reserve properties is provided in Table 1.2-3.

For presentation purposes, the Cuyuna North Range underground mines and ore reserve properties are grouped into six study areas (Fig. 1.2-6). Dark blue areas on the map represent mine pits. Since cessation of mining activities, these pits have filled with water to form lakes. Natural lakes are shown in light blue.

It should be noted that several shafts, drifts and mine workings appear within pit lakes. Underground activity preceded the open pit activity in these areas. Subsequent figures will also show where subsidence, due to underground mining activity, has increased the size of some pit lakes beyond the actual pit boundaries.

Figure 1.2-7 displays surface features and jurisdictional entities that can impact the use of underground mine workings for CAES on the Cuyuna North Range. Distance from major Minnesota Power transmission lines to the underground workings range from less than one mile to approximately four miles. For major Great River Energy transmission lines, the distance is somewhat greater – over three miles to approximately eight miles.

There are several jurisdictions under which many of the mines fall. These include the municipalities of Crosby, Ironton, Trommald and Cuyuna, Crow Wing County, and the Crow Wing State Forest. Of greatest concern is the location of much of the underground workings within or adjacent to the Cuyuna Country State Recreation Area (CCSRA). The CCSRA is outlined in blue in Figure 1.2-7.

The CCSRA has been described in detail in Section 1.1 under Factors Affecting Usage of the Armour No. 1 and Armour No. 2 Mine Features and the Cuyuna Shafts in Series for CAES storage. It has become widely popular among mountain bikers nationally and internationally for the trail system that has been developed in and around the legacy mining features of much of the Cuyuna North Range. While the potential for future mining was retained under the CCSRA charter, use of the area for CAES would likely face major obstacles.

**Table 1.2-2. Summary listing of underground mines on the Cuyuna North Range.**

CUYUNA NORTH RANGE UNDERGROUND MINE SUMMARY														
Mine	Other Names	S	T	R	Parcel	UG	OP	ML	Shaft Only	Main Shaft Compartments	Depth (Ft.)	Overburden (Ft.)	Top Level	Bottom Level
1	Algoma Mine	33	47	29	NE-NW	X	X			2	160	60	80 Ft. Level	160 Ft. Level
2	Arko Mine	9	46	29	Lot 1	X	X			3	108		77 Ft. Sub	108 Ft. Sub
3	Armour No. 1 Mine	10	46	29	SE-NE	X	X			5	800	65	100 Ft. Sub	800 Ft. Level
4	Armour No. 2 Mine	11	46	29	SW-NE & S1/2-NW	X	X			5	582	63	77 Ft. Sub	800 Ft. Level
5	Bonnie Belle Mine	10	46	29	N1/2-NE-SE	X				2	263		106 Ft. Sub	373 Ft. Level
6	Croft Mine	1	46	29	SE-SW & SE Diag 1/2 SW-SW	X				3	630	110	112 Ft. Level	630 Ft. Level(?)
7	Feigh Mine	10	46	29	S1/2-NW, N1/2-SW	X	X			5	153		97 Ft. Level	153 Ft. Level
8	Ferro Mine	32	47	29	SE-NE	X				2	157	55-60		149 Ft. Level
9	Gloria Mine	28	47	29	E1/2-SE & SE NE	X				3	110		100 Ft. Level	100 Ft. Level
10	Hopkins Mine	3	46	29	SE1/4	X	X			3	145	50	117 Ft. Level	130 Ft. Level
11	Huntington Mine	9	46	29	Lots 4 & 5, SW-SW & NE-SW	X	X			5	190		76 Ft. Level	150 Ft. Level
12	Ironton Mine	11	46	29	NW-SW	X				3	348	65	158 Ft. Sub	383 Ft. Level
13	Joan No. 1	3	46	29	SW 1/4-NE 1/4 & Lot 5	X				2	200		NA	NA
14	Joan No. 3 Mine	34	47	29					X	NA	NA		NA	NA

Table 1.2-2 (Continued).

CUYUNA NORTH RANGE UNDERGROUND MINE SUMMARY														
Mine	Other Names	S	T	R	Parcel	UG	OP	ML	Shaft Only	Main Shaft Compartments	Depth (Ft.)	Overburden (Ft.)	Top Level	Bottom Level
15	Joan No. 4 Mine	32	47	29	NE-SE	X				2	121		91 Ft. Level	121 Ft. Level
16	Kennedy Mine	29,30	47	29	Lot 6 (29) & N1/2-SE-SE (30)	X				5	383	125	120 Ft. Level	362 Ft. Level
17	Louise Mine	3	46	29	Lot 7 & SE-SW	X	X			5	325	50	85 Ft. Level	325 Ft. Level
18	Mangan Mine	3	46	29	Lots 5 & 6	X	X			3	160	60	97 Ft. Level	160 Ft. Level
19	Mangan No. 2 Mine	10	46	29	NE-NE	X	X			NA	110	52	Sub	110 Ft. Level
20	Meacham mine	11,12	46	29	NE-NE (11), NW-NW (12)	X				5	354	70	85 Ft. Level	350 Ft. Level
21	Merritt No. 1 Mine	33	47	29	NW-SW	X				4	264		80 Ft. Level	264 Ft. Level
22	Merritt No. 2 Mine	33	47	29	W1/2-NW	X				3	102		80 Ft. Level	238 Ft. Level
23	Milford Mine	23	47	29	SW1/4 & SW-SE	X				3	280		125 Ft. Sub	280 Ft. Level
24	Northland Mine	20	47	28	S1/2-NE & S1/2-NW				5	169	137		169 Ft. Level	169 Ft. Level
25	Pontiac Mine	34	47	29	SE-NW	X				NA	NA		NA	NA
26	Preston Mine	27	47	29	NW-NW				X	NA	NA		NA	NA
27	Sultana Mine	3	46	29	SW-SE	X	X			2	91		65 Ft. Level	91 Ft. Level
28	Thompson Mine	11	46	29	NW-NE	X	X	X		5	250	65	150 Ft. Level	250 Ft. Level

**Table 1.2-3.** Summary table of Cuyuna North Range or reserve properties.

	Ore Reserve	S	T	R	Parcel	Res. Est. Tons	Est. Year	Data Avail	Assay Data	Surface Owner	Fee Owner	P.
1	Aune Reserve (H-40)	34	47	29	NW-SW	106,300	1958	X	X	Crow Wing County	J.C. Campbell, Jr., et al.	
2	Crosby Reserve (H-50)	18	46	29	Lot 1	234,190	1986	X	X	Private	Hanna Iron Ore Div. (5/8) & Crosby Iron Co.	
3	Erich Reserve (X-60)	31	47	28	Lot 5 (E1/2-SW)	367,600	1966	X	X	Private	George H. Crosby Estate, Northern City Nat'l Bank, The Hanna Mining Co. (7/240), et al.	
4	Federal Reserve (X-37)	31	47	28	E1/2-NE	388,065	1986	X	X	Private	Federal Mining Co.	
5	Hennen Reserve (H-49)	17	46	29	E1/2-NW & NE-SW	NA	1964	X		Private	The Hanna Mining Co.	
6	Hunter Reserve (X-35)	22	47	29	SE-SW, SW-SE	142,725	1967	X	X	Private	Louise Hunter	
7	Kona Reserve (X-21)	31	47	28	SW-NE	533,100	1958	X	X	City of Cuyuna	City of Cuyuna	
8	MN Land & Colonization Reserve (H-41)	23	47	29	NE-SE, Lot 4 (SE-NE)	NA	1963	X		Private	The Hanna Mining Company	
9	Pontiac Mine Reserve	34	47	29	SE-NW & S1/2-NE	524,679	1970	X	X	Private	The Hanna Mining Company	
10	Sisters Mine Reserve	34	47	29	SW-NW	38,780	1970 1958	X	X	Private	Benedictine Sisters Benevolent Assn.	
11	Whitmarsh Reserve (H-66)	27	47	29	NW-NE	154,900	1986	X	X	Private	The Hanna Mining Company	

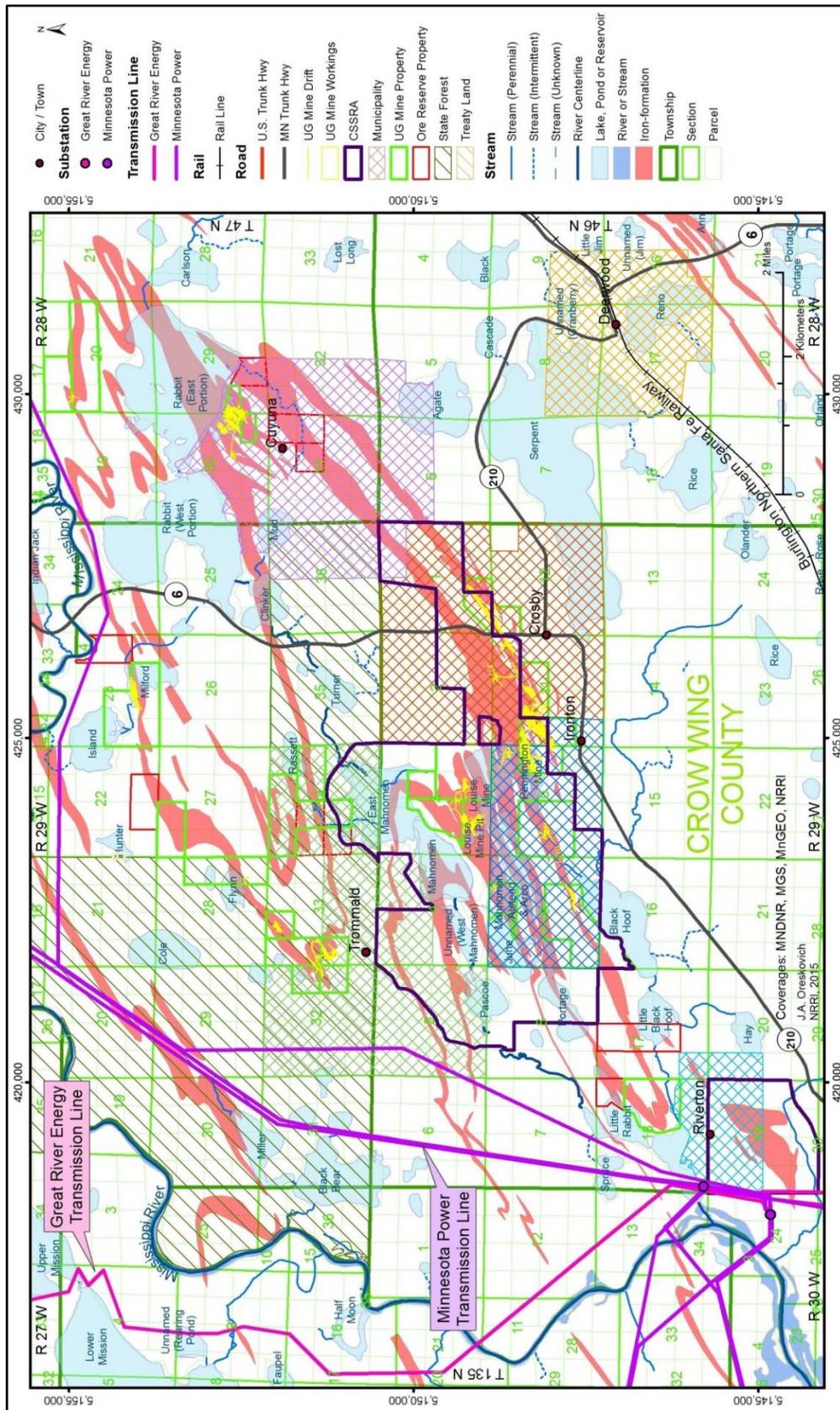


Figure 1.2-7. Cuyuna North Range regional base map and hydrographic features.

Cuyuna North Range Study Area 1

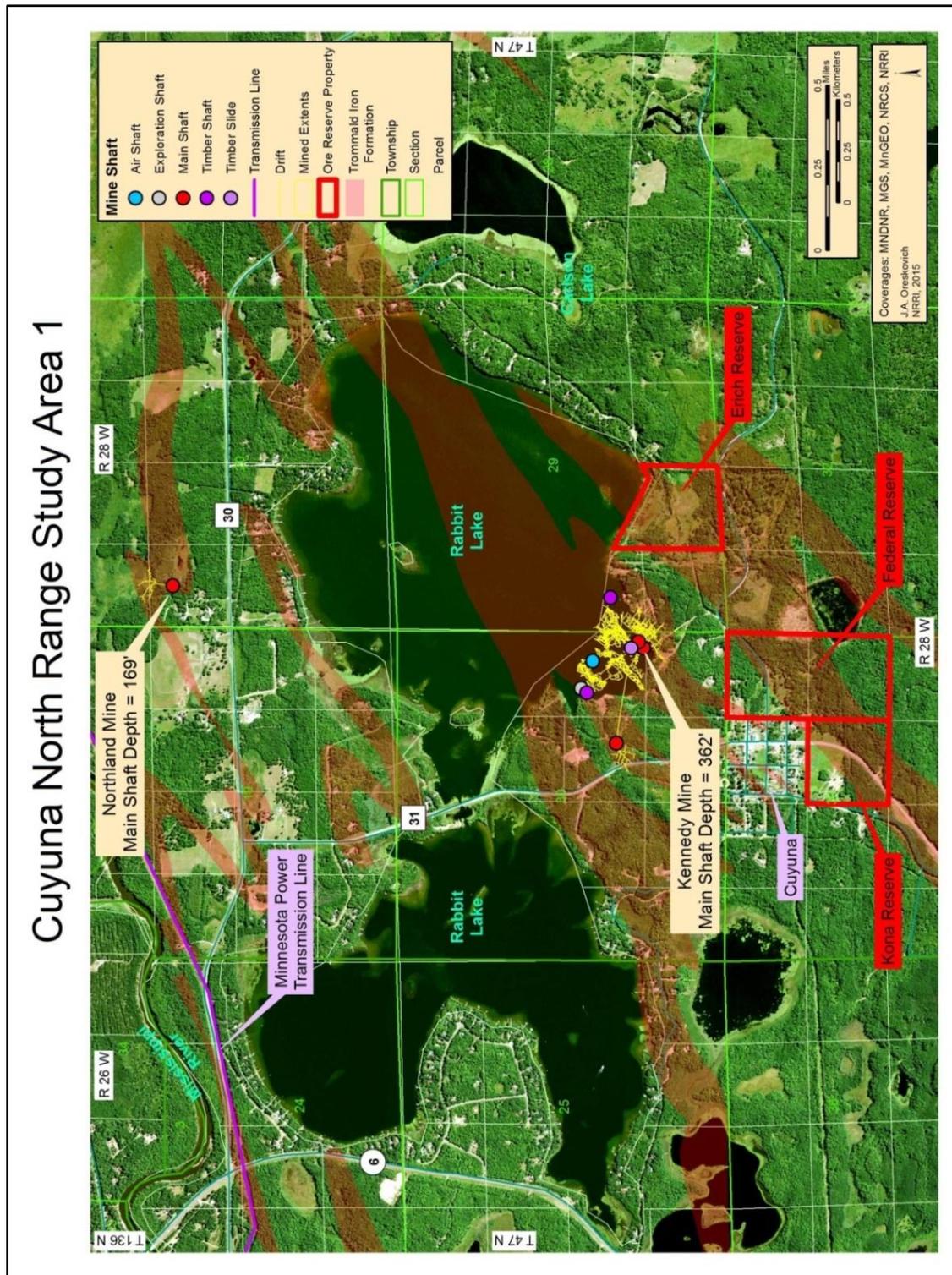


Figure 1.2-8. Cuyuna North Range Study Area 1: Kennedy and Northland mines; Kona, Federal and Erich ore reserves.

Cuyuna North Range Study Area 1 includes the Kennedy and Northland mines and the Kona (X-21), Federal (X-37), and Erich (X-60) ore reserve properties. The Kennedy mine and the three ore reserve properties are located near the town of Cuyuna on the southern side of the eastern lobe of Rabbit Lake (Fig. 1.2-8). The Northland mine resides to the north of the eastern lobe of Rabbit Lake.

### Kennedy Mine

Kennedy Mine Summary								
Mine	Range	S	T	R	Parcel	UG	OP	ML
Kennedy	North Range	29,30	47	28	Lot 6 (29) & N1/2-SE-SE (30); formerly included Lot 5 & NW-SE (30), now listed as the Robert OP mine	X		
Shaft Sinking	1st Opened	1st Shipment	Last Shipment	Total Ore Shipped (LT)	Last Operator	Last Known Fee		
1907	1907	1911	1925	1,369,079	Rogers, Brown Ore Co.	US Bank Duluth		
Overburden (Ft.)	Mine Depth	Top Level	Lowest Level	Mining Method	Orebody Strike	Orebody Dip		
125 avg.	362	120 Ft. Level	362 Ft. Level	top slicing & caving	N 45 E	55 to 70 SE		
Shaft Type								
wooden drop shaft; modern 5-compartment timber-lined shaft, with skipways (2), cageway, ladderway and pipeway								

The Kennedy mine was the first mine on the Cuyuna Range, opening in 1907. Operated through 1925, the mine produced 1,369,079 tons of ore (Skillings Mining Review, 2005). It is located just north-northeast of the town of Cuyuna, near what was then the shore of the eastern lobe of Rabbit Lake (Fig. 1.2-8). Subsidence caused by caving, coupled with subsequent mining of the lake bed in the 1950s and beyond by the Rabbit Lake (Section 29) and Robert (Section 30) open pit mines, has incorporated nearly all of the workings into the current lake bed.

The first shaft was sunk by the Rogers-Brown Ore Company in July, 1907, reaching ledge in April, 1908 (Aulie and Johnson, 2002). Ore was stockpiled from August, 1908 until April, 1911, when the first ore was shipped. In the meantime, more lands were leased and a second, 4-compartment shaft, was sunk in April, 1909, reaching ledge in November of that year (Aulie and Johnson, 2002).

The Kennedy mine is located on a series of folds in the Trommald Formation that yielded hematitic and goethetic ores, as well as manganiferous ores in the northernmost parts of the mine (Schmidt, 1963). Zapffe (1915a) reported that initially “four closely parallel lenses of ore” were mined, with that being largely reduced to two by 1915. The main shaft lies between the two southeasternmost of these northeast-trending lenses (Harder and Johnson, 1918). This can be seen in Figure 1.2-10.

Harder and Johnson (1918) describe the Trommald Formation in the Kennedy mine as mainly ferruginous chert containing local irregular bodies of iron ore. Above a depth of 210 feet, the iron-formation is entirely oxidized. Many unoxidized phases were seen by the 262-foot level. Schmidt (1963) places most of the Kennedy workings in the thin-bedded facies of the Trommald

Formation, which he describes as being relatively thick in this region (roughly 200 to 300 feet), overlying over 100 feet of thick-bedded facies.

Surface overburden at the Kennedy mine averaged 125 ft. (Zappfe, 1915a). Maps indicate that the main part of the mine was worked on 10-foot intervals from the top level at a depth of 120 feet to the bottom of the haulage level at 362 feet. There were three main haulage levels that connected to the main shaft. The haulage levels were at depths of 150, 262, and 362 feet. The Kennedy mine was worked by the top slicing and caving method (Zappfe, 1915a).

It is unclear from the maps and documents found to date as to just which of the Kennedy mine shafts was the original shaft. Undated Kennedy mine maps label a shaft located 130 feet northeast of the main No. 2 hoisting shaft in Lot 5 as Shaft No. 1 (Fig. 1.1-8). Crowell & Murray in their 1914 (second) edition of The Iron Ores of Lake Superior cite the location of the Kennedy mine as the NW-SE of S30-T47-R28, suggesting that the earliest part of the mine was the isolated western-most extension. Anna Himrod's history of the Cuyuna Range in Aulie and Johnson (2002) complicates matters even further, as she writes of the lease signing for "Lot 5 of the NW1/4 of the SE1/4 of Section 30, T47 R28" contingent on a shaft being sunk before June 1, 1908.

Little information was found on the western extension mine workings other than their appearance on 1925 and 1926 maps of the Kennedy mine and vicinity, and on 1959 and more recent undated maps of the Robert open pit mine. These workings are mentioned here because they may hold potential for CAES. The western extension mine workings are located at a distance from the main body of the Kennedy mine, as well as from the current shore of Rabbit Lake. They are situated in an apparently unpopulated area along County State Aid Highway (CSAH) 31 within 1.75 miles (by road) of a major Minnesota Power transmission line.

The western-most workings appear as a shaft and set of drifts, with the drifts enclosed in an area marked as caved ground. The shaft is noted as caved on an undated—but more recent (circa 1960s)—map obtained of the Robert mine. The shaft caving was likely done in preparation for building up a rail grade for a rail spur approaching from the southeast to serve the Robert mine. The shaft resides beneath the southwestern shoulder of the rail grade

A 1926 map of the Kennedy mine and vicinity labels the drifts of the western extension as the 150-foot level. The extent of the caving would seem to imply more extensive workings than those at 150 feet and above, since Zappfe (1915a) reported that the surface averages 125 feet in depth in the vicinity of the Kennedy mine.

The greatest mine depth noted in Crowell & Murray (1914) was 295 feet, with a level at 262 feet. This depth would ring true for the main shaft, the No. 2 hoisting shaft, which would eventually be sunk to a depth of 383 feet, but the No. 2 hoisting shaft is not located in the NW-SE parcel. The western extension shaft could conceivably meet Crowell & Murray's (1914) description, as a single >1,300-foot-long drift that connects the western extension workings with the 262-foot-level drifts extending from the No. 2 hoisting shaft.

The connecting drift, as shown on the 262-foot-level map, passes through a minimum of 600 feet of rock on its eastern end before reaching one of the ore lenses of the main part of the mine. The easternmost 400 feet of rock is comprised of hard green slate, green schist, grey rock, and hard green schist in going from west to east. If drawn to scale, the drift appears to be 10 feet wide. Sealing off the eastern end of this drift would isolate the western extension shaft and mine workings for CAES purposes.

The engineering design of the Kennedy mine's No. 2 Hoisting Shaft, which served as the main shaft, is shown in Fig. 1.2-9. Outside dimensions are 12 feet x 16 feet. The design schematic and mine maps indicate that this is a 4-compartment shaft. Edwards (1913) describes this shaft as "a modern 5-compartment timber-lined shaft, with two skipways, cageway, ladderway and pipeway." The discrepancy appears to lie in whether or not the ladderway and pipeway were distinct compartments.

The shaft is 383 feet deep. Overburden depth at the shaft is 121 feet. Mine maps show pockets of ore removed by slicing up to depths as shallow as 114 and 119 feet, as well as 125 feet. This information would seem to indicate that the ore was mined right up to the base of the overburden, as had been seen on the Mesabi Range.

Notes on the shaft design sheet in Figure 1.2-9 indicate that this shaft was flooded on August 12, 1924, signaling an end to mining operations. The last shipment of ore from the Kennedy mine occurred in 1925 (Skillings Mining Review, 2005), likely from stockpile. The shaft was subsequently dewatered to approximately 20 feet below the 262 foot level beginning on February 24, 1950, a level where it was maintained for a period of time, likely through the life of the Rabbit Lake mine.

The Rabbit Lake mine, an open pit mine, lies immediately to the north of the Kennedy mine in Lot 6 (S29-T47N-R28W), and parts of Sections 20, 29, and 30-T47N-R28W underlying Rabbit Lake (Skillings Mining Review, 2005). A dike was built across the narrows between the eastern and western lobes of Rabbit Lake in 1945 (Schmidt, 1963). Water was subsequently pumped out of the eastern lobe to gain access to the Rabbit Lake orebody.

The Rabbit Lake mine was operated by Pickands-Mather & Company from 1952 to 1965 (Aulie and Johnson, 2001). M.A. Hanna operated the mine from 1966 to 1968 and made stockpile shipments 1969-1970 and 1972-1973. The Rabbit Lake mine became the sixth largest producer on the Cuyuna Range (Skillings Mining Review, 2005), delivering non-manganiferous goethetic and hematitic ores from entirely within the thin-bedded facies of the Trommald Formation (Schmidt, 1963).

The Robert mine, also an open pit mine, overlies the workings of the Kennedy mine in most of Lot 5, Section 30, as well as extending into the lakebed of Rabbit Lake. Mined elevations within the pit were unreadable on the scanned images obtained. No determination could be made as to whether the Kennedy underground workings were mined out by the Robert pit workings.

No dates were found for the opening of the Robert mine, although it would have operated contemporaneously with the Rabbit Lake mine while the dike was maintained. Final shipment for the Robert mine was made in 1966 (Skillings Mining Review, 2005). Together, the Kennedy, Robert, and Rabbit Lake mines produced nearly 7.2 MLT (1,369,079 LT, 2,422,836 LT, and 4,638,517 LT, respectively) of ore (Skillings Mining Review, 2005).



Kona Reserve (X-21)

The Kona reserve (SW-NE S31-T47-R28) lies immediately south of the city of Cuyuna and abuts the Federal reserve to the east (Fig. 1.2-8). The City of Cuyuna is the fee owner on this property.

The most recent ore reserve estimate for this property was apparently done in 1958. Obtained from the MDOR Mineral Tax Office in Eveleth, MN, these data are presented in Table 1.2-4. Assay data for the Kona reserve is presented in Table 1.2-7, together with that from the Federal and Erich reserves. It is noted on the ore reserve estimate that the ores on the Kona and Federal reserve properties occur in seams that are separated from each other.

**Table 1.2-4.** Kona Reserve (X-21) ore reserve estimate.

Ore Reserve Estimate <sup>1,2</sup>							
Property	Parcel	S	T	R	Data	Surface Owner <sup>3</sup>	Fee Owner
Kona Reserve (X-21)	SW-NE	31	47	28	X	City of Cuyuna	City of Cuyuna
Year	Type		Re-class	Recovery Factor	Tons	Density Factor	
1958	UG Direct - Iron				137,800		
	UG Wash ore concentrate - iron				253,600		
	UG Wash ore concentrate – mang.				141,700		
	<b>Total Tons:</b>				<b>533,100</b>		
<sup>1</sup> Upper table information from Beltrame (1977), unless otherwise noted. Data consists of drill hole data, cross-sections, reserve estimates, etc. on microfilm at MDOR Minerals Tax Office in Virginia, MN. <sup>2</sup> Lower table information from MDOR Minerals Tax Office data files. <sup>3</sup> Data from MN DNR GIS coverage own_mnstwdpy2 (2008).							

Federal Reserve (X-37)

The Federal Reserve (X-37) (E1/2-NE S31-T47-R28) is located immediately east of the city of Cuyuna and the Kona Reserve (Fig. 1.2-8). According to a report contained in the MDOR data file with the Federal Reserve ore estimates, the reserve's ore body lies on the south limb of the anticline on which the Kennedy mine is located. The iron-formation strikes northeast-southwest here and dips very steeply south.

Twenty holes were drilled. The deepest of these was 615 feet. The report indicates that lenses or stringers of merchantable ore (> 55% dry iron) occur in thicknesses of two to twelve feet. These stringers are interbedded with ore of lower grade (50%-55% dry iron) and rock layers. Assay data for the Federal Reserve is presented in Table 1.2-5.

Development costs for an underground mine were included in the report. Depth for the proposed shaft was 410 feet. Development work would entail 2,400 feet of drifts in rock and ore, principally rock.

**Table 1.2-5.** Federal Reserve (X-37) ore reserve estimate.

Ore Reserve Estimate <sup>1,2</sup>							
Property	Parcel	S	T	R	Data	Surface Owner <sup>3</sup>	Fee Owner
Federal Reserve (X-37)	E1/2-NE	31	47	28	X	Private	Federal Mining Co.
Year	Type		Re-class	Recovery Factor	Tons	Density Factor	
1986	UG Wash ore concentrate			65%	113,165	14	
	UG Wash ore concentrate			60%	274,900	14	
				<b>Total Tons:</b>	<b>388,065</b>		
1958	UG Direct – Iron (Merch)				174,100		
	UG Wash ore concentrate - iron				274,900		
				<b>Total Tons:</b>	<b>449,000</b>		

<sup>1</sup>Upper table information from Beltrame (1977), unless otherwise noted. Data consists of drill hole data, cross-sections, reserve estimates, etc. on microfilm at MDOR Minerals Tax Office in Virginia, MN.

<sup>2</sup>Lower table information from MDOR Minerals Tax Office data files.

<sup>3</sup>Data from MN DNR GIS coverage own\_mnstdwp2 (2008).

Beltrame (1977) lists the Federal Reserve as exhausted; however, a 1986 document found at MDOR yields a net estimate of 388,065 tons of wash ore concentrate available by underground methods. An earlier (1958) estimate had indicated the presence of 449,000 tons, 174,100 of which were classified as merch ore. The merch ore tonnage was subsequently reclassified to wash ore concentrate using a 65% recovery factor, resulting in the lower figure for 1986. Tonnage was determined by cross-section estimate.

### Erich Reserve (X-60)

The Erich Reserve (X-60) (Lot 5 (E1/2-SW) S31-T47-R28) lies east of the Kennedy mine on the eastern lobe of Rabbit Lake (Fig. 1.2-8). No information was found on this reserve beyond the ore reserve estimate presented in Table 1.2-6 and the assay data presented in Table 1.2-7.

**Table 1.2-6.** Erich Reserve (X-60) ore reserve estimate.

Ore Reserve Estimate <sup>1,2</sup>							
Property	Parcel	S	T	R	Data	Surface Owner <sup>3</sup>	Fee Owner
Erich Reserve (X-60)	Lot 5 (E1/2-SW)	31	47	28	X	Private	George H. Crosby Estate, Northern City Nat'l Bank, The Hanna Mining Co. (7/240), et al.
Year	Type		Re-class	Recovery Factor	Tons	Density Factor	
1966	UG NB Wash ore concentrate				367,600		

<sup>1</sup>Upper table information from Beltrame (1977), unless otherwise noted. Data consists of drill hole data, cross-sections, reserve estimates, etc. on microfilm at MDOR Minerals Tax Office in Virginia, MN.

<sup>2</sup>Lower table information from MDOR Minerals Tax Office data files.

<sup>3</sup>Data from MN DNR GIS coverage own\_mnstdwp2 (2008).

The ore reserve estimates for the Kona, Federal, and Erich reserves also contain assay data. These data are presented in Table 1.2-7.

**Table 1.2-7.** Assay data for the Kona (X-21), Federal (X-37), and Erich (X-60) ore reserves.

Assay Data <sup>1</sup>										
Property	Tons	Tons	Dry						Natural	
			Fe	P	Si	Mn	Al	Moist.	Fe	Mn
Kona (Reserve (X-21))	UG Direct - Iron	137,800	57.83	0.232	8.64	0.24	1.59	14.00		
	UG WOC - iron	253,600	56.46	0.250	12.23	0.64	-	12.00		
	UG WOC - mang.	141,700	46.27	0.117	11.80	9.52	-	12.00		
Federal Reserve (X-37)	UG Direct - Iron (Merch)	174,100	57.59	0.244	8.87	0.19	1.59	14.00		
	UG WOC - iron	274,900	57.95	0.210	10.50	0.27	-	12.00		
Erich Reserve (X-60)	UG NB WOC	367,600	55.87	0.224	8.76	0.27	0.77	10.00 <sup>2</sup>	50.28	

<sup>1</sup>Source: MDOR file. Institute of Technology Office of Ore Estimation, August 4, 1970.  
<sup>2</sup>This figure is an assumed moisture based on Rabbit Lake experience according to the ore reserve report.

### CAES Potential for Cuyuna North Range Area 1: Kennedy Mine and Kona, Federal and Erich Ore Reserves

Proximity to and submersion beneath the eastern lobe of Rabbit Lake makes use of the main body of Kennedy mine workings for CAES purposes highly unlikely. However, the western extension shaft and mine workings may hold CAES potential as described beneath the Kennedy Mine heading above. In addition, the Kona, Federal, and Erich ore reserve properties offer potential for mining to generate a CAES cavern. The mined product would be natural iron ore.

Figures 1.2-10 through 1.2-13 illustrate the base map, hydrographic, elevation and surface ownership features of the region housing the Kennedy mine and the three ore reserve properties. The Kennedy mine and all three reserves lie within the municipal boundary of the city of Cuyuna (Fig. 1.2-10). The ore reserve properties appear undeveloped for the most part over the iron-formation, although County State Aid Highway (CSAH) 31 cuts through the Kona reserve, as does a state snowmobile trail.

With the exception of the northeast portion of the Erich Reserve, the reserve properties are uplands. An intermittent stream drains the properties into Rabbit Lake.

The City of Cuyuna has surface ownership of the Kona Reserve property while the Federal and Erich reserves are on private land (Fig. 1.2-11). The Kennedy mine property, as well as several parcels bordering on the reserves, is state-owned tax forfeit property that is administered by Crow Wing County. Fee owners for the reserves are shown in Tables 1.2-4 through 1.2-6.

**Positives:**

- The reserve properties are located in a lightly populated area. Little development is shown over the iron-formation;
- Land surface is relatively flat uplands;
- Road access to the Federal and Kona reserves via County State Aid Highway (CSAH) 30 and CSAH 31 from Minnesota Trunk Highway (MNTH) 6 is less than three miles. MNTH 6 is the major north-south arterial route in the region (Fig. 1.2-3);
- Distance from the Federal and Kona reserves to a major Minnesota Power transmission line is approximately 2.2 miles along CSAH 31 and CSAH 30. Distance from the city of Cuyuna power supply to the reserve properties is 0.5 to 1.0 mile;
- The City of Cuyuna is fee owner on the Kona reserve. There is state land adjacent to the Federal reserve and directly southwest of the Erich reserve;
- There are sizable ore reserves of natural iron ore and manganiferous ore for potential CAES cavern construction; and
- A mine shaft and underground drifts located 0.3 miles west of the main Kennedy mine shaft could potentially be isolated (Fig. 1.2-10). Little information was found on these workings other than placement on maps. A >1,300-foot-long drift connects these workings to the main Kennedy mine. The shaft is located 350 feet from MNTH 6. Some of the drifting extends beneath the highway.

**Negatives:**

- The Kennedy mine shaft and workings are submerged and cannot be considered;
- CSAH 31 cuts across the iron-formation of the Kona reserve;
- The western extension mine shaft has been caved and lies beneath a raised railroad grade; and
- Depth and placement of the ore reserves within the reserve properties were not ascertained as part of this study. This information is available at MDOR in Virginia, MN.

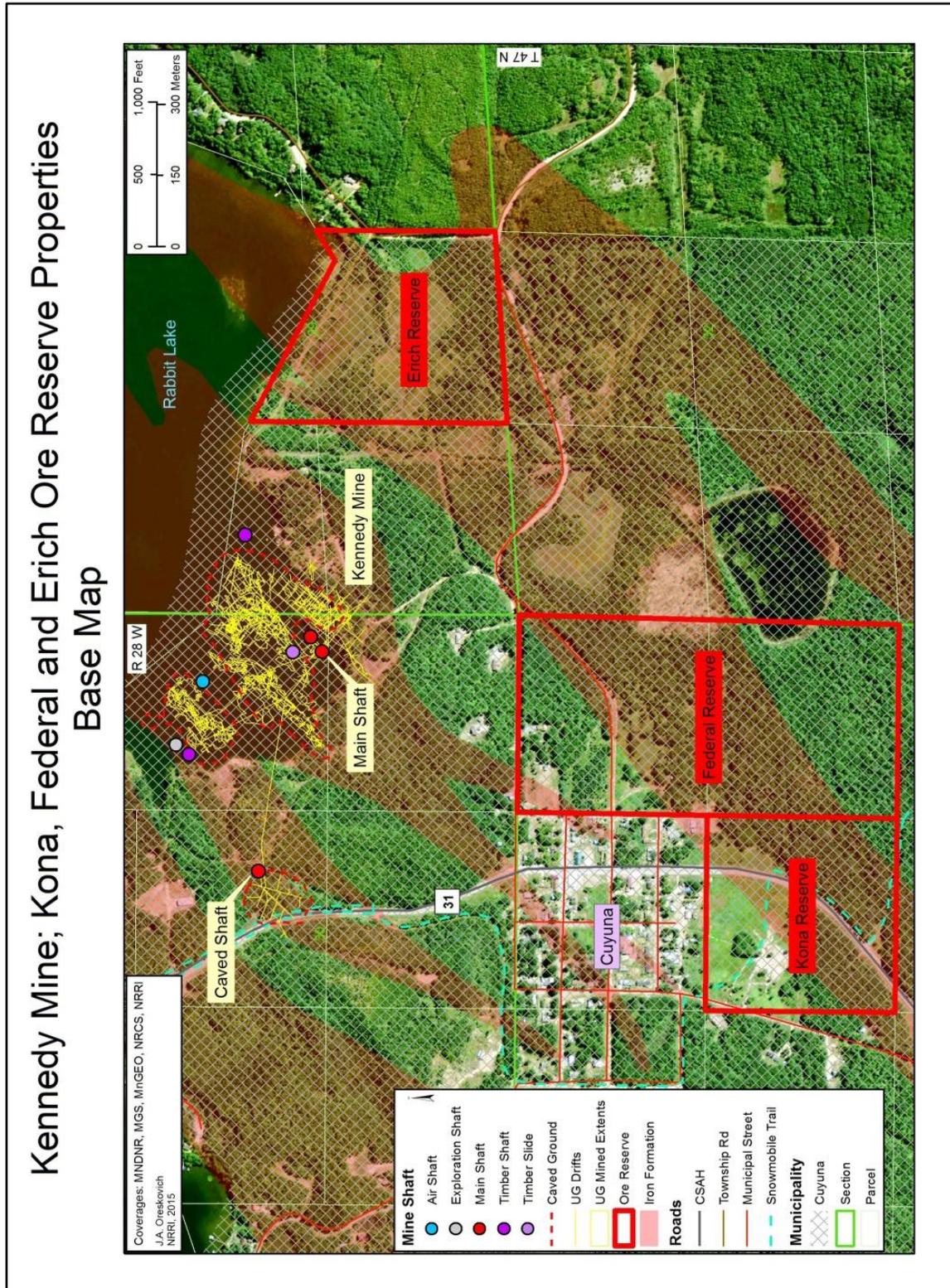


Figure 1.2-10. Base map of the Kennedy Mine and Kona, Federal and Erich ore reserves area.

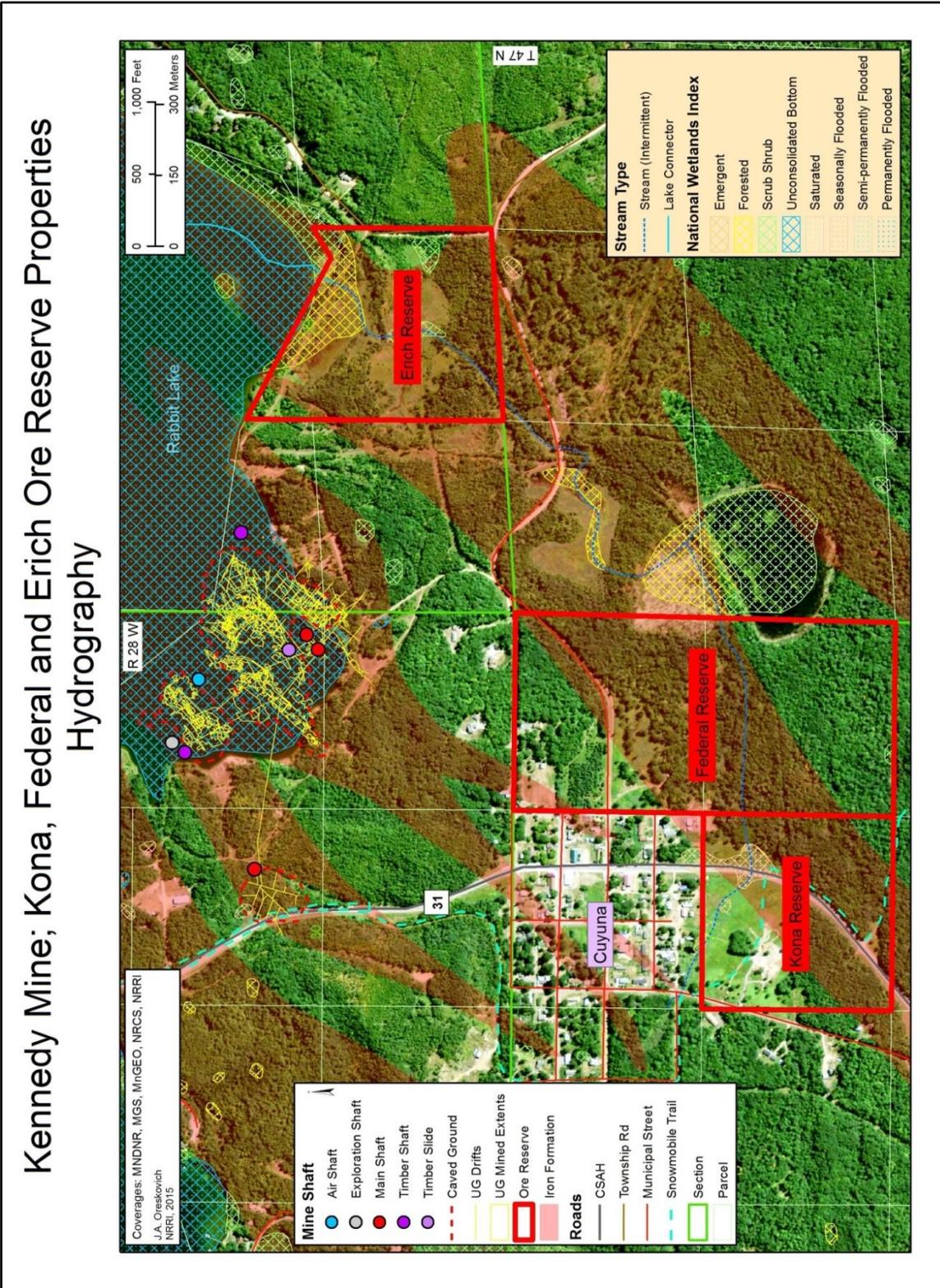


Figure 1.2-11. Hydrography map of the Kennedy Mine and Kona, Federal and Erich ore reserves area.

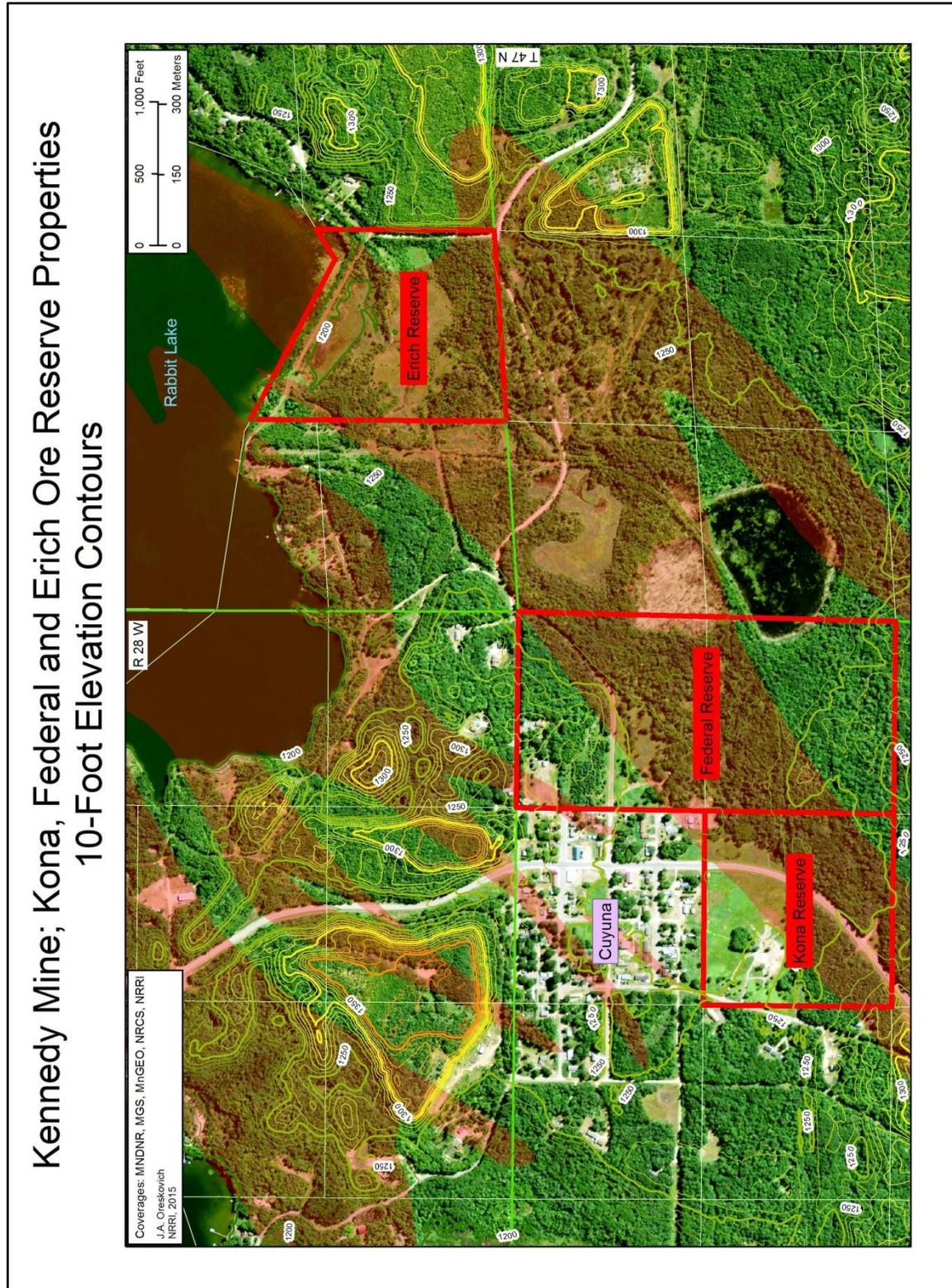


Figure 1.2-12. Elevation contour map of the Kennedy Mine and Kona, Federal and Erich ore reserves area.

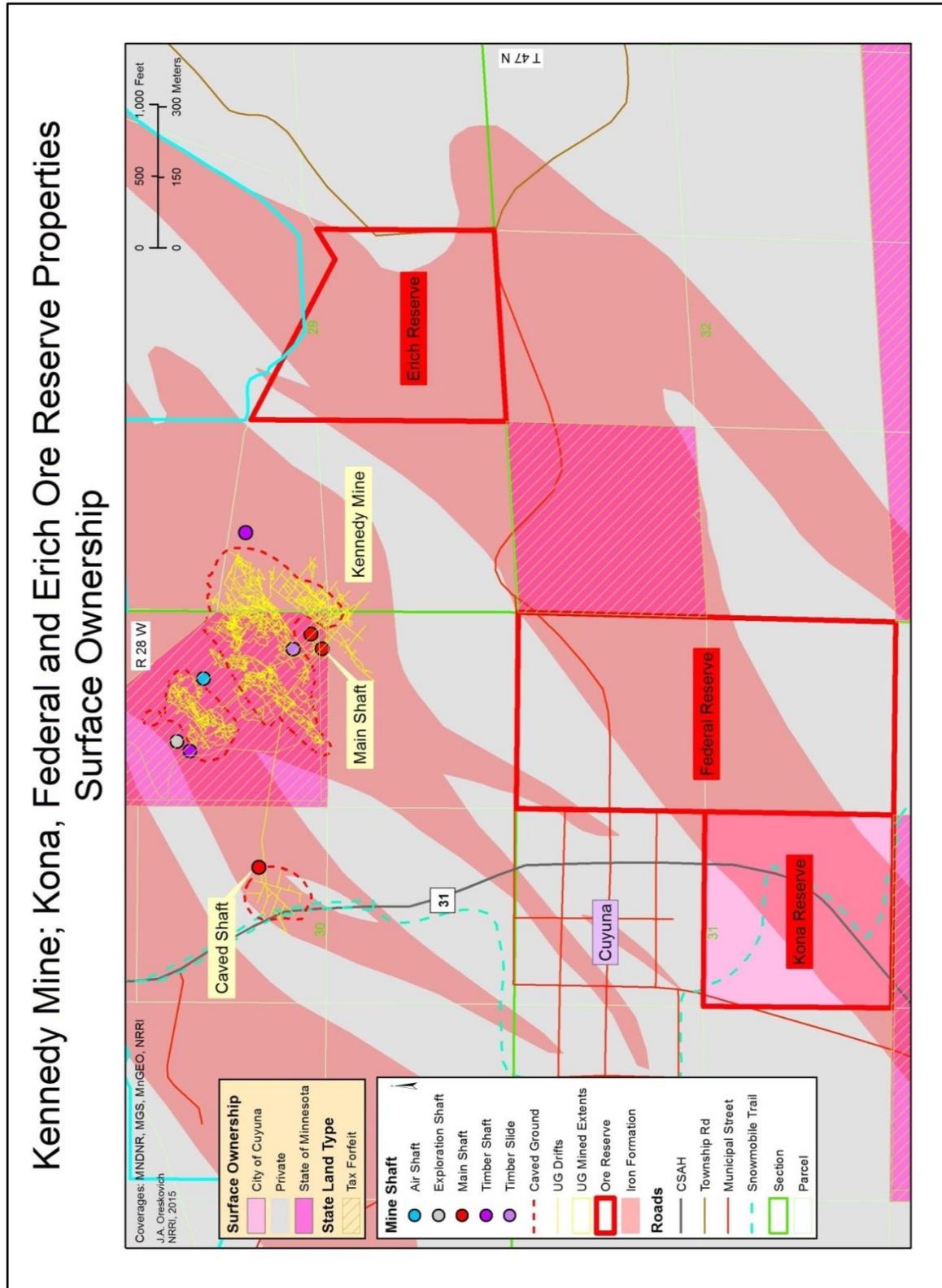


Figure 1.2-13. Surface ownership map of the Kennedy Mine and Kona, Federal and Erich ore reserves area.

Northland Mine

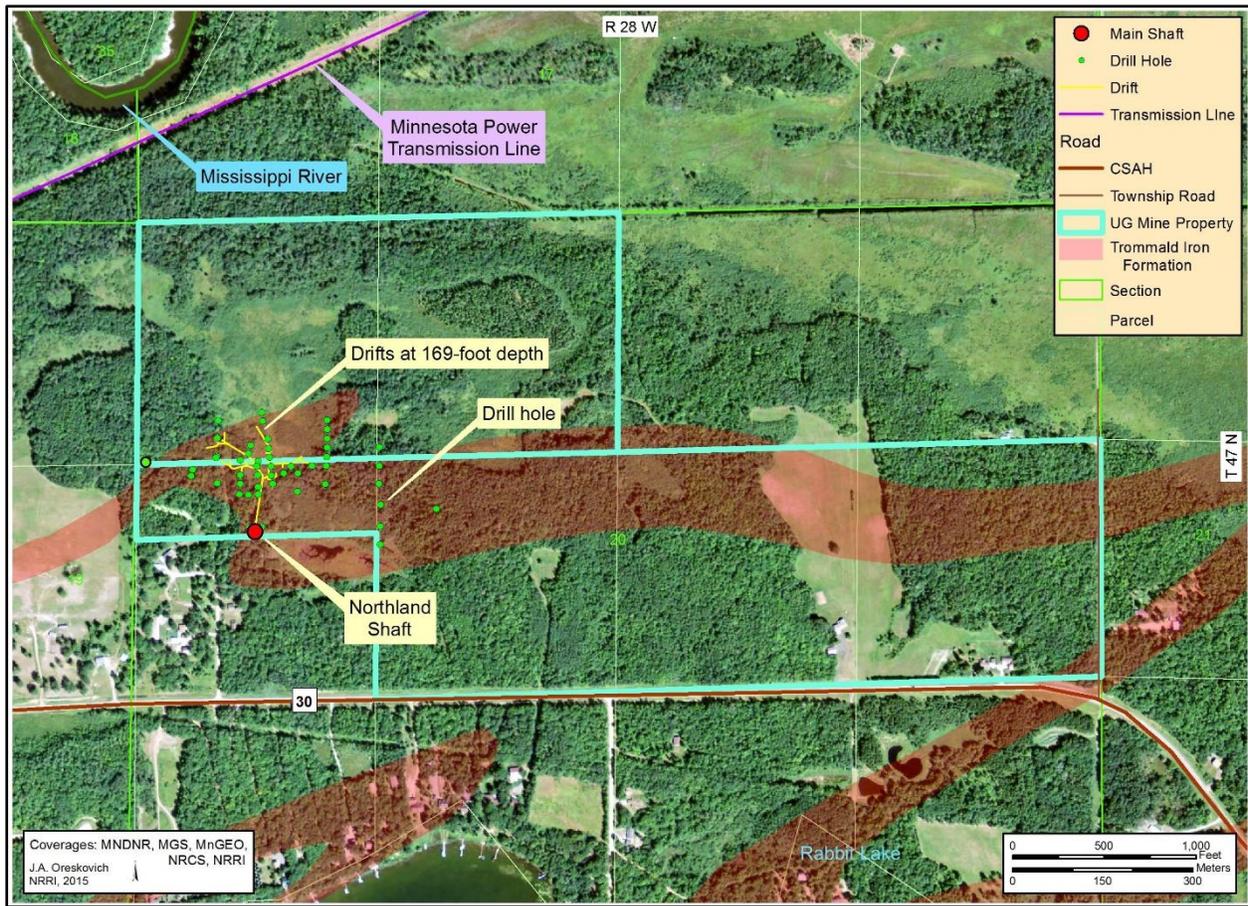


Figure 1.2-14. Northland mine.

Mine	Range	S	T	R	Parcel	UG	OP	ML
Northland	North Range	20	47	28	N1/2-NW, S1/2-NE & S1/2-NW (except S 912' of SW1/4-NW1/4)	X		
Shaft Sinking	Stockpile Shipment	Total Ore Shipped (LT)			Last Operator	Last Known Fee		
1918	1941	4,575			NA	State (N1/2-NW); Chas. W. Potts, et al. (S1/2-NE & S1/2-NW)		
Overburden (Ft.)	Mine Depth (Ft.)	Main Level	Shaft Type					
~137	169	169-Ft. Level	5-compartment					

The Northland mine property comprises the N1/2-SW S20-T47-R28 (State property) and the S1/2-NE and S1/2-NW S20-T47-R28 (except the S 912 feet of the SW-NW) (Potts property) (Fig. 1.2-14). The Northland mine shaft was sunk just prior to the end of WWI (Schmidt, 1963). Development of the mine was never completed, apparently due to lack of demand with the end of the war. Ore stockpiled in 1918 during the early development stage was shipped in 1941 (Schmidt, 1963). Shipments totaled 4,575 LT (Skillings Mining Review, 2005). The ore from the Northland mine is a manganiferous hematite (Crowell & Murray, 1923).

Mine maps show the Northland shaft to be a 5-compartment shaft. Drifts are shown at a depth of 169 feet (Fig. 1.2-14). Drifting may be the extent of the mine workings, with the small tonnage stockpiled and shipped. The drifts are potentially still open (not collapsed) but are likely water-filled.

The Northland shaft is located on the Potts property in the SW-NW forty. Drifting extended into the State forty (NW-NW). An undated Hanna Coal and Ore Company map shows a proposed pit layout for the Northland mine that straddles the line between the Potts and State properties. However, 2013 NAIP (National Agriculture Imagery Program) aerial photos do not show any disturbances in the area of the mine that would be indicative of an open pit mine.

A 1958 ore reserve estimate found at the MDOR office in Eveleth notes that all mining facilities were removed from the property, the old shaft was covered, and it was not known whether the shaft had been caved. The 1962 ore reserve estimate notes that “the old shaft is visible but caved and covered over. The foundations of the headframe are caving into the shaft. It would be impossible to rehabilitate this shaft.”

The 1962 ore reserve estimate declares the Northland mine exhausted. Of note is that only the Potts properties (SW-NW & SE-NW) are listed. It reports that assay data on remaining material from drill hole analyses indicate “a low iron, high silica manganiferous material.” Assay results are shown in Table 1.2-8.

**Table 1.2-8.** Northland mine Potts property assay data.

Assay Data <sup>1</sup>										
Dry									Natural	
Property	Type	Tons	Fe	P	Si	Mn	Al	Moist.	Fe	Mn
Northland (SW-NW & SE-NW)	NA	exhausted	30.29	0.145	27.11	13.41	1.59	11.00		

<sup>1</sup>Source: MDOR data file.

On the 1958 ore reserve estimate, the Potts and State properties are separated out. Under the Potts property the reserve is listed as “none.” Under the State property, tonnages and assay data were provided for four types of underground ore: iron merch and wash ore concentrate, and manganiferous merch and wash ore concentrate. Ore reserve data for the State property is provided in Table 1.2-9. Assay data for the State property is provided in Table 1.2-10.

**Table 1.2-9.** Northland mine State property ore reserve estimate.

Ore Reserve Estimate <sup>1,2</sup>							
Property	Parcel	S	T	R	Data	Surface Owner <sup>3</sup>	Fee Owner
Northland Mine	N1/2-NW	20	47	28	X	MN DNR	State
Year	Type	Re-class	Recovery Factor	Tons	Density Factor		
1958	UG Merch - Iron			8,600			
	UG Wash ore concentrate - iron			20,100			
	UG Merch – mang.			38,500			
	UG Wash ore concentrate – mang.			15,200			
				<b>Total Tons:</b>	<b>82,400</b>		
<sup>1</sup> Upper table information from Beltrame (1977), unless otherwise noted. Data consists of drill hole data, cross-sections, reserve estimates, etc. on microfilm at MDOR Minerals Tax Office in Virginia, MN. <sup>2</sup> Lower table information from MDOR Minerals Tax Office data files. <sup>3</sup> Data from MN DNR GIS coverage own_mnstwdpy2 (2008).							

**Table 1.2-10.** Northland mine State property assay data.

Assay Data <sup>1</sup>										
Dry									Natural	
Property	Type	Tons	Fe	P	Si	Mn	Al	Moist.	Fe	Mn
Northland (N1/2-NW)	UG Merch – Iron	8,600	59.01	0.220	8.08	0.28		14.00		
	UG WOC - Iron	20,100	53.98	0.250	12.38	0.60		12.00		
	UG Merch – Mang.	38,500	43.14	0.208	10.64	9.28		16.00		
	UG WOC – Mang.	15,200	41.59	0.260	13.21	8.64		12.00		
<sup>1</sup> Source: MDOR data file.										

Schmidt (1963) reports that the Northland mine shaft “is near the upper contact of the Trommald Formation on the northwest limb of a large southwest-plunging syncline.” He adds that the mine “is believed to be on a southwest-plunging drag fold in which the lower contact of the Trommald Formation appears much more folded than the upper.”

This tighter fold of the lower contact can be seen in the upper (State) property in Figure 1.2-14. The lower contact of the Trommald Formation with the underlying Mahnommen Formation is to the north-northeast (outside) of synclinal basin S<sub>1</sub> relative to the location of the Northland mine, as seen in Figure 1.2-5. The Northland shaft appears as the red dot on the far northeastern flank of the syncline. The upper contact of the Trommald Formation with the overlying Rabbit Lake Formation is present to the south-southwest (inside) of synclinal basin S<sub>1</sub> at the Northland mine site. The Northland mine lies within a zone of moderately manganiferous thin-bedded facies iron-formation, just north of the pinch-out of the overlying thick-bedded facies (Schmidt, 1963).

McSwiggen et al. (1995) studied a Northland mine drill hole as part their determination that hydrothermal and exhalative processes played important roles during the deposition of the Trommald Iron Formation. This could lead to exploration for “sediment-hosted, submarine exhalative (SEDEX), Pb-Zn-Ag deposits.” The Northland drill hole was over 800 feet deep. The stratigraphic column of the Northland drill hole presented in McSwiggen et al.’s (1995) report ran

from a depth of 300 feet to approximately 850 feet. Red, iron-rich slate of the Trommald Formation is shown from 300 to 340 feet. The remainder of the hole is Mahnomen Formation.

#### CAES Potential for Cuyuna North Range Area 1: Northland Mine Area

Figures 1.2-15 through 1.2-18 illustrate the base map and hydrographic features, 2-foot elevation contours, and surface ownership of the Northland mine area. The Northland mine resides in a flat open area that lies between the Mississippi River to the north and the eastern lobe of Rabbit Lake to the south (Fig. 1.2-15). There is maximum relief of 34 feet in the slightly populated to unpopulated vicinity of the mine. Elevation over the mine site is generally 1,212 ft., rising to 1,216 ft. at the shaft (Fig. 1.2-17). The upper banks of the Mississippi River to the north lie at a comparable elevation (1,212 ft.), dropping to a river elevation of 1,180 ft. at the time the LiDAR elevation data was collected (2008). Water level in Rabbit Lake at this same time was at 1,198 ft.

There is an abundance of saturated soils in the immediate vicinity of the mine (Fig. 1.2-16). A drainage ditch 1/3 mile northeast of the mine site runs from the wetlands area to the Mississippi River.

Surface ownership of the Northland mine property is both private and state (Fig. 1.2-18). The shaft occurs on the Potts property with some drifting extending into the state property. The state portion is MN DNR Division of Forestry Trust Fund (Swamp) land.

##### Positives:

- The Northland mine site is well-situated relative to power access. There is a major Minnesota Power transmission line located less than one-half mile to the northwest.
- Drill hole and assay data are available;
- The mine sported a 5-compartment shaft. While the shaft condition is unknown, the drifts may be open, depending on the competency of the roof rock;
- There appears to have been little development near the mine property; and
- There may be potential for SEDEX mineral exploration at the Northland mine site.

##### Negatives:

- Saturated soils are present at the mine site; and
- Drifting is at a relatively shallow depth (169 feet).

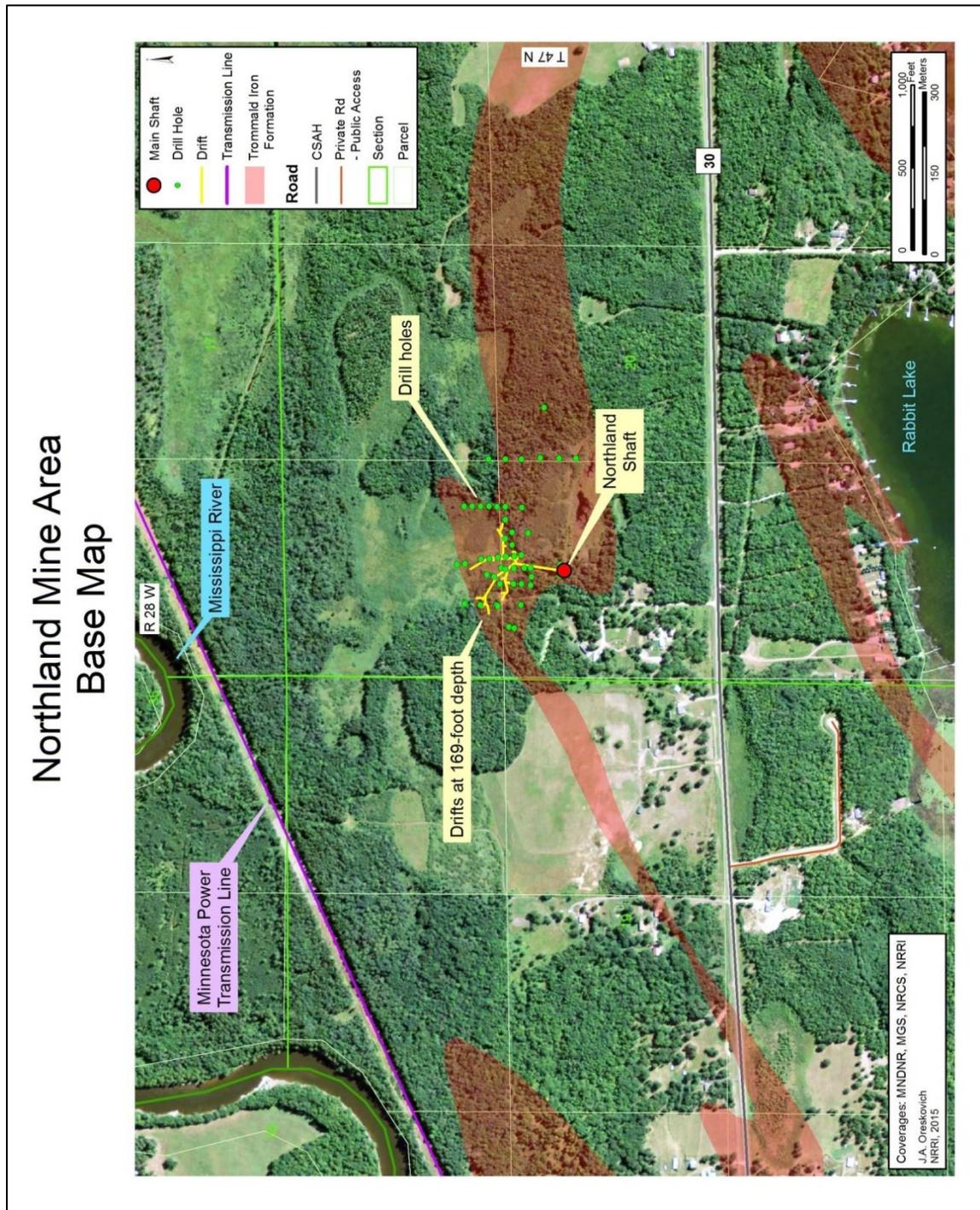


Figure 1.2-15. Northland mine area base map.

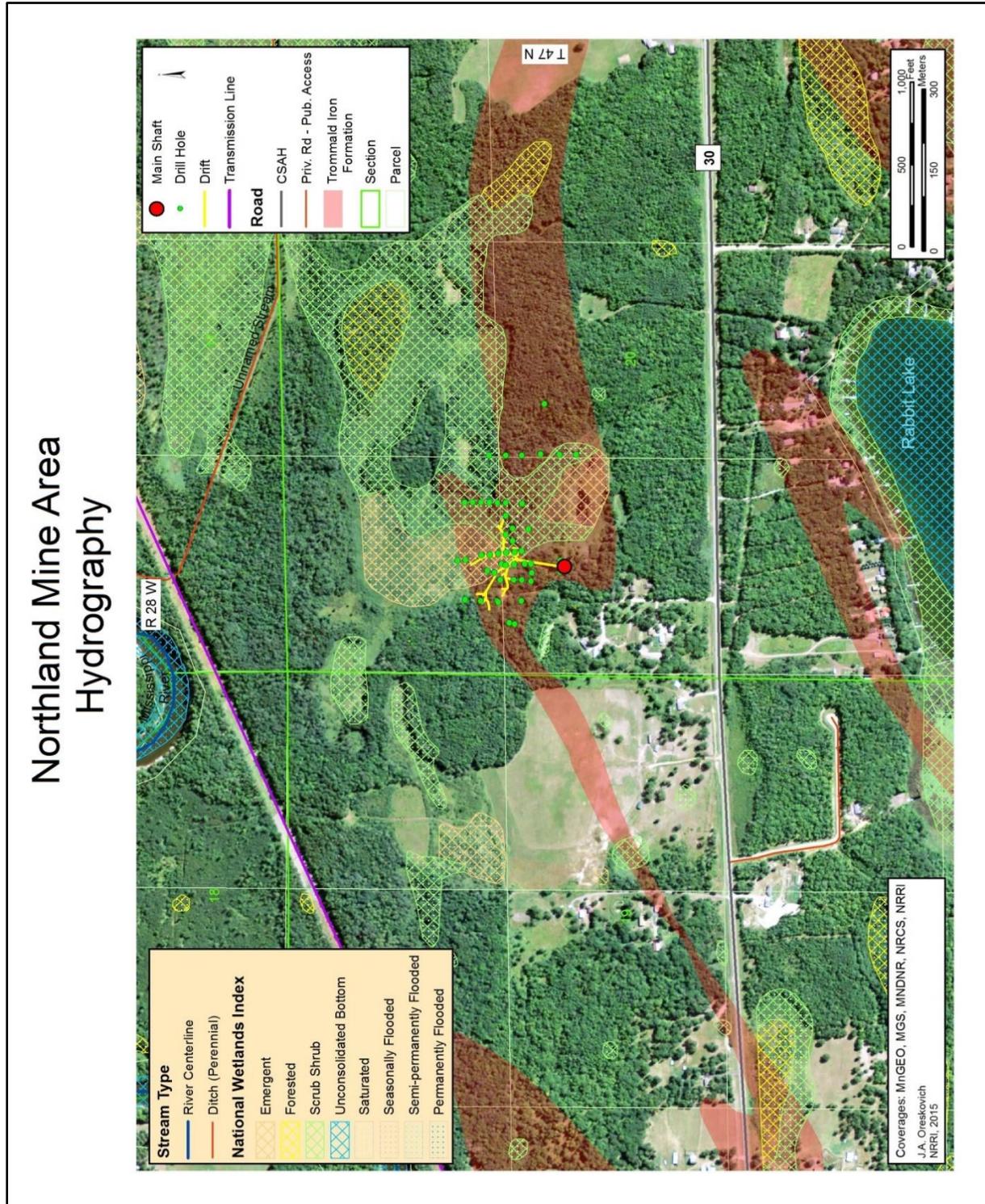


Figure 1.2-16. Northland mine area hydrographic features map.

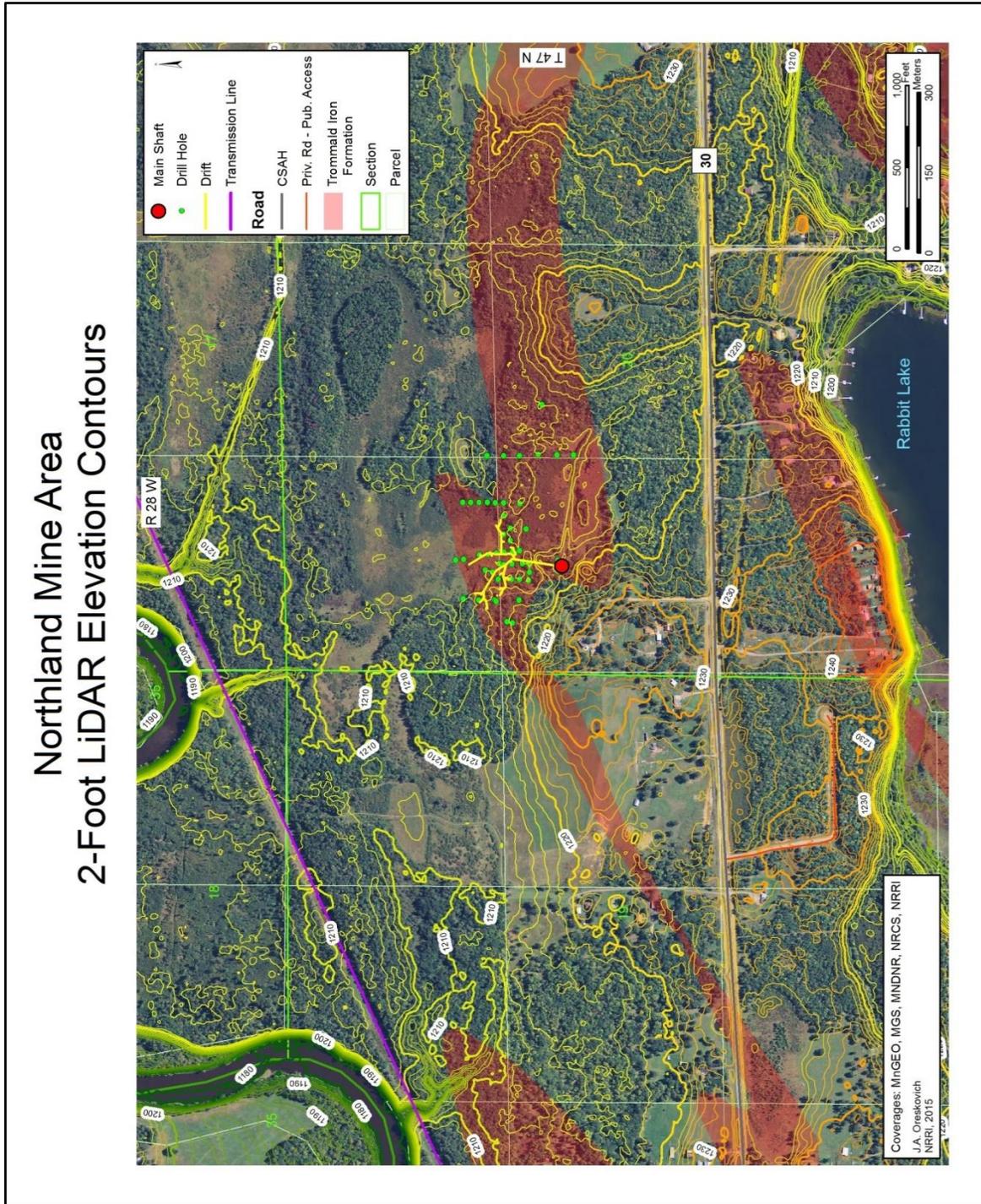


Figure 1.2-17. Northland mine area 2-foot Lidar contours elevation map.

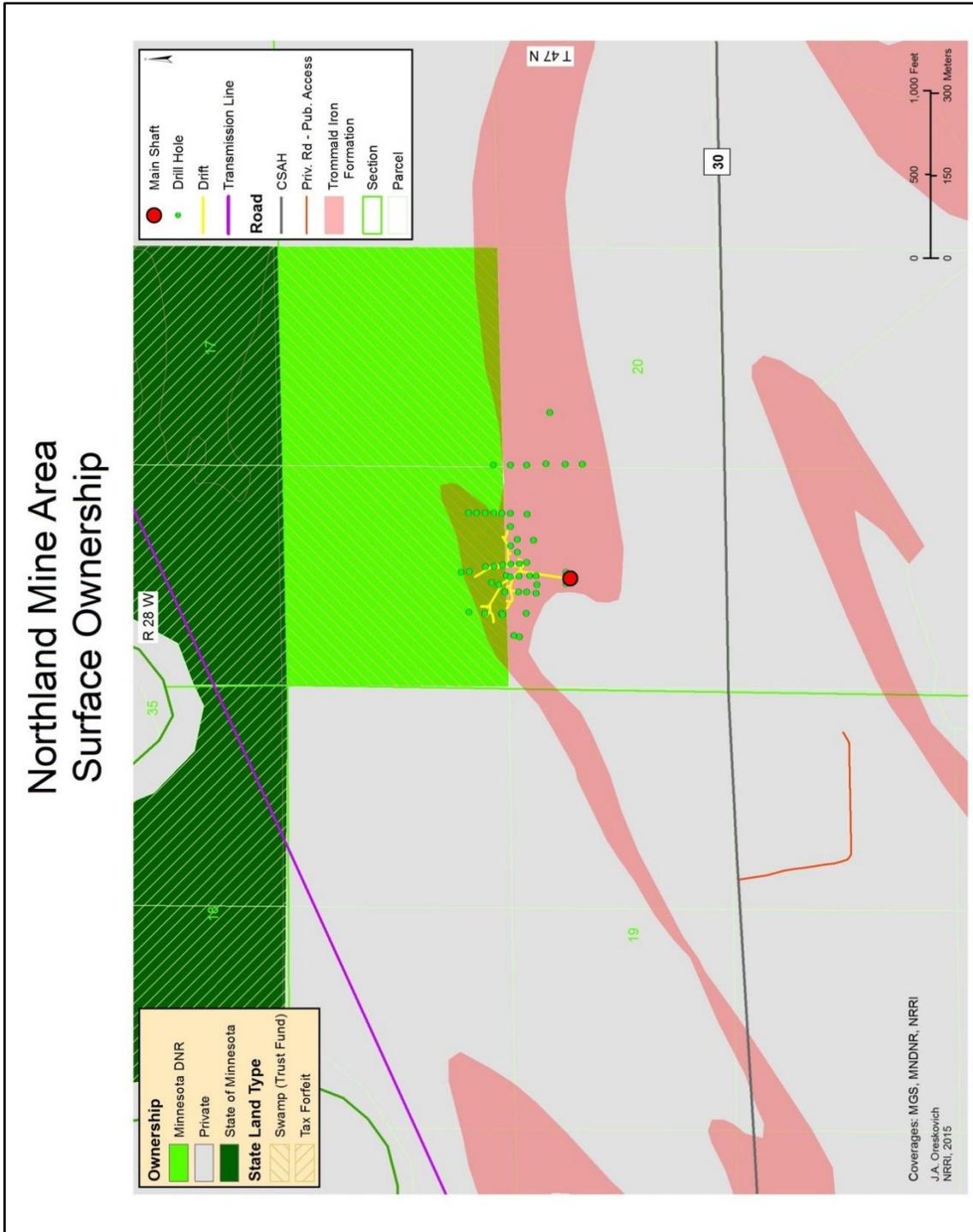
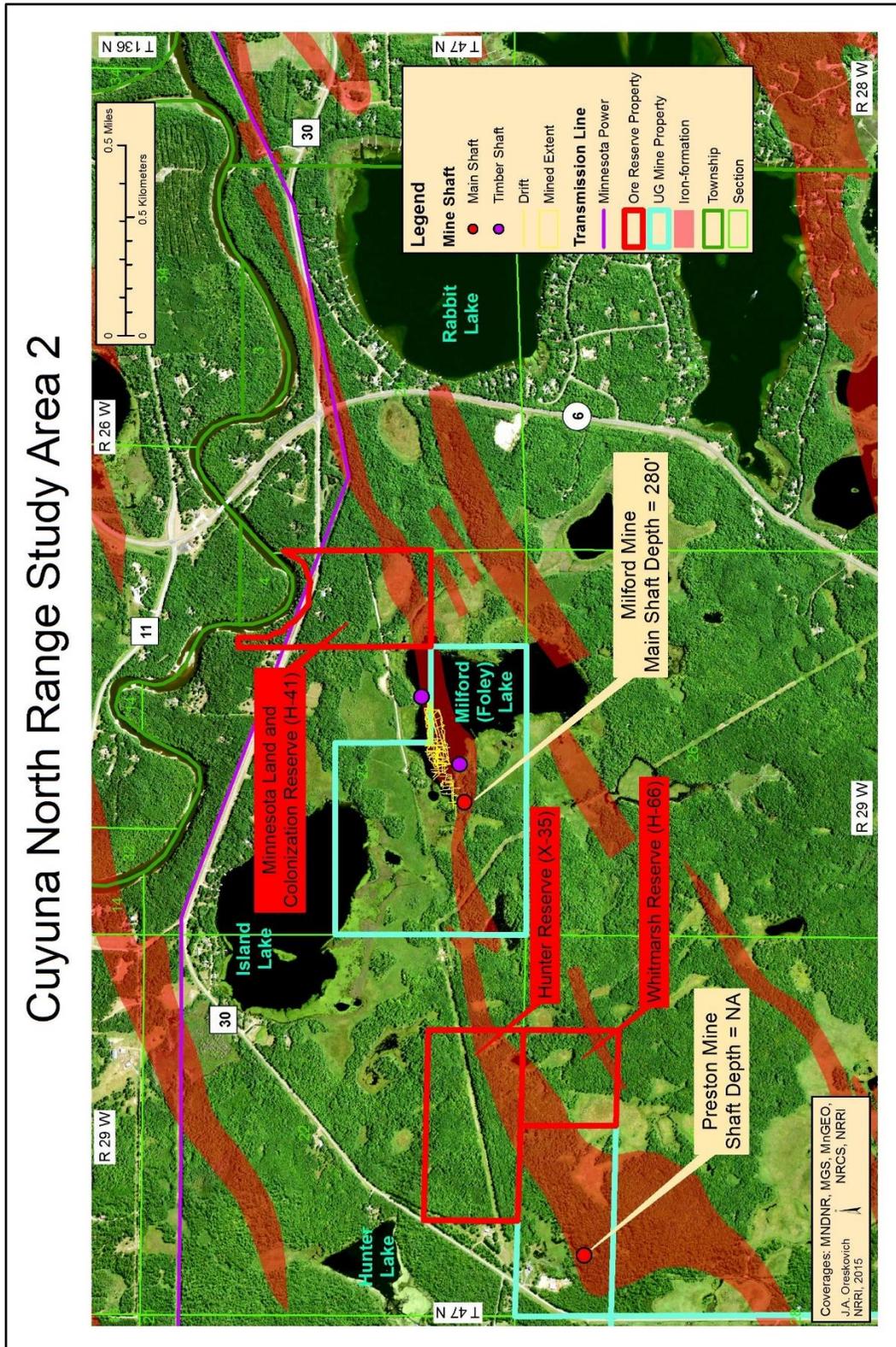


Figure 1.2-18. Northland mine area surface ownership map.

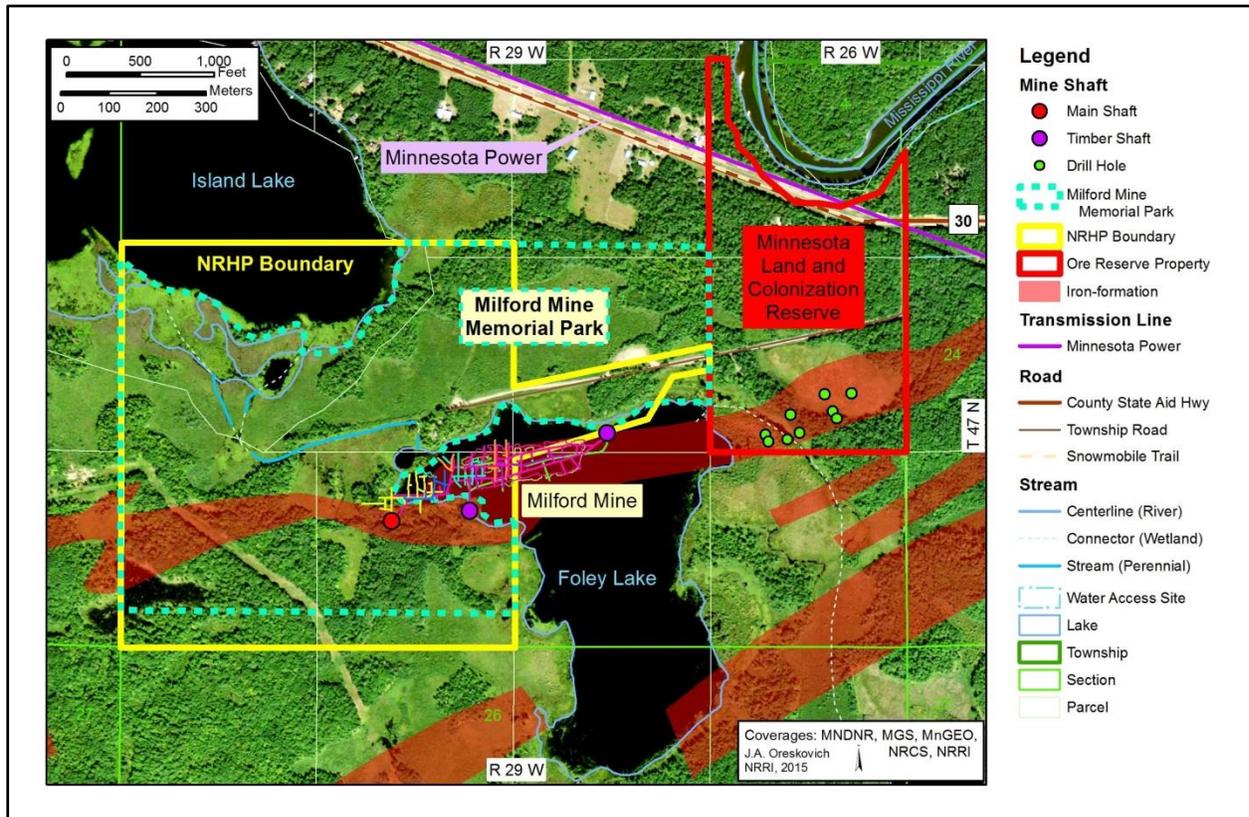
Cuyuna North Range Study Area 2



**Figure 1.2-19.** Cuyuna North Range Study Area 2: Milford and Preston mines; Hunter, Whitmarsh, and Minnesota Land and Colonization Reserves.

Cuyuna North Range Study Area 2 lies south of the Mississippi River and west of Rabbit Lake. Included in the study area are the Milford and Preston mines and the Hunter (X-35), Whitmarsh (H-66), and Minnesota Land and Colonization (H-41) reserves (Fig. 1.2-19). Data for the Preston mine property is presented as the Preston Reserve (I-1).

Milford Mine



**Figure 1.2-20.** Milford mine, site of Minnesota's worst mining disaster that resulted in 41 lives lost in 1924. The site has been added to the National Register of Historic Places (yellow outline after NRHP, 2011). Currently in development is the Milford Mine Memorial Park (blue dashed outline after SEH, 2007).

Mine	Former Name	Range	S	T	R	Parcel	UG	OP	ML
Milford	Ida Me	North Range	23	47	29	SW1/4 & SW-SE	X		
Shaft Sinking	1st Shipment	Last Shipment	Total Ore Shipped (LT)		Last Operator	Last Known Fee			
1917	1918	1933	1,266,172 LT		Amherst Mining Co.	State; Foley Trust; Pittsburgh Pacific Co.; and Hassman Trust			
Top Level		Main Level	Lowest Level		Shaf ts	Main Shaft Location			
125 Ft. Sub Level		135, 200, & 280-Ft. Levels	280-Ft. Level		3	in iron-formation			

The Milford mine is located in the SW1/4 and SW-SE of S23-T47-R29 (Skillings Mining Review, 2005; Fig. 1.2-20). It is situated in an area of low relief, relatively isolated from other mines (Fig. 1.2-6). The Milford Mine property is now owned by the State of Minnesota.

Opened in 1917, the Milford mine was worked by the top-slicing method (Crowell & Murray, 1923). Maps portray the Milford shaft as a 3-compartment shaft that today is reported to be covered with wire mesh and surrounded by a fence (Hohman-Caine and Goltz, 2008). Ore from the Milford mine was a soft, brown, manganese hematite (Crowell & Murray, 1923).

Although the Milford mine workings in Figure 1.2-20 appear to extend into the NW-SE parcel, this is merely a function of the GIS parcel coverage used (see the paragraphs on geo-ratification under Method at the beginning of Section 1.2). The Milford mine workings are geo-rectified to GPS coordinates of the main and timber shafts located in the SW1/4 parcel provided by Amanda Gronhovd, 10,000 Lakes Archaeology, Inc. When overlain on a current parcel map obtained from Crow Wing County's GIS Public Mapping Service, the mine workings plot correctly relative to the county's drawn parcel boundaries.

### **Milford Mine Disaster**

The Milford mine was the site of Minnesota's worst mining disaster. On February 5, 1924, 41 men lost their lives when the mine flooded with water. According to the site's National Register of Historic Places (NRHP) Registration Form (2011), the mine was 200 feet deep when the accident occurred. It had drifts between the 125-foot sub-level and the 200-foot level. The main shaft was the only opening, and only the 135- and 200-foot levels were connected to the shaft. Seven men survived. Six who were working on the 175-foot level were able to climb a raise to the 135-foot level and reach the shaft. The seventh had been working on the 200-foot level at the base of the shaft.

It was determined that the water came in from the overlying muskeg swamp/pool subsequent to collapse of the partially hung-up roof of a room on the 165-foot level. That roof had been blasted down four days prior to the incident. The swamp had a direct connection to nearby Lake Foley, thus adding its pressure to fill the mine to within 35 feet of the shaft collar elevation (National Register of Historic Places, 2011).

The mine was reopened in November of that same year, 1924, following recovery of the last individual. The swamp was drained and kept so for the duration of mining, which ceased in 1932. Also, a small dam was constructed between the mine and the swamp (National Register of Historic Places, 2011).

Shaft depth was apparently extended to 280 feet according to mine maps that indicate workings on the 280-foot level. Two timber shafts were also sunk, providing potential additional escape routes.

### **Milford Mine Memorial Park**

Today, the Milford mine and its environs are the site of the Milford Mine Memorial Park (Fig. 1.2-20). The park, encompassing the SW1/4 and NW-SE of S 23-T47-R29, is dedicated to the 41

miners who perished in the mine. In August, 2011, the National Park Service added the Milford Mine Historic District to the National Register of Historic Places (Crow Wing County Land Services Department press release, Aug. 26, 2011). The Historic District covers roughly 180 acres within the Milford Mine Memorial Park.

*Minnesota Land and Colonization Reserve (H-41)*

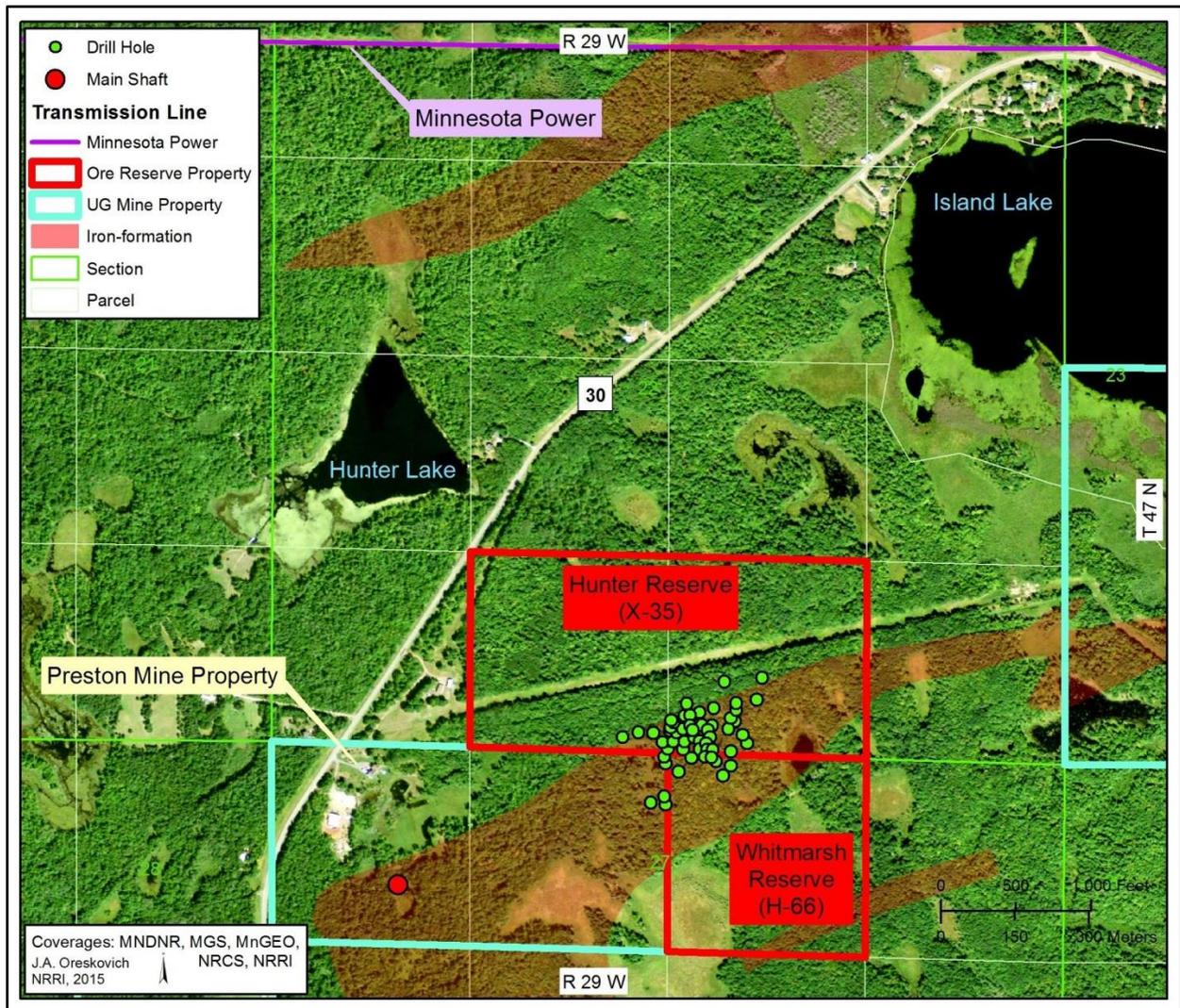
The Minnesota Land and Colonization Reserve (H-41) is located in the NE-SE and Lot 4 (SE-NE) of S23-T47-R29. Multiple drill holes are shown on this property in Figure 1.2-20. While not obtained for this study, ore reserve estimates were done on the Minnesota Land and Colonization Reserve in 1958 and 1963. These records are available with attendant data on microfilm at the MDOR office in Virginia, MN. Table 1.2-11 presents header information on the reserve property acquired from Beltrame (1977).

**Table 1.2-11.** Minnesota Land and Colonization Reserve (H-41) ore reserve estimate.

Ore Reserve Estimate <sup>1,2</sup>							
Property	Parcel	S	T	R	Data	Surface Owner <sup>3</sup>	Fee Owner
MN Land & Colonization Reserve (H-41)	NE-SE, Lot 4 (SE-NE)	23	47	29	X	Private	The Hanna Mining Company
Year	Type		Re-class	Recovery Factor	Tons	Density Factor	
1963					NA		

<sup>1</sup>Upper table information from Beltrame (1977), unless otherwise noted. Data consists of drill hole data, cross-sections, reserve estimates, etc. on microfilm at MDOR Minerals Tax Office in Virginia, MN.  
<sup>2</sup>Lower table information from MDOR Minerals Tax Office data files.  
<sup>3</sup>Data from MN DNR GIS coverage own\_mnstwdpy2 (2008).

Preston Mine



**Figure 1.2-21.** Preston Mine; Hunter and Whitmarsh Reserve properties.

Mine	Range	S	T	R	Parcel	UG	OP	ML	Shaft Sinking	Total Ore Shipped	Operator
Preston	North Range	27	47	29	NW-NW	X			1918	Shaft was later abandoned; no ore was mined	Coates and Tweed

The Preston mine property comprises two 40-acre parcels in a broadened part of the Trommald Iron Formation (Fig. 1.2-21). Grout and Wolff (1955) mapped this as a drag fold in the Preston orebody and indicated that it may be complicated by faulting. They further note that the width of the iron-formation here is likely due to folding and repetition of beds.

The Preston mine shaft was sunk in 1918 and it has been reported that the shaft was later abandoned with no ore mined (Schmidt, 1963). The mapped location of the shaft (Fig. 1.2-21)

was obtained from Schmidt's (1963) Plate 2. Schmidt reported searching for but finding no hoisted bedrock in the vicinity of the shaft. This could imply that the shaft never reached bedrock or that hoisted materials were later used to backfill the shaft. No indication of shaft depth has been found. The shaft likely resides in thin-bedded facies of the Trommald formation (Schmidt, 1963).

Ore reserve data for the Preston mine property (Preston Reserve (I-1)) obtained from MDOR is shown in Table 1.2-12. The ore was reclassified in 1986 using a recovery factor of 80% (high-recovery ore). Table 1.2-13 provides assay data from the 1986 ore reserve estimate.

**Table 1.2-12.** Preston Reserve (I-1) ore reserve estimate.

Ore Reserve Estimate <sup>1,2</sup>							
Property	Parcel	S	T	R	Data	Surface Owner <sup>3</sup>	Fee Owner
Preston Reserve (I-1)	NW-NW	27	47	29	X	Private	Inland Steel Co.
Year	Type	Re-class		Recovery Factor	Tons	Density Factor	
1986	UG Wash ore concentrate	X		80%	97,341	14	
	UG Mang. Wash ore concentrate	X		80%	85,657	14	
	<b>Total Tons:</b>				<b>182,998</b>		
1958	Merch ore				228,747		

<sup>1</sup>Upper table information from Beltrame (1977), unless otherwise noted. Data consists of drill hole data, cross-sections, reserve estimates, etc. on microfilm at MDOR Minerals Tax Office in Virginia, MN.  
<sup>2</sup>Lower table information from MDOR Minerals Tax Office data files.  
<sup>3</sup>Data from MN DNR GIS coverage own\_mnstwdpy2 (2008).

**Table 1.2-13.** Preston Reserve (I-1) assay data.

Assay Data <sup>1</sup>										
Dry									Natural	
Property	Type	Tons	Fe	P	Si	Mn	Al	Moist.	Fe	Mn
Preston Reserve (I-1)	UG WOC	97,341	60.10	0.090	5.00	1.90	9.0			
	UG WOC – Mang.	85,657	49.10	0.150	5.00	10.50	9.0			

<sup>1</sup>Source: MDOR data file.

### Hunter Reserve (X-35)

The Hunter reserve property consists of two forty-acre parcels, the SE-SW and SW-SE of S22-T47-R29. It abuts the Preston mine property and Whitmarsh reserve property to their north (Fig. 1.2-21). The ore reserve data is restricted to the SW-SE parcel.

The 1967 ore reserve estimate in Table 1.2-14 details the ore types and tonnages present on the property. The ores have been reclassified from the previous estimate done in 1962. Beneficiation data was listed as 10% rock reduction, 70% (Hi. Rec.) and 60% wash ore recovery for iron ore and 60% wash ore recovery for manganese ore.

**Table 1.2-14.** Hunter Reserve (X-35) ore reserve estimate.

Ore Reserve Estimate <sup>1,2</sup>							
Property	Parcel	S	T	R	Data	Surface Owner <sup>3</sup>	Fee Owner
Hunter Reserve (X-35)	SE-SW, SW-SE <sup>4</sup>	22	47	29	X	Private	Louise Hunter
Year	Type	Re-class		Recovery Factor <sup>5</sup>		Tons	Density Factor
1967	UG NB Hi Recovery Wash Ore Conc.	X		70%		81,936	
	UG NB Wash Ore Concentrate	X		60%		24,686	
	UG Mang. Wash Ore Concentrate	X		60%		36,103	
<b>Total Tons:</b>						<b>142,725</b>	
1962	NB Merch					129,956	
	Mang. Merch					19,543	
	NB Wash Ore Concentrate					27,086	
	Mang. Wash Ore Concentrate					28,145	
<b>Total Tons:</b>						<b>204,730</b>	

<sup>1</sup>Upper table information from Beltrame (1977), unless otherwise noted. Data consists of drill hole data, cross-sections, reserve estimates, etc. on microfilm at MDOR Minerals Tax Office in Virginia, MN.

<sup>2</sup>Lower table information from MDOR Minerals Tax Office data files.

<sup>3</sup>Data from MN DNR GIS coverage own\_mnstdwp2 (2008).

<sup>4</sup>Ore reserve data is for the SW-SE parcel.

<sup>5</sup>Recoveries were noted on ore reserve estimate as rock deduction (10%) and wash ore (70% and 60%).

Notes attached to the 1967 Hunter Reserve ore estimate state that: “A shaft would have to be sunk to a minimum depth of 500 feet to mine this ore since the ore dips steeply (75°) and extends 450 feet below the surface.” It is recommended that the ore be mined in conjunction with that of the Whitmarsh property to the south.

It is further noted that the ore is high in moisture and phosphorus. Assay data is provided in Table 1.2-15. While no assay data was available for alumina, the notes stated that alumina values in this area are typically greater than 2%. Washing reduces alumina, but at the expense of iron units.

**Table 1.2-15.** Hunter Reserve (X-35) assay data.

Assay Data <sup>1</sup>										
Dry									Natural	
Property	Type	Tons	Fe	P	Si	Mn	Al	Moist.	Fe	Mn
Hunter Reserve (X-35) SW-SE 1967	UG NB Hi-Rec WOC	81,936	61.83	0.224	5.50	0.25		10.00	55.64	
	UG NB WOC	24,686	58.00	0.200	8.00	0.38		10.00	52.20	
	UG Mang. WOC	36,103	50.66	0.148	8.77	8.29		10.00	45.59	7.46
Hunter Reserve (X-35) SW-SE 1962	NB Merch	129,956	61.33	0.214	5.75	0.23		16.00	51.52	
	Mang. Merch	19,543	51.61	0.168	7.00	8.71		10.00	41.67	7.06
	NB WOC	27,086	58.00	0.200	8.00	-		10.00	52.20	
	Mang. WOC	28,145	50.00	0.140	10.00	8.00		10.00	45.00	7.20

<sup>1</sup>Source: MDOR data file.

Notes attached to the 1962 ore reserve estimate indicate that an old exploration shaft was begun on the Hunter property that did not reach ledge. A Butler Bros. map of the Hunter-Whitmarsh properties found at MN DNR shows what appear to be two such structures. One is located in the Hunter property while the other straddles the property line between the Hunter and Whitmarsh properties.

### Whitmarsh Reserve (H-66)

The Whitmarsh reserve (NW-NE S27-T47-R29) lies directly east of the Preston mine property and directly south of the Hunter reserve (Fig. 1.2-21). As indicated in the ore reserve estimate in Table 1.2-16, the ores were reclassified in 1986 from those shown in 1967. Beneficiation data (rock reduction and recovery rate) were not provided, but is likely similar to that of the Hunter reserve. Assay data for the Whitmarsh reserve is provided in Table 1.2-17.

Notes attached to the 1962 ore reserve estimate indicated that the Whitmarsh ore lies “in close proximity to the Hunter property line and several orebodies cross the line and are on both properties.” It is further noted that the ore occurs in narrow seams approximately 125 feet below surface.

**Table 1.2-16.** Whitmarsh Reserve (H-66) ore reserve estimate.

Ore Reserve Estimate <sup>1,2</sup>								
Property		Parcel	S	T	R	Data	Surface Owner <sup>3</sup>	Fee Owner
Whitmarsh Reserve (H-66)		NW-NE	27	47	29	X	Private	The Hanna Mining Company
Year	Type		Re-class		Recovery Factor		Tons	Density Factor
1986	UG NB Hi Recovery Wash Ore Conc.		X				65,500	
	UG Mang. Wash Ore Concentrate		X				89,400	
	<b>Total Tons:</b>						<b>154,900</b>	
1962	UG NB Merch Ore						68,572	
	UG Mang. Merch Ore						91,086	
	UG NB Wash Ore Concentrate						24,823	
	UG Mang. Wash Ore Concentrate						35,589	
<b>Total Tons:</b>						<b>220,070</b>		

<sup>1</sup>Upper table information from Beltrame (1977), unless otherwise noted. Data consists of drill hole data, cross-sections, reserve estimates, etc. on microfilm at MDOR Minerals Tax Office in Virginia, MN.

<sup>2</sup>Lower table information from MDOR Minerals Tax Office data files.

<sup>3</sup>Data from MN DNR GIS coverage own\_mnstdwp2 (2008).

<sup>4</sup>Ore reserve data is for the SW-SE parcel.

**Table 1.2-17.** Whitmarsh Reserve (H-66) assay data.

Assay Data <sup>1</sup>										
Dry									Natural	
Property	Type	Tons	Fe	P	Si	Mn	Al	Moist. <sup>2</sup>	Fe <sup>2</sup>	Mn <sup>2</sup>
Whitmarsh Reserve (H-66)	UG NB Merch	68,572	58.64	0.152	7.70	0.71		16.00	49.26	0.60
	UG Mang. Merch	91,086	43.46	.0190	8.61	10.57		16.00	36.51	8.88
	UG NB WOC	24,823	56.37	0.102	8.72	1.03		8.00	51.86	0.95
	UG Mang. WOC	35,589	41.28	0.240	9.00	15.49		8.00	37.98	14.25

<sup>1</sup>Source: MDOR data file.  
<sup>2</sup>Assumed.

*CAES Potential for Cuyuna North Range Area 2: Milford and Preston Mines; Minnesota Land and Colonization, Hunter and Whitmarsh Reserves*

Figures 1.2-22 through 1.2-25 illustrate the base map, hydrography, elevation, and surface ownership features of Cuyuna North Range Study Area 2. This is a region that is sparsely populated to unpopulated in the vicinity of the mine and ore reserve properties, particularly over the subcrop of the iron-formation (Fig. 1.2-22).

There is road access to the mine and reserve properties via state and county highways MNTN 6 and CSAH 30. A major Minnesota Power transmission line lies to the north within 0.25 to 1.0 mile of the iron-formation subcrop within the properties. An old railroad grade runs east-northeast to the north of the iron-formation in the Hunter reserve property.

The Milford Mine Memorial Park and the National Park Service-designated Milford Mine Historic District are outlined in Fig. 1.2-22. The Historic District lies within the confines of the park. The apparent discrepancy is explained by the GIS coverages used to plot the two boundaries. The park boundaries were digitized to Crow Wing County PLS whereas the Historic District, as well as the mine and ore reserve properties, were digitized to the MN DNR PLS derived from topo maps. The Park and Historic District would be unavailable for CAES development.

Wetlands impact the Minnesota Land and Colonization (MLC) reserve and the Milford Mine area while having little impact in the Preston Mine and Hunter and Whitmarsh reserves relative to the iron-formation (Fig. 1.2-23). Much of the area drilled in the MLC is surfaced with saturated scrub shrub or forested wetlands. A perennial stream runs northward through the MLC reserve into the northeastern tip of Milford (Foley) Lake. The Milford Mine area has seasonally flooded scrub shrub wetlands near the mine.

The Hunter and Whitmarsh reserves have three minor wetlands mapped in the vicinity of the extensive drilling shown that range in size from 0.21 to 0.33 acres in size. These are saturated scrub shrub wetlands. There is a saturated emergent wetland 0.28 acre in size near the Preston mine shaft.

There is little to slight elevation change in the immediate areas of shafts and drill holes in Study Area 2, with the exception of some stockpiles near the Milford mine (Fig. 1.2-24). Other than the state-owned Milford mine property, the surface is privately owned in each of the mine

and reserve properties in Study Area 2 (Fig. 1.2-25). The MLC reserve abuts state property to the south and west.

Positives:

- There are four unmined ore reserves (including the Preston Mine) in Study Area 2;
- The region is sparsely populated;
- There is a major Minnesota Power transmission line within 1 mile to the north.
- There is road access to the properties via MNTH 6 and CSAH 30;
- An old railroad grades runs north of the iron-formation through the Hunter reserve;
- There is little wetland impact on the Preston, Hunter, and Whitmarsh properties; and
- There is state land adjacent to the MLC reserve.

Negatives:

- The Milford Mine is unavailable because it is part of the Milford Mine Memorial Park and the Milford Mine Historic District;
- The MLC reserve is impacted by saturated wetlands; and
- A perennial stream cuts across the iron-formation through the drilled area of the MLC reserve.

CAES Potential for Cuyuna North Range Area 2: Preston Mine; Hunter and Whitmarsh Reserves

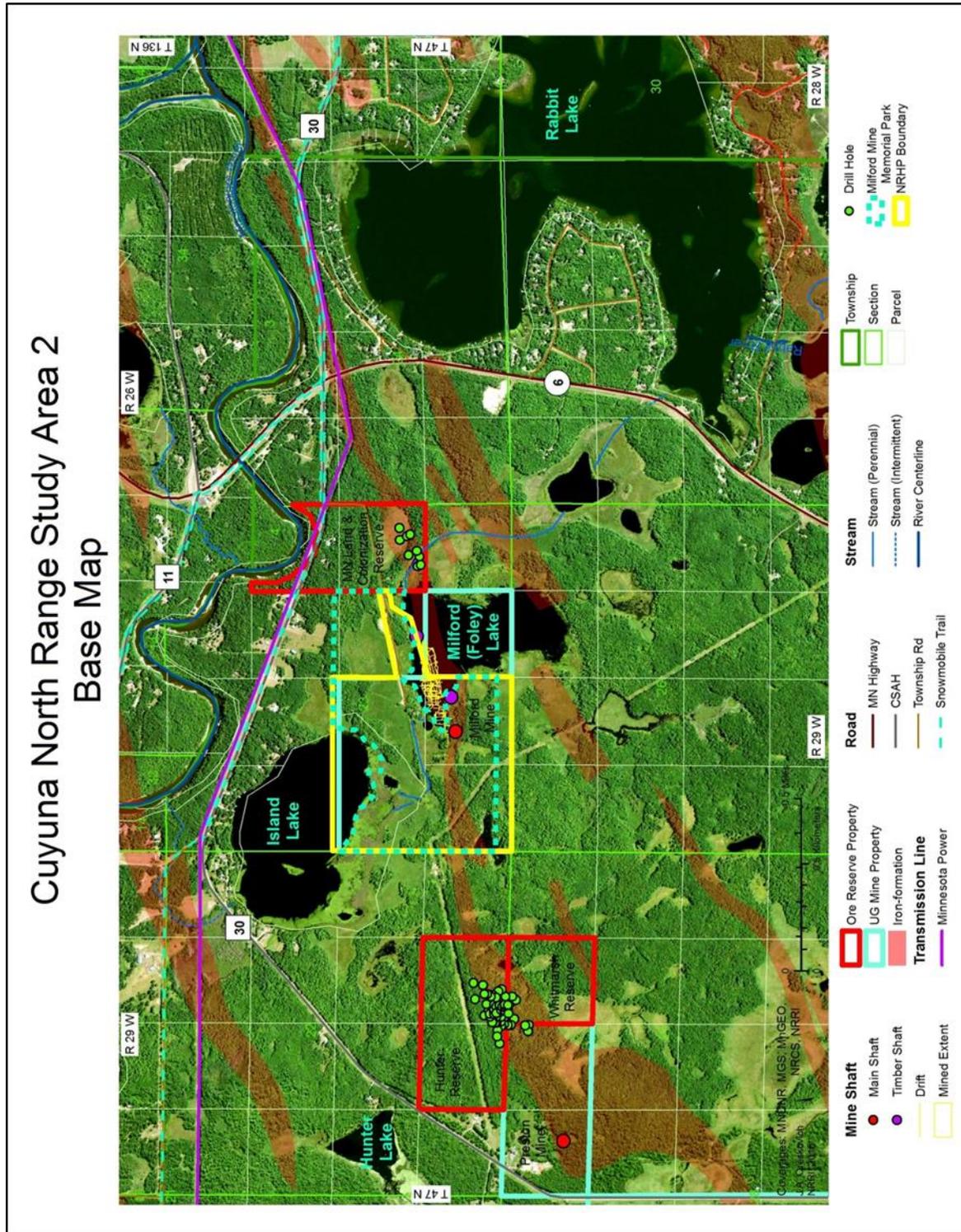


Figure 1.2-22. Cuyuna North Range Study Area 2 base map.

## Cuyuna North Range Study Area 2 Hydrography Map



Figure 1.2-23. Cuyuna North Range Study Area 2 hydrography map.

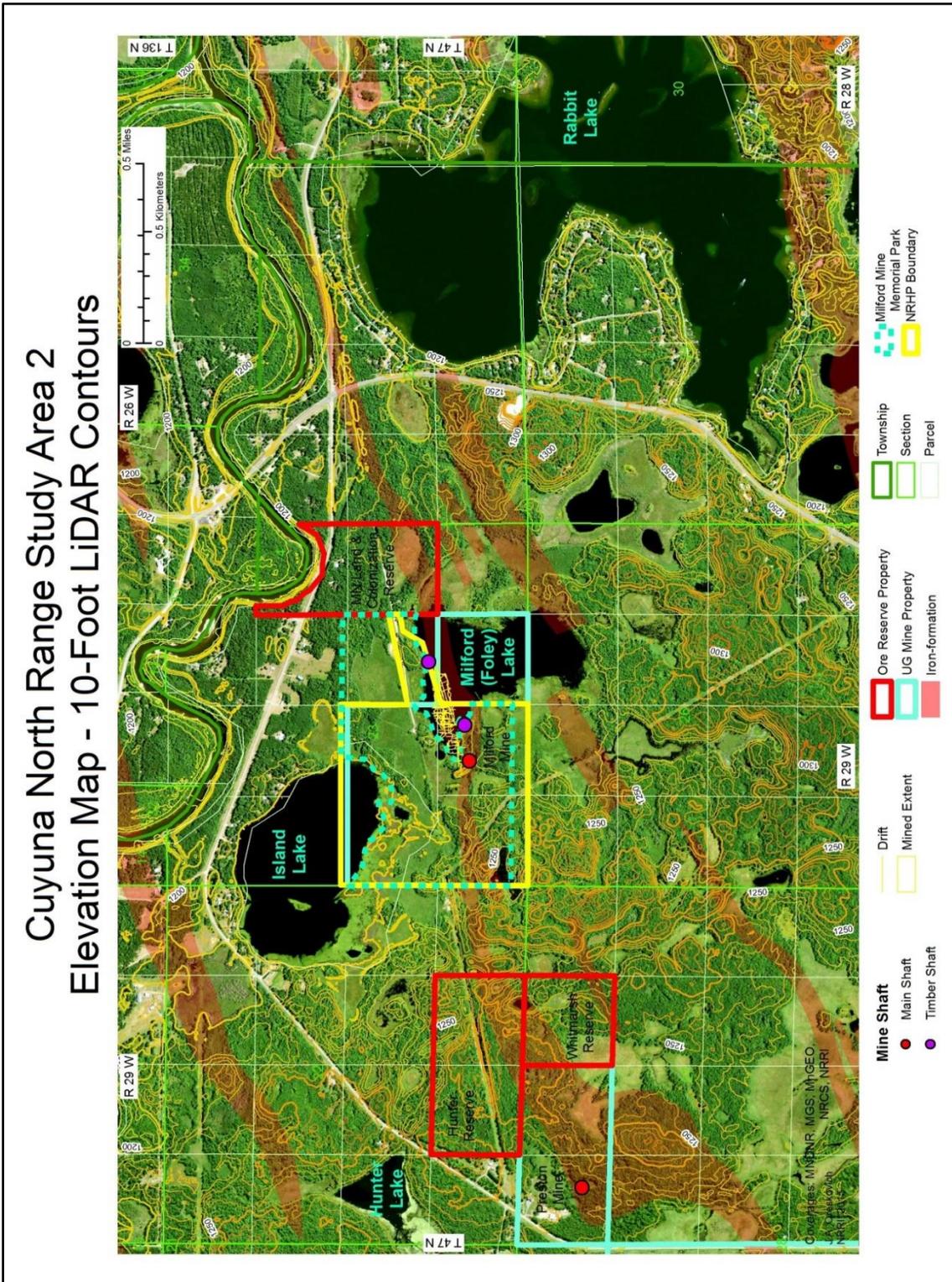


Figure 1.2-24. Cuyuna North Range Study Area 2 elevation map: 10-foot LiDAR contours.

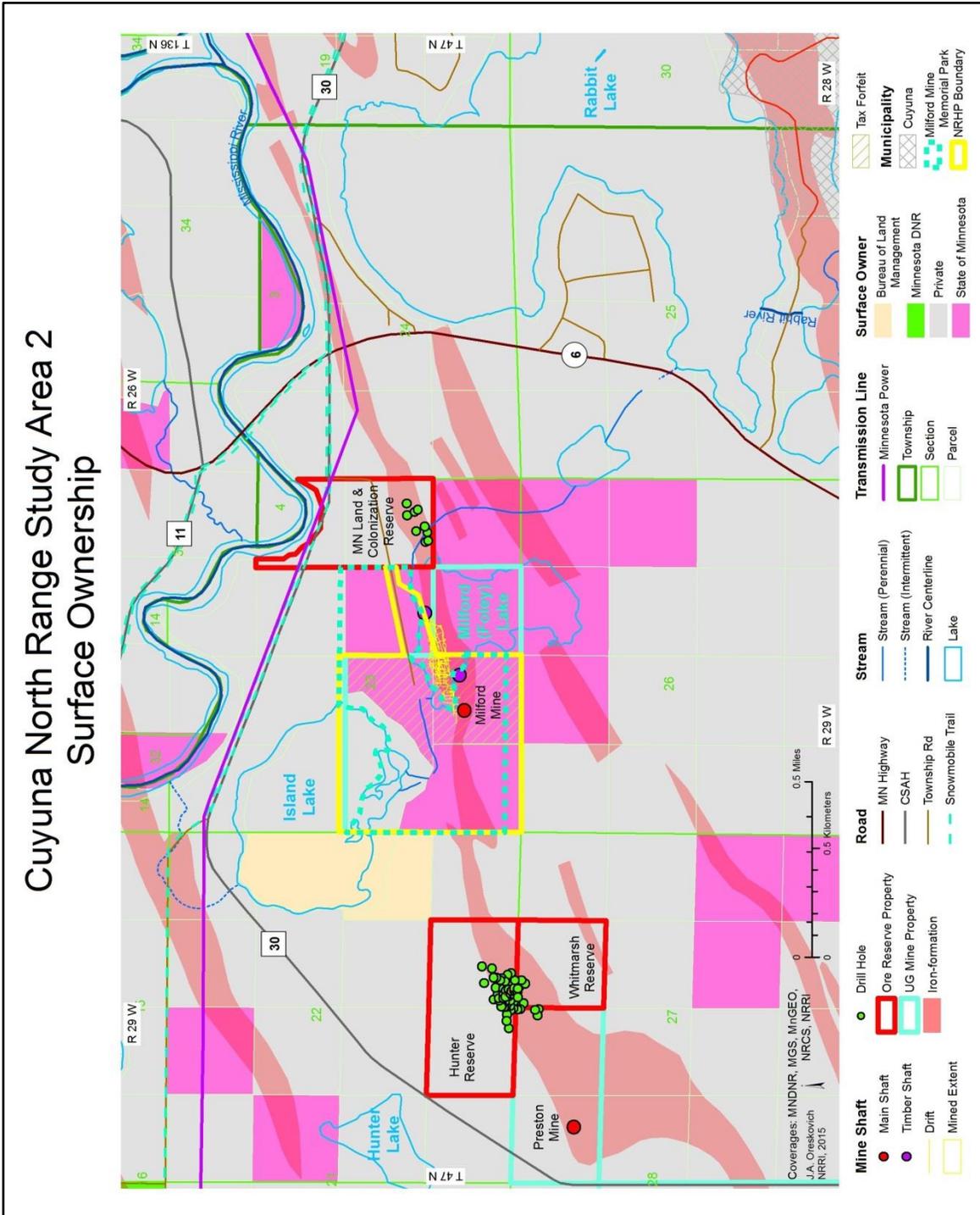


Figure 1.2-25. Cuyuna North Range Study Area 2 surface ownership map.

Cuyuna North Range Study Area 3

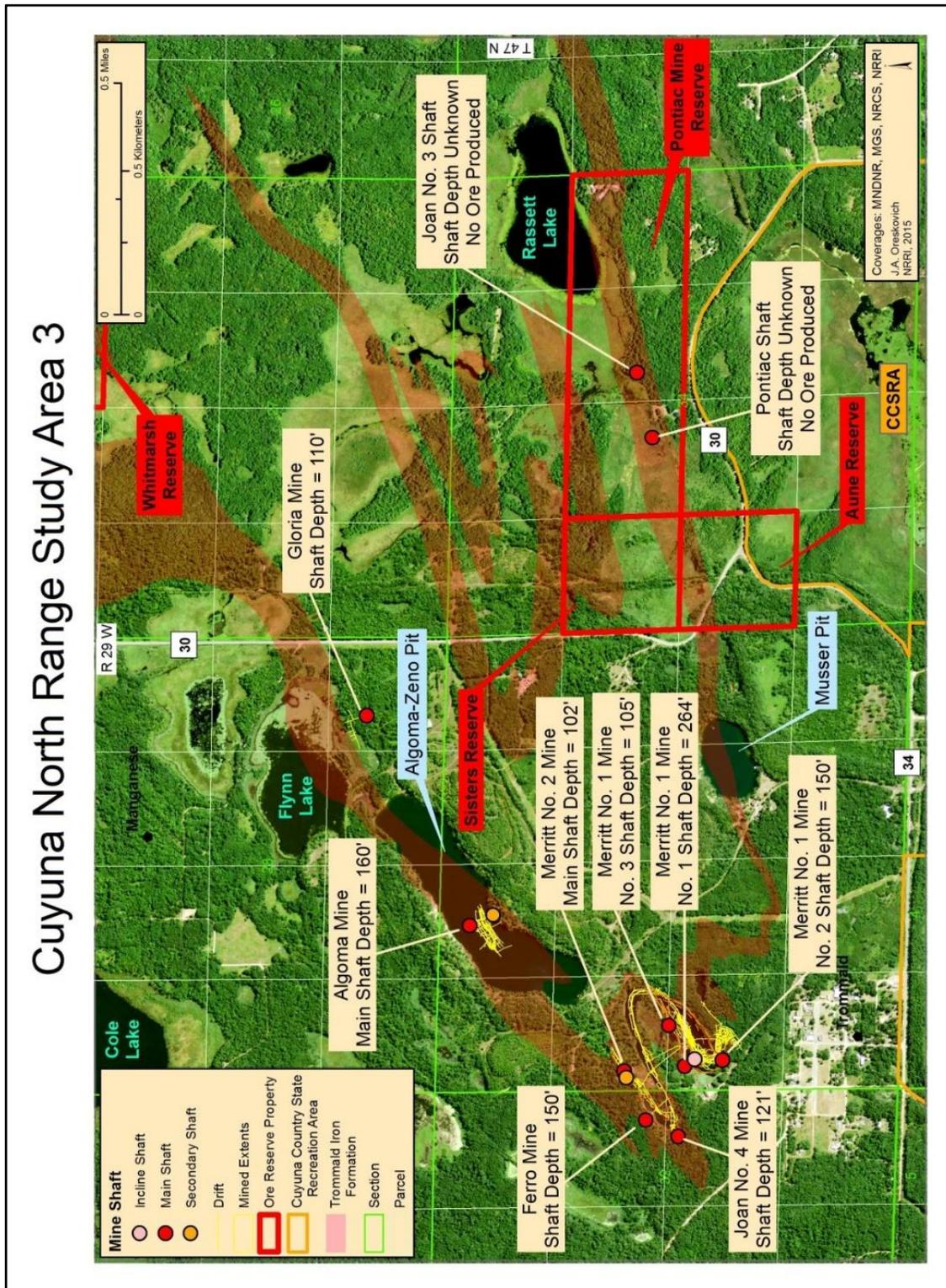
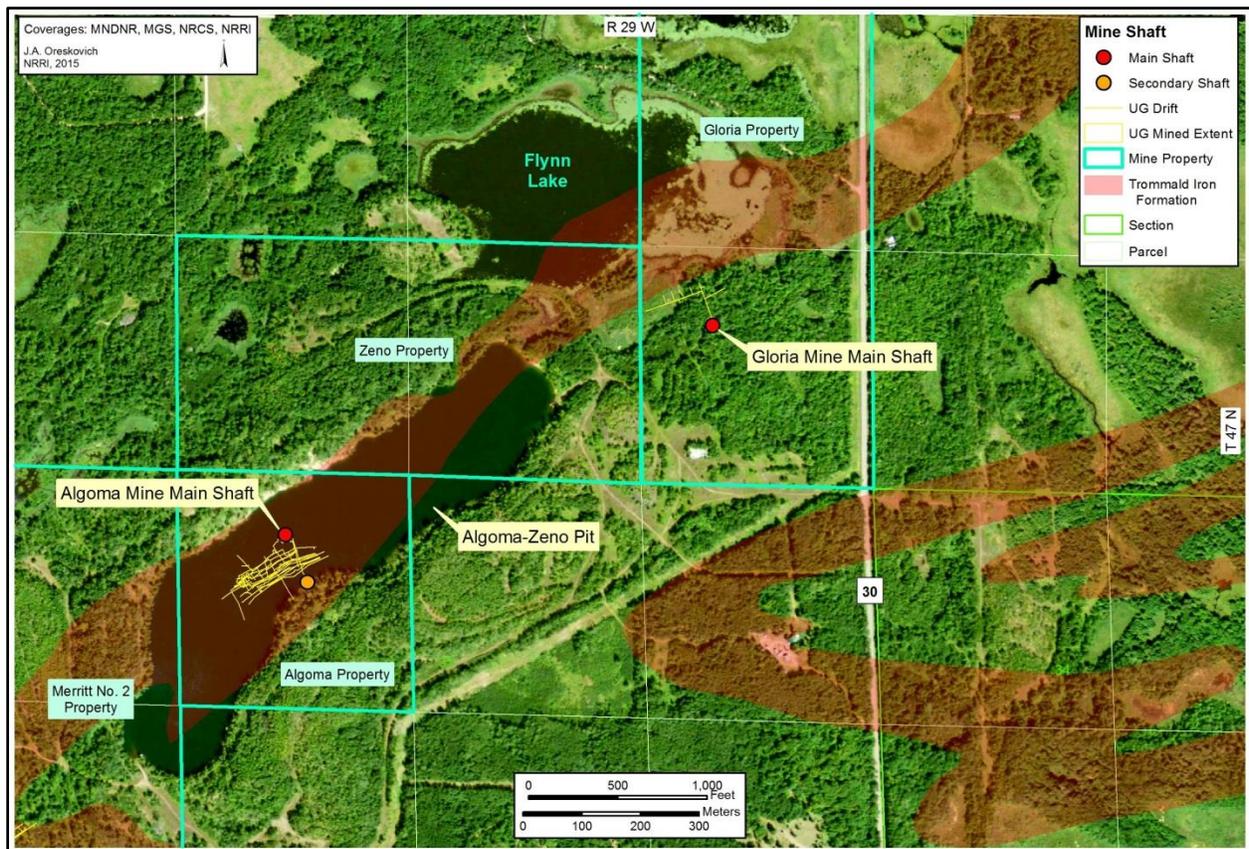


Figure 1.2-26. Cuyuna North Range Study Area 3: Gloria, Algoma, Merritt Nos. 1 and 2, Ferro, Pontiac, and Joan Nos. 3 and 4 mines; Aune and Sisters Reserves.

The mines in Study Area 3 are addressed along the trend of the iron-formation from northeast to southwest, and then around the fold and back to the east. These mines form the heart of the manganese district on the Cuyuna North Range; hence, the now ghost town of Manganese is shown in Figure 1.2-6. Only the foundations of former homes remain today.

The Gloria and Algoma mines (Fig. 1.2-27), together with the Ferro and Merritt mines to the south, were identified as high manganese mines by Schmidt (1963). The Ferro, Joan No. 4, Merritt No. 1, and Merritt No. 2 mines, located in separate parcels (Fig. 1.2-28) and begun by three separate entities, are closely grouped and interconnected in drag folds on the keel of the broad synclinal structure of the Cuyuna North Range ( $S_1$  in Fig. 1.2-5). The structure of these mines, designated the Merritt Group, is a synclinorium that plunges  $60^\circ$  to the northeast (Grout and Wolff, 1955). The trace of the orebody is reflected on the surface in ponded waters caused by surface stripping (Merritt No. 1 mine) and surface subsidence due to caving. Mine maps indicate that the surface was stripped above the Merritt No. 1 workings, but there is no mention of open pit mining or milling in the literature.



**Figure 1.2-27.** Gloria and Algoma mine sites. The Algoma orebody was subsequently mined by open pit methods in conjunction with the Zeno orebody.

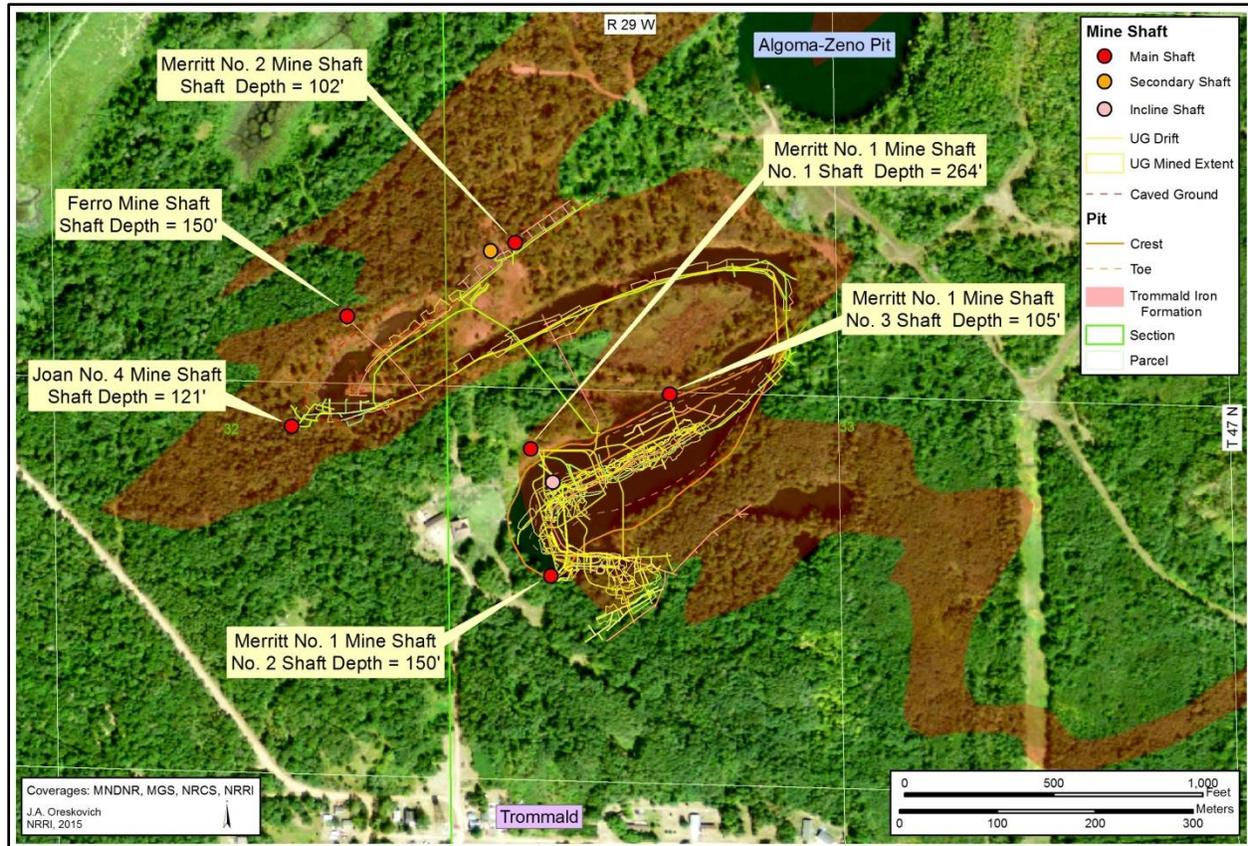


Figure 1.2-28. Ferro, Joan No. 4, and Merritt Nos. 1 and 2 mine sites.

Gloria Mine

Gloria Mine										
Former Name	S	T	R	Parcel	UG	OP	ML	Shaft Sinking	First Shipment	Last Shipment
Donahue, McKenzie	28	47	29	E1/2-SE & SE-NE	X			1916	1919	1920:from stkpl in 1931
Mine Depth (Ft.)	Drifts		Ore Shipped (LT)		Last Operator		Last Known Fee			
110	100-Ft. Level		2,074		Gloria Mining Co.		Lauretta Manganiferous Mines; State			
Shaft: 3-compartment; concrete to ledge										

The Gloria mine began with shaft sinking in 1916 (Schmidt, 1963). A map found notes that the drifts shown are at the 100-foot level. Schmidt placed the Gloria shaft near the middle or top of the thick-bedded facies of the Trommald Formation.

According to a MDOR 1963 ore estimate report, the Gloria mine shaft has been caved. This same report indicates that there is a small tonnage of underground ore remaining that is high in silica and manganese and that a new shaft would be required to retrieve it. An older (1958) ore reserve estimate states, “There is no minable ore on the Gloria because streaks are thin and have

no continuity.” It also notes that the 2,074 tons of ore produced apparently came from the drifting that was done.

### Algoma Mine

Algoma Mine										
Former Name	S	T	R	Parcel	UG	OP	ML	Shaft Sinking	First Shipment	Last Shipment UG
Iron Mtn, Hoch	33	47	29	NE-NW	X	X		1911-1912; 1913	1913	1920; 1931 from stockpile
Overburden (Ft.)	UG Mine Depth (Ft.)			Top Level	Bottom Level		Shaft	Mining Method		
110	160			80-Ft. Level	160 Ft.		Lath Shaft	Top-slicing; overhand stoping; square setting		
OP Mine Name	Last Shipment OP			Total Ore Shipped UG & OP (LT)			Last Operator		Last Known Fee	
Algoma-Zeno	1984			1,246,696			Pittsburgh Pacific Co.		Gorham-Garbett Co.	

The Algoma mine shaft was sunk in 1911 (Schmidt, 1963), five years prior to the Gloria shaft. The orebody in the underground workings was described by Schmidt as “a series of four thin manganese-rich lenses parallel to the bedding of the enclosing iron-formation,” ranging from 4 to 30 feet thick. Separating the lenses were 4- to 35-foot-thick ferruginous chert zones. Mining occurred along strike for 300 to 400 feet; depth was to the 160-foot level. Two mining methods were used in the underground workings: top slicing and overhand stoping with square-setting (Schmidt, 1963).

Two shafts were found on maps and are shown in Figure 1.2-27. One of these was noted as the No. 3 shaft, indicating the presence of an additional shaft not shown in the figure. Subsequent to Schmidt’s report, the Algoma shafts and underground workings were removed by open-pit mining in conjunction with the Zeno properties to the north. The orebody on the Algoma property appears mined out, with a combined total of nearly 1.25 MT of ore shipped from the underground and open pit mine workings.

### Ferro Mine

Ferro Mine										
Former Name	S	T	R	Parcel	UG	OP	ML	Shaft Sinking	First Shipment	Last Shipment
Duluth-Brainerd	32	47	29	SE-NE	X			1913, 1915	1915	1944
Overburden (Ft.)	UG Mine Depth (Ft.)			Top Level	Bottom Level		Total Ore Shipped (LT)	Last Operator	Last Known Fee	
55-60	157				149-Ft. Level		181,307	Hanna	Lange, R.J.	

The Ferro mine was the first of four closely-grouped operations (Fig. 1.2-28) to open (1913). It operated from 1916 to 1921, after which it was idled until 1942 when it was operated for two years by Butler Bros., apparently through the Merritt mine (Schmidt, 1963).

The Ferro shaft is located in the footwall of the orebody (Harder and Johnston, 1918). Schmidt places the Ferro orebody in the bottom of a syncline that is part of a group of drag folds. The shaft is located northwest of the drag fold axis. The orebody dips steeply from approximately 65° southeast to vertical, paralleling the bedding of the iron-bearing rocks (Harder and Johnston, 1918). Ore was produced from one distinct layer that ranged from 40 to 80 feet thick, with much of the layer around 45 feet thick (Schmidt, 1963).

Documents and a map indicate a cross-cut from the shaft to the orebody at a depth of 149 feet that is the main haulage level, according to Harder and Johnston (1918), who reported current (1918) workings at a depth of 75 feet. Only two maps were found depicting the Ferro workings, and little detail is shown. The shaft appears as a 2-compartment shaft. Harder and Johnston (1918) also mention a timber shaft that is 157 feet deep, but that shaft was not shown.

The maps show a drift at a depth of 238 feet extending from the adjacent Merritt No. 2 mine and looping through the Ferro and adjacent Joan No. 4 mine to the south before swinging back into the Merritt No. 2 property (Fig. 1.2-28). This drift appears to be of later vintage, possibly the Butler Bros. workings in the 1940s. There is no apparent connection to the higher level workings in the original Ferro mine.

The 1963 Ferro Mine ore reserve estimate from MDOR notes that the Ferro shaft is caved and the workings are no longer accessible. It describes the remaining identified orebody as three narrow seams of manganiferous iron material (MDOR data file). The tonnage is “so small and discontinuous that it is not economically mineable under present conditions.” Tonnages and assay data from 1963 and 1958 are provided in Table 1.2-18.

**Table 1.2-18.** Ferro Mine assay data.

Assay Data <sup>1</sup>										
Dry									Natural	
Property	Type	Tons	Fe	P	Si	Mn	Al	Moist.	Fe	Mn
Ferro Mine 1963	Crude mang. iron	25,893	30.8	0.063	11.3	23.2				
Ferro Mine 1958	UG merch iron	13,000							45.64	
	UG mang. WOC	12,700							46.00 <sup>2</sup>	

<sup>1</sup>Source: MDOR data file.  
<sup>2</sup>Combined natural iron and manganese content.

Joan No. 4 Mine

Joan No. 4 Mine										
Former Name	S	T	R	Parcel	UG	OP	ML	Shaft Sinking	First Shipment	Last Shipment
	32	47	29	NE-SE	X			1917	1917	1944 from stkpl
Shaft Type	UG Mine Depth (Ft.)			Top Level	Bottom Level	Total Ore Shipped (LT)		Last Operator	Last Known Fee	
2-compartment	121			91-Ft. Level	121-Ft. Level	59,430		Butler Bros.	Swanson, Jesse L., et al.	

The Joan No. 4 mine lies directly south of the line separating the Ferro and Joan No. 4 properties (Fig. 1.2-28). A composite map found at MDOR shows drifting on main levels at 91 and 121 feet and sub-levels at 101 and 111 feet.

The Joan No. 4 mine opened in 1917 and ore was shipped through 1920 (Skillings Mining Review, 2005). Schmidt (1963) notes that Butler Bros. mined ore from the Joan No. 4 mine in 1943, probably through the Merritt mine. Grout and Wolff (1955) write that the northeast-plunging syncline of Upper Cherty member (reference to the Biwabik Iron Formation of the Mesabi Range) in the Joan No. 4 property yielded some of the highest grade manganese ore in the Cuyuna District.

According to the 1963 Joan No. 4 mine ore reserve estimate, the property is considered exhausted (MDOR data file). The 1958 estimate notes that 5,700 tons of underground merchant manganese remains, but the ore is discontinuous, making it uneconomical to mine under present conditions. The natural combined iron and manganese content for the remaining tonnage is 44.64% (Table 1.2-19).

**Table 1.2-19.** Joan No. 4 Mine assay data.

Assay Data <sup>1</sup>										
Dry									Natural	
Property	Type	Tons	Fe	P	Si	Mn	Al	Moist.	Fe	Mn
Joan No. 4 1963	UG merch mang.	5,700							44.64 <sup>2</sup>	

<sup>1</sup>Source: MDOR data file.  
<sup>2</sup>Combined natural iron and manganese content.

Merritt No. 1 and Merritt No. 2 Mines

Merritt No. 1 Mine											
Former Name	S	T	R	Parcel	UG	OP	ML	Shaft Sinking	First Shipment	Last Shipment	
	33	47	29	NW-SW	X			1916	1917	1961	
Shaft Type	UG Mine Depth (Ft.)		Top Level	Bottom Level	Total Ore Shipped (LT)	Last Operator	Last Known Fee				
4-compartment	264		80-Ft. Level	284-Ft. Level	626,469	Pittsburgh Pacific Co.	State				
Mining Method: top-slicing and caving											
Merritt No. 2 Mine											
Former Name	S	T	R	Parcel	UG	OP	ML	Shaft Sinking	First Shipment	Last Shipment	
	33	47	29	W1/2-NW	X			Oct. 1916	1918	1967	
Shaft Type	UG Mine Depth (Ft.)		Top Level	Bottom Level	Total Ore Shipped (LT)	Last Operator	Last Known Fee				
4-compartment	238		80-Ft. Level	238-Ft. Level	418,949	Hanna	Gorham-Garbett Co.				
Mining Method: top-slicing and caving											

Shaft sinking for both the Merritt No. 1 and Merritt No. 2 mines (Fig. 1.2-28) began in 1916 (Aulie and Johnson, 2002). Ore was first shipped from the No. 1 mine in 1917, followed by the No. 2 mine in 1918 (Skillings Mining Review, 2005). Ore was produced intermittently from these properties from 1917 to 1943 (Schmidt, 1963).

Butler Bros. operated both of these underground mines from 1938 to 1943 for high manganese ore production according to a letter from The M.A. Hanna Company to the School of Mines at the University of Minnesota dated June 25, 1956 (MDOR data file). The Hanna letter describes the ore zones as “nearly vertical and narrow for the most part, and inclined and erratic in some instances.”

The letter goes on to say that some of the old drill holes “indicate substantial footages of iron grade ore,” but the drill hole data available at the time was insufficient to “intelligently establish realistic widths for vertical or inclined ore zones which could conceivably be mined by underground methods.” To do so would require a large amount of angle drilling.

Both of the Merritt mines were operated by the top-slicing and caving method (Schmidt, 1963). Maps show the mines were worked from depths of 80 feet to 238 feet (Merritt No. 2) and 264 feet (Merritt No. 1). Schmidt (1963) notes that an inclined shaft located on the Merritt No. 1 property was used to remove ore from both mines (also from the Ferro and Joan No. 4). Based on maps obtained, the surface material above the Merritt No. 1 underground workings was stripped off and an incline shaft was developed during the latter part of the 1920s. The last shipments of ore were made from the Merritt No. 1 mine in 1961 and the Merritt No. 2 mine in 1967 (Skillings Mining Review, 2005).

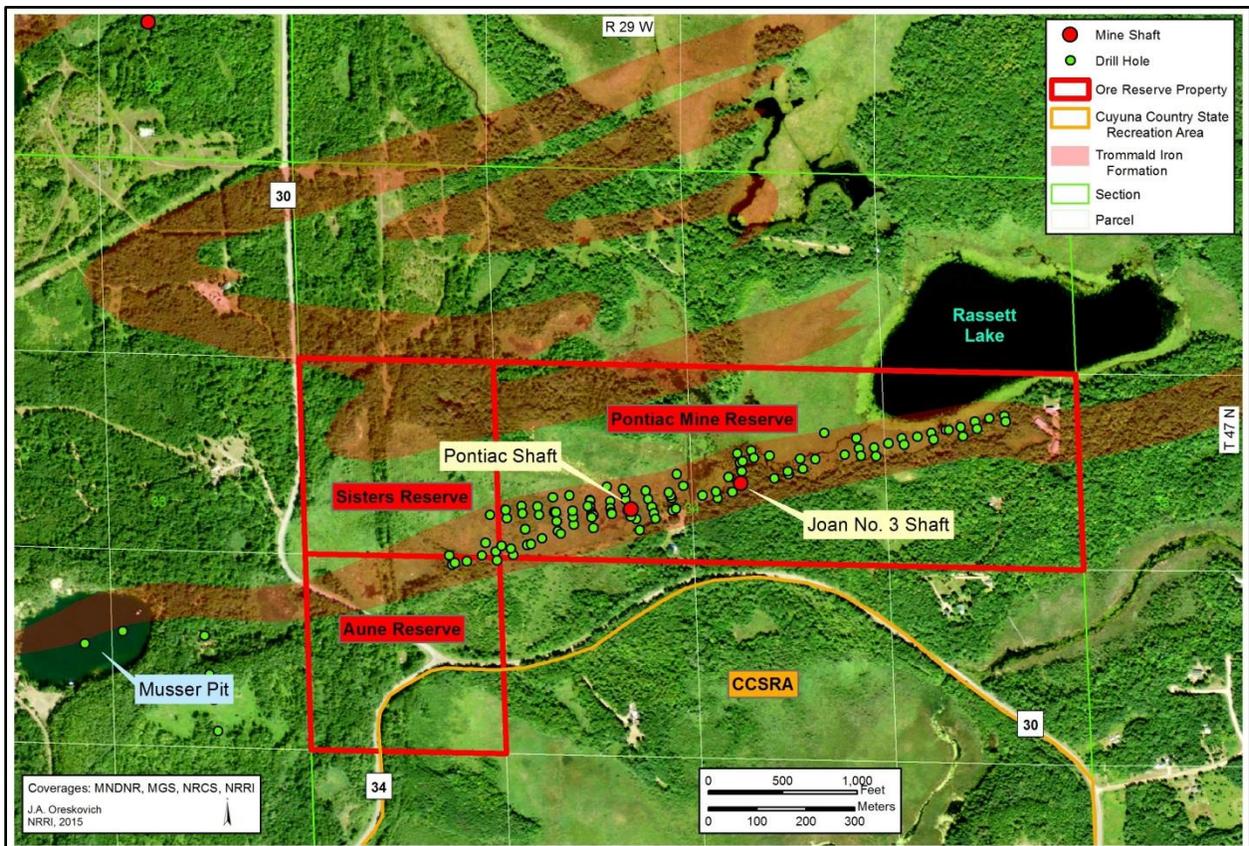
Table 1.2-20 provides tonnages and assay data on remaining ore for the Merritt No. 1 and Merritt No. 2 properties. The 1963 ore reserve estimate for the Merritt No. 1 mine states that

the shaft has caved and the drifts are flooded, requiring re-timbering prior to any further use (MDOR data file).

**Table 1.2-20.** Merritt Mines assay data.

Assay Data <sup>1</sup>										
Dry									Natural	
Property	Type	Tons	Fe	P	Si	Mn	Al	Moist.	Fe	Mn
Merritt No. 1 1963	UG Wash Iron	84,800	56.37	0.096	10.00	0.80		8.00		
	UG Wash Mang.	61,000	42.09	0.075	10.30	15.00		8.00		
	Total Tons:	145,800								
Merritt No. 2 1958	UG Merch Mang.	50,187							45.70 <sup>2</sup> (17.06 <sup>3</sup> )	

<sup>1</sup>Source: MDOR data file.  
<sup>2</sup>Combined natural iron and manganese content.  
<sup>3</sup>Natural silica.



**Figure 1.2-29.** Pontiac and Joan No. 3 shaft locations; Pontiac Mine, Sisters, and Aune ore reserve properties.

Pontiac and Joan No. 3 Mines (Pontiac Mine Reserve)

Mine	Former Name	S	T	R	Parcel	UG	Shaft Sinking	Last Operator	Last Known Fee
Pontiac	Clark	34	47	29	SE-NW; S1/2-NE	X	1918	The Hanna Mining Co. (?)	NA
Joan No. 3		34	47	29	(SW-SE)	X	1916-1917	The Hanna Mining Co. (?)	NA

According to Beltrame (1977), the Pontiac mine property comprises the S1/2-NE, NW-NE, N1/2-NW, SE-NW, and NE-SW of S34-T47-R29. The Pontiac mine shaft and Pontiac ore reserves are confined to the SE-NW and S1/2-NE parcels (Fig. 1.2-29). Only this portion of the Pontiac property is addressed here.

The Pontiac mine originated as the Clark mine, with a shaft sunk in April, 1918 (Aulie and Johnson, 2002). MN DNR and MDOR maps show a 3-compartment shaft (Pontiac Shaft in Figure 1.2-29) in the Clark property (SE-NW S34, T47N, R29W). Shaft depth was not provided. Schmidt (1963) reported that the mine was abandoned because it wasn't ready to produce by the end of World War 1.

The mine name was changed to the Pontiac mine in 1925. While it was reported that there were no shipments of ore from the Pontiac mine (Aulie and Johnson, 2002), undated notes were found at MDOR that included material classified as "stocked in 1925" (Table 1.2-19) as part of the total Clark and Joan No. 3 ore reserve estimated tonnage (MDOR data files).

The Joan No. 3 mine shaft was sunk in December, 1916 (Aulie and Johnson, 2002). MN DNR and MDOR maps portray the Joan No. 3 shaft as a one compartment shaft. No ore was shipped from the Joan No. 3 mine. It became part of the Pontiac mine property in 1928 (Aulie and Johnson, 2002).

The Pontiac (Clark) and Joan No. 3 mine properties, together with the parcel in the SE-NE 34-47-29, comprise the Pontiac Reserve (Fig. 1.2-29). The Pontiac reserve resides on one continuous limb of iron-formation with the Sisters and Aune reserves to the west and southwest. The orebody extends under Rasset Lake on the east side of the property while a wet swamp covers the remainder of the property (MDOR data files).

Ore on the Pontiac, Sisters, and Aune reserve properties occurs in steeply-dipping, thin, discontinuous lenses or seams according to MDOR data file notes. On the Pontiac properties, these lenses of ore range from 15 to 40 feet wide and from 100 to 180 feet in depth. Reference is made to two iron ore layers and three manganiferous ore layers on the Clark-Joan No. 3 properties. Mine levels were designed at 125, 135, 145, 155, 165, 175, 185, and 200 feet. Surface ranges from 60 to 80 feet thick (MDOR data files).

Despite the lack of any reported shipments, there are notes referencing drifting, slicing, and a contract crew working on the 165-foot level of the Clark-Joan No. 3 properties. Recommendation was made to abandon further advance on the 165-foot level and "to drift under the ore now developed on the 200 ft. level starting the drift just north of Raise No. 226." The notes state that doing so would "make it possible to mine the ore now cut up by No. 4 Contract" (MDOR data files).

Reference is also made to producing ore the following year at something like the present rate. The tonnage factor used in prepared ore estimates for the property was to be checked against that obtained from the ore volume removed in slices and the tonnage shipped “this month.” Lastly, it was noted that, due to the weight obtained throughout the mine, the 200-foot level would require a large amount of retrimbering the present year (MDOR data files).

The above mining-related paragraphs warrant further investigation for verification as they appear to contradict other sources. More details, including drill hole data, cross-sections, and potential mine plans, should be available on microfilm at the MDOR offices in Virginia, MN. If these notes hold true for the Pontiac reserve property, there may be potential for CAES.

An undated Hanna Mining Co. surface map of the Pontiac mine found at MDOR shows drill hole locations along the northeast trend of the iron-formation through the Pontiac, Sisters, and Aune reserve properties. The drill holes shown in Figure 1.2-29 were digitized from this map. Included on the Hanna map was the design of a pit roughly 850 feet by 300 feet centered on the Pontiac mine shaft.

The Pontiac mine ore reserve estimate for the three parcels as of January 2, 1970, is provided in Table 1.2-21. There is a significant ore tonnage indicated. Assay data are provided in Table 1.2-22.

**Table 1.2-21.** Pontiac Mine ore reserve estimate.

Ore Reserve Estimate <sup>1,2</sup>							
Property	Parcel	S	T	R	Data	Surface Owner <sup>3</sup>	Fee Owner
Pontiac	SE-NW & S1/2-NE	34	47	29	X	Private	The Hanna Mining Company
Year	Type	Re-class		Recovery Factor		Tons	Density Factor
1970	UG Mang. Direct Shipping Ore					235,925	
	UG Iron WOC					20,296	
	UG Mang. Heavy Media Conc.					268,458	
Total Tons:						524,679	
<sup>1</sup> Upper table information from Beltrame (1977), unless otherwise noted. Data consists of drill hole data, cross-sections, reserve estimates, etc. on microfilm at MDOR Minerals Tax Office in Virginia, MN. <sup>2</sup> Lower table information from MDOR Minerals Tax Office data files. <sup>3</sup> Data from gis.co.crow-wing.mn.us (2015).							

**Table 1.2-22.** Pontiac Mine Reserve assay data.

Assay Data <sup>1</sup>										
Dry									Natural	
Property	Type	Tons	Fe	P	Si	Mn	Al	Moist.	Fe	Mn
Pontiac SE-NW & S1/2-NE	UG Mang. Direct Shipping Ore	235,925	32.50	0.090	15.56	19.33	1.5	10	29.25	17.39
	UG Iron WOC	20,296	58.02	0.140	6.86	2.79	1.5	8	53.37	2.56
	UG Mang. Heavy Media Conc.	268,458	32.72	0.090	17.26	17.86	1.5	10	29.44	16.16
<sup>1</sup> Source: MDOR data file.										

Sisters Reserve

The Sisters reserve lies in the SW-NW of S34-T47-R29, directly west of the Pontiac mine property and north of the Aune reserve (Fig. 1.2-29). The ore, as in the Pontiac property, is generally in thin, discontinuous and highly-dipping seams. The orebody resides beneath a wet swamp (MDOR data files).

The 1963 ore reserve estimate for the Sisters property references the 32,300 tons of underground wash iron concentrate reported in the 1958 ore reserve estimate (Table 1.2-23) (MDOR data files). The 1963 estimate notes that the concentrate “is not a saleable product under present conditions”; therefore, there is no mineable ore on the property. However, the 1970 ore reserve estimate reports a tonnage for underground heavy media manganiferous concentrate (6,480 tons) (MDOR data files). Remarks with the 1970 estimate state that this ore material “is an extension of the narrow lens of manganiferous material originating in the Pontiac Mine and feathers out to material of little value to the west.” To be economical, this ore would have to be mined as part of the Pontiac mine. Assay data from the 1970 and 1958 ore reserve estimates are provided in Table 1.2-24.

**Table 1.2-23.** Sisters Reserve ore estimate.

Ore Reserve Estimate <sup>1,2</sup>							
Property	Parcel	S	T	R	Data	Surface Owner <sup>3</sup>	Fee Owner
Sisters Reserve	SW-NW	34	47	29	X	Private	Benedictine Sisters Benevolent Assn.
Year	Type	Re-class		Recovery Factor		Tons	Density Factor
1970	UG Heavy media mang. conc.					6,480	
1958	UG Iron WOC					32,300	

<sup>1</sup>Upper table information from Beltrame (1977), unless otherwise noted. Data consists of drill hole data, cross-sections, reserve estimates, etc. on microfilm at MDOR Minerals Tax Office in Virginia, MN.  
<sup>2</sup>Lower table information from MDOR Minerals Tax Office data files.  
<sup>3</sup>Data from gis.co.crow-wing.mn.us (2015).

**Table 1.2-24.** Sisters Reserve assay data.

Assay Data <sup>1</sup>										
Dry									Natural	
Property	Type	Tons	Fe	P	Si	Mn	Al	Moist.	Fe	Mn
Sisters Reserve (1970)	UG Heavy media mang. conc.	6,480	32.21	0.090	14.93	21.08		10.00	28.98	18.97
Sisters Reserve (1958)	UG Iron WOC	32,300							48.60	

<sup>1</sup>Source: MDOR data file.

Aune Reserve

The Aune reserve lies directly south of the Sisters reserve in the NW-SW of S34-T47-R29. It resides on one continuous limb of iron-formation with the Sisters and Pontiac properties, along the far northeastern edge of the property as seen by the location of drill holes in Figure 1.2-29. The 1958 ore estimate for the Aune “40” notes that the three properties should be considered as one unit (MDOR data files).

Ore on the Aune property occurs as discontinuous streaks and the iron-formation is overlain by swamp (MDOR data files). Data from the 1958 ore reserve estimate on the Aune property are presented in Table 1.2-25. Assay data are presented in Table 1.2-26.

**Table 1.2-25.** Aune Reserve (H-40) ore reserve estimate.

Ore Reserve Estimate <sup>1,2</sup>							
Property	Parcel	S	T	R	Data	Surface Owner <sup>3</sup>	Fee Owner
Aune Reserve	NW-SW	34	47	29	X	Crow Wing County	J.C. Campbell, Jr., et al.
Year	Type	Re-class		Recovery Factor		Tons	Density Factor
1958	UG Merch Mang.					89,100	
	UG WOC					17,200	
	<b>Total Tons:</b>					106,300	

<sup>1</sup>Upper table information from Beltrame (1977), unless otherwise noted. Data consists of drill hole data, cross-sections, reserve estimates, etc. on microfilm at MDOR Minerals Tax Office in Virginia, MN.

<sup>2</sup>Lower table information from MDOR Minerals Tax Office data files.

<sup>3</sup>Data from gis.co.crow-wing.mn.us (2015).

**Table 1.2-26.** Aune Reserve assay data.

Assay Data <sup>1</sup>										
Dry									Natural	
Property	Type	Tons	Fe	P	Si	Mn	Al	Moist.	Fe	Mn
Aune Reserve (1958)	UG Merch Mang.	89,100	43.72	0.145	11.19	4.46		14.00	41.44 <sup>2</sup>	
	UG WOC	17,200	53.00		12.50	0.70		10.00	47.70	

<sup>1</sup>Source: MDOR data file.

<sup>2</sup>Combined iron and manganese.

CAES Potential for Cuyuna North Range Study Area 3: Gloria, Algoma, Ferro, Joan No. 4, Merritt No. 1, Merritt No. 2, Pontiac, and Joan No. 3 Mines; Pontiac, Sisters, and Aune Reserves

Figures 1.2-30 through 1.2-33 illustrate the base map, hydrography, elevation, and surface ownership features of the Cuyuna North Range Study Area 3, the manganese district of the Cuyuna North Range. This area is a lightly populated region that lies just north of the Cuyuna Country State Recreation Area (CCSRA) and, therefore, is not subject to the restrictions therein. All of the mines and ore reserve properties of Study Area 3 reside within the Crow Wing State Forest.

Minnesota Power has a major transmission line within 1½ miles of the mine properties (Fig. 1.2-6). The Pontiac-Sisters-Aune reserve properties are within 2½ miles of the transmission line. Access to the reserve properties and the Gloria mine property would come off of CSAH 30 while the Ferro-Joan No. 4-Merritt mine properties would be accessed from CSAH 34 to the south through the city of Trommald (Fig. 1.2-30).

The Gloria shaft (caved) and drifts appear isolated and untouched. The Algoma shafts and underground workings have been mined out. The Ferro, Joan No. 4, and Merritt orebodies have been mined extensively, but more angle drilling could prove up an iron grade resource to mine for a CAES cavern. A substantial number of holes were drilled on the unmined orebody of the Aune, Sisters, and Pontiac reserves, providing data for CAES cavern consideration.

The Merritt No. 1 shaft is the deepest in the region at 264 feet and drifting at this level in the orebody through the Merritt No. 2, Ferro, and Joan No. 4 properties could provide a cavern for CAES. An incline shaft from ledge to the 264 foot level of the Merritt No. 1 mine presents a challenge. Draining the ponded waters may not be an option with a residence located nearby.

The Gloria, Ferro, Joan No. 4, Merritt No. 1 (No. 1 shaft), and Merritt No. 2 shafts are located in upland regions (Fig. 1.2-31). The Gloria orebody resides beneath emergent wetlands that are seasonally flooded. There are ponded waters over the Ferro, Joan No. 2, and Merritt orebodies due to stripping (Merritt No. 1) and subsidence. The Aune-Sisters-Pontiac orebody resides in an extended lowland region (Fig. 1.2-32). The orebody is overlain with saturated forested and scrub shrub wetlands. A perennial stream flows southwestward across the southern part of the original Pontiac (Clark) parcel, passing directly over the plotted Pontiac shaft location. The stream turns just short of the parcel's western border to flow southward toward Mahnomen Lake.

Surface ownership of the mines and reserves in Study Area 3 is private, with the exception of the Aune reserve, located on a tax-forfeited 40-acre parcel held by Crow Wing County (Fig. 1.2-33). The Sisters and Joan No. 3 parcels, as well as the northern half (20 acres) of the Pontiac (Clark) parcel in the Aune-Sisters-Pontiac reserve, are classified by Crow Wing County as rural vacant land for tax purposes. So, too, are the Gloria, Ferro, and Merritt No. 2 mine properties. The southern half (20 acres) of the Pontiac (Clark) parcel (buildings located in the southeast corner) and the eastern 40-acre parcel of the Pontiac reserve (buildings located in the northeast corner south of Rasset Lake) are classified as residential one unit, as are the two eastern 5-acre parcels of the Joan No. 4 property and the western 5-acre and remaining 35-acre parcels of the Merritt No. 1 property. The remaining western 21.47-acre parcel in the northern part of the Joan No. 4 property is classified as residential 2-3 units. Surface ownership data were obtained from plat information on the Crow Wing County website (<http://gis.co.crow-wing.mn.us/link/jsfe/index.aspx>).

#### CAES Positives:

- Existing shaft and workings of the Gloria mine;
- Existing shafts, untapped (?-possibly- existing mine development) Aune-Sisters-Pontiac reserve for potential cavern;
- Manganese district;
- Untapped iron ore reserve on the Merritt No. 1 and No. 2 mine properties;
- Relatively close to major transmission lines - within 1.5 miles of mine properties and 2.5 miles of reserve properties;
- Road access via county highways;

- Location in rural vacant area; and
- Location outside of the CCSRA.

CAES Negatives:

- Saturated wetlands overlying the Aune-Sisters-Pontiac reserve; seasonally flooded emergent wetlands overlying the Gloria mine;
- Perennial stream over/near Pontiac mine shaft;
- Additional drilling of angle holes required to define Merritt untapped iron reserve;
- Inclined shaft from ledge to 264-foot level beneath Merritt No. 1 mine “lake”;  
and
- Private residence located near shore of the Merritt No.1 “lake.”

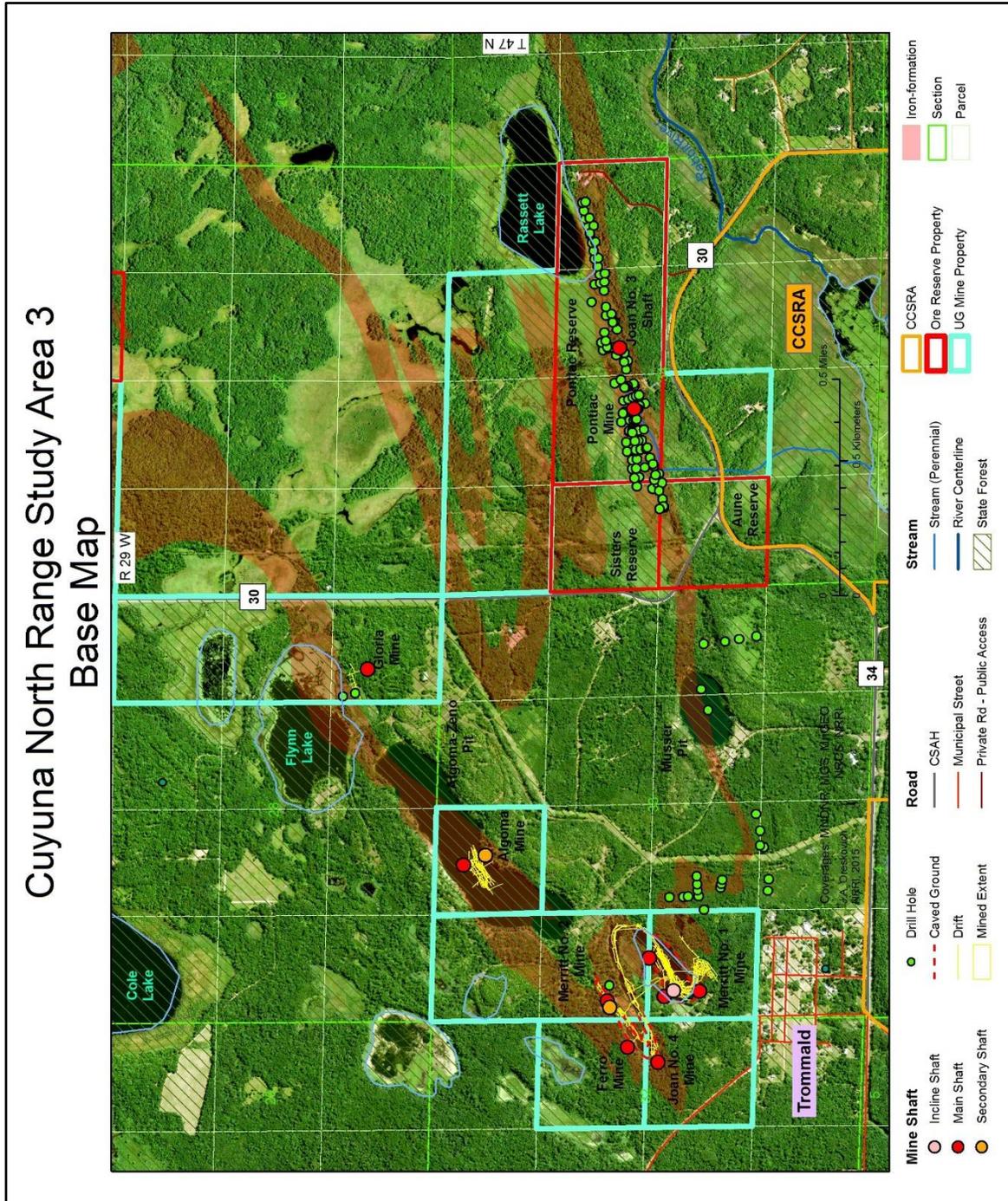


Figure 1.2-30. Cuyuna North Range Study Area 3 base map.

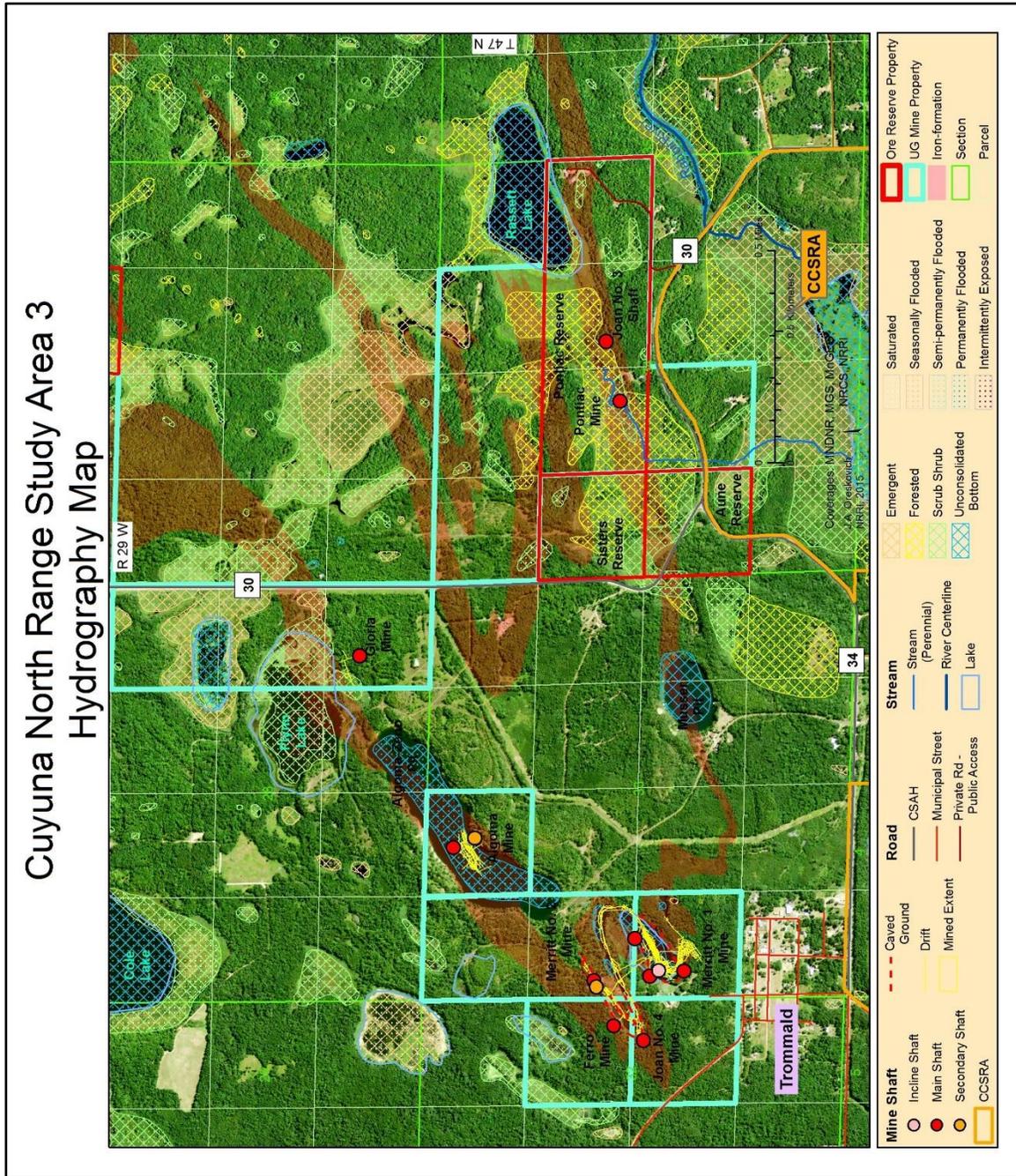


Figure 1.2-31. Cuyuna North Range Study Area 3 hydrography map.

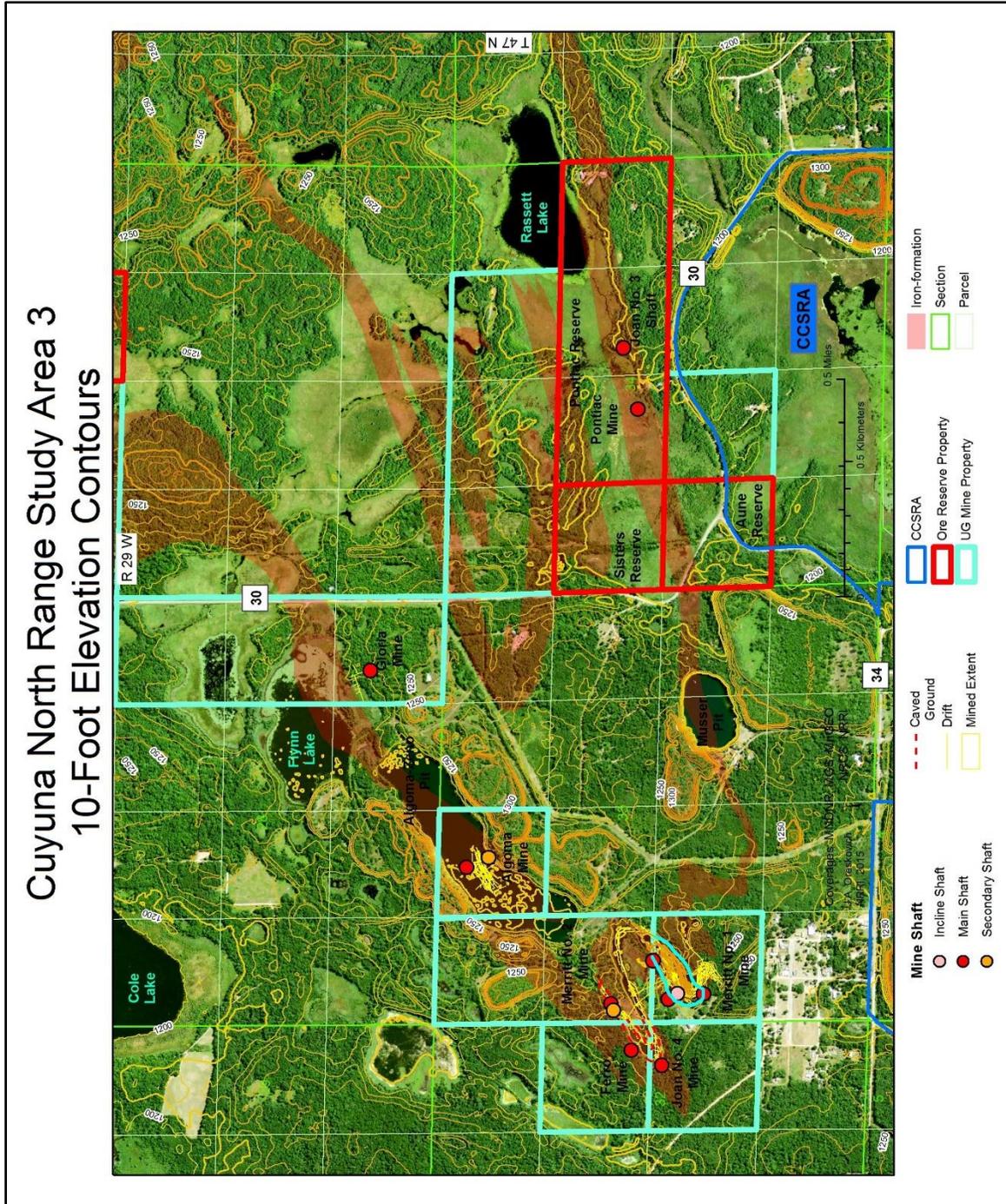


Figure 1.2-32. Cuyuna North Range Study Area 3 10-foot LiDAR contours elevation map.

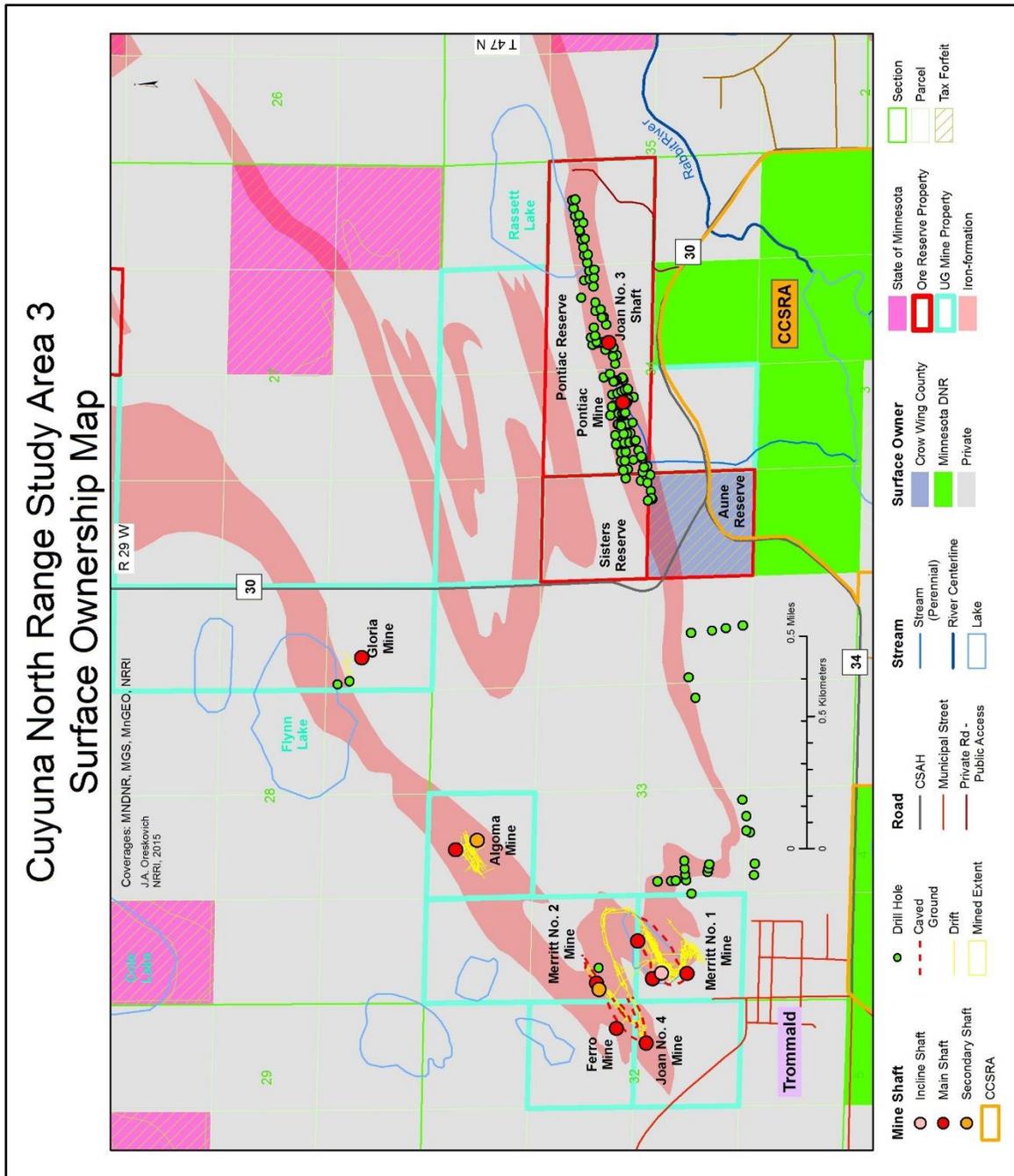


Figure 1.2-33. Cuyuna North Range Study Area 3 surface ownership map.

Cuyuna North Range Study Area 4

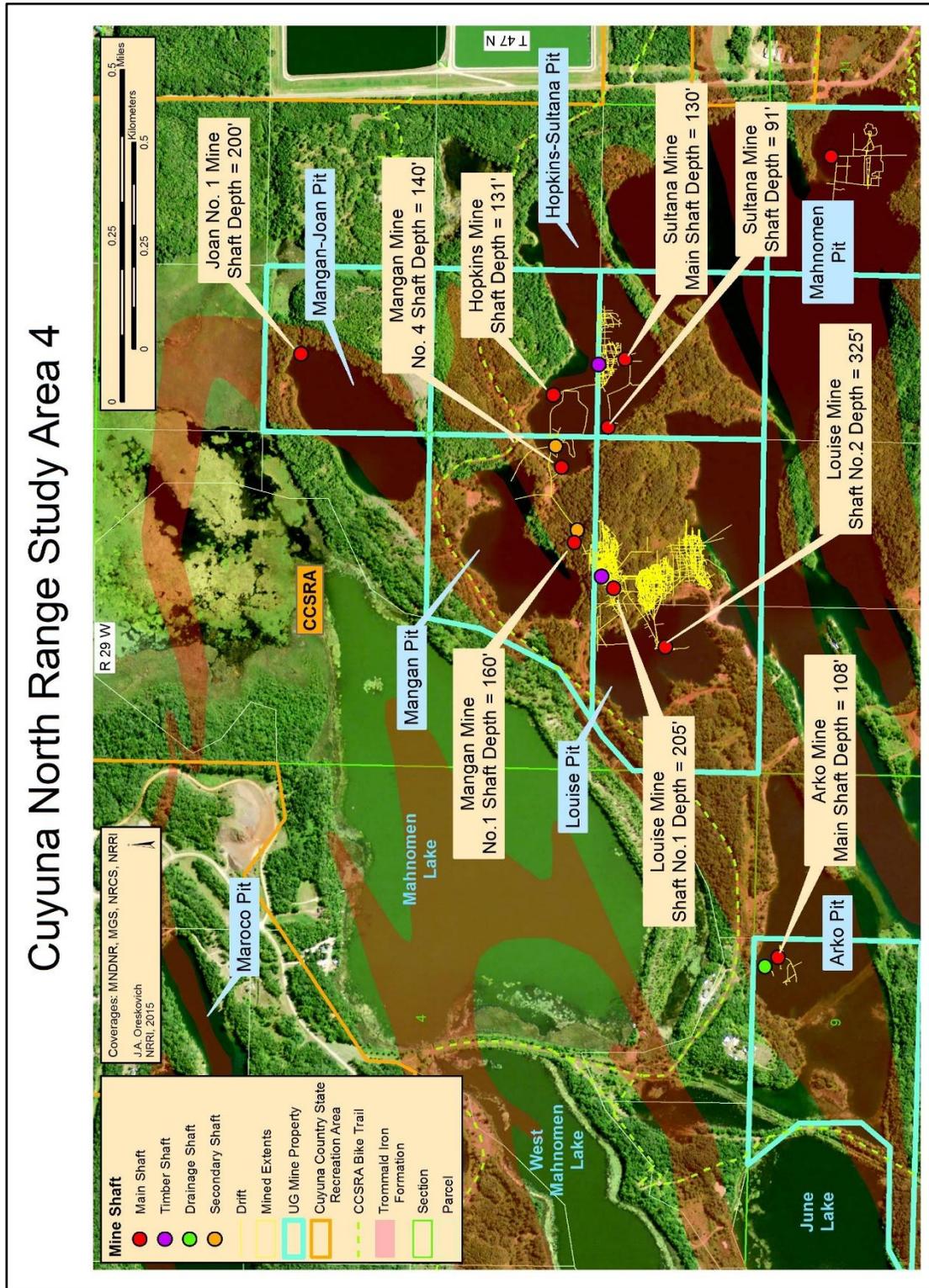
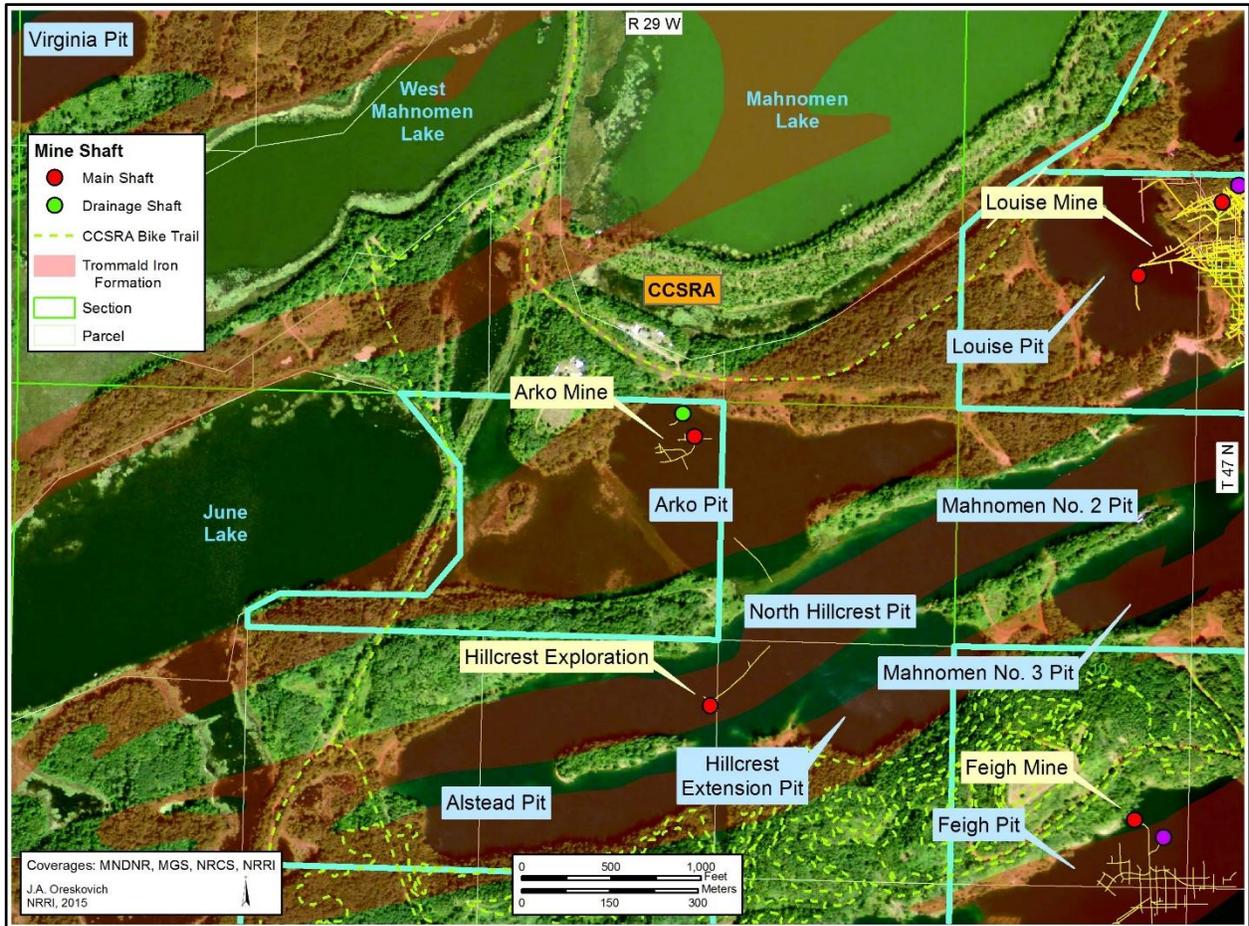


Figure 1.2-34. Cuyuna North Range Study Area 4: Arko, Louise, Mangan, Hopkins, Sultana and Joan No. 1 mines.

The underground mines of Study Area 4 reside entirely within the Cuyuna Country State Recreation Area (CCSRA). They are also surrounded by or encompassed within the open pit mines that dominate the immediate area. In addition, the area abuts a series of natural lakes (Mahnomen, West Mahnomen, and June) along its northwestern side. The likelihood of using any of the shafts or underground mine workings in this study area for CAES purposes is very slim.

Arko Mine



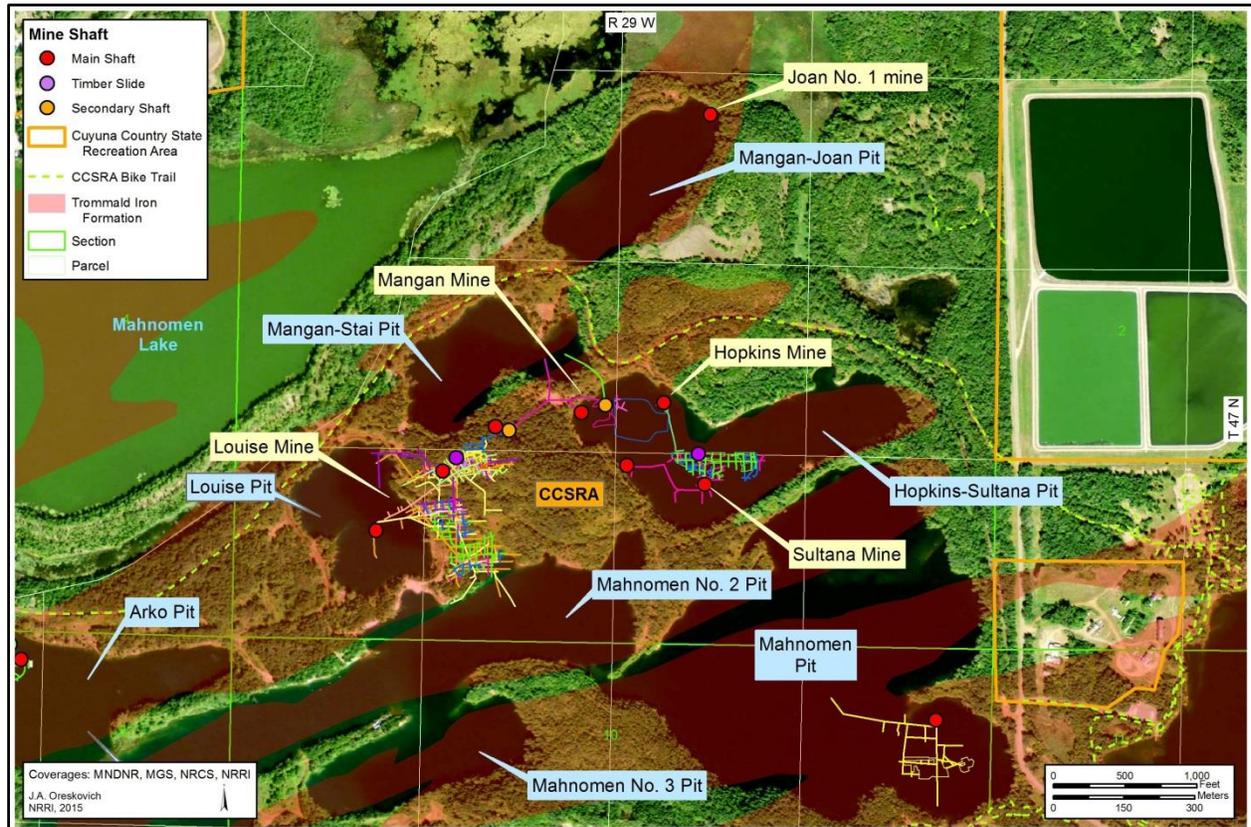
**Figure 1.2-35.** The Arko mine, initially an underground mine that was subsequently open-pitted, lies amidst natural lakes and mine pit lakes.

Mine	Former Name		Range	S	T	R	Parcel	UG	OP	ML
Arko			North Range	9	46	29	Lot 1	X	X	
Shaft Sinking	1st Shipment	Last Shipment	Total Ore Shipped	Last Operator		Last Known Fee				
1916	1918	1960	461,999	Hanna		Boutin, H.L. et al; State				
Overburden (Ft.)	Mine Depth	Top Level	Lowest Level	Mining Method		Shaft Type				
	108 Ft.	77-Ft. Level	108-Ft. Level			3-compartment				

The Arko mine began as an underground mine with a shaft sunk in 1916 (Schmidt, 1963). The underground mine was located in Lot 1 of S9-T46-R29 (Fig. 1.2-35). A “small amount” of ore was shipped from 1918 to 1920 (Schmidt, 1963; Crowell & Murray, 1920).

Crowell & Murray (1920) report that the greatest vertical depth in the Arko underground mine was 108 feet. The main shaft is portrayed on a mine map as a 3-compartment shaft. The only map found of the Arko underground workings shows drifting at the 108-foot main level and on the 77-foot and 85-foot sub-levels. In addition, some mined extents are shown on the 85-foot sub-level. Today, both the shafts and underground workings reside within the Arko pit. Schmidt (1963) reports that the Arko property was stripped around 1938 for open pit mining.

Structurally, the Arko pit resides in a broad fold of iron-formation where a conspicuous syncline extends the length of the mine (Schmidt, 1963). Together with a less-conspicuous anticline, the two comprise a drag-fold pair that caused the considerable width of the iron-formation at bedrock surface in this location (Schmidt, 1963).



**Figure 1.2-36.** The Louise, Mangan, Joan No. 1, Hopkins and Sultana mines are shown with their open pit counterparts.

Louise Mine

Mine	Former Name	Range	S	T	R	Parcel	UG	OP	ML
Louise	Cuyuna-Mille Lacs	North Range	3	46	29	Lot 7 & SE-SW	X	X	
Shaft Sinking	1st Shipment	Last Shipment	Total Ore Shipped		Last Operator		Last Known Fee		
October, 1911	1913	1976	4,630,807		Pittsburgh Pacific Co.		John Hopkins Trust		
Overburden (Ft.)	Mine Depth (UG)	Top Level (UG)	Lowest Level (UG)		Mining Method		Shaft Type		
50	235 Ft.	85-Ft. Level	<b>325-Ft. Level</b>				5-compartment; 10' x 18' inside collar		

The Louise Mine, located in Lot 7 and the SE-SW of S3-T46-R29, shipped the first manganiferous ore from the Cuyuna District (Schmidt, 1963). The mine was opened as the underground Cuyuna-Mille Lacs mine in 1911. Schmidt (1963) describes two orebodies in the mine, one north and one south. The two orebodies can be seen in the Louise Mine underground workings in Figure 1.2-36. The north orebody is continuous with that seen in the southern part of the Mangan Mine to the north.

The Louise mine No. 1 shaft and associated timber shaft (Fig. 1.2-34) are two of only four shafts in Study Area 4 that have not been compromised by subsequent open pit mining. Both of these shafts are 205 feet deep. The No. 1 shaft is a 3-compartment shaft, while the timber shaft is a 4-compartment shaft. Ore was mined on 10-foot levels from 95 feet to 205 feet. The Louise mine No. 2 shaft, no longer available due to open pit mining, was a 5-compartment shaft that was 325 feet deep. A Butler Bros. insurance map found in the archives at the Minnesota Discovery Center in Chisholm, MN gave the inside collar dimensions of the No. 2 shaft as 10 feet by 18 feet.

The extensive underground workings in the Louise underground mine are connected directly to the Louise and Mahnomen No. 2 pits. They are connected via the Mangan mine underground workings to both the Mangan-Stai and Hopkins-Sultana pits. Open pit mining on the Louise property began in 1948, several years subsequent to the idling of the underground workings in 1943 (Schmidt, 1963).

Mangan (No. 1) Mine

Mine	Former Name	Range	S	T	R	Parcel	UG	OP	ML
Mangan (UG)		North Range	3	46	29	NE-SW	X		
Shaft Sinking	1st Shipment	Last Shipment	Total Ore Shipped		Last Operator		Last Known Fee		
1915	1916								
Overburden (Ft.)	Mine Depth	Top Level	Lowest Level		Mining Method		Shaft Type		
	160'						round timber shaft; 3-compartment		
Mine	Former Name	Range	S	T	R	Parcel	UG	OP	ML
Mangan-Stai (OP)		North Range	3	46	29	NE-SW & Lot 6		X	
Shaft Sinking	1st Shipment	Last Shipment	Total Ore Shipped		Last Operator		Last Known Fee		
		1979	1,163,126		Pittsburgh Pacific Co.		Peterson; State		

Crowell & Murray (1920) report that the Mangan No. 1 (Mangan) mine opened in 1916. They list the Mangan mine's greatest vertical depth as 160 feet. The Mangan mine is located in the NE-SW of S3-T46-R29.

There are two main shafts on the Mangan property (Fig. 1.2-36). The first, Shaft No. 1, is a 3-compartment shaft located in the southwestern part of the property on an extension of the Louise mine's north orebody. It is at least 160 feet deep, based on Crowell & Murray's (1920) report. The second, Shaft No. 4, also shown on maps as a 3-compartment shaft, is located in the southeastern part of the property on the Hopkins-Sultana orebody, where it is now part of the Hopkins-Sultana pit. This shaft was a minimum of 140 feet deep, as determined from mine drifts on maps.

To the northwest of the underground workings, an orebody was mined by open pit methods with the adjacent Stai property to the west, forming the Mangan-Stai pit. Another orebody in the Mangan property to the north was mined in conjunction with the adjacent Joan No. 1 property to the east to form the Mangan-Joan pit (see Joan No. 1 Mine).

Joan No. 1 Mine

Mine	Former Name	Range	S	T	R	Parcel	UG	OP	M L
Joan No. 1 (UG)		North Range	3	46	29	SW-NE	X		
Shaft Sinking	1st Shipment	Last Shipment	Total Ore Shipped		Last Operator		Last Known Fee		
1916	1917	1919 (UG)	5,338		Joan Mining Co.				
Overburden (Ft.)	Mine Depth	Top Level	Lowest Level		Mining Method		Shaft Type		
	200'						2-compartment; 8' x 16'		
Mine	Former Name	Range	S	T	R	Parcel	UG	OP	M L
Mangan-Joan (OP)		North Range	3	46	29			X	
Shaft Sinking	1st Shipment	Last Shipment	Total Ore Shipped		Last Operator		Last Known Fee		
	1949	1963	914,596		Pittsburgh Pacific Co.		Swanson, Jesse L., et al.		

The Joan No. 1 mine is located in the SW-NE of S3-T46-R29 (Fig. 1.2-36). Work on the mine began with shaft sinking in 1916, and manganiferous ores were shipped from 1917 to 1919 (Schmidt, 1963). Harder and Johnston (1918) noted that the orebody outline was irregular and appeared to be a band approximately 12 feet wide following generally in a northerly direction.

No maps were found of the underground workings of the Joan No. 1 mine. Crowell & Murray (1917) note that the greatest vertical depth of the mine was 200 feet. The shaft location appeared on a map of the Mangan and Louise mines. File notes (MDOR data files) indicate a 2-compartment shaft that was 8 feet by 16 feet in size. The Joan No. 1 mine shaft appears within the Mangan-Joan pit in Figure 1.2-36, making it unavailable for further use. Schmidt (1963) writes that the mine pit intersected some parts of the underground workings.

Stripping for an open pit mine on the Joan No. 1 property was done in 1949 (Schmidt, 1963). It was worked in conjunction with the Mangan property to the west as the Mangan-Joan pit. Ore was shipped until 1963 (Skillings Mining Review, 2005). Schmidt (1963) reports that both manganiferous iron ore and iron ore were produced from the Joan No. 1 mines.

Hopkins and Sultana Mines

Mine	Former Name	Range	S	T	R	Parcel	UG	OP	ML
Hopkins	Section 30 Mine	North Range	3	46	29	N 1/2 of SE	X		
Shaft Sinking	1st Shipment	Last Shipment	Total Ore Shipped		Last Operator		Last Known Fee		
1915									
Overburden (Ft.)	Mine Depth	Top Level	Lowest Level		Mining Method		Shaft Type		
50	145' (shaft)		130'				3-compartment		
Mine	Former Name	Range	S	T	R	Parcel	UG	OP	ML
Sultana		North Range	3	46	29	SW-SE	X		
Shaft Sinking	1st Shipment	Last Shipment	Total Ore Shipped		Last Operator		Last Known Fee		
1914	1916		35,169 (UG)						
Overburden (Ft.)	Mine Depth	Top Level	Lowest Level		Mining Method		Shaft Type		
	130	65-Ft. Level	91-Ft. Level (?)		sub-level slicing		2-compartment		
Mine	Former Name	Range	S	T	R	Parcel	UG	OP	ML
Hopkins-Sultana	Hopkins; Sultana	North Range	3	46	29	SE 1/4		X	
Shaft Sinking	1st Shipment	Last Shipment	Total Ore Shipped		Last Operator		Last Known Fee		
		1979	990,735		Pittsburg Pacific Co.		Joyce, et al; Pittsburg Pacific Co.; State		

The Hopkins and Sultana mines began as underground mines—the Hopkins in the N1/2-SE of S3-T46-R29 and the Sultana in the SW-SE of S3-T46-R29. They were subsequently individually open-pitted, according to a 1967 mine map found, and later operated as one mine, the Hopkins, occupying the SE1/4 of S3-T46-R29 (Skillings Mining Review, 2005). The Hopkins pit extended into the Mangan property to the west. Both manganese iron ores and iron ores were produced (Schmidt, 1963). Figure 1.2-36 shows how rising waters have joined the two pits to form one large pit lake.

The Hopkins mine began in 1915 as the Section 30 mine (Aulie and Johnson, 2002). The Hopkins shaft is shown on maps as a 3-compartment shaft. Harder and Johnston (1918) report that the shaft is 145 feet deep. A 10-foot-wide drift extends southward at the 130-foot level from the Hopkins shaft to meet the workings of the Sultana mine at the property line.

Two Sultana mine shafts, both shown on maps as 2-compartment shafts, were sunk in 1914 according to Harder and Johnston (1918). The first was an exploratory shaft, located in the northwest corner of the property (Fig. 1.2-36), that was designated Shaft No. 1. The second shaft, Shaft No. 2, the main hoisting shaft, is located in the north central part of the property. Crowell & Murray (1917) report the Sultana mine's greatest vertical depth as 130 feet. Maps from 1917 indicate that ore was mined on the 65 foot and 75 foot levels, with a main haulage level at 91 feet. Crowell & Murray (1920) report that the mine first opened in 1915. The only ore shipment reported was 35,169 tons in 1916, with the mine idled as of the 1920 printing and no longer listed in the 1923 (Crowell & Murray) edition.

CAES Potential for Cuyuna North Range Study Area 4: Arko, Louise, Mangan (No. 1), Joan No. 1, Hopkins, and Sultana Mines

Figures 1.2-37 through 1.2-40 illustrate the base map, hydrography, elevation and surface ownership features of the Cuyuna North Range Study Area 4. All of the shafts and underground mine workings located in Study Area 4 reside within the borders of the CCSRA. The CCSRA is a destination venue prized locally, nationally, and internationally for the mountain bike trail system developed over and around the legacy mining features of the Cuyuna North Range (See Section 1.1: Cuyuna Country State Recreation Area).

Location within the CCSRA almost certainly makes the shafts and underground workings of Study Area 4 off-limits for CAES purposes at the present time. While the right to mine ore was maintained in the CCSRA charter, this likely would not extend to CAES use of existing mine features located completely within the CCSRA. Future demand for manganese may alter this scenario.

In addition to location within the CCSRA, Study Area 4 is a region of natural lakes and mine pit lakes (Fig. 1.2-38). Beyond competition with sportsmen and recreational boaters, there is a strong likelihood that these water bodies are interconnected. Channels, underground mine drifting, fractured rock from mine blasting and over-topping of adjoining mine pit walls with rising waters are all potential contributing factors. What impacts one water body (such as draining for CAES purposes) can impact multiple surrounding water bodies. With the exception of the Louise and Mangan underground mine workings, nearly all of the underground workings have been subsequently mined out by open pit mining.

Land regions within Study Area 4 are uplands. Much of the immediate area is covered by stockpiles, as evidenced in the contour lines of Figure 1.2-39. Of note is that the only available shaft for CAES use in Study Area 4 (Louise and Mangan) appears overlain by a stockpile or stockpile base.

Figure 1.2-40 illustrates surface ownership in Study Area 4. Much of the land within the CCSRA has been acquired by the State of Minnesota Department of Natural Resources, including some parcels that are not shown as such on this map. The Louise mine and Louise pit parcels, as well as the Hopkins and Joan No. 1 parcels, remain private at this time, according to the Crow Wing County on-line parcel map/tax information website.

CAES Positives:

- Potential for future mining; and
- State (MN DNR) as major surface owner.

CAES Negatives:

- Location within the CCSRA;
- Terrain comprised largely of lakes and mine pits;
- High potential for underground connectivity of water bodies; and
- Residence of most mine shafts within pit lakes.

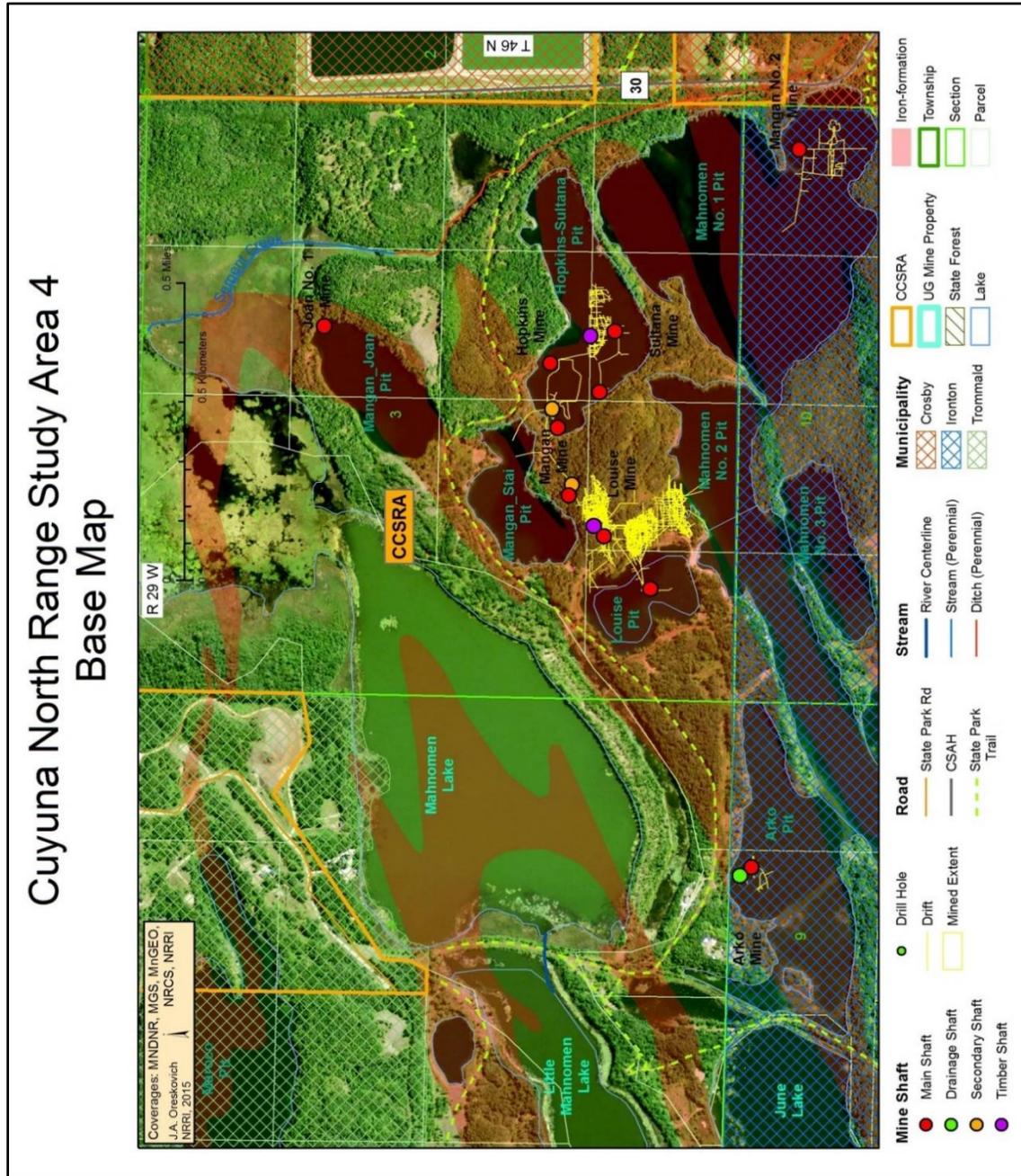


Figure 1.2-37. Cuyuna North Range Study Area 4 base map.

# Cuyuna North Range Study Area 4 Hydrography Map

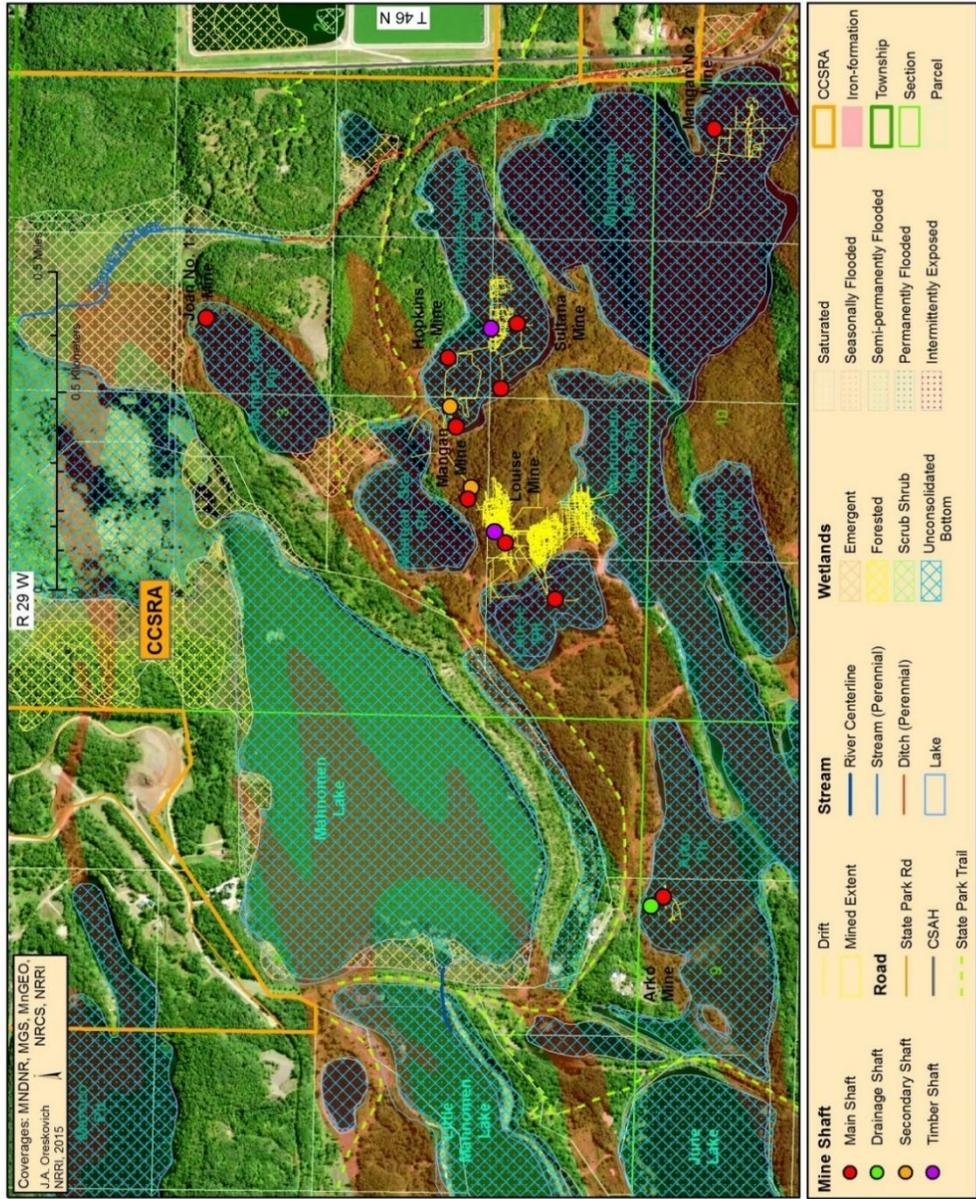


Figure 1.2-38. Cuyuna North Range Study Area 4 hydrography map.



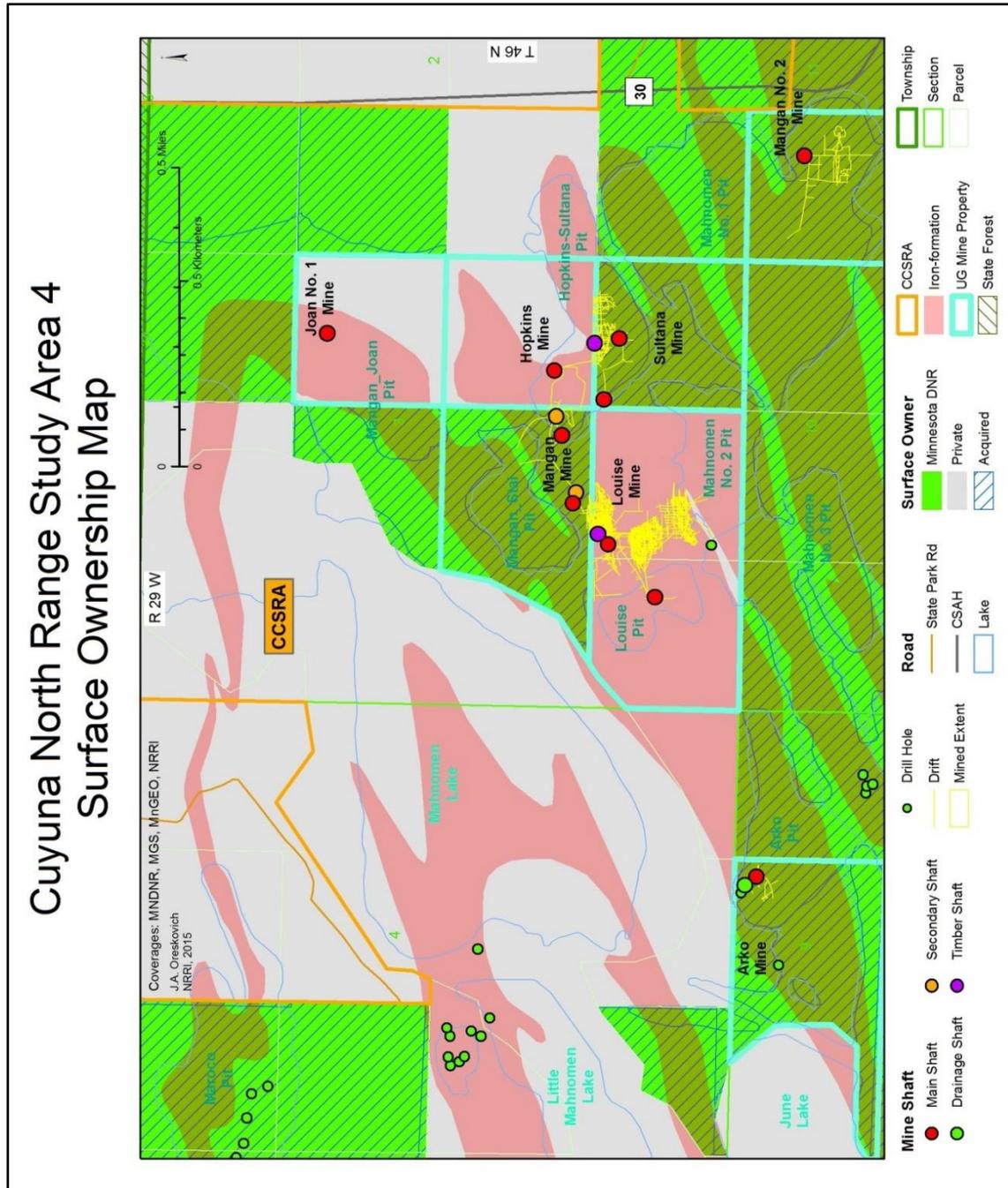
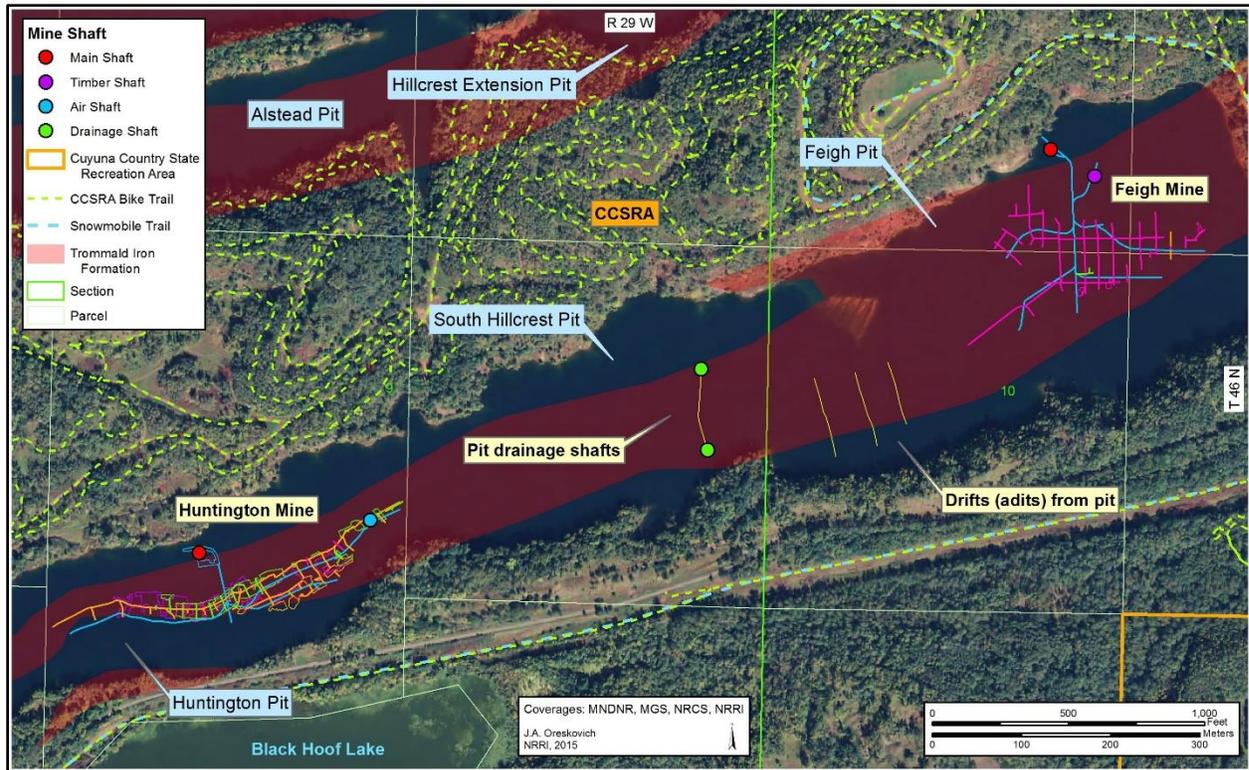


Figure 1.2-40. Cuyuna North Range Study Area 4 surface ownership map.



The Huntington, Feigh, and Martin mines, together with the Crosby and Hennen reserves, comprise Cuyuna North Range Study Area 5. All three mines opened as underground mines and were subsequently operated as open pit mines. The three mines reside within the CCSRA, while the reserves are located outside of it.



**Figure 1.2-42.** Huntington and Feigh mines, both of which were subsequently worked as open pit mines.

Huntington Mine

Mine	Former Name	Range	S	T	R	Parcel	UG	OP	ML
Huntington		North Range	9	46	29	Lots 4 & 5, SW-SW & NE-SW	X	X	
Shaft Sinking	1st Shipment	Last Shipment	Total Ore Shipped			Last Operator	Last Known Fee		
1918	1922	1961	1,111,047			Hanna	Pittsburg Pacific Co.; Various; State		
Overburden (Ft.)	Mine Depth	Top Level	Lowest Level		Mining Method	Shaft Type			
	190 Ft. (UG)	76-Ft. Level	150-Ft. Level		slicing & caving	5-compartment			

The Huntington mine property comprises Lots 4 and 5, the SW-SW and the NE-SW of S9-T46-R29, abutting the Alstead mine property to the north (Fig. 1.2-41). Opened as an

underground mine in 1918, the Huntington produced ore in 1922 and 1924 (Schmidt, 1963). The mine was subsequently stripped in the early 1940s (Aulie and Johnson, 2002) and mined by open pit methods. Time and rising waters have transformed the former Huntington mine and three other contiguous former open pit mines—the Martin, South Hillcrest, and Feigh—into one long pit lake. As seen in Figure 1.2-42, the coalesced pits have consumed the full width of the iron-formation subcrop.

Schmidt (1963) has described the structure of the Huntington, South Hillcrest, Feigh, and neighboring Pennington mines as a “tight asymmetrical anticline, probably sheared on one or several planes near the axis.” Grout and Wolff (1955) noted that the Huntington orebody generally has a monoclinial 75 degree dip to the southeast. The Huntington orebody lies within the thin-bedded facies of the Trommald Iron Formation (Schmidt, 1963).

Maps portray the Huntington shaft as a five-compartment shaft. Depth of the shaft, now submerged near the north edge of the Huntington pit (Fig. 1.2-42), was not found; however, Crowell & Murray (1920) reported the greatest vertical depth for the underground Huntington mine as 190 feet. Mine maps from 1925 indicate that the 150-foot level is the main haulage level, with ore mined on the 66-, 76-, 86-, and 96-foot levels. Ore was mined by the slicing and caving method (Crowell & Murray, 1920).

Two shafts are shown in the neighboring South Hillcrest pit in Figure 1.2-42. These served as drainage shafts for the pit, with a connecting drift between them. There were no actual underground workings in the South Hillcrest mine. Both the Huntington and South Hillcrest properties reside within the CCSRA.

### Feigh Mine

Mine	Former Name	Range	S	T	R	Parcel	UG	OP	ML
Feigh		North Range	10	46	29	S1/2-NW, N1/2-SW	X	X	
Shaft Sinking	1st Shipment	Last Shipment	Total Ore Shipped			Last Operator	Last Known Fee		
1917	1919	1961	3,764,538			Hanna	State		
Overburden (Ft.)	Mine Depth	Top Level	Lowest Level		Mining Method	Shaft Type			
	153 Ft. (UG)	97-Ft. Level	153-Ft. Level		slice & cave	5-compartment			

The Feigh mine lies in the S1/2-NW and N1/2-SW of S10-T46-R29 (Fig. 1.2-42). The mine opened as an underground mine in 1917 and began shipping ore in 1919 (Crowell & Murray, 1920). The Feigh mine shaft is submerged near the northern edge of the Feigh pit.

One map was found of the underground workings of the Feigh mine. It shows a five-compartment shaft and workings on four levels: the 153-foot haulage level and 97-, 107-, and 123-foot levels. The Feigh underground mine was worked by the slicing and caving method (Crowell & Murray, 1920). The Feigh orebody, like that of the Huntington, generally has a steep monoclinial dip of 75° to the southeast (Grout and Wolff, 1955).

The Feigh property was partially stripped in 1937, after which the mine was operated as an open pit mine (Schmidt, 1963). Skillings Mining Review (2005) reports that over 3.76 long tons of ore were shipped from the Feigh mine. The final shipment was made in 1961. The State of

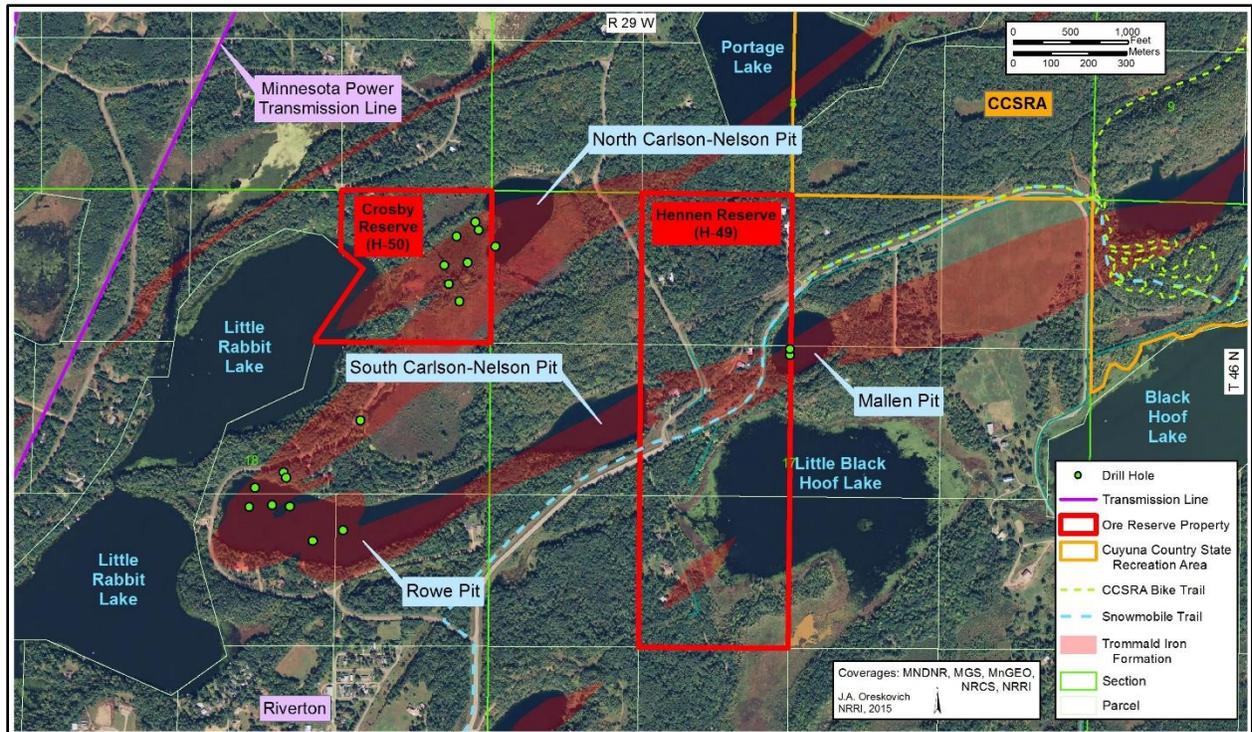
Minnesota is the fee owner of the Feigh mine property (Skillings Mining Review, 2005), which resides within the CCSRA.

### Martin Mine

Mine	Former Name	Range	S	T	R	Parcel	UG	OP	ML
Martin		North Range	16	46	29	Lot 2	X	X	
Shaft Sinking	1st Shipment	Last Shipment	Total Ore Shipped			Last Operator	Last Known Fee		
1917	1918	1960	326,518			Hanna	State		
Overburden (Ft.)	Mine Depth	Top Level	Lowest Level			Mining Method	Shaft Type		
NA	217 Ft. (UG)	NA	NA			slicing & caving	NA		

The Martin Mine is located in Lot 2 of S16-T46-R29 at the western end of the Huntington pit (Fig. 1.2-41). It opened as an underground mine in 1917, with the first ore shipment made in 1918 (Crowell & Murray, 1920). The Martin orebody lies on the same steeply dipping (75°) monoclinical fold as the Huntington, South Hillcrest, and Feigh mines, although it is apparently off-set from the west end of the Huntington mine by a fault or sharp fold (Grout and Wolff, 1955). The orebody is located in the thin-bedded facies of the Trommald Iron Formation (Schmidt, 1963).

No maps were found for the underground workings of the Martin Mine. Crowell & Murray (1920) reported that the greatest vertical depth in the Martin underground mine was 217 feet and that the mine was worked by the slicing and caving method. The Martin mine was subsequently stripped and worked by open pit methods, with ore shipments from the pit commencing in 1944 (Schmidt, 1963). The State of Minnesota is the fee owner of the Martin mine property (Skillings Mining Review, 2005), which resides within the CCSRA.



**Figure 1.2-43.** Crosby and Hennen reserves.

### Crosby Reserve (H-50)

The Crosby reserve (H-50) lies adjacent to the North Carlson-Nelson pit in Lot 1 of S18-T46-R29 (Fig 1.2-43). This places the reserve outside of the CCSRA, making it more amenable to CAES development. The Crosby reserve lies within ½ mile of a major Minnesota Power transmission line.

A 1958 letter from The M.A. Hanna Company to the School of Mines, University of Minnesota, states that exploration drilling on the Crosby reserve was completed in 1957 (MDOR data files). This is relatively recent for a property that was not developed. An open pit operating layout was subsequently prepared but never employed.

The ore reserve estimate in Table 1.2-27 reflects the open pit design plan and includes trespass on the Carlson-Nelson property to remove all of the Crosby reserve ore. The table also includes tonnages for an underground orebody beneath the planned pit. Table 1.2-28 contains assay data for the Crosby reserve.

According to the 1958 ore reserve estimate (MDOR data files), the ore in the Crosby reserve property lies “in a synclinal trough which dips rapidly to the east to the north limb of the Carlson-Nelson Mine.” The M.A. Hanna Company letter notes that “the bottom of the ore trough dips on approximately a 35% slope in a northeasterly direction toward the north Carlson-Nelson property.” Depth to the orebody wasn’t noted. Reference is made to the large amount of overstripping required to reach the progressively deeper ores on the east side of the property.

**Table 1.2-27.** Crosby Reserve ore estimate.

Ore Reserve Estimate <sup>1,2</sup>								
Property	Parcel	S	T	R	Data	Surface Owner <sup>3</sup>	Fee Owner	
Crosby Reserve (H-50)	Lot 1	18	46	29	X	Private	Hanna Iron Ore Div. (5/8) & Crosby Iron Co.	
Year	Type		Re-class		Recovery Factor		Tons	Density Factor
1986	OP Wash Ore Conc. (former Merch)		X		65%		131,690	14
	OP Wash Ore Conc.				60%		102,500	14
					<b>Total Tons OP:</b>		234,190	
1958 (1959)	OP Merch - Iron						200,600	
	OP Wash Ore Conc. - Iron						92,000	
					<b>Total Tons OP:</b>		292,600	
	OP Merch - Iron (Carlson-Nelson trespass)						37,700	
	OP Wash Ore Conc. - Iron (Carlson-Nelson trespass)						15,200	
							52,900	
	UG Merch - Iron <sup>4</sup>						42,400	
	UG Wash Ore Conc. - Iron <sup>4</sup>						18,400	
				<b>Total Tons UG:</b>		60,800		
				<b>Total Tons 1958 (1959) (OP+OP trespass+UG):</b>		406,300		

<sup>1</sup>Upper table information from Beltrame (1977), unless otherwise noted. Data consists of drill hole data, cross-sections, reserve estimates, etc. on microfilm at MDOR Minerals Tax Office in Virginia, MN.

<sup>2</sup>Lower table information from MDOR Minerals Tax Office data files.

<sup>3</sup>Data from MN DNR GIS coverage own\_mnstwdpy2 (2008).

<sup>4</sup>UG tonnage is below the proposed pit.

**Table 1.2-28.** Crosby Reserve assay data.

Assay Data <sup>1</sup>										
Property	Type	Tons	Dry						Natural	
			Fe	P	Si	Mn	Al	Moist.	Fe	Mn
Crosby Reserve 18-46-29 Lot 1 (1958)	OP Merch - Iron	200,600	54.99	0.189	9.35	0.19	1.10	12.00		
	OP WOC - Iron	92,000	55.07	0.236	9.21	0.16	0.93	10.00		
	<b>Total OP Reserve:</b>	292,600	55.02	0.204	9.31	0.18	1.05	11.37		
	UG Merch - Iron	42,400	54.60	0.190	9.02	0.22	1.19	12.00		
	UG WOC - Iron	18,400	55.06	0.177	9.62	0.23	0.96	10.00		
	<b>Total UG Reserve:</b>	60,800	54.74	0.186	9.20	0.22	1.12	11.39		

<sup>1</sup>Source: MDOR data file.

Hennen Reserve (H-49)

The Hennen reserve (H-49) property encompasses three 40-acre parcels comprising the E1/2-NW and NE-SW of S17-T46-R29 (Fig. 1.2-43). The orebody of the Hennen reserve is located on a possible drag fold between the Mallen pit to the east and the South Carlson-

Nelson pit to the west. Ore reserve estimates and assay data were not acquired for the Hennen reserve for this project. Beltrame (1977) indicates that estimates were made for the Hennen reserve in 1956, 1963, and 1964 (Table 1.2-29). The estimates are available on microfilm at the MDOR office in Virginia, MN.

**Table 1.2-29.** Hennen Reserve (H-49) ore reserve estimate.

Ore Reserve Estimate <sup>1,2</sup>							
Property	Parcel	S	T	R	Data	Surface Owner <sup>3</sup>	Fee Owner
Hennen Reserve (H-49)	E1/2-NW & NE-SW	17	46	29	X	Private	The Hanna Mining Co.
Year	Type	Re-class		Recovery Factor		Tons	Density Factor
1964, 1963, 1956	NA					NA	
<sup>1</sup> Upper table information from Beltrame (1977), unless otherwise noted. Data consists of drill hole data, cross-sections, reserve estimates, etc. on microfilm at MDOR Minerals Tax Office in Virginia, MN. <sup>2</sup> Lower table information from MDOR Minerals Tax Office data files. <sup>3</sup> Data from MN DNR GIS coverage own_mnstwdpy2 (2008).							

*CAES Potential for Cuyuna North Range Study Area 5: Huntington, Feigh, and Martin Mines; Crosby and Hennen Reserves*

Figures 1.2-44 through 1.2-47 illustrate the base map, hydrography, elevation, and surface ownership features of the Cuyuna North Range Study Area 5. The Feigh, Huntington, and Martin mines reside within the CCSRA. Multiple mountain bike trails over stockpiles on the northwest side of the Feigh and Huntington mines can be seen in Figure 1.2-44. The underground workings reside within the pit lake and have likely been mined out. The mine pit lake extends the full width of the iron-formation in the immediate area indicating that the orebody has been mined out.

The Crosby and Hennen reserves lie outside of the CCSRA and hold potential for mining to produce a CAES cavern. A major Minnesota Power transmission line passes within one-half mile of the Crosby reserve and one mile of the Hennen reserve. There is access to both reserves via county and township roads off of MN trunk highway 210 to the south. County road 128 and Irondale township road 204 cross the iron-formation in the Hennen reserve. The city of Riverton lies one-half mile south of the Crosby reserve and one-half mile southwest of the Hennen reserve.

There are wetlands in the vicinity of the Crosby reserve (Fig. 1.2-45). These include seasonally flooded scrub shrub wetlands and intermittently exposed unconsolidated bottom wetlands. The Hennen reserve is in an uplands area and is not impacted by wetlands.

LiDAR elevation contours in Figure 1.2-46 show the presence of stockpiles ranging in height from 60 feet just north of the Hopkins-Sultana pit to 190 feet on the north side of the Feigh pit. There are 60-foot-high stockpiles to both the northwest and southeast of the iron-formation in the Crosby reserve.

There is very low relief, maybe two to three feet, over nearly all of the iron-formation within the Crosby reserve, with the exception of a northeast-trending elongated eight foot rise along the axis between two lobes of the iron-formation on a possible drag fold.

There is as much as twelve feet of relief over the iron-formation in the Hennen reserve. Some of this is related to the Mallen pit and County Road 128 that runs the length of the iron-formation.

Although not shown in Figure 1.2-46, surface ownership of both the Crosby and Hennen reserves is divided into multiple parcels that are privately owned. Much of it is classified as non-commercial seasonal residential recreational property (Crow Wing County GIS Public Map Service, 1915). Structures can be seen in Figure 1.2-44. The land between the Crosby and Hennen reserves is state-owned tax forfeit land.

CAES Positives:

- The Crosby and Hennen reserves are located outside of the CCSRA;
- Both reserves are adjacent to previous mining activities;
- Ore reserve estimates are available for both reserves;
- There is a transmission line within one-half or one mile of both reserves;
- There is road access to the properties; and
- There is state land bordering on the Crosby and Hennen reserve properties.

CAES Negatives:

- The Huntington, Feigh, and Martin mines reside within the CCSRA;
- The Huntington, Feigh, and Martin underground workings and orebodies are apparently mined out, as is the South Hillcrest orebody between the Huntington and Feigh mines;
- There are multiple structures in close proximity to the Crosby and Hennen reserves;
- There are multiple private recreational land parcels on and adjacent to the Crosby and Hennen reserves; and
- The Crosby reserve resides in a wetlands area.

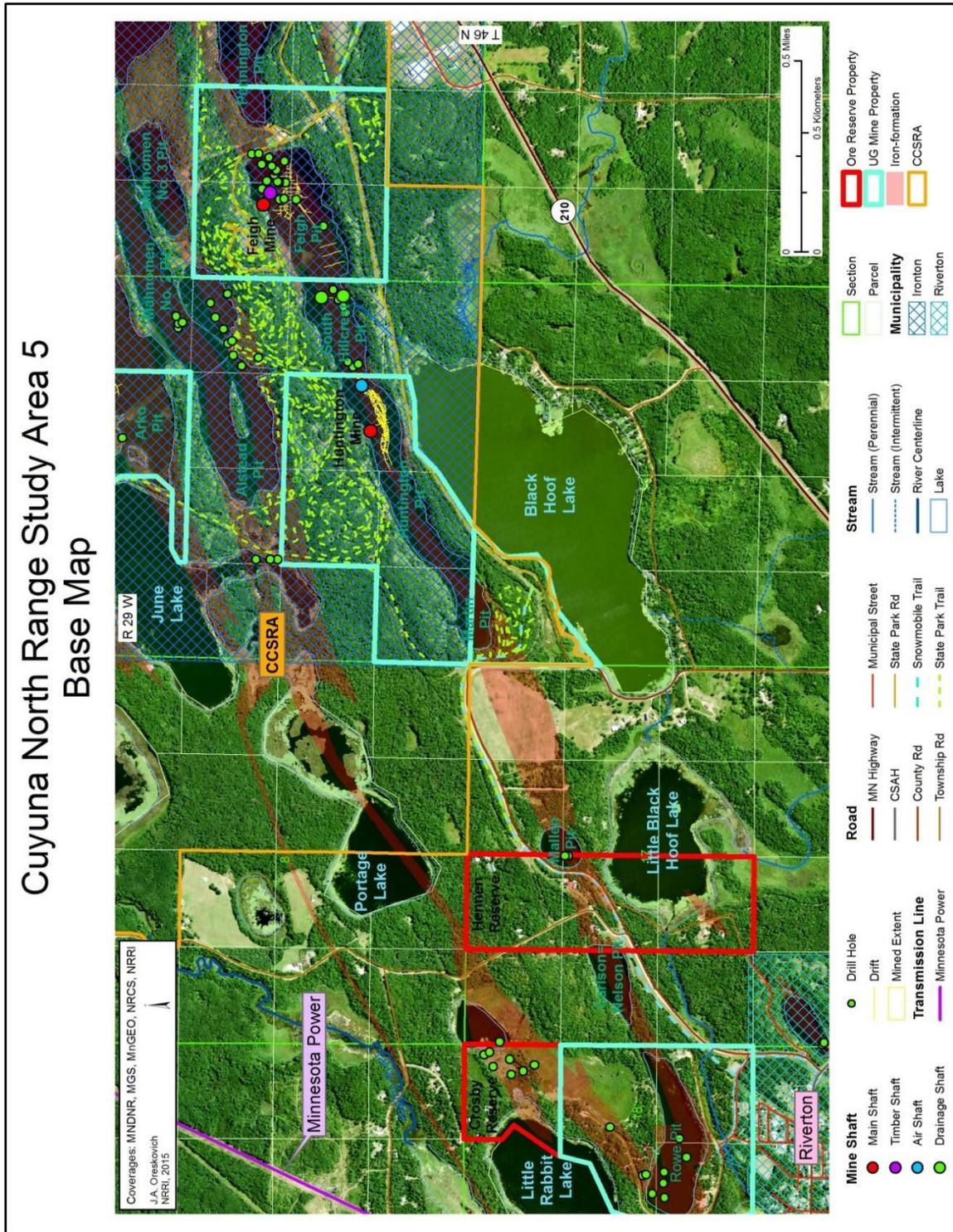


Figure 1.2-44. Cuyuna North Range Study Area 5 base map.

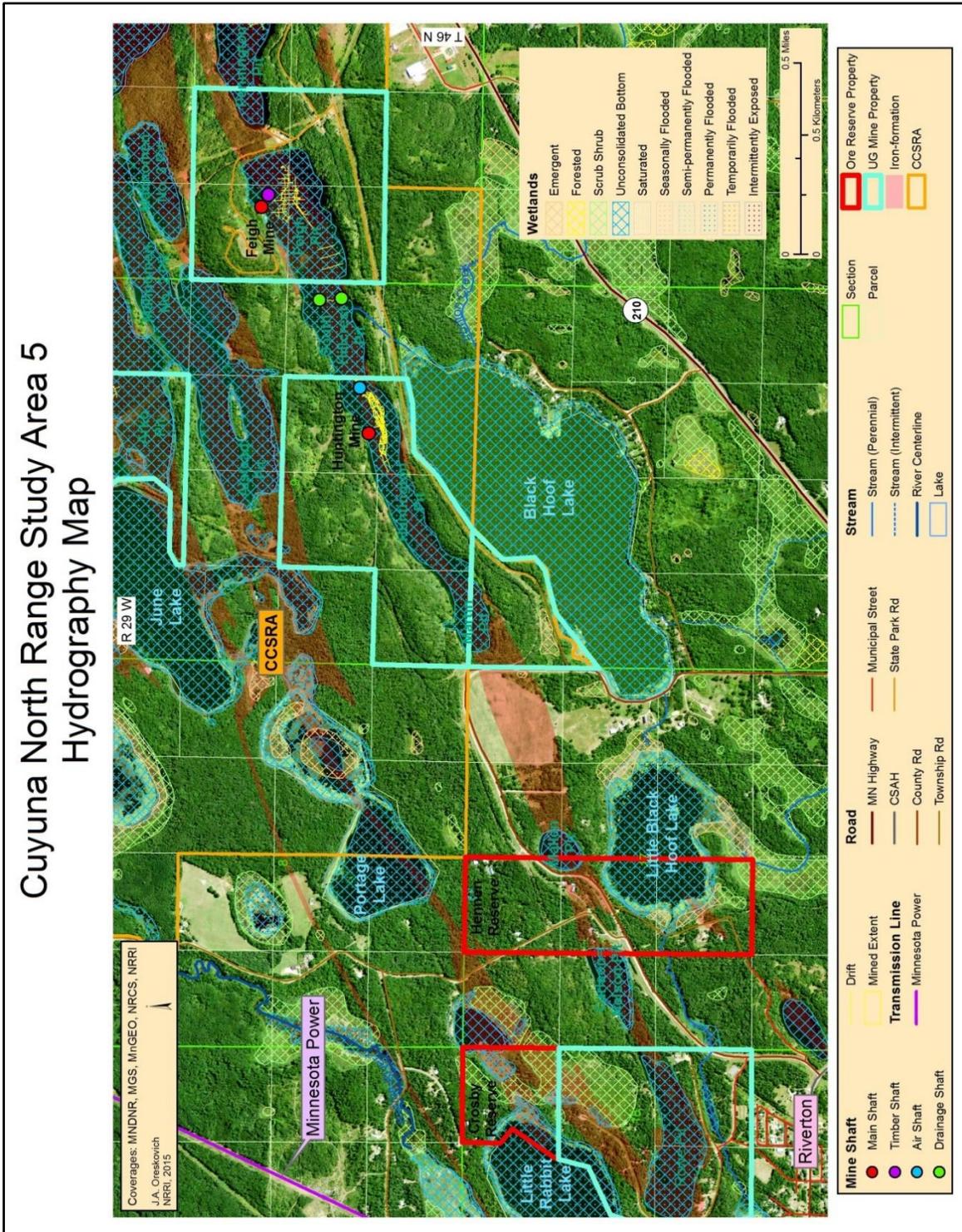


Figure 1.2-45. Cuyuna North Range Study Area 5 hydrography map.

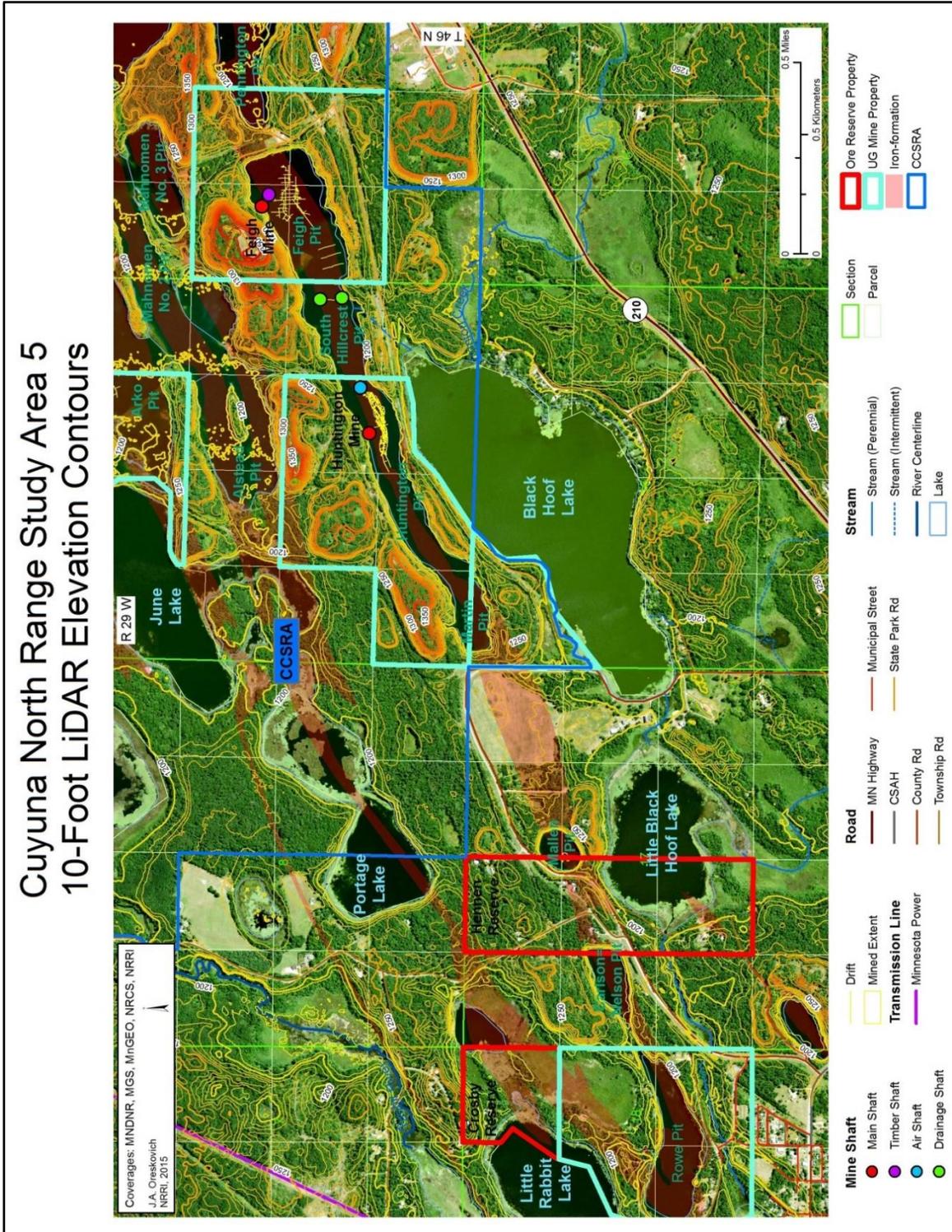


Figure 1.2-46. Cuyuna North Range Study Area 5 10-foot LiDAR elevation contours.

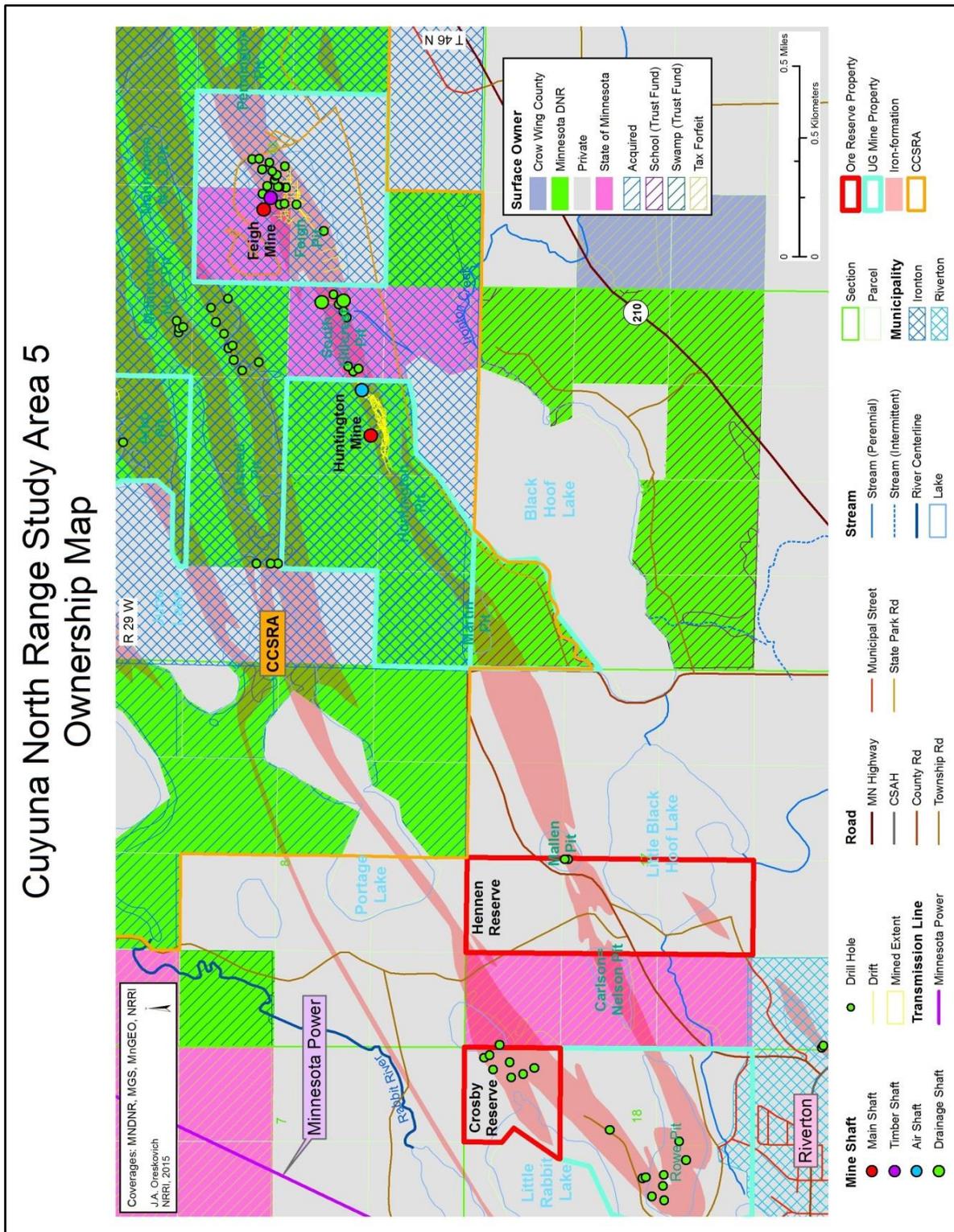
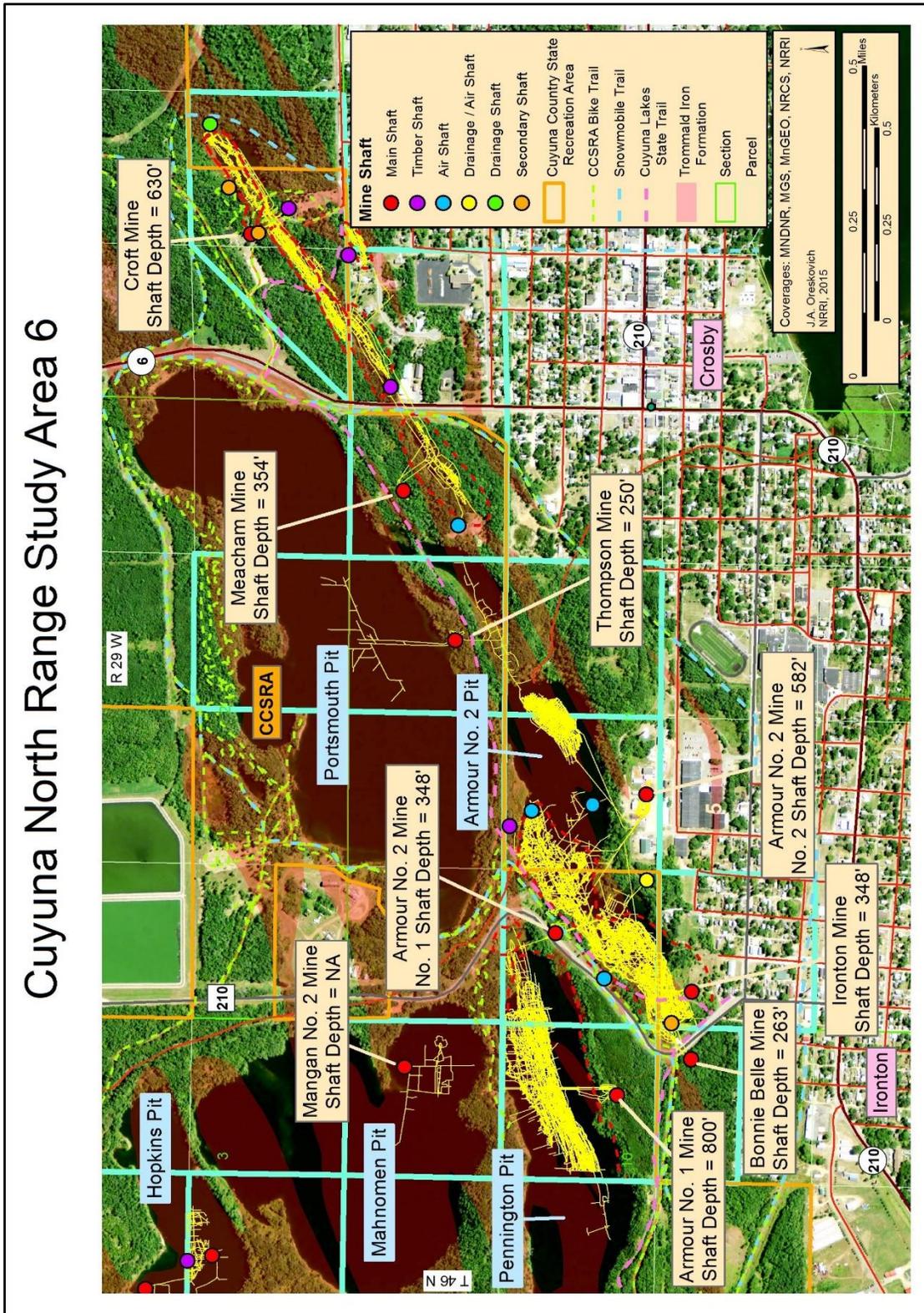


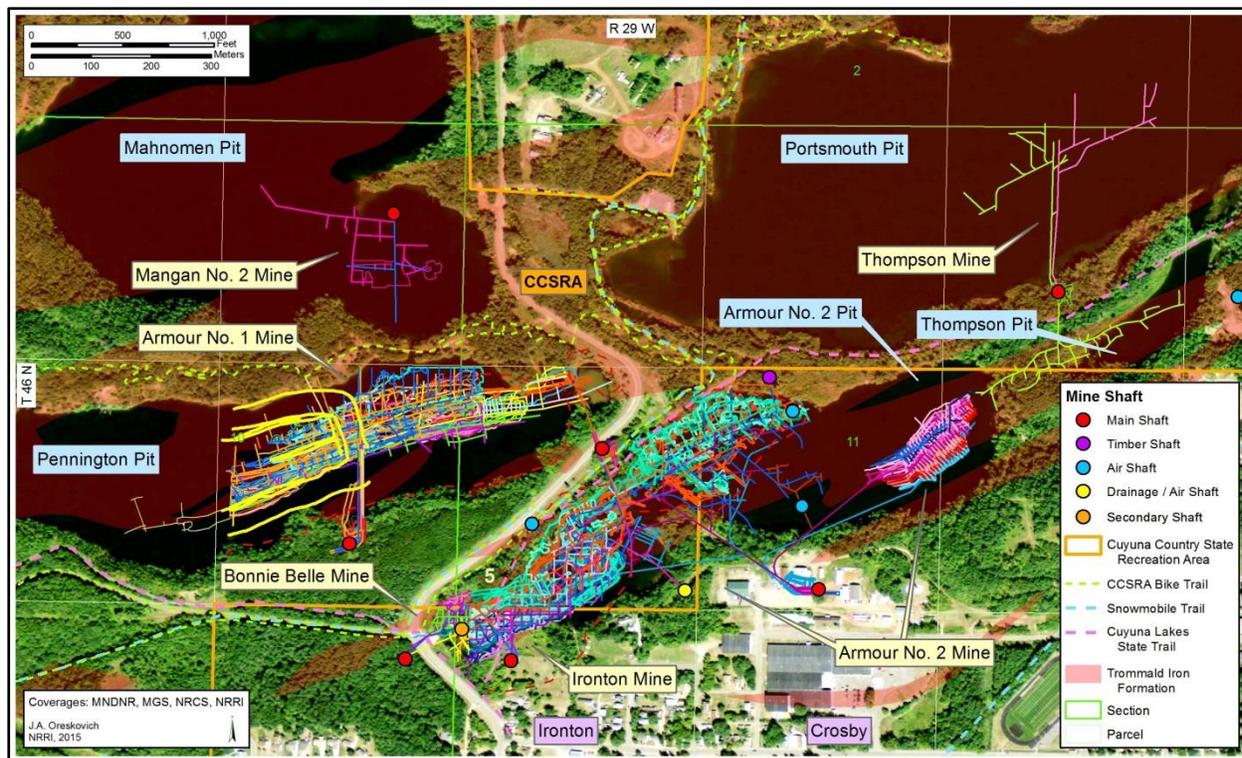
Figure 1.2-47. Cuyuna North Range Study Area 5 surface ownership map.

Cuyuna North Range Study Area 6



**Figure 1.2-48.** Cuyuna North Range Study Area 6: Mangan No. 2, Armour Nos. 1 and 2, Bonnie Belle, Ironton, Thompson, Meacham, and Croft mines.

The underground mines of Study Area 6—Mangan No. 2, Armour Nos. 1 and 2, Bonnie Belle, Ironton, Thompson, Meacham, and Croft—lie within or abut the boundaries of the CCSRA. Those mines (Bonnie Belle and Ironton) that are outside the CCSRA are connected via underground workings to mines within the CCSRA.



**Figure 1.2-49.** The extensive underground workings of the Armour mines and the Bonnie Belle and Ironton mines are displayed, along with those of the Mangan No. 2 and Thompson mines.

Mangan No. 2

Mine	Former Name	Range	S	T	R	Parcel	UG	OP	ML
Mangan No. 2		North Range	10	46	29	NE-NE	X	X	
Shaft Sinking	1st Shipment	Last Shipment	Total Ore Shipped			Last Operator	Last Known Fee		
1916	1916	1956	2,175,086 (UG & OP)			Pickands Mather & Co.	State		
Overburden (Ft.)	Mine Depth	Top Level	Lowest Level		Mining Method	Shaft Type			
52	110 Ft. (UG)	Sub-level (UG)	110-Ft. Level (UG)			round timber shaft			

The Mangan No. 2 mine (Fig. 1.2-49) began as an underground operation, with shaft sinking in 1916 (Harder and Johnston, 1918). The first ore shipment occurred later that same year (Skillings Mining Review, 2005). Maps show drifting on a main level and workings on one sub-

level. The greatest vertical depth in the underground mine was 110 feet (Crowell & Murray, 1917). This depth was used as that of the main level for this report.

At some time prior to 1920, the Mangan No. 2 mine began operating as an open pit mine (Crowell & Murray, 1920), and the underground workings were mined out. The pit was 250 feet deep by 1920 (Crowell & Murray, 1920). While the Mangan No. 2 pit was eventually operated as part of the Mahnommen Group, it was considered to be a separate orebody (Schmidt, 1963).

The Mangan No. 2 resides on the northeast end of a large syncline that is over three miles in length, extending southwest to the Rowe mine (Schmidt, 1963) (Fig. 1.1-37). Schmidt (1963) places the Mangan No. 2 ores in the thin-bedded facies of the Trommald Formation. Both manganiferous iron ores and iron ores were produced from the Mangan No. 2 (Harder and Johnston, 1918).

### Armour No. 1 Mine

Mine	Former Name	Range	S	T	R	Parcel	UG	OP	ML
Armour No. 1		North Range	10	46	29	SE-NE	X	X	
Shaft Sinking	1st Shipment	Last Shipment	Total Ore Shipped			Last Operator	Last Known Fee		
1910-1911	1912	1960	6,827,844 (UG & OP)			Inland Steel Company	State		
Overburden (Ft.)	Mine Depth	Top Level	Lowest Level	Mining Method		Shaft Type			
65	800 Ft.	100-Ft. Sub	800-Ft. Level	slicing & caving, part open pit		circular concrete shaft in surface; 5-compartment wooden shaft, 12' x 16'			

The Armour No. 1 shaft (Fig. 1.2-49), the deepest on the Cuyuna Range at 800 feet, was sunk in 1910. It operated as an underground mine for several years, shipping ore in 1912 and 1913. The mine was idled in July of 1913 until stripping of the western end of the orebody began for open pit mining in 1915 (Harder and Johnston, 1918). Shipments were made from the open pit that same year. Underground mining resumed by 1926 and continued until 1959, as indicated on mine maps that were found.

Mining of the Armour No. 1 orebody was continuous from a depth of 100 feet to 800 feet. The top slicing and caving method was used (Schmidt, 1963; Crowell & Murray, 1917). Zapffe (1933) describes the Armour No. 1 orebody as consisting of “two narrow bands of ore of great depth on the limbs of a closely pressed syncline dipping southeast.” Schmidt (1963) reports that both red-brown and brown iron ores and manganiferous iron ores were produced.

Although located within the CSSRA, the Armour No. 1 mine holds potential for CAES use. It is discussed in detail in Section 1.1 of this report (Scenario 3: Use of Legacy Mining Features (Medium Volume Storage Facility)). Included is a schematic of the shaft design.

Armour No. 2 Mine

Mine	Former Name	Range	S	T	R	Parcel	UG	OP	ML
Armour No. 2		North Range	11	46	29	SW-NE & S1/2-NW	X	X	
Shaft Sinking	1st Shipment	Last Shipment	Total Ore Shipped			Last Operator	Last Known Fee		
1910-1911	1912	1968	9,140,463 (UG & OP)			Inland Steel Co.	State		
Overburden (Ft.)	Mine Depth	Top Level	Lowest Level	Mining Method		Shaft Type			
63	582 & 800 Ft.	77-Ft. Sub	582-Ft. Level	slicing & caving; stoping; part OP		circular concrete shaft in surface (No. 1); 5-compartment (Nos. 1 & 2); 12' x 16' (No. 2)			

The Armour No. 2 mine (Fig. 1.2-49) was opened around the same time as the Armour No. 1, and, likewise, first shipped ore in 1912 (Schmidt, 1963). Three orebodies were mined in the Armour No. 2 properties. Zapffe (1933) describes the orebodies as “partly on the same syncline” as the Armour No. 1 mine and “partly on a series of minor folds to the south resulting from uplift of the trough of the major syncline” (seen as S<sub>4</sub> in Fig. 1.2-5).

The Armour No. 2 mine was served initially by a 348-foot-deep 5-compartment shaft located in schist between the two northernmost orebodies. This shaft connected to the Armour No. 1 shaft via a ¼ mile long drift, so that each could serve as an air shaft for the other mine (Edwards, 1913). Maps show this drift to be on the 168-foot level of the Armour No. 2 mine.

The first orebody, located in the northeast corner of the SW-NW S11-T46-R29, is a continuation of the Armour No. 1 orebody. With the exception of ore mined on the 168-foot level or higher, ore from this orebody would have been mined through the Armour No. 1 mine and hoisted out through the Armour No. 1 shaft.

Maps found indicate that ore was mined as deep as 730 feet in this parcel, if not deeper. While maps show that the main haulage drift on the 800-foot level extends from the Armour No. 1 property into the Armour No. 2 property, the orebody itself is shown only in outline form for volume calculation purposes. There was insufficient information found to determine if the orebody had mined from the 800-foot level.

The second orebody trends northeastward through all three parcels from the southwestern corner of the SW-NW S11-T46-R29 to the northwestern portion of the SW-NE S11-T46-R29. This was the main orebody mined in the Armour No. 2. Mining was done by both underground and open pit methods. A second 5-compartment shaft was sunk in the southern part of the SE-NW S11-T46-R29, now part of the Crosby Industrial Park.

Orebody A, the third orebody, is located to the southeast of the second orebody. The orebody trends northeastward across the boundary between the two easternmost parcels. Orebody A was mined subsequent to the open pit mining noted in the previous paragraph.

Greater detail on the Armour No. 2 mine, including a schematic of the shaft set detail of the second main shaft (Shaft No. 2), is presented in Section 1.1 of this report (Scenario 3: Use of Legacy Mining Features (Medium Volume Storage Facility)). The No. 2 shaft resides outside of the CCSRA and may hold potential for CAES.

Bonnie Belle Mine

Mine	Former Name	Range	S	T	R	Parcel	UG	OP	ML
Bonnie Belle	Liberty	North Range	10	46	29	N1/2-NE-SE	X		
Shaft Sinking	1st Shipment	Last Shipment	Total Ore Shipped			Last Operator	Last Known Fee		
January, 1918	1918	1925	225,706			Liberty Mining Co.	State		
Overburden (Ft.)	Mine Depth	Top Level	Lowest Level	Mining Method		Shaft Type			
	373 Ft.	106-Ft. Sub	373-Ft. Level	Stoping (?)		2-compartment			

The Bonnie Belle mine is located on the southwestern extension of the Armour No. 2 mine's main orebody, in the far northeastern corner of the NE-SE of S10-T46-R29 (Fig. 1.2-49). Mine maps indicate that the Bonnie Belle mine extended into the far southeastern corner of the Armour No. 1 property.

Shaft sinking occurred in 1918 for the Liberty mine (Aulie and Johnson, 2002), the original name of the Bonnie Belle mine. The first ore shipment was reportedly made that same year (Skillings Mining Review, 2005). A total of 224,706 tons of ore was shipped from this property. It was operated by the Inland Steel Co. in conjunction with the Ironton mine from 1923 to 1925 (Schmidt, 1963).

Mine maps depict the shaft as a two-compartment shaft. The shaft is noted as being 263 feet deep in Figure 1.2-48 because that is the depth of the lowest crosscut seen on maps. There are lower drifts seen on maps in the mine area (at the 333-foot sub-level and 373-foot level), but they are coming in from the Ironton mine to the east. The 373-foot level in the Bonnie Belle mine is the equivalent of the 348-foot level in the Ironton mine.

The stoping method of mining was used, at least in the upper regions of the mine. Legends on maps of the 106- and 116-foot sub-levels reference the mined extents mapped as "stoped ground."

Schmidt (1963) writes that the Bonnie Belle orebody was enclosed in chlorite schist, as was this same orebody in the Armour No. 2 and Ironton mines. He notes that high-grade red non-bessemer ore was produced from the Bonnie Belle mine.

Ironton Mine

Mine	Former Name	Range	S	T	R	Parcel	UG	OP	ML
Ironton	Cuyuna-Duluth	North Range	11	46	29	NW-SW	X		
Shaft Sinking	1st Shipment	Last Shipment	Total Ore Shipped			Last Operator	Last Known Fee		
1912-1913	1913	1933 (stkpl)	968,166			Inland Steel Co.	Burns, H.		
Overburden (Ft.)	Mine Depth	Top Level	Lowest Level	Mining Method		Shaft Type			
65	383 Ft.	158-Ft. Sub	383-Ft. Level	top-slicing & caving		wooden lath shaft; 3-compartment			

The Ironton Mine, opened as the Cuyuna-Duluth mine, was developed during 1912 and 1913 (Schmidt, 1963). Its first ore shipment occurred in 1913 (Skillings Mining Review, 2005). It

is located in the far northwestern corner of the NW-SW of S11-T46-R29, on the same orebody as the Bonnie Belle mine and the main portion of the Armour No. 2 mines (Fig. 1.2-49).

The Ironton mine was opened with a wooden lath shaft (Zapffe, 1915a). Maps show a 3-compartment shaft. The mined orebody clips the parcel corner as it trends to the northeast, and its steep dip to the southeast is easily seen in cross-sections found. Schmidt (1963) notes that the Ironton orebody is bounded above and below by a gray-green schist. Drill holes on cross-sections show schist from ledge to the 200-foot level and 220-foot sub-level within 75 and 80 feet, respectively, of iron-formation at ledge. Ore was mined to the 383-foot level.

Ironton mine ore was a high-grade red and bluish hematite with little manganese (Schmidt, 1963). The top-slicing and caving method of mining was employed.

### Thompson Mine

Mine	Former Name	Range			S	T	R	Parcel	UG	OP	ML
Thompson		North Range			2	46	29	SW-SE	X	X	
					11	46	29	W1/2-NE	X	X	X
Shaft Sinking	1st Shipment	Last Shipment	Total Ore Shipped			Last Operator		Last Known Fee			
January, 1911	1912										
Overburden (Ft.)	Mine Depth	Top Level	Lowest Level	Mining Method		Shaft Type					
65	305 Ft.	150-Ft. Level (S)	250-Ft. Level (N & S)			5-compartment					

The Thompson mine shaft is located between two northeastward-trending orebodies (Fig. 1.2-49). It was sunk in January 1911 by the Inland Steel Company in the NW-NE of S11-T46-R29 (Aulie and Johnson, 2002). The shaft was a circular concrete shaft sunk through 65 feet of surface (Zapffe, 1915b). Shown on maps as a 5-compartment shaft, it reached a minimum depth of 250 feet, the depth of crosscuts to both the north and south orebodies. The Thompson shaft was included in CAES “Scenario 3b: Mine shafts in series” in Section 1.1 of this report.

Underground workings of the Thompson mine extended northward into the SW-SE of S2-T46-R29 and southward into the SW-NE of S11-T46-R29. Maps showed drifting at the 250-foot level in both the north and south orebodies. Drifting was also shown on the 150-foot level in the northern orebody. Schmidt (1963) noted that development of the Portsmouth orebody, which evolved into one of the largest pits on the Cuyuna Range (Fig. 1.2-49), originated in 1913 with the northward crosscut from the Thompson shaft into the northern part of the NW-NE parcel in Section 11.

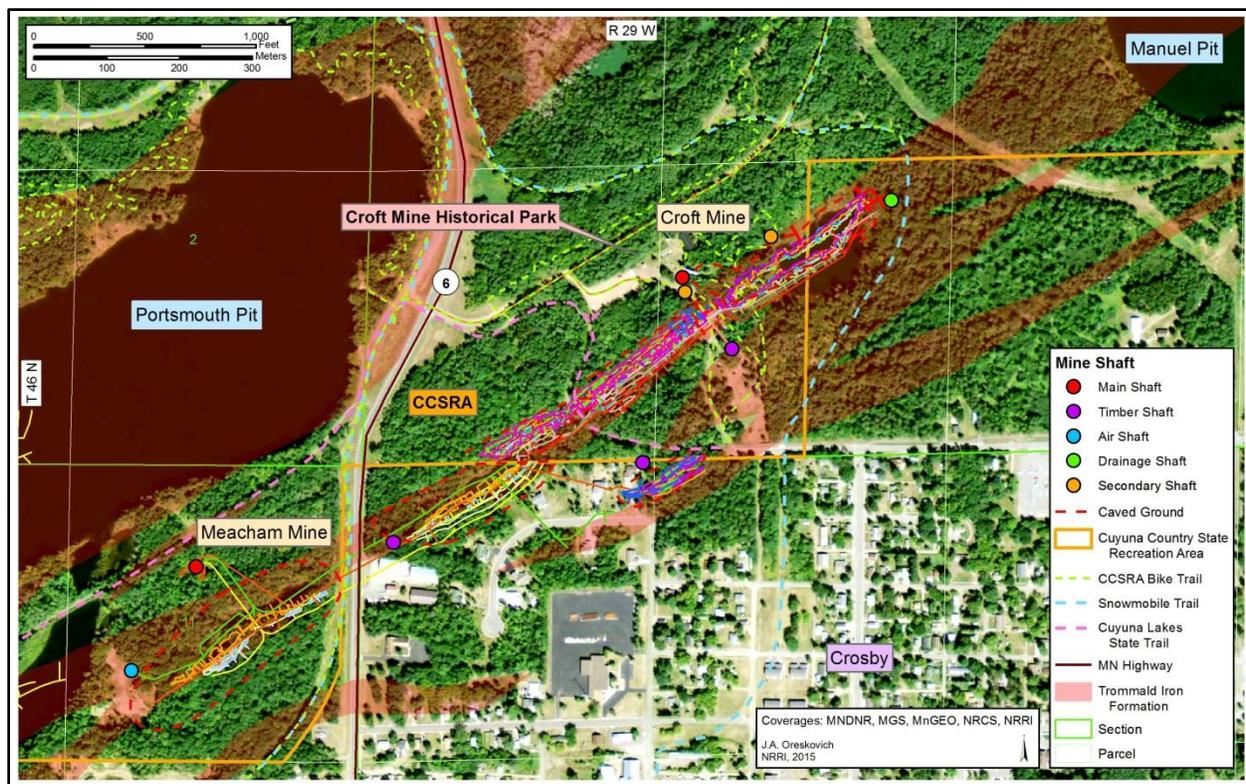
Ore shipments from the Thompson mine began in 1912 (Crowell & Murray, 1917), with shipments made from both orebodies in 1913 (Zapffe, 1915a). The underground workings in the southern orebody were shut down in mid-1915, with subsequent stripping of the orebody for open pit mining (Harder and Johnston, 1918). Meanwhile, underground mining continued in the northern orebody (Schmidt, 1963).

In the fall of 1916, open pit mining of the southern orebody ceased and a milling operation, which combines open pit and underground mining, was begun (Harder and Johnston, 1918). Ore was once again hoisted out through the shaft. A good description of the milling process,

together with a picture of the Thompson milling pit, can be found in Ostrand (1918). The milling pit was later filled with stripping from another mine (Schmidt, 1963).

Underground operations in the northern orebody ceased around this same time and stripping for an open pit operation was begun (Harder and Johnston, 1918). The northern orebody in Section 2 was mined as the Wearne pit (Schmidt, 1963). The Wearne pit was eventually incorporated into the Portsmouth mine.

The presence of two orebodies in the Thompson mine is due to a narrow infolded strip of Rabbit Lake Formation in the Trommald Formation (Schmidt, 1963). The northern orebody is part of the Portsmouth orebody, while the southern orebody lies on the same belt as the Armour No. 2 pit to the southwest and the Meacham underground mine to the northeast.



**Figure 1.2-50.** Underground workings of the Meacham and Croft mines. The Croft mine as shown represents only the upper half of this 630-foot-deep mine. Note its designation as a Historical Park.

Meacham Mine

Mine	Former Name	Range	S	T	R	Parcel	UG	OP	ML
Meacham		North Range	11	46	29	NE-NE	X	X	
			12	46	29	NW-NW, NE-NW	X		
Shaft Sinking	1st Shipment	Last Shipment	Total Ore Shipped			Last Operator	Last Known Fee		
1910	1916	1934	1,339,020			Pickens Mather & Co.	Minnesota Power, State		
Overburden (Ft.)	Mine Depth	Top Level	Lowest Level		Mining Method	Shaft Type			
70	354 Ft.	85 Ft. Level	350 Ft. Level		slicing & caving	circular concrete shaft; 5-compartment			

The Meacham mine opened in 1909 (Crowell & Murray, 1914) with a shaft located in the NE-NE of S11-T46-R29 (Fig. 1.2-50). The Meacham shaft reached a depth of 354 feet (Crowell & Murray, 1920). It is a circular concrete shaft to ledge, through 60 to 70 feet of surface (Zapffe, 1915a and Harder and Johnston, 1918, respectively). Maps portray the Meacham shaft as a 5-compartment shaft.

There were workings on the 85-, 105-, and 115-foot levels at the time of Harder and Johnston's report (1918), with the main hoisting level at 154 feet. Maps were found for 15 levels from the 135-foot level to the 350-foot level. Mining was done on ten foot intervals, for the most part, through the 305-foot level. The 350-foot level was the bottom crosscut and hoisting level. The slicing and caving mining method was used (Crowell & Murray, 1920).

Literature constrains the Meacham mine to a northern and central belt of iron-formation in the NE-NE of S11-T46-R29 and the NW-NW S12-T46-R29. Maps, however, show underground workings of the Meacham mine on a third, southern belt of ore in the far northeastern corner of the NE-NW of S12-T46-R29.

Ore was first shipped from the Meacham mine in 1916 (Skillings Mining Review, 2005). Both brown iron ores and manganiferous iron ores were produced (Schmidt, 1963). Workings of the Meacham underground mine are connected with those of the Croft underground mine located to the northeast along the same belt of iron-formation. Schmidt (1963) reports that the NW-NW of S12-T46-R29 was worked as part of the Croft mine from 1929 to 1931. The northwestern corner of the NE-NE of S1-T46-R29 was added to the Portsmouth mine in 1928 (Aulie and Johnson, 2002).

Croft Mine

Mine	Former Name	Range	S	T	R	Parcel	UG	OP	ML
Croft		North Range	1	46	29	SE-SW & SE Diag 1/2 SW-SW	X		
Shaft Sinking	1st Shipment	Last Shipment	Total Ore Shipped			Last Operator	Last Known Fee		
1914	1916	1934	1,770,669			Pickands Mather & Co.	State; Anderson, Allen et al.		
Overburden (Ft.)	Mine Depth	Top Level	Lowest Level	Mining Method		Shaft Type			
110	630 Ft.	112-Ft. Level	NA	caving		3-compartment: circular concrete shaft through surface; rectangular steel shaft below			

The Croft mine hosts the second deepest mine shaft on the Cuyuna Range. It is a 5-compartment shaft that extends to a depth of 630 feet (Schmidt, 1963), located in the SE-SE of S1-T46-R29 (Fig. 1.2-50). The mine extends into the SE diagonal ½ of the SW-SW of S1-T46-R29 to meet the Meacham mine. It was opened in 1914 and made its first ore shipment in 1916 (Skillings Mining Review, 2005).

The Croft ore deposit is described by Zapffe (1933) as “an unusually narrow lens” that is one mile long and 40 to 60 feet wide, located on a southward-dipping monocline. The mine’s great depth to narrow width makes it unique. Zapffe (1933) noted that the Croft mine was the only mine on the Cuyuna Range shipping Bessemer ore. The ore is high in iron content at 59.80% dry iron (53.67% natural iron), purplish-red in color and of rather fine structure, and is not treated prior to shipping (Zapffe, 1933).

While the Croft mine shaft extends down 630 feet (Schmidt, 1963), the workings shown on the maps in Figures 1.2-48 and 1.2-50 only reflect workings from the 112- to 333-foot levels. Ore was mined on 22 levels to this depth, using 10-foot and 11-foot intervals. Maps for any levels beneath the 333-foot level have not been acquired to date.

With the exception of the northeastern 20% of the orebody, the Croft mine workings reside within the CCSRA. One shaft, a drainage shaft, remains outside of the CCSRA. The level(s) at which this shaft connects to the mine workings is unknown.

In addition to the Croft mine’s residency within the CCSRA, the mine site has been designated the Croft Mine Historical Park (Fig. 1.2-50). Included among the park buildings is a partial replica of the underground mine that provides visitors with a sense of being underground among the workings. The mine site is accessible by road, snowmobile trail and multiple state park bicycle trails.

CAES Potential for Cuyuna North Range Study Area 6: Mangan No. 2, Armour Nos. 1 and 2, Bonnie Belle, Ironton, Thompson, Meacham, and Croft Mines

Figures 1.2-51 through 1.2-54 illustrate the base map, hydrography, elevation and surface ownership features of the Cuyuna North Range Study Area 6. Although most of the underground mine workings in Study Area 6 reside within the CCSRA, there are several factors

that lead to their consideration for CAES potential. Among these are relative location within the CCSRA, accessibility, and size and depth of the remnant mine features.

The underground mine workings of Study Area 6 lie between large pit lakes to the north and the cities of Ironton and Crosby to the south (Fig. 1.2-51). Their location just inside the southern boundary of the CCSRA keeps them removed from most of the mountain biking trails of the recreation area. However, there is a bike trail, as well as a snowmobile trail, that passes between the Armour No. 1 and the Armour No. 2 mines. Of more consequence is the Cuyuna Lakes State Trail, a paved asphalt trail that traverses east-west through the immediate area of the Study Area 6 underground workings, passing very close to the Bonnie Belle, Ironton, Armour No. 2 (No. 1 shaft), Thompson and Meacham shafts.

There is easy road access to the site from both Ironton and Crosby, as well proximity to two state highways, MNTH 210 (east-west) and MNTH 6 (north-south). While there are no major electrical transmission lines in the immediate area, there should be access to the nearby power grid for the cities of Ironton and Crosby. All of the underground workings in Study Area 6 are located within the municipal borders of Ironton or Crosby.

Distance to major transmission lines, both Great River Energy and Minnesota Power, is approximately six miles along MNTH 210 to the west. An overland route running from immediately south of the city of Riverton could shorten this distance by one mile. Distance from a major Minnesota Power transmission line to the north along MNTH 6 is slightly less than five miles.

The workings of the Mangan No. 2 mine and the Thompson mine's north orebody have been subsequently mined out. While the Armour No. 1 mine is seen within the confines of the Pennington pit, much of this is due to surface subsidence caused by the underground workings. Only the western part of the property was open pitted for a relatively short time in the earlier life of the mine. The underground workings were not sacrificed for the open pit.

The Armour No. 2 pit, likewise, did not disturb earlier underground workings as it mined a separate orebody. The underground workings shown within the pit are below the base of the pit. They were mined subsequent to the open pit mining.

The Armour No. 1, Croft, and Armour No. 2 mines have the deepest shafts on the Cuyuna Range at 800, 630, and 582 feet, respectively. The Croft shaft and mine is likely off-limits due to its designation as a Historic Park. The second Armour No. 2 main shaft (Shaft No. 2) is located outside of the CCSRA and within the Crosby Industrial Park. Access to the crosscuts and mine workings for CAES purposes could be gained from outside the CCSRA. Although located within the CCSRA, the Armour No. 1 shaft's location near the southern CCSRA perimeter may prove allowable in accessing the shaft, crosscuts and workings.

Figure 1.2-52 shows the land areas surrounding the underground mines and mine pits to be uplands with very little to no impact from wetlands in usable areas near mine shafts. The only stream traversing the area is Serpent Creek, a perennial drainage drift. The parcel containing the Armour No. 2 mine pit has been designated a water access site by the MDNR Trails and Waterways Unit. The parcel lies just outside of the CCSRA.

LiDAR elevation contours in Figure 1.2-53 indicate the presence of two stockpiles to the east and southeast of the Armour No. 2 pit. They also indicate subsidence along the length of the Meacham and Croft underground workings.

Most of the CCSRA land has been acquired by the Minnesota Department of Natural Resources (Fig. 1.2-54). There is private land in the industrial park where the Armour No. 2 shaft (Shaft No. 2) is located (Crow Wing County GIS Public Map Service, 1915).

CAES Positives:

- Deepest three mine shafts on the Cuyuna Range (800', 630' 582');
- Lengthy crosscuts through hard schist; likely uncollapsed (Armour Nos. 1 and 2; see detail in Section 1.1);
- Shafts in close proximity in a series;
- Shaft locations near or outside of southern CCSRA border;
- Local and highway road access;
- Uplands surrounding mine shafts; and
- Shaft located in industrial park (Armour No. 2).

CAES Negatives:

- Located mostly within the CCSRA;
- Nationally and internationally recognized mountain biking area/tourism draw;
- Recreational boating/fishing area;
- Croft Mine Historical Park;
- Relatively distant from major transmission lines;
- Cuyuna Lakes State Trail (paved) through immediate area; and
- Probable water level impacts due to likely underground connections from one mine to the next and to pit lakes.

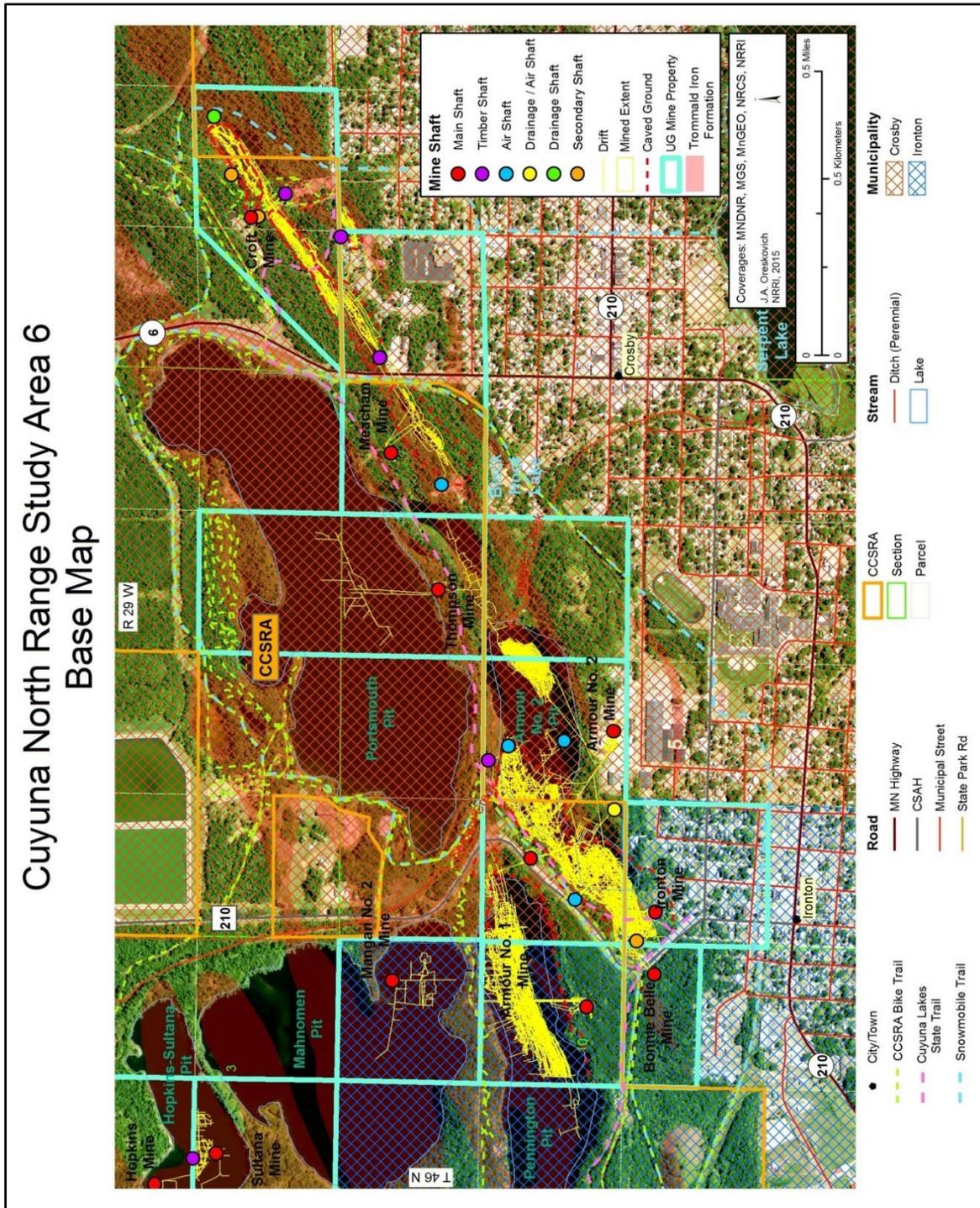


Figure 1.2-51. Cuyuna North Range Study Area 6 base map.

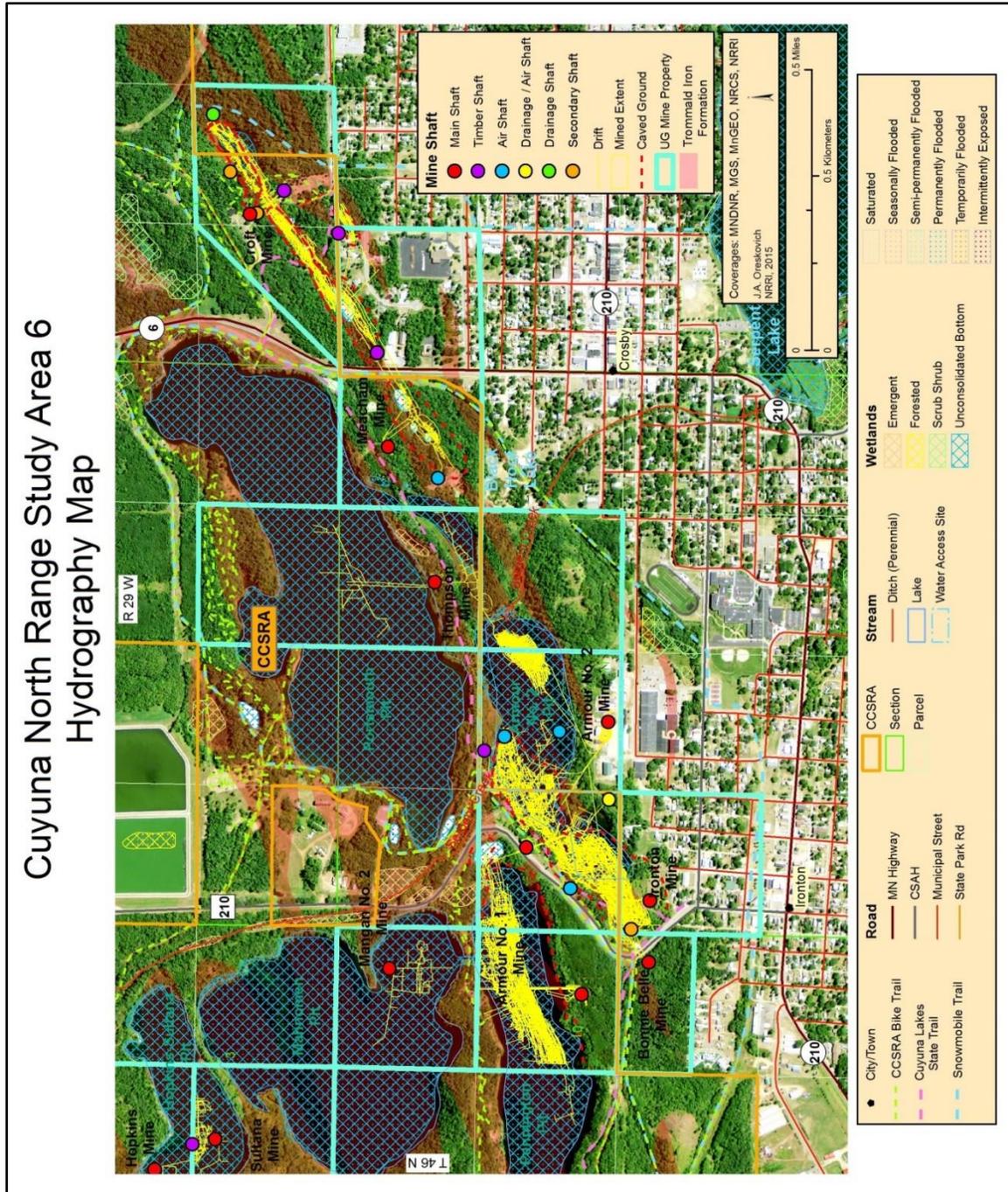


Figure 1.2-52. Cuyuna North Range Study Area 6 hydrography map.

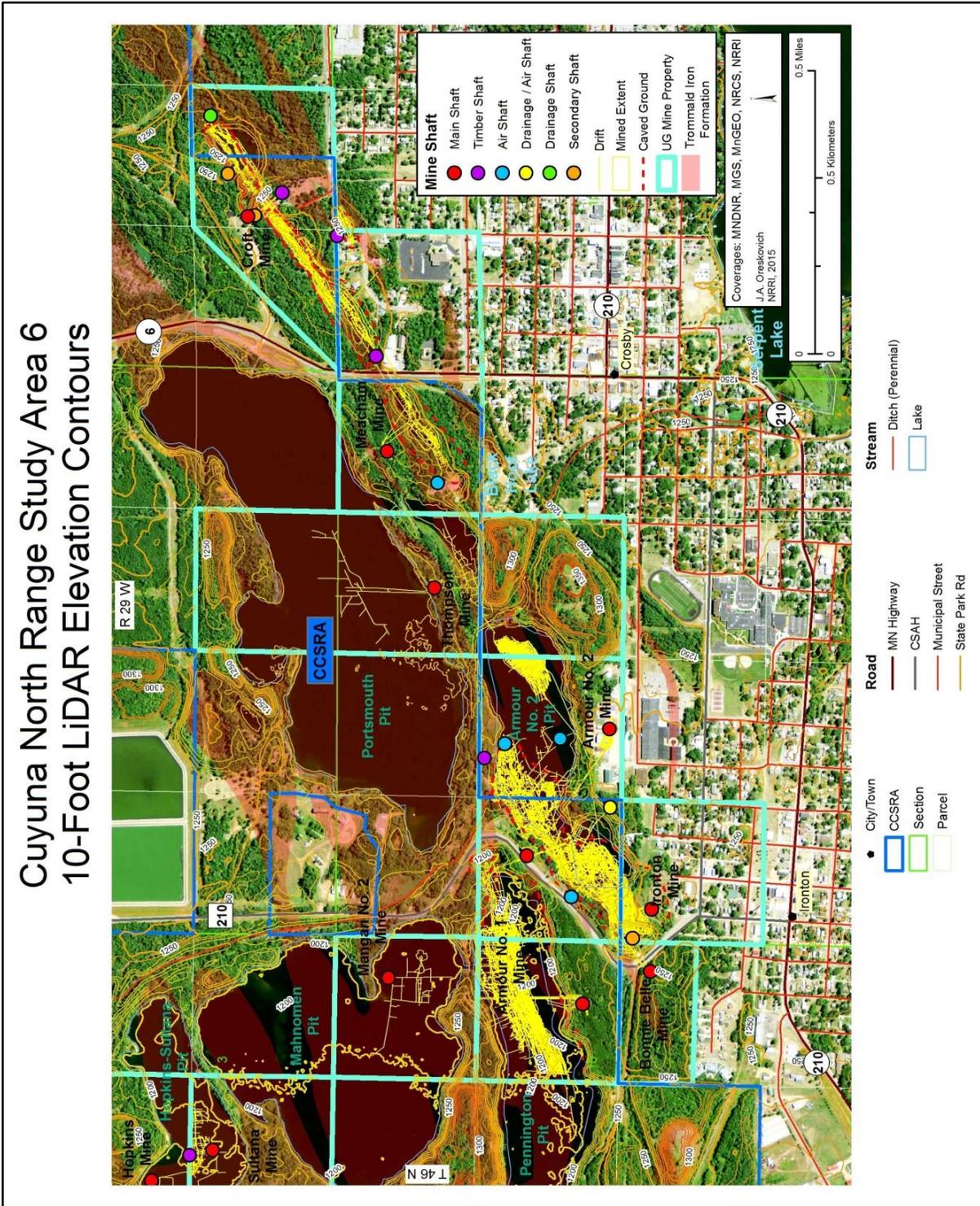


Figure 1.2-53. Cuyuna North Range Study Area 6 10-Foot LiDAR elevation contours.

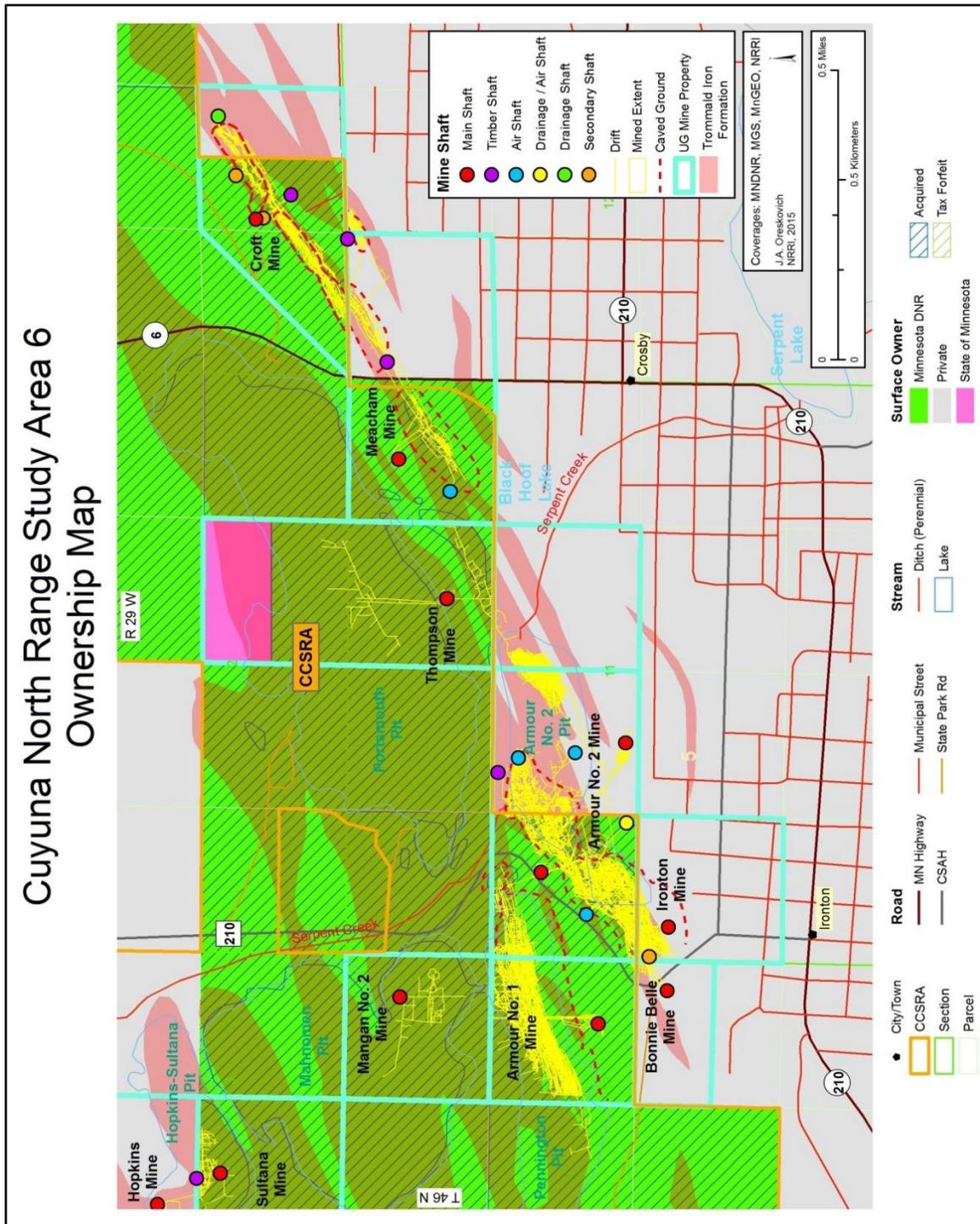


Figure 1.2-54. Cuyuna North Range Study Area 6 surface ownership map.

**Cuyuna South Range**

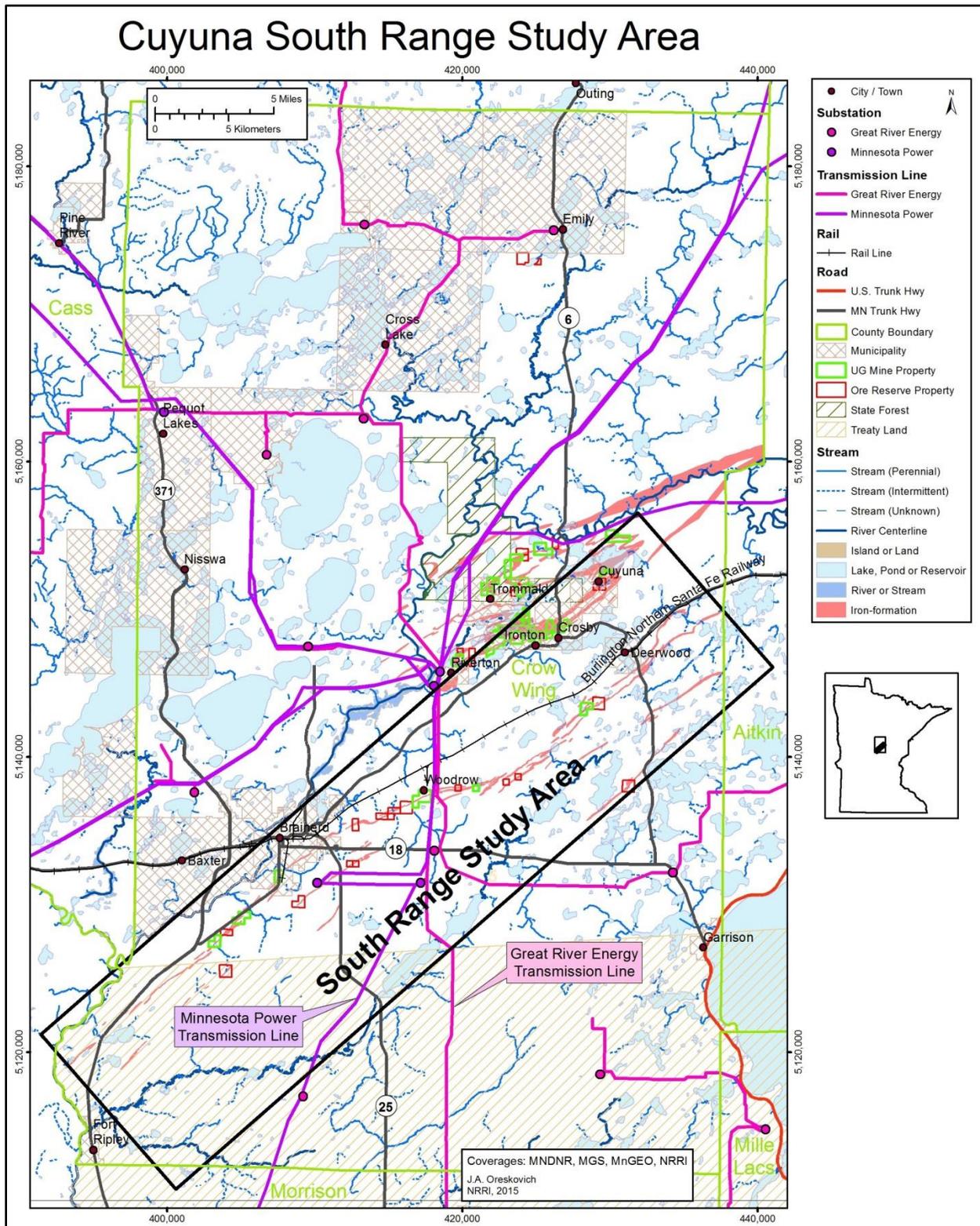
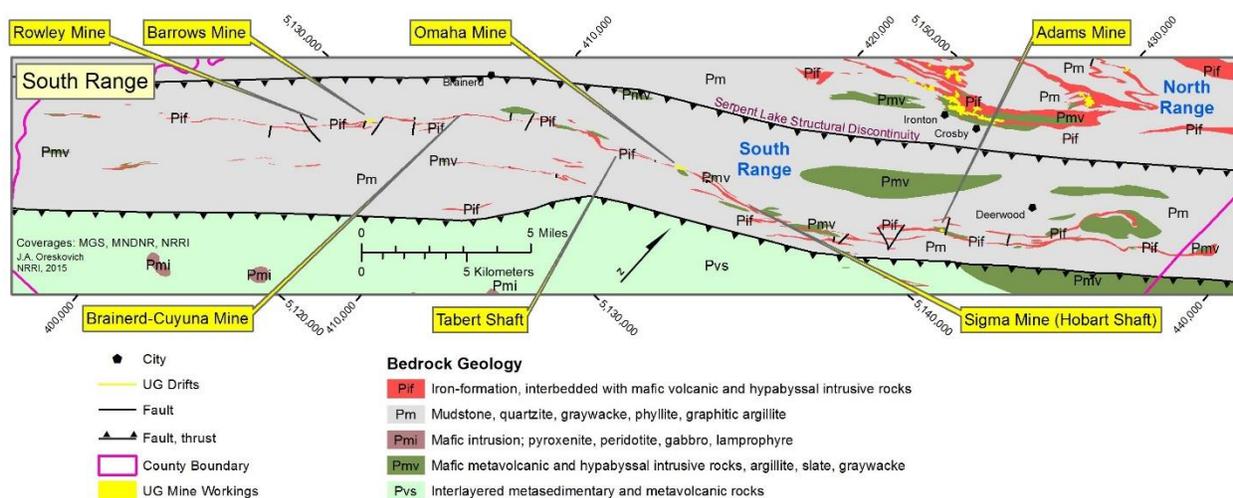


Figure 1.2-55. Cuyuna South Range study area base map.

The Cuyuna South Range extends northeastward from Morrison County, crossing the southern half of Crow Wing County from its southwestern corner to its east-central border, and continuing on into Aitkin County. All underground iron ore mining on the Cuyuna South Range took place within Crow Wing County. While the Gorman mine, an open pit mine, operated for a few years in Morrison County in the early 1950s, only those mines and ore reserve properties of the Cuyuna South Range that reside within Crow Wing County are discussed herein (Fig. 1.2-55).

The South Range iron-formation presents as a discontinuous band or bands of narrow lenses and layers (Fig. 1.2-56). Small stretches of two or three parallel bands were attributed by Harder and Johnston (1918) to be, in places, broken bands of iron-formation “where the ends are pushed past each other as in a drag fold or thrust fault.” In other places, they attributed the parallel bands to extensive folding.



**Figure 1.2-56.** Bedrock geology map of the Cuyuna South Range. (Source: Minnesota Geological Survey State Map Series S-22, 2011.)

The South Range iron-formation differs from the Trommald Iron Formation of the North Range in that much of it is “closely associated with mafic to intermediate volcanic rocks and hypabyssal intrusions,” implying Algoma-type iron-formation origin in small basins with associated volcanic activity (Morey, 1990). The Trommald Iron Formation of the North Range has historically been considered a classic Lake Superior type iron-formation, as is the Biwabik Iron Formation of the Mesabi Range. This classification is currently being reevaluated in light of new data (McSwiggen and Cleland, n.d.).

The South and North ranges lie within separate tectonic panels of the fold and thrust belt south of the Animikie Basin (Figs. 1.2-2, 1.2-4). These two tectonic panels are separated by the Serpent Lake structural discontinuity (Fig 1.2-56). Southwick et al. (1988) have defined three mappable rock units on the Cuyuna South Range: “1) more or less uniform metabasalt; 2) a complex sequence composed of mafic volcanic and hypabyssal rocks, graphitic slate or schist, and iron-formation, all interbedded; and 3) nongraphitic slate, argillite, and metasiltstone.”

South Range orebodies are generally longer and narrower than those of the North Range, with little or no minor folding; North Range orebodies are wider and can be very irregular in shape because of a greater amount of minor folding (Zapffe, 1915b). Zapffe (1915b) describes the general structural attitude of orebodies on both ranges as that of “steeply dipping lenses encased in barren rock of various types.” In differentiating between ores of the South and North ranges, Zapffe notes that South Range ores are predominantly limonitic and brown versus predominantly hematitic and red on the North Range.

Zapffe (1933) described unoxidized South Range iron-formation as a banded slaty amphibole magnetite with an abundance of iron carbonate. More recent publications (Southwick et. al, 1988, and Morey, 1990, among others) expand on Zapffe’s earlier description. Zapffe (1933) reported that the South Range ore is a single bed repeated, in comparison to an upper and lower band of ore on the North Range.

Churn drilling was used for the most part in exploration of the Cuyuna District due to the softness of the ores (Donovan, 1915). Not only the ores, but the iron-formation itself was soft enough for churn drilling on the South Range. Diamond drilling accounted for as little as 15% of the total drilling on one multi-parcel deposit that was typical of the South Range (32% of the drilling from ledge down) (Donovan, 1915). North Range iron-formation was likewise soft, but to a lesser degree than that of the South Range. In addition, the boulder pavements sometimes encountered on the Mesabi Range were not found in the Cuyuna District (Donovan, 1915).

Table 1.2-30 is a summary table of Cuyuna South Range underground mines. Seven mines were started on the Cuyuna South Range in Crow Wing County, with shafts sunk between 1905 and 1915. All were short-lived. Only four of these mines shipped ore, two of rather insignificant amounts: the Brainerd-Cuyuna (3,199 long tons) and the Adams (5,535 long tons). The Barrows and Omaha (Wilcox) mines shipped 56,439 and 279,316 long tons, respectively. The final year of ore shipments from an underground mine on the Cuyuna South Range was 1919.

For this report, the Cuyuna South Range has been divided into five study areas (Fig. 1.2-57). The study areas are presented from east to west. Maps of the mine and ore reserve properties are provided. Data files at the MDOR Minerals Tax Office in Eveleth, MN were searched for information on ore reserve properties that were identified in Beltrame (1977). Typical findings were ore reserve estimates and assay data, which are presented in table format.

Table 1.2-31 provides an alphabetical summary listing of the ore reserve properties. The ore reserve properties are included here as potential sites to mine to create a CAES cavern. While these orebodies may have been too small to make full-fledged underground mining economically feasible, they provide an opportunity to off-set costs of CAES cavern construction. Additional drilling, sampling and assaying would be necessary to prove up the resource. Original data (drill holes, cross-sections and assay results) are available on microfilm at the MDOR office in Virginia, MN.

**Table 1.2-30.** Summary table of Cuyuna South Range underground mines.

CUYUNA SOUTH RANGE UNDERGROUND MINE SUMMARY															
Mine	Other Names	S	T	R	Parcel	UG	OP	ML	Shaft Only	Main Shaft Compartments	Depth (Ft.)	Overburden (Ft.)	Top Level	Bottom Level	Page
1	Adams Chesquitawney	30	46	28	SE-NW, Lots 2 (SW-NW) & 3 (NW-SW)	X				NA	207	123	200-Ft. Level	200-Ft. Level	
2	Barrows	10 11	44 44	31 31	N1/2-SE & SE-NE SW-NW	X				3	160	110	110-Ft. Level	160-Ft. Level	
3	Brainerd-Cuyuna	36	45	31	E1/2-SW & PRT of NW-SE	X				3	164	90	154-Ft. Level	154-Ft. Level	
4	Omaha Mine Wilcox, Woodrow	13	45	30	SE-NW	X				3	230	93	125-Ft. Sub	200-Ft. Sub	
5	Rowley	16	44	31	SE-NE & N1/2-SE	X			X?	NA	350?	100	NA	NA	
6	Sigma Hobart Shaft	8	45	29	SW-SE	X				NA	120	76	114-Ft. Level	114-Ft. Level	
7	Tabert	22	45	30	N1/2-NE	X			X?	NA	NA	NA	NA	NA	

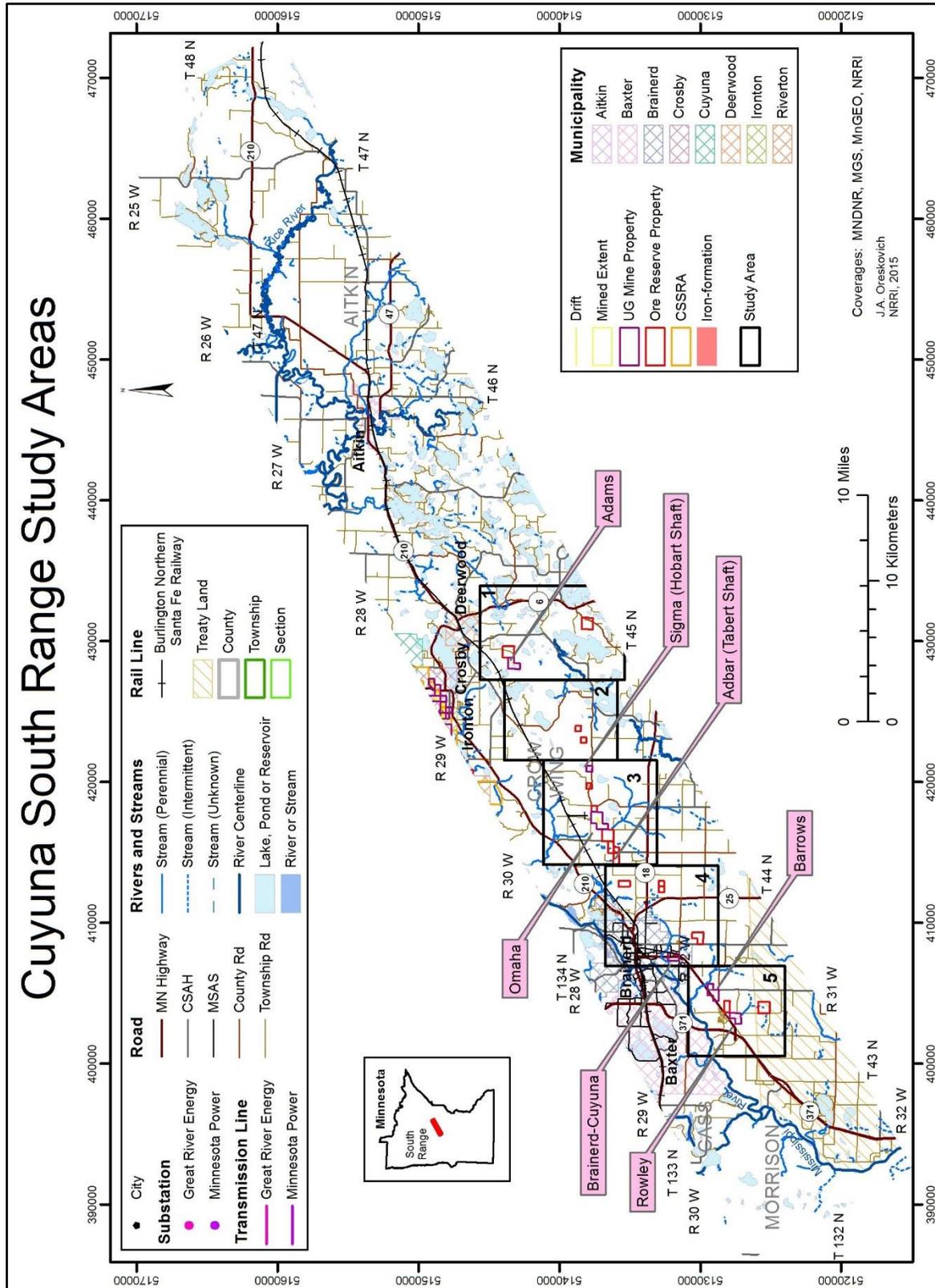


Figure 1.2-57. Location map of Cuyuna South Range study areas and underground mines.

**Table 1.2-31. Summary table of Cuyuna South Range ore reserve properties.**

	Ore Reserve	S	T	R	Parcel	Res. Est. Tons	Est. Year	Data Avail. <sup>1</sup>	Assay Data	Surface Owner	Fee Owner	Page
1	Barrows Mine	10	44	31	N1/2-SE & SE-NE	506,060	1965	X	X	Private	Taylor Properties	
		11	44	31	SW-NW							
2	Barrows Reserve (H-1) Brainerd-Cuyuna Mine	15	44	31	N1/2-NW	330,875	1986	X		Private	Hanna Iron Ore Div.	
		36	45	31	NW-SE	32,825	1986	X	X	City of Brainerd	Brainerd; Madison, DR.	
3	Clearwater Lake Reserve (X-43)	8	45	28	E1/2-SE	286,000	1965	X	X	Private	Bergman, Knutsen, Street, & Ulman, (Trustee), Presbyterian Synod of Lakes & Prairies et al.	
		9	45	28	W1/2-SW	197,000						
4	Crow Wing Reserve	30	46	28	NE 1/4	484,700	1989	X		Private	U.S. Steel Corp.	
5	Cuyuna Reserve (H-2)	21	45	30	SW-NE & NW-SE	806,006	1986	X		Private	Hanna Iron Ore Div. (22.5%)	
6	Dunn Reserve (H-3)	14	45	30	S1/2-SW	1,416,617	1986	X		Private	Hanna Iron Ore Div.	
7	Gunderson Reserve (O-34)	7	45	29	SE-SE	NA	1958	X		Private	U.S. Steel Corp.	
8	NWI Reserve (X-46)	10	45	29	SE-NW	NA	1958	X		Private	Glacier Park Co.	
9	NWI Reserve (X-47)	13	45	30	NE-NE	NA	1985	X		Private	Glacier Park Co. (1/2); U.S. Steel Corp. (1/2)	
10	NWI Reserve (X-48)	14	45	30	SE 1/4	NA		X		Private	Burlington Northern Inc.	
11	NWI Reserve (X-49)	33	45	30	NW-NE	NA	1967	X		Private	Burlington Northern Inc.	
12	NWI Reserve (X-50)	33	45	30	NE-NW	NA	1967	X		Private	Glacier Park Co.	
13	NWI Reserve (X-51)	22	44	31	SW 1/4	531,429	1965	X		Private	Glacier Park Co.	
14	NWI Reserve (X-52)	6	44	30	S1/2-SW & NE-SW	296,074	1967	X	X	Private	Glacier Park Co.	
15	NWI Reserve (X-53)	9	45	29	NE-SE	NA	1958	X		Private	Burlington Northern Inc.	
16	Omaha Mine Reserve	13	45	30	E1/2-NW, SW-NW & NW-SW	1,447,542	1965	X	X	Private	State; Swindlehurst et al.	
17	Polk Reserve (X-58)	23	45	30	NW-NW	132,321	1986	X		Private	Univ. of Minn. et al.	
18	Tabert Reserve (H-24)	22	45	30	NE-NE & S1/2 NW-NE	220,849	1986	X		Private	Hanna Iron Ore Div.	

<sup>1</sup>Data available (including drill hole assay data and geologic cross-sections) on microfilm at the MDOR Minerals Tax Office in Virginia, MN.

Cuyuna South Range Study Area 1

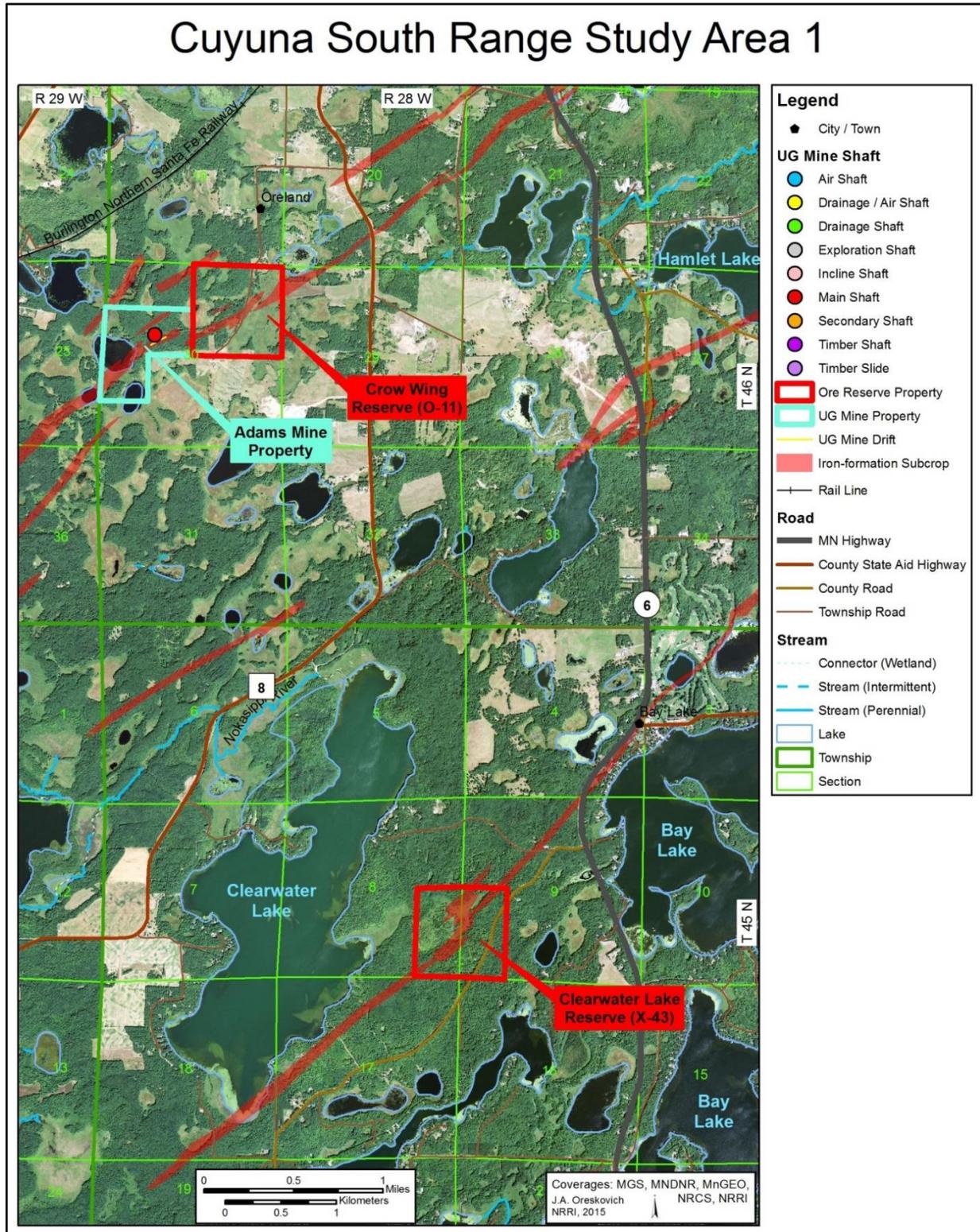


Figure 1.2-58. Cuyuna South Range Study Area 1: Adams mine; Crow Wing and Clearwater Lake reserves.

The Cuyuna South Range Study Area 1 lies to the southeast of the North Range cities of Crosby and Ironton. The Burlington Northern Santa Fe rail line, seen in the northwest corner of Figure 1.2-58, separates the two ranges. Residing within one mile of the boundary separating Crow Wing and Aitkin counties, Study Area 1 contains the eastern-most mine of the South Range, the Adams mine, as well as two ore reserve properties, the Crow Wing (O-11) and Clearwater Lake (X-43) reserves. Study Area 1 is populated by multiple lakes of varying scale, as well as wetlands in the vicinity of the properties mentioned.

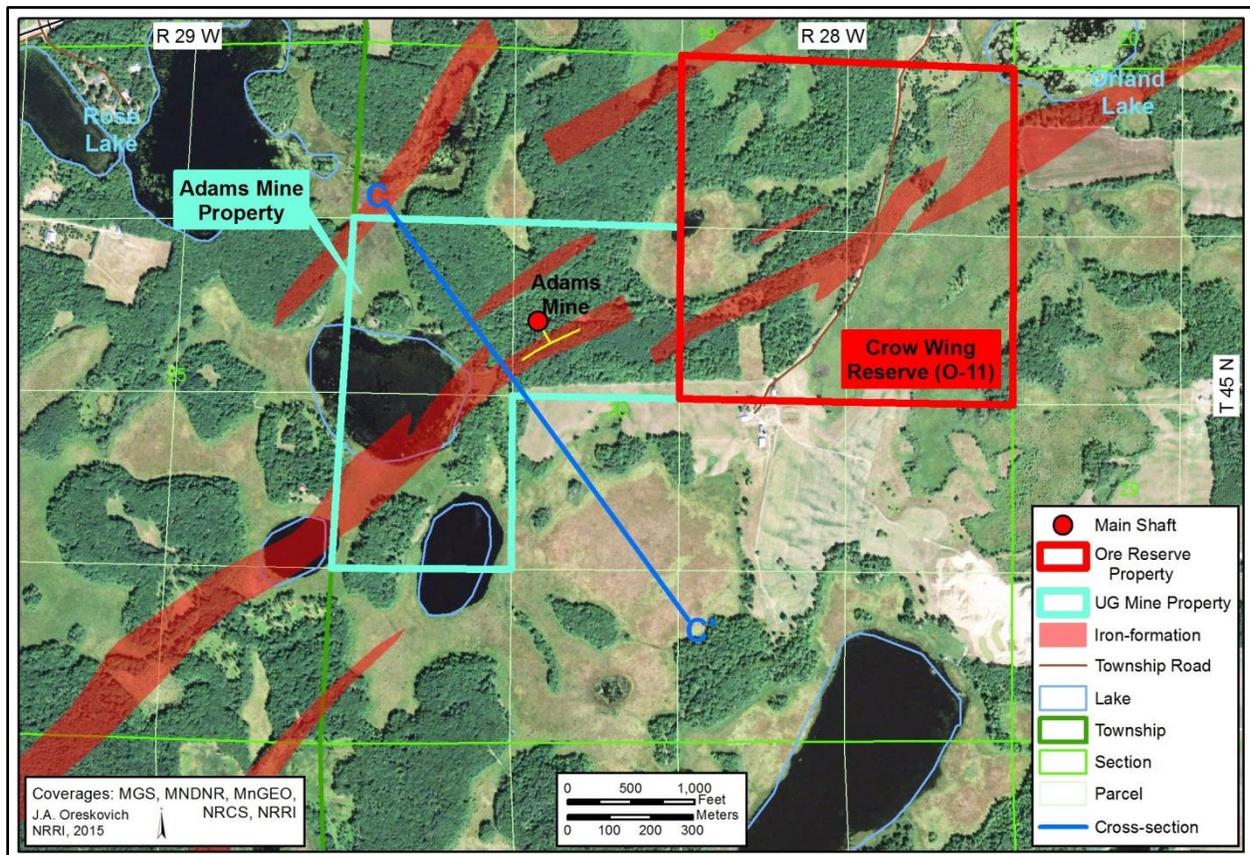


Figure 1.2-59. Adams mine and Crow Wing Reserve (O-11).

Adams Mine

Mine	Former Name	Range	S	T	R	Parcel	UG	OP	ML
Adams	Chesquitawney	South Range	30	46	28	SE-NW, Lots 2 (SW-NW) & 3 (NW-SW)	X		
Shaft Sinking	1st Shipment	Last Shipment	Total Ore Shipped			Last Operator	Last Known Fee		
1908-1909; 1912	1914; 1918	1918	5535			Biwango Mining Co.	University; State		
Overburden (Ft.)	Mine Depth	Top Level		Lowest Level	Mining Method	Shaft Type			
123	207 Ft.			200-Ft. Level		circular concrete			

The Adams mine property encompasses the SE-NW and Lots 2 (SW-NW) and 3 (NW-SW) of S30-T46-R28. The mine itself resides in the SE-NW parcel (Fig. 1.2-59).

A timber drop-shaft was first sunk on the Adams property in 1908 (The Iron Trade Review, 1916b). This shaft was abandoned at 52 feet without having encountered ledge (Harder and Johnston, 1918). Cuyler Adams picked up the lease on the property several years later. In 1912, a circular concrete shaft was sunk to open up the Adams mine, which operated during 1913 and 1914 (Harder and Johnston, 1918). The shaft was 237 feet deep, with 123 feet in surface and 100 feet in rock (Edwards, 1913). The Adams mine is the easternmost mine on the Cuyuna South Range.

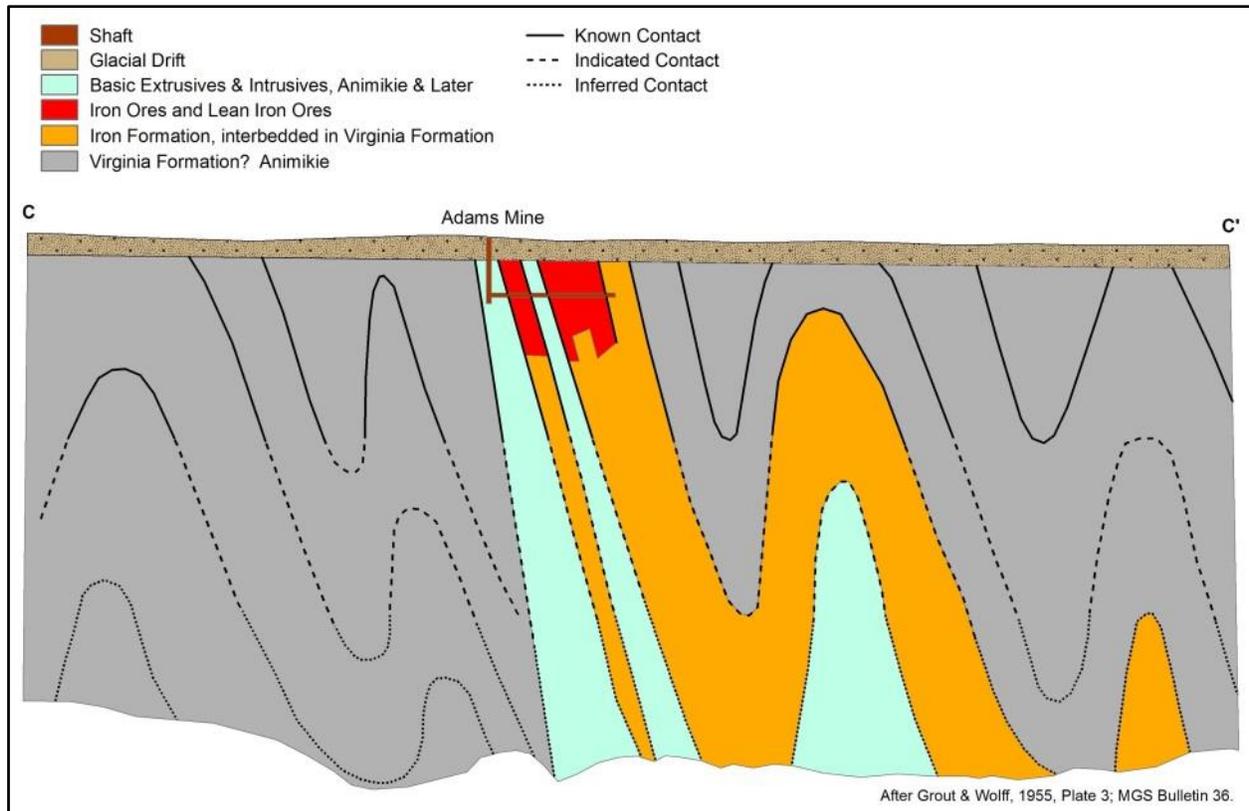
A 200-foot crosscut was driven at the 200-foot level of the shaft. From the crosscut, a 500-foot drift was driven into the length of the orebody that was 150 feet wide at this depth (Zapffe, 1915a). The Iron Trade Review (1915d) reports that this drift is 600 feet long, encountering “a remarkable run of ore, averaging nearly 60 per cent in iron” that had not been previously known from the drilling.

No maps of the Adams mine were found. The Adams shaft location (Fig. 1.2-59) was taken from Grout and Wolff (1955), Plate 2. The workings, as shown in Figure 1.2-59, are approximate. They were drawn based on the written description in Zapffe (1915a).

Figure 1.2-60 (after Grout and Wolff, 1955, Plate 3) depicts the regional rock strata in a schematic cross-section drawn along line C – C’ near the Adams mine in Figure 1.2-59. The schematic illustrates the degree of folding and steep dips typical of the region. As drawn by Grout and Wolff, the crosscut from the shaft intersects two orebodies.

The main orebody in the Adams mine has a maximum width of 150 feet, an average depth of at least 100 to 150 feet, and a length that could exceed 1,000 feet. Early Minnesota tax commission estimates listed the ore tonnage at 906,357 tons (Iron Trade Review, 1916b). While this tonnage averaged 55.86% iron, much of it was as high as 58 or 59% iron. More recent ore reserve estimates for the Adams mine were not sought for this project.

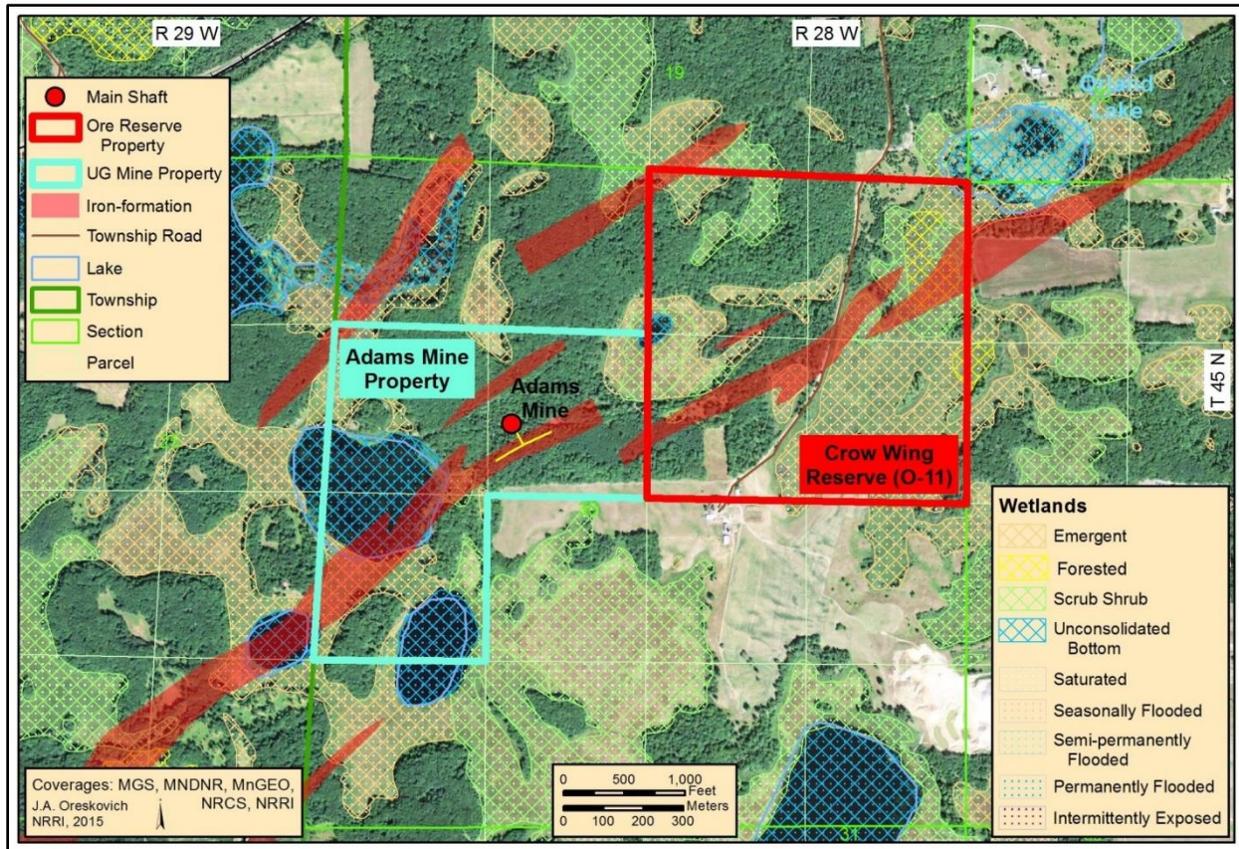
Ore was stockpiled as development work was undertaken, and the mine was shut down before any ore was shipped (Zapffe, 1915a), although Harder and Johnston (1918) reported that some ore was shipped in 1914. No reason was found as to why the mine was shut down. The Adams mine had been a personal undertaking by Cuyler Adams, but the Iron Trade Review (1916b) reported that there were no consumers of ore interested in or affiliated with it. A total of 5,538 tons of ore was eventually shipped from stockpile in 1918 (Skillings Mining Review, 2005).



**Figure 1.2-60.** Schematic of the Adams mine orebody (after Grout and Wolff (1955), Plate 3).

Figure 1.2-60 illustrates the current hydrographic conditions around the immediate Adams mine and Clearwater Lake reserve region. Early investigators had “Invariably predicted serious water troubles for Cuyuna operators” due to “morainial topography...dotted with hundreds of lakes, ponds, extensive marshes and swamps” (The Iron Trade Review, 1916b). Water issues were especially expected for the Adams mine, where “several ponds are within a few hundred feet of the shaft and are co-extensive with large wet marshes hemmed in by hilly highland.” The prevailing sandy soil of the Cuyuna Range was presumed to be a reservoir for ground water, likely to “prove productive of treacherous flows of quicksand” (The Iron Trade Review, 1916b).

While multiple shaft sinking operations on the South (and North) Range did encounter such conditions, apparently the Adams mine, with its concrete drop shaft, did not. No reference was made in The Iron Trade Review (1916b) article to the earlier 1908 attempt at shaft sinking on this parcel with a timber drop shaft. The 1908 shaft, sunk for the Adams mine’s predecessor, the Chesquitawney mine, was reportedly abandoned at 52 feet due to water problems (Aulie and Johnson, 2002). It was not determined whether the two mines (Adams and Chesquitawney) sought to develop the same orebody.



**Figure 1.2-61.** Adams mine and Crow Wing reserve hydrography map.

Crow Wing Reserve (O-11)

The Crow Wing Reserve occupies the NE1/4 of S30-T46-R28. It abuts the Adams mine property to the west (Fig. 1.2-59). Figure 1.2-61 shows saturated wetlands over or in close proximity to much of the iron-formation on this parcel.

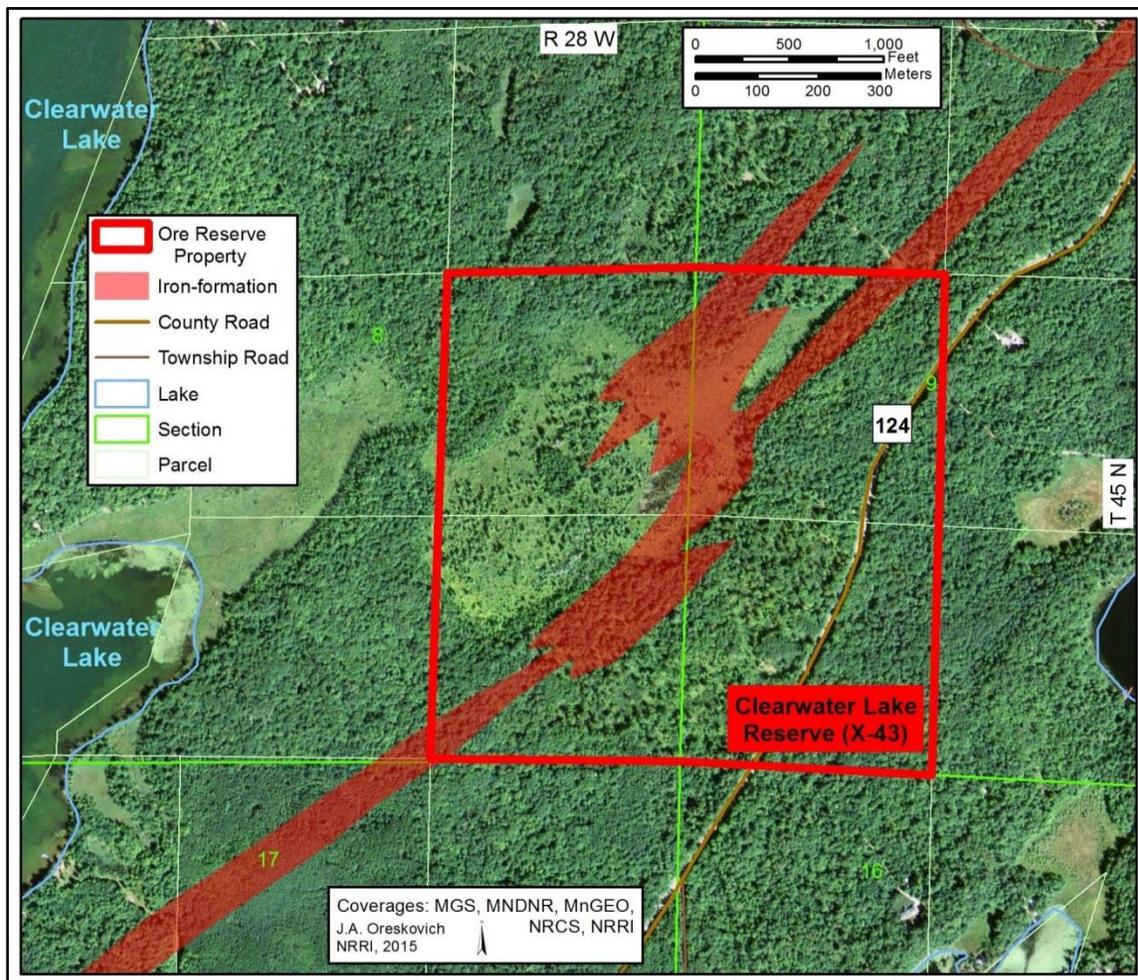
Table 1.2-32 presents data from the 1989 Crow Wing Reserve (O-11) ore reserve estimate. There is some drill hole data available in the Crow Wing Reserve data file at MDOR, as well as cross-sections and more information on microfilm.

**Table 1.2-32.** Crow Wing Reserve ore reserve estimate.

Ore Reserve Estimate <sup>1,2</sup>							
Property	Parcel	S	T	R	Data	Surface Owner <sup>3</sup>	Fee Owner
Crow Wing Reserve (O-11)	NE 1/4	30	46	28	X	Private	U.S. Steel Corp.
Year	Type	Re-class		Recovery Factor		Tons	Density Factor
1989 (NE-NE)	UG Wash Ore Conc.	X		65%		302,100	14
1989 (SW-NE)	UG Wash Ore Conc.					78,100	
1989 (SE-NE)	UG Wash Ore Conc.					104,500	
<b>Total Tons:</b>						484,700	
1958	UG Merch Ore					745,710	

<sup>1</sup>Upper table information from Beltrame (1977), unless otherwise noted. Data consists of drill hole data, cross-sections, reserve estimates, etc. on microfilm at MDOR Minerals Tax Office in Virginia, MN.  
<sup>2</sup>Lower table information from MDOR Minerals Tax Office data files.  
<sup>3</sup>Data from MN DNR GIS coverage own\_mnstwdpy2 (2008).

Clearwater Lake Reserve (X-43)



**Figure 1.2-62.** Clearwater Lake Reserve (X-43).

The Clearwater Lake Reserve (X-43) resides in the E1/2-SE of S8-T45-R28 and the W1/2-SW of S9-T45-R28 (Fig. 1.2-62). The location of the orebody within the Clearwater Lake reserve property was not determined. Saturated and permanently flooded wetlands over much of the iron-formation could impede CAES cavern development at this site (Figure 1.2-62).

1965 ore reserve data for the Clearwater Lake Reserve (MDOR data file) is presented in Table 1.2-33. Table 1.2-34 presents assay data from the Clearwater Lake Reserve 1965 ore reserve estimate.

**Table 1.2-33.** Clearwater Lake Reserve (X-43) ore reserve estimate.

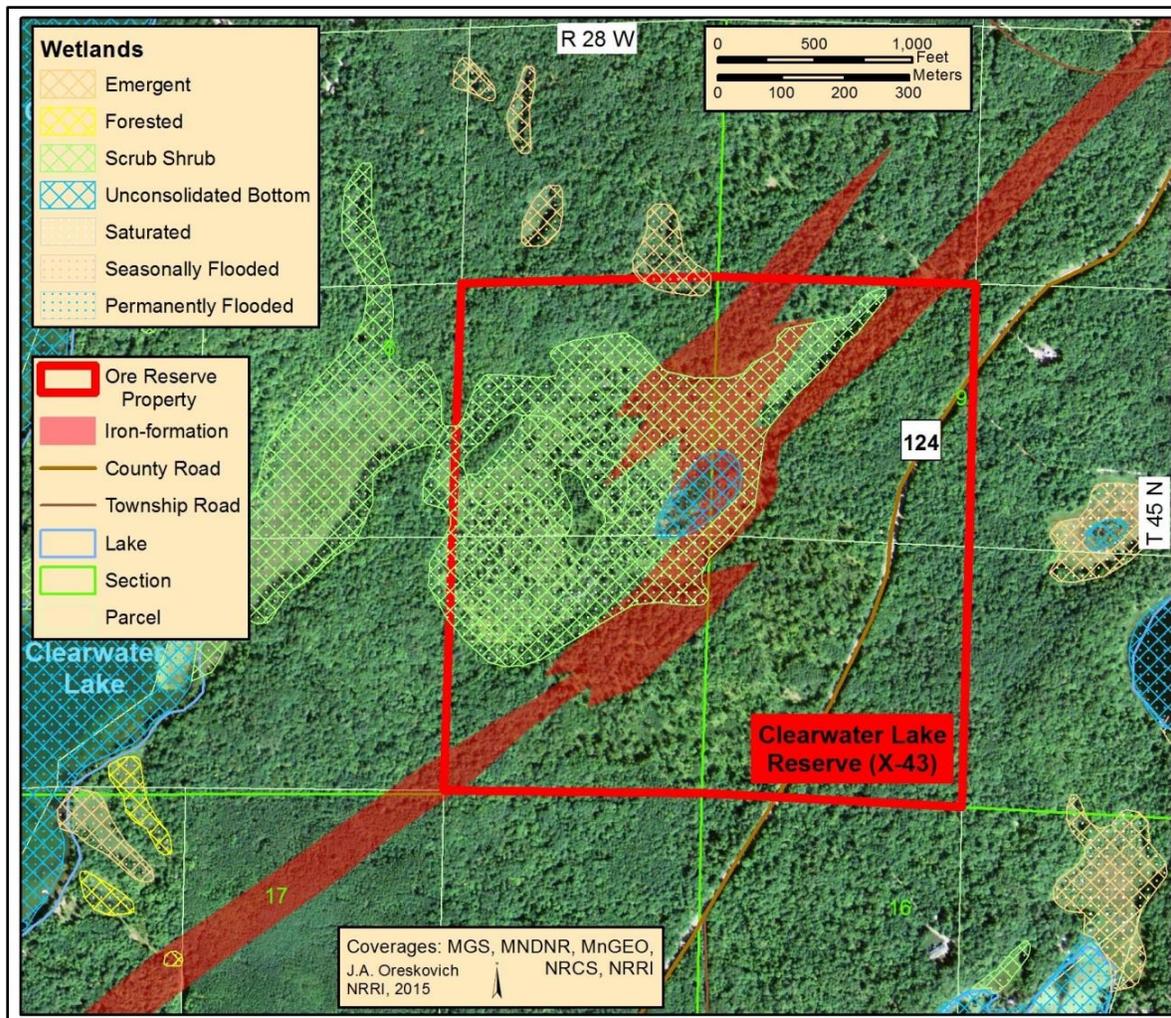
Ore Reserve Estimate <sup>1,2</sup>							
Property	Parcel	S	T	R	Data	Surface Owner <sup>3</sup>	Fee Owner
Clearwater Lake Reserve (X-43)	E1/2-SE	8	45	28	X	Private	Bergman, Knutsen, Street, & Ulman, (Trustee), Presbyterian Synod of Lakes & Prairies et al.
	W1/2-SW	9	45	28			
Year	Parcel	Type			Recovery Factor	Tons	Density Factor
1965	E1/2-SE	UG Non-Bessemer Wash Ore Conc.			65%	168,200	14
		UG Manganiferous Wash Ore Conc.			64%	117,800	16
	W1/2-SW	UG Non-Bessemer Wash Ore Conc.			65%	75,800	14
		UG Manganiferous Wash Ore Conc.			64%	121,200	16
1965	E1/2-SE				<b>Total Tons:</b>	286,000	
	W1/2-SW				<b>Total Tons:</b>	197,000	

<sup>1</sup>Upper table information from Beltrame (1977), unless otherwise noted. Data consists of drill hole data, cross-sections, reserve estimates, etc. on microfilm at MDOR Minerals Tax Office in Virginia, MN.  
<sup>2</sup>Lower table information from MDOR Minerals Tax Office data files.  
<sup>3</sup>Data from MN DNR GIS coverage own\_mnstwdpy2 (2008).

**Table 1.2-34.** Clearwater Lake Reserve (X-43) assay data.

Assay Data <sup>1</sup>										
Dry									Natural	
Property	Type	Tons	Fe	P	Si	Mn	Al	Moist.	Fe	Mn
Clearwater Lake Res. (E1/2-SE)	NB WOC	168,200	59.00	0.330	3.50	0.90	2.50	9.00	53.69	0.82
	Mang. WOC	117,800	54.00	0.210	4.00	4.50	2.70	9.00	49.14	4.10
Clearwater Lake Res. (W1/2-SW)	NB WOC	75,800	59.00	0.300	4.00	1.30	2.20	9.00	53.69	1.18
	Mang. WOC	121,200	53.00	0.200	6.00	4.50	3.00	9.00	48.23	4.10

<sup>1</sup>Source: MDOR data file.



**Figure 1.2-63.** Clearwater Lake Reserve (X-43) hydrography map.

CAES Potential for Cuyuna South Range Study Area 1: Adams Mine and Crow Wing (O-11) and Clearwater Lake Reserve (X-43)

The Adams mine warrants further investigation for CAES potential for several reasons. There has been development work done underground at the mine. While no maps of the underground workings were found to date, there are several references in literature to the shaft, crosscut, drift, development underground of a 150-foot width of ore and description of rock along the crosscut. A high tonnage of ore (>900,000 tons) was estimated by the Minnesota tax commission for the Adams orebody in 1916, although how much that has been reduced on more recent estimates with beneficiation was not investigated for this study. Ore reserve estimates, drilling data and maps should be available on microfilm at the MDOR office in Virginia, MN. The Crow Wing and Clearwater Lake reserves (Fig. 1.2-63) also hold significant—though less—tonnage than the Adams mine reserve.

The shaft itself could prove interesting. It is a circular concrete shaft sunk through 123 feet of surface. Harder and Johnston (1918) report that the shaft was sunk by the New York Foundation Company in 1912. In a passage on the Rowley mine of the Cuyuna South Range from Anna Himrod's history of the Cuyuna Range (reproduced in Aulie and Johnson, 2002), she documents that:

“The concrete shafts that had been sunk by the New York Foundation Company were round, 15 to 20 feet in diameter with walls four or five feet thick. They were sunk by the caisson method of removing the dirt from under them and letting the weight of the shaft sink it into place. After the shaft was anchored to ledge, the dividers or partitions within the shaft were put into place.”

These statements were made in contrast to an oblong concrete shaft designed and used several years later by C.B. Rowley for the Rowley mine. Sunk between 1915 and 1917, the Rowley mine shaft had inside dimensions of 6 feet x 14 feet and walls that were only 18 inches thick. Mr. Rowley put his dividers in place while pouring concrete for each section and also made other adaptations for the Rowley shaft (Aulie and Johnson, 2002).

South Range Study Area 1 properties are located in very lightly populated rural to remote areas. The Adams mine likely has access off the Oreland Mine Rd. that runs north to south through the Crow Wing reserve property into a farmstead located immediately to its south. This road crosses the iron-formation in the reserve property. Where the Crow Wing reserve orebody is located relative to the road was not determined. Distance from N-S County Highway 8 to the farmstead is over 1.5 miles; it would be slightly more to the Adams mine.

The Clearwater Lake reserve is located approximately ½ mile off of N-S artery MN State Highway 6 on County Road 124. CR-124 runs through the ore reserve property. It roughly parallels the iron-formation but is located to the southeast of it.

Direct distance to rail (Burlington Northern-Santa Fe (BNSF)) from the Adams mine is only 0.7 miles. The original rail grade into the Adams mine, shown on the 1912 Deerwood topo map, is clearly visible on current aerial photos. The original rail line came down from the north, crossing the former Northern Pacific (now BNSF) tracks, and entering the mine site from the east.

Access to major electrical transmission lines is less favorable in Study Area 1 as distances exceed six miles. Distance is greater for the Clearwater Lake reserve. Transmission lines are located to the west (Fig. 1.2-57).

Wetlands could impact each of the three sites dependent upon location of the orebodies within the properties. The Adams mine shaft site and most of the iron-formation subcrop west of Oreland Mine Rd. in the Crow Wing reserve property are free of wetlands. West of the shaft area and east of Oreland Mine Rd. wetlands are abundant. An unnamed lake located approximately 0.1 miles west of the Adams shaft may impact the existent underground workings.

In the Clearwater Lake reserve, a substantial portion of the iron-formation subcrop is overlain by wetlands. These wetlands are connected to Clearwater Lake. The lake is located 0.25 miles from the western property boundary. Location of the orebody within the property was not determined.

State property abuts the Adams mine property to the south. The Adams mine parcels and those of the Crow Wing Reserve are privately owned by the same party (Crow Wing County GIS Public Map Service, 1915). They are classified as rural vacant land. Fee holders for the Adams property are the University of Minnesota and the State of Minnesota. Fee holder for the Crow Wing reserve is U.S. Steel (Skillings Mining Review, 2005).

State land abuts the NE-SE parcel of the Clearwater Lake reserve to the west. The Clearwater Lake reserve parcels are privately owned by a church-related group, as is the fee (Crow Wing County GIS Public Map Service, 1915; Skillings Mining Review, 2005). The parcels are classified as church properties.

Positives:

- Existing 231-foot-deep shaft of circular concrete for 123 feet. 200-foot crosscut, 500-600 feet of drifting;
- Substantial ore tonnage;
- Properties in sparsely populated areas;
- Short distance to rail (Adams mine and Crow Wing reserve);
- Short distance to major arterial route (Clearwater Lake reserve);
- Neighboring state land parcels; and
- University, state, and U.S. Steel mineral ownership of the Adams mine and Crow Wing reserve parcels.

Negatives:

- Distance to major transmission lines > 6 miles;
- Wetland impacts; and
- Proximity to lakes.

Cuyuna South Range Study Area 2

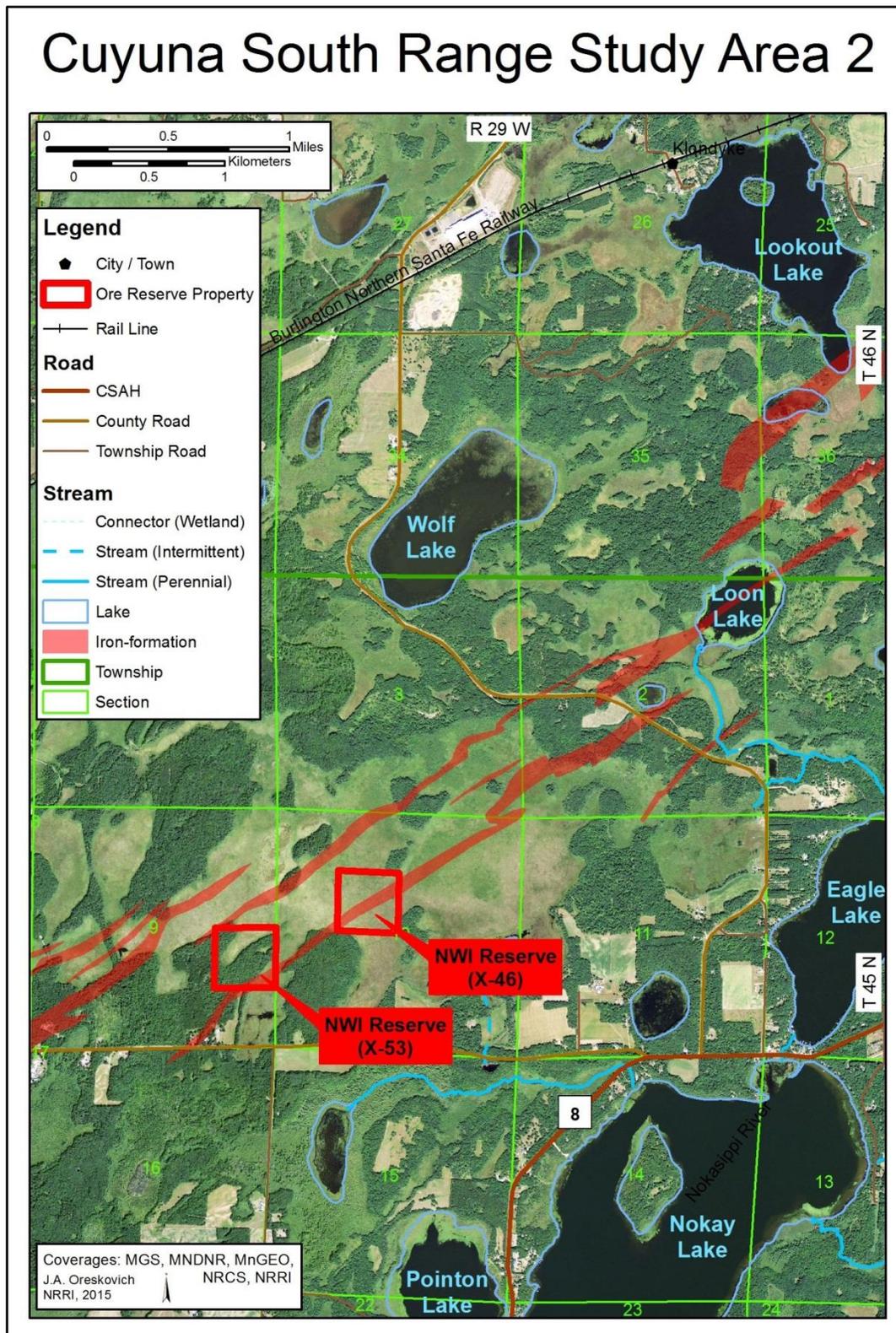
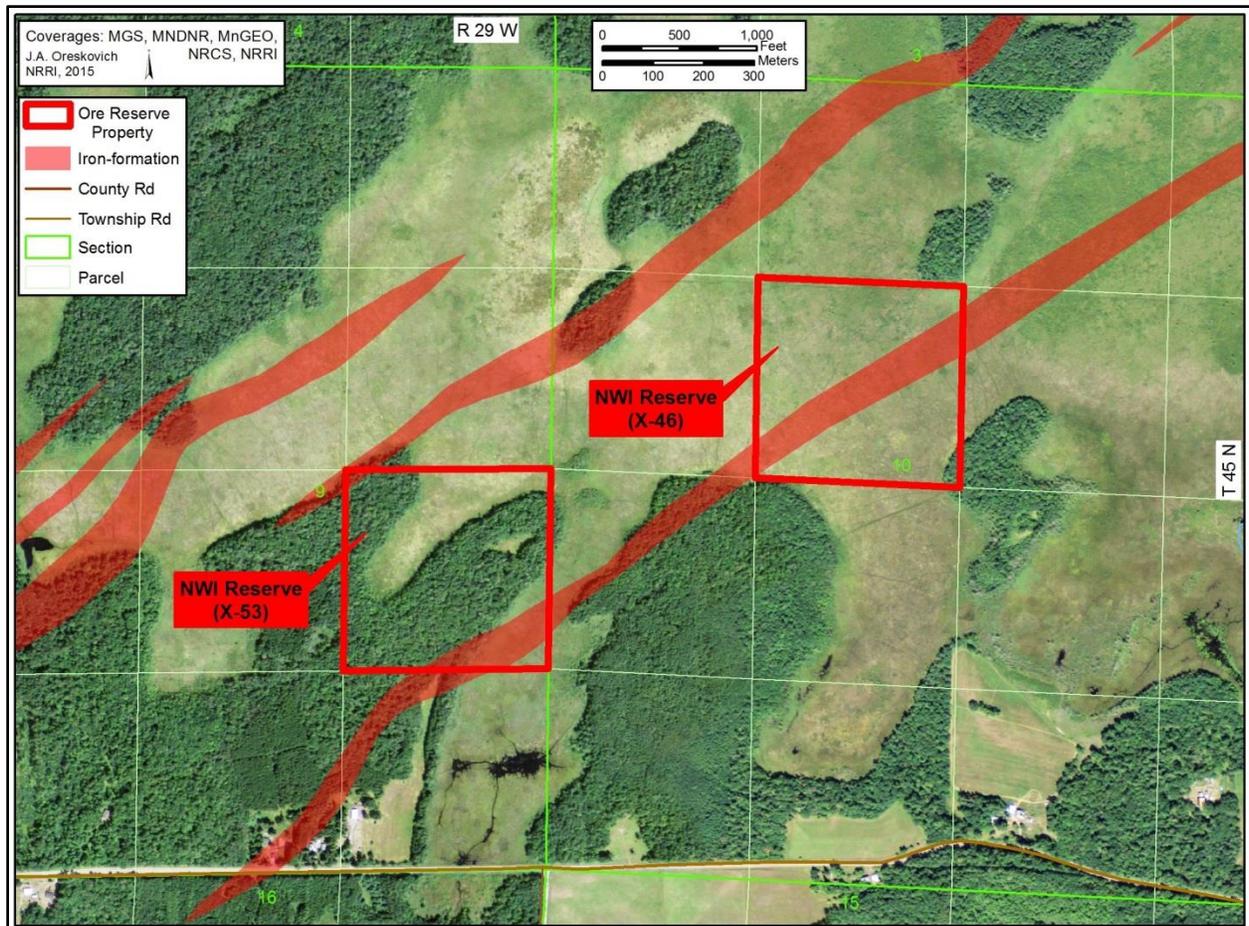


Figure 1.2-64. Cuyuna South Range Study Area 2: NWI Reserves (X-46 and X-53).

In Cuyuna South Range Study Area 2, the iron-formation traverses a largely unpopulated region of densely tree-covered uplands and open lowlands that are wetlands of some type (Fig. 1.2-64). While no mining occurred in Cuyuna South Range Study Area 2, two NWI (Northwestern Improvement Co.) ore reserves, X-46 and X-53, were identified here. Due to extensive wetland coverage, CAES activity may be difficult in this region.

### NWI Reserve (X-46) and (X-53)



**Figure 1.2-65.** NWI Reserves X-46 and X-53.

NWI Reserve (X-46) lies in the SE-NW of S10-T45-R29 (Fig. 1.2-65). The iron-formation trends northeast-southwest, corner to corner, through the center of this 40-acre parcel. Overlying the iron-formation are saturated emergent wetlands that extend over nearly two-thirds of Section 10, as well as over nearly one-quarter of Section 3 to the north (Fig. 1.2-66). These wetlands are contiguous with seasonally flooded emergent wetlands that cover nearly one-quarter of Section 9 to the west. The closest access to this property is County Road 159 nearly one-half mile to the south.

No ore reserve estimate was obtained for NWI Reserve (X-46). Beltrame (1977) cites an estimate done in 1958. Data is available on microfilm at the MDOR office in Virginia, MN. A map found in the MDOR data files shows six angled holes were drilled on the property. Data from Beltrame (1977) are presented in Table 1.2-35.

**Table 1.2-35.** NWI Reserve (X-46) ore reserve estimate.

Ore Reserve Estimate <sup>1,2</sup>							
Property	Parcel	S	T	R	Data	Surface Owner <sup>3</sup>	Fee Owner
NWI Reserve (X-46)	SE-NW	10	45	29	X	Private	Glacier Park Co.
Year	Type		Re-class	Recovery Factor		Tons	Density Factor
1958	NA					NA	

<sup>1</sup>Upper table information from Beltrame (1977), unless otherwise noted. Data consists of drill hole data, cross-sections, reserve estimates, etc. on microfilm at MDOR Minerals Tax Office in Virginia, MN.  
<sup>2</sup>Lower table information from MDOR Minerals Tax Office data files.  
<sup>3</sup>Data from MN DNR GIS coverage own\_mnstwdpy2 (2008).

### NWI Reserve (X-53)

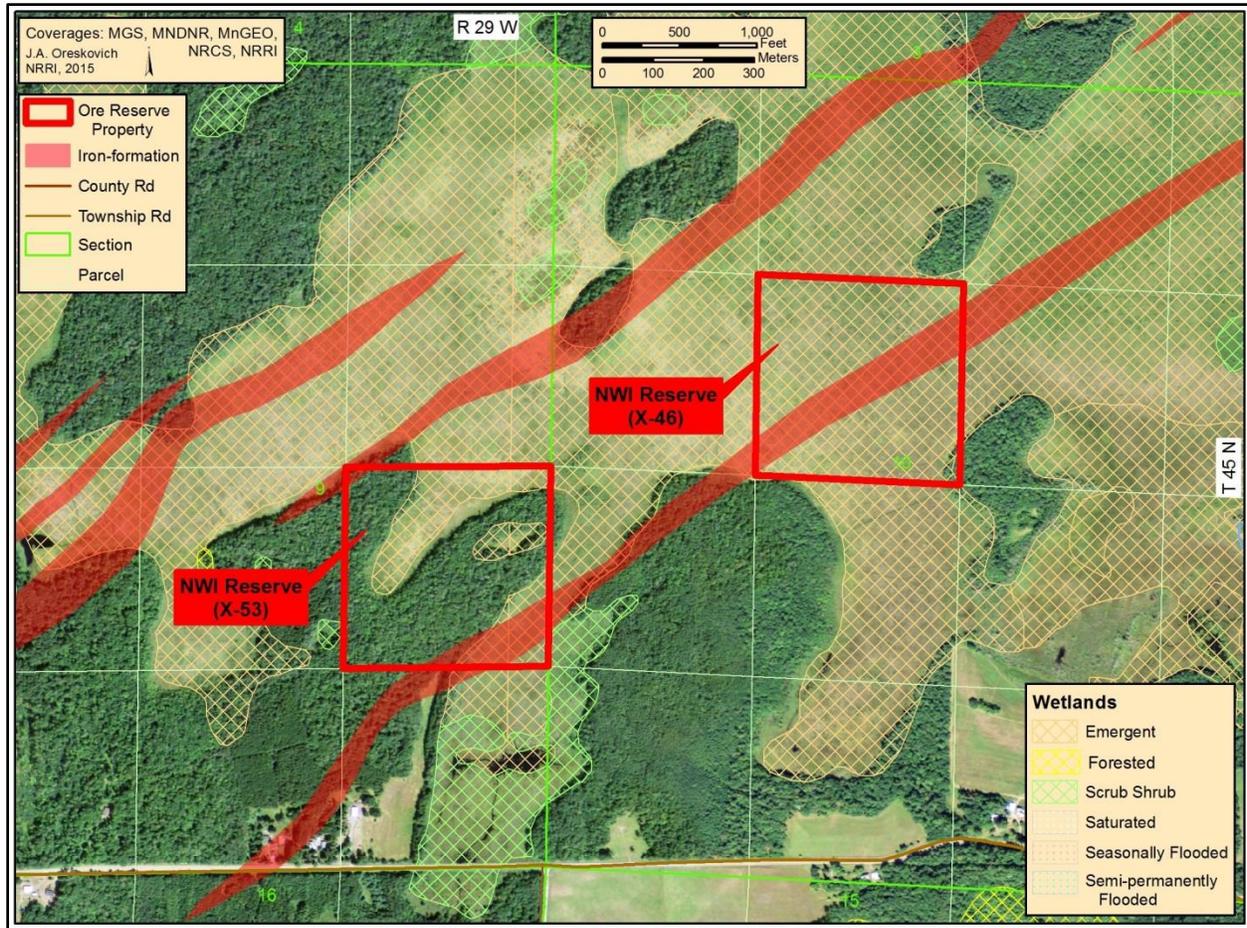
NWI Reserve (X-53) lies to the southwest of NWI Reserve (X-46) in the NE-SE of S9-T45-R29 (Fig. 1.2-65). The iron-formation cuts across the southeastern corner of this parcel. The iron-formation is overlain, for the most part, by saturated or seasonally flooded emergent wetlands contiguous with those overlying NWI Reserve (X-46) (Fig. 1.2-66).

No ore reserve data were found for this property. Data from Beltrame (1977) are presented in Table 1.2-36. A map found in the data files at MDOR showed two angled drill holes on the property. More information is available on microfilm at the MDOR office in Virginia, MN.

**Table 1.2-36.** NWI Reserve (X-53) ore reserve estimate.

Ore Reserve Estimate <sup>1,2</sup>							
Property	Parcel	S	T	R	Data	Surface Owner <sup>3</sup>	Fee Owner
NWI Reserve (X-53)	NE-SE	9	45	29	X	Private	Burlington Northern Inc.
Year	Type		Re-class	Recovery Factor		Tons	Density Factor
1958	NA					NA	

<sup>1</sup>Upper table information from Beltrame (1977), unless otherwise noted. Data consists of drill hole data, cross-sections, reserve estimates, etc. on microfilm at MDOR Minerals Tax Office in Virginia, MN.  
<sup>2</sup>Lower table information from MDOR Minerals Tax Office data files.  
<sup>3</sup>Data from MN DNR GIS coverage own\_mnstwdpy2 (2008).



**Figure 1.2-66.** NWI Reserves (X-46) and (X-53) hydrography map.

***CAES Potential for Cuyuna South Range Study Area 2: NWI Reserves (X-46) and X-53)***

No ore reserve estimates were acquired for the two reserve parcels in Study Area 2. The two parcels are unpopulated. NWI (X-46) and approximately 1/3 of NWI (X-53), including the iron-formation subcrop, reside in a low region of seasonally flooded emergent wetlands that extends for over 700 acres. A 14-foot rise sub-parallel the subcrop to the northwest in the NWI (X-53) parcel (Fig. 1.2-66).

County road CR-159 runs east-west 0.25 and 0.5 miles south of NWI (X-53) and NWI (X-46), respectively. There are a few homesteads/farmsteads along the north side of CR-159 in the immediate region. Major Great River Energy and Minnesota Power electrical transmission lines are located within 3.5 miles to the west of both parcels.

Surface ownership of both ore reserve parcels is private. The land has been classified as rural vacant land (Crow Wing County GIS Public Map Service, 2015). Fee owners are Glacier Park (NWI-46) and Burlington Northern Inc. (NWI-53) (Beltrame, 1977).

**Positives:**

- Both ore reserve parcels are classified as rural vacant land; and
- The parcel fee owners hold mine lands on the Mesabi Range, also.

**Negatives:**

- Ore reserve tonnages were not obtained for the two parcel;
- Both parcels reside within a large (700 acre) wetland area; and
- Distance to major electrical transmission lines exceeds 3.0 miles.

Cuyuna South Range Study Area 3

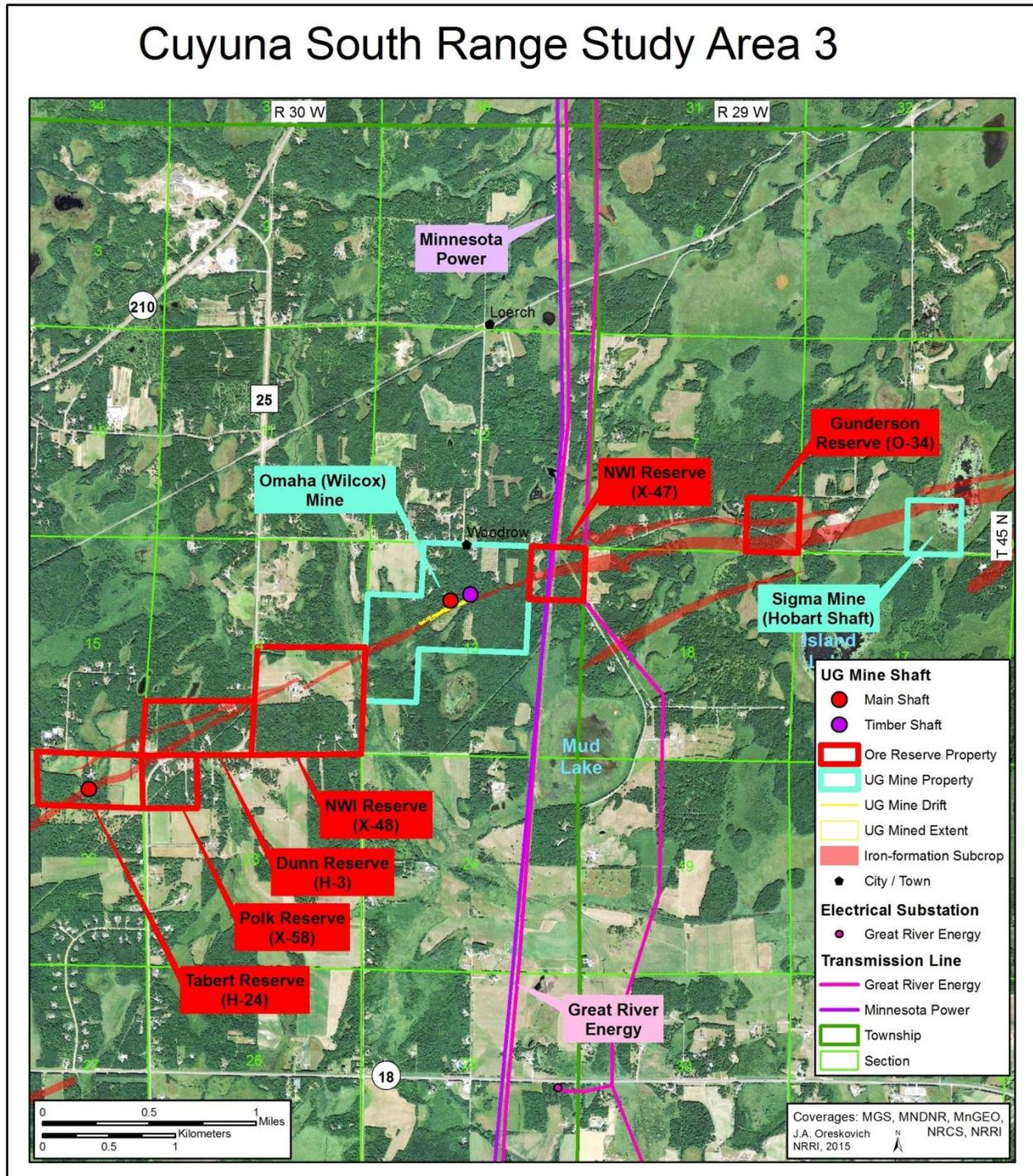
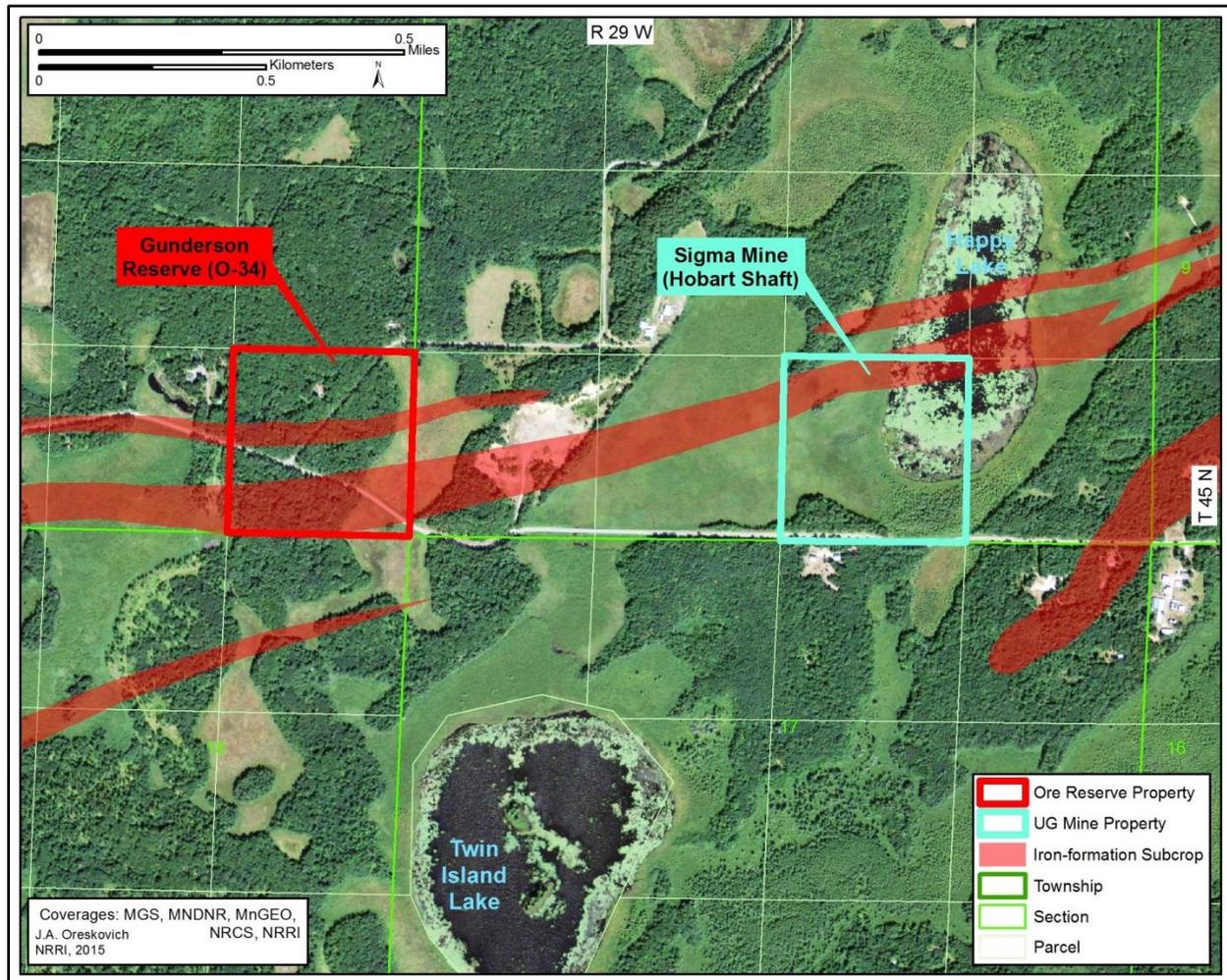


Figure 1.2-67. Cuyuna South Range Study Area 3: Omaha (Wilcox) and Sigma mines; Tabert (H-24), Polk (X-58), Dunn (H-3), NWI (X-48), NWI (X-47), and Gunderson (O-34) reserves.

Cuyuna South Range Study Area 3 covers a broader area than Study Area 2 (Fig. 1.2-67). Resident within Study Area 3 are two former mines, the Sigma and the Omaha, and six ore reserve properties, the Gunderson (O-34), NWI (X-47), NWI (X-48), Dunn (H-3), Polk (X-58), and Tabert (H-24) reserves. These properties are contiguous with the exception of the Gunderson reserve. The Omaha mine was the largest producer on the Cuyuna South Range.

The iron-formation of Study Area 3 crosses lowlands in the east to more upland regions in the west. Centered on the town of Woodrow, populated areas increase to the west. Major power transmission lines of both Great River Energy and Minnesota Power run north and south through the center of this study area.



**Figure 1.2-68.** Sigma mine and Gunderson (O-34) reserve.

*Sigma Mine*

Mine	Former Name	Range	S	T	R	Parcel	UG	OP	ML
Sigma (Hobart Shaft)		South Range	8	45	29	SW-SE	X		
Shaft Sinking	1st Shipment	Last Shipment	Total Ore Shipped	Last Operator		Last Known Fee			
1905			Abandoned	Hobart Iron Co. (Pickands, Mather & Co.)		NA			
Overburden (Ft.)	Mine Depth	Top Level	Lowest Level	Mining Method		Shaft Type			
76	120 Ft.		114-Ft. Level			NA			

The Sigma mine property occupies the SW-SE of S8-T-45-R-29 (Fig. 1.2-68). This parcel is now owned by Crow Wing County (Crow Wing County GIS Public Map Service, 2015). Sinking of the Hobart exploration shaft of the Sigma mine in 1905 marked the first attempt at underground work in the Cuyuna District (Harder and Johnston, 1918).

The Hobart shaft was a small exploration shaft, 126 feet deep, from which a 200-foot crosscut and an 80-foot drift were driven (The Iron Trade Review, 1915d). No map was found showing the shaft location. Harder and Johnston (1918) write that the 200-foot crosscut runs south from the shaft at the 114-foot level and the drift runs east from the crosscut through 80 feet of lean ore. This information would place the shaft on the north side of the orebody, in the far northwestern corner of the parcel. Bedding in the mine was steep, averaging 80° (Harder and Johnston, 1918).

The Hobart shaft was deluged with water in November 1905 from an underground water body located 50 feet from the shaft (Aulie and Johnson, 2002). The mine was abandoned in early 1906 (Harder and Johnston, 1918). The Sigma mine is not listed in Beltrame (1977), and ore reserve data were not acquired. An article in The Iron Trade Review (1915d) noted that the property had only been partly drilled, adding that it offers good opportunity for a large tonnage.

Surface ownership of the Sigma mine property belongs to Crow Wing County. The land is classified as county public property (Crow Wing County GIS Public Map Service, 1915). The Sigma parcel is bounded on its southern edge by County Road CR-159. Great River Energy and Minnesota Power electrical transmission lines run north and south 1.7 miles to the west (Fig. 1.2-67). Figure 1.2-69 shows the hydrography of the area surrounding the Sigma mine property. Happy Lake occupies the northeastern portion of the property where it overlays the iron-formation. The lake is surrounded by scrub shrub wetlands that are seasonally flooded.

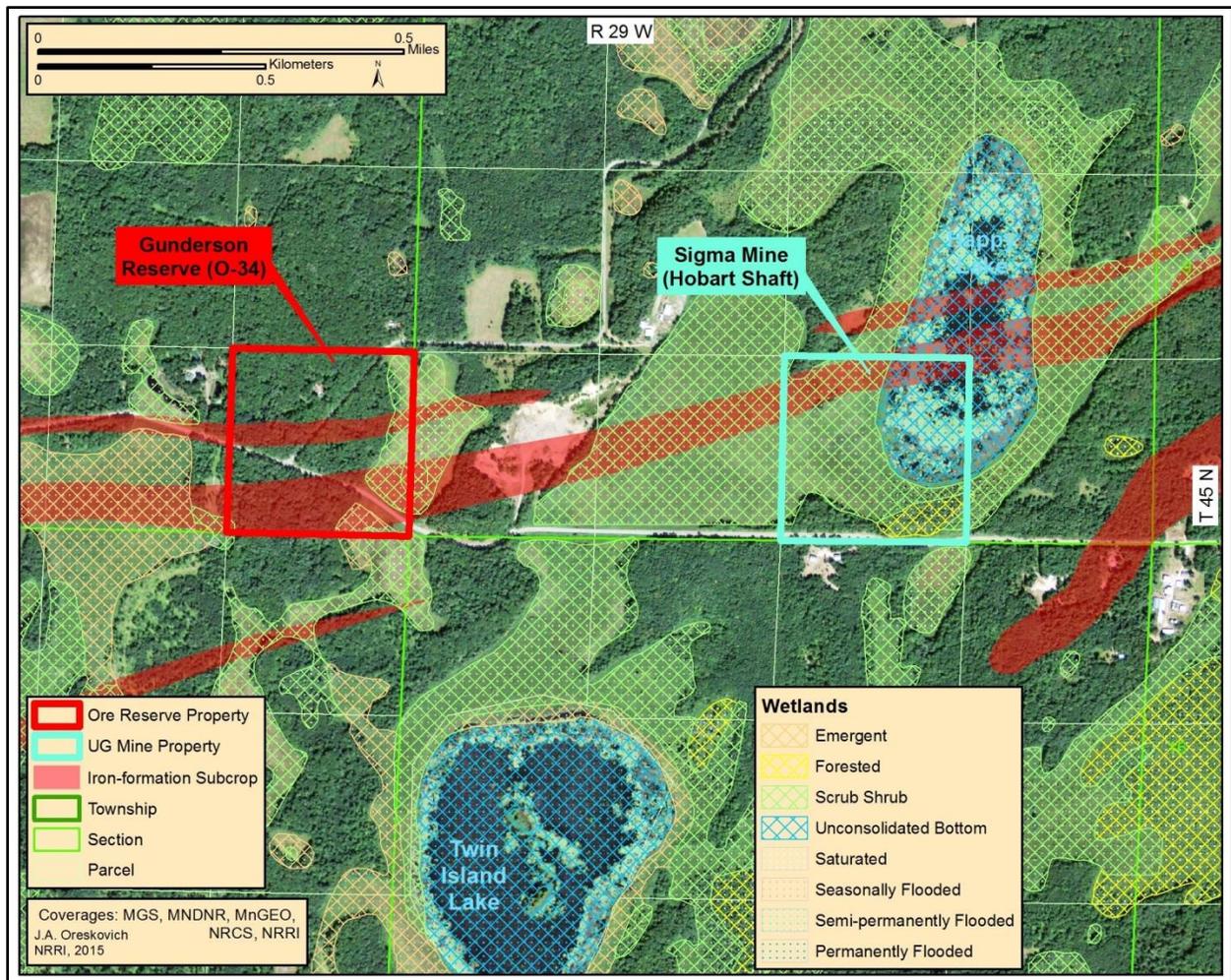


Figure 1.2-69. Hydrography map of the Sigma mine and Gunderson reserve area.

Gunderson Reserve (O-34)

The Gunderson Reserve (O-34) is located three parcels due west of the Sigma mine property (Fig. 1.2-68), abutting state land to the south. Two bands of iron-formation run east-west through the Gunderson property. The broad southern band ranges from 350 to 430 feet in width. The narrower northern band ranges from 110 to 160 feet in width. The Gunderson Reserve property is likely the 40-acre parcel described in The Iron Trade Review (1916d) article *Good results follow careful work* as having “a substantial tonnage of excellent red ore.” The tonnage had been developed by E.J. Longyear and was the only red ore known to date on the South Range.

County Road CR-159 crosses the southern band of iron-formation in the Gunderson property, running southeast-northwest through the southern half of the parcel (Fig. 1.2-69). Township Road 431 cuts the northern band from the northeast as it joins CR-159 midway between the two bands. Except for the two roads, the iron-formation in the Gunderson property appears unencumbered on aerial imagery.

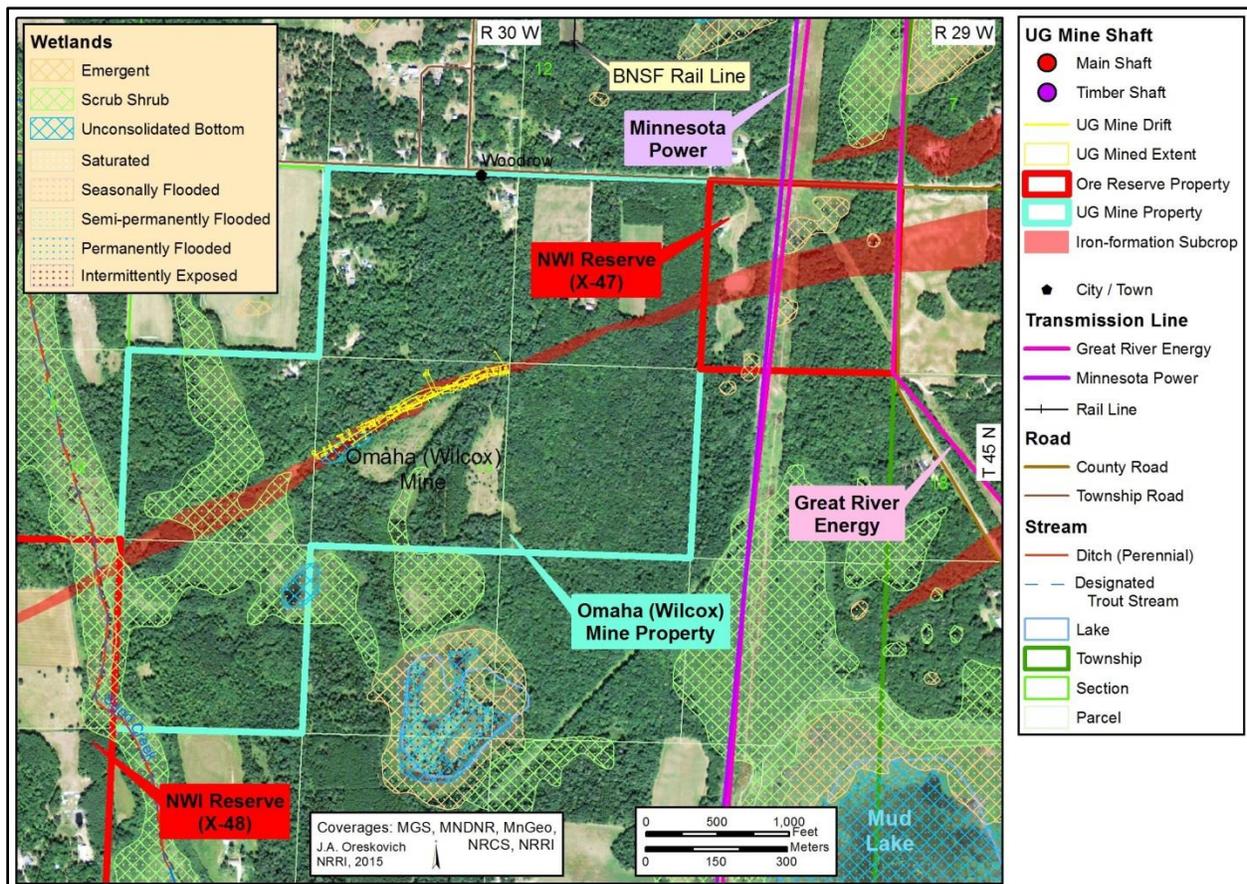
Main Great River Energy and Minnesota Power electrical transmission lines run north-south < 1 mile to the west of the property. The Gunderson property encounters wetlands over the iron-formation along its eastern side (Fig. 1.2-69). These wetlands are mostly seasonally flooded scrub shrub wetlands, with emergent wetlands in the southeast corner.

Ore reserve tonnages were not obtained for this property. Base data from Beltrame (1977) is provided in Table 1.2-31. Notes indicate that drill hole data is available in the MDOR data file, in addition to data available on microfilm as indicated in Beltrame (1977).

**Table 1.2-37.** Gunderson Reserve (O-34) ore reserve estimate.

Ore Reserve Estimate <sup>1,2</sup>							
Property	Parcel	S	T	R	Data	Surface Owner <sup>3</sup>	Fee Owner
Gunderson Reserve (O-34)	SE-SE	7	45	29	X	Private	U.S. Steel Corp.
Year	Type	Re-class		Recovery Factor		Tons	Density Factor
1958	NA					NA	

<sup>1</sup>Upper table information from Beltrame (1977), unless otherwise noted. Data consists of drill hole data, cross-sections, reserve estimates, etc. on microfilm at MDOR Minerals Tax Office in Virginia, MN.  
<sup>2</sup>Lower table information from MDOR Minerals Tax Office data files.  
<sup>3</sup>Data from Crow Wing County GIS Public Map Service (2015).



**Figure 1.2-70.** Omaha (Wilcox) Mine and NWI Reserve (X-47).

NWI Reserve (X-47)

Directly east of the Omaha mine property is the NWI (X-47) reserve, located in the NE-NE of S13-T45-R30. The iron-formation runs northeast-southwest across the center of the property. **This reserve property is crossed north-south by both Minnesota Power and Great River Energy transmission lines (Fig. 1.2-69). Another Great River Energy transmission line approaches the property from the southeast and runs north along its eastern edge.**

According to parcel data available from the Crow Wing County GIS Public Map Service (2015), the NE-NE parcel is divided from north to south into two 20-acre lots. The western lot is classified as non-commercial seasonal residential recreational land. The eastern lot is classified as rural vacant land. A cleared right-of-way runs diagonally northwest-southeast through this lot, cutting across the iron-formation, as does the north-south right-of-way for the major transmission lines that separates the two lots.

The hydrography map in Figure 1.2-71 shows patchy semi-permanently flooded emergent wetlands to the north and south of the iron-formation on the NWI (X-47) reserve property. One small (approximately 100 feet in diameter) seasonally flooded emergent wetland lies over the iron-formation.

A letter from the Meridian Land and Mineral Co., a subsidiary of Burlington Northern Inc., dated August 6, 1985, was found in the MDOR data files requesting a reclassification from underground merch ore to underground wash ore concentrate for this reserve, as shown in Table 1.2-38. Ore reserve tonnages were not obtained.

**Table 1.2-38.** NWI (X-47) Reserve ore reserve estimate.

Ore Reserve Estimate <sup>1,2</sup>							
Property	Parcel	S	T	R	Data	Surface Owner <sup>3</sup>	Fee Owner
NWI Reserve (X-47)	NE-NE	13	45	30	X	Private	Glacier Park Co. (1/2); U.S. Steel Corp. (1/2)
Year	Type		Re-class	Recovery Factor	Tons		Density Factor
1985	UG Wash Ore Concentrate		X	65%	NA		
1958	UG Merch Ore				NA		

<sup>1</sup>Upper table information from Beltrame (1977), unless otherwise noted. Data consists of drill hole data, cross-sections, reserve estimates, etc. on microfilm at MDOR Tax Office in Virginia, MN.

<sup>2</sup>Lower table information from MDOR Minerals Tax Office data files.

<sup>3</sup>Data from Crow Wing County GIS Public Map Service (2015).

Omaha (Wilcox) Mine

Mine	Former Name	Range	S	T	R	Parcel	UG	OP	ML
Omaha (Wilcox)	Wilcox, Woodrow	South Range	13	45	30	SE-NW	X		
Shaft Sinking	1st Shipment	Last Shipment	Total Ore Shipped			Last Operator	Last Known Fee		
1914	1915	1919	279,316			Omaha Iron Co.	State; Swindlehurst et al.		
Overburden (Ft.)	Mine Depth	Top Level	Lowest Level	Mining Method			Shaft Type		
93	230 Ft.	125-Ft. Sub	200-Ft. Level	Top slicing & square setting			timber drop shaft; 3-compartment		

The Omaha mine opened as the Wilcox mine with shaft sinking in 1914 (Harder and Johnston, 1918). Crowell & Murray (1920) list the mine as the Woodrow, formerly the Omaha. The mine itself resides in the SE-NW of S13-T45-R30, while the Omaha property encompasses the NW-SW, SW-NW, E1/2-NW and W1/2-NE of S13-T45-R30 (Fig. 1.2-70).

The Wilcox mine held the best all-around record for wooden drop shaft sinking according to Zapffe (1915c). Measuring 6 feet by 16 feet inside at the bottom, the shaft was sunk through 66 feet of sand and gravel and a 25-foot clay layer sitting on ledge in three months. A letter found in the MDOR data files from a consulting mining engineer to a potential investor, dated October 17, 1917, described the shaft as a 230-foot-deep three-compartment shaft, with two compartments for hoisting and one for pump and ladderway. The mine itself was described in the letter as:

“a well developed property...with sublevels at 110, 125, 140 and 151 ft. and a main haulage level at 200 ft. The mine is well laid out for the recovery of ore, economically and rapidly. Numerous raises have been put up from the 200 ft. level to facilitate the removal of the ore. The orebody has been crosscut in many places from the foot wall to the hanging wall, thus defining the rock boundaries. The underground conditions covering ventilation, drainage and timbering are all very good. Ground conditions are easy and no unusual pressure is shown on the timbers. The waterflow is 1100 gallons per minute...”

The letter goes on to say:

“The orebody is definitely proven for more than 4,000 ft. with an average width of about 55 ft. and a depth of 350 ft. This depth is shown by the drills on inclined holes, so the actual vertical depth is unknown but it is in excess of 350 ft. The mine has been opened up sufficiently so that the quality and character of ore is established. The amount of ore from descriptions above mentioned has been carefully estimated by me at 3,500,000 tons, with a grade of 55 1/2% iron, .25% phosphorous and 9% silica.”

Harder and Johnston (1918) noted that the “Wilcox” mine was the only South Range mine to produce steadily since opening. The mine produced and shipped 279,316 tons of ore from

1915 to 1919 (Skillings Mining Review, 2005), the largest tonnage produced on the Cuyuna South Range. It nearly doubled that of the Gorman open pit mine that operated over thirty years later (1951-1952) (Skillings Mining Review, 2005).

Although this tonnage was relatively large for the Cuyuna South Range, it did not begin to put a dent in the tonnage described in the quoted letter above. A 1965 ore reserve estimate for the Omaha mine property, adjusted for wash ore concentrate, indicates that a substantial tonnage of ore remains. This estimate was also found in the data files at MDOR. Data from the estimate are provided in Tables 1.2-39 and 1.2-40.

**Table 1.2-39.** Omaha Mine ore reserve estimate.

Ore Reserve Estimate <sup>1,2</sup>							
Property	Parcel	S	T	R	Data	Surface Owner <sup>3</sup>	Fee Owner <sup>4</sup>
Omaha (Wilcox)	E½-NW, SW-NW & NW-SW	13	45	30	X	Private	State; Swindlehurst et al.
Year	Type	Re-class		Recovery Factor		Tons	Density Factor
1965 (SW-NW)	NB Wash Ore Conc.					573,600	
1965 (NW-SW)	NB Wash Ore Conc.					58,080	
1965 (SE-NW)	NB Wash Ore Conc.					815,862	
<b>Total Tons:</b>						1,447,542	
<sup>1</sup> Upper table information from Beltrame (1977), unless otherwise noted. Data consists of drill hole data, cross-sections, reserve estimates, etc. on microfilm at MDOR Minerals Tax Office in Virginia, MN. <sup>2</sup> Lower table information from MDOR Minerals Tax Office data files. <sup>3</sup> Data from MN DNR GIS coverage own_mnstwdpy2 (2008). <sup>4</sup> Skillings Mining Review (2005).							

**Table 1.2-40.** Omaha Mine assay data.

Assay Data <sup>1</sup>										
Dry									Natural	
Property	Type	Tons	Fe	P	Si	Mn	Al	Moist.	Fe	Mn
Omaha Mine (NW-SW & SW-NW)	NB Wash Ore Conc.	631,680	56.50	0.275	8.10	0.24	2.80	10.00	50.85	
Omaha Mine (SE-NW)	NB Wash Ore Conc.	815,862	57.00	0.400	7.20	3.30	4.00	10.00	51.30	
<sup>1</sup> Source: MDOR data file.										

Further notes on the 1965 ore reserve estimate state that the Omaha mine main shaft:

“has caved in ± 30 ft. below the surface with 8” to 12” dia. trees growing out of the cave. About 100 ft. southwest of the shaft the surface caves extend 200 to 400 feet east & west. The mine is flooded since at the time of operating...Top slicing & square set methods were used for mining...The E.S.R. for an open pit

operation here would be approximately 8.2 to 1 which is not economic. The material is very high in phosphorus and alumina which makes it undesirable as a blast furnace feed...”

Figures 1.2-71 and 1.2-72 illustrate the underground workings of the Omaha mine in plan view and 3-D view, respectively. The 3-D views are provided in both normal map view (North is up) and rotated view (North is to the south-southeast) in order to show the relationships between the shafts, crosscuts, and orebody. Crosscuts extend at the 125-foot and 600-foot levels from the main shaft to the orebody. A timber shaft located northeast of the main shaft was sunk to the 125-foot Level. A crosscut extends at this level from the timber shaft to the orebody.

The underground workings shown in Figures 1.2-71 and 1.2-72 were digitized from 1917 maps drawn at a time when the mine was still the Wilcox mine. The mine name was changed to Omaha in 1917 when the property was taken over by the Omaha Mining Company (Aulie and Johnson, 2002). Maps showing workings on the 151-foot sub-level were not found.

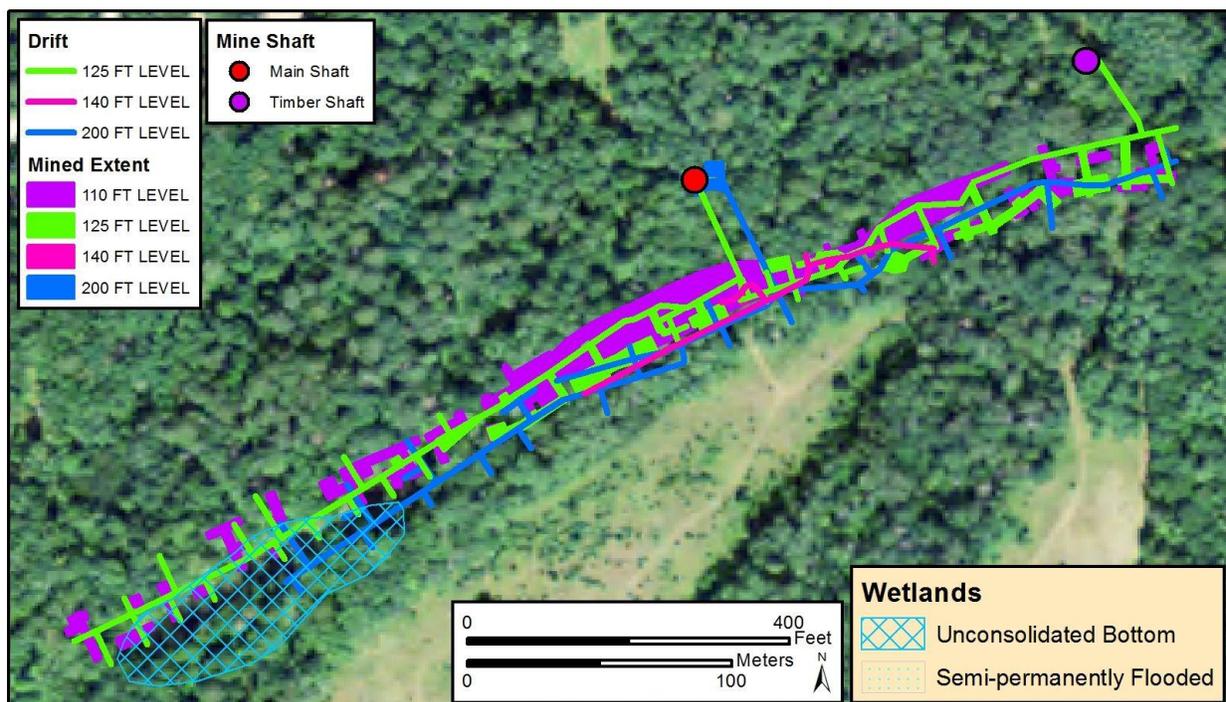
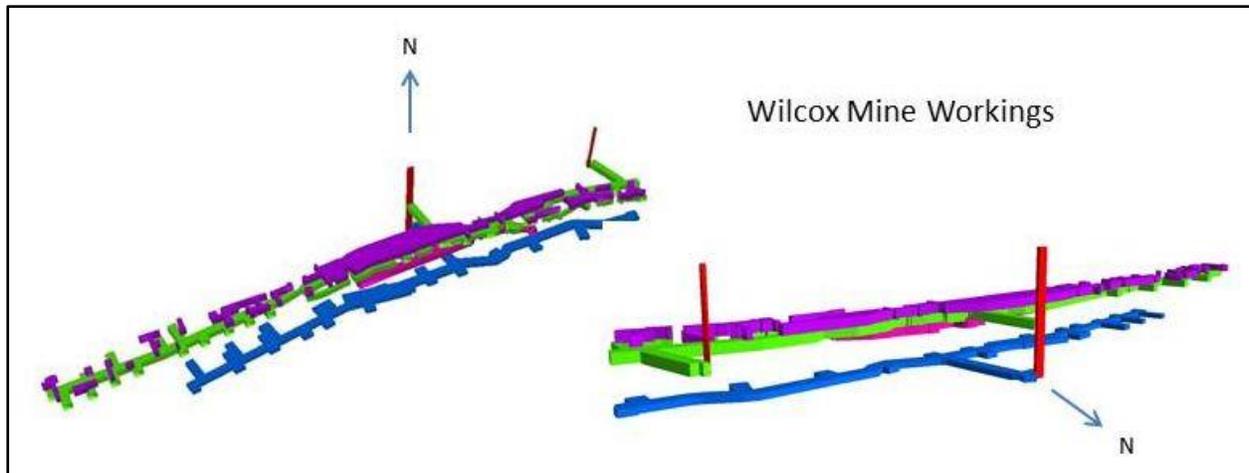


Figure 1.2-71. Omaha mine workings.

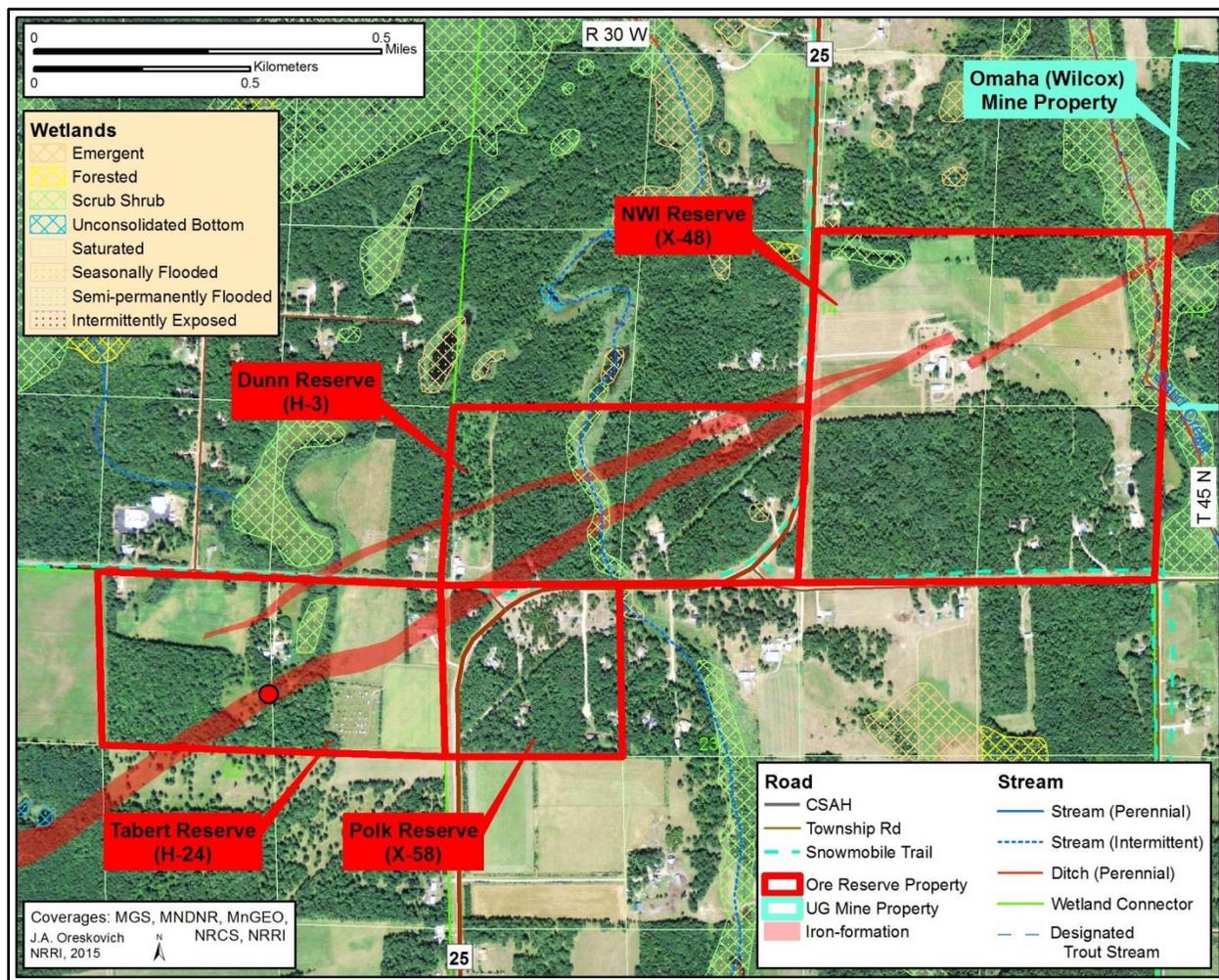


**Figure 1.2-72.** 3-D views of the Omaha mine workings, in normal map view and in rotated view. See map legend in Figure 1.2-71.

The Omaha mine property as outlined in Fig. 1.2-70 is privately owned by multiple parties. The original mine site located in the SE-NW parcel, as well as the SW-NE, SW-NW, NW-SW, and the E1/2-NW-NE parcels, are classified as rural vacant properties (Crow Wing County GIS Public Map Service, 1915). These properties are underlain by iron-formation. There is a homestead within 0.025 miles of the iron-formation in the W1/2-NW-NE.

The townsite of Woodrow lies immediately north of the Omaha property (Fig. 1.2-70). Township Road 428 traverses the northern property boundary, separating the two, while County Road CR-159 runs north-south 0.25 miles to the east. The original rail spur into the mine site had come from the north along the center lines of S12 and S13. The spur came off of the Northern Pacific (now BNSF) tracks. Major Great River Energy and Minnesota Power electrical transmission lines run north-south < 0.1 mile east of the Omaha property.

The E1/2-NW and W1/2-NE parcels, including the mine site, are upland regions. There is ponding over the western portion of the mine's underground workings, likely due to surface subsidence. Seasonally flooded scrub shrub wetlands overlie much of the iron-formation in the SW-NW parcel (Fig. 1.2-70).



**Figure 1.2-73.** Tabert, Polk, Dunn, and NWI (X-48) reserves.

### NWI Reserve (X-48)

The NWI (X-48) reserve resides in the SE  $\frac{1}{4}$  of S14-T45-R30, immediately west of the Omaha mine property and east of the Dunn reserve (Fig. 1.2-73). The two bands of iron-formation trending northeastward in the Dunn reserve converge to form one band in the NW-NW parcel of the NWI reserve. Stopping short of midway through the N  $\frac{1}{2}$  of the property, this single band of iron-formation is off-set to the southeast by 245 feet, where it continues trending northeastward across the NE-NW parcel.

The iron-formation crosses farm fields for most of its extent in the NWI Reserve (X-48) property. The off-set of the iron-formation occurs in the immediate vicinity of the farmhouse and other farm structures located in the southeast corner of the NW-NW forty. Surface ownership is private. The N1/2-SE through which the iron-formation runs is classified as agricultural land (Crow Wing County GIS Public Map Service, 2015).

Semi-permanently flooded emergent wetlands line Sand Creek where it crosses the iron-formation in the far northeastern corner of the property. These, in turn, are flanked by seasonally-flooded scrub shrub wetlands, making for a total width of 375 feet of wetlands overlying the iron-formation along the eastern edge of the NWI property. CSAH 25 runs north-south along the western property line while a township road runs east-west along the southern boundary. The Brainerd Snodeo snowmobile trail flanks both roads.

No ore reserve data was obtained for NWI Reserve (X-48). Beltrame (1977) lists 1958 as the date of the most recent ore reserve estimate as of his report. There may be more recent information available on microfilm at the MDOR office in Virginia. Base data from Beltrame (1977) are provided in Table 1.2-41.

**Table 1.2-41.** NWI Reserve (X-48) ore reserve estimate.

Ore Reserve Estimate <sup>1,2</sup>							
Property	Parcel	S	T	R	Data	Surface Owner <sup>3</sup>	Fee Owner
NWI (X-48)	SE 1/4	14	45	30	X	Private	Burlington Northern Inc.
Year	Type		Re-class	Recovery Factor		Tons	Density Factor
1958	NA					NA	
<sup>1</sup> Upper table information from Beltrame (1977), unless otherwise noted. Data consists of drill hole data, cross-sections, reserve estimates, etc. on microfilm at MDOR Minerals Tax Office in Virginia, MN. <sup>2</sup> Lower table information from MDOR Minerals Tax Office data files. <sup>3</sup> Data from MN DNR GIS coverage own_mnstwdpy2 (2008).							

### Dunn Reserve (H-3)

The Dunn reserve lies in the S1/2-SW of S14-T45-R30, immediately north of the Polk reserve property and west of NWI Reserve (X-48) (Fig. 1.2-73). There are two bands of iron-formation that pass from southwest to northeast through the two forties. A map from the MDOR data files indicates 37 holes were drilled across the iron-formation in this property, with an additional four holes drilled into the extension of the orebody southwestward into the Polk reserve property.

Data from the 1986 ore reserve estimate are provided in Table 1.2-42, showing a significant tonnage of ore. Surface ownership of the Dunn reserve parcels is private and involves multiple parties. The western and eastern parcels have been sub-divided into four and five lots, respectively, most around 10 acres in size. All but two non-adjacent lots are classified as residential one-unit, the two others being classified as rural vacant land (Crow Wing County GIS Public Map Service, 2015).

A farmstead occupies the southwestern corner of the SW-SW parcel, while a home resides atop the iron-formation in the adjacent lot. Another homestead/farmstead is situated over the northern band and part of the southern band of iron-formation in the northeastern part of the SE-SW. The remainder of the iron-formation across the two parcels appears unencumbered.

**Table 1.2-42.** Dunn Reserve ore reserve estimate.

Ore Reserve Estimate <sup>1,2</sup>							
Property	Parcel	S	T	R	Data	Surface Owner <sup>3</sup>	Fee Owner
Dunn Reserve (H-3)	S1/2-SW	14	45	30	X	Private	Hanna Iron Ore Div.
Year	Type		Re-class	Recovery Factor	Tons	Density Factor	
1986 (SE-SW)	UG Wash Ore Concentrate		X	65%	608,432	14	
1986 (SW-SW)	UG Wash Ore Concentrate		X	65%	808,185	14	
<b>Total Tons:</b>					1,416,617		
1958	UG Merch Ore				2,179,411		

<sup>1</sup>Upper table information from Beltrame (1977), unless otherwise noted. Data consists of drill hole data, cross-sections, reserve estimates, etc. on microfilm at MDOR Minerals Tax Office in Virginia, MN.

<sup>2</sup>Lower table information from MDOR Minerals Tax Office data files.

<sup>3</sup>Data from MN DNR GIS coverage own\_mnstwdpy2 (2008).

The Dunn reserve appears free from wetland impacts with the exception of seasonally-flooded scrub shrub wetlands lining an intermittent stream that flows northward through the property. The stream and wetlands cross both bands of iron-formation near the center of the property (Fig. 1.2-69). CSAH 25 runs along the eastern edge of the property before curving to the southwest in the southeastern property corner to run west along the southern property boundary. The Brainerd Snodeo snowmobile trail runs along CSAH 25.

### Polk Reserve (X-58)

The Polk reserve lies in an upland area immediately south of the Dunn reserve and east of the Tabert Reserve in the NW-NW of S23-T45-R30 (Fig. 1.2-73). The iron-formation passes through the far northwestern corner of the property. CSAH 25 runs along the northern property edge, turning southwest to parallel the iron-formation and then south near the western property border. Ironwood Dr. NE, a township road, crosses the iron-formation from the northwest to meet CSAH 25.

The Polk reserve property has been parceled out as a subdivision. There is a home to the northwest of CSAH 25, overlying the iron-formation. The Brainerd Snodeo snowmobile trail runs along the northern edge of the property, crossing the iron-formation.

Data from the 1986 ore reserve estimate obtained from the MDOR data files is presented in Table 1.2-43. The 1958 tonnage was reclassified from merch ore to wash ore concentrate using a 65% recovery factor.

**Table 1.2-43.** Polk Reserve (X-58) ore reserve estimate.

Ore Reserve Estimate <sup>1,2</sup>							
Property	Parcel	S	T	R	Data	Surface Owner <sup>3</sup>	Fee Owner
Polk Reserve (X-58)	NW-NW	23	45	30	X	Private	Univ. of MN et al.
Year	Type		Re-class	Recovery Factor	Tons		Density Factor
1986	UG Wash Ore Concentrate		X	65%	132,321		14
1958	UG Merch Ore				203,571		

<sup>1</sup>Upper table information from Beltrame (1977), unless otherwise noted. Data consists of drill hole data, cross-sections, reserve estimates, etc. on microfilm at MDOR Minerals Tax Office in Virginia, MN.

<sup>2</sup>Lower table information from MDOR Minerals Tax Office data files.

<sup>3</sup>Data from MN DNR GIS coverage own\_mnstwdpy2 (2008).

*Tabert Reserve (H-24)*

The Tabert reserve property occupies the N½-NE of S22-T45-R30, directly west of the Polk Reserve (Fig. 1.2-73). A shaft was sunk on the Tabert property by the Adbar Development Company in the fall of 1915, but it was abandoned due to bad ground (Harder and Johnston, 1918). Harder and Johnston reported that a second shaft was started in 1916. This shaft had not reached bedrock at the time of the report. A shaft location was found on a map in the MDOR Minerals Tax Office data files.

A letter in the file from Robert Adams to the Director of Mines, dated June 7, 1917, states that the ore on the western forty is “so badly mixed up as to be of little value.” The ore on the eastern forty, expected to continue across the full 80 acres, was shown “to pinch out and make but a comparatively small lens of ore running in from the northeast.” A home/farmstead sits atop the iron-formation at this location.

The iron-formation on the Tabert reserve property runs through an upland area of woods, farm fields and a homestead (Fig. 1.2-73). A second, narrow band of iron-formation to the northwest parallels the main band of iron-formation on the property. County State Aid Highway (CSAH) 25 runs north-south just east of the property, while a township road borders the property to the north. The Brainerd Snodeo snowmobile trail also follows the northern property line. There is a seasonally flooded scrub shrub wetland, roughly 150 feet by 425 feet in size, lying between the two bands of iron-formation in the NE-NE parcel. A similar, more extensive wetland lies beyond the narrow band of iron-formation in the property to the north of the Tabert reserve.

Data from the 1986 Tabert Reserve ore reserve estimate are presented in Table 1.2-44. Some drill hole data is available in the MDOR’s data files in addition to the full set of data available on microfilm.

**Table 1.2-44.** Tabert Reserve ore reserve estimate.

Ore Reserve Estimate <sup>1,2</sup>							
Property	Parcel	S	T	R	Data	Surface Owner <sup>3</sup>	Fee Owner
Tabert (H-24)	NE-NE	22	45	30	X	Private	Hanna Iron Ore Div.
	S1/2 NW-NE	22	45	30			
Year	Type		Re-class	Recovery Factor	Tons	Density Factor	
1986 (NE-NE)	UG Wash Ore Concentrate		X	65%	175,384	14	
1986 (S1/2-NW-NE)	UG Wash Ore Concentrate		X	65%	45,465	14	
					<b>Total Tons:</b>	220,849	
1958	UG Merch Ore				339,767		

<sup>1</sup>Upper table information from Beltrame (1977), unless otherwise noted. Data consists of drill hole data, cross-sections, reserve estimates, etc. on microfilm at MDOR Minerals Tax Office in Virginia, MN.  
<sup>2</sup>Lower table information from MDOR Minerals Tax Office data files.  
<sup>3</sup>Data from MN DNR GIS coverage own\_mnstwdpy2 (2008).

CAES Potential for Cuyuna South Range Study Area 3: Sigma and Omaha mines; Gunderson (O-34), NWI (X-47), NWI (X-48), Dunn (H-3), Polk (X-58), and Tabert (H-24) reserves

Cuyuna South Range Study Area 3 comprises a large area containing two former mine properties and 6 ore reserve properties. Factors pertinent to CAES have been detailed for each mine/ore reserve property in Study Area 3 in the preceding individual property sections. Study Area 3 merits further study for CAES potential for reasons highlighted below.

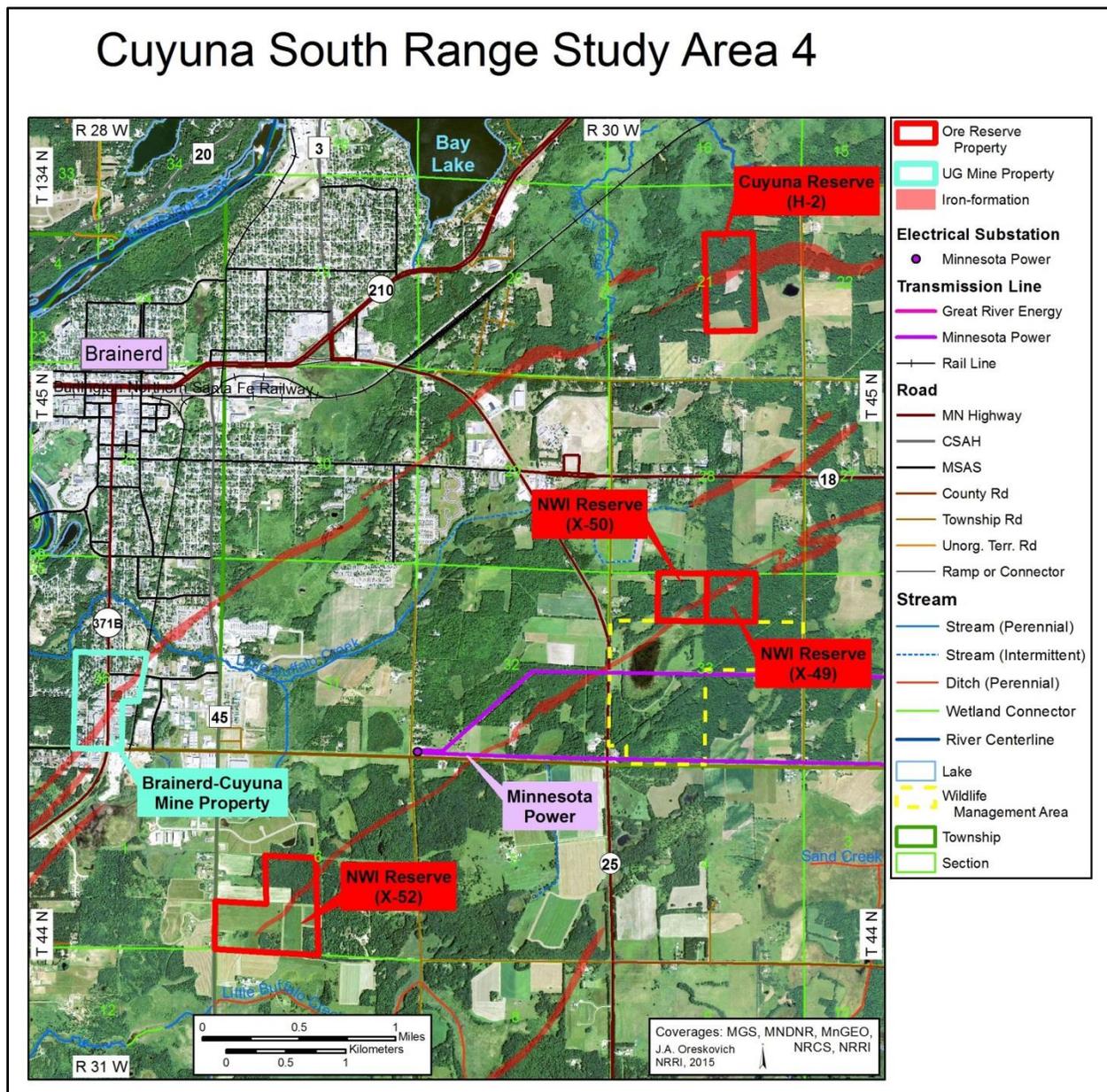
Positives:

- The main Great River Energy and Minnesota Power electrical transmission lines run north-south through the center of Study Area 3;
- Remnant underground mining features are present at both the Omaha and Sigma (Hobart Shaft) mines and possibly the Tabert shaft;
- Significant ore tonnages are available to offset the cost of new cavern construction (Omaha, Dunn, Polk, and Tabert properties; possibly more as estimates were not acquired for several of the properties);
- Distance to rail for movement of mined products averages approximately 1 mile;
- The Sigma mine property is county owned;
- There is state land immediately south of the Gunderson reserve;
- There are limited impacts from wetlands due to higher topography; and
- There are multiple stretches of iron-formation unencumbered by surface structures in the mine and reserve properties of Study Area 3.

Negatives:

- Location of defined orebodies within the mine and reserve properties is unknown;
- Some of the known tonnage areas have surface structures; and
- Sigma mine property topped with wetlands; orebody runs beneath Happy Lake.

## Cuyuna South Range Study Area 4



**Figure 1.2-74.** Cuyuna South Range Study Area 4: Brainerd-Cuyuna Mine; NWI (X-49, X-50, and X-52) and Cuyuna (H-2) reserves.

In Cuyuna South Range Study Area 4, the iron-formation is seen as occurring in multiple northeast-trending bands of disjointed lenses (Fig. 1.2-74). The region becomes more populated as it approaches the city of Brainerd to the west. A mine resides within the Brainerd city limits. The mine and one ore reserve lie on the northwestern-most band of iron-formation, while three more ore reserves lie on a band of iron-formation to the southeast. A major Minnesota Power transmission line comes into the area from the east.

Cuyuna Reserve (H-2)

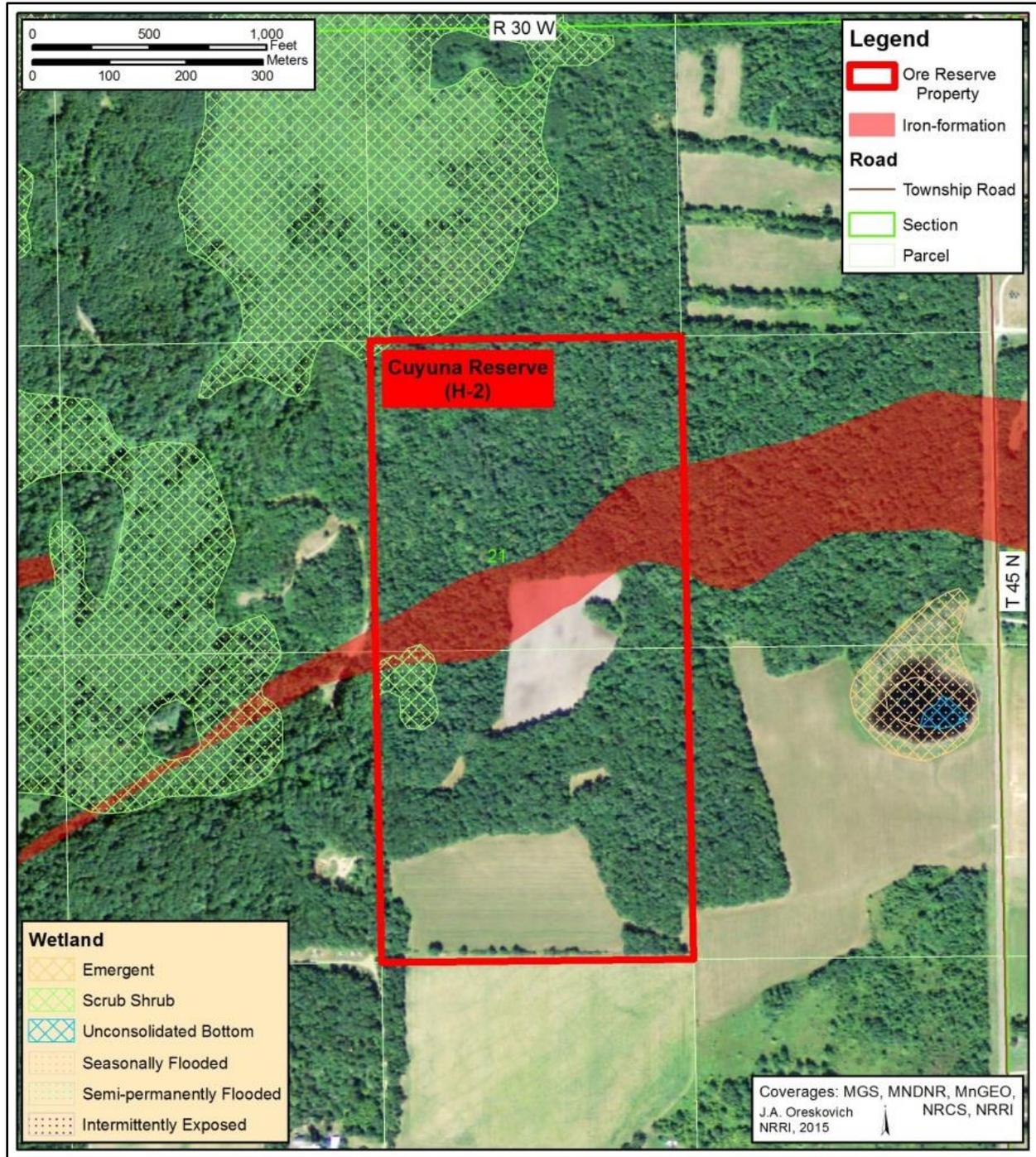


Figure 1.2-75. Cuyuna Reserve (H-2).

The Cuyuna Reserve (H-2) is located in the SW-NE and NE-SW of S21-T45-R30. This reserve is apparently the property referred to in The Iron Trade Review (1915d) article *Good Results Follow Careful Work* as showing “astonishing” results from partial explorations done by E.J. Longyear. The tract was said to contain a larger tonnage of ore at 60% iron than any other, some of it analyzing at 65 and 66% iron.

Seen in Figure 1.2-75, the iron-formation diagonally crosses the southern half of the SW-NE parcel, clipping the very northwestern tip of the NW-SE parcel. Both parcels are privately owned and classified as agricultural land (Crow Wing County GIS Public Map Service, 2015). A farm field straddles the center of the two parcels, overlying iron-formation. Of note, the parcel adjoining the SW-NE parcel to the west is owned by USX Corporation.

The Cuyuna reserve property is situated 0.25 miles west of Township Road 485 and 0.25 north of Township Road 18. The BNSF rail line passes within 0.5 miles to the northwest of the property. There is a Minnesota Power transmission line located 1.75 miles south of the property and main Great River Energy and Minnesota Power transmission lines located 3.0 miles east of the property. The Cuyuna reserve property shows little impact from wetlands other than an area of seasonally flooded scrub shrub wetlands overlying the southern portion of the iron-formation at the western side of the tract.

Data, including cross sections, pertaining to the 1958 Cuyuna Reserve ore reserve estimate are available on microfilm at the MDOR office in Virginia, MN. According to the 1958 estimate, there were 1,240,009 tons of merch ore on the property. The ore reserve was reclassified in 1986 to 806,006 tons of wash ore concentrate by applying a 65% recovery factor (Table 1.2-45). This is a significant tonnage of ore.

**Table 1.2-45.** Cuyuna Reserve (H-2) ore reserve estimate.

Ore Reserve Estimate <sup>1,2</sup>							
Property	Parcel	S	T	R	Data	Surface Owner <sup>3</sup>	Fee Owner
Cuyuna Reserve (H-2)	SW-NE & NW-SE	21	45	30	X	Private	Hanna Iron Ore Div. (22.5%)
Year	Type	Re-class		Recovery Factor		Tons	Density Factor
1986	UG Wash Ore Conc.	X		65%		806,006	14
1958	UG Merch Ore					1,240,009	

<sup>1</sup>Upper table information from Beltrame (1977), unless otherwise noted. Data consists of drill hole data, cross-sections, reserve estimates, etc. on microfilm at MDOR Minerals Tax Office in Virginia, MN.  
<sup>2</sup>Lower table information from MDOR Minerals Tax Office data files.  
<sup>3</sup>Data from MN DNR GIS coverage own\_mnstwdpy2 (2008).

Drill hole data are available in the Cuyuna Reserve (H-2) data file at MDOR. The file also contains an undated paper supplied by C. Zapffe stating that only a small amount of drilling has been done on this property.

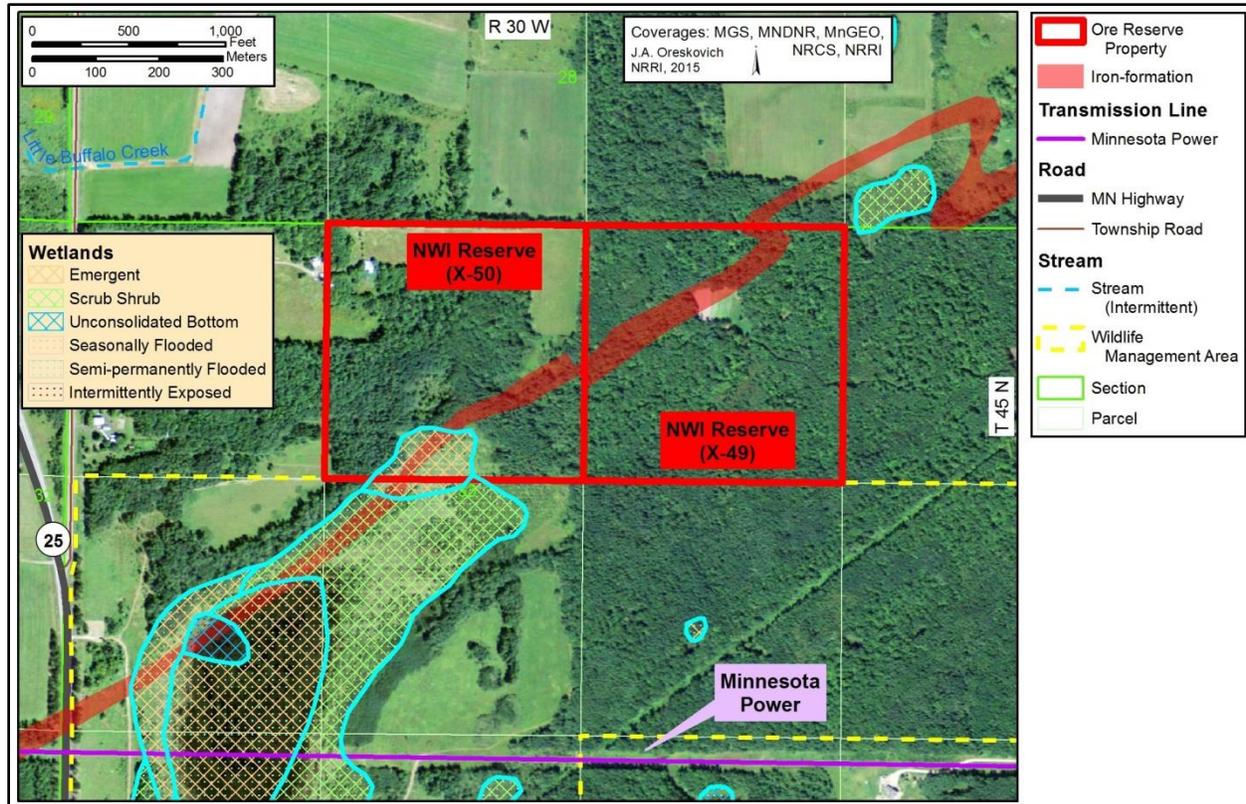


Figure 1.2-76. NWI (X-49) and NWI (X-50) reserves.

### NWI Reserve (X-49)

NWI Reserve (X-49) is located east of Brainerd in the NW-NE of S33-T45-R30 (Fig. 1.2-76). The iron-formation runs diagonally northeast-southwest through the northwestern portion of the parcel, ranging from 125 to 175 feet in width. There is a fold in the iron-formation at the parcel's northern border. An off-set in the iron-formation occurs at the western property line.

The reserve abuts NWI Reserve (X-50) to the west. It is located 0.25 miles west of Township Road 485 and 0.5 miles south of Minnesota Highway 18. A major Minnesota Power transmission line runs east-west 0.25 miles to the south. Directly to the south of the NWI Reserve (X-49) property is a 312-acre MN DNR Wildlife Management Area, the Poor Farm WMA.

NWI Reserve (X-49) resides in an upland area. The open field located over the iron-formation in Fig. 1.2-76 occupies the highest elevation on the property. Parcel ownership is private. The property is classified as rural vacant land (Crow Wing County GIS Public Map Service, 2015).

The ore reserve estimate for NWI Reserve (X-49) was not acquired. As seen in Table 1.2-46, ore reserve estimates were done in 1967 and 1958 (Beltrame, 1977). Data are available on microfilm at the MDOR office in Virginia, MN.

**Table 1.2-46.** NWI Reserve (X-49) ore reserve estimate.

Ore Reserve Estimate <sup>1,2</sup>							
Property	Parcel	S	T	R	Data	Surface Owner <sup>3</sup>	Fee Owner
NWI Reserve (X-49)	NW-NE	33	45	30	X	Private	Burlington Northern Inc.
Year	Type		Re-class	Recovery Factor		Tons	Density Factor
1967	NA					NA	
1958	NA					NA	
<sup>1</sup> Upper table information from Beltrame (1977), unless otherwise noted. Data consists of drill hole data, cross-sections, reserve estimates, etc. on microfilm at MDOR Minerals Tax Office in Virginia, MN. <sup>2</sup> Lower table information from MDOR Minerals Tax Office data files. <sup>3</sup> Data from MN DNR GIS coverage own_mnstdwpy2 (2008).							

NWI Reserve (X-50)

NWI Reserve (X-50) is located in the NE-NW of S33-T45-R30, adjacent to NWI Reserve (X-49) (Fig. 1.2-76). The iron-formation is a continuation of that in the (X-49) property, off-set 80 feet to the northwest at the eastern property border. Width of the iron-formation is reduced from 125 feet at the eastern border of 60 feet at the southern border.

The iron-formation in NWI (X-50) is overlain by wooded uplands until it narrows towards the south, where it is overlain by a seasonally flooded emergent wetland. This wetland is contiguous to the south with a large seasonally flooded scrub shrub wetland that is part of a 312-acre MN DNR Wildlife Management Area, the Poor Farm WMA. The WMA is used as an outdoor classroom/educational site by the Brainerd schools (MN DNR GIS coverage bdry\_adwma2py3).

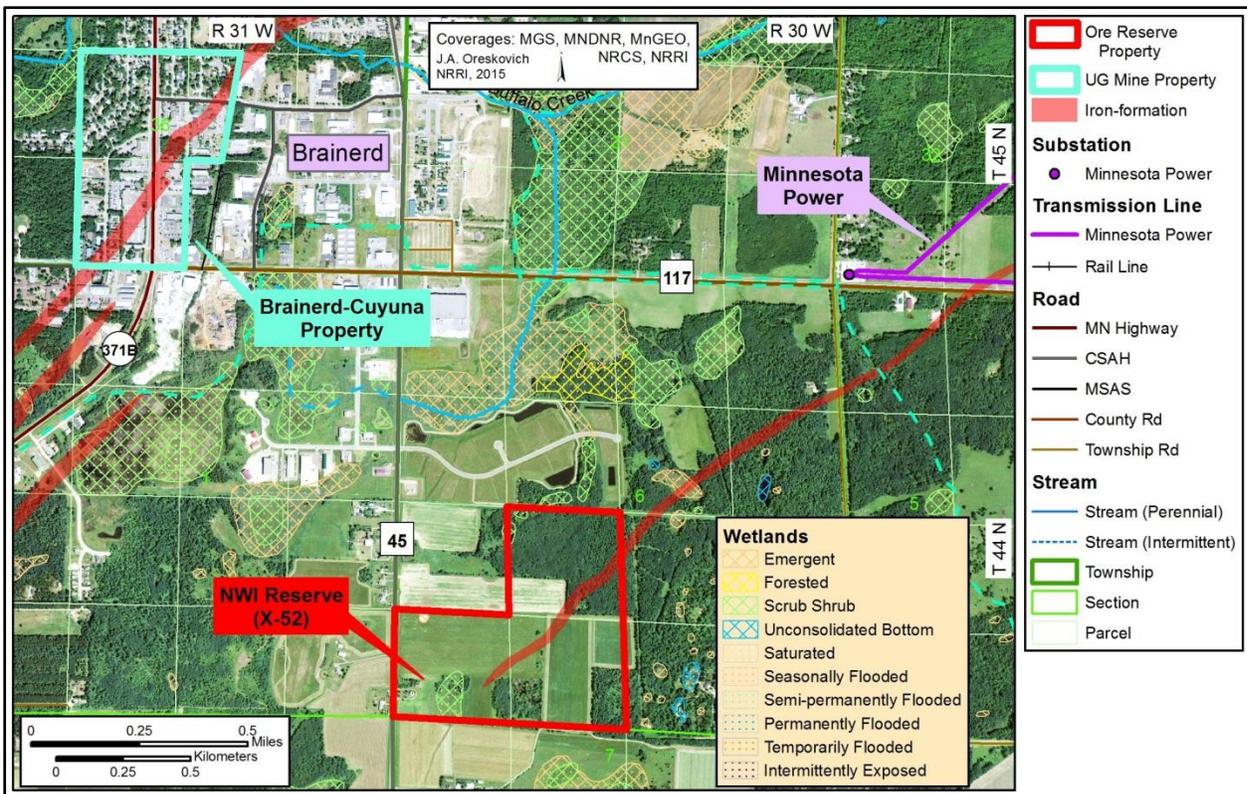
MNTH 25 Township Road 794 lie one-quarter mile to the west of NWI (X-50). A major Minnesota Power transmission line runs east-west one-quarter mile to the south. Ownership of the (X-50) reserve property is private. The parcel has been classified as rural vacant land, although structures appear in the northwestern corner (Crow Wing County GIS Public Map Service, 2015).

The ore reserve estimate for NWI Reserve (X-50) was not acquired. Ore reserve estimates were done in 1967 and 1958 per Beltrame (1977) (Table 1.2-47). An undated paper supplied by C. Zapffe states that the NWI Reserve (X-50) property has been explored across the entire length of the orebody and the width of the ore is definite (MDOR data files). Drill hole data are available in the NWI Reserve (X-50) MDOR data file, in addition to data available on microfilm.

**Table 1.2-47. NWI Reserve (X-50) ore reserve estimate.**

Ore Reserve Estimate <sup>1,2</sup>							
Property	Parcel	S	T	R	Data	Surface Owner <sup>3</sup>	Fee Owner
NWI Reserve (X-50)	NE-NW	33	45	30	X	Private	Glacier Park Co.
Year	Type	Re-class		Recovery Factor		Tons	Density Factor
1967	NA					NA	
1958	NA					NA	

<sup>1</sup>Upper table information from Beltrame (1977), unless otherwise noted. Data consists of drill hole data, cross-sections, reserve estimates, etc. on microfilm at MDOR Minerals Tax Office in Virginia, MN.  
<sup>2</sup>Lower table information from MDOR Minerals Tax Office data files.  
<sup>3</sup>Data from MN DNR GIS coverage own\_mnstwdpy2 (2008).



**Figure 1.2-77. Brainerd-Cuyuna mine and NWI (X-52) reserve.**

Brainerd-Cuyuna Mine

Mine	Former Name	Range	S	T	R	Parcel	UG	OP	ML
Brainerd-Cuyuna	Sixth Street	South Range	36	45	31	E1/2-SW & PRT of NW-SE	X		
Shaft Sinking	1st Shipment	Last Shipment	Total Ore Shipped			Last Operator	Last Known Fee		
1913, 1914	1915	1918	3,199			Brainerd-Cuyuna Mining Co.	Brainerd; Madison, DR		
Overburden (Ft.)	Mine Depth	Top Level	Lowest Level		Mining Method	Shaft Type			
90	164		154 Ft. Level			wooden drop shaft; 3-compartment			

The Brainerd-Cuyuna mine is located within the City of Brainerd in the E1/2-SW and NW-SE (west of the rail road tracks) of S36-T45-R31 (Fig. 1.2-77). The shaft, located northwest of the iron-formation in the NE-SW of Section 36, is 164 feet deep (Harder and Johnston, 1918). The shaft is a wooden drop shaft sunk through 90 feet of surface. It is connected to the orebody by a 100-foot crosscut (The Iron Trade Review, 1915d). A page attached to the 1966 ore reserve estimate found at MDOR states that the “shaft area is covered by a concrete slab, however caving on one side indicates that the shaft collar has collapsed.”

The shaft and crosscut, which is at the 154-foot level, are in foot-wall slate (Harder and Johnston, 1918). The crosscut leads to the northernmost of two lens-like orebodies in the mine containing “yellowish and brownish limonite typical of the south range.” Comprised mainly of soft yellow ochereous ore, the north lens is separated by a thin bed of barren rock from the south lens. Located southeast of the north lens, the south lens is somewhat manganiferous and darker in color (Harder and Johnston, 1918).

At the time of operation, the Brainerd-Cuyuna mine was situated south of the city of Brainerd. A 1915 topo map shows a roughly 700-foot-long rail spur coming from the present-day BNSF tracks into the mine site southeast of the shaft. The mine property has since been platted and incorporated into the city as it expanded southward, allowing no opportunity for CAES use of existing underground mine features at the site.

Ore reserve data for the Brainerd-Cuyuna mine property was found at MDOR. It is presented in Table 1.2-48. Assay data for the mine property is presented in Table 1.2-49.

**Table 1.2-48.** Brainerd-Cuyuna Mine ore reserve estimate.

Ore Reserve Estimate <sup>1,2</sup>							
Property	Parcel	S	T	R	Data	Surface Owner <sup>3</sup>	Fee Owner
Brainerd-Cuyuna Mine	E1/2-SW & NW-SE (W of RR tracks)	36	45	31	X	City of Brainerd	Brainerd; Madison, DR.
Year	Type	Re-class		Recovery Factor		Tons	Density Factor
1986 (NW-SE)	UG Wash Ore Conc.	X		65%		32,825	14
1974 (NW-SE)	UG Merch Ore					50,500	
1966 (NW-SE W of RR)	UG NB Wash Ore Conc.					267,135	
1966 (E1/2-SW)	UG NB Wash Ore Conc.					189,326	
<b>1966 Total Tons:</b>						456,461	
<sup>1</sup> Upper table information from Beltrame (1977), unless otherwise noted. Data consists of drill hole data, cross-sections, reserve estimates, etc. on microfilm at MDOR Minerals Tax Office in Virginia, MN. <sup>2</sup> Lower table information from MDOR Minerals Tax Office data files. <sup>3</sup> Data from M DNR GIS coverage own_mnstwdpy2 (2008).							

**Table 1.2-49.** Brainerd-Cuyuna Mine assay data.

Assay Data <sup>1</sup>										
Property	Type	Dry							Natural	
		Tons	Fe	P	Si	Mn	Al	Moist.	Fe	Mn
Brainerd-Cuyuna Mine (1966)	NB WOC	456,461	56.81	0.475	8.00	0.31	2.70	12.50	49.71	
<sup>1</sup> Source: MDOR data file.										

### NWI Reserve (X-52)

NWI Reserve (X-52) is located in the S1/2-SW and NE-SW of S6-T44-R60 (Fig. 1.2-77). The iron-formation runs diagonally northeast-southwest from the east-central border of the NE-SW parcel to approximately 450 feet into the southeastern portion of the NW-SW parcel where it pinches out. Land ownership of the reserve parcels is private. The land is classified as agricultural (Crow Wing County GIS Public Map Service, 2015).

The property is an upland area of forest and fields devoid of wetlands in the vicinity of the iron-formation. CSAH 45 runs north-south along the western property line of the SW-SW parcel. There are major Minnesota Power transmission lines coming in from the east to a substation located three-quarters of a mile to the northeast of the property.

Ore reserve data for NWI Reserve (X-52) was found in the MDOR data files and is presented in Table 1.2-50. An undated paper, noted as being supplied by C. Zapffe, states that the orebody is very narrow (MDOR data files). The 1967 estimate removes the NE-SW parcel from the taxable reserves listing following reclassification from merch ore to wash ore concentrate. Assay data for NWI Reserve (X-52) are presented in Table 1.2-51.

**Table 1.2-50.** NWI Reserve (X-52) ore reserve estimate.

Ore Reserve Estimate <sup>1,2</sup>							
Property	Parcel	S	T	R	Data	Surface Owner <sup>3</sup>	Fee Owner
NWI Reserve (X-52)	S1/2-SW & NE-SW	6	44	30	X	Private	Glacier Park Co.
Year	Type	Re-class		Recovery Factor		Tons	Density Factor
1967 (S1/2-SW)	UG NB Wash Ore Conc.			65%		296,074	
1967 (NE-SW)	UG NB Wash Ore Conc.			65%		0	
<b>1967 Total Tons:</b>						296,074	
1958 (S1/2-SW)						345,321	
1958 (NE-SW)						119,786	
<b>1958 Total Tons:</b>						465,107	
<sup>1</sup> Upper table information from Beltrame (1977), unless otherwise noted. Data consists of drill hole data, cross-sections, reserve estimates, etc. on microfilm at MDOR Minerals Tax Office in Virginia, MN. <sup>2</sup> Lower table information from MDOR Minerals Tax Office data files. <sup>3</sup> Data from MN DNR GIS coverage own_mnstwdpy2 (2008).							

**Table 1.2-51.** NWI Reserve (X-52) assay data.

Assay Data <sup>1</sup>										
Dry									Natural	
Property	Type	Tons	Fe	P	Si	Mn	Al	Moist.	Fe	Mn
NWI Reserve (X-52) S1/2-SW (1967)	UG NB WOC	286,074	59.74	0.280	5.50	-	-	10.00	53.77	
<sup>1</sup> Source: MDOR data file.										

**CAES Potential for Cuyuna South Range Study Area 4: Brainerd-Cuyuna Mine; Cuyuna (H-2), NWI (X-49), NWI (X-50), and NWI (X-52) Reserves**

Cuyuna South Range Study Area 4 encompasses one former mine and four ore reserve properties located in the Brainerd area. The Brainerd-Cuyuna mine lies within the city of Brainerd. It is overlain by houses and other building structures, making it inaccessible for CAES purposes.

Factors pertinent to CAES have been detailed for each ore reserve property in Study Area 4 in the preceding individual property sections. These factors are summarized below.

**Positives:**

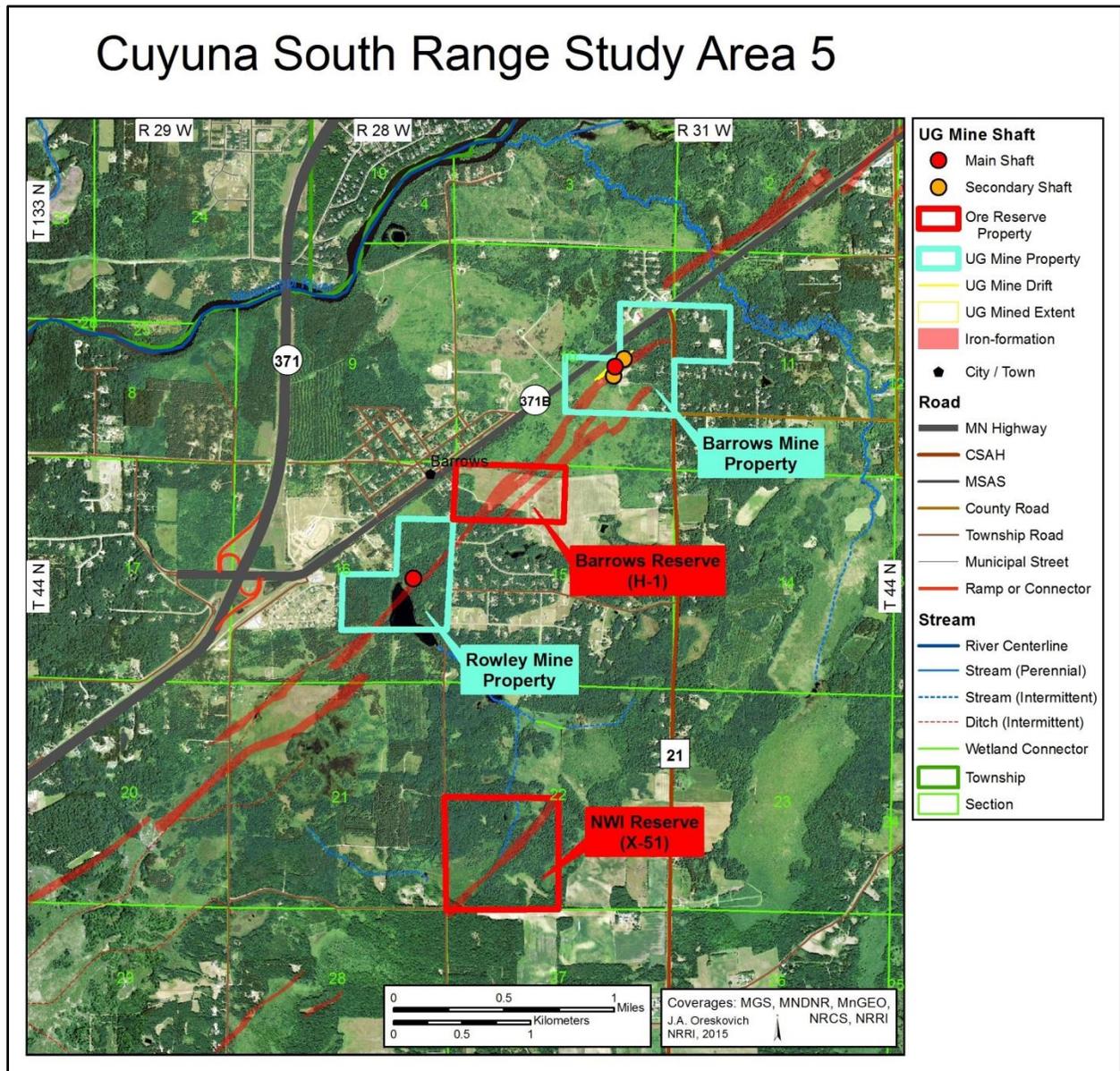
- Significant ore tonnages are available to off-set the cost of CAES cavern construction (Cuyuna and NWI (X-52) reserves); NWI (X-49) and NWI (X-50) ore reserves were not acquired for this project;
- There is little impact from wetlands in the immediate vicinity of the iron-formation, with the exception of the southern portion of NWI (X-50) reserve;
- Road access is within 0.25 miles of each property where not immediately adjacent;
- A major Minnesota Power electrical transmission line runs within 0.5 mile of the NWI (X-49) and (X-50) reserve properties and 1.75 miles of the Cuyuna Reserve.

- The main north-south Great River Energy and Minnesota Power transmission lines lie 3.0 miles to the east of the Cuyuna and NWI (X-49) reserves;
- The NWI (X-52) reserve lies within 0.75 miles of a Minnesota Power substation;
  - The Cuyuna Reserve is within 0.5 miles of the BNSF rail line; and
  - NWI (X-49) and NWI (X-50) are classified as rural vacant land.

Negatives:

- The Brainerd-Cuyuna mines resides within the city of Brainerd; the mine workings underlie homes and businesses; and
- The NWI (X-49) and NWI (X-50) reserves border on a 312-acre state WMA to the south used as an outdoor classroom/educational site for the Brainerd schools (MN DNR GIS coverage bdry\_adwma2py3). Wetlands over the southern portion of the iron-formation in NWI (X-50) are contiguous with those of a 30-acre bullrush marsh in the WMA.

Cuyuna South Range Study Area 5



**Figure 1.2-78.** Cuyuna South Range Study Area 5: Barrows and Rowley mines; Barrows (H-1) and NWI (X-51) reserves.

Cuyuna South Range Study Area 5 encompasses the southwestern-most mines and ore reserves located on the South Range within Crow Wing County. Two mines and one ore reserve are located along the more continuous band of iron-formation occurring in the area (Fig. 1.2-78). A second ore reserve property occupies a separate lens of iron-formation located roughly one mile to the southeast.

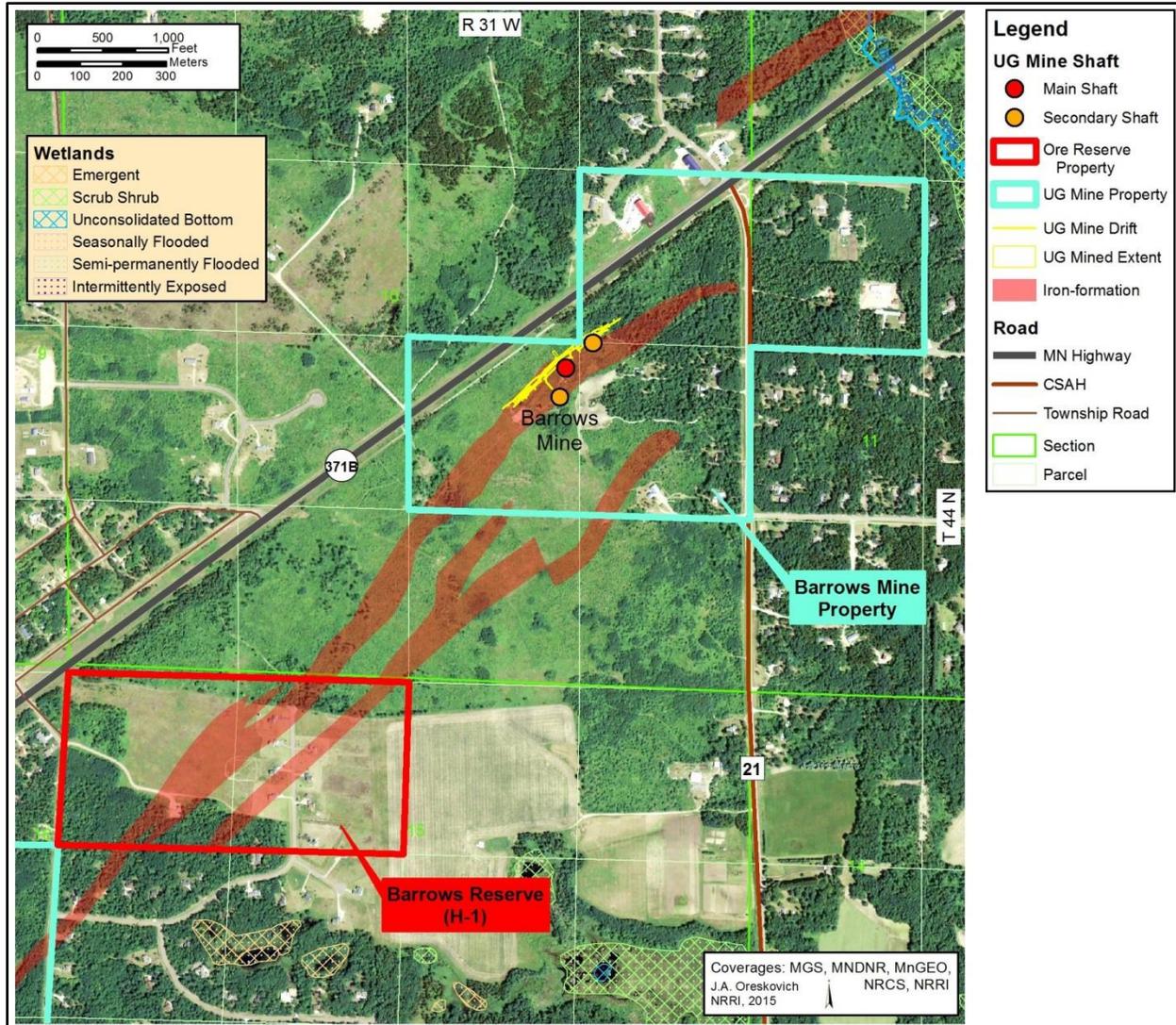


Figure 1.2-79. Barrows mine and Barrows (H-1) reserve.

Barrows Mine

Mine	Former Name	Range	S	T	R	Parcel	UG	OP	ML
Barrows		South	10	44	31	N1/2-SE & SE-NE	X		
		Range	11	44	31	SW-NW			
<b>Shaft Sinking</b>	<b>1st Shipment</b>	<b>Last Shipment</b>	<b>Total Ore Shipped</b>			<b>Last Operator</b>	<b>Last Known Fee</b>		
1911 & 1912	1913	1914	56,439			Hanna	Taylor Properties		
<b>Overburden (Ft.)</b>	<b>Mine Depth</b>	<b>Top Level</b>	<b>Lowest Level</b>			<b>Mining Method</b>	<b>Shaft Type</b>		
110	160 Ft.		160-Ft. Level			stopping	timber drop shaft; 3-compartment		

The Barrows mine property is located in the N1/2-SE and the SE-NE of S10-T44-R31 and the SW-NW of S11-T44-R31 (Fig. 1.2-79). Two bands of iron-formation lie within the Barrows mine property in Section 10. The mine is located in the northwestern band.

The Barrows Mine (Fig. 1.2-79) was the first producing mine on the Cuyuna South Range (Harder and Johnston, 1918). Difficulties plagued shaft sinking at the Barrows mine in 1911 as both a test shaft and a second shaft, started as a timber drop shaft, were abandoned at 80 feet and 50 feet, respectively, before reaching ledge. In early 1912 a third shaft, again a timber drop shaft, was sunk and finally ledged (Harder and Johnston, 1918). The shaft is 160 feet deep.

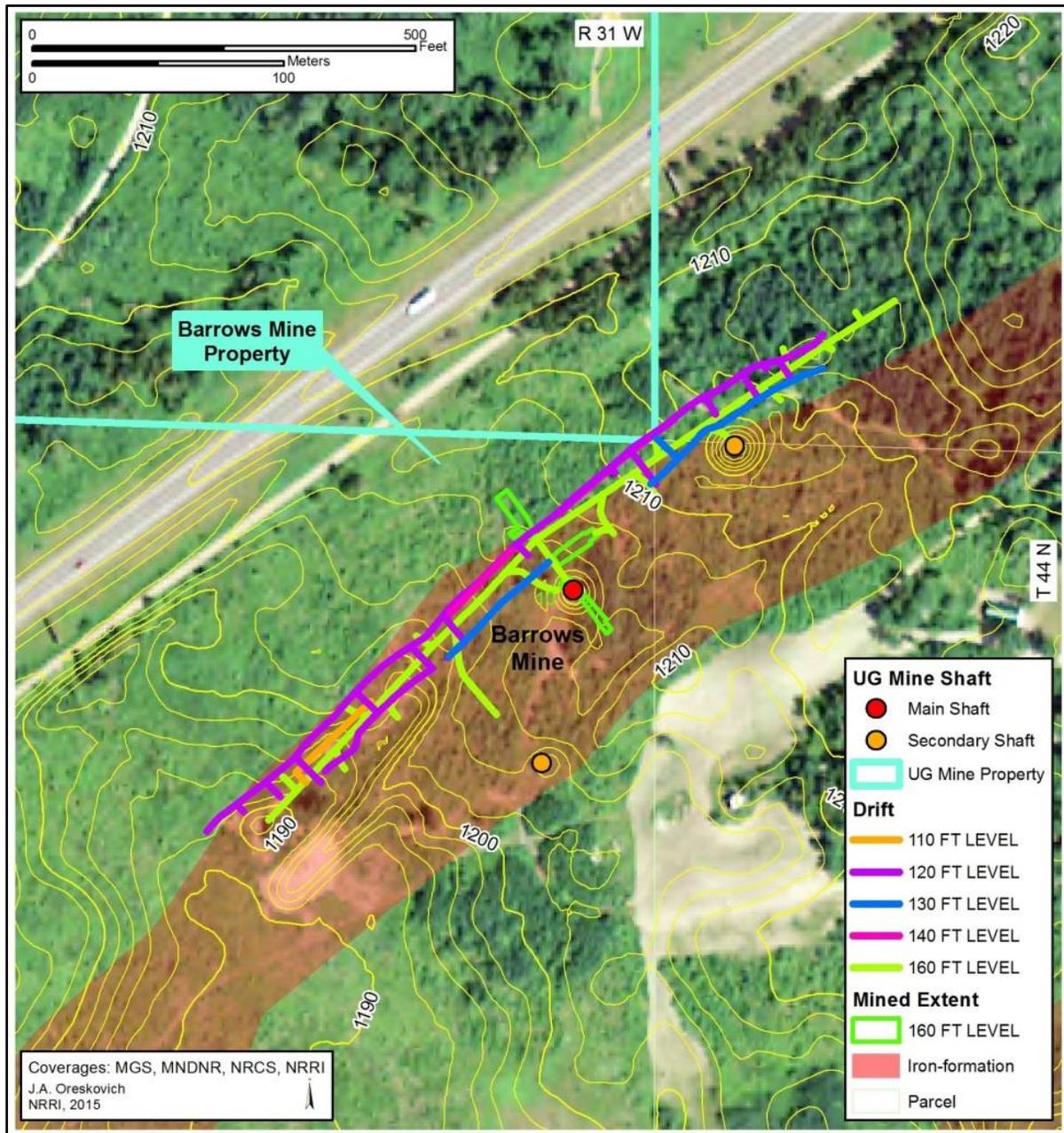


Figure 1.2-80. Two-foot LiDAR contours highlight Barrows mine shaft locations.

Shaft locations become very obvious when 2-foot LiDAR elevation contours are applied to a map of the Barrows mine area (Fig. 1.2-80). The main shaft (Shaft No. 2), a 3-compartment shaft, lies in a 6- to 8-foot circular depression; the secondary shaft to the northeast (Shaft No. 1) lies in a 10-foot depression. Both shafts have crosscuts at the 160-foot level. Shaft No. 3 appears on the mine map as a 5-compartment shaft that is not connected to the mine workings.

Shaft names do not appear to be indicative of the order in which they were sunk. The shafts reside in the hanging wall of the orebody.

Mining took place on the 110-, 120-, 130-, 140- and 160-foot levels according to the map found. The stoping method of mining was used (Crowell & Murray, 1917).

The Barrows mine produced ore during 1913 and 1914, at which time the lease was let go (Harder and Johnston, 1918). Total ore shipped was 56,439 tons. There have been no shipments of ore from the Barrows mine since 1914 (Skillings Mining Review, 2005).

The Barrows mine property is a mix of forest and field devoid of wetlands of note (Fig. 1.2-79). The population has encroached on the mine property from the east. Lots within the ore reserve property are privately owned. The mine workings reside in lots classified as rural vacant land and agricultural land (Crow Wing County GIS Public Map Service, 2015).

MNTH 371B runs northeast-southwest through the property to the northwest of the iron formation. CSAH 21 runs north-south along and through the property on the section line. The closest major electrical transmission line to the Barrows mine is a Minnesota Power line that comes into a substation from the east 3.7 miles to the northeast of the mine.

A 1965 ore reserve estimate for the Barrows mine that included assay data was found in the MDOR data files. These data are presented in Tables 1.2-52 and 1.2-53, respectively. A significant amount of ore remains in the reserve. The ore reserve statement notes that the mine shaft is caved.

**Table 1.2-52.** Barrows Mine ore reserve estimate.

Ore Reserve Estimate <sup>1,2</sup>							
Property	Parcel	S	T	R	Data	Surface Owner <sup>3</sup>	Fee Owner
Barrows Mine	N1/2-SE & SE-NE	10	44	31	X	Private	Hanna Iron Ore Div.
	SW-NW	11	44	31			
Year	Type	Re-class		Recovery Factor		Tons	Density Factor
1965	UG Wash Ore Conc.					506,060	
1958						548,006	

<sup>1</sup>Upper table information from Beltrame (1977), unless otherwise noted. Data consists of drill hole data, cross-sections, reserve estimates, etc. on microfilm at MDOR Minerals Tax Office in Virginia, MN.

<sup>2</sup>Lower table information from MDOR Minerals Tax Office data files.

<sup>3</sup>Data from MN DNR GIS coverage own\_mnstwdpy2 (2008).

**Table 1.2-53.** Barrows Mine assay data.

Assay Data <sup>1</sup>										
Dry									Natural	
Property	Type	Tons	Fe	P	Si	Mn	Al	Moist.	Fe	Mn
Barrows Mine	UG WOC	506,060	57.96	0.335	8.27	0.33	1.29	12.50	50.72	

<sup>1</sup>Source: MDOR data file.

### Barrows Reserve (H-1)

The Barrows reserve property is located to the southwest of the Barrows mine, occupying the N1/2-NW of S15-T-44-R31 (Fig. 1.2-79). It touches on the corner of the Rowley mine property to the southwest. Like the Barrows mine property, there are two bands of iron-formation running through the property. The northwestern band is particularly broad within the property boundaries.

The Barrows reserve property is covered with an upland mix of forest, farm land and open fields that are devoid of wetlands of note. Homes have been established across the iron-formation in the NE-NW parcel along a road running due north near the center of the parcel. The NE-NW parcel has a substantially lower ore reserve tonnage than the NW-NW parcel.

The NW-NW parcel is classified as rural vacant land with the exception of a square four-acre parcel in the southeastern quadrant that is classified commercial (Crow Wing County GIS Public Map Service, 2015). There is a communication tower on this small lot directly overlying the iron-formation. It accessed by a road from MNTH 371B that runs northeast-southwest to the west of the property, just touching on the northwestern corner. Distance from the NW-NW parcel to the nearest major electrical transmission line, at the Minnesota Power substation to the northeast, is >4.0 miles.

This property (the Barrows reserve) likely contains what was described in The Iron Trade Review (1916b) as “one of the largest and most compact deposits of attractive ore per south range forty.” Much of the ore had analyzed at over 60% iron, while 50 feet of drill core from one angle hole averaged less than 2% silica.

Some drill hole data are available in the data files at MDOR; more is available on microfilm. A 1986 ore reserve estimate provides ore tonnages on the property. Data are presented in Table 1.2-54.

**Table 1.2-54.** Barrows Reserve ore reserve property.

Ore Reserve Estimate <sup>1,2</sup>							
Property	Parcel	S	T	R	Data	Surface Owner <sup>3</sup>	Fee Owner
Barrows Reserve (H-1)	NE-NW & NW-NW	15	44	31	X	Private	Hanna Iron Ore Div.
Year	Type	Re-class	Recovery Factor		Tons		Density Factor
1986 (NE-NW)	UG Wash Ore Conc.				29,486		14
1986 (NW-NW)	UG Wash Ore Conc.	X	65% (former MO) 60% (WOC)		53,709 247,680		14
<b>1986 Total Tons:</b>					330,875		
1965 (NE-NW)	UG Wash Ore Conc.				29,486		
1965 (NW-NW)	UG Merch Ore				82,629		
	UG Wash Ore Conc.				247,680		
<b>1965 Total Tons:</b>					359,795		
<sup>1</sup> Upper table information from Beltrame (1977), unless otherwise noted. Data consists of drill hole data, cross-sections, reserve estimates, etc. on microfilm at MDOR Minerals Tax Office in Virginia, MN. <sup>2</sup> Lower table information from MDOR Minerals Tax Office data files. <sup>3</sup> Data from MN DNR GIS coverage own_mnstwdpy2 (2008).							

Rowley Mine

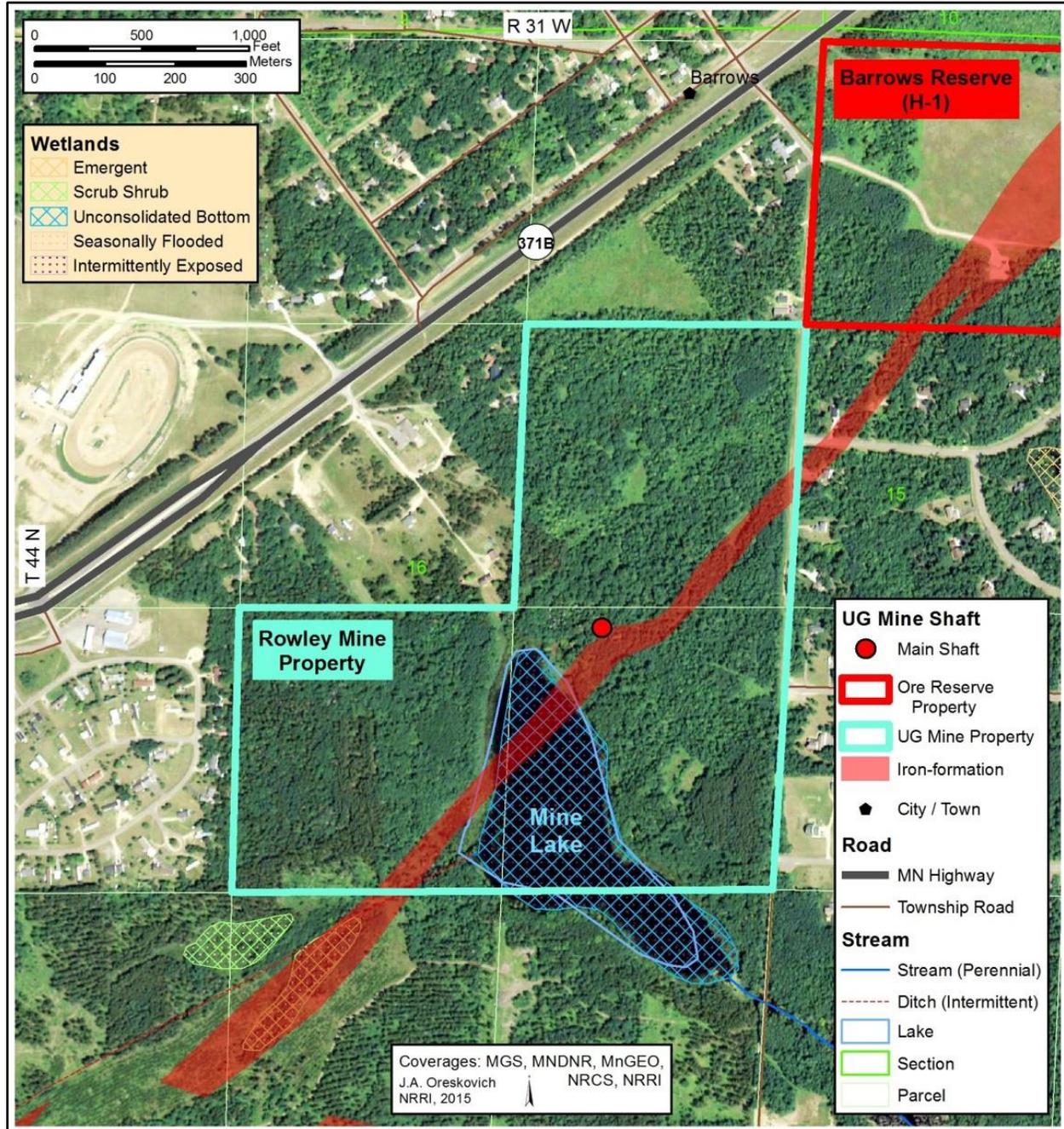


Figure 1.2-81. Rowley mine.

Mine	Former Name	Range	S	T	R	Parcel	UG	OP	ML
Rowley		South Range	16	44	31	SE-NE & N1/2-SE	X		
Shaft Sinking	1st Shipment	Last Shipment	Total Ore Shipped			Last Operator	Last Known Fee		
1915									
Overburden (Ft.)	Mine Depth	Top Level	Lowest Level			Mining Method	Shaft Type		
100	350 Ft.						rectangular concrete drop shaft		

The Rowley mine property resides in the SE-NE and N1/2 SE of S16-T44-R31 (Fig. 1.2-81). The iron-formation trends northeastward at roughly a 45° angle across the three parcels. It widens to the north of Mine Lake in the NE-SE before narrowing again prior to passing into the SE-NE parcel. Land cover consists mostly of forested uplands and Mine Lake, which overlies the iron-formation for half of its extent in the NE-SE parcel.

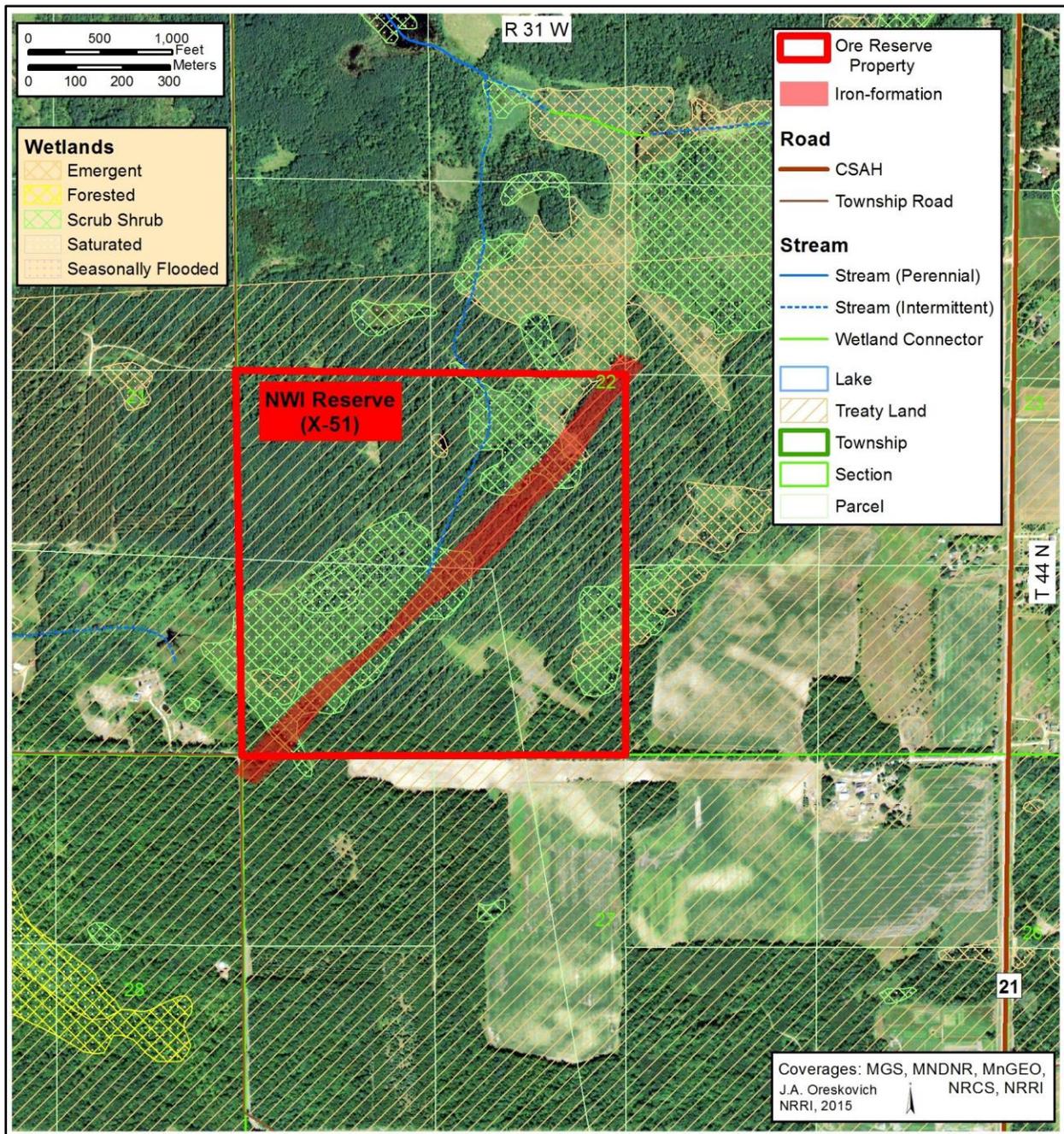
Little information was found on the Rowley mine. Zapffe (1915a) wrote of a concrete shaft being sunk on the Rowley property. Aulie and Johnson (2002) note that the shaft, of C.B. Rowley's design, was a rectangular drop shaft, measuring 6 feet by 14 feet (inside dimensions) with 18-inch-thick walls. The shaft was sunk through quick sand in surface that was 100 feet thick, as reported by Crowell & Murray (1917), who gave the mine's greatest depth as 350 feet. This greatly exceeds the depth of any other mine on the South Range. No maps were found for the Rowley mine. The mine was abandoned in 1917 due to water problems (Aulie and Johnson, 2002).

Since no maps were found showing the location of the Rowley shaft, the shaft's placement as shown in Figure 1.2-79 is a best guess based on use of GIS coverages. The property boundary (3 parcels) was found in a MDOR data file. Overlaying NAIP imagery (NRCS) with parcel boundaries (MN DNR), the iron-formation (MGS) and 2-foot LiDAR elevation contours (MnGEO), resulted in finding a likely location. The site selected is adjacent to the iron-formation on the hanging wall side of a circular 10-foot depression. The depression is immediately adjacent to a 100 foot diameter circular 12-foot rise to the east-southeast that could be a stockpile for materials removed in the construction of a 350-foot-deep shaft.

The Rowley mine is located within 0.1 mile of MNTH 371B. The property is nearly five miles from the closest major electrical transmission line, at the Minnesota Power substation to the northeast. The Rowley property is privately owned. All three parcels are classified as managed forest lands (Crow Wing County GIS Public Map Service, 2015).

Some drill hole data are available for the Rowley property in the data files at MDOR. This would suggest that there are more data available on microfilm at the MDOR office in Virginia. The Rowley mine does not appear in Beltrame's (1977) listing of ore properties on the Cuyuna Range.

NWI Reserve (X-51)



**Figure 1.2-82.** NWI (X-51) reserve.

NWI Reserve (X-51) is located in the SW1/4 of S22-T44-R31. This site is a lightly populated area of forested uplands, open fields, and wetlands. A distinct lens of iron-formation occurs almost entirely within the property boundary as it stretches from the southwest to northeast

corners (Fig. 1.2-82). A significant amount of the iron-formation is overlain by seasonally flooded scrub shrub wetlands, particularly where it lies within the S1/2-SW1/4.

Township Road 405 runs south and west from the southwest corner boundary of the NWI (X-51) property. CSAH 21 runs north-south one-half mile east of the property. Major electrical transmission lines are 4.6 miles to the southeast (Minnesota Power) and 5.0 miles to the northeast (Minnesota Power substation)

The NWI Reserve (X-51) resides within the 1837 Chippewa treaty lands. The property is privately owned. It is classified as rural vacant land (Crow Wing County GIS Public Map Service, 2015). State tax forfeit property that is administered by Crow Wing County abuts the northern half of the reserve property along the western side.

A 1965 ore reserve estimate, cross-sections, and map of the NWI Reserve (X-51) orebody outline at ledge were found in the data files at MDOR. Ore estimate data is presented in Table 1.2-55.

**Table 1.2-55.** NWI Reserve (X-51) ore reserve estimate.

Ore Reserve Estimate <sup>1,2</sup>								
Property	Parcel	S	T	R	Data	Surface Owner <sup>3</sup>	Fee Owner	
NWI Reserve (X-51)	SW1/4	22	44	31	X	Private	Glacier Park Co.	
Year	Type		Re-class		Recovery Factor		Tons	Density Factor
1965	Wash Ore Conc.		X		60%		531,429	
1958	Wash Ore Conc. & Merch Ore (?)						816,831	

<sup>1</sup>Upper table information from Beltrame (1977), unless otherwise noted. Data consists of drill hole data, cross-sections, reserve estimates, etc. on microfilm at MDOR Minerals Tax Office in Virginia, MN.  
<sup>2</sup>Lower table information from MDOR Tax Office data files.  
<sup>3</sup>Data from MN DNR GIS coverage own\_mnstwdpy2 (2008).

### CAES Potential for Cuyuna South Range Study Area 5: Barrows and Rowley Mines; Barrows (H-1) and NWI (X-51) Reserves

Two mines—one of which was a producer—and two ore reserve properties comprise Cuyuna Study Area 5. Details relative to CAES potential are included in the paragraphs above for each of the mines and reserves. A summary of pertinent factors are provided below.

#### Positives:

- The Barrows mine has two 160 foot deep shafts and void space from mining on five levels;
- The Rowley mine shaft may be as deep as 350 feet;
- Significant ore reserves remain on the Barrows mine property and occur in the Barrows and NWI (X-51) reserve properties to produce a saleable product to offset the costs of creating a CAES cavern. Reserve data for the Sigma mine property was not obtained;
- Barrows mine, Barrows reserve and much of the Rowley mine properties are dry uplands;

- 
- Most of the Study Area 5 mines and reserve properties are classified as rural vacant, agriculture or forest management land; and
  - Study Area 5 properties are served by MNTN 371B and/or CSAH 21.

Negatives:

- Much of the iron-formation in the NWI (X-51) reserve is impacted by wetlands;
- The iron-formation near the Rowley shaft runs under Mine Lake. The mine was abandoned due to water problems;
- A communications tower sits atop the iron-formation in the Barrows reserve; and
- Study Area 5 mine and ore reserve properties lie at the greatest distance from major electrical transmission lines of all those on the South Range, with the exception of the Adams mine and Crow Wing reserve on the far eastern end of the South Range.

Emily District

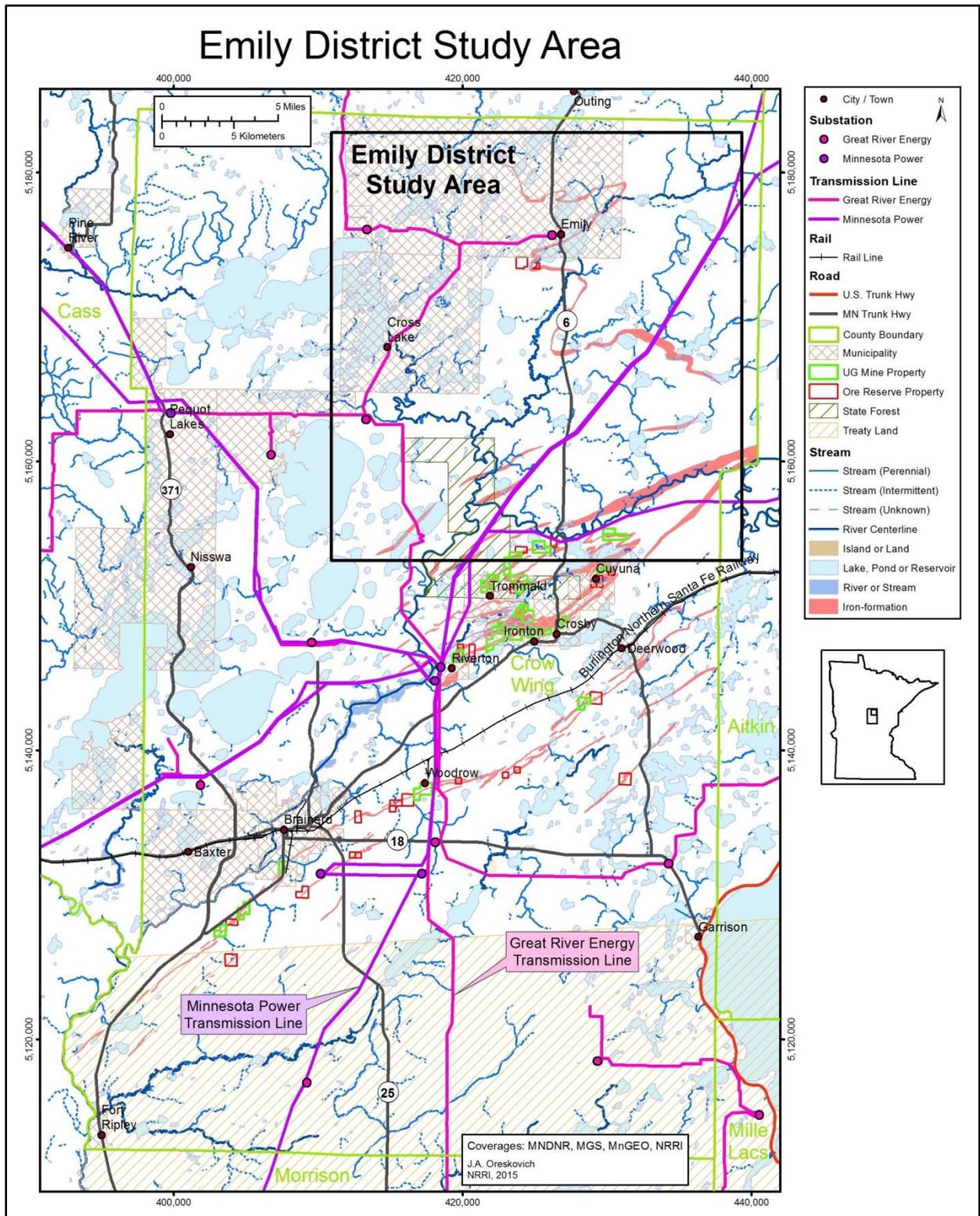
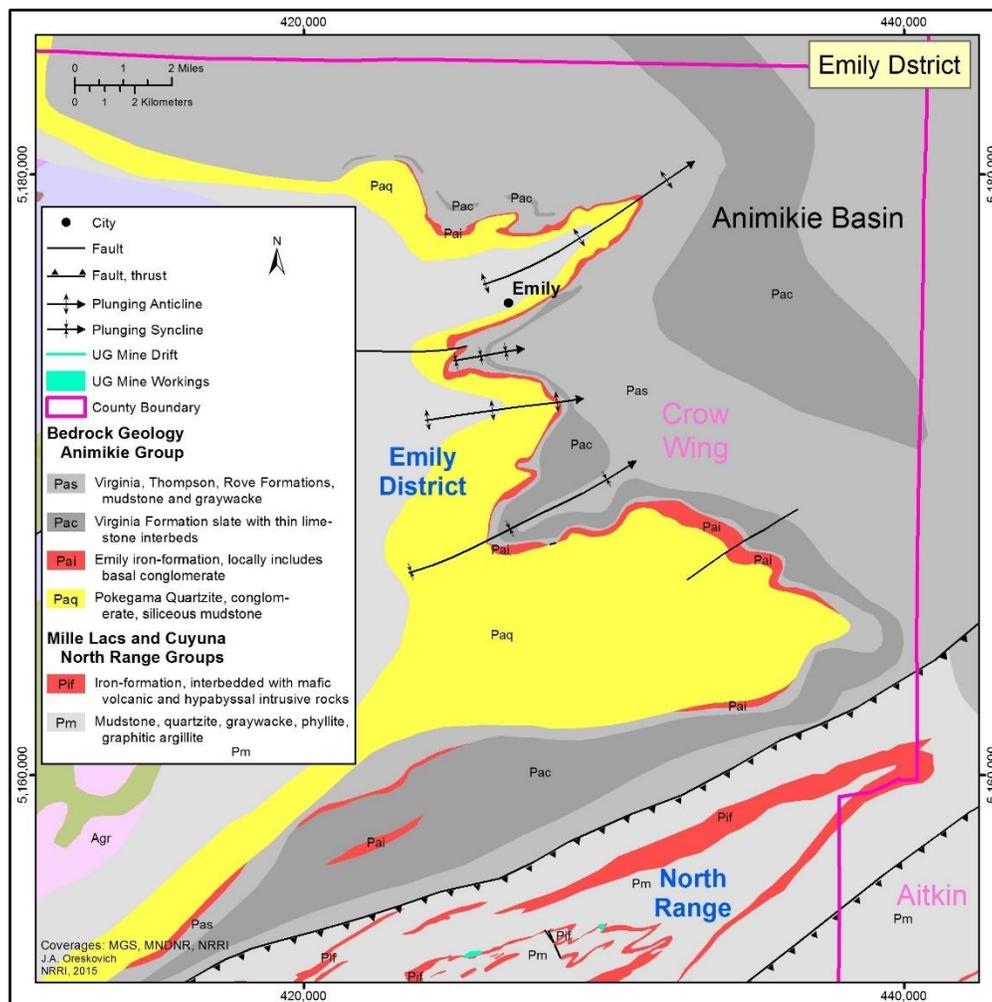


Figure 1.2-83. Emily District study area.

The Emily District study area is located in the northeastern corner of Crow Wing County, directly north of the Cuyuna North Range (Fig. 1.2-83). The city of Emily, located in the northern part of the district, lies along MNTH 6 on the western shore of Lake Emily. Ruth Lake lies < 0.5 miles to the north. Emily’s municipal boundary incorporates the entire township in which it is located, including the site of recent interest in manganese extraction. Power is brought into the city of Emily via a major Great River Energy transmission line.

The Emily District is located on the southwestern end of the Animikie Basin. It lies immediately north of the Cuyuna North Range and the Fold and Thrust Belt that precipitated formation of the Animikie Basin (Figs. 1.2-84, 1.2-2). Like the Biwabik Iron Formation on the northern rim of the basin, the Emily Iron Formation is underlain by Pokegama Quartzite and overlain by the Virginia Formation. Stratigraphic differences, however, distinguish the two suites of rocks, making them distinct units. For geologic detail on the Emily District, the reader is referred to Severson et al. (2003), and Morey (1990).



**Figure 1.2-84.** Bedrock geology map of the Emily District. (Source: Minnesota Geological Survey State Map Series S-22, 2011; Boerboom and Chandler, 2004.

Severson et al. (2003) subdivide the Emily District into a northern district and a southern district. In the northern Emily district, the trend of the Emily Iron Formation varies considerably with folding (Fig. 1.2-84). In the southern Emily district, lenses of Emily Iron Formation trend in the typical northeasterly direction.

The northern Emily District has received the most attention in terms of drilling interest, some as recent as the current decade. An indication of the extent of drilling in the northern Emily district can be seen Fig. 1.2-85. Initially drilled in search of iron ore, more recent drilling in the Emily District is attempting to define the manganese resource. Despite all of the drilling that has taken place, there has been no mining to date in the Emily District.

### Emily District Study Area

Three properties identified by Beltrame (1977) comprise the Emily District Study Area, all located in Severson et al.'s (2003) northern Emily district. Two of these properties were listed simply by name without the designation reserve following the name. These are the Crockett and Andrews properties that lie on the northern limb of an east-northeast-plunging anticline in the Ruth Lake area (Morey, 1990) (Fig. 1.2-85). The third property, the Emily-Shawmut reserve (P-27), resides in the hinge region on the northern limb of the broad, shorter, east-plunging anticline that lies south of Dahler Lake and Lake Emily.

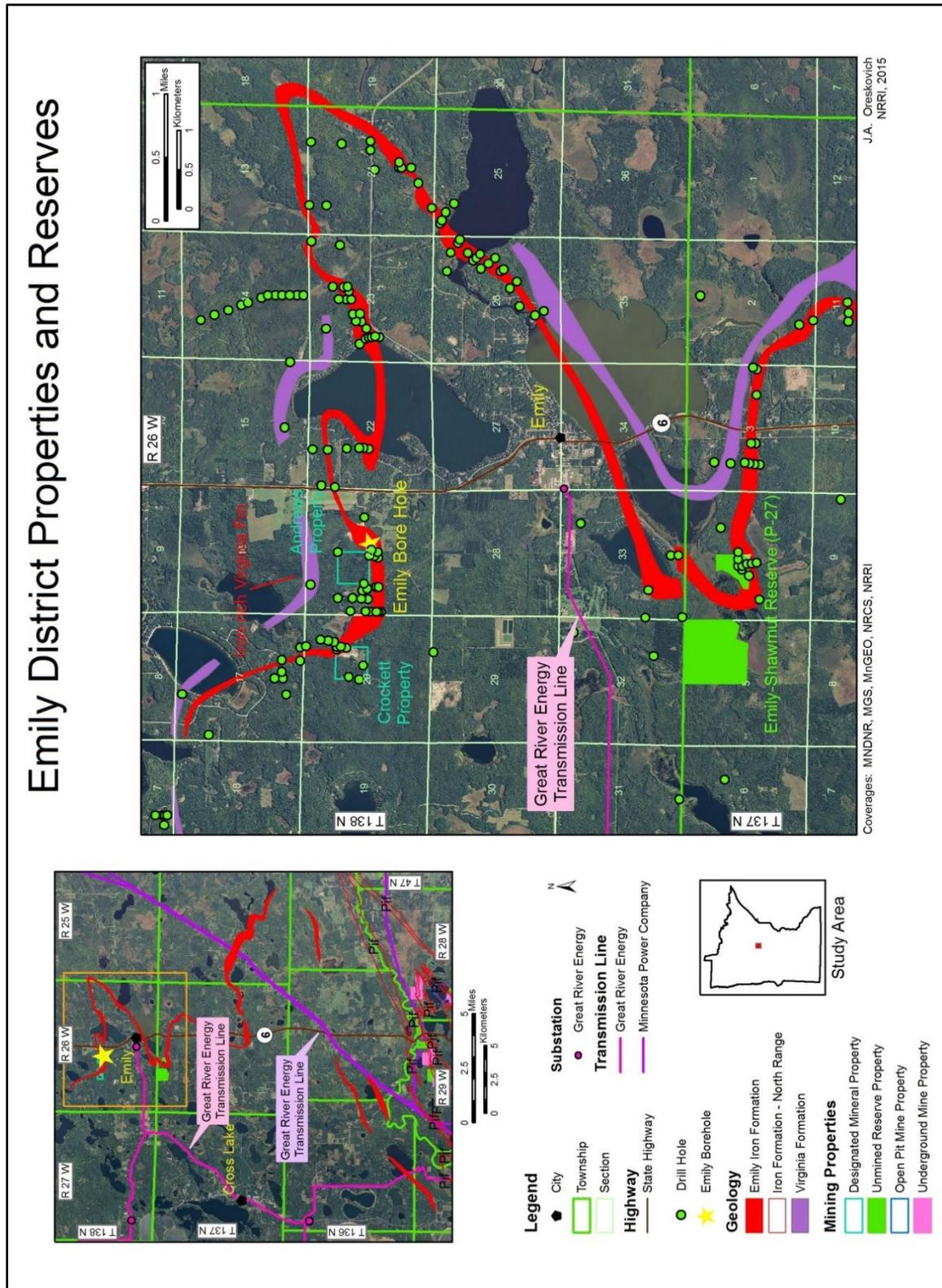


Figure 1.2-85. Emily District properties and reserves.

Crockett and Andrews Properties

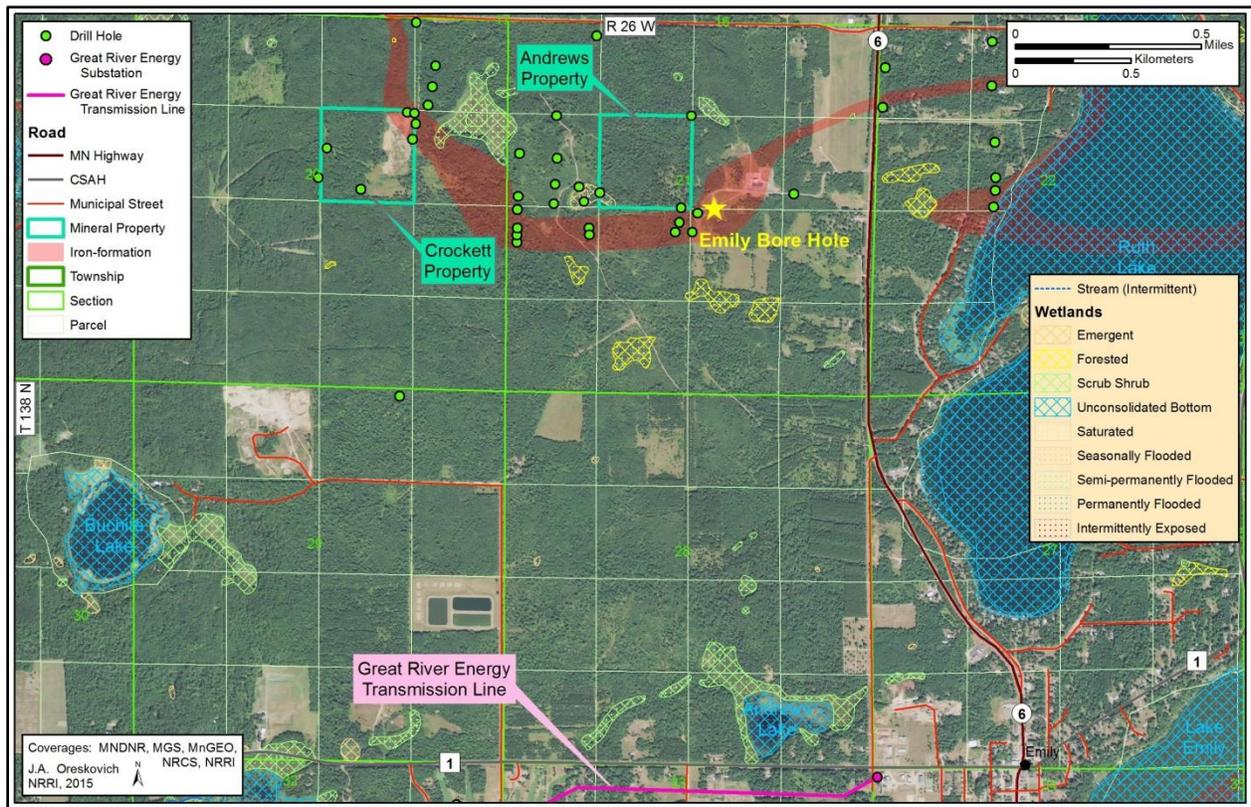


Figure 1.2-86. Crockett and Andrews properties.

Property	Parcel	S	T	R	Data	Surface Owner <sup>1</sup>	Fee Owner
Crockett	SW-NE	20	138	26		Natural Resources Management LLC	Frank W. Crockett et al.

<sup>1</sup>Crow Wing County GIS Public Map Service, 2015

Property	Parcel	S	T	R	Data	Surface Owner <sup>1</sup>	Fee Owner
Andrews	SE-NW	21	138	26		Private	Lee W. Andrews

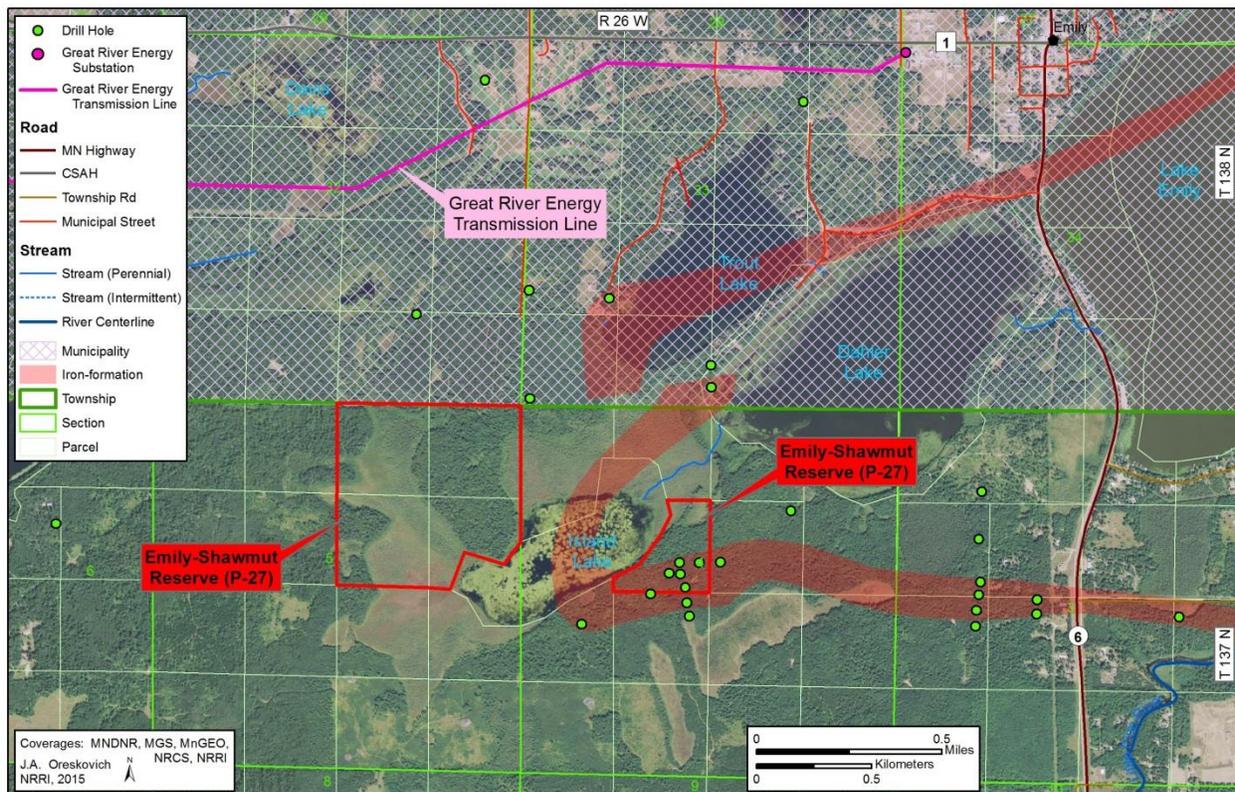
<sup>1</sup>Crow Wing County GIS Public Map Service, 2015

The Crockett property occupies the SW-NE of S20-T138-R26 while the Andrews property is located in the SE-NW S21-T138-R26. Figure 1.2-86 illustrates the location of these properties along the trend of Emily Iron Formation hosting the Emily Borehole, part of a current venture by Cooperative Mineral Resources (CMR) to extract and utilize the manganese resources of the Emily District. The bore hole project is discussed in detail in Section 1.1 of this report. No further detail on the Crockett and Adams properties or their development was acquired for this report.

The Crockett and Andrews properties are located approximately five miles north of a major Great River Energy electrical transmission line that comes into the city of Emily from the west. A

municipal street runs east-west 0.25 miles north of the properties. North-south artery MNTH 6 lies within 0.5 miles to the east of the Andrews property and 1.2 miles to the east of the Crockett property. Both properties reside in uplands, with little to no impact from wetlands. The Crockett and Andrews properties both reside within the city of Emily municipal boundary.

### Emily-Shawmut Reserve (P-27)



**Figure 1.2-87.** Emily-Shawmut Reserve (P-27).

The Emily-Shawmut reserve consists of two parcels of land separated by Island Lake (Fig. 1.2-87). The larger of the two parcels, the west Emily-Shawmut, comprises the SW-NE, Lot 2 (SE-NE), and Lots 1 and 4 (N1/2-NE) of S5-T137-R26 (Beltrame, 1977). Documents in the data files at MDOR reference only the NE-NE and W1/2-NE parcels. The property was drilled by Pickands Mather & Co. in 1955. One churn hole was drilled in the center of the quarter section (MDOR data files). The ore reserve and assay data presented for the west Emily-Shawmut reserve in Tables 1.2-56 and 1.2-57 appear to be based on this one drill hole.

Notes attached to the ore reserve estimate discuss the requisites for mining the western Emily-Shawmut reserve. Underground mining would necessitate draining nearby Island Lake and leaving a 50-foot safety pillar of ore between the workings and the overlying unconsolidated material (MDOR data files). Overburden thickness is 290 feet. The mineable ore unit is 155 feet

thick, extending from 340 feet to 495 feet in depth. The ore is a high phosphorus, high alumina material.

The east Emily-Shawmut property is Lot 5 (SE-NW) of S4-T137-R26. As seen in Fig. 1.2-87, several holes were drilled in this and neighboring properties. The 1962 ore estimate describes the ore as “manganiferous aluminiferous and low in natural iron” (MDOR data files). The estimate reports that a shaft would have to be sunk through more than 250 feet of surface and 300 feet of rock for mining.

Impacting shaft sinking would be the adjacent Island Lake and fluctuating lake levels. The ore estimate noted that the lake level had risen three feet since the 1956 ore estimate was done, flooding the area overlying the orebody. The surface was described as muskeg swamp. This field observation would be more accurate than the wetlands coverage shown in Figure 1.2-88.

The western Emily-Shawmut reserve property lies within 0.6 miles of a major Great River Energy electrical transmission line that runs into the city of Emily. The eastern property is within 1.2 miles of the line. Both properties reside just outside of the city of Emily municipal boundary (Fig. 1.2-87).

Both properties occupy an unpopulated region without direct road access. A significant amount of the western reserve property is overlain with saturated wetlands, as is the northern part of the eastern reserve property (Fig. 1.2-88). The western reserve property lies within 0.25 miles of a municipal road to the north that connects to east-west CSAH 1. The eastern reserve lies within 1.0 mile of north-south artery MNTH 6 to the east.

**Table 1.2-56.** Emily-Shawmut Reserve (P-27) ore reserve estimate.

Ore Reserve Estimate <sup>1,2</sup>							
Property	Parcel	S	T	R	Data	Surface Owner <sup>3</sup>	Fee Owner
Emily-Shawmut Reserve (P-27)	Lot 5 (SE-NW)	4	137	26	X	Private	Shawmut Co. et al.
	NE-NE & W1/2-NE	5					
Year	Type		Re-class	Recovery Factor	Tons	Density Factor	
1964 (West Reserve – S5)	UG Mang. Wash Ore			70%	292,500		
	UG Mang. Heavy Media Ore			50%	290,180		
1962 (East Reserve - S4)	UG Mang. Heavy Media Conc.				207,323		

<sup>1</sup>Upper table information from Beltrame (1977), unless otherwise noted. Data consists of drill hole data, cross-sections, reserve estimates, etc. on microfilm at MDOR Minerals Tax Office in Virginia, MN.

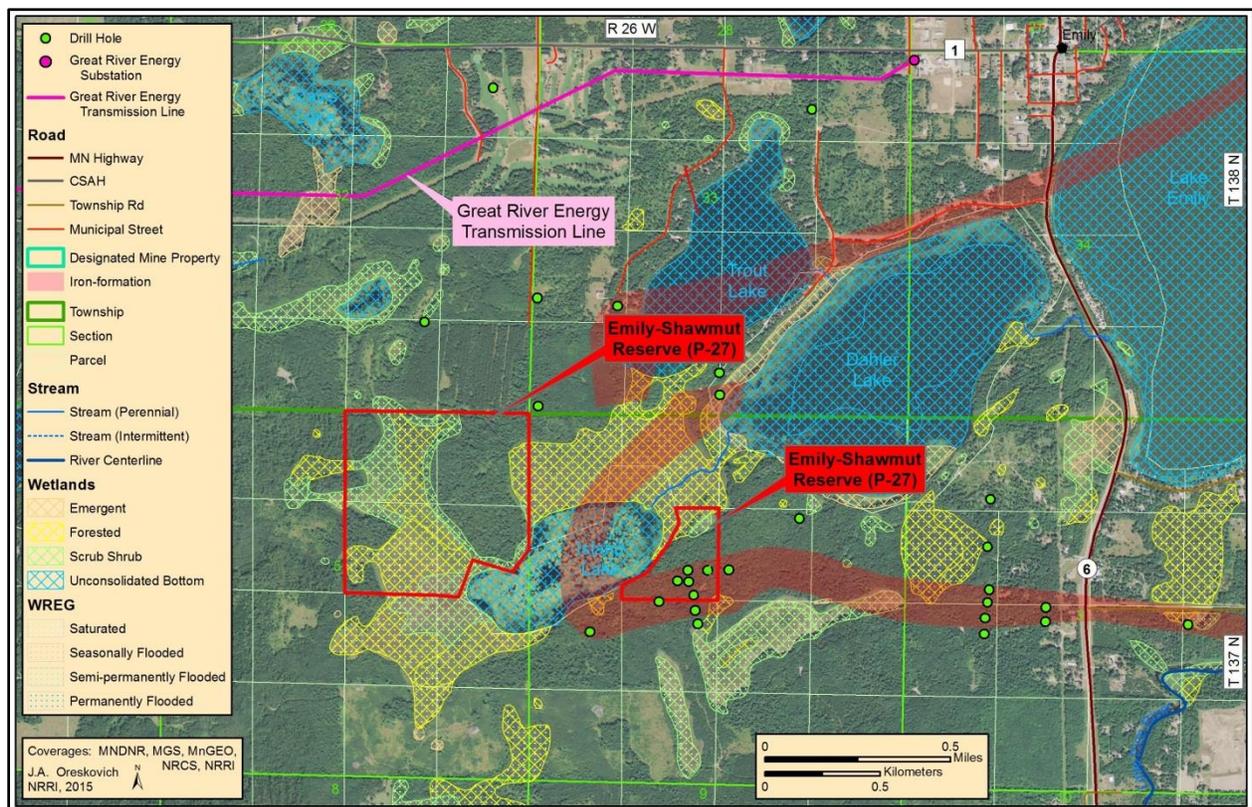
<sup>2</sup>Lower table information from MDOR Minerals Tax Office data files.

<sup>3</sup>Crow Wing County GIS Public Map Service (2015).

**Table 1.2-57.** Emily-Shawmut Reserve (P-27) assay data.

Assay Data <sup>1</sup>										
Property	Type	Tons	Dry						Natural	
			Fe	P	Si	Mn	Al	Moist.	Fe	Mn
Emily-Shawmut Res. - West: 1964	Mn. W.O	292,500	47.45	0.871	6.68	9.11	3.50	12.00	41.76	8.02
	MN. H.M.O.	290,180	46.88	0.967	10.47	10.32	4.95	12.00	41.25	9.08
Emily-Shawmut Res. - East: 1962	Mang. H.M.C.	207,323	42.55	0.502	10.43	12.33	3.40	10.00*	38.30*	11.10*

<sup>1</sup>Source: MDOR data file.  
\*Assumed.



**Figure 1.2-88.** Hydrography map of the Emily-Shawmut Reserve area.

CAES Potential for the Emily District

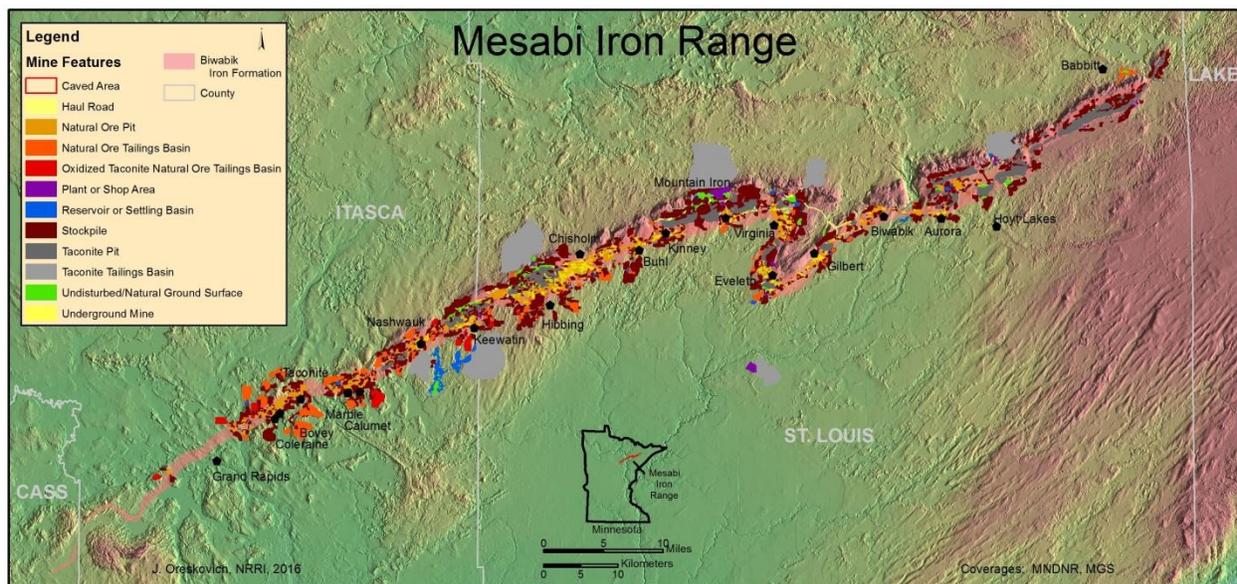
No mining has taken place in the Emily District to date. The district has and is drawing interest for its manganese deposits. Multiple studies have been conducted on the manganese resource. Core drilling, experimental work on mining methodology, laboratory assaying, and product

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testing have been conducted since 2009 on a deposit located west of Ruth Lake north of the city of Emily (Emily Borehole site, Fig. 1.2-86). An attempt was made to extract manganese by borehole solution mining. This approach is discussed in Section 1.1 of this report. While borehole mining would have provided an additional approach to generating a CAES cavern in the region, results at the selected site proved unfavorable. Roof caving was experienced contemporaneously with the extraction of ore material, causing the void space to collapse.

Further study is needed to identify potential orebodies in the Emily District for CAES purposes. Both the northern and southern parts of the district are well situated relative to major electrical transmission lines. Both Great River Energy and Minnesota Power have major lines that run into and through the Emily District (Fig. 1.2-85).

## UNDERGROUND MINE WORKINGS ON THE MESABI IRON RANGE



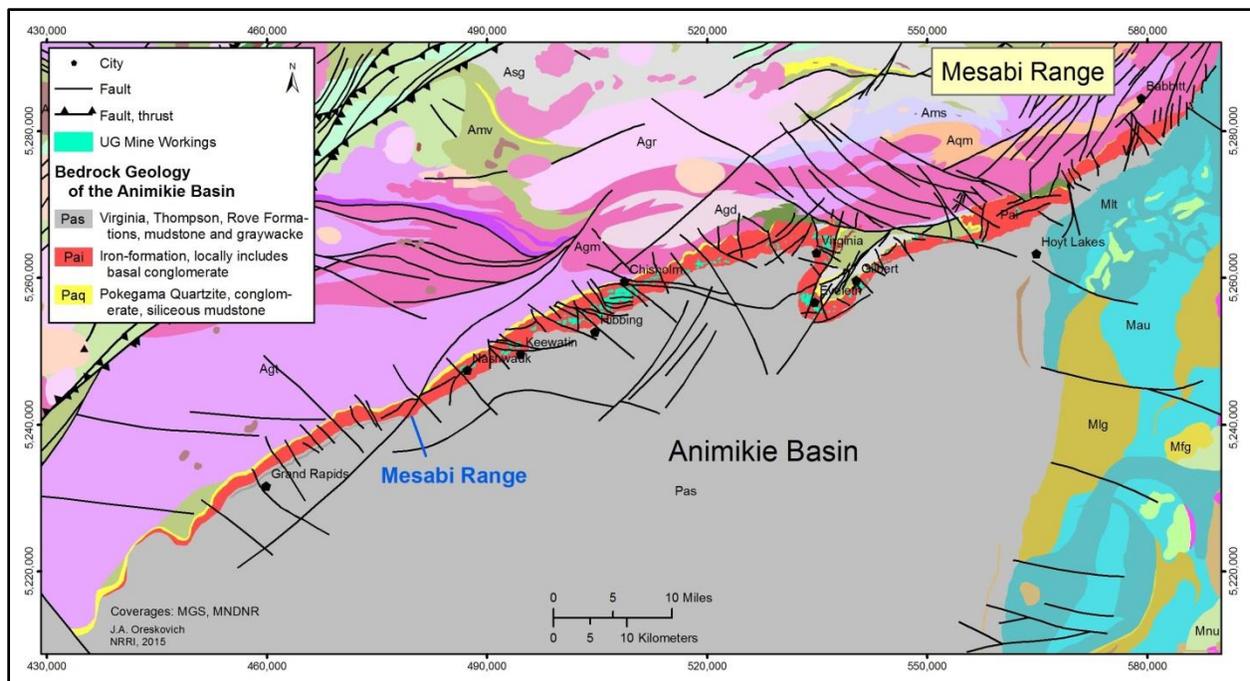
**Figure 1.2-89.** Mesabi Range location map with mining features.

The Mesabi Iron Range is both a geographical and geological feature of northeastern Minnesota. Defined by the subcrop of the Biwabik Iron Formation (BIF), the Mesabi Range trends northeastward from Cass County to the St. Louis County/Lake County line, a distance of 110 miles (Fig. 1.2-89). Width of the Mesabi Range varies from < 1 mile to 3 miles.

### **Geology**

The Mesabi Range lies along the northern rim of the Animikie Basin (Fig. 1.2-90). Here the sediments of the Paleoproterozoic Animikie Group that comprise the Mesabi Range were deposited. The Biwabik Iron Formation (BIF) is the central unit of the Animikie Group on the Mesabi Range. The BIF is underlain by the Pokegama Formation (argillite, siltstone, and quartzite) and overlain by the Virginia Formation (carbonaceous argillite and argillite) in a conformable sequence (Severson et al., 2010).

The BIF is a blanket deposit that reaches its greatest thickness (730-780 feet near Eveleth) in the Virginia Horn area (Severson et al., 2010). The Virginia Horn is the large regional fold seen in Figure 1.2-89 near the city of Virginia. BIF thickness is 175-300 feet at the far eastern end of the Mesabi Range and around 500 feet at Coleraine towards the western end. The BIF thins out and ends southwest of Grand Rapid. Beds are gently dipping to the south-southeast at roughly 7° to 15°. These dips are in stark contrast to the steeply dipping (75°-80°) beds of the Cuyuna North and South Ranges.



**Figure 1.2-90.** Bedrock geology of the Mesabi Range area (Source: Minnesota Geological Society State Map Series S-22, 2011).

### Mining History

Ore production from the BIF has been ongoing for 124 years and will continue well into the future. Production came solely from natural (non-magnetic) iron ores during the first 60 years of Mesabi Range mining history. Pockets of soft red ore were strewn the length of the Mesabi Range, resulting in production from over 375 natural iron ore mines.

In the mid-1950s, the first taconite processing plant came on line, and both natural and taconite ores were produced into the 1960s and early 1970s. Subsequent to additional taconite processing plants coming on line, natural ore mining became relegated to scam mining operations.

Seven taconite mining and processing operations came on line from the mid-1950s through 1977:

1. Reserve Mining Company (pit near Babbitt, processing plant at Silver Bay), 1955, currently operated as Northshore Mining;
2. Erie Mining Company (Aurora-Hoyt Lakes), 1957, became LTV Steel Mining Co., closed in 2001, site currently occupied by Mesabi Nugget iron concentrate plant (2009, currently idled) and the proposed Polymet copper-nickel-PGE operation;
3. Eveleth Taconite Company (Eveleth), 1965, currently operated as United Taconite LLC;
4. U.S. Steel Minntac operation (Mountain Iron), 1967 (precursor Pilotac began operations in the 1950s);

5. National Steel Pellet Company (Keewatin), 1967, currently operated as U.S. Steel Keewatin Taconite (Keetac);
6. Butler Taconite (Nashwauk), 1967, closed in 1985, plant dismantled, current site of Essar Steel Minnesota (taconite processing plant under construction);
7. Hibbing Taconite Company (Hibbing), 1976, “Hibtac”; and
8. Inland Steel Minorca Mine (Virginia), 1977, currently operated as ArcelorMittal Minorca Mine, with pits near Gilbert and Biwabik.

For over 30 years subsequent to the coming on line of the Minorca plant in 1977, there were no new mining starts-ups of any consequence on the Mesabi Range. Then in 2009, Magnetation Inc. began producing high-quality iron concentrate at a new plant in Keewatin. Rather than mining an untapped orebody, the Magnetation process uses a waste product, reclaimed tailings from previous natural (red) ore processing operations, as plant feed. Magnetation Inc. has brought an additional three plants on line on the Mesabi Range since 2009, the most recent in 2014. Tailings are recovered from the tailings basins of former natural ore mines.

In 2010, the Mesabi Nugget plant came on line. Located on the grounds of the former LTV taconite operation, Mesabi Nugget produces 97 percent iron nuggets. Such nuggets are used to feed electric-arc-furnace mini mills. The increasing prevalence of mini steel mills has reduced the market capacity for traditional taconite pellets, used as feedstock to the older, inefficient, highly energy intensive steel blast furnaces. As more mini mills come on line, blast furnaces are shutting down. Mesabi Nugget is the first commercial iron nugget plant in the world ([www.superiormineral.com](http://www.superiormineral.com)).

Providing feed for the Mesabi Nugget plant is the Mining Resources LLC plant near Chisholm that utilizes Magnetation technology. Mining Resources LLC is an 80/20 joint venture between Steel Dynamics Inc. and Magnetation Inc. (<http://www.magnetation.com/mining-resources-llc/>). The Chisholm plant is the third of four Magnetation plants noted above. As of this writing, both Mesabi Nugget and the Mining Resources LLC plant at Chisholm have been idled due to low iron ore prices.

Currently under construction and projected to come on line in 2016 is the Essar Steel Minnesota taconite operation located on the site of the former Butler Taconite operation near Nashwauk. Originally intended as a mining-to-steel operation with a mini mill on site, the scope of the Essar Steel Minnesota operation has been reduced to mining and taconite pellet production. In addition to traditional acid and flux pellets, the plant will have the capability to produce direct reduction grade pellets ([www.essarsteelmn.com](http://www.essarsteelmn.com)).

### **CAES Potential on the Mesabi Range**

For this study, CAES potential on the Mesabi Range, as on the Cuyuna Range, is based on the ability to make use of existing underground natural iron ore mining features or to create a CAES cavern from identified unmined mineral resources. The looming presence of taconite mining—past, present, and future—on the Mesabi Range has significant import on viable use of existing underground mining features for CAES purposes. Taconite mining, coupled with past open pit mining of natural ore subsequent to initial underground activity, leaves few isolated locations

that would not significantly impact water levels across important areas or that could contain the pressures required for a CAES facility.

Taconite is an extremely hard rock that requires intensive blasting to release material for excavation. Blasting can be heard and felt at great distances from the mines across the Mesabi Range, even beyond 10 miles north on the far side of the Laurentian Divide. Such activity can be expected to have considerable impact on the structure and support of nearby existing underground mine features. Taconite blasting can undermine the integrity of the rock surrounding underground mines in close proximity, providing potential escape routes for compressed air.

As should be noted in the ensuing maps presented in Figures 1.2-91, 1.2-94, 1.2-96, and 1.2-99, taconite mining has swallowed up many former underground and open pit natural ore mines, just as the natural ore pits often did to underground workings previously. Whereas in previous years the established southern limits of taconite pits were pre-defined by a stripping ratio that goes back decades, new technology and equipment now allow for economical stripping to much greater depths. This new stripping paradigm has and will result in further expansion of taconite pits down dip to the south, where they will encroach on even more of the old underground workings.

Figures 1.2-91, 1.2-94, 1.2-96, and 1.2-99 illustrate the location of underground mines and the extent of underground mine workings on the Mesabi Range as mapped to date. The maps are presented from west to east across the Mesabi Range. Only the locations of main mine shafts are shown on the maps. Not included are timber, air, pumping, and other types of secondary shafts. A total of over 800 shafts have been mapped thus far on the Mesabi Range in the extent shown. This starkly contrasts with the 78 shafts mapped on the Cuyuna Range.

The maps presented in Figures 1.2-91, 1.2-94, 1.2-96, and 1.2-99 cover only the extent of underground mining on the Mesabi Range that has been mapped to date under the MDNR-LAM underground mine mapping program. Therefore, mining activity located west of the Hoadley and Hawkins underground mines near the city of Nashwauk (Fig. 1.2-91) is not shown. Not shown, in addition to the underground mine workings on the westernmost quarter of the Mesabi Range, are the former Butler taconite operation and currently under construction Essar Steel taconite operation. On the eastern end, the Siphon mine (Fig. 1.2-99) marks the easternmost extent of underground mining activity on the Mesabi Range. Open pit mining activity located east of the Siphon Mine, therefore, is not shown, including the full extent of the Northshore Mining taconite operation and the former LTV Steel Dunka taconite pit.

In addition to underground mines (yellow), many pit lakes (blue) are identified on the maps. These are former natural ore open pit mines, kept dry during time of operation by means of dewatering pumps. Subsequent to cessation of mining activities, the pumps were withdrawn, allowing inflow of ground, surface, and rain water to fill the mine pits to present day levels. The same holds true for underground mine workings; they were pumped to keep dry during periods of operation and subsequently allowed to flood. There should be no expectation of a “dry” underground mine among those located on the Mesabi Range.

A third set of features identified in Figures 1.2-91, 1.2-94, 1.2-96, and 1.2-99 are those related to taconite mining (pink). These features include the extensive taconite mine pits that appear as a pinkish color against the backdrop of the iron-formation, as well as plant sites and tailings basins.

Related to taconite, but not individually identified in Figures 1.2-91, 1.2-94, 1.2-96, and 1.2-99, are several dark pink polygons. These are sites proposed by Mark Severson in Fosnacht et al. (2011) as potential underground lower reservoirs for pumped hydro energy storage (PHES) as part of NRRI's PHES study (Fosnacht et al., 2011). The sites are based on evaluation of available deep drilling information where "the depths to ore zones and their estimated thicknesses are known to some degree" (Severson, in Fosnacht et al., 2011). Severson's drilling data, in part, was coupled with use of GIS coverages to define corresponding upper and lower PHES reservoirs among existing mine features.

One of multiple scenarios explored during the study was the use of an existing mine feature as an upper reservoir paired with a "to be mined" underground taconite resource. Such identified underground taconite resources could suit the needs of CAES as well. Only those locations identified by Severson in Fosnacht et al. (2011) that fall within the confines of Figures 1.2-91, 1.2-94, 1.2-96, and 1.2-99 are shown. Fosnacht et al. (2011) should be consulted for additional sites.

Several selected sites that may hold potential for CAES are presented following the map set. These include both underground mines and potentially mineable underground excavation sites. The potential underground excavation sites will be referenced for detail to Fosnacht et al. (2011). The report is available for download online at <http://d-commons.d.umn.edu/jspui/handle/10792/2895>.

Mesabi Range Study Area 1: Nashwaug to Chisholm

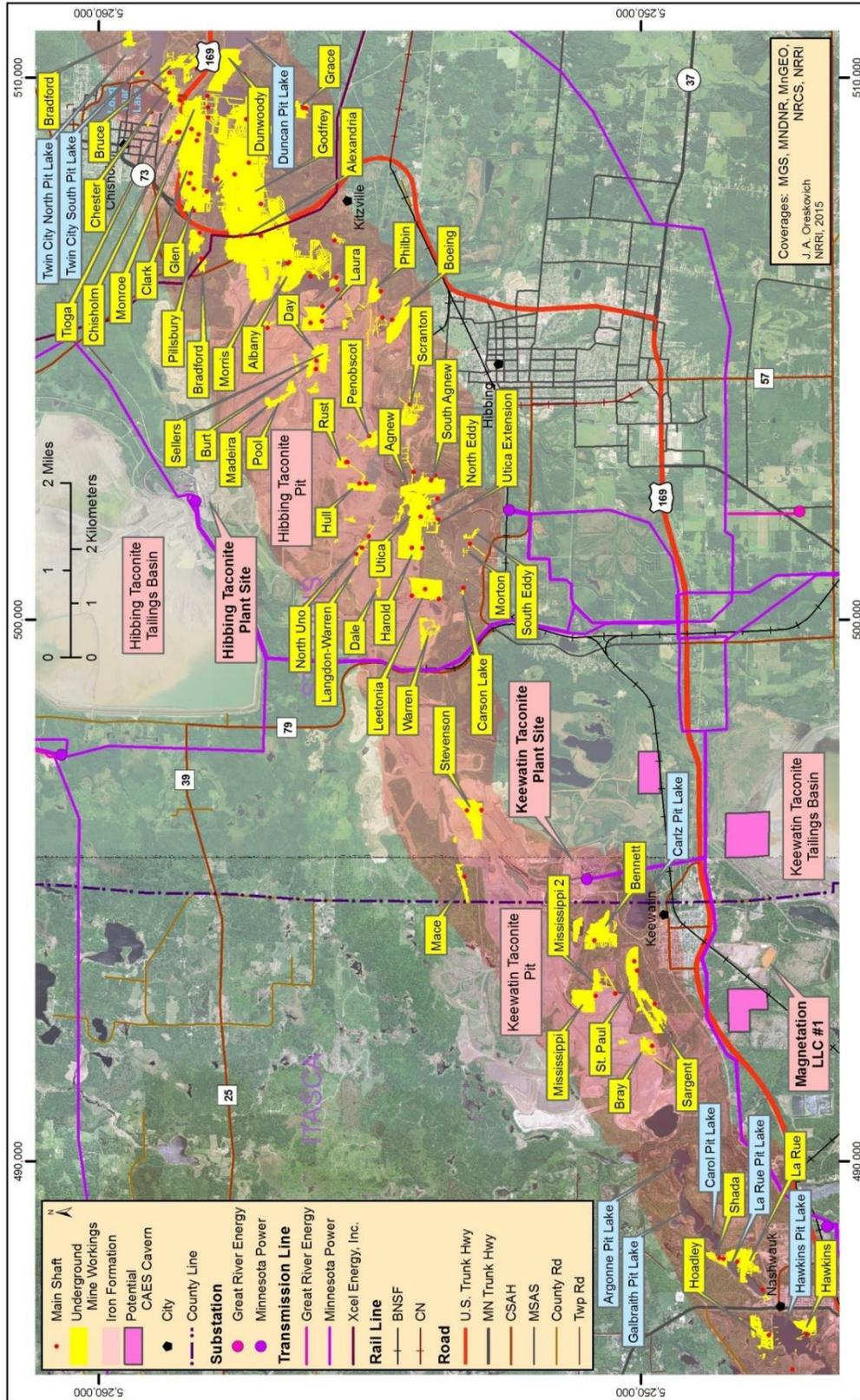
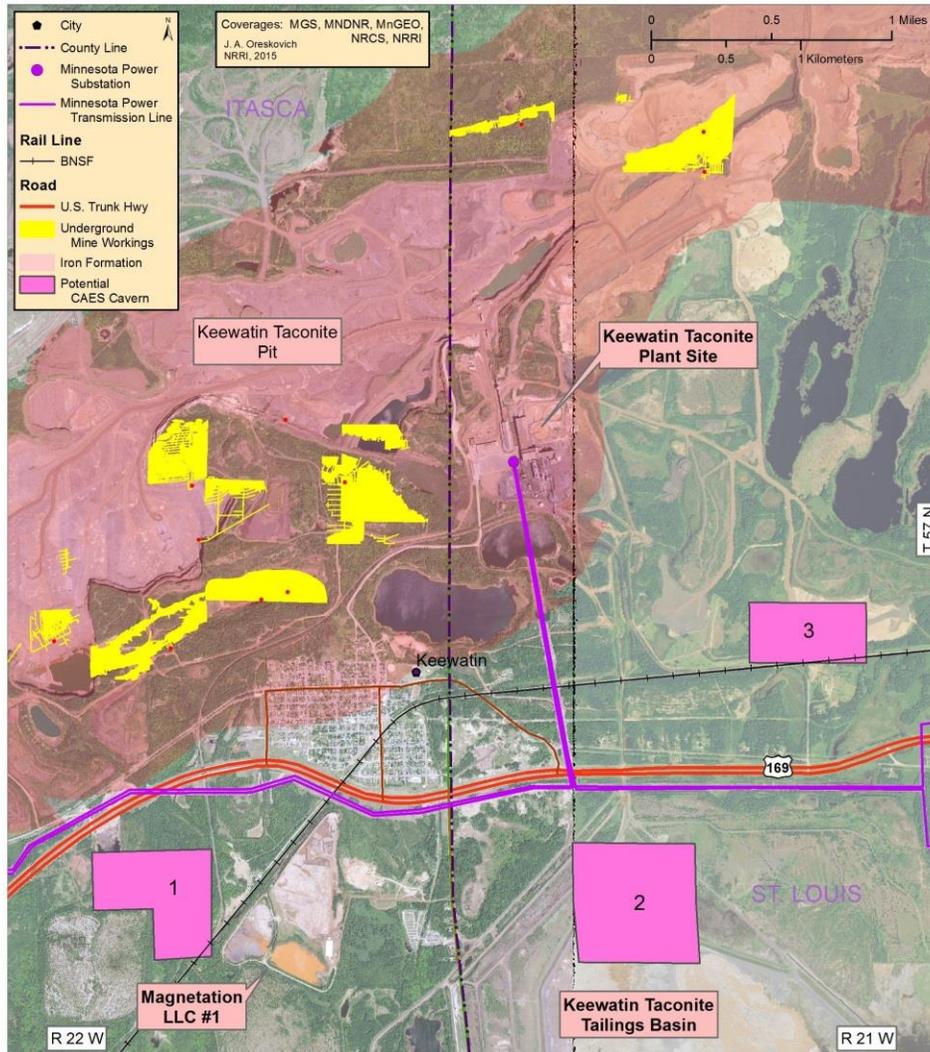


Figure 1.2-91. Mapped underground mine workings from Nashwaug to Chisholm.

### CAES Potential for Mesabi Range Study Area 1: Nashwauk to Chisholm

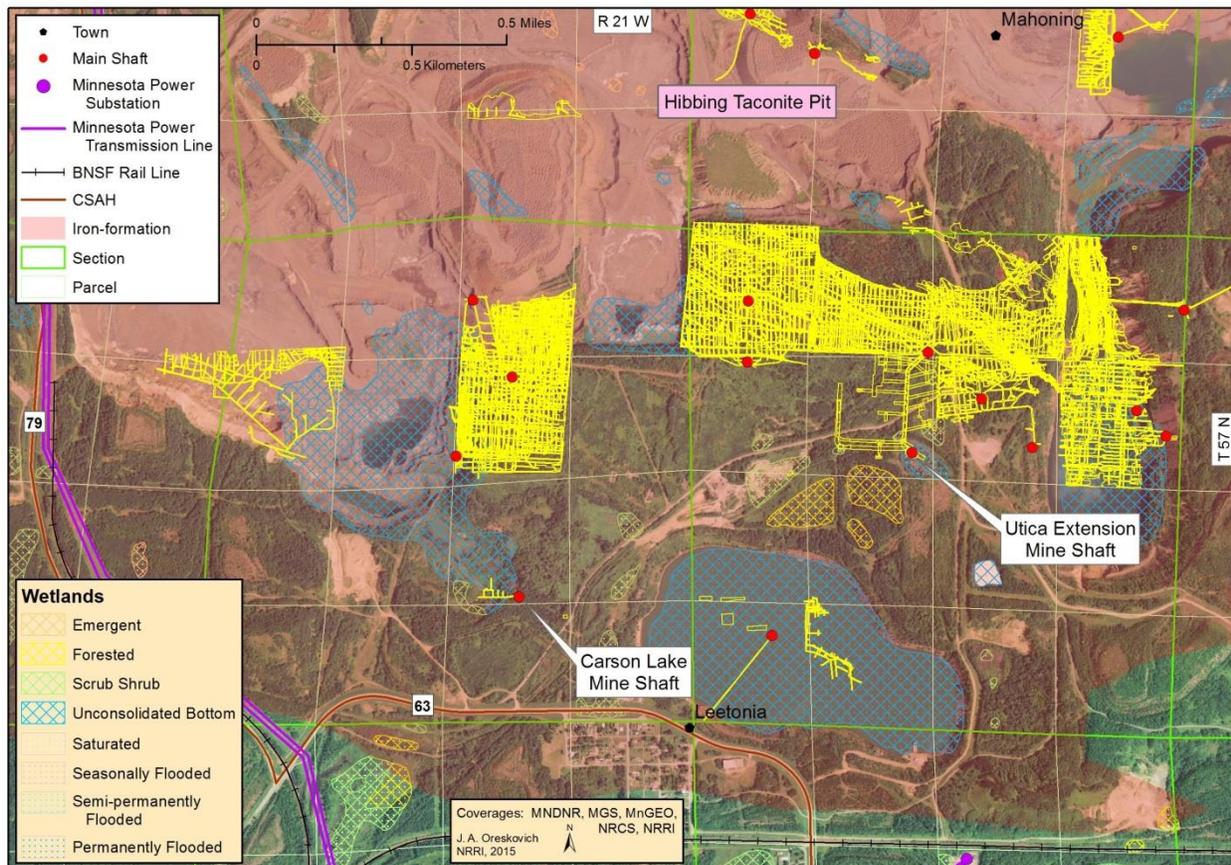
Five potential sites located between Nashwauk and Chisholm (Fig. 1.2-91) are presented here. The three western-most sites were identified by Severson in Fosnacht et al. (2011) as mineable underground resources for pumped hydro lower reservoir construction. The other two sites have existing underground workings.



**Figure 1.2-92.** Potential excavated cavern sites near Keewatin Taconite.

The first three sites (Fig. 1.2-92) lie within the Keetac-Mesabi Chief Area of Fosnacht et al. (2011: Section 2.5.4, p. 258-270). Site 1 is the proposed lower reservoir in Scenario 3c (p. 264); Site 2 is the proposed lower reservoir in Scenario 3b (p. 263); and Site 3 is the proposed lower reservoir in Scenario 3a (p. 262). Maps on p. 266-270 of the Fosnacht et al. (2011) report illustrate the proposed caverns relative to base map, hydro, elevation contour, ownership, and geologic features.

Figure 1.2-93 displays the locations of the Carson Lake and Utica Extension mines. The Carson Lake mine is located in the NW-SE of S10-T57-R21. The Carson Lake mine shaft extends to a depth of 161 feet. A main drift runs west on the 161-foot level for approximately 430 feet, with several side drifts extending a short distance to the north from it. There is also a pump room near the shaft on the 161-foot level.



**Figure 1.2-93.** Carson Lake and Utica Extension Mines.

The Carson Lake mine is of interest for several reasons. It is relatively isolated and may escape extension of the Hibbing Taconite pit to the south. It does not lie within Hibbing Taconite's permit to mine. There is a major Minnesota Power transmission line within 0.5 miles of the mine to the southwest and a Minnesota Power substation within 1 mile to the southeast.

Carson Lake was the name of a previously existing lake that was drained back in 1918 or so in order to establish the mine that first produced ore in 1919 (Skillings Mining Review, 2005). Only 5,156 tons of natural ore were shipped from the mine. Minnesota mining directories indicate that the property has been classified as the Carson Lake Reserve since at least 1923.

The Carson Lake mine and reserve natural orebody are located on MN DNR Division of Forestry land. This land is swamp trust fund land that MN DNR-LAM has expressed interest in seeing mined (J. Arola, pers. comm., 2009). The State of Minnesota is the fee holder on the property.

The Utica Extension mine (Fig. 1.2-93) occupies the SE-NW of S11-T57-R21. This mine is not listed in the Skillings Mining Directory (2005). Maps of the mine were obtained from Great Northern Iron Ore Properties (GNIOP), located in Hibbing.

The maps show a 3-compartment shaft with motor drifts extending from it to the north on the east side of the property and to the west across the property before turning north on the western side of the property. The motor drifts are at an elevation of 738 feet. Drill hole collars in the immediate area are at 926 feet, indicating a shaft depth of at least 188 feet. Running westward from the shaft and directly overlying the north-bearing motor drifts on the east and west sides of the property are sub drifts at an elevation of 761 feet. There is a timber shaft located 350 feet to the west of the main shaft that is connected to both levels.

The Utica Extension mine shaft was clearly visible in past aerial photos of the site. It resides in what was a coal lay-down yard for the city of Hibbing. A visit to the site back in 2008 revealed an approximately 40-foot circular depression of subsidence rimmed by the blackened sediments of the coal yard. Foundations from the shaft remain and are seen tilted into the subsidence cone.

Another feature of note regarding the Utica Extension mine is that the GNIOP maps show proposed motor and sub drifts for the mine in addition to those that were already completed. The proposed drifts extend across the northern half of the two forties located to the west of the Utica Extension property, the SW-NW of S2-T57-R21 and the SE-NE of S-10-T57-R21. These properties remain unmined.

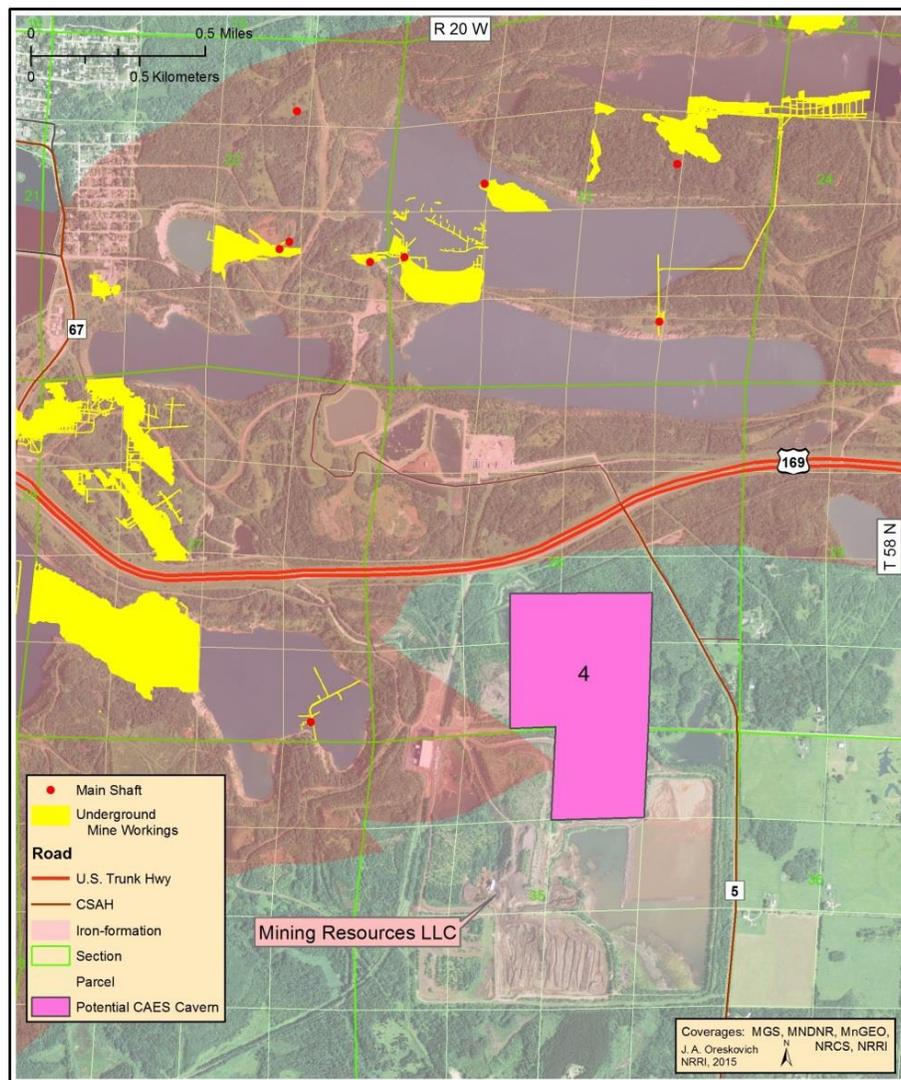
Utilization of the Utica Extension underground workings for CAES would entail isolating the mine drifts from the underground workings of the Utica mine to the north and the North Eddy mine to the east (Figs. 1.2-91 and 1.2-93).



CAES Potential for Mesabi Range Study Area 2: Chisholm to Virginia

Only one site from Figure 1.2-94, the area between Chisholm and Virginia, will be highlighted here. Site 4 (Fig. 1.2-95) lies in an area identified by Severson in Fosnacht et al. (2011) as a potential mineable underground resource for pumped hydro lower reservoir construction. Site 4 was designed as the lower reservoir for Scenarios 1, 2, and 3 (p. 307) under Site 3 (Douglas/Duncan/Dunwoody Area), Chisholm-Buhl Area of Fosnacht et al. (2011: Section 2.5.8, p. 303-314). Maps on p. 309-314 of Fosnacht et al. (2011) illustrate the proposed cavern relative to base map, hydro, elevation contour, ownership, and geologic features.

Site 4 is located adjacent to the Mining Resources LLC processing plant and mine site. Natural ore tailings are recovered from the former Duncan tailings basin and processed into high quality concentrate by means of the Magnetation process. This mine/plant provided feed to the Mesabi Nugget plant near Aurora-Hoyt Lakes on the eastern end of the Mesabi Range. Both the Mining Resources LLC operation and Mesabi Nugget are currently idled.



**Figure 1.2-95.** Potential excavated cavern site near Chisholm.

Mesabi Range Study Area 3: Virginia to Biwabik

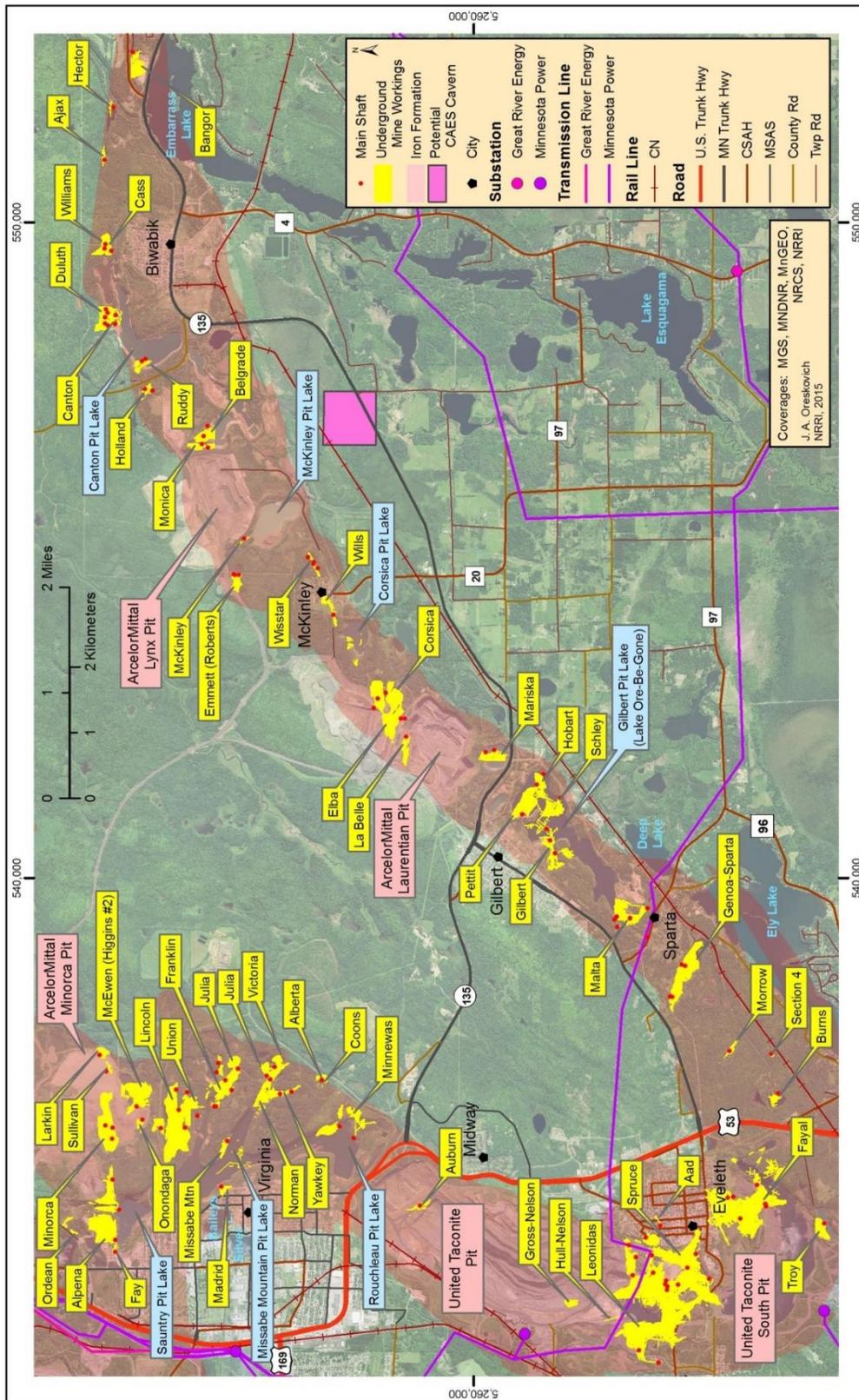
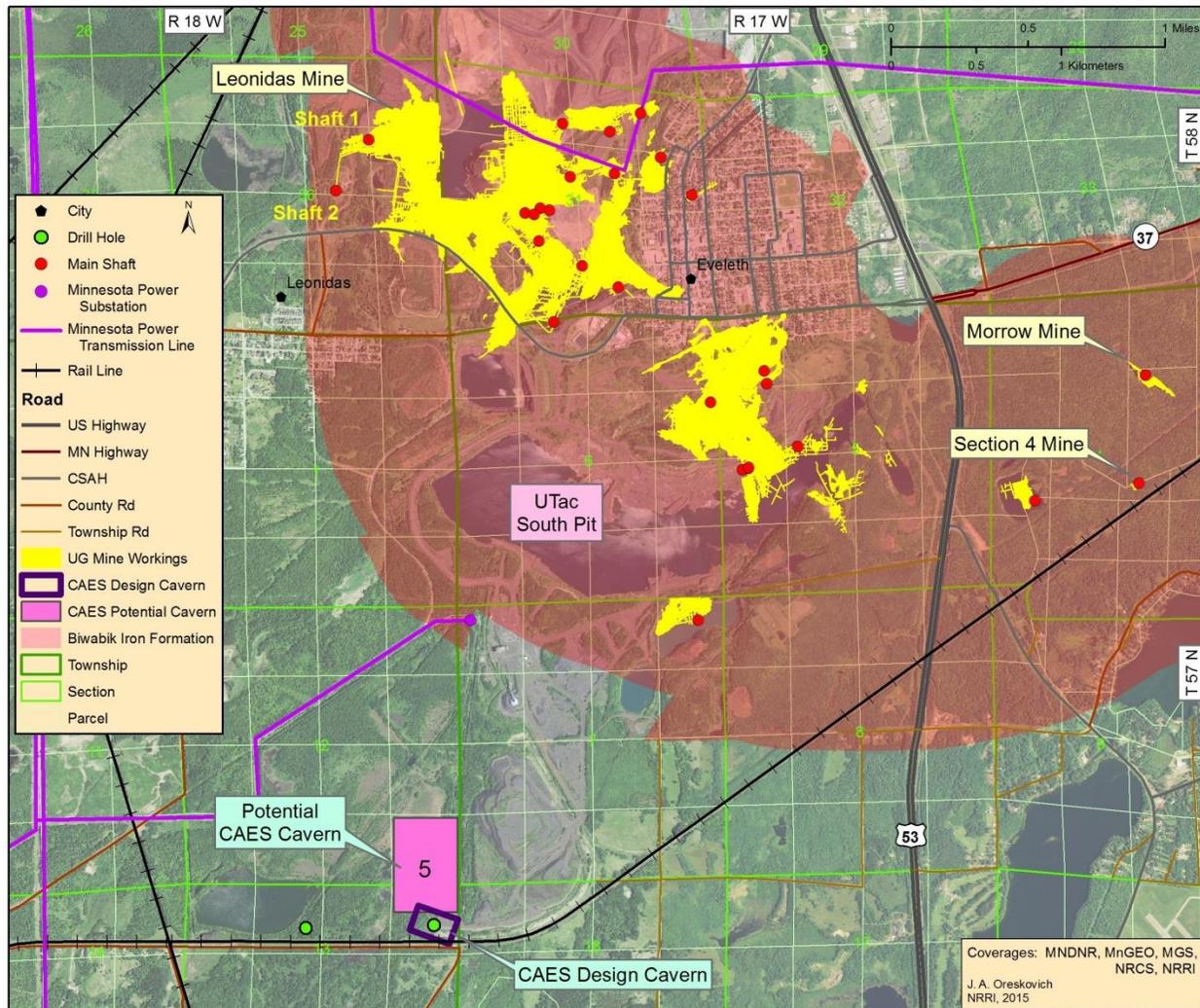


Figure 1.2-96. Mapped underground mine workings from Virginia to east of Biwabik.

Five sites from the area portrayed in Figure 1.2-96, Virginia to Biwabik, are addressed here. The first four sites are spread across the southern end of the fold comprising the Virginia Horn (Fig. 1.2-97). One site involves utilizing the shafts and drifts of the Leonidas mine, located on the western side of the United Taconite South pit west of Eveleth, for CAES purposes. Two sites located southeast of Eveleth, the Morrow and Section 4 mines, similarly involve use of existing shafts and drifts. The fourth site, located down-dip to the south of the iron-formation, south of Eveleth, entails mining a taconite orebody to produce a cavern for CAES. The fifth site, located between McKinley and Biwabik, also entails mining a taconite orebody.



**Figure 1.2-97.** Potential CAES sites near Eveleth, Minnesota.

The Leonidas mine has the deepest shaft, Shaft No. 1, on the Mesabi Range at 600 feet. The Leonidas mine has been extensively worked by both underground and open pit methods. According to various mine-level maps, both methods were worked simultaneously in close proximity while maintaining an ore pillar between the two operations. The Leonidas underground

workings have been partially mined out; however, the pit depth did not reach the deepest levels of the underground mine on the northwest side of the mine. Coarse tailings from the United Taconite and/or former Eveleth Taconite operations have been used to partially fill the pit.

What makes this mine interesting is the presence of a second shaft, Shaft No. 2 (Fig. 1.2-97). This shaft is located west and south of Shaft No. 1, well away from the workings of the mine. No elevation was found for the drift that extends over 650 feet northward from Shaft No. 2.

The Leonidas mine 600-foot-level map shows two roughly parallel eight-foot-wide drifts extending gently southwest from Shaft No. 1 to meet a drift running due south. The northernmost drift is labeled as a conveyor drift. Where the two drifts merge heading south, one 12-foot-wide drift is formed. The northern end of the north-south drift is also labeled as a conveyor drift.

There is a 60-foot gap between the detailed map of the workings on the 600-foot level of the mine and the surface map showing Shaft No. 2 and the north-bearing drift. Assuming the north-bearing drift is one and the same with that shown on the 600-foot-level map, the implication is that Shaft No. 2 is also at least 600 feet deep. Depth, isolation, slim chance of further mining the Leonidas area, and close proximity to the major Minnesota Power electrical transmission line running to the United Taconite operation makes the Leonidas mine a favorable candidate for further CAES study.

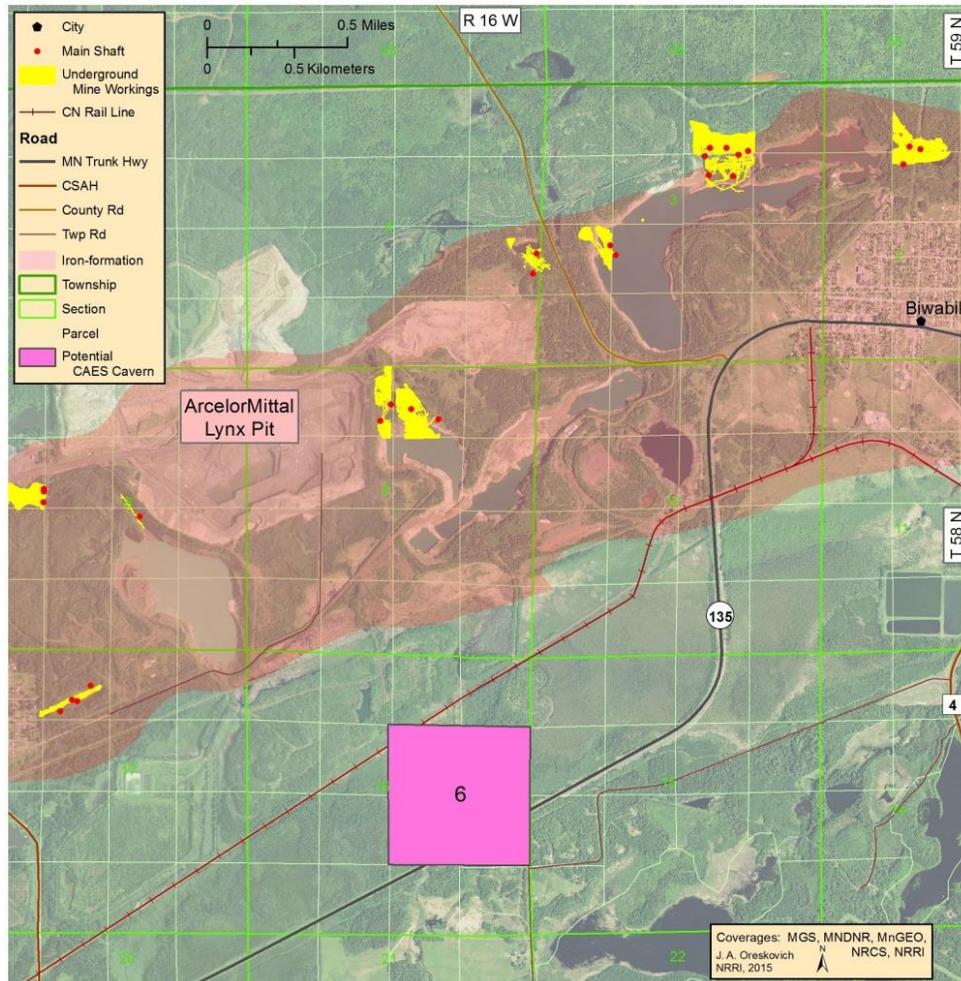
The Section 4 and Morrow mines are cited here due to their isolation from other mine workings (Fig. 1.2-97). The Section 4 mine is a very small mine. Its shaft is at least 185 feet deep as there are workings on the 145-, 160-, and 185-foot levels. There is no mention of the Section 4 mine in any of the mining directories. In this way, it appears similar to the number of very small mines that sprung up on the Vermilion Range.

The Morrow mine (Fig. 1.2-97), upon further investigation, is unsuitable for CAES purposes. It was operated as both an underground and open mine.

The fourth selected site in the Virginia to Biwabik area (Potential CAES Cavern No. 5 in Fig. 1.2-97) was designed as the lower reservoir for Scenarios 2 and 3 of the UTac Area in Fosnacht et al. (2011: Section 2.5.13, p. 358-368). The location was chosen in accordance with Severson's determination of a mineable resource for the lower reservoir in a pumped hydro system (Fosnacht et al., 2011). Maps on p. 364-368 of Fosnacht et al. (2011) illustrate the proposed cavern relative to base map, hydro, elevation contour, ownership, and geologic features.

Figure 1.2-97 also shows the location of the CAES design cavern selected for geotechnical studies in this report. This site is discussed fully as Scenario No 2: Excavated Cavern By Mining A Mineral Resource (High Volume Storage Facility) in the section titled, "Potential Scenarios For CAES In Minnesota," this report. The size and layout of the cavern was determined by: 1) specs obtained from the facilities team; 2) Severson's data in Fosnacht et al. (2011) for the deep drill hole on which it is centered; and 3) the geologic structural controls on the area due to the folding and faulting in the Virginia Horn area.

The final site to be addressed in the Virginia to Biwabik area of Figure 1.2-96 is a potential excavated cavern designed as the lower reservoir of a pumped hydro scenario for the McKinley-Biwabik Area in Fosnacht et al. (2011: Section 2.5.15, p. 384-392). The site is located south of the ArcelorMittal Lynx Pit, between McKinley and Biwabik, where it resides down-dip and off the iron-formation sub-crop (Fig. 1.2-98). Maps on p. 387-392 of Fosnacht et al. (2011) illustrate the proposed cavern relative to base map, hydro, elevation contour, ownership, and geologic features.



**Figure 1.2-98.** Potential excavated cavern site near Biwabik.

Mesabi Range Study Area 4: Biwabik to Hoyt Lakes

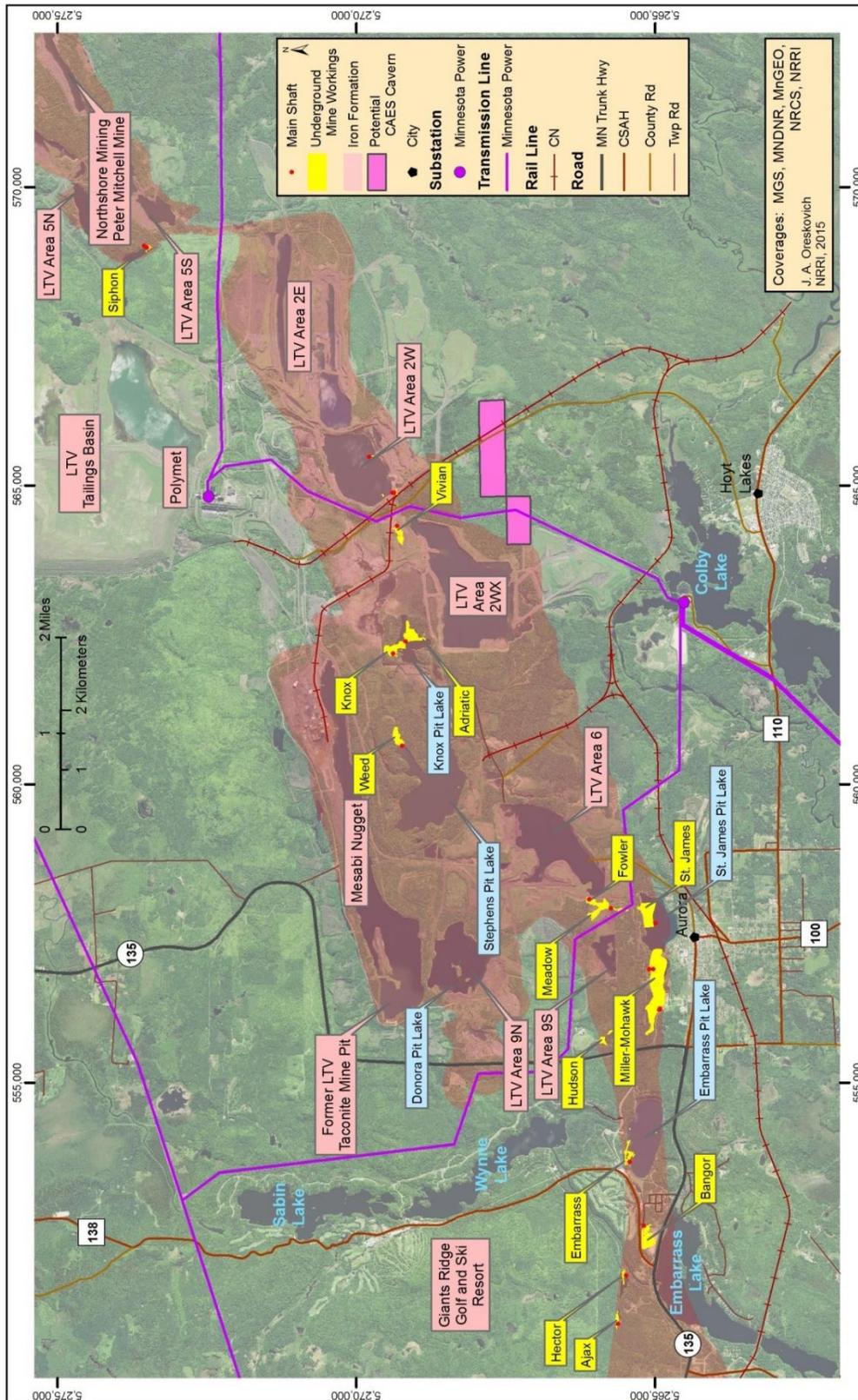
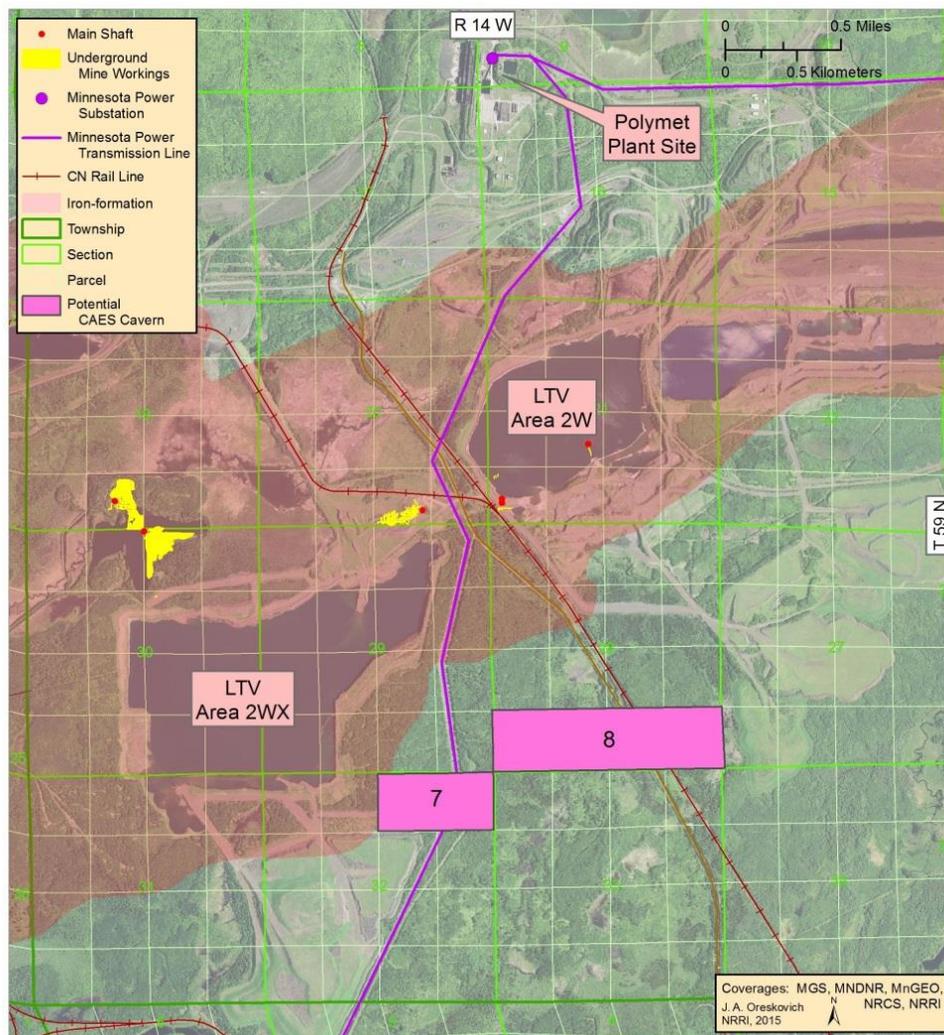


Figure 1.2-99. Mapped underground mine workings from Biwabik to Hoyt Lakes.

CAES Potential for Mesabi Range Study Area 4: Biwabik to Hoyt Lakes

Two adjacent sites from the area between Biwabik and Hoyt Lakes, shown in Figure 1.2-99, are noted here. Potential CAES cavern No. 8, as seen in Figure 1.2-100, is the designed excavated/mined lower reservoir for Scenario 2 of the LTV West Area in Fosnacht et al. (2011: Section 2.5.16, p. 393-409).

It is noted in Fosnacht et al. (2011) that the proposed location of the lower reservoir was constrained by available drilling data. Potential CAES cavern No. 7 (Fig. 1.2-100) was proposed as part of a more viable PHES system should further drilling prove it up. This location would allow use of a different mining feature for the upper reservoir in order to place more distance between the proposed PHES system and current mining activity. Maps on p. 399-409 of Fosnacht et al. (2011) illustrate the proposed caverns relative to base map, hydro, elevation contour, ownership, and geologic features.

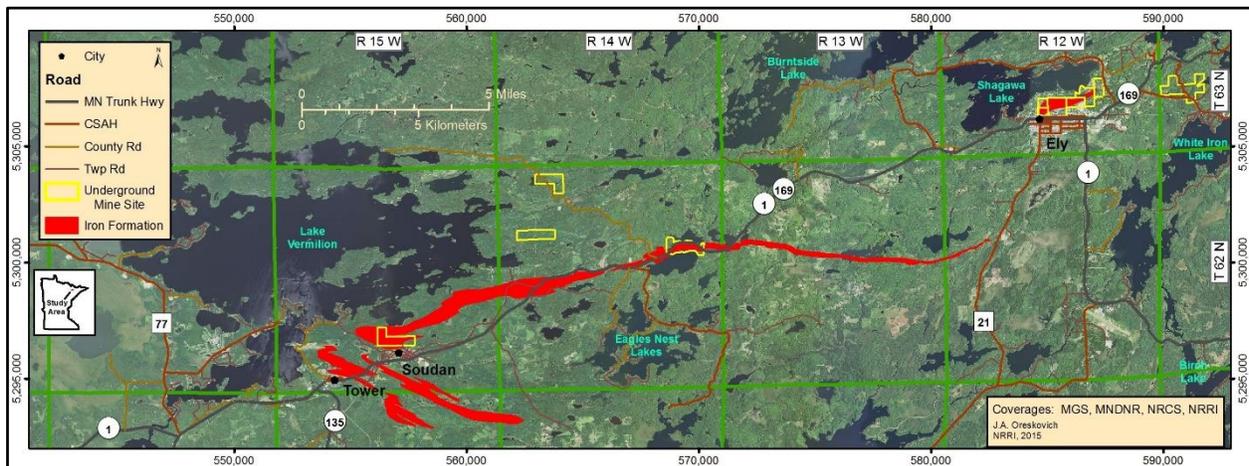


**Figure 1.2-100.** Potential excavated caverns near Hoyt Lakes.

## UNDERGROUND MINE WORKINGS ON THE VERMILION IRON RANGE

There are no high-voltage electrical transmission lines currently serving Minnesota's Vermilion Iron Range. However, the underground natural iron ore mines of the Vermilion district are briefly addressed here for future potential. There may be potential for a smaller scale local CAES in conjunction with wind or via the accumulator technology described in the succeeding section.

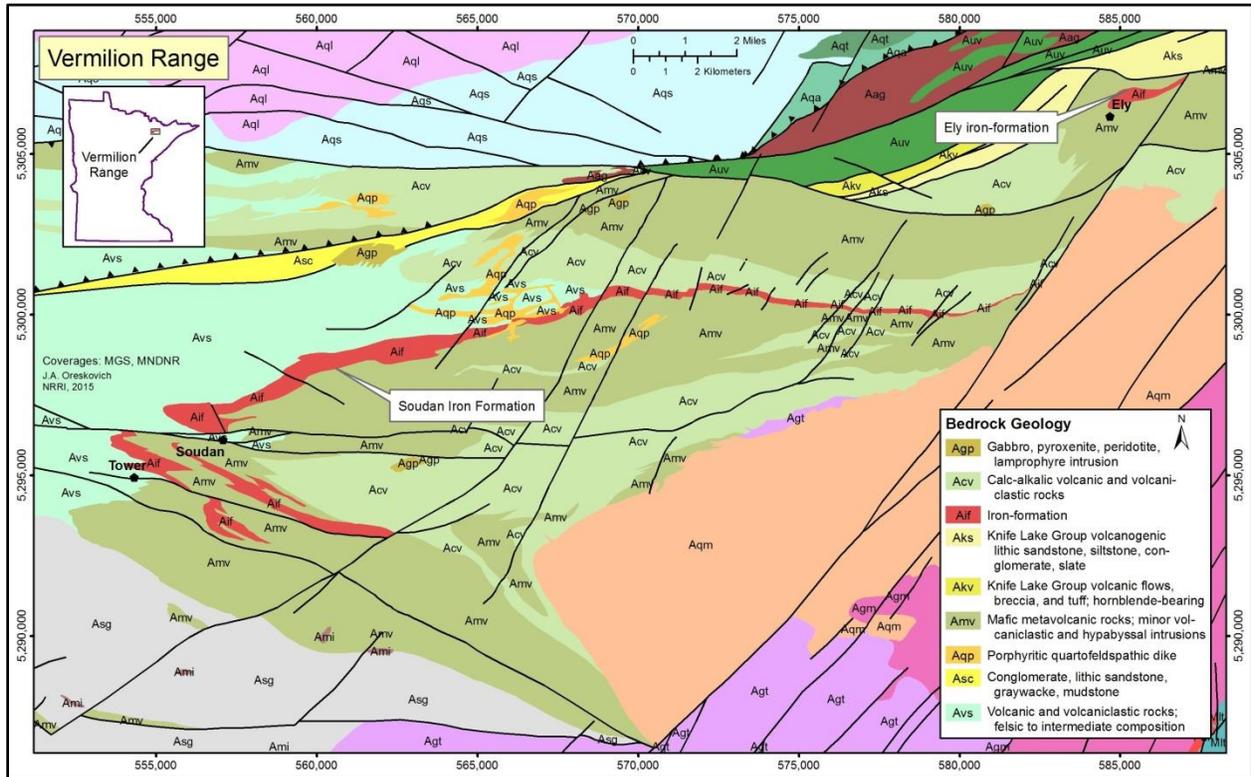
The Vermilion Iron Range is the oldest of the three Minnesota iron-ranges discussed herein, both in terms of geologic age (Neoproterozoic) and mining history. The Vermilion Iron Range extends from just west of the city of Tower near Lake Vermilion to east of the city of Ely located near Shagawa Lake (Fig. 1.2-101). The subcrop and mined extent of iron-formation on the Vermilion Range spans a distance of approximately 25 miles along a generally northeastern trend.



**Figure 1.2-101.** Location map of the Vermilion Range showing the subcrop of the Soudan Iron Formation and the iron-formation at Ely.

Figure 1.2-102 illustrates the bedrock geology of the Vermilion Range area. Only the units in the vicinity of the iron-formations have been labeled. The Soudan Iron Formation occurs in the eastern two-thirds of the Vermilion district, while the iron-formation of the Ely area is a separate unit.

The Soudan Iron Formation is of the Algoma type—lenses of iron-formation associated with volcanic activity. The Soudan Iron Formation is enclosed in the mafic metavolcanic rocks of the Ely Greenstone in the southwestern and eastern portions of the district (Fig. 1.2-102). In the northwestern portion of the district, the Soudan Iron Formation is overlain by the volcanic rocks of the Lake Vermilion Formation.



**Figure 1.2-102.** Bedrock geology of the Vermilion Iron Range (Source: Minnesota Geological Survey State Map Series S-22, 2011).

Machamer (1968) describes the iron ores of the Vermilion District as “hard massive hematite, fractured to a greater or lesser extent and occurring in an equally hard jaspilitic iron-formation.” He noted that the ores produced from the Ely mines were called “soft ores” by the miners. Machamer attributes this to the fact that the hematites at Ely were brecciated fragments of the same massive blue hematite found at Soudan. The brecciated fragments were loosely cemented by a second generation of finely crystalline hematite (Machamer, 1968).

Table 1.2-58 provides a summary listing of the underground mines on the Vermilion Iron Range. These include the major producers (1.45 – 41 MT: Soudan, North and South Chandler, Pioneer, Savoy, Section 30, Sibley, and Zenith) as well as minor producers (< 25,000 T). Brief descriptions of the minor operations are provided in the Table 1.2-58.

Table 1.2-1. Iron ore mines of the Vermilion Range.

	Mine	S	T	R	Parcel	Began (shaft)	Closed (Last Ship)	Shaft	Depth (Ft.) <sup>8</sup>	Crosscut Level	Notes	Ore Shipped <sup>2</sup> (LT)
1	Almar <sup>1</sup>	15	62	14		1910	1912	2-cmp		128-foot	200 feet of shaft and drift completed; drifted south from shaft; drill hole down 795' in considerable iron	
2 <sup>6</sup>	Anderson <sup>1</sup>	4	62	12		1890 1891	1925	6' x 10' ID New shaft 300' E	70 300+	90-foot; 210-foot; 300-foot; 4 working levels	120 acres; ore struck in DHs at 126'. 3 active shafts on Lucky Boy-Anderson sites (adjoining, along with Camp).	
3	Armstrong Bay <sup>1,2</sup>	7 8	62 62	14 14	S1/2-SE S1/2-SW	1916	1923				Opened as La Rue mine; adit driven 180+ feet, 90 feet below hilltop; 117' deep winze, several crosscuts in winze and adit; by 1922, 1,200' of UG workings including 66-ft shaft, 2 adits; development on 2 levels	4,748
4 <sup>6</sup>	Camp <sup>1</sup>	33	63	12		1911			40+		80 acres; shaft down 40' in solid ore.	
5	Handler North <sup>2</sup>	28	63	12	NE-SE	1888	(1942)		920 <sup>3</sup>			9,504,759
6	Handler South <sup>2</sup>	28	63	12	SE-SE	1888	(1957)		800 <sup>3</sup>			2,396,154
7	Chicago-Vermilion Iron Company <sup>1</sup>	34 35	63 63	15 15		1910	1911		30	Planned at 100 feet	5 test pits; a 30-foot shaft by windlass and bucket (man power); trenches showed a vein of ore 300-500 feet wide.	
8	Chippewa Iron Mining Company <sup>7</sup>	29 30	63 63	11 11		1917	1920	3-cmp	345	100-, 200-, 300-foot; 276' drift on 100-ft.	Just east of Section 30 mine; 2 shifts working in Feb, 1920; lease surrendered in June, 1920; shaft mistakenly sunk in ore	
9	Consolidated Vermilion and Extension Mine <sup>1,2</sup>	4 5	62 62	14 14	S1/2-NW, SW-NE & NW-SE	1888, 1910 (1916) <sup>7</sup> 1911 (1916) <sup>7</sup>	(1920)	Vermilion Extension	440	120-foot, 240-foot?, 340-foot; 440-foot 300-foot	100' shaft begun in 1888, cross-cut expected at that level; not completed. Two main shafts sunk later: Vermilion shaft, sunk in 1910, depth = 440'; Extension shaft, sunk in 1913, depth = 130'. Clean high-grade ore in drift at 120'. 1400' of drifts in the two shafts. Ore hoisted by Sept. 1912.	22,893
10	Howard Mine <sup>1</sup>	8	63	9							No records of mine development; probably strictly a manual operation; shaft and waste pile.	
11 <sup>6</sup>	Lucky Boy <sup>1</sup>	5	62	12		1910 1912	1925	6' x 10' ID New shaft 756' N	160 79	South at 150' for 350' Stopped due to water	80 acres; shaft on Anderson-Lucky Boy line; drifts were 7' x 8', clear & heavily timbered; ore struck in DHs at 126'.	

Table 1.2-58 (Continued).

Mine	S	T	R	Parcel	Began (shaft)	Closed (Last Ship)	Shaft	Depth (Ft.) <sup>8</sup>	Crosscut Level	Notes	Ore Shipped <sup>2</sup> (LT)
12 McComber <sup>1,2</sup>	13	62	14	Lots 3 & 4 Lots 2, 3 & 4	1888	(1919)	2-cmp, 5' x 9'	200	60-foot		8,386
	14	62	14		?			60-foot			
13 Pioneer <sup>2</sup>	27	63	12	SW-1/4	1889	(1967)	5' x 12'	1,466 <sup>3</sup>	100-foot	Shaft in hanging wall, 4.1-ft. drift on 100' level.	41,112,587
	35	63	15		1910	NA		100			
14 Rice Bay Iron Company <sup>1</sup>	26	63	12	E1/2-NW	(1899)	(1916)		650 <sup>3</sup>			1,866,378
16 Scott-Bevier Iron Company <sup>1</sup>	36	63	15		1910			90	50'		
17 Section 25 (Romberg) <sup>1</sup>	25	63	12		1912		3-cmp, Fargo	262'	262'	150' W of S30 W line; <1 mile W of S 30 Mine; x-cut 90' to N; drifts 44' to NW & 40' to NE in Hi-grade Bessemer ore (67% iron)	
18 Section 30 <sup>2,5</sup>	30	63	11	Lots 1, 2, 3, 5, 6, SW-NE, SE-NW & NW-SE	1906 (1910) <sup>7</sup>	(1923)		650 <sup>3</sup>	Initial 4 drifts at 118' (first encountered)		1,457,295
19 Sibley <sup>2</sup>	26	63	12	SW-NW & NW-SW	1899	(1954)		1,285 <sup>3</sup>			9,808,202
	27	63	12	Lot 1							
20 Soudan <sup>2</sup>	27	62	15	N1/2-SW & NW-SE	1884	(1963)		2,707 <sup>3</sup>			16,010,044
	28	62	15	SE-NE & NE-SE							
21 White Iron Lake Mine <sup>1</sup>	2	62	12		1905	NA	NA	67'	NA	Cross-cut 108' N & S at 150' lev., drift W for 50'; main shaft in N wall of orebody	
					1906	2-cmp, 7'x14'	175'	150'			
22 Zenith <sup>2</sup>	27	63	12	N1/2-SE	1892	(1964)		1,800 <sup>4</sup>			21,561,128

<sup>1</sup>Stenlund, 1988.

<sup>2</sup>Skills Mining Review, 2005.

<sup>3</sup>Crowell & Murray, 1923.

<sup>4</sup>Machamer, 1968.

<sup>5</sup>Stenlund, 1992.

<sup>6</sup>The Anderson, Camp and Lucky Boy properties were adjoining. Details were difficult to distinguish among the three. The four workings levels were likely at 90', 150', 200' or 210', and 300'.

<sup>7</sup>First ore shipment.

<sup>8</sup>Depths listed are as of the dates of sources used. As such, they may not be the final mined depth.

Figure 1.2-103 shows the locations of underground natural iron ore mines in the western part of the Vermilion District. Mine specifics can be found in Table 1.2-58. The Soudan mine has large open stopes and great depth (2,700 feet) that would make it an ideal candidate for CAES consideration. However, this underground mine is part of a state park that offers underground mine tours to the public. It is also the site of the University of Minnesota’s deep underground mine science and engineering laboratory.

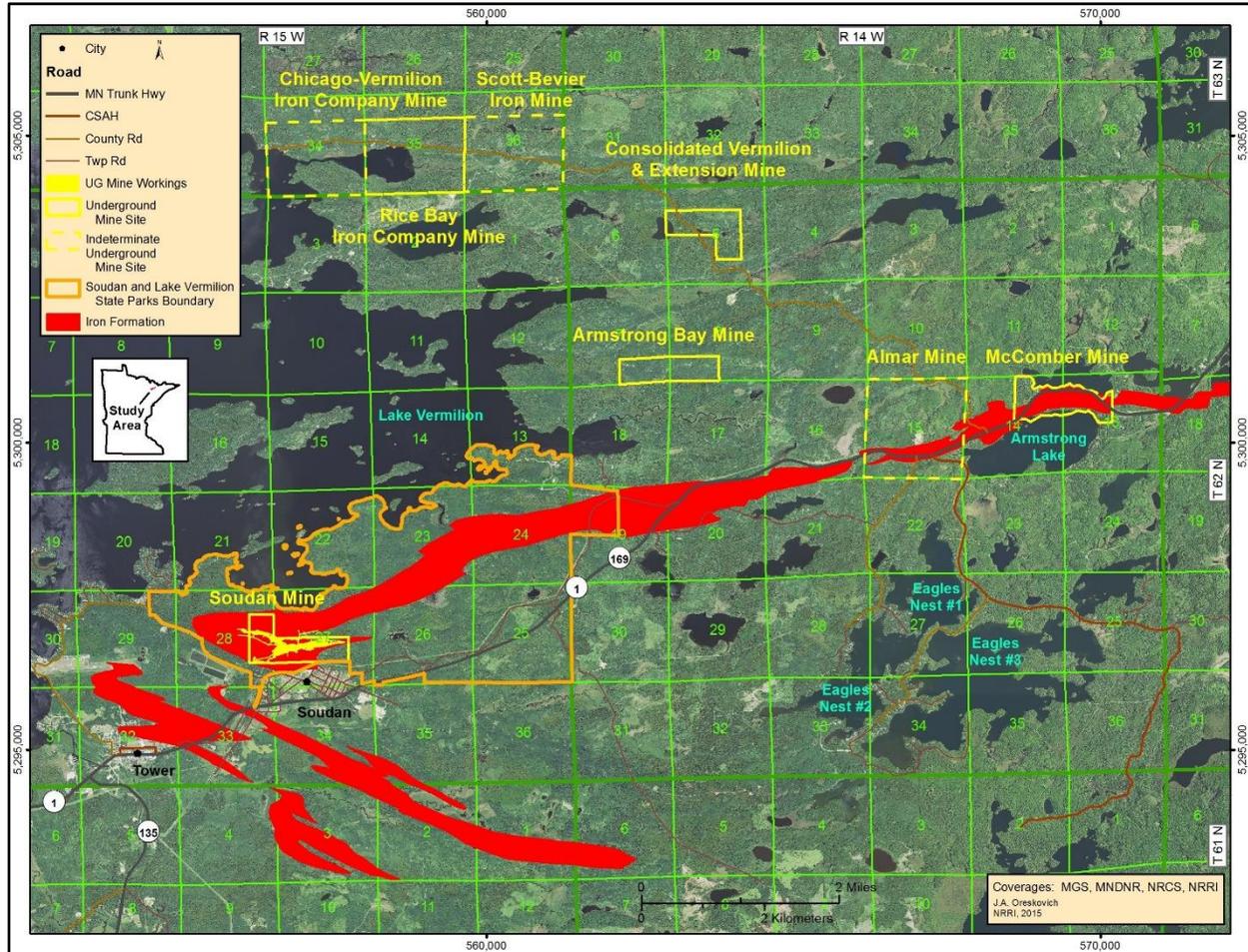


Figure 1.2-103. Underground iron ore mines ranging from Lake Vermilion to Armstrong Lake.

Figure 1.2-104 shows the locations of underground natural iron ore mines in the eastern part of the Vermilion District. Mine specifics can be found in Table 1.2-58. The iron-formation at Ely, as noted above, is separate from that of the Soudan Iron Formation in the western part of the district. The six mines located along the subcrop of iron-formation shown on the northern edge of the city of Ely (Fig. 1.2-104) are deep and interconnected.

During 1982 and 1983, studies were conducted by the Minnesota Geological Survey (MGS) on the six underground mines at Ely under the U.S. Department of Energy’s Underground Energy Storage Program (Walton and McSwiggen, 1983). Specifically, the waters that have filled Pioneer Lake on the surface (formed from surface subsidence due to the underground workings) and the underground cavities produced by the Ely mines were evaluated with promising results for seasonal thermal energy storage (STES) (Kannberg, 1984). Estimated water volume at the time was 469-595 ft.<sup>3</sup> (16.2-17 million m<sup>3</sup>) (Walton and McSwiggen, 1983).

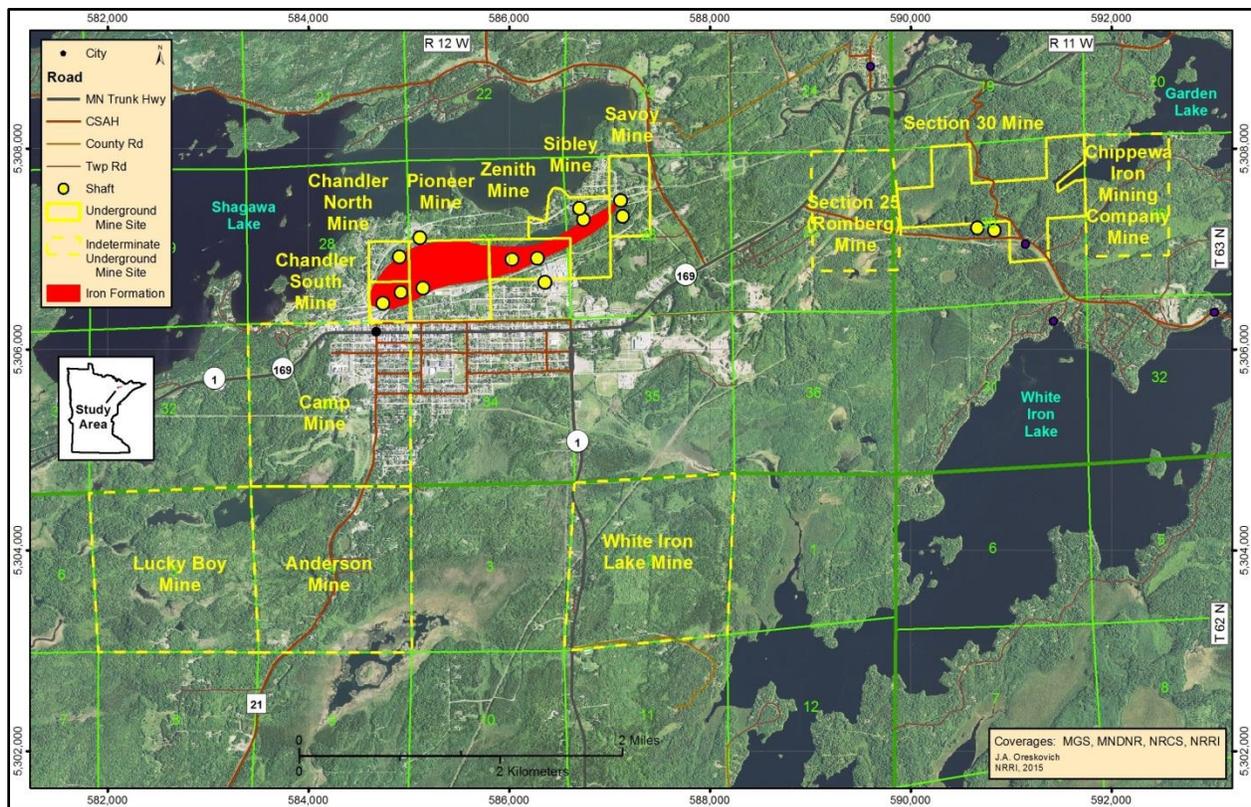


Figure 1.2-104. Underground iron ore mines of the Ely area.

## POTENTIAL LOCATIONS FOR DEPLOYMENT OF THE HYDROSTOR TECHNOLOGY

In light of the development of this new underwater CAES technology, mine pit lakes across the Mesabi and Cuyuna Ranges were looked at for sufficient depth (> 55 meters or 180 feet) to potentially support such a system. Twenty-five mine pit lakes on the Mesabi Range and eight mine pit lakes on the Cuyuna Range have been identified as meeting the depth criterion. There are other deep mine pits on the Mesabi Range that have not been included, as they are impacted by current/near future mining activities. In addition, the Mangan-Joan pit lake on the Cuyuna Range likely meets the depth criterion, although that could not be verified.

The designated Mesabi Range pit lakes occur within nine distinct areas outlined and numbered as inset maps in Figure 1.2-105. This figure serves as a location key to the listing of inset maps and resident mine pit lakes presented in Table 1.2-59. Also provided in the table are the pit lake water depths, data sources, and current references. The full inset maps follow in Figures 1.2-106 through 1.2-114.

The designated Cuyuna mine pit lakes are presented in similar fashion. Figure 1.2-115 holds the inset map key that links to the associated data in Table 2.1-60. Due to close proximity, seven of the eight pit lakes are resident within one inset map, seen in Figure 1.2-117, while the eighth appears in a separate inset map in Figure 1.2-116.

The map key figures provide an overall view of the various inset maps relative to the distribution of high voltage lines (230 kV and 500kV). A 500 kV Excel Energy transmission line from Montreal Hydro in Canada to Forbes passes through the Mesabi Range west of Chisholm (Fig. 1.2-105). The proposed 500 kV Minnesota Power Great Northern Transmission Line would likewise run from Montreal Hydro and pass through the western end of the Mesabi Range along the east side of the Canisteo pit (Fig. 1.2-108). Great River Energy has a 500 kV transmission line coming up from the south into the substation at Forbes, located approximately ten miles south of the central Mesabi Range.

Two 230 kV Minnesota Power transmission lines run through Mesabi Inset Map 2 just south of the Greenway, Lind, and West Hill Pits (Fig. 1.2-107). Another passes through Mesabi Inset Map 5 in the central Mesabi Range between Chisholm and Buhl, directly over the Hartley-Burt pit (Fig. 1.2-110). The northeastern extension of this transmission line runs along the northern side of the Mesabi Range until it dips through the Minntac taconite mine property north of Mountain Iron in Mesabi Inset Map 6 (Fig. 1.2-111). Here the line runs into a substation located between the plant site and Minntac's East Pit. This substation is located just south of the Minnesota Power Taconite Ridge wind farm.

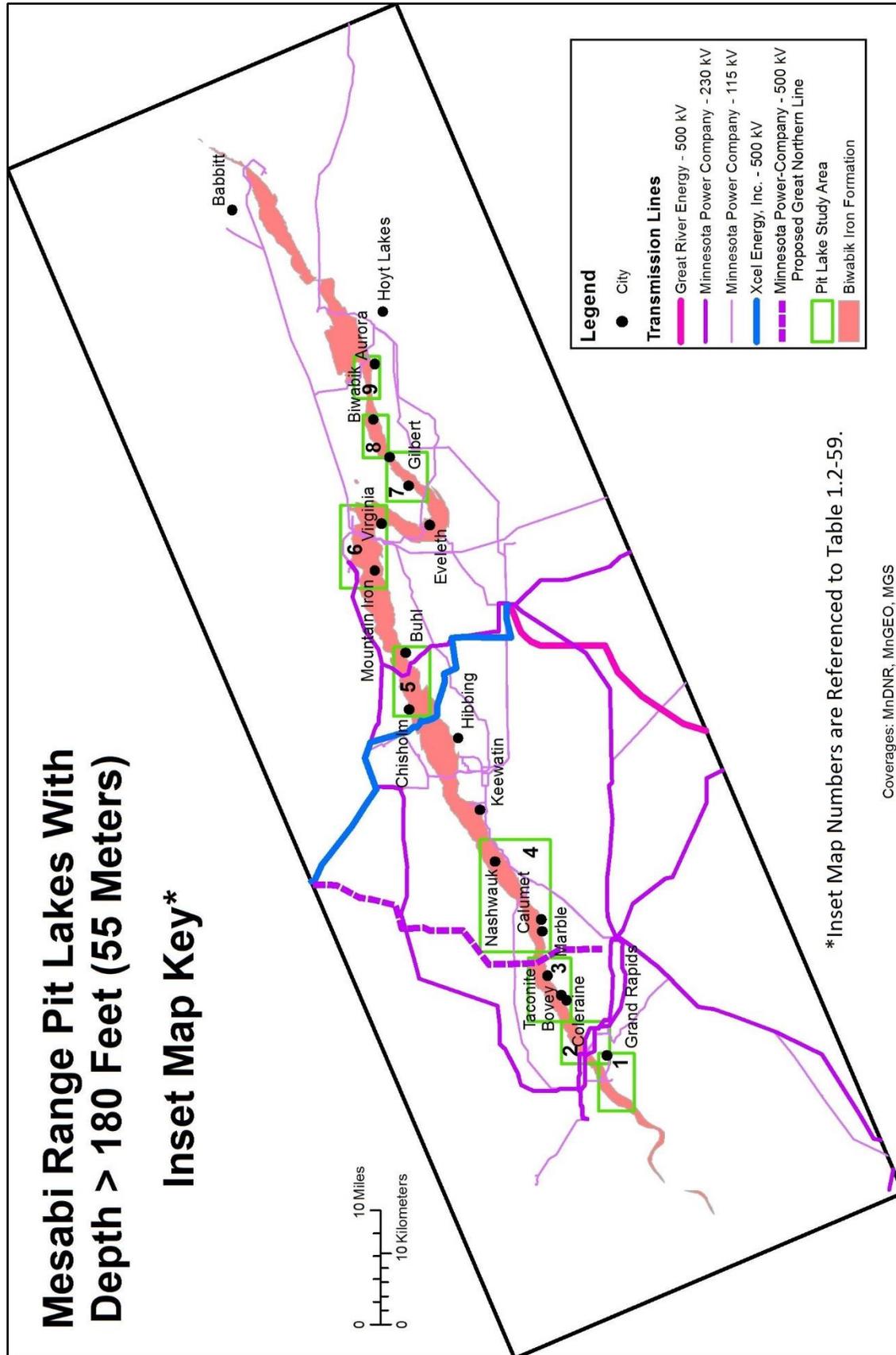
On the Cuyuna Range, a 500 kV Great River Energy transmission line comes up from the south, passing along the west side of the Sagamore Pit in Cuyuna Inset Map 1 (Fig. 1.2-116) before turning west into a substation located 1.3 miles west of the city of Riverton. A 230 kV Minnesota Power transmission line runs east, then north, from that same substation, passing along the western side of the Cuyuna North Range within 0.6 to 3 miles of the designated pits of Cuyuna Inset Map 2 (Fig. 1.2-117).

Proximity to high voltage transmission lines and pit lake water depths ranging from 180 ft. (55 m) to over 500 ft. (153 m) make both the Mesabi and Cuyuna ranges suitable prospects for further investigation of the balloon or "accumulator" technology for CAES. The taconite mines of

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the Mesabi Range provide an added incentive in that they are high-demand consumers of electrical power. Wind energy is already being brought into the grid at the Minntac site.

As an interesting sidebar to the CAES balloon technology, the Portsmouth, Feigh, and Mangan-Joan pits on the Cuyuna Range already have history with balloon technology. On August 19, 1957, a 350-foot-tall balloon launched from the bottom of the Portsmouth pit carried a manned capsule 19.5 miles above the earth's surface as part of the U.S. Air Force Man High II project. The flight's purpose was to test how humans react to such high altitudes in preparation for sending men into space ([http://www.twincities.com/minnesota/ci\\_6658848#](http://www.twincities.com/minnesota/ci_6658848#)). Prior to the manned flight, other test flights were launched from the Portsmouth, Feigh, and Mangan-Joan mine pits in 1956 and 1957 (<http://www.stratocat.com.ar/bases/11e.htm>). The mine pits were used because their depths, walls, and surrounding surface stockpiles protected the balloon skin from damage by strong surface winds.



**Figure 1.2-105.** Inset map key for Mesabi Range pit lakes with sufficient depth to host CAES balloon technology.

**Table 1.2-2.** Inset map listing of Mesabi Range pit lakes with sufficient depth to host CAES balloon technology.

<b>Inset Map</b>	<b>Vicinity</b>	<b>Mine Pit Lake</b>	<b>Water Depth (Ft.)</b>	<b>Date (As Of)</b>
1	West of Grand Rapids	Tioga No. 2	225 <sup>1</sup>	2005
2	Northeast of Grand Rapids	Greenway Pit	290 <sup>1</sup>	1990
		Lind Pit	260 <sup>5</sup>	2006
		West Hill Pit	205 <sup>2</sup>	NA
3	Coleraine to Taconite	Canisteo Pit (SW)	245 <sup>6</sup>	2013
		Canisteo Pit (Central)	215 <sup>6</sup>	2013
		Canisteo Pit (NE)	305 <sup>5</sup>	2013
4	Marble to Nashwauk	Gross Marble Pit	190 <sup>5</sup>	2006
		Hill Annex Pit	260 <sup>5</sup>	2006
		Butler Pit	265 <sup>3</sup>	2006
		Hawkins Pit	200 <sup>3</sup>	2006
		La Rue Pit	200 <sup>1</sup>	2007
5	Chisholm to Buhl	Monroe-Tener Pit	275 <sup>3</sup>	2006
		Twin Cities South Pit	265 <sup>3</sup>	2006
		Fraser Pit	430 <sup>3</sup>	2006
		Sherman Pit	300 <sup>3</sup>	2006
		Hartley-Burt Pit	220 <sup>3</sup>	2006
		Forster Pit	185 <sup>3</sup>	2006
		Grant Pit	335 <sup>3</sup>	2002
6	Mountain Iron to Virginia	Mountain Iron Pit	230 <sup>7</sup>	2004
		Sauntry Pit	195 <sup>4</sup>	2012
		Missabe Mountain Pit	300 <sup>4</sup>	2011
7	Gilbert Area	Gilbert Pit (Lake Ore-Be-Gone)	440 <sup>1</sup>	2014
8	West of Biwabik	McKinley Pit	430 <sup>3</sup>	2006
		Canton Pit	310 <sup>3</sup>	2006
9	East of Biwabik to Aurora	Embarrass (Sabin) Pit	465 <sup>1</sup>	2013
		St. James Pit	380 <sup>1</sup>	2013

**Data sources:**<sup>1</sup>MN DNR Fisheries Survey (year as noted).<sup>2</sup>MN DNR Pit lake bathymetry map (year as noted).<sup>3</sup>MN DNR-Waters shapefile as of 2006.<sup>4</sup>Pit map + 2011 LiDAR (surface).<sup>5</sup>Mesaba Energy Project Environmental Supplement Part 2.<sup>6</sup>MN DNR Canisteo Mine Pit Outflow Project.<sup>7</sup>2004 Mesabi Grid DEM

Inset Map 1: West of Grand Rapids

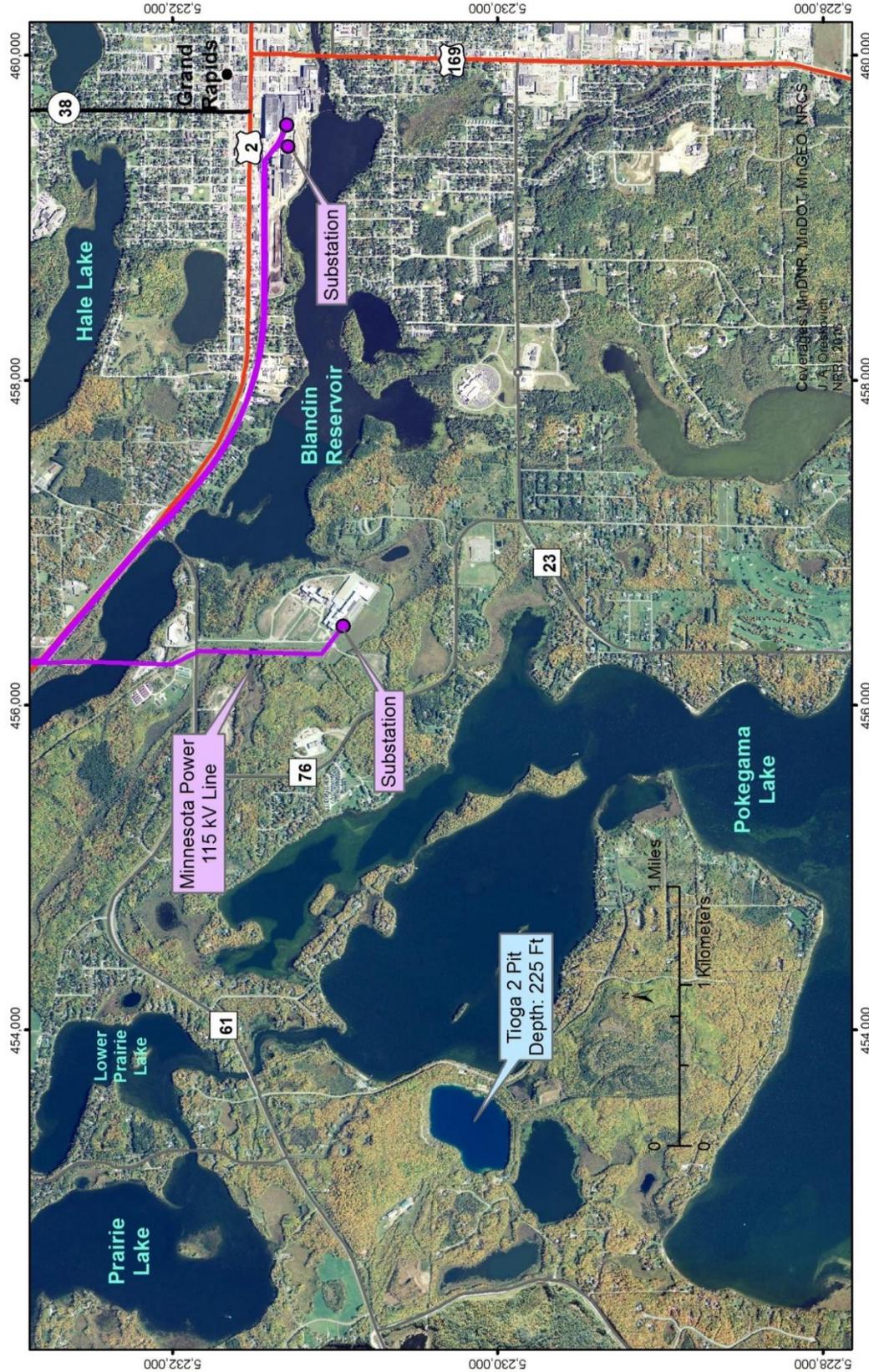
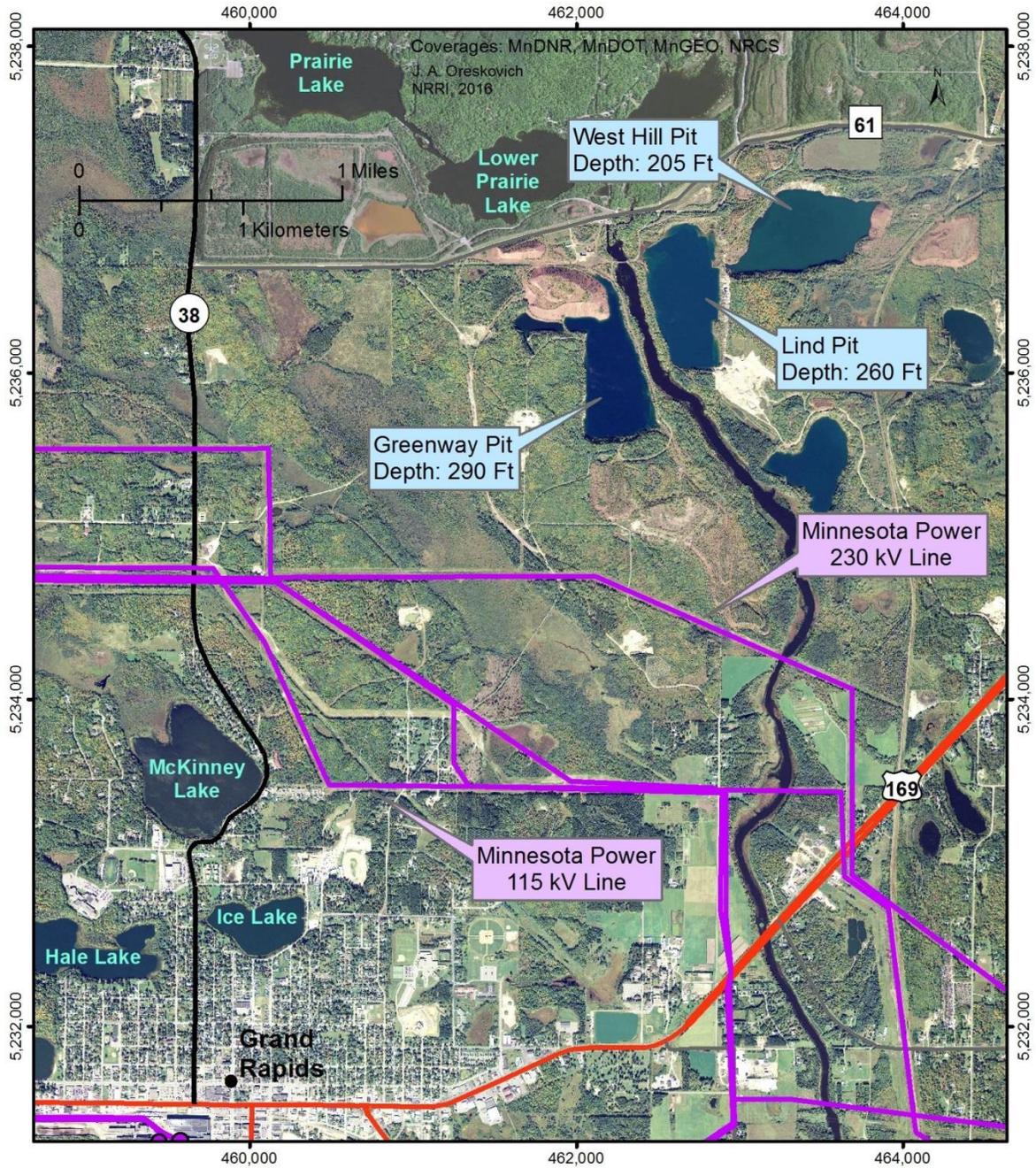


Figure 1.2-106. Tioga No. 2 pit, located west of Grand Rapids.

**Inset Map 2: Northeast of Grand Rapids**



**Figure 1.2-107.** Greenway, Lind and West Hill pits located northeast of Grand Rapids.

Inset Map 3: Coleraine to Taconite

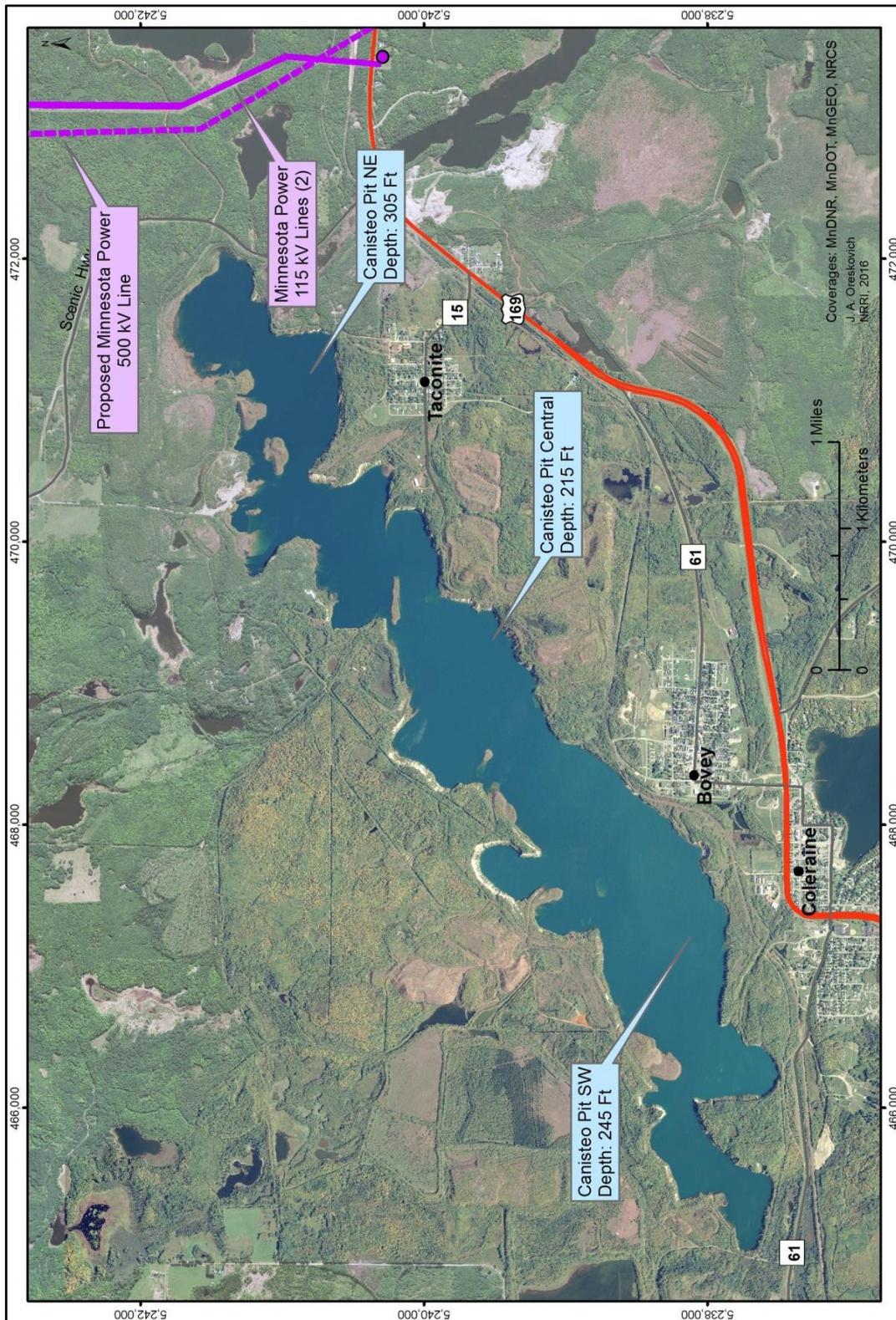


Figure 1.2-108. Inset Map 3: The Canisteo pit stretching from Coleraine to Taconite.

Inset Map 4: Marble to Nashwaug

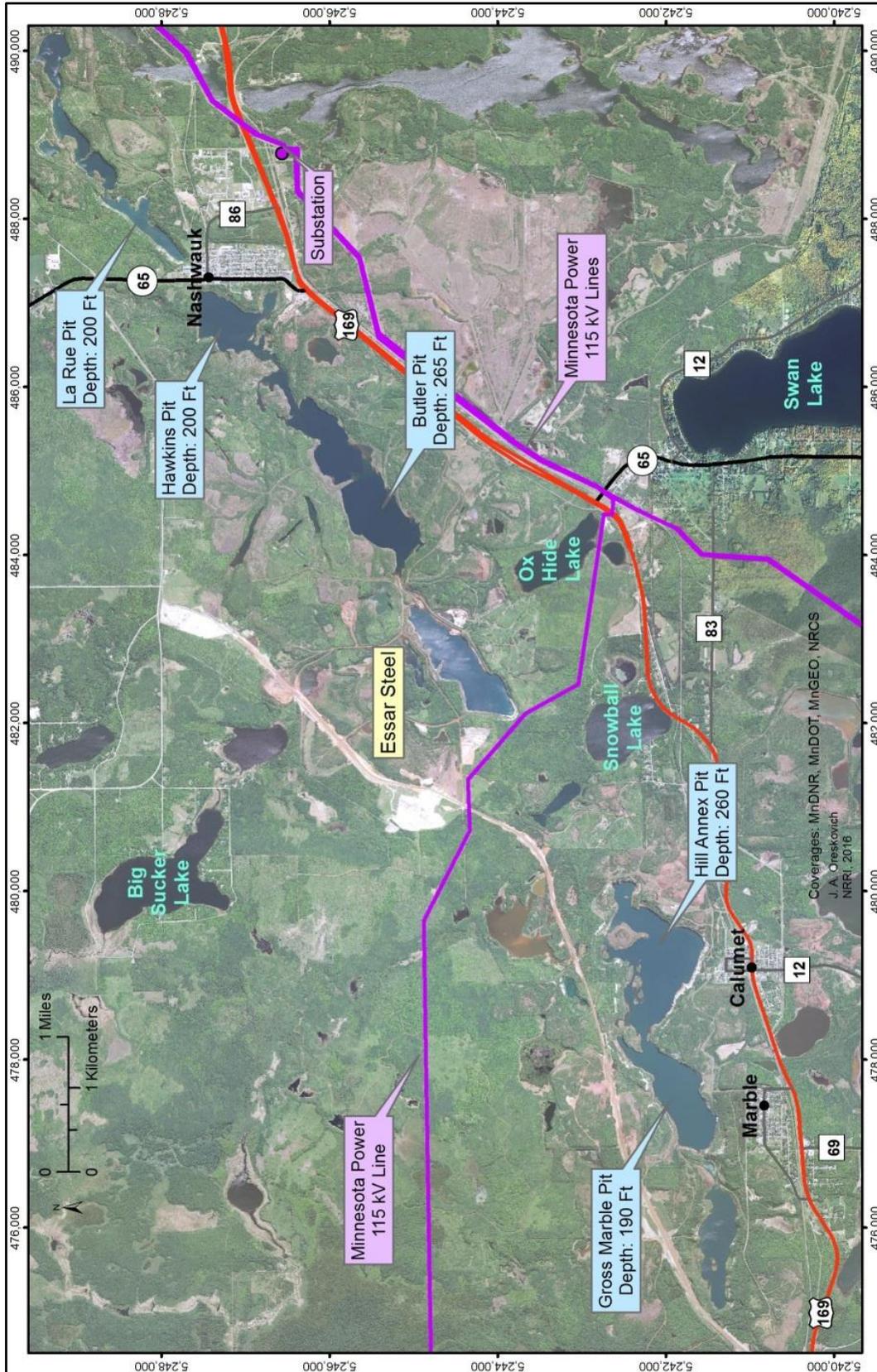


Figure 1.2-109. Inset Map 4: The Gross Marble, Hill Annex, Butler, Hawkins, and La Rue pits extending from Calumet to Nashwaug.

Inset Map 5: Chisholm to Buhl

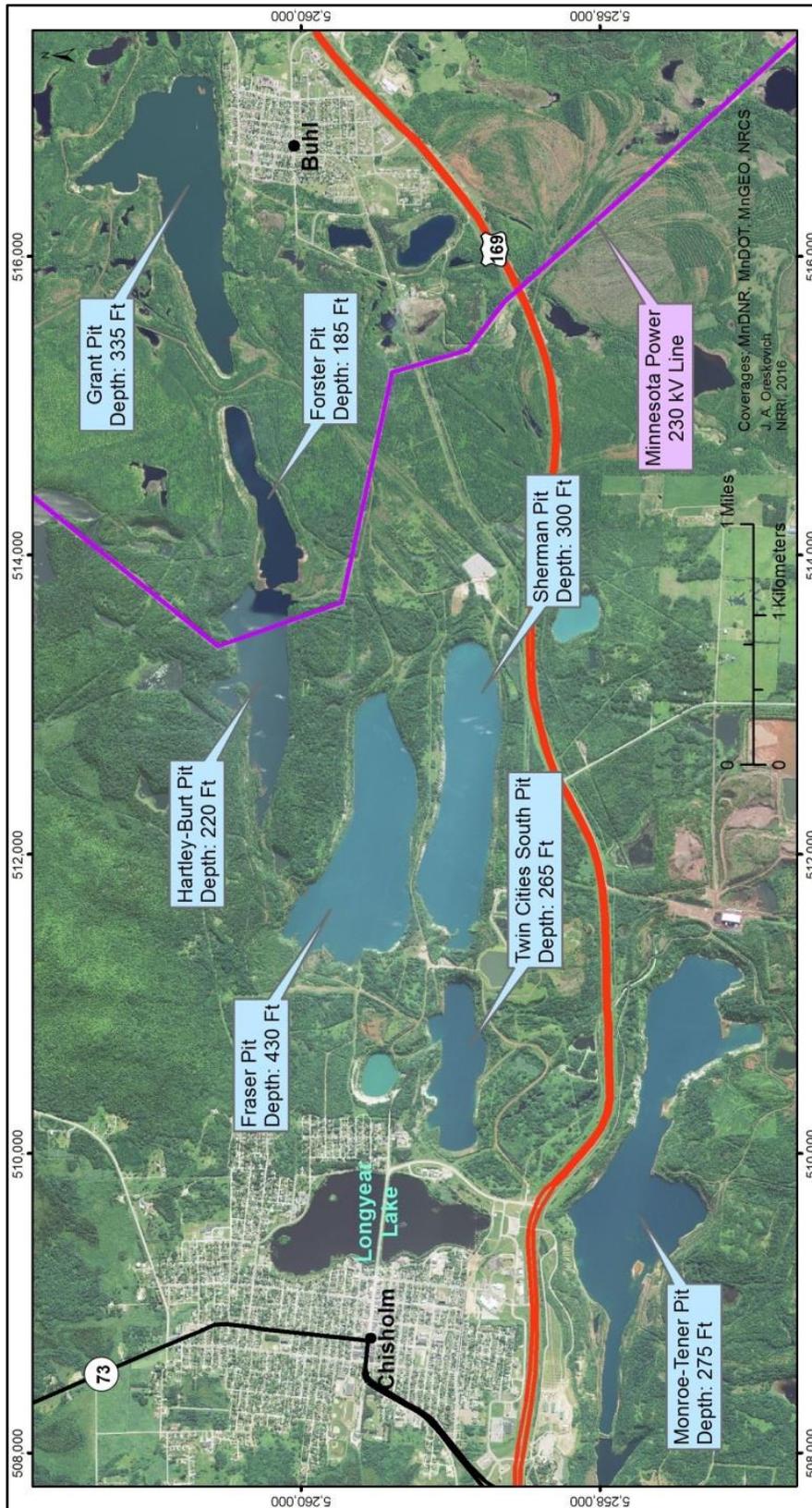


Figure 1.2-110. Inset Map 5: The Monroe-Tener, Twin Cities South, Fraser, Sherman, Hartley-Burt, Forster, and Grant pits extending from Chisholm to Buhl.

Inset Map 6: Mountain Iron to Virginia

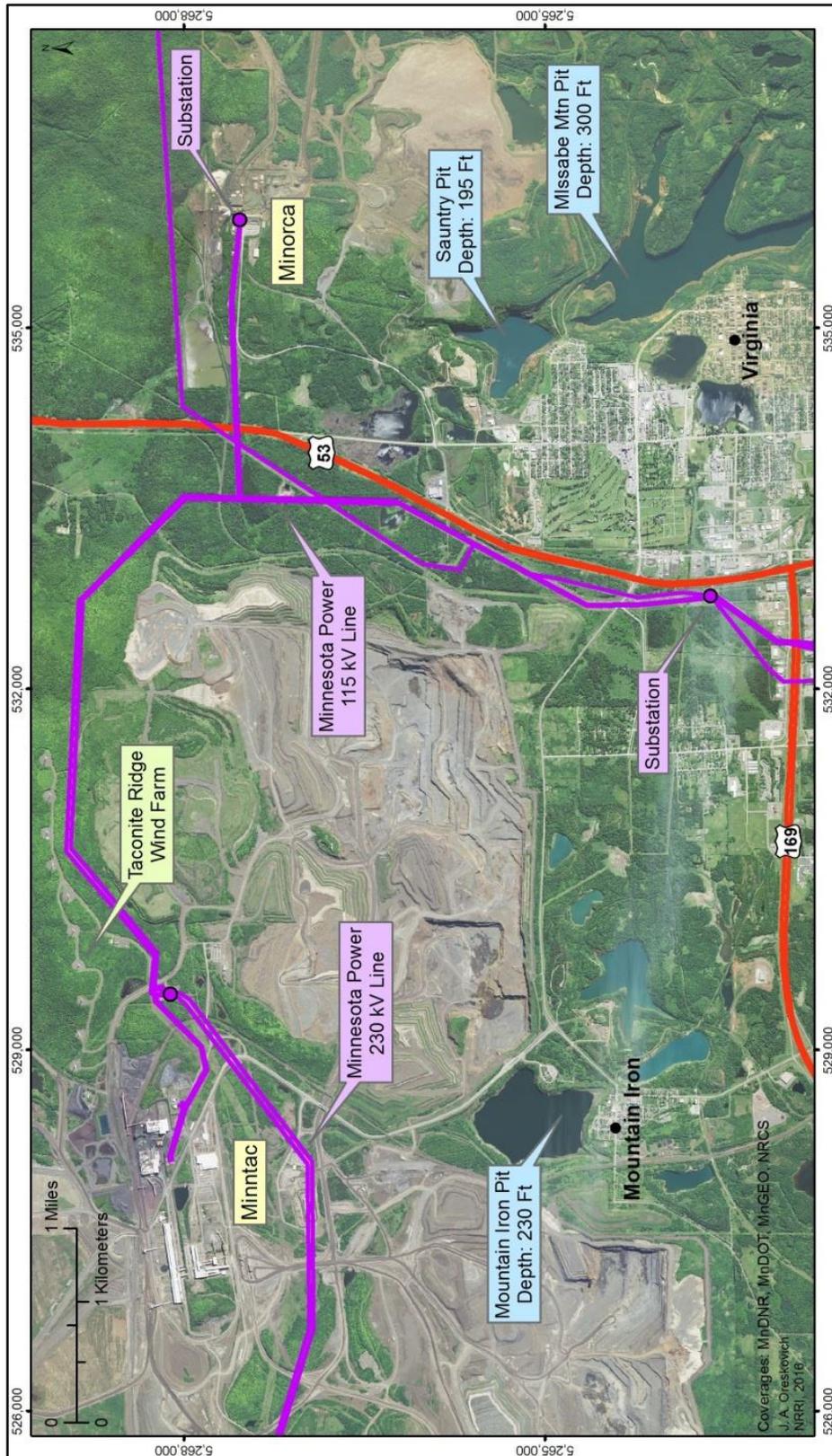
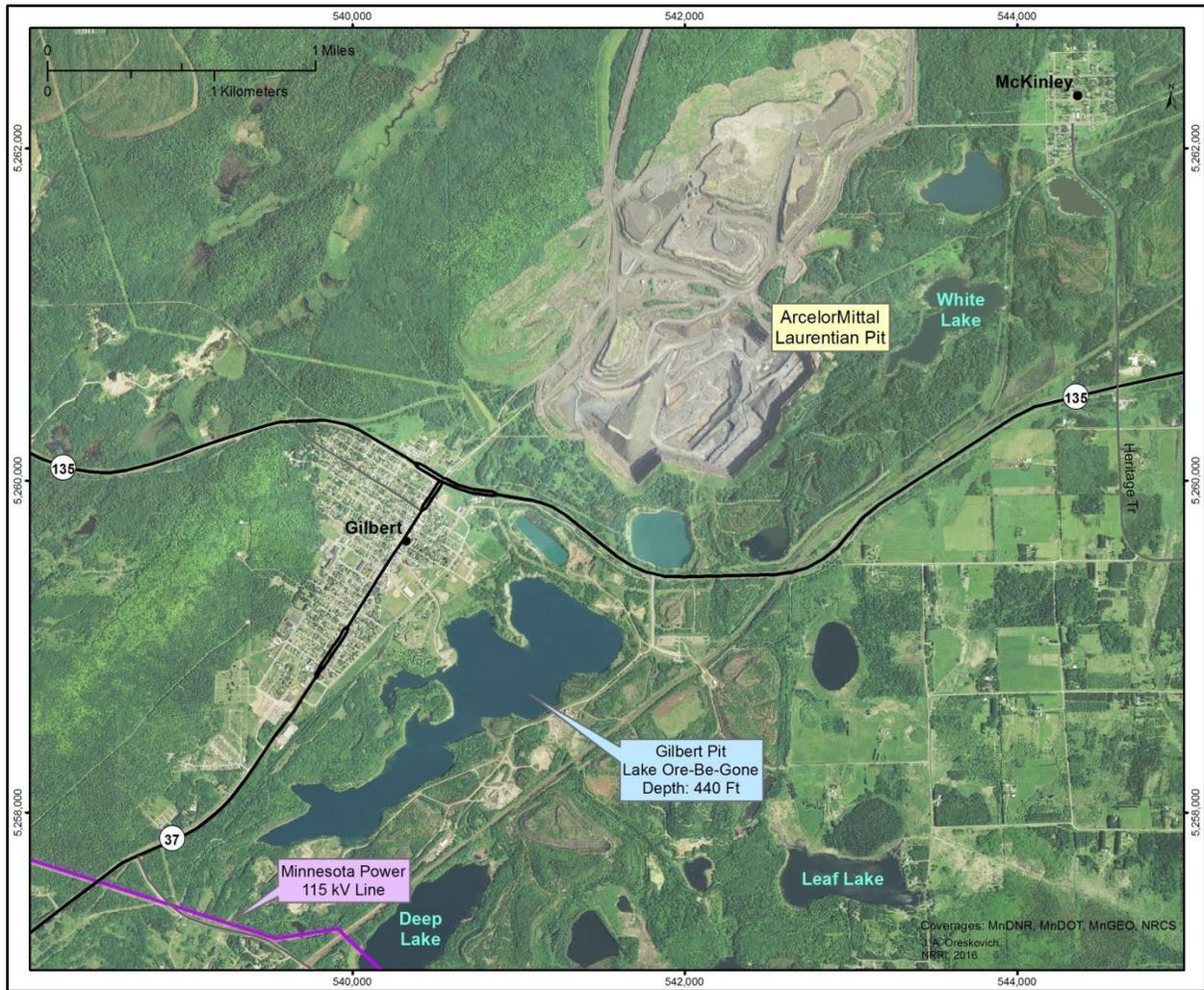


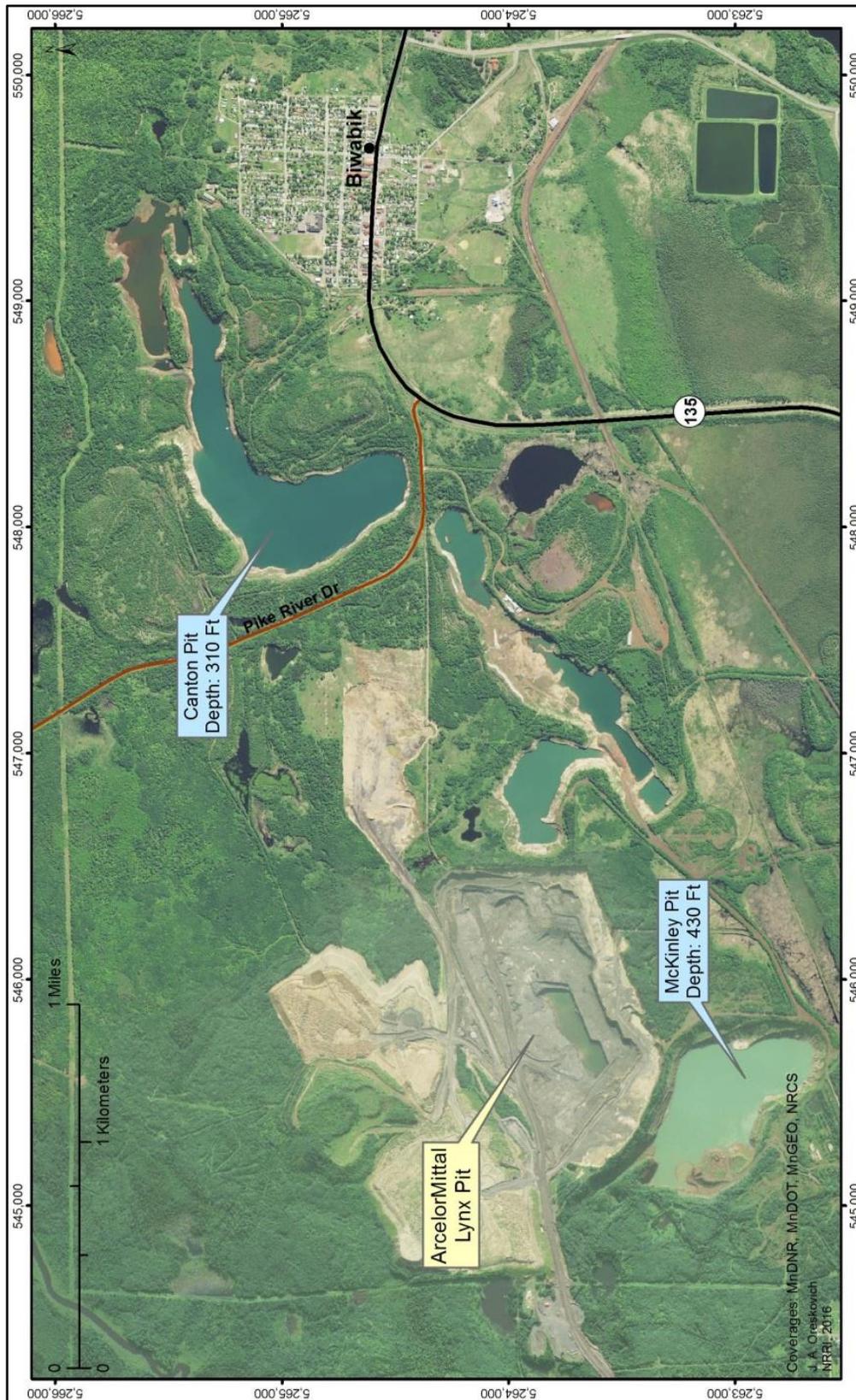
Figure 1.2-111. Inset Map 6: The Mountain Iron, Sauntry, and Missabe Mountain pits at Mountain Iron and Virginia.

**Inset Map 7: Gilbert Area**



**Figure 1.2-112.** Inset Map 7: The Gilbert Pit (Lake Ore-Be-Gone) located southeast of Gilbert.

**Inset Map 8: West of Biwabik**



**Figure 1.2-113.** Inset Map 8: The McKinley and Canton pits located west of Biwabik.

Mesabi Range Pit Lake Study Area 9: East of Biwabik to Aurora

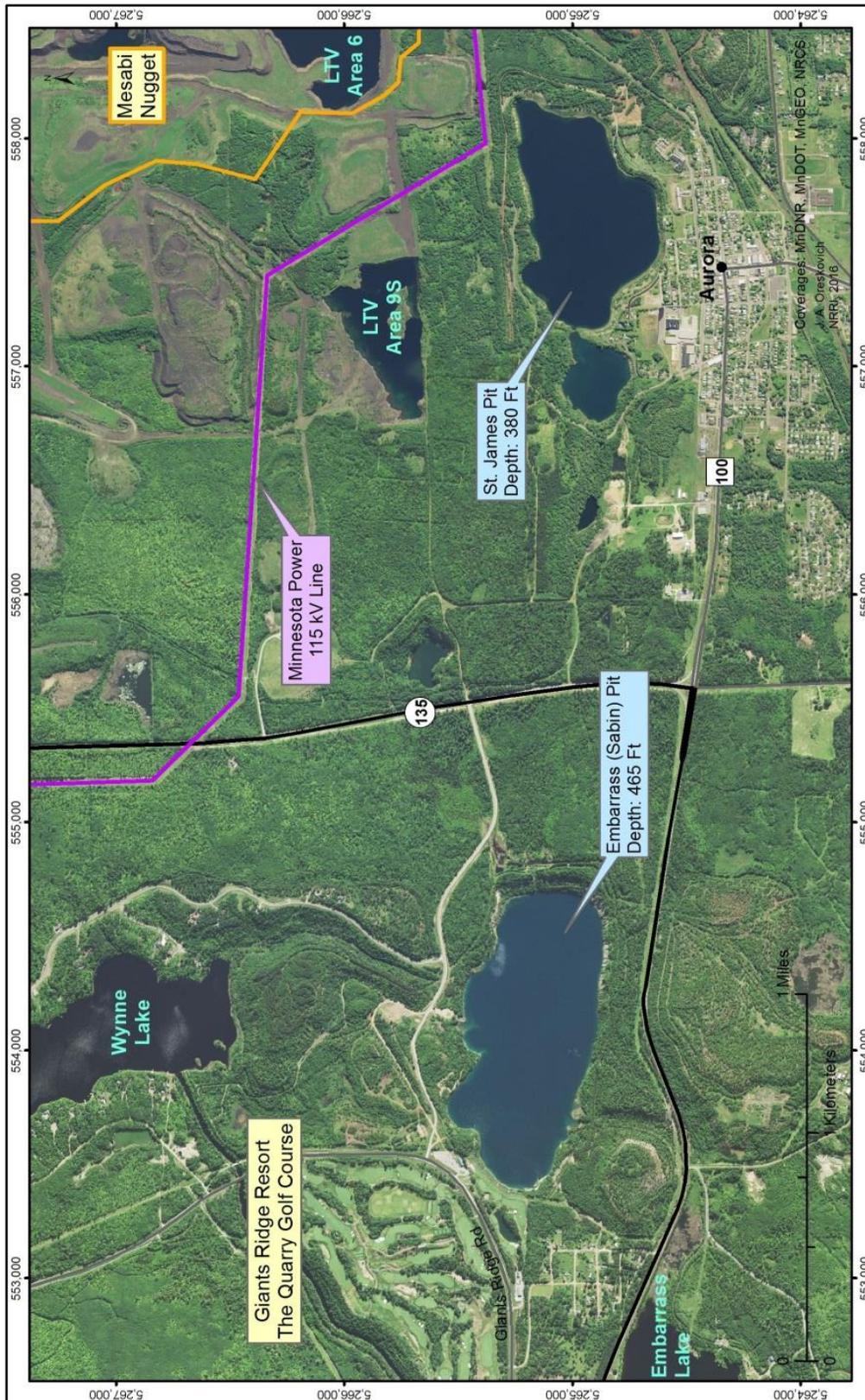
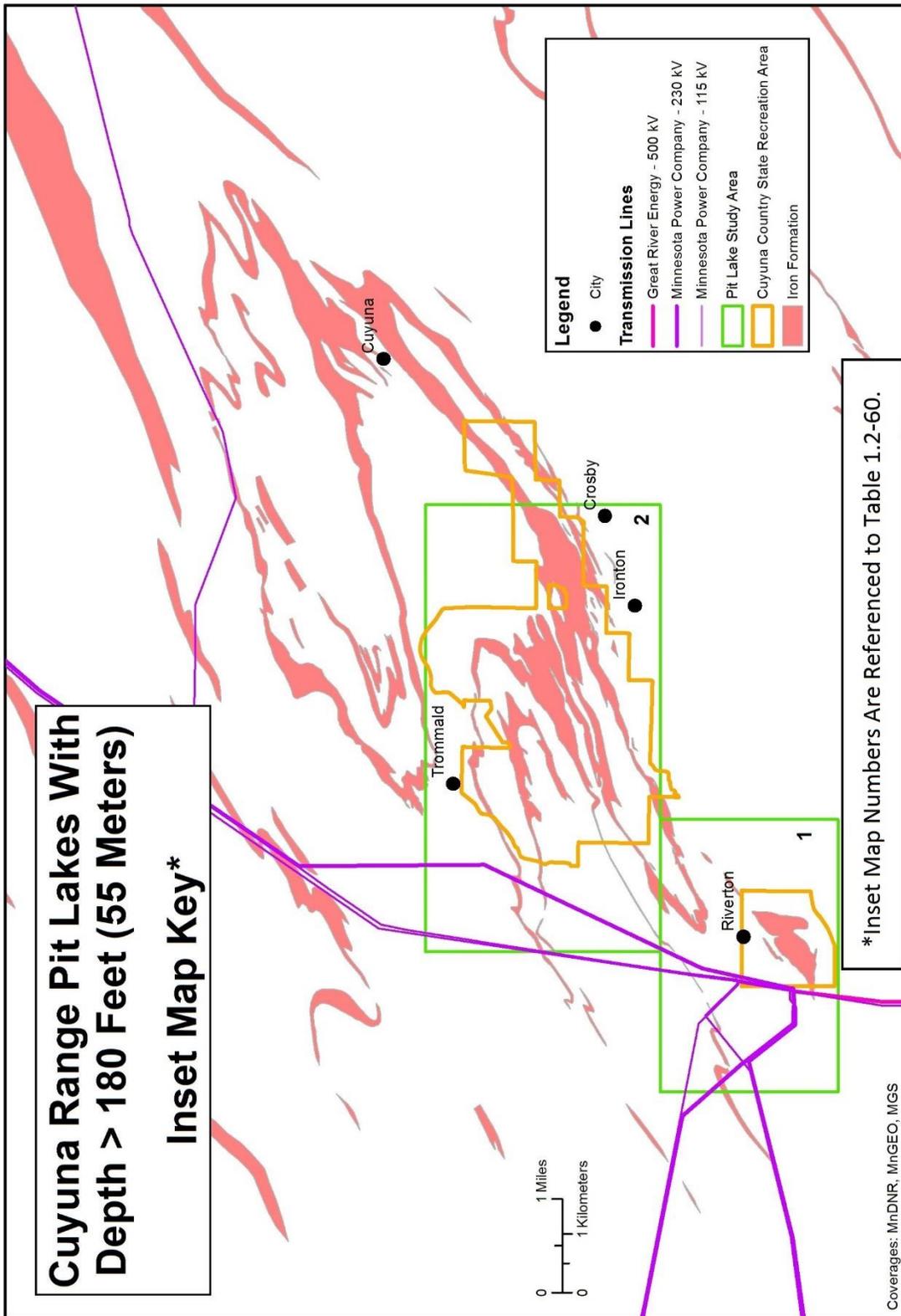


Figure 1.2-114. Inset Map 9: The Embarrass and St. James pits located from east of Biwabik to Aurora.

**CUYUNA RANGE**



**Figure 1.2-115.** Inset map key for Cuyuna Range pit lakes with sufficient depth to host CAES balloon technology.

**Table 1.2-3.** Inset map listing of Cuyuna Range pit lakes with sufficient depth to host CAES balloon technology.

Study Area	Vicinity	Mine Pit Lake	Water Depth (Ft.)	Date (As Of)
1	Riverton Area	Sagamore Pit	210 <sup>1</sup>	2008
2	Cuyuna North Range	Maroco Pit	265 <sup>2</sup>	1992
		Louise Pit	185 <sup>3</sup>	2008
		Mahnomen No. 1 Pit	525 <sup>1</sup>	2010
		Portsmouth	395 <sup>1</sup>	2010
		Feigh Pit	258 <sup>1,2</sup>	2012
		Pennington Pit	259 <sup>1</sup>	2010
		Armour No. 2	210 <sup>3</sup>	2008
Data source: <sup>1</sup> MN DNR Fisheries Survey (year as noted). <sup>2</sup> MN DNR Pit lake bathymetry map (year as noted). <sup>3</sup> Pit map + 2008 LiDAR (surface).				

Cuyuna Range Pit Lake Study Area 1: Riverton Area

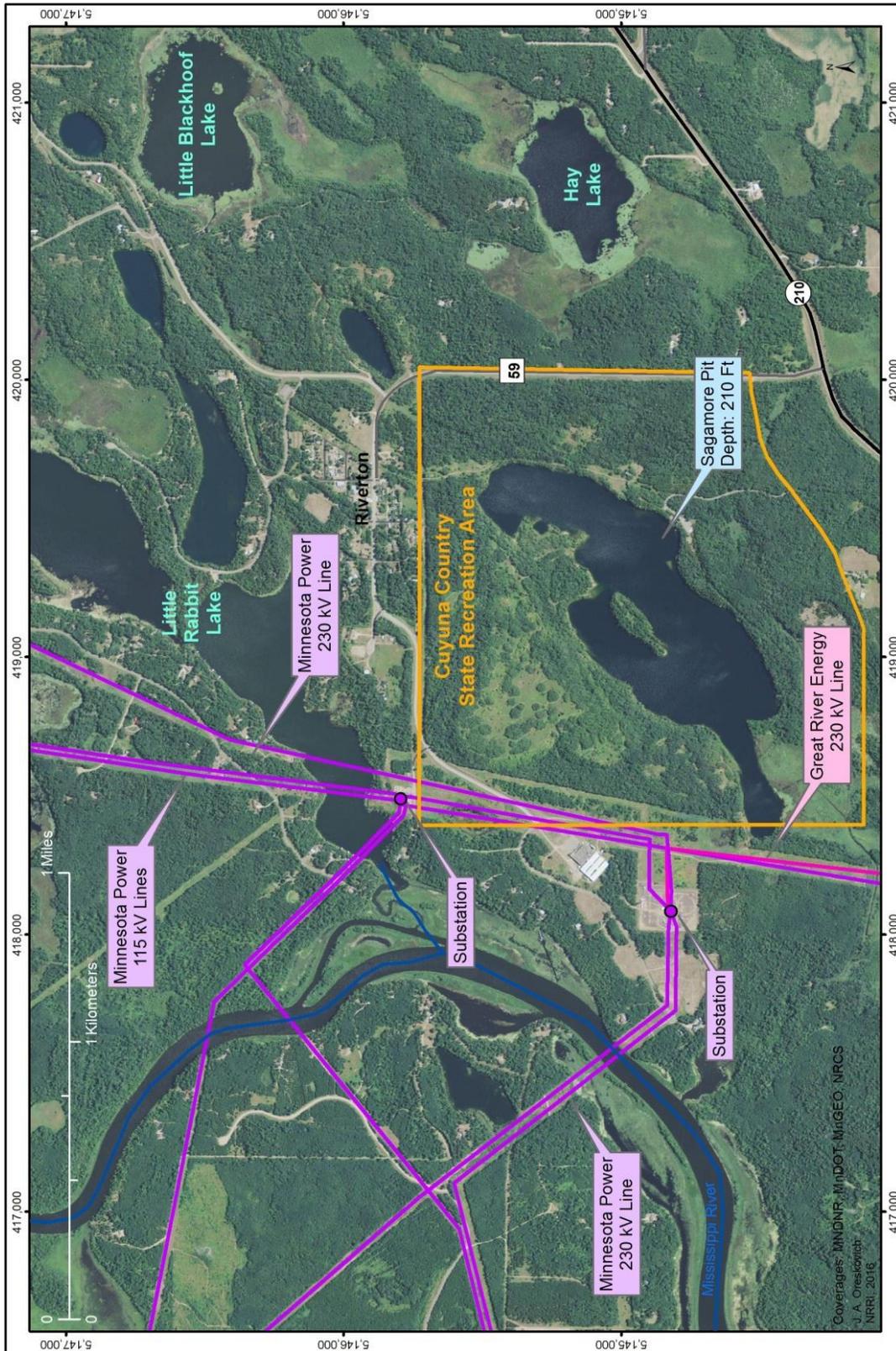


Figure 1.2-116. Cuyuna Inset Map 1: The Sagamore pit at Riverton.

Cuyuna Inset Map 2: Cuyuna North Range

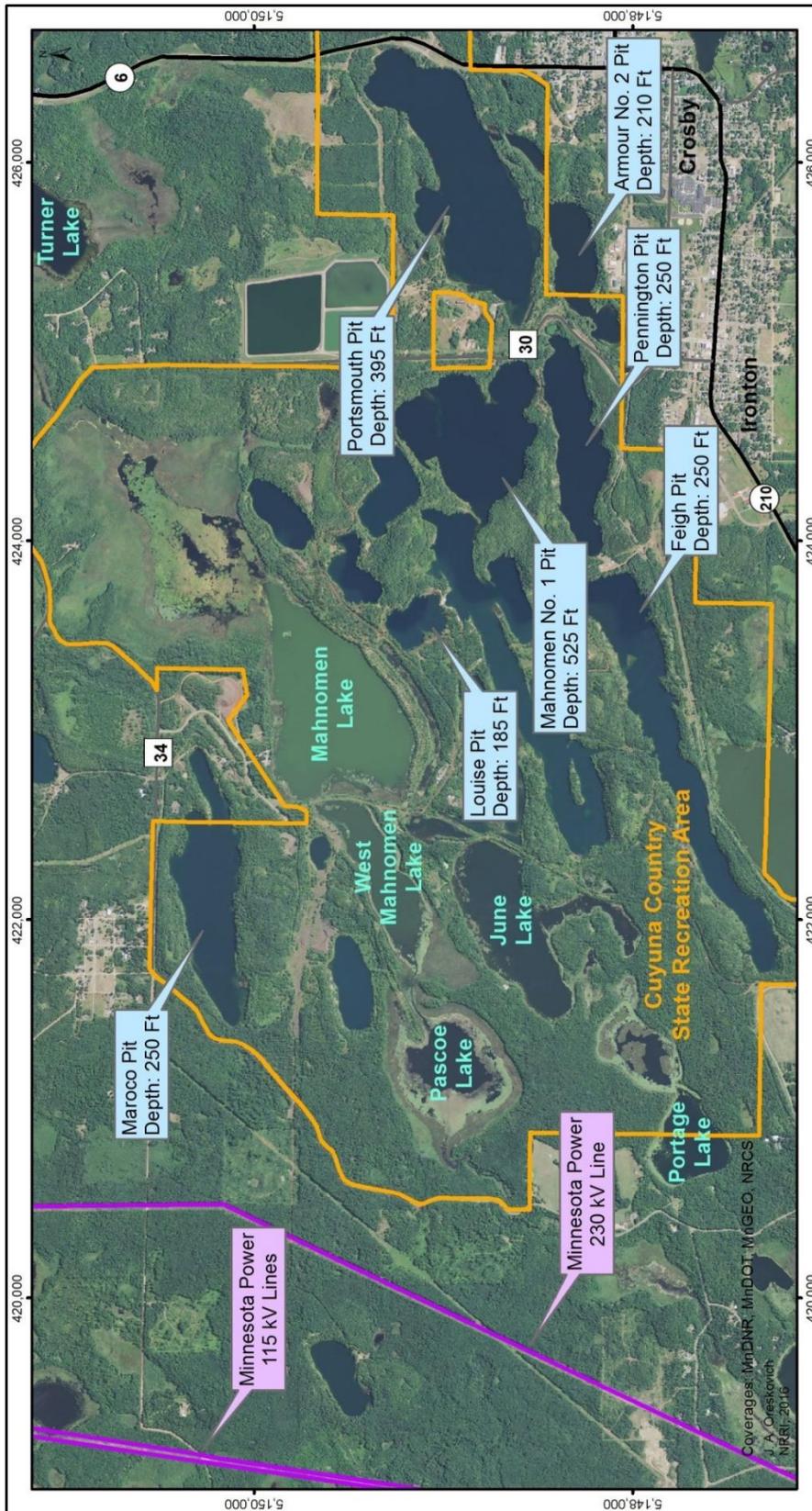


Figure 1.2-117. Cuyuna Inset Map 2: The Maroco, Louise, Mahnomen No. 1, Feigh, Pennington, Armour No. 2, and Portsmouth pits on the Cuyuna North Range.

## DISCUSSION

The underground workings of Minnesota's Cuyuna, Mesabi, and Vermilion iron ranges were reviewed in this course of this study for potential use in CAES. Over two-thirds of the Mesabi Range underground mines had been previously mapped and made available in digital format. Similar mapping work for the Cuyuna Range was undertaken as part of this study. With the exception of the previously mapped Soudan mine, digital mapping of the Vermilion Range remains to be undertaken. Distance from the power grid makes the underground mines of the Vermilion Range unlikely candidates for CAES.

Both the Cuyuna and Mesabi ranges are well positioned with regard to high-voltage electrical transmission lines. The Cuyuna Range is centrally located within the state. It is situated near a hub in the electrical grid, with a 500 kV line (Great River Energy) coming up from the south and 230 kV lines (Minnesota Power) running west and north.

The Mesabi Range, with its high-demand energy requirements from the taconite operations, has two existing and one proposed 500 kV transmission line(s) coming into or passing through the area. Each is operated by one of the three major energy suppliers within the state. The Great River Energy line comes up from the south into the Forbes substation located approximately ten miles south of the mid-Mesabi Range area. Excel Energy's line runs south from Manitoba Hydro in Canada, passing through the central portion of the range and into the Forbes substation. The proposed Minnesota Power Great Northern transmission line will run south from Manitoba Hydro in Canada through the western part of the Mesabi Range near Taconite. In addition, Minnesota Power has 230 kV transmission lines in the immediate area running east-west both north and south of the western two-thirds of the Mesabi Range, as well as one running north-south through the center of the range between Chisholm and Buhl.

### Use of Existing Underground Mine Features for CAES

Two underground mines on the Cuyuna Range, the Armour No. 1 and Armour No. 2, were looked at in depth for CAES purposes. These are two of the three deepest mines on the Cuyuna Range at 800 feet and 580 feet, respectively. The second deepest mine on the Cuyuna Range is the Croft at 630 feet. The Croft mine was not considered for CAES as it is part of the Croft Mine Historical Park that features the mine itself and simulates the underground mining that occurred there.

The five-compartment shafts and lengthy cross-cuts to the orebody employed by both Armour mines could potentially serve CAES purposes but would entail costly engineering. Ideally, the cross-cuts could be isolated from the mined orebody to provide a medium-scale operation. The extensive workings of both mines, however, although caved, would provide significant void volume for CAES if a method were devised to contain the compressed air.

The underground workings from both Armour mines reside beneath pit lakes. The Armour No. 1 mine is located beneath as much as 140 feet of water on its western end in the Pennington pit lake. Pennington pit lake bathymetry was put out by the MN DNR Division of Fish and Wildlife in 1988, with pit lake outlines drawn from 1977 aerial photos. Water depth may have increased since that time.

Armour No. 2 workings that have the greatest potential for CAES are those of Orebody A located in the eastern part of the mine. These workings lie beneath the Armour No. 2 pit lake. The pit was mined prior to the underground workings of Orebody A. Based on 2008 Crow Wing County Lidar data and Armour No. 2 pit map elevation data, the water in the Armour No. 2 pit lake may be as much as 220 feet in depth over the underground workings of Orebody A.

What makes Orebody A attractive is that this isolated orebody was likely mined by stoping methods. Mining occurred on 25-foot intervals above the main 378-foot level to the 253-foot sub-level, and on 30 foot-intervals between the main 582-foot level and the 378-foot level. Stopping would have created large open rooms in hard rock, resulting in large void spaces.

In order to use either of these properties for CAES purposes, some sort of cement capping at pit lake bottom would likely be required. Cofferdams could isolate the eastern portion of the Pennington pit lake—and perhaps the eastern part of the Armour No. 2 pit lake—in order to limit dewatering for construction purposes. Testing for inter-basin connectivity due to mine blasting, unmapped drifting and porous rock layers would be prerequisite to consideration for CAES activities.

The Armour No. 1 mine is located just within the southern boundary of the Cuyuna Country State Recreation Area (CCSRA). Its shaft is located south of the Pennington pit lake and away from the park trails. A low-impact use may be amenable to the park statutes. Orebody A of the Armour No. 2 mine is located outside of the CCSRA boundary. The shaft is accessible from within the Crosby Industrial Park. Although not as deep as the Armour No. 1 mine, location and stoped mine workings may make this the more feasible option of the two.

There are some smaller, shallower, isolated mines on the Cuyuna Range that are located outside of the CCSRA, such as the Northland and Gloria mines on the Cuyuna North Range, that could serve as test cases for small-scale CAES. Other mine workings were identified on the Mesabi Range, including a shaft and cross-cut drifts from the Leonidas mine at 600 foot depth, and the Utica Extension mine shaft and development drifts. Many of the remnant underground mine features on the Mesabi Range are subject to encroachment by expanding taconite operations.

### **Mining Known Ore Reserves to Create CAES Caverns**

In addition to mapping existing underground mine features on the Cuyuna Range, known natural iron ore reserve properties were mapped. These are properties that are held on the Minnesota mineral tax rolls. Ore reserve tonnages and assay data were reported for the reserve properties. Mining an ore reserve yields the potential for creating a CAES cavern to spec while producing a saleable product to offset development costs.

Natural iron ore reserve properties from the Cuyuna North and South ranges and the Emily District were included. Similar ore reserve properties exist on the Mesabi Range, although they were not included in this report. One such property of note is the Carson Lake property west of Hibbing. A shaft was sunk and some development drifting was done on the property, with a small tonnage of ore shipped.

Another potentially mineable resource available to create a CAES cavern to spec is taconite. Several properties across the Mesabi Range hosting probable taconite ore at depths exceeding 1,000 feet were presented in this report. These locations had been identified from available deep

drill holes. The sites are located down-dip, south of what has been defined for years as the southern boundary of the Mesabi Range.

There are several advantages to selection of one of these deep taconite sites. Encroachment from existing taconite operations would be unlikely. These sites are removed from the day to day blasting of taconite rock, an extremely hard rock. The intensity and frequency of blasting across the Mesabi Range can cause fracturing of the country rock. Enclosure in pristine taconite rock at the reported depths would lessen the amount of secondary containment need to store compressed air at the pressures required.

### **Use of Deep Mine Pits for the “Accumulator” Method of CAES**

Depths for mine pit lakes across the Cuyuna and Mesabi Ranges were determined in order to identify those exceeding 180 feet, the depth of a pilot operation currently being conducted in Lake Ontario in Toronto, Canada. A promising new technology has been developed using balloon “accumulators” attached to the lake bed for CAES. The accumulators are expanded with compressed air via current CAES technology, while the hydrostatic pressure of the water drives the compressed air on demand back into the system to drive a turbine.

Twenty-five pit lakes on the Mesabi Range and eight pit lakes on the Cuyuna Range were identified as meeting the 180-foot depth criteria. They have been presented in this report. If this technology proves viable and scalable as theorized, mine pit lakes may prove well-suited as hosts. Their depths could minimize impacts to surface recreational use, allowing for co-existence even within a high-use area such as the CCSRA on the Cuyuna Range.

## **CONCLUSIONS**

Use of existing underground mine features for CAES, while technically doable, would likely prove cost-prohibitive due to investigative, dewatering, isolation, capping, and containment needs. This doesn't even take into consideration the environmental impacts and effects on surrounding water bodies due to interconnectivity from blasting, drifting, and porous rock layers. Preliminary work would be substantial in comparison to that required for the two other mine-related CAES methods discussed above.

Mining a saleable ore product to generate a CAES cavern to spec is a viable option worth pursuing. This holds promise for large-scale CAES operations. In particular, the depths at which taconite ore could be mined would serve best for containment of the high pressures required per open volume area in a large-scale CAES.

Finally, for small to medium size CAES operations, use of pit lakes to host the accumulator technology, when proven, will likely prove to be the most cost-effective, as well the most environmentally benign CAES method of those studied herein. Probable co-existence in pit lakes with those activities currently enjoyed there makes the accumulator method potentially the least disruptive CAES method. Additionally, the accumulator CAES method has the added benefit of being “green,” a fitting attribute to complement the concept of energy storage.

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## **Appendix 1.2-A**

### **North Cuyuna Range Geologic Column (Details of Biwabik Formation)<sup>1</sup>**

This is a reprint of the geologic column developed by Grout and Wolff (1955) that appears on p. 56-57). While the relationship of North Cuyuna Range stratigraphy to that of the Biwabik Formation has been revised with time, Grout and Wolff (1955) provide a quick reference to the beds found in each of the Cuyuna North Range mines and their placement in the stratigraphic sequence.

<sup>1</sup>Grout, F.F., and Wolff, J.F., Sr., 1955, The geology of the Cuyuna District, Minnesota: A progress report: Minnesota Geological Survey, Bulletin 36, 144 p.

<b>NORTH CUYUNA RANGE GEOLOGIC COLUMN<sup>1</sup></b>		
<b>Formation and Beds</b>	<b>Thickness in Ft.</b>	<b>Orebody Showing These Formations &amp; Beds</b>
VIRGINIA FORMATION	5000 +	(South Range member, thin beds)
BIWABIK FORMATION		
<b>UPPER SLATY MEMBER</b>		
Manganiferous slaty iron-formation	200-350*	Armour No. 2, Ironton, Thompson, Meacham, Croft, Manuel
Banded thin-bedded cherty iron-formation	175-400*	
Gray slate or schist <sup>†</sup>	330-330	Armour-Croft Group
Evenly banded thin-bedded cherty iron-formation	180-250*	Armour No. 1, Pennington, Feigh, Huntington, Martin, South Hillcrest, Portsmouth, Kennedy, Yawkey
Sericitic and graphitic slates	50-50	Rabbit Lake, Mallen
Manganiferous carbonate slate	150-185	Portsmouth, Yawkey, Mahnomen No. 1, Mangan No. 2, T. 137 N., R. 26 W.?
Banded iron-formation	150-175	Mahnomen Group, Mangan No. 2, Louise and Portsmouth. Milford, Northland?
Gray siliceous slate with quartzite lenses	80-80	
Green manganiferous carbonate slate with cherty bands	210-250	Louise-Alstead Group, Hopkins, Arko, Sultana, Sagamore, Northland?
Green siliceous slate with lenses of quartzite and graywacke	170-230	Louise, Hopkins, Sultana, North Hillcrest
Subtotal, Upper Slaty Member	1695-2300	
<b>UPPER CHERTY MEMBER</b>		
Granular and banded cherty taconite with black manganiferous iron ores	80-165	Joan, Mangan No. 1, Louise, Hopkins, Sultana, Merritt Group, Gloria, Preston, Hunter, Pontiac
<b>LOWER SLATY MEMBER</b>		
Fine-banded pink taconite slaty iron-formation	40-140	
Dark green and gray manganiferous slaty carbonate iron-formation	115-115	
Dark green and gray magnetic and manganiferous green slaty-carbonate iron-formation	115-115	Mahnomen Lake, Virginia, Maroco, Section 6, Rowe, Merritt Group, Ruth Lake Group
Black magnetic slaty iron-formation	80-80	
Quartzitic graywacke	20-20	
Grey slate, graywacke and thin quartzite lenses	330-380 <sup>††</sup>	
Subtotal, Lower Slaty Member	700-750	

<b>NORTH CUYUNA RANGE GEOLOGIC COLUMN<sup>1</sup></b>		
<b>Formation and Beds</b>	<b>Thickness in Ft.</b>	<b>Orebodies Showing These Formations &amp; Beds</b>
<b>LOWER CHERTY MEMBER</b>		
Lean chert	15-25	
Granular and banded cherty taconite	70-180	
Granular manganiferous cherty taconite	10-30	Maroco, Section 6, Rowe, Ruth Lake Group
Slaty manganiferous taconite	3-10	
Contorted jaspery chert (algal) and conglomerate	2-5	
Subtotal, Lower Cherty Member	100-250 <sup>**</sup>	
Total thickness, iron formation	2575-3465	
<b>Underlying POKEGAMA FORMATION</b>		
Quartzite and quartz slates	350 or more	Maroco, Section 6, Rowe, Sagamore, Emily and Ruth Lake areas
-----	<b>(Unconformity)</b>	-----
<b>Probably EARLIER PRECAMBRIAN</b>		
Dense limestone and chert (dolomitic?)	250 or more	T. 137 and 138 N., R. 26 and 27 W.
-----	<b>(Unconformity)</b>	-----
<b>Probably ARCHEAN</b>		
Green schists (pyritiferous)	?	Sections 5 and 6, T. 46 N., R. 29 W., Section 32, T. 47 N., R. 29 W.
<sup>1</sup> Modified from Grout & Wolff (1955).		
<sup>*</sup> Wide range of thickness may result from igneous intrusives.		
<sup>*</sup> See p. 65-67 of Grout and Wolff (1955).		
<sup>**</sup> Thicknesses may have been exaggerated by folding.		

**Appendix 1.2-B**

**[CuyunaRange\\_UndergroundMineWorkings.xlsx](#)**

(Excel file available by clicking the link above;  
file is also on DVD in back pocket of paper copies of this report.)

**CuyunaRange\_UndergroundMineWorkings.xlsx Header Definitions**

Mine:	Mine name
SourceNo	Number assigned to source document/map
Former Name:	Previous names for the mine
Later Name:	Subsequent mine name
Range:	Iron Range (North Range, South Range)
S:	Section
T:	Township (North)
R:	Range (West)
Forty:	Parcel(s)
UG:	Underground Mine
OP:	Open Pit Mine
ML:	Milling Operation
ShaftSinking:	Date of shaft sinking
1st_Opened:	Date first operated (may be date of shaft sinking)
1stShp_UG:	Date of first ore shipment from underground workings
LastShp_UG:	Date of last ore shipment from underground workings
OreShppd_UG:	Total long tons of ore shipped from underground workings
1stStrip:	Date of first stripping operations from open pit mining
1stShp_OP:	Date of first ore shipment from open pit operations
LastShp_OP:	Date of last ore shipment from open pit operations
OreShppd_OP:	Total long tons of ore shipped from open pit operations
1stML:	Start date of milling operations
1stShp_ML:	Date of first ore shipment from milling operations
LastShp_ML:	Date of last ore shipment from millings operations
OreShpd_ML:	Total long tons of ore shipped from milling operations
1stShp_Stkpl:	Date of first ore shipment from stockpile
LastShp_Stkpl:	Date of last ore shipment from stockpile
OreShppd_Stkpl:	Total long tons of ore shipped from stockpile
Total_Ore_Shipped:	Total long tons of ore shipped from underground, open pit, milling and stockpile combined
Oper1:	First mine operator
Oper1_Date:	Dates of operation under first mine operator
Oper2:	Second mine operator
Oper2_Date:	Dates of operation under second mine operator
Oper3:	Third mine operator
Oper3_Date:	Dates of operation under third mine operator
LastOperator:	Last known mine operator
LastKnownFee:	Last known fee holder of the mine property
Top Level:	Highest level mined as determined from maps or literature
Main Level:	Main haulage levels, typically cross-cuts from shaft
Lowest Level:	Lowest level, typically a haulage level, as determined from maps or literature

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Depth:	Depth (in feet) of shaft or known mine workings
Shafts:	Number of mine shafts as determined from maps or literature
Mshaft:	Number of main shafts
Mshaft_Type:	Main shaft type, including shape, construction material, number of compartments
Mshaft_Shape:	Main shaft dimensions
Mshaft_Loc:	Main shaft location reference re rock type, rock formation, hanging wall or foot wall
Mshaft_FT:	Main shaft depth as determined from maps or reported in literature
Overburden_FT:	Overburden (surface) thickness in feet
XCutLevel_FT:	Depth of crosscut level in feet
XCutLength_FT:	Length of crosscut from shaft to orebody in feet
OreWidth_FT:	Width of orebody at crosscut level in feet
Tshaft1_FT:	Depth of No. 1 timber shaft in feet
UG_Method:	Underground mining method employed
OP_Method:	Open pit mining method employed
Formation:	Rock formation mined
Facies:	Reference to location in Schmidt's (1963) thin-bedded or thick-bedded facies
Orebody_Strike:	Strike of orebody
Orebody_Dip:	Dip of orebody
Notes:	Notes of interest from source document
SourceMap:	Title of map used as source document
OreType1:	Source document-defined ore type for the mine
OreType2:	A second source document-defined ore type for the mine
OreType3:	A third source document-defined ore type for the mine
OreType4:	A fourth source document-defined ore type for the mine
OreType5:	A fifth source document-defined ore type for the mine
OreType6:	A sixth source document-defined ore type for the mine
ManganOre:	Presence of mangiferous ore as determined from source document
OreResEst:	Year(s) for which MDOR tax reserve estimates were made
Source:	Data source for the information provided
Page:	Page number within the data source from which information was obtained
AdditionalNotes:	Additional information acquired from the data source, often quoted directly

**CuyunaRange\_UndergroundMineWorkings.xlsx Source Documents**

1. Beltrame, R.J., 1977, Directory of Information on Cuyuna Range Geology and Mining: Minnesota Geological Survey, Information Circular 13, 52 p.
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13. Harder, E.C., and Johnston, A.W., 1918, Preliminary report on the geology of east-central Minnesota, including the Cuyuna iron-ore district: Minnesota Geological Survey, Bulletin 15, 178 p.
14. HIL22DRPIT01 (1922 Hillcrest Mine Map)
15. [http://www.mnhs.org/shpo/nrhp/docs\\_pdfs/0006\\_milfordmine.pdf](http://www.mnhs.org/shpo/nrhp/docs_pdfs/0006_milfordmine.pdf)
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22. 1918 Mine Map, Dept. of Revenue
23. National Register of Historic Places Registration Form, 2011, Milford Mine Historic District, retrieved from <http://crowwing.us/DocumentCenter/Home/View/115>, 09/25/14.
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  29. The Iron Trade Review, 1916a, Iron Range developments in 1915: The Penton Publishing Co., Cleveland, OH, v. 58, p. 81-92.
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### **Appendix 1.2-C**

#### **[Underground mine workings of the Cuyuna Range in shapefile and geodatabase format](#)**

(Appendix 1.2-C files available by clicking the link above;  
files are also available on DVD in back pocket of paper copies of this report.)

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### GIS Coverages of Cuyuna Range Underground Mining Features

GIS coverages of the Cuyuna Range underground mining features that were developed and used in the course of this study are included, with metadata, on DVD with this report. The coverages were developed in Esri® ArcMap™ 10.1. Coverages are provided in both shape file and geodatabase format.

#### Shape Files:

1. cuyuna\_underground\_driftsln.shp (mine drifts as polylines);
2. cuyuna\_underground\_minedextentspy.shp (mined extents as polygons);
3. cuyuna\_underground\_shaftspt.shp (mine shafts as points);
4. cuyuna\_underground\_minespy.shp (all shafts, drifts and mined extents as polygons);  
and
5. cuyuna\_underground\_mineproperties.shp (mine and ore reserve parcels as polygons).

#### File Geodatabase:

fgdb\_cuyuna\_undergroundmines (cuyuna\_undergroundmines.gdb)

#### with feature classes:

1. drifts (mine drifts as polylines);
2. minedextents (mined extents as polygons);
3. shafts (mine shafts as points);
4. mines (all shafts, drifts and mined extents as polygons); and
5. mineproperties (mine and ore reserve parcels as polygons).

**Appendix 1.2-D**

**[Mine maps of Cuyuna Range underground mines](#)**

(Appendix 1.2-D files are available by clicking the link above; files are also available on DVD in back pocket of paper copies of this report.)

**Appendix 1.2-E**

**[Geo-rectified mine maps of Cuyuna Range underground mines in JP2 or TIFF format](#)**

(Appendix 1.2-E files are available by clicking the link above;  
files are also available on DVD in back pocket of paper copies of this report.)

**Appendix 1.2-F**

**Selected Bibliography of Cuyuna Range Mining and Geology**

Hauck, S.A. and Oreskovich, J.A.

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### Selected Bibliography of Cuyuna Range Mining and Geology

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**CHAPTER 2:****GEOTECHNICAL ENGINEERING CONSIDERATIONS FOR COMPRESSED AIR ENERGY STORAGE (CAES) IN NORTHERN MINNESOTA USING UNDERGROUND MINE WORKINGS****Geotechnical Engineering Team**

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Synopsis

CAES plants compress air when there is an excess of electric energy production and generates electric energy using a turbine when the demand exceeds the production.

A literature review shows the existence of operating CAES plants in the U.S. and Germany and planned CAES plants that for adverse geotechnical or economic reasons were never built. A comprehensive report by Succar and Williams (2008) provides the background theoretical basis for designing air storage capacity and storage pressure for CAES plants.

This theoretical basis has been used to make a preliminary estimation of underground air storage requirements for a CAES plant in northern Minnesota. A preliminary analysis shows that existing (abandoned) mining shafts and drifts alone in the Iron Ranges of Minnesota would not provide enough air storage capacity for the initially envisioned energy production of 100 MW sustained for 10 hours. The air storage capacity would need to be complemented with new caverns built with that purpose. Additional geotechnical considerations for constructing and operating the caverns are examined.

**Section 2.0:  
Introduction**

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## **INTRODUCTION**

This report summarizes the work done to address some key questions related to geotechnical aspects of the system, in particular, size and shape of required underground cavities, and re-use of existing mine workings in northern Minnesota. The report is structured in four sections. After this introduction, Section 2.1 presents a literature review of CAES systems (with focus on geotechnical engineering aspects of the system) and also includes a brief technical description of existing and planned CAES plants as found in published literature. Section 2.2 outlines the main considerations to take into account for designing underground excavations for CAES plants. Finally, Section 2.3 includes a set of three PowerPoint presentations on various topics (mostly with a geotechnical engineering focus) that have been developed as part of the project, to present advances of the research and promoting discussions within the team during the scheduled meetings for the project. This information is supplemental to information developed by other Teams involved with this study.

**Section 2.1:  
Literature Review of CAES Systems with  
Focus on Geotechnical Engineering Aspects**

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A CAES plant compresses air when there is an excess of electric energy production in the grid and generates electric energy using a turbine when the demand exceeds the production. The storage of compressed air to produce energy in this way is typically done in underground chambers, which could be existing cavities, e.g., mining rooms, drifts, and shafts, or cavities created with this specific purpose, e.g., in salt formations, new cavities can be relatively easily created by dissolution, although the dissolution process can last for more than a year.

According to Cavallo (2007), the air storage needs not only depend on the pressure of the air to be stored, but also on the power of the plant and the amount of time the compressed air will be expanded, i.e., circulating through turbines, and generating electricity. Cavallo (2007) mentions 200 MW of power for a CAES plant as a reasonable target to achieve, and although he does not mention the lapse of time this power is to be maintained, i.e., the energy to be produced, nor the pressure at which the air will stored, he indicates a rough value of air storage need as being 1,000,000 m<sup>3</sup> for a 200 MW target plant.

In terms of the pressure at which the air is to be stored, Li et al. (n.d.) mentions the value of 7 MPa (or 70 bar [1015 psi]) as a value to consider.

According to Denholm and Sioshansi (2009), who have studied the CAES systems from an economical point of view mainly, air storage capacity should be such to be able to maintain discharge for 20 hours at nominal power, i.e., basically the longest possible throughout a day. Also, considering that less time is needed to charge than to discharge the air (the authors mention a typical charge-discharge ratio of 0.72), Denholm and Sioshansi (2009) recommend using a series of small air compressors to get more flexibility in the use of excess of energy that drives the compressors and so to optimize this excess energy and have less idle lapses in the production of energy by CAES.

Succar and Williams (2008) present a comprehensive treatment of the CAES system. The report by Succar and Williams not only addresses critically important factors to account in the design of CAES system but also presents a review of existing and planned CAES plants. In what follows, the description of actual and planned CAES plants, as outlined in their publication, will be summarized first, followed by the technical considerations presented in their report.

Succar and Williams (2008) describe first the two existing (functional) CAES plants: 1) the Huntorf power plant, near Bremen, Germany; and 2) the McIntosh power plant in McIntosh, Alabama.

The Huntorf plant has been operating since 1978. Originally designed to generate 290 MW, the capacity was increased in 2006 to generate 321 MW of electricity. The plant is capable of sustaining that power for three hours by storing air in two cavities with a total storage volume of 310,000 m<sup>3</sup>. The cavities were excavated by dissolution method in a salt formation. The cavities do not have lining ('rock salt', or halite, is a rock that creeps in time, and so an ideal self-sealing, basically impermeable rock to host compressed air without the need of lining). The working pressure of the air stored in the chambers varies from 66 to 48 bar (957 psi to 696 psi [6.6 to 4.8 MPa]). The turbine that generates electricity works at 46 bars (667 psi), so the stored air pressure has to be throttled to this pressure (2 bars of air pressure is mentioned to be lost in throttle and pipes). The report by Succar and Williams (2008) also mentions that in the first years of operation of the plant, the air reacted with the salt in the cavity and oxidized the piping; this resulted in the

need of replacing the original metal pipes in the plant (those in contact with the compressed air) by fiber-glass reinforced plastic pipes.

The McIntosh power plant in McIntosh, Alabama, has been operating since 1991 and is reported to produce 110 MW of electricity. The plant is capable of sustaining that power for 26 hours by storing air in a single chamber of 560,000 m<sup>3</sup> (as in the case of the Huntorf plant, the chamber was excavated in a salt formation by the dissolution method, and it does not have lining). The working pressure of the air stored in the chamber varies from 74 to 45 bar (1,073 psi to 653 psi [7.4 to 4.5 MPa]).

Succar and Williams (2008) also describe two planned CAES plants that have not been built: 1) the Norton CAES plant, in Norton, Ohio; and 2) the Iowa Stored Energy Park, northwest of Des Moines, Iowa.

The Norton CAES plant in Ohio is planned to produce 2,700 MW of electricity, after final expansion. In contrast with the Huntorf and McIntosh plants, an abandoned limestone mine (that was excavated using room and pillar method) will be used to store 9,600,000 m<sup>3</sup> of compressed air. The working air pressure ranges between 110 and 55 bars (1,595 psi to 798 psi [11 and 5.5 MPa]). The construction of the project (owned by First Energy since 2009) is being delayed due to economic reasons. Current low power prices and insufficient demand are mentioned as the causes of the delay in construction.

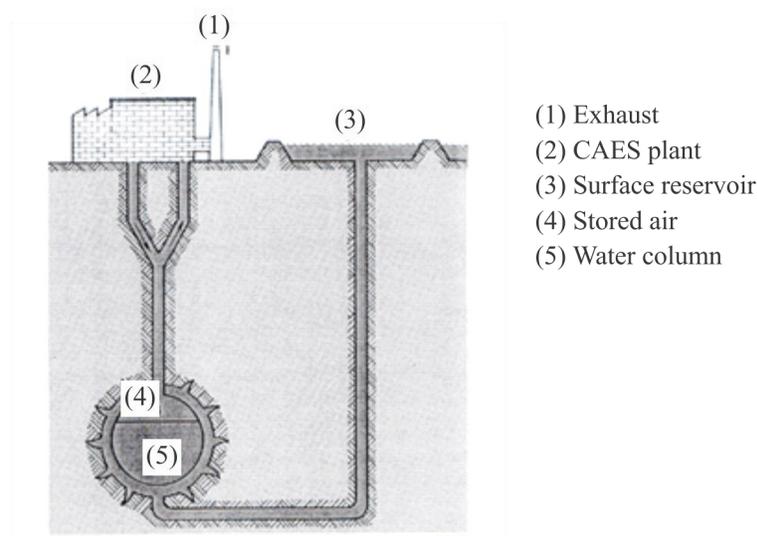
The Iowa Stored Energy Park was planned to produce 268 MW of electricity. The compressed air was to be stored in an aquifer in porous rock. It was originally planned to be finished and to start operation in 2011. The project was halted during the phase of design. A publication by Schulte et al. (2012) summarizes the eight-year development of the Iowa Stored Energy Park project and discusses in detail the reasons of the failure of the project. They mention that after many field surveys and after spending considerable amount of money in air injection in-situ testing, it was determined that the porous rock did not have the required permeability to properly transmit the compressed air within the aquifer. Due to this, and due to the lack of an alternative suitable location for the air storage, the project was terminated.

A report by Rettberg and Holridge (2012) describe another case of a failed CAES project. This project, known as Seneca Lake CAES project near Watkins Glen, New York, was planned to produce between 130 and 210 MW of electricity using a cavern in a salt formation (mined by dissolution) with a storage capacity of 150,000 m<sup>3</sup>. The range of air pressure was initially considered to vary from 100 to 50 bars (1,450 psi to 725 psi [10 to 5 MPa]) for a period of discharge time of 10 to 12 hours (the charging period was designed to be 8 hours). The system was designed to complete 260 (charge/discharge) cycles per year. Preliminary thermodynamic and geomechanical studies showed that the difference in pressure would produce a change of temperature during charge/discharge cycles of 45°C, with temperatures on the walls of the cavity ranging between 60°C (or 140°F) and 15°C (or 60°F). This high change in temperature was expected to produce spalling of the walls of the cavern (deterioration of the rock due to repeated change from compression to tension), and therefore significant modifications of the original design had to be implemented. Among them, the limiting operating pressures were changed to 100 to 80 bars (1,450 psi to 1,160 psi [10 to 8 MPa]), maintaining the original planned size of the cavern (for the rock conditions, the volume of 150,000 m<sup>3</sup> was established to be the maximum volume possible). The reduction in differences in pressure and the maximum size of a cavern dictated an increase in the total storage of air needed to produce the target energy for the plant.

This increase resulted in the need to construct two additional caverns, each of them with the originally planned total volume of 150,000 m<sup>3</sup>, i.e., air storage requirements tripled in the revised design. The radical changes in the design resulted in a significant increase in the cost for building the plant, making the CAES plant economically unfeasible.

The comprehensive report by Succar and Williams (2008) discusses in depth the technical requirements of air storage for a CAES plant; in particular, the report presents equations and diagrams from where volumes of air storage can be computed as a function of the energy to generate, and as a function of the working pressure of the air. The capacity of air storage depends on the mode in which the air will be stored and retrieved, and the pressure at which the air will enter the turbine. In terms of the pressure at which air will be stored, two possibilities exist: 1) constant pressure storage; and 2) constant volume storage.

In the constant pressure storage (or constant cavern pressure) option, the air in the chamber is compressed by hydrostatic pressure from a water reservoir located on the surface. To get the target working pressure, the depth of the chamber is chosen so as to get the correct hydrostatic pressure to compress the air. Figure 2.1-1 illustrates the concept. Succar and Williams (2008) mention that one of the problems to address in the constant pressure scheme is the avoidance of the ‘champagne effect’ by which water could raise through the reservoir shaft and lead to unstable loss of head and blowout of the cavern (Giramonti et al., 1978). The case of constant pressure storage described above is also referred to as Case 1 later in this report.



**Figure 2.1-1.** Constant pressure CAES storage with surface reservoir and compensating water column (after Succar and Williams, 2008).

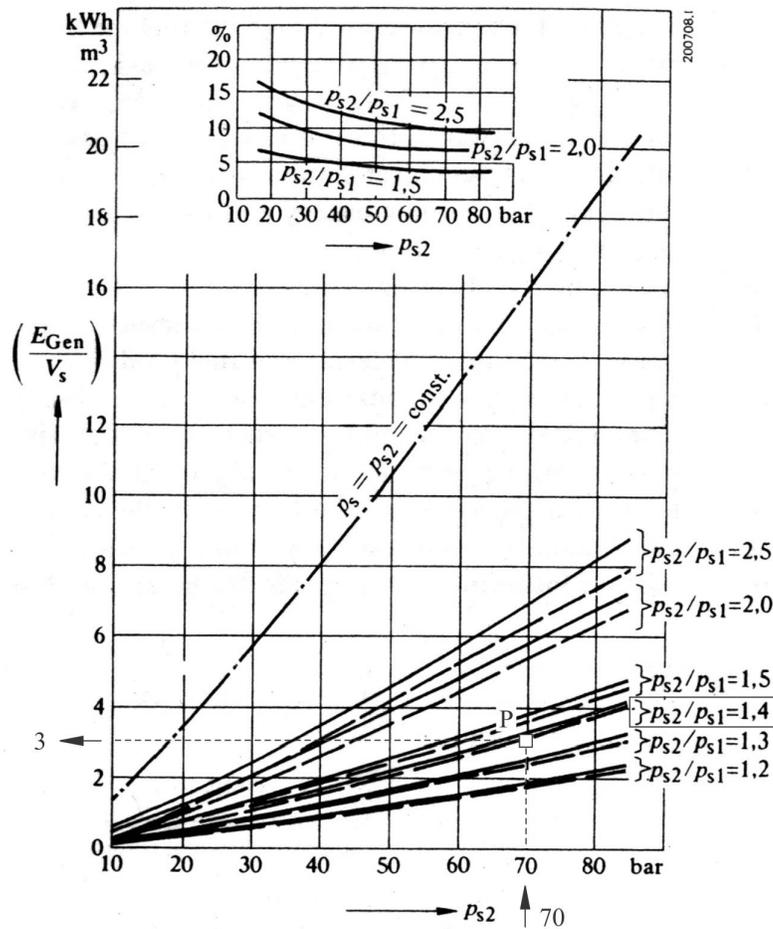
In the constant volume storage (or variable cavern pressure) option, the pressure of the air falls during extraction from the chamber. This pressure-decreasing air can be input into the turbine directly, i.e., using a variable-pressure turbine, or, otherwise, throttled to the working pressure of a (constant-pressure) turbine. These two possibilities are referred to as Cases 2 and 3, respectively, in the text below.

Of the two options described above, the first one (constant cavern pressure) requires less volume of air storage than the first one (variable cavern pressure). Nevertheless, the second option is ‘more flexible’ than the first, in that it does not require a reservoir on the surface nor a specific depth of the chamber in relation to the reservoir. This condition may be the reason why existing and planned CAES systems described earlier on, favored the use of the second option, i.e., these plants do not use a water reservoir to maintain a constant pressure of the air within the caverns.

Succar and Williams (2008) present equations to compute the storage volume requirements. They distinguish three cases, namely: Case 1, corresponding to constant pressure storage option; Case 2, corresponding to the constant volume storage option and variable turbine inlet pressure; and Case 3, also corresponding to constant volume storage, but considering a constant turbine inlet pressure. The results from these equations are summarized in the diagram of Figure 2.1-2.

In the diagram of Figure 2.1-2, the horizontal axis represents the maximum pressure of the air (in bars) at which the storage chamber will operate, while the vertical axis represents the so-called density of energy, which is the amount of stored energy (in kWh) per unit of storage volume (in m<sup>3</sup>). As discussed earlier, there are three cases of operation of the plant, i.e., Cases 1, 2, and 3, and these are represented by curves with different lines in the diagram, namely, dash-dot-dash line for Case 1 (upper most line in the diagram), continuous line for Case 2, and dashed line for Case 3. The curves for Cases 2 and 3 are grouped into pairs corresponding to the ratio of initial-to-final pressure during operation, i.e., the ratio  $p_{s2}$  and  $p_{s1}$ . It is seen from the diagram that the amount of density of energy provided by Case 2 is slightly larger than that for Case 3. The inset diagram on top of the main diagram in Figure 2.1-2 represents the loss of energy (in percent) for Case 3 as compared with Case 2. From this diagram it is seen, in particular, that the throttling losses become relatively small, e.g., below 10%, for large values of initial pressures, e.g.,  $p_{s2} > 60$  bar. Because the penalty for not throttling the pressure in Case 2 is offset by the benefits of higher turbine efficiency and simplified system operation in Case 3, it is more beneficial to operate a CAES plant as in Case 3, i.e., using constant turbine inlet pressure, as exemplified by the Huntorf and McIntosh plants, both of which use this mode of operation.

To illustrate the use of the diagram in Figure 2.1-2, an example is presented in the lower right corner of the figure. The objective of the example is to show how the capacity of storage can be simply obtained from the diagram for a proposed CAES plant when the power of the plant, the time the power will be sustained, the working pressures, and whether a variable turbine inlet pressure (Case 2) or a constant turbine inlet pressure (Case 3), are known.



$E_{Gen}$  = Generator energy  
 $V_s$  = Storage volume  
 $p_{s2}$  = Upper storage pressure  
 $p_{s1}$  = Lower storage pressure  
 - - - - - = Reservoir, case 1  
 ————— = Reservoir, case 2  
 - - - - - = Reservoir, case 3  
 $T_{EHD} = 825 \text{ }^\circ\text{K}$ ,  $T_{END} = 1100 \text{ }^\circ\text{K}$

Example:

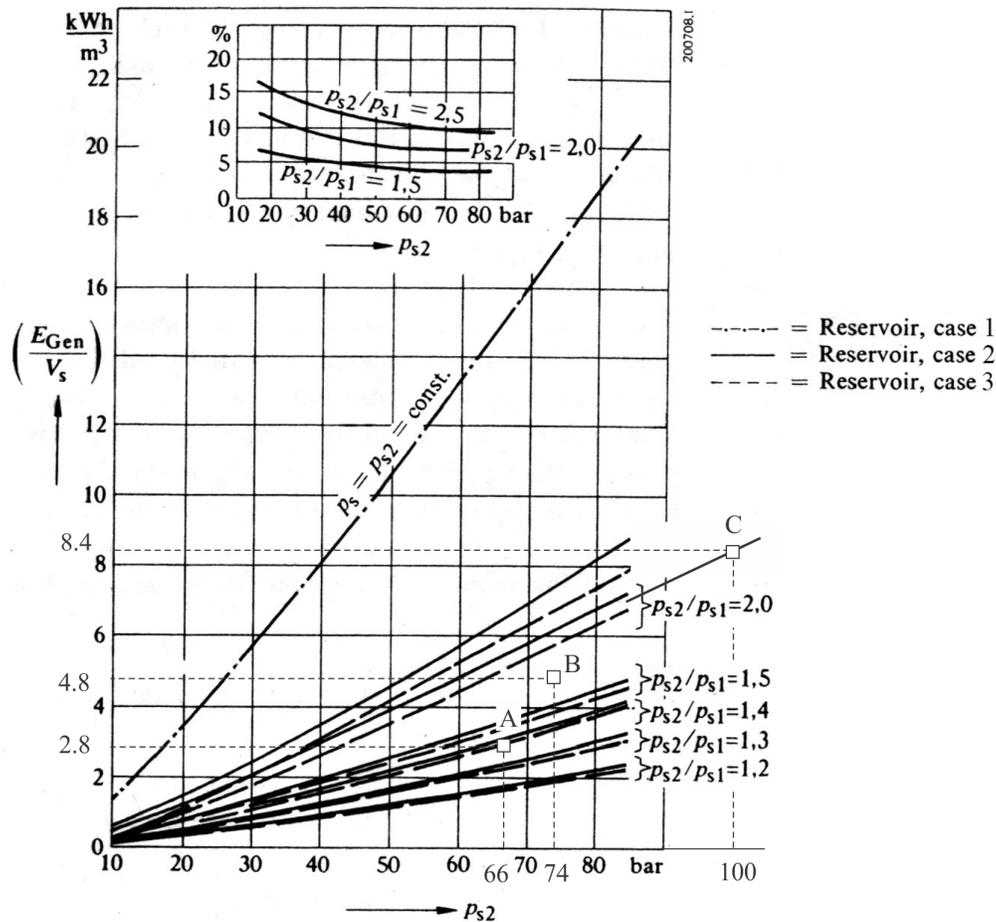
Proposed CAES plant will generate 100 MW operating for 5 hours (i.e., produced energy will be  $E_{gen} = 500,000 \text{ kWh}$ ). Constant turbine inlet pressure will be used (Case 3); maximum pressure  $p_{s2}$  will be 70 bar (7 MPa); minimum pressure  $p_{s1}$  will be 50 bar (5 MPa), i.e.,  $p_{s2}/p_{s1} = 1.4$ . From the diagram,  $E_{gen} / V = 3$  (see Point P). Therefore the required storage volume results to be  $V = E_{gen} / 3 = 166,667 \text{ m}^3$ .

**Figure 2.1-2.** Diagram summarizing the relationship between generated energy, storage volume, upper and lower storage pressure and operation case (Cases 1, 2, or 3) described in the main text. The insert (point P and associated text) represents an example of use of the diagram as described also in the main text. After Succar and Williams (2008).

Also, to illustrate the use of the diagram in Figure 2.1-2 in the context of the existing and planned CAES projects described previously, Figure 2.1-3 is the same diagram but shows the existing plants (Huntorf and McIntosh) and another planned plant plots (the text added at the bottom of the diagram in Figure 2.1-3 summarizes the computations needed to find the ordinates of the points representing these cases, namely A, B and C, respectively). This exercise shows that the points that represent the CAES plants align satisfactorily well within the theoretical expected positions, and therefore, illustrates a first estimate of the storage volume required to develop a CAES system, at least roughly, by application of equations and/or diagram presented in Succar and Williams (2008). The exercise also suggests that the energy generated by existing and planned plants is significantly below the ‘ideal,’ i.e., maximum, energy that a constant pressure storage option (Case 1) could provide. Considering that in the mining district of Northern Minnesota there exists a significant number of lakes formed in abandoned mine pits, a question that arises from the exercise in Figure 2.1-3 (in particular the relative position of points A, B, and C with respect to the curve for Case 1) is whether the advantage of having artificial lakes above underground mining works could be used to target the development of a constant pressure storage option to boost the production of the envisioned CAES system in northern Minnesota.

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A - Huntorf Plant

P:  $\sim(290+321)/2=305.5$  MW (power)  
 t: 3 hrs (time)  
 Egen: 916,500 kW hr (energy)  
 ps2: 66 bar; ps1: 48 bar  
 ps2/ps1: 1.38 (ratio upper/lower pressure)  
 V: 310,000 m<sup>3</sup> (storage volume)  
 Egen/V: 2.96 kW hr/m<sup>3</sup> (computed)  
 Egen/V:  $\sim 2.8$  kW hr/m<sup>3</sup> (from diagram)  
 Error:  $\sim 5.7\%$

B - McIntosh Plant

P: 110 MW  
 t: 26 hrs  
 Egen: 2,860,000 kW hr  
 ps2: 74 bar; ps1: 45 bar  
 ps2/ps1: 1.64  
 V: 560,000 m<sup>3</sup>  
 Egen/V: 5.11 kW hr/m<sup>3</sup> (comp.)  
 Egen/V:  $\sim 4.8$  kW hr/m<sup>3</sup> (diagr.)  
 Error:  $\sim 6.1\%$

C - Seneca Plant

P: 130 MW (minimum assumed)  
 t: 10 hrs (minimum assumed)  
 Egen: 1,300,000 kW hr  
 ps2: 100 bar; ps1: 50 bar  
 ps2/ps1: 2.0  
 V: 150,000 m<sup>3</sup>  
 Egen/V: 8.67 kW hr/m<sup>3</sup> (comp.)  
 Egen/V:  $\sim 8.4$  kW hr/m<sup>3</sup> (diagr.)  
 Error:  $\sim 3.1\%$

**Figure 2.1-3.** Same diagram as in Fig. 2.1-2, including the position of the two existing CAES plants (Huntorf and McIntosh) and one of the planned plants (Seneca), described in the main text.

**Section 2.2:  
Geotechnical considerations for the design of  
underground excavations for a CAES plant**

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Duluth MN**

**and**

**Dr. Javier Arzúa Touriño,  
Department of Natural Resources and Environment Engineering,  
University of Vigo  
Galicia, Spain**

When defining the potential location for a CAES plant, the type of air storage method is probably the most important factor to consider. There are two types of storage possibilities, namely: 1) surface storage; and 2) underground storage. A surface storage can be implemented by using large steel or concrete tanks (which tend to have a negative visual impact and tend to be expensive in terms of land use and construction). Alternatively, it can be implemented using large submerged 'air bags,' as proposed by Ter-Gazarian (1994); this is perhaps an option that could be further explored for northern Minnesota, considering the large number of existing lakes, some of them in the form of abandoned open pit mines, and also the existence of Lake Superior. Underground air storage can be implemented excavating in salt deposits or depleted gas or oil fields (both of which, unfortunately, do not exist in Minnesota) or aquifers, which require very specific geologic requirements, as demonstrated by the failed Iowa Stored Energy Park project described in the previous section. Finally, an underground storage option can be implemented by the use of existing or abandoned mines or by excavating a new cavern for that purpose. This underground storage option will be considered in the remaining of this section.

The volume of air storage is another important factor to consider in the conception of a CAES system. As seen in the previous section, this volume is related to other critically important variables such as the nominal power of the plant and the discharging time (the multiplication of these two variables defining the amount of energy produced by the plant), and the range of operating pressures and the type of system used., e.g., Cases 1, 2, or 3 described in Section 2.1 and Figure 2.1-2).

During discussions with team members of this project, a target power of 100 MW to be sustained for at least ten hours was envisioned for a CAES system in northern Minnesota. Considering: 1) a typical average working pressure of 70 bars (1,015 psi or 7 MPa); 2) a ratio of initial-to-final pressure equal to 1.4, i.e., choosing the more 'flexible' constant volume storage option, and without distinguishing at this stage on whether Cases 2 or 3 would be chosen; and 3) taking as a basis the very same example worked out in Figure 2.1-2 (considering ten hours instead of five hours), the equations/diagram in Succar and Williams (2008) suggest the need of approximately 300,000 m<sup>3</sup> of air storage capacity (the actual volume would be 333,333 m<sup>3</sup> but, for simplicity, the figure will be rounded off to 300,000 m<sup>3</sup>).

To put this amount of volume (300,000 m<sup>3</sup>) into perspective, Figure 2.2-1 shows a cross-section of an existing shaft of an abandoned iron mine on the Cuyuna Range in central Minnesota (cross-sections of mining drifts, particularly those that were used for access and ore transportation, could be expected to have similar cross-section areas). Without subtracting the space occupied by the support, the area of the cross-section in Figure 2.2-1 results to be 13.54 m<sup>2</sup>. Therefore, for getting 300,000 m<sup>3</sup> of air storage using these shafts or tunnels, a total length of shaft (or tunnel) of 22,160 meters (or 72,703 feet) will be required (see computations on the right side of Fig. 2.2-1). Although this length of tunneling is not uncommon in large mines (and probably could be found in some abandoned mines of central and northern Minnesota, after dewatering them), and given the amount of volume involved, it seems worth exploring the possibility of using not only existing mining excavations, but new openings that could be created with the objective of air storage.

With this purpose, in what follows, a general discussion about technical considerations for storage options, applicable to both existing and new excavations, is provided.



Also in regard to the shape of the opening, according to Kovari (1993) the volume-to-surface ratio for the opening is another important factor to consider. The larger the volume-to-surface ratio, the smaller the amount of reinforcement and/or support needed for the same storage volume. The best option would be a spherical cavity (the geometric construction with largest volume-to-surface ratio), but for construction reasons, e.g., need to have planar floors for equipment to work on efficiently, this shape of cavity is difficult to implement. The next option includes a toroid shape, but this shape can lead to hoop tensile stresses on the walls closest to the center of the toroid, i.e., the inner core with negative curvature, and so a toroid shape has to be discarded as well. From a construction point of view, a cylindrical opening, e.g., with truncated or slightly curved floor as needed, is the next ideal shape. Then, with reference to targeting to have a large volume-to-surface ratio for the cavity, a cylindrical (or truncated cylindrical shape) with a ratio of diameter-to-length (of cylinder) closest to one, seems to be the best alternative.

The next consideration is whether the openings have to be chambers (or tunnels) or shafts (the difference between chambers-or-tunnels and shafts is that the former have axes that are horizontal, or near horizontal, while the latter have vertical, or near vertical). According to Kovari (1993), chambers or tunnels tend to have a large floor surface area, therefore, accumulation of sediment and/or bacterial growth is a possibility. In this regard, shafts seem to be a better alternative. Also, chambers/tunnels have a large roof area, which will be a matter of concern in that reinforcement or support will be necessary in cases of rock masses with average-to-poor quality (although in the case of rock masses with very good quality, chambers or tunnels without support nor reinforcement would be possible as well; in these cases, using chambers/tunnels or shafts would not make a difference in terms of required support). Shafts do have the advantage that they can be constructed with circular shape (maintaining a flat floor for excavation equipment to work on), although shafts have the disadvantage that they are more time consuming and more expensive to build than tunnels of similar shape and volume. In view of what it is mentioned above, for rocks of very good quality, as could be expected in the iron-formations or in the Duluth Complex in northern Minnesota, there seems not be a marked difference in using chambers (or tunnels) or shafts as storage openings.

According to Kovari (1993) another consideration is whether to use a single cavity or a group of cavities. In hard rock, even under extreme favorable conditions, the cross-sectional area of cavities seldom exceeds 800 to 1,000 m<sup>2</sup> – this would correspond to diameters of 30 to 35 m if circular cross-sections are considered. For example, for the volume of 300,000 m<sup>3</sup> mentioned previously, which was envisioned for a CAES plant in northern Minnesota, a cavern with a typical section of 600 m<sup>2</sup> yields a length of 500 m (or 1640 ft.), which although still far from having a diameter-to-length (of cylinder) ratio close to one, as suggested by Kovari (1993), would at least diminish the amount of length needed in comparison with the shaft section discussed in Figure 2.2-1. With regard to the required length of cavern of 500 m computed above, having three caverns of length 167 m each or, alternatively, four caverns of length 125 m each would be a better option than having a single longer cavern (of 500 m). This is because with various caverns used to store air, there exists the opportunity of performing maintenance operations in a chamber without having to stop the entire plant. Also, a group of cavities would also allow gradual increase in the capacity of storage and, therefore, the capacity of the plant.

Another fundamental aspect to consider in the conception of a CAES system is whether the caverns will be lined or unlined. This will depend on the integrity of the rock and the potential for use of a water curtain to control system pressure.

In the context of storing compressed natural gas, Sofregaz and LRC (1999) states that the term ‘lining’ refers to the need to install a barrier to stop leakage of gas (or air) into the rock mass. The term ‘lining’ does not refer to support, e.g., concrete rings or steel sets applied on the walls of the opening, or reinforcement, e.g., cables or rockbolts, that are typically installed in underground openings such as tunnels, caverns and shafts with the purpose of maintaining structural stability of the opening. In this regard, it could be mentioned that (at least at first sight) underground openings in typically hard rocks of Minnesota’s three iron-formations or the Duluth Complex would not impose the demand of significant (if any) support or reinforcement to guarantee the structural stability of the openings.

With the understanding that lining refers to that layer of material, e.g., steel, concrete, or plastic, installed on the periphery of the cavern to avoid leakage of air/gas, Sofregaz and LRC (1999) mention that the liner should be designed mainly to withstand the internal pressure of the gas stored, and also to withstand straining that will be expected to occur when the surrounding rock mass undergoes minor movements, e.g., due to slipping along jointing or similar, due to the repeated cycles of loading and unloading that the cavern will be subject to during its service life (see also Rutqvist et al., 2012).

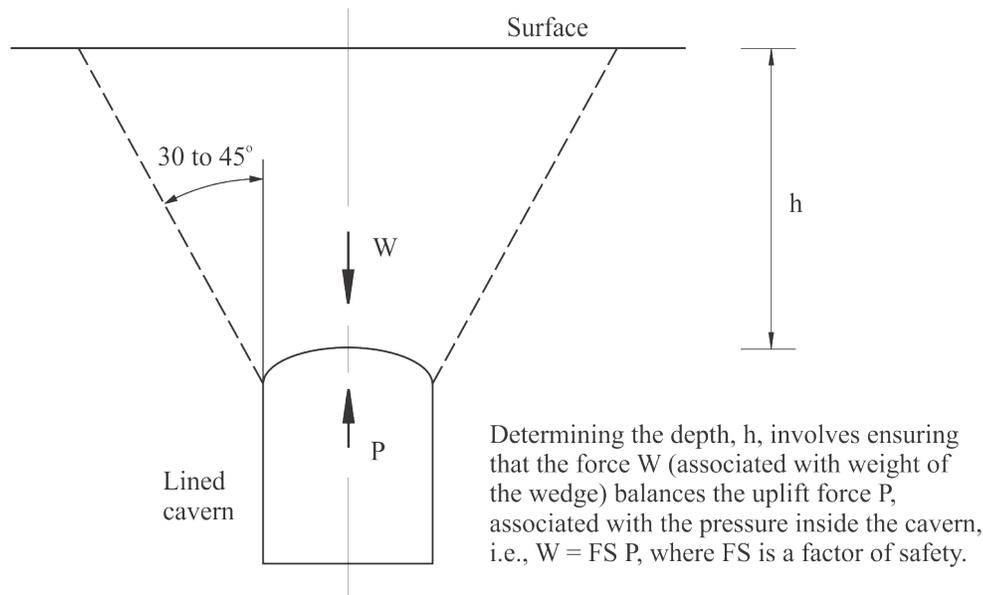
According to Sofregaz and LRC (1999), lining for underground gas storage usually consists of thin steel plates inside the cavern. This steel lining is welded in place and the void between the rock and the steel plates filled with concrete. Because the interface between the concrete and steel is supposed to accommodate movement, a viscous layer or film derived from petroleum is typically installed behind the steel plates before backfilling the void between steel and rock with concrete.

Sofregaz and LRC (1999) also mentions that a synthetic membrane could be used instead of the steel lining. In such case, attention must be given to the fact that some of the condensates contained in natural gas may soften plastic materials and therefore, long-term imperviousness could not be guaranteed. This problem may not be such in the case of compressed air storage for a CAES plant. Considering that using a synthetic membrane in place of a steel layer could bring down the costs for lining the opening, this option should be investigated for the case of an air storage for a CAES plant, if the option of using lining will be considered to prevent leakages.

Another important factor to consider in the design of the cavity is its depth relative to the ground surface. The selection of the depth also depends on whether the cavity will be lined or unlined, as briefly explained below.

In general, lined caverns can be emplaced at shallow depths provided the balance between the uplift force generated by the internal pressure and downward force associated with the weight of the rock above the cavern is such that failure (or detachment) of the overburden rock is prevented (considering an appropriate factor of safety, as normally done in geotechnical design). Figure 2.2-3 illustrates the concept of determining the depth of lined caverns using this approach. When considering the weight of the material above the cavern, a conical ‘wedge’ with lateral sides inclined 30 to 45° with respect to the vertical are typically considered (Sofregaz and LRC, 1999; Rutqvist et al., 2012). It should be emphasized that the approach represented in Figure 2.2-3 is a simplistic approach that, among others, does not consider the initial stresses existing in

the ground. For example, from laboratory and numerical experiments, Tunsakul et al. (2013) found that the angle formed by the sides of the conical wedges and the horizontal at the time of failure can actually vary between 0 and 90°. In view of this, more detailed analyses, e.g., using finite element models which account for all mechanical variables involved in the problem, should be preferred.

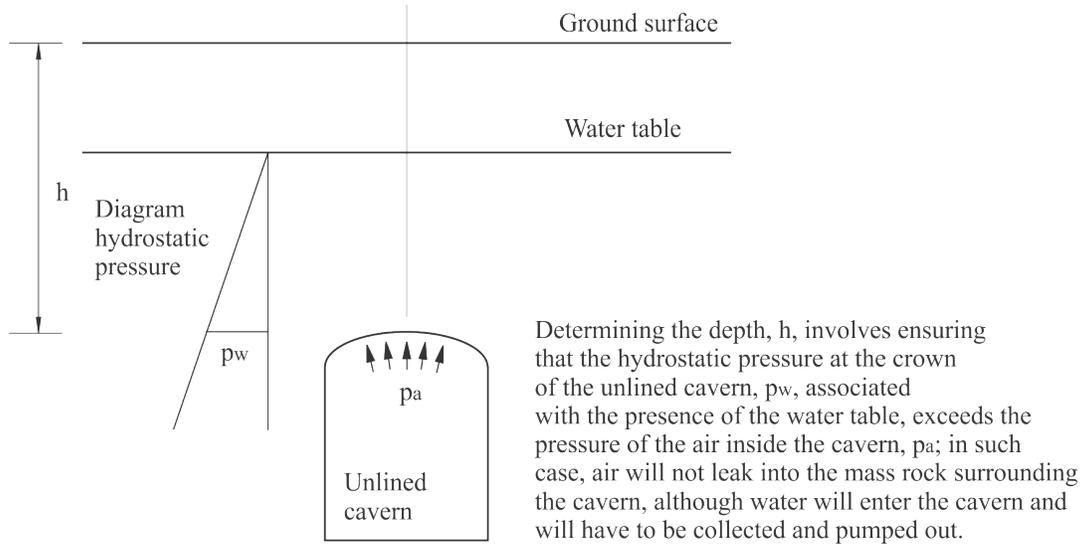


**Figure 2.2-3.** Determination of depth of emplacement of a shallow lined cavern for gas/air storage.

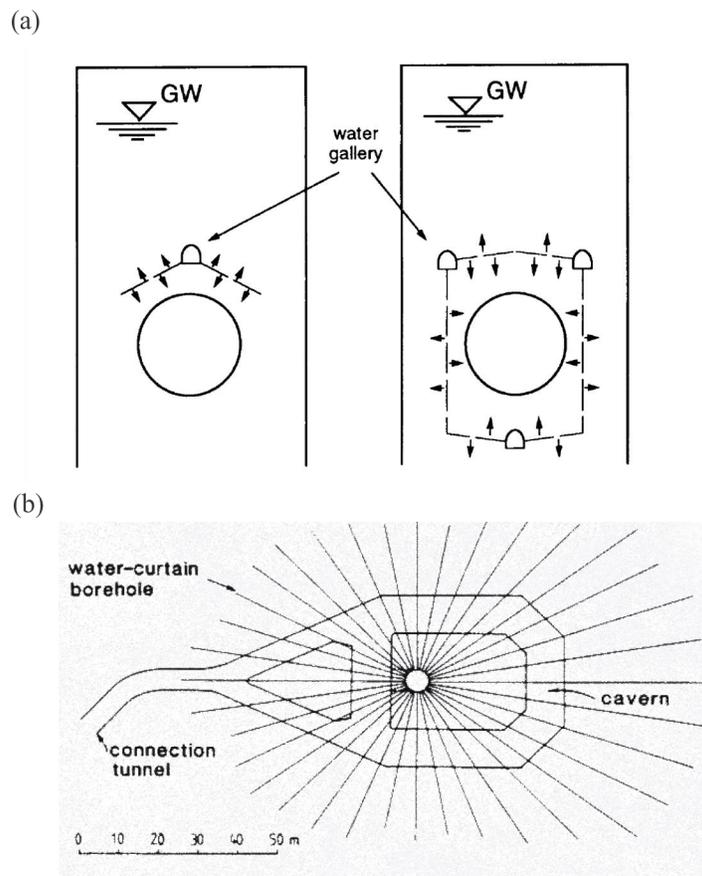
Caverns can also be constructed without liner (see, for example, Blindheim et al., 2004; and Kovari 1993).

In the case of unlined caverns, leakage can be prevented by choosing a depth such that the hydrostatic pressure of the water surrounding the cavern is equal or greater than the pressure at which the gas is to be stored (see Fig. 2.2-4). In this concept, when the hydrostatic pressure of the water exceeds the pressure of the gas (a case that will indeed occur during operation) water will enter the cavity and will have to be collected at the bottom of the cavern, and periodically pumped out of the cavern. Also, due to the seepage of water into the cavern, attention will have to be placed on the groundwater table, with particular regard to the depression of the water table that will tend to develop and which will influence the initially predicted values of hydrostatic pressure at the level of the cavern.

An alternative way of preventing leakage, e.g., when no phreatic surface exists or when smaller depths than dictated by a phreatic surface under hydrostatic conditions is desired for the caverns, is to use water curtains. In this concept, represented in Figure 2.2-5, water is injected under pressure (equal or greater than the pressure at which the gas is to be stored) in water galleries which surround the cavity. This system requires constant pumping of water during operation and is more expensive than the one discussed earlier on (see Figure 2.2-4).



**Figure 2.2-4.** Determination of depth of emplacement of an unlined cavern for gas/air storage.



**Figure 2.2-5.** (a) Cross-sections of unlined caverns with two water curtains configurations: umbrella (left); and circumvating (right) configurations—from Kovari (1993); (b) Plan view of air cushion surge unlined chamber with water infiltration—from Blindheim et al. (2004).

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**Section 2.3:**  
**PowerPoint presentations (draft versions) developed for discussion of  
geotechnical engineering aspects of underground excavations for CAES plants**

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This section presents a set of three PowerPoint presentations that have been developed as part of the project, to present advances of the research and promoting discussions within the team during the scheduled meetings for the project. The titles of the presentations are as follows:

- Presentation 1 (of 3): Initial literature review about general geotechnical aspects of CAES plants.
- Presentation 2 (of 3): Geotechnical considerations dictating the design of underground excavations for CAES plants.
- Presentation 3 (of 3): Compiled bibliography (geotechnical engineering focus).

PRESENTATION 1

Initial literature review  
about geotechnical aspects  
of CAES plants

Javier Arzúa-Touriño  
Carlos Carranza-Torres

Cavallo, 2007

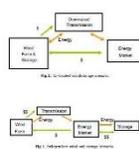
- The storage not only depends on the pressure needed but also on the power of the plant (200 MW seems to be an standard) and the amount of time the compressed air is going to be expanding and generating electricity, these reasons drive Cavallo to think in the order of 1 Mm<sup>3</sup> for a 200 MW plant (just rough values).

Li et al. (Compressed air energy storage for offshore wind turbines)

- Compressed air should be at a pressure of around 7 Mpa (~70 bar).

Denholm & Sioshansi, 2009

The value of compressed air energy storage with wind in transmission-constrained electric power systems  
Paul Denholm<sup>1\*</sup>, Ramin Sioshansi<sup>2</sup>  
<sup>1</sup>North Carolina State University, 1017 Old East Campus Dr., Raleigh, NC 27695  
<sup>2</sup>North Carolina State University, 1017 Old East Campus Dr., Raleigh, NC 27695



- The authors mainly present an economically focused point of view, comparing co-located and independent CAES systems.
  - Co-located means that the CAES plant is directly connected to a wind plant.
  - Independent means that CAES is not related to any wind plant, CAES only takes the energy from the transmission lines when the production exceeds the demand and returns the energy to the grid when the opposite happens.
  - At first sight, co-location would be more suitable, but each case has to be particularly studied in order to avoid extremely high terrain prices or to take advantage of high-value ancillary or capacity services.
- They also comment that CAES is more suitable for energy storage than pumping plants, because it is easier to find suitable locations for CAES than for pumping and also CAES plants have less environmental impact.

Denholm & Sioshansi, 2009

The value of compressed air energy storage with wind in transmission-constrained electric power systems  
Paul Denholm<sup>1\*</sup>, Ramin Sioshansi<sup>2</sup>  
<sup>1</sup>North Carolina State University, 1017 Old East Campus Dr., Raleigh, NC 27695  
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- They point to some technical data which could be interesting for us:
  - Storage should maintain discharge for 20h at nominal power.
  - CAES requires less time to charge than to discharge:
    - 0.72 charge hours/discharge hour.
    - Or it is possible to install a smaller compressor, trying to optimize the excess energy (and have less idle losses), they used it in Huntorf CAES plant. This aspect has to be considered to the long term (compressor life and expected increase in energy consumption).
  - From an economical point of view it is desirable large caverns with large storage capacities with at least 100 – 120 discharge hours.
    - And not only from an economical point of view, although the wind turbines are located where the wind blows most days, there will be some days when there is no breeze, but energy consumption will exist anyway, if we have a storage able to maintain discharge for three or four days we will get rid of these "no windy" days.

Succar and Williams, 2008

Compressed Air Energy Storage: Theory, Resources, And Applications For Wind Power  
8 April 2008 PEI  
Samir Succar and Robert H. Williams

- They point out that (in the appropriate rock masses) the presence of oxygen can lead to oxidation reactions, corrosion and even the development of bacteria. Oxidation reactions could also lead to a drop in the oxygen content of the air, which could reduce turbine performance or could require more air flow.

Succar and Williams, 2008

Compressed Air Energy Storage: Theory, Resources, And Applications For Wind Power  
8 April 2008 PEI  
Samir Succar and Robert H. Williams

- They briefly comment the four existing/projected plants (in that moment):
  - Huntorf, Germany, 290 MW (1978), (capacity increased to 321 MW, 2006)
    - Three hours of storage
    - Two sodium salt caverns (310 000 m<sup>3</sup>)
    - Working pressure between 48 and 66 bar (turbine works at 46 bar, stored air pressure is throttled to this pressure, 2 bar loss in throttle and pipes)
    - In first times of the plant, the air combined with the salt of the cavity oxidized the piping. This forced to change the piping, using fiberglass reinforced plastic pipes and some special measures were also considered to avoid turbine corrosion (not specified).
    - It has been working since its construction, 35 years ago, not so bad.

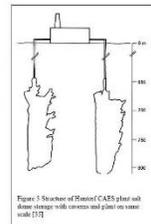


Figure 1 Structure of Huntorf CAES plant with three storage caverns and 2 pipes on each cavern [17]

Succar and Williams, 2008

Compressed Air Energy Storage: Theory, Resources, And Applications For Wind Power

8 April 2008 PEI

Samir Succar and Robert H. Williams

- Mc. Intosh, Alabama, 110 MW (1991)
  - 26 hours of storage
  - Solution salt cavern into a salt dome (560 000 m<sup>3</sup>)
  - Working pressure between 45 and 74 bar.



Figure 10 McIntosh CAES system compressor train (left) and combustion turbine (right)

Succar and Williams, 2008

Compressed Air Energy Storage: Theory, Resources, And Applications For Wind Power

8 April 2008 PEI

Samir Succar and Robert H. Williams

- Norton, Ohio, 800 MW (stopped)
  - The plant is planned to expand to 2700 MW (9x300 MW)
  - An abandoned limestone mine is going to be used (9 600 000 m<sup>3</sup>)
  - Working pressure between 55 and 110 bar.
  - The project was bought by First Energy in 2009, they are delaying the building construction due to economic reasons (they argue low power prices and insufficient demand)



Figure 11 A rendering of the proposed 2700 MW CAES plant based on an abandoned limestone mine at Norton, OH [51]

Succar and Williams, 2008

Compressed Air Energy Storage: Theory, Resources, And Applications For Wind Power

8 April 2008 PEI

Samir Succar and Robert H. Williams

- Iowa Stored Energy park, 268 MW
  - Aquifer based storage, using a porous rock.
  - This kind of storage is based in gas storage experience.
  - It was going to be finished in 2011.
  - Now we know that the porous rock did not have the suitable characteristics and the project has been abandoned.



Figure 12 Diagram of the Iowa Stored Energy Park [58]

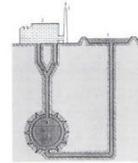
Succar and Williams, 2008

Compressed Air Energy Storage: Theory, Resources, And Applications For Wind Power

8 April 2008 PEI

Samir Succar and Robert H. Williams

- The authors comment the two possibilities of operation:
  - Constant volume – this option implies that the pressure falls during operation (air pressure throttle or variable pressure turbine).
  - Constant pressure – this option needs a surface water reservoir and the correct depth to get the working pressure. In this case also “champagne effect” has to be considered.



Succar and Williams, 2008

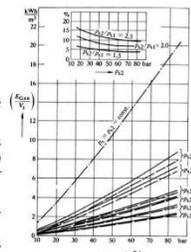


Fig. – Determining the size of the reservoir  
 $E_{\text{cav}}$  = Compressor energy  
 $V_s$  = Storage volume  
 $P_1$  = Upper storage pressure  
 $P_2$  = Lower storage pressure  
 --- Reservoir, case 1  
 --- Reservoir, case 2  
 --- Reservoir, case 3  
 $T_{\text{amb}}$  = 293 K,  $T_{\text{cav}}$  = 3100 K

- In page 30, they comment the storage volume requirement.
  - They present a series of formulae to develop this graph where the energy storage density ( $E_{\text{cav}}/V_s$ ) gives an idea of the amount of energy stored per unit of volume.
  - If the cavern is operated at constant pressure, the smallest the cavern.
  - If the cavern is operated at constant volume, it is also needed to know the relation between upper storage pressure and lower storage pressure.

Ter – Gazarian (Chapter 7)



- This chapter begins analyzing the energetic aspect of the compressor/turbine cycle.
- Explains how the solution caverns are developed and points out that the preferable shape is a vertical cylinder with a shape factor 6:1.
- Points out that Huntorf and Mc Intosh plants operate around 1,000 cycles per year.
- Competent rock caverns are considered expensive, due to the excavation and stabilization costs, but this cost is relatively low because of the possibility of operation at constant pressure.

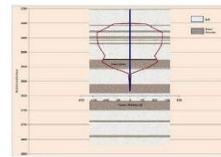
Ter – Gazarian (Chapter 7)



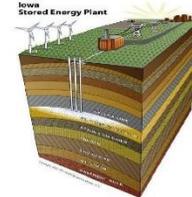
- Another option is the storage of compressed air in big flexible submerged containers, the depth will put the pressure. The main problems regard the finding of suitable locations and the high-pressure piping needed to connect these submerged “air-bags” with the plant.
- He briefly comments the existing plants, all data have been already commented, the only new point is:
  - Huntorf: the compressor is smaller than expected, it lasts 8h to compress the air, while the turbine lasts only 2-3 h in expanding it, this explains the high number of cycles per year.

Examples of failed CAES projects

- New York
- Seneca CAES project



- Iowa



NETL – Seneca CAES project, NY (2012)



- Solution mining salt cavern.
- Initially:
  - 5,000,000 ft<sup>3</sup> = 150,000 m<sup>3</sup>
  - Max. pressure = 1,500 psig (10 MPa)
  - Min. pressure = 750 psig (5 MPa)
  - 8h charging
  - 10-12h discharging
  - Around 260 cycles per year
  - Temperature inside the cavern 95°F = 35°C



LNG tanks in Gijon, Spain, they have a capacity of 150,000 m<sup>3</sup> each, sizing roughly 60 m (200 ft) in diameter and 50 m (165 ft) in height.

NETL – Seneca CAES project, NY (2012)



- Parsons Brinkerhoff Energy Storage Services (PBESS) was in charge of the development of the caverns.
- Prior the development, some thermodynamic and geo-mechanical models were performed, which revealed:
  - Temperature in cavern walls varies between 140°F (60°C) and 60°F (15°C).
  - **This temperature jump is high and quick enough for the salt on the cavern ceiling and walls to go from compression (normal state due to the weight of the overburden above the cavern) into tension; this would cause spalling of salt which would lead to deterioration of the cavern particularly at the air production well penetration.**

NETL – Seneca CAES project, NY (2012)



- To solve this issue, PBESS recommended some modifications to the project:
  - Limit operating pressures to between 1500 psig (10 MPa) and 1150 psig (8 MPa) which will limit the temperature difference.
  - Maintain at least 50 ft (15 m) of salt on the ceiling of the cavern to ensure the integrity of the pressure boundary of the cavern for 30 years of plant operation.
  - Limit the cavern diameter to 270 ft (82 m) or less to maintain a safe roof loading on the cavern during operation.
  - Limiting the operating pressures would require a cavern size increase to meet the airflow requirements of the CAES plant. The cavern would need to be approximately **three times larger than the 5 million ft<sup>3</sup> single cavern** originally planned for the project (450,000 m<sup>3</sup>).

NETL – Seneca CAES project, NY (2012)



- Based on the geology in the area, the development of a new, larger single cavern was not recommended. PBESS recommended that the maximum cavern size be approximately five million cubic feet in size.
- Based on this recommendation, PBESS recommended that a series of three new caverns, each approximately 5 million ft<sup>3</sup> operating in parallel would be the best design option for the CAES plant. Under this plan, the CAES plant could be placed into commercial operation at a much earlier time (with limited operating time at full load) with at least one cavern ready for service.
- **Due to this change in the project, capital costs and the delayed begin in the operations at full load plus the usage forecast in that moment, converted the project in not favorable.**



NETL – Seneca CAES project, NY (2012)

- They conclude:
  - “The research herein, therefore, is particular to the site-specific factors that influenced the design and the current and forecasted generation mix and energy prices in Upstate New York and may not necessarily indicate that CAES plants cannot be economically constructed in other places in New York State or the world.”



Sandia Report: Lessons from Iowa (2012)

- In this report, the authors summarize the eight years of development that carried out to try to put into operation a 270 MW CAES plant using an aquifer as storage.
- After many field surveys, some test wells and before spending between \$12 million and \$20 million in additional air injection in situ testing with no guarantee of success, it was determined that **the porous rock did not had the required permeability to correctly transmit the compressed air.**
- Project Team members decided to terminate the project, since they did not have an alternative suitable location for the storage.



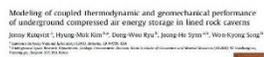
Sandia Report: Lessons from Iowa (2012)

- In this report, it becomes evident that they used the correct way to do the things, despite all the efforts, they found a dead end and had to abandon the project.
- **Despite the problem of the geology, this document touches many points of interest that can help us in our own project. We should consider it as a helping guide for our purpose.**



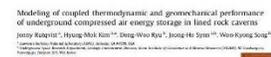
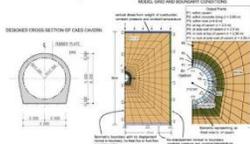
Rutqvist et al., 2012

- Very interesting, it is focused on what happens with the concrete liner due to cycling stresses originated by temperature and pressure changes during cycles of charge/discharge.
- They begin talking about natural gas storage, where the caverns are lined with welded steel, but they point that due to the highly cycling operations (at least one cycle per day, 50 years = 20,000 cycles) the fatigue should be a problem to take into consideration in CAES.
- They also point that **the load is absorbed by the rock mass, and the lining is only useful to avoid leakages.** Even though it is very probable that leakage occurs but it usually has low impact on plant performance.



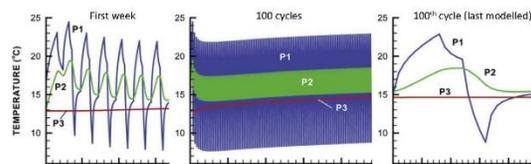
Rutqvist et al., 2012

- Also the concrete lining should include a steel mesh and fibers to increase its tensile strength, which will be the kind of stress (tension) that concrete lining is going to suffer.
- They point that during the idle time (no charge or discharge), the air temperature will decrease due to heat exchange with lining (not with rock mass) and, so, the same will occur with the pressure.
- They modelled a circumferential cavity using FLAC (geomechanics) and TOUGH (thermodynamics).



Rutqvist et al., 2012

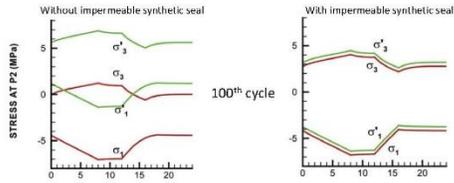
- It is very interesting fig. 2b, which shows that for a 100 cycle period (3-4 months) lining temperature (P2) has increased in 2°C.
  - *what will it be after 20,000 cycles?*



Rutqvist et al., 2012

Modeling of coupled thermodynamic and geomechanical performance of underground compressed air energy storage in lined rock caverns  
 Junmyung Kang<sup>1</sup>, Hong-Mook Kim<sup>1\*</sup>, Dong-Woon Park<sup>2</sup>, Jaehyeon Shim<sup>1\*</sup>, Won-Kyung Song<sup>1\*</sup>  
<sup>1</sup>Department of Rock and Soil Engineering, Seoul National University, Seoul, Korea; <sup>2</sup>Department of Geotechnical Engineering, Seoul National University, Seoul, Korea

- They point that installing a synthetic seal inside the lining reduces the tension stress (due to effective stresses, which also consider pore pressure).



Rutqvist et al., 2012

Modeling of coupled thermodynamic and geomechanical performance of underground compressed air energy storage in lined rock caverns  
 Junmyung Kang<sup>1</sup>, Hong-Mook Kim<sup>1\*</sup>, Dong-Woon Park<sup>2</sup>, Jaehyeon Shim<sup>1\*</sup>, Won-Kyung Song<sup>1\*</sup>  
<sup>1</sup>Department of Rock and Soil Engineering, Seoul National University, Seoul, Korea; <sup>2</sup>Department of Geotechnical Engineering, Seoul National University, Seoul, Korea

- There are some mechanical behavior characteristics which are the same in the concrete lining, the excavation disturbed zone and the rock mass, this could induce to errors in the model since the actual behavior for the three materials is not the same.

Table 1  
 Material properties used in a finite element modeling of CAES in a lined rock caverns

Property	Material		
	Rock mass	ECC lining	Concrete lining
Young's modulus, E (GPa)	25	35	35
Poisson's ratio, $\nu$ (-)	0.3	0.3	0.3
Thermal expansion coefficient, $\alpha$ (1/°C)	$1.0 \times 10^{-5}$	$1.0 \times 10^{-5}$	$1.0 \times 10^{-5}$
Effective porosity, $\mu$ (dimensionless)	0.05	0.05	0.3
Permeability, $k$ (m <sup>2</sup> )	$1.0 \times 10^{-17}$	$1.0 \times 10^{-17}$	$1.0 \times 10^{-14}$
Residual gas saturation (dimensionless)	0.0	0.0	0.0
Residual liquid saturation	0.05	0.05	0.05
Gravimetric water content, $w$ (%)	1.47	1.47	1.47
Void Coefficient, $e_v$ (MPa)	0.595	0.595	0.595
Thermal conductivity, $\lambda$ (W/mK)	2	2	2
Specific heat (J/kg °C)	900	900	900

PRESENTATION 2

Geotechnical considerations dictating the design of underground excavations for CAES plants

Javier Arzúa-Tourifo  
Carlos Carranza-Torres

What is CAES?

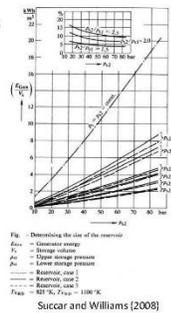
• CAES is the acronym for Compressed Air Energy Storage.

• A CAES plant (generally associated to wind turbines) compresses air when there is an excess of electric energy production in the grid and generates electric energy using a turbine (burning or not natural gas) when the demand exceeds the production.



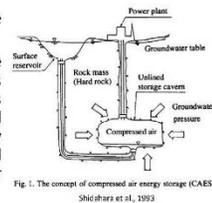
How much storage do we need?

- There are four main factors involving this question:
  - Constant volume or constant pressure storage
  - Range of operating pressures
  - Discharging time
  - Plant nominal power
 } Amount of needed energy
- Succar and Williams (2008) showed this graph, one can see that operating at constant pressure allows to get much more energy per unit of volume (energy density).



Constant volume or constant pressure storage? (Succar and Williams, 2008; Shidahara et al., 1993)

- In a constant volume storage, the pressure decreases as the air/gas discharges.
- In a constant pressure storage the pressure remains constant during discharge. In this case some kind of volume compensation is needed, when talking about underground caverns, this compensation is achieved by means of a surface water reservoir connected with the cavern in such a way that the water enters the storage as the air leaves it.



What kind of storage do we need?

- This is the first and key question in determining the location of the CAES plant.
- There are two types of storage:
  - Surface storage:
    - Large steel or concrete tanks → High visual impact, Expensive (terrain + construction)
    - Large submerged "air bags" (Ter-Gazarian, 1994) → Social rejection to use Minnesota lakes?
  - Underground storage:
    - Salt deposits → Do not exist in Minnesota as far as I know
    - Depleted gas/oil fields → Very specific geologic requirements
    - Aquifers → Very specific geologic requirements
    - Hard rock caverns (existing/abandoned mines or purpose excavated)

What shape should the cavity have?

K. Kovári, 1993.

- Better circular, but if the cavity is horizontal, some practical disadvantages arise and a compromise has to be achieved using an horizontal floor and elliptical walls and roof (horse-shoe shape).

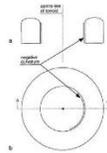


Fig. 4. Possible shapes of cross section for CGES-Cavities

Volume to surface ratio of the cavity?

K. Kovári, 1993.

- The greater the ratio of the excavated rock the less is the amount of reinforcement/support/lining needed.
- The best option is the spherical, but for constructional reasons such a shape has to be discarded.
- Next option includes a toroid shape, but such a shape can lead to tensile stresses in the inner walls and lining due to their negative curvature.
- Therefore it is better a cylindrical shape having a diameter as close to the length as possible.



Chambers/tunnels or shafts?

K. Kovári, 1993.

- Chambers have a large floor surface area, if there is water the interface between air/gas and water is very large, which can lead to bacterial growth and air/gas dissolution. So, better shafts.
- Chambers have a large roof area, which is always a matter of concern and usually requires the greatest amount of rock support. The better the rock mass properties are, the less is the difference between chambers and shafts.
- Shafts can be constructed in circular shape, so from a static point of view, better shafts.
- Shaft excavation is a rule more time consuming and more expensive than that of a chamber, so better chambers.
- Shafts have a restriction, they have to be vertical, in the case of chambers one can choose the direction of the cavern to avoid unfavorable geological conditions, so better chambers.

Single cavity or group of cavities?

K. Kovári, 1993.

- In hard rock, even under extreme favorable conditions, the cross-sectional area of rock cavities seldom exceeds 800 to 1000 m<sup>2</sup>, i.e. a diameter of 30 to 35 m. For shafts in good rock, a greater diameter can be selected than for a chamber under the same rock conditions.
- For a volume of 150,000 m<sup>3</sup> a chamber with a more common section of 600 m<sup>2</sup> yields a length of 250 m, which is not convenient. It would be better to obtain a number of chambers/shafts approx. 30 m in diameter and 100-125 m in length.
- It is possible that the cost of operating separated chambers be greater than for a single larger chamber, but it will give opportunity to perform maintenance operations in a chamber without having to stop the entire plant.
- A group of cavities also would allow to increase progressively the capacity of storage and, therefore, the capacity of the plant.

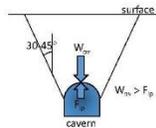
Concepts of lining

(Sofregaz & LRC, 1999)

- In this context the lining term does not include reinforcement/support techniques like rock bolts or shotcrete (+ steel mesh + fibers) which have to be included to ensure the long term cavern stability (Sofregaz & LRC, 1999; Rutqvist et al. 2012).
- Lining is only intended to prevent leakage of the compressed air into the rock mass, it is not going to support any load due to inner pressure, although it is going to suffer some kind of strain because of the surrounding rock movements (Sofregaz & LRC, 1999)
- Lining for underground gas storage usually consists of relatively thin steel plates which are welded in-situ inside the cavern; the void between the wall of the cavern and the steel plates is filled with concrete (Sofregaz & LRC, 1999)
- The interface between concrete and steel lining needs to be allowed to slide, in order to accommodate movements of the rock mass without breaking the lining. A film of some viscose petroleum derived product is usually used (Sofregaz & LRC, 1999)
- Also a synthetic membrane could be used instead of the steel, but I have not found any example of such a membrane because all the expertise is based on natural gas storage and it is known that some of the condensates contained in natural gas may soften plastic materials and long-term imperviousness cannot be guaranteed (Sofregaz & LRC, 1999). This is a point to be investigated for the CAES systems.

Lined cavern

- Lined caverns can be excavated at a shallow depth, leakage is prevented by the lining, the weight of the overburden is the force that will prevent the roof uplift. (Sofregaz & LRC, 1999; Rutqvist et al. 2012)
- The most simple approach to obtain the needed depth is to consider the weight of a cone with an angle of 30° to 45°. (Sofregaz & LRC, 1999)
- But this approach does not consider the in-situ ratio of stresses which can modify this angle from 0° to almost 90° (Tunsakul et al. 2013). An estimation of this ratio should be performed for each chosen location in order to correctly determine the depth.



Unlined cavern

- Unlined caverns need more depth because the hydrostatic pressure is what prevents the leakage, i.e. the hydrostatic pressure has to be bigger than the inner pressure of the air/gas in every moment (Blindheim et al.)

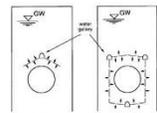
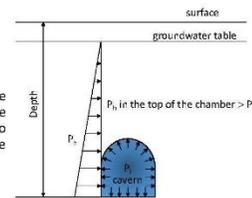
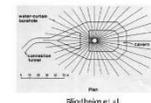


Fig. 14. Water cavern configurations: a) shallow, b) intermediate section. K. Kovári, 1993



- The depth can be reduced by means of using water curtains which can increase the hydrostatic pressure around the excavation but also increases the operational costs. (Blindheim et al.)



## PRESENTATION 3

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(geotechnical engineering focus)

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**CHAPTER 3:****CAES IN NORTHERN MINNESOTA USING UNDERGROUND MINE WORKINGS****Facilities Team**

Jeffrey D.G. Marr, St. Anthony Falls Laboratory  
James Tucker, St. Anthony Falls Laboratory

**Synopsis**

This chapter summarizes research on compressed air energy storage feasibility in northern Minnesota from the perspective of facility design. The research begins with fundamentals of compressed air energy storage and essential design considerations for site selection. Because CAES plants can vary in their purpose and financial structure, the study examines a range of technological approaches including conventional CAES and advanced CAES, and through this examines various sizes of plants and operational configurations. The chapter concludes by summarizing three preliminary feasibility studies for northern Minnesota. The studies examine three distinct sites with unique technological approaches, sizes, locations and operational goals.

**Section 3.0:  
Facilities Team Final Report**

**Jeffrey D.G. Marr and James Tucker  
St. Anthony Falls Laboratory  
University of Minnesota  
Minneapolis MN**

## INTRODUCTION

This report summarizes the research efforts of the Facilities Team, one of the four teams collaborating on a preliminary feasibility of Compressed Air Energy Storage (CAES) in northern Minnesota. The efforts of the Facilities Team covered a broad range of study that included the following key areas:

- a) Use of abandoned mine pit lakes for CAES (Section 3.1);
- b) Review and summary of fundamentals of compressed air physics and thermodynamics (Section 3.2);
- c) Review of CAES technologies and assessment of technology readiness of emerging systems (Section 3.3);
- d) Survey and analysis of existing or planned CAES plants (Section 3.4);
- e) Development of preliminary engineering design parameters to be considered in planning and design of a CAES plant (Section 3.5);
- f) Review of important energy market regulation and rules affecting facility design and operation (Section 3.6); and
- g) Preliminary design of three CAES sites selected in northern Minnesota (Section 3.7).

The three other teams involved in the project included the Environmental Assessment Team, Geotechnical Assessment Team, and the Economic and Policy Assessment Team. The findings of the other teams are not summarized in this section; however, appropriate design and feasibility, even at the conceptual stage, required collaboration between all four teams.

**Section 3.1:  
Use of Abandoned Mine Pit Lakes  
for Compressed Air Energy Storage**

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## USE OF ABANDONED MINE PIT LAKES FOR COMPRESSED ENERGY STORAGE

During a recent trip to the Toronto area, NRRI researchers became aware of a technology implementation underway by Ontario Power off-shore of Toronto Island. This technology is used to store electrical energy by converting the electricity to stored compressed air and using the hydrostatic pressure of Lake Ontario to minimize overall costs in creating the air storage facility. We think this same concept could be implemented on both the Cuyuna and Mesabi Iron Ranges, where many deep mine pit lakes exist, and there is already the electrical grid infrastructure to facilitate energy storage for the grid. The advantage of using the pit lakes is multifold:

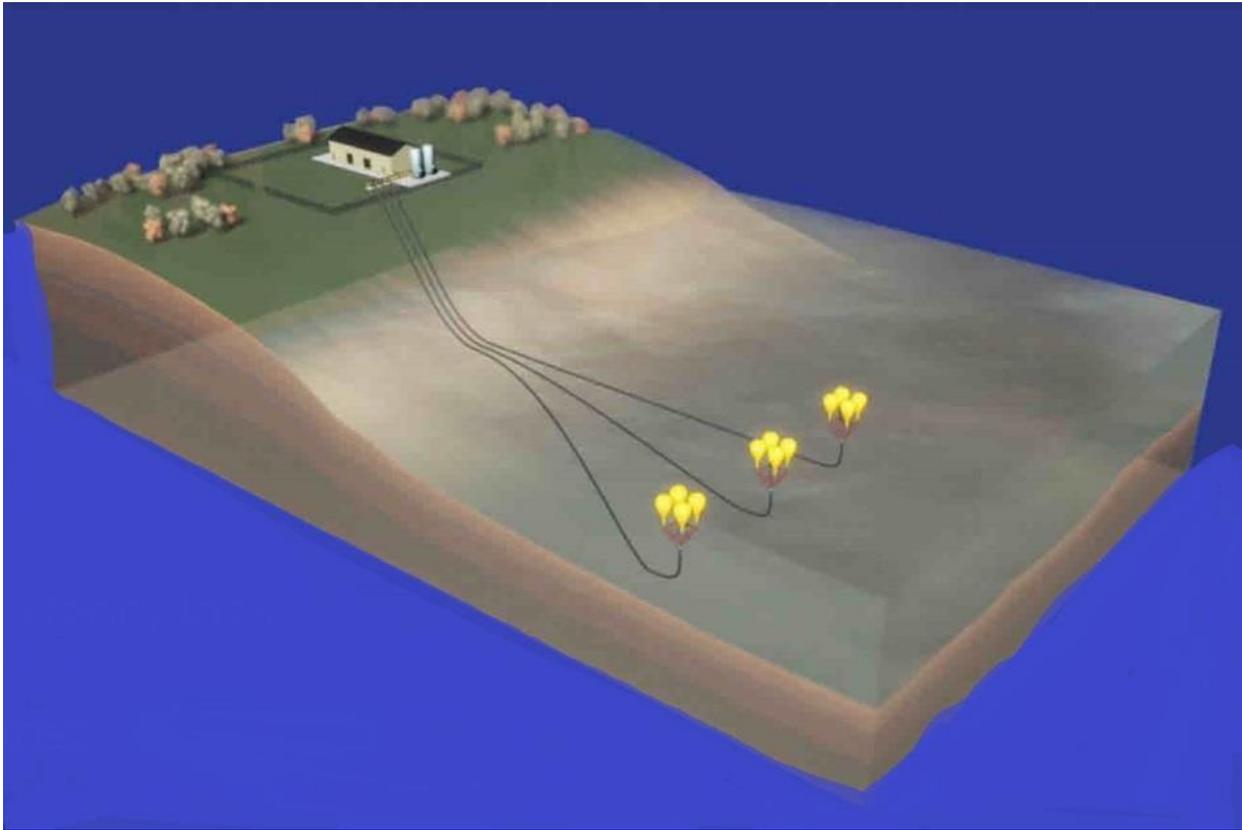
1. Construction of the storage cavern is done at reduced cost;
2. Air lines from the surface to the storage facility can be done without a massive drilling program and larger, more efficient air transfer piping can be employed;
3. Surface equipment can be expanded as the storage need increases over time;
4. The storage facility can be maintained at lower overall pressures by using the water to move the air out of the system;
5. Land disturbance to create a deep cavity for the air storage facility is totally eliminated and rock properties need not be considered since the water cap provides the necessary hydraulic pressure; and
6. The viability of the concept can be monitored through the work being done for Ontario Hydro in Toronto area.

The essence of the concept is summarized by Mr. Cam Lewis (pers. comm., 2016), President of Hydrostor, the company implementing this technology:

*“The Hydrostor technology is a straight forward technology in terms of the operating rationale. Electricity (energy) is taken from the grid and used to drive a compressor. The compressor converts the energy into compressed air and this air is sent to accumulators that are located below the surface of a body of water. The air is pressurized to match the pressure found at the depth of the accumulators meaning that the accumulators are required to hold very little pressure <10psi in most cases. The air displaced the water that is in the accumulators and is stored here until power is required back at the grid. When power is required at the grid the flow is reversed and the weight of water forces the air back to surface at pressure and is directed through an expander wheel which turns a generator converting the energy in the air back into electricity.”*

The basic essence of the technology is shown in Figure 3.1-1. It involves a land-based system tied to the electrical grid that houses compressors and turbines and generation equipment to cycle the air back and forth and an underwater air storage unit to contain the compressed air. When the electricity is not needed for grid use, it runs compressors to move air into the underwater storage vessels, and when electricity is needed, the compressed is moved back to the surface to run the turbine generator to produce electricity. The Hydrostor system also can feature an energy capture system to capture heat energy when the air is compressed

to warm the air before expansion into the turbine. This increases the overall round trip efficiency of the energy manipulation system 60 to 80%.



**Figure 3.1-1.** Overview of Hydrostor compressed air energy storage concept.

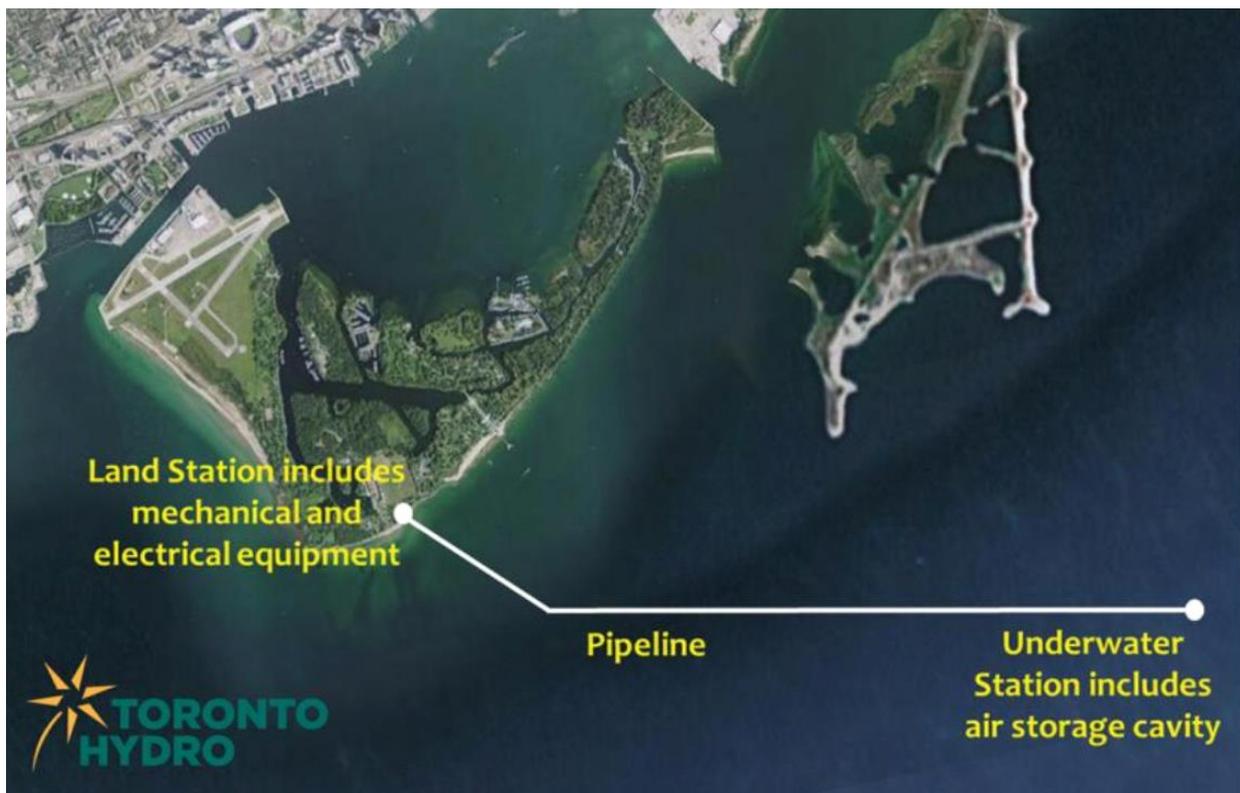
Mr. Cam Lewis of Hydrostor further summarizes the concept as follows (pers. comm., 2016):

*Another portion of the Hydrostor technology that is also used in the system is thermal storage. Since the act of compressing air creates an excess of heat this is energy that is normally lost. Hydrostor captures this heat generated during compression, stores it, and then delivers it back into the air stream as it returns from the accumulator but prior to the expander. This storage increases the round trip efficiency of the system reducing energy losses."*

As noted above, the system converts electricity running compressors into compressed air that is stored under pressure in the storage system under water. It is returned as mechanical energy that is used to drive a conventional turbine to spin a generator that can then produce electricity that can be returned to the grid when the electricity is needed. This system is environmentally friendly in that it uses air as its medium and cycles the air back and forth to store and produce the electricity. As is mentioned by Hydrostor (C. Lewis, pers. comm., 2016),

the system “uses custom designed high temperature compressors, expanders, and generators from Tier 1 North American equipment manufacturers. Hydrostor does not make our own rotating equipment but rather works with global companies to provide solid, warranted equipment in a wide variety of power and scope. Further, the systems including the compressor motor and expander generator can be either induction or synchronous, however if synchronous equipment is used, there is an option to operate it in “floating” mode to provide voltage support, reactive power, and black start capabilities. Selecting the equipment is completed based on charge and discharge time but it should be noted that on a project such as this greater than 10MW will likely be required to make financial sense.” The system is a hybrid of the typical pumped hydro energy storage system and compressed air energy storage and as such should have both low capital and operating costs for large scale energy storage.

The concept is being implemented by Ontario Power as part of their renewable energy system and is located on Toronto Island in Lake Ontario with the under water storage facility at a depth of roughly 200 feet. The location of the facility is shown in Figure 3.1-2.



**Figure 3.1-2.** Hydrostor underwater CAES reference facility on Toronto Island.

In discussing the potential of this concept with Mr. Lewis, he felt that the use of abandoned, very deep mine pits could be highly advantageous for the concept. He indicated the following (C. Lewis, pers. comm., 2016): “Re-allocation of spent assets such as spend mines can be very advantageous as energy storage sites without the very significant impact of converting the unit

*to a pumped hydro system. It is my understanding that several open pit abandoned mines exist in the Cuyuna and Mesabi iron ranges in Minnesota with depths up to 750'. Depending on the characteristics of the mine converting the mine to contain underwater air storage would be an excellent fit. Additionally, being located in Minnesota other opportunities exist that can be added to the system to increase operational flexibility and lower cost."*

Further, he mentioned that a significant cost associated with Underwater Compressed Air Energy storage is marine construction and the building and locating of the accumulators (C. Lewis, pers. comm., 2016):

*"What we feel at Hydrostor would work to lower construction costs would be to pump out one of the pits to allow for direct construction on the mine floor. Once empty a road to site could be created allowing for bed prep and in situ construction of the accumulators. This would remove the need for marine construction equipment, allow the accumulator to be built (to whatever size is required) directly on the bed. The routing of the airline to surface would also benefit as no drilling would be required and therefore no size restriction allowing for the use of a larger pipe with less friction, more flow, and easily ballasted. Future aspects of growth can be taken into consideration at this point as well. With a larger accumulator and pipe constructed only future expansion of the on shore equipment as to be addressed if future needs arise.*

*The equipment on shore can be sized according to the needs of the project at the present time. Due to the fact that the charge is decoupled from the discharge which is also decoupled from the generation, increasing the size in the future is simply adding another compressor and expander. The thermal store for the system may also be added to store the heat from compression. The compressor motor and expander generator can be either induction or synchronous, however if synchronous equipment is used, there is an option to operate it in "floating" mode to provide voltage support, reactive power, and black start capabilities. Selecting the equipment is completed based on charge and discharge time but it should be noted that on a project such as this greater than 10MW will likely be required to make financial sense."*

## **Concluding Comments**

Minnesota is uniquely positioned with the water resources that can take advantage of this technology concept. Its 130+ year mining history has resulted in the creation of deep mining related pit lakes that would seem to be ideal candidates for this energy storage concept. Hydrostor is excited about the possibility of using pit mines for their accumulator locations. It is something that they have briefly looked into and can offer some very real low cost options for energy utilizing them. Hydrostor indicates that they are not limited to project size as they work with our partner AECOM on projects to offer fully backed turnkey solutions. With building the different components to meet different sizes for their clients it allows them to incur capital costs when they really need the asset instead of overbuilding at the beginning for something that is required a decade down the road. Low cost from ease of construction combined with flexibility to create a genuine useable asset is what Hydrostor Technology can bring to the

table. Based on the discussion and the technology review, it is recommended that further consideration be given to this compressed air energy storage option for use in Minnesota. It should lower the cost associated with the other options noted in this report and also puts Minnesota in a unique position for large scale energy storage for the Midwest region of the U.S.

**Section 3.2:  
Review and Summary of Fundamentals of  
Compressed Air Physics and Thermodynamics**

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## FUNDAMENTALS OF COMPRESSED AIR ENERGY STORAGE

This section provides a very brief review of basis behind compressed air as a form of energy storage.

### PROPERTIES OF AIR, WORK OF COMPRESSION, ENERGY

Air is the ubiquitous name given to the atmospheric gases surrounding Earth. Air is a mixture of gases (nitrogen, oxygen, carbon dioxide, argon, and other gases) that envelop and exchange with the Earth's surface and makes life possible by support of respiration, photosynthesis and by regulating Earth's climate. Because air is a gas and is compressible, its properties change in response to changing environmental conditions such as weather, sun exposure, wind, or elevation. The properties of air such as temperature, pressure, density, and relative humidity are dynamic and adjust toward a state of equilibration that balances environmental conditions.

Air is a compressible fluid, i.e., meaning that air density (mass of air per volume) is variable. The behavior of air compressibility is commonly described by the Ideal Gas Law, which is applicable to air.

$$PV = nRT \quad (3.2-1)$$

Where,

P = air pressure

V = volume

n = amount of gas (e.g., moles)

R= gas constant

T = absolute temperature

For the purpose of this report, the important observations drawn from equation 3.2-1 are the relationships between pressure, temperature, and volume for a gas. For a fixed quantity of air within a fixed walled container, decreasing the volume of this gas, such as through compression, will have the response of increased pressure and/or increasing temperature.

### **Flow energy**

Compressing a gas from an initial state, often one equilibrated with atmospheric conditions, to a new state requires energy to perform the work. The molecules of a quantity of gas are forced into a smaller volume resulting in increased temperatures and pressure of the gas. *Flow work* is defined as the work required to move a fluid through the cross-section of a control volume, as if by a piston. The piston exerts a force on the fluid over a certain distance. Consider the following:

$$F = PA \quad (3.2-2)$$

Where,

F = force exerted by piston in order to move the fluid

P = fluid pressure

A = cross-sectional area of control volume

This energy can be transferred into mechanical or fluid power to drive equipment or can be stored until needed. Compression of a gas and storage of that energy is the basis for compressed air energy storage.

$$W = FL \quad (3.2-3)$$

$$W = PAL \quad (3.2-4)$$

$$W = PV \quad (3.2-5)$$

Where,

W = work done by piston

L = distance through which the piston moves the fluid

V = displaced volume of fluid in the piston

### **Internal Energy**

The internal energy of a gas is related to microscopic potential and kinetic energy where potential energy is derived from molecular structures, bonds, and other molecular geometries and kinetic derives from the motion and vibration of these particles (Klotz and Rosenberg, 2008).

The change in internal energy for a “closed” system is as follows:

$$dE = \delta Q + \delta W \quad (3.2-6)$$

Where,

E = internal energy

Q = heat added to the system

W = work performed on the system (PV)

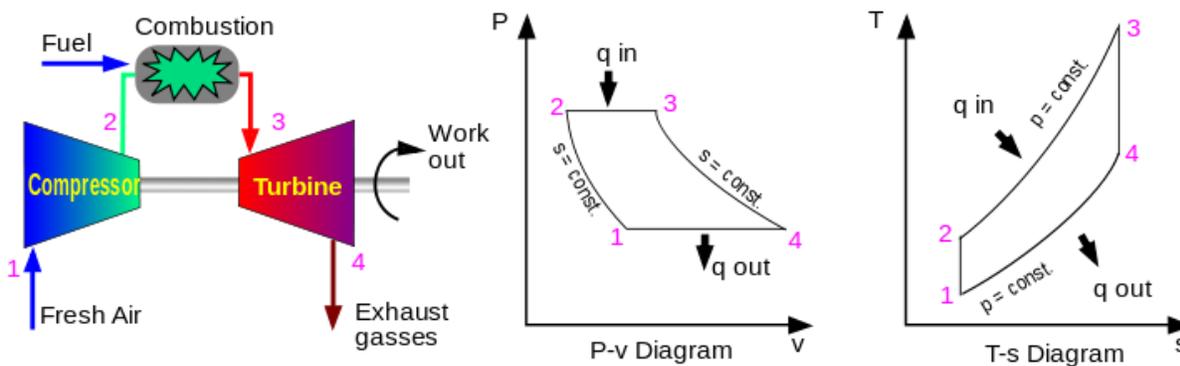
### **GAS TURBINES AND THE BRAYTON CYCLE**

Compressed air energy storage utilizes the physics and thermodynamics of air compression in two ways. The first is in air storage. Compressed air that has elevated internal potential energy is stored in above ground or below ground storage containers. Second, compressed air is released from storage and combined with the combustion fuel process in a combustion turbine and expanded to generate electricity. Figure 3.2-1 provides a summary of the basic

operation and thermodynamic cycle of a simple gas turbine that is referred to as the Brayton Cycle. Both processes described above are captured in Figure 3.2-1.

The left schematic is of a simple combustion turbine (CT). Fresh air enters the system and is compressed (numbered steps 1 & 2). The compressed air then enters the combustion chamber (steps 2 & 3), where it is mixed with a combusted fuel that heats and accelerates the fluid into the expansion section. After leaving the combustion chamber, the heated air is expanded through a turbine that rotates a shaft and generator, producing work (steps 3 & 4).

The middle and right panels in Figure 3.2-1 show the theoretical pressure-velocity and temperature-entropy relationships through the CT process.  $Q_{in}$  and  $Q_{out}$  refer to locations where heat is added (fuel combustion) and removed from the system. In a standard CT, air is compressed, heated in natural gas combustors, and expanded through a turbine, transforming some of the chemical energy in the fuel into mechanical energy.



**Figure 3.2-1.** Summary of Brayton (Source: [http://en.wikipedia.org/wiki/Brayton\\_cycle#/media/File:Brayton\\_cycle.svg](http://en.wikipedia.org/wiki/Brayton_cycle#/media/File:Brayton_cycle.svg).)

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**Section 3.3:  
Review of CAES Technologies and Assessment of  
Technology Readiness of Emerging Systems**

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## OVERVIEW OF COMPRESSED AIR ENERGY STORAGE TECHNOLOGIES

Compressed Air Energy Storage is a bulk energy storage technique with energy capacities that range from 10-1000 MWh. Large volumes of air are compressed and stored either below ground in excavated or natural geologic structures or above ground in pressure vessels. The air is compressed during times of low electric energy demand. Later, when the electric demand is greater, the stored compressed air is expanded to drive electric generators.

CAES plants are generally classified into two classes based on whether or not they burn fossil fuel. CAES systems that consume fossil fuel in the expansion process are defined herein as *Conventional CAES*. These plants are not strictly energy storage facilities but are a hybrid of a compressed air storage system and a combustion turbine power plant. Two commercial plants of this type exist today. The second class of CAES systems does not use fossil fuels; they are true energy storage systems and, herein, are referred to generally as *Advanced CAES*. It is important to note that, at present, no commercial plants of this type are in operation, but several technologies are nearing commercial viability or have large prototype facilities. Included in this class are *Adiabatic CAES* and *Near-Isothermal CAES*.

As was reviewed in Section 3.2, the thermodynamics associated with compression of a gas results in the production of heat and, conversely, expansion of a gas consumes heat. For utility scale energy storage, the temperature changes are substantial. How the CAES plant deals with heat generation/loss within the facility design is a major factor in the efficiency of the plant. Before proceeding with description of technologies, a few important thermodynamic terms are introduced below:

***Diabatic*** – refers to general processes of gain or loss of heat. For diabatic CAES systems, thermal energy is added to the system by burning fossil fuels.

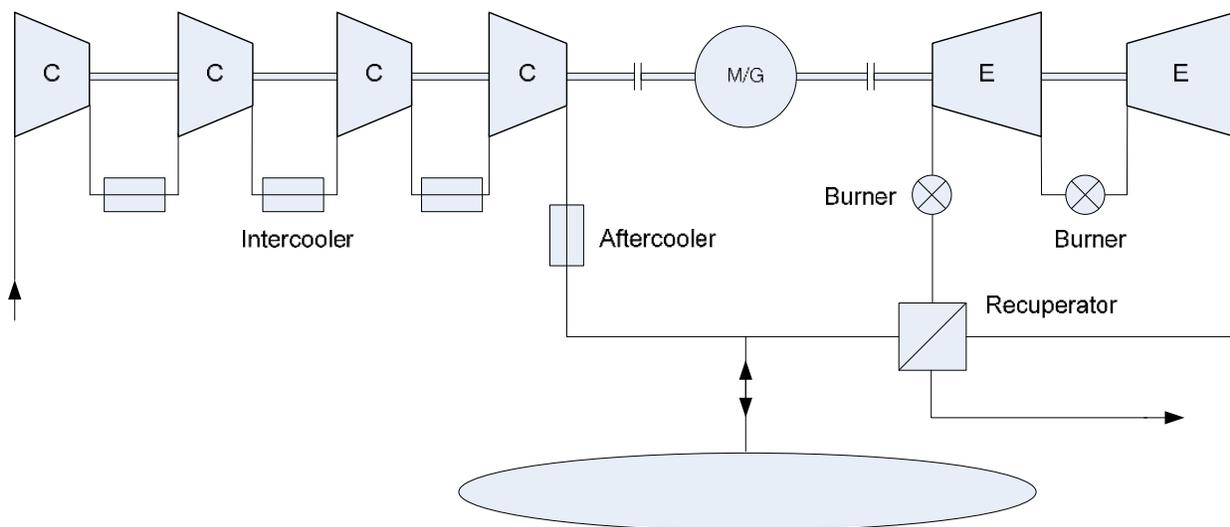
***Adiabatic*** – refers, in general, to processes where heat is not gained or lost. For adiabatic CAES systems, air becomes hot during compression and the heat is carefully stored and used at a later time to reheat the air during expansion.

***Isothermal*** – refers, in general, to processes in which the temperature does not vary. For isothermal CAES, the gas temperature is held at a near constant temperature during compression and during expansion stages, thus increasing the efficiency of the process.

### Conventional CAES

Conventional or diabatic CAES combines mechanical energy storage with combustion turbine technology. There are only two commercial-scale CAES plants in operation today, i.e., one in Huntorf, Germany and one in McIntosh, Alabama. Both of these plants store the compressed air in solution-mined salt caverns. The system has four main components: the compressor, the storage vessel, the combustor and the expander. The conventional CAES, like a gas turbine, is an engine (power plant) that converts the chemical energy of a fuel into mechanical energy. The compression process is accomplished in multi-stage compressors, cooling the compressed air to near ambient temperature between each stage and dumping the

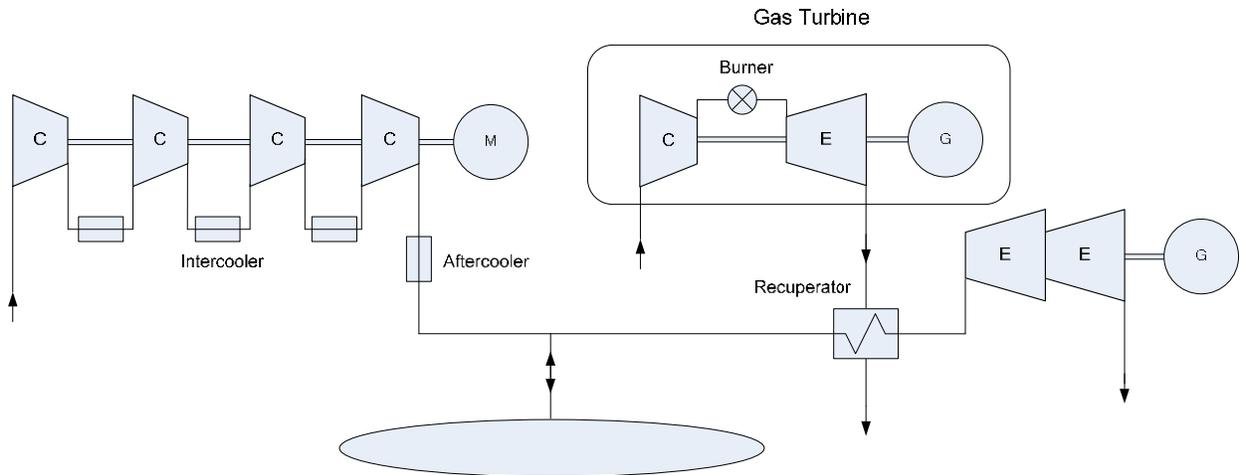
heat of compression to the atmosphere, as seen in Figure 3.3-1. This procedure is standard gas compression technology, and it reduces the energy needed to compress the air. After the last stage, an aftercooler is used, which again reduces the air temperature to near ambient. Cooling the air at this stage is necessary to minimize the thermal stress in the walls of the cavern (Succar and Williams, 2008). The heat of compression is dumped into the environment as waste heat. When energy is needed, the high pressure air is heated and expanded through a multi-stage turbine using fossil fuel combustors. Raising the temperature of the air prior to expansion serves two purposes: it not only prevents the air from becoming excessively cold, which would cause icing of the turbine blades, but it substantially increases the energy content of the air, allowing more power to be produced in the turbine.



**Figure 3.3-1.** Compression process being accomplished in multi-stage compressors (Kim et al., 2012).

### **Second Generation Diabatic CAES**

This design consists of an off-the-shelf combustion turbine that produces typically 40% of the total plant output. The other 60% is derived from a conventional CAES system that uses waste heat from the combustion turbine to heat the stored air before expansion (Fig. 3.3-2). This design is very flexible in size. With the use of different size combustion turbines, these plants can be sized as low as 5 MW and up to 300 MW. Plants based on this design have been proposed for the sites in Seneca, NY, Norton, OH, and Tehachapi, CA.



**Figure 3.3-2.** Schematic of a second generation diabatic CAES plant (Kim et al., 2012).

### **Advanced CAES**

The second class of CAES technologies is called Advanced CAES. The distinguishing feature of these technologies is that they do not use fossil fuel in combustors. They are not hybrid systems but pure storage systems. This CAES system is fundamentally different from Conventional CAES, where power production is derived from both the compressed air, as well as the fossil fuel. An advantage of Advanced CAES is that facilities are not dependent on the economic uncertainty of natural gas price volatility and potential carbon dioxide (CO<sub>2</sub>) emission charges.

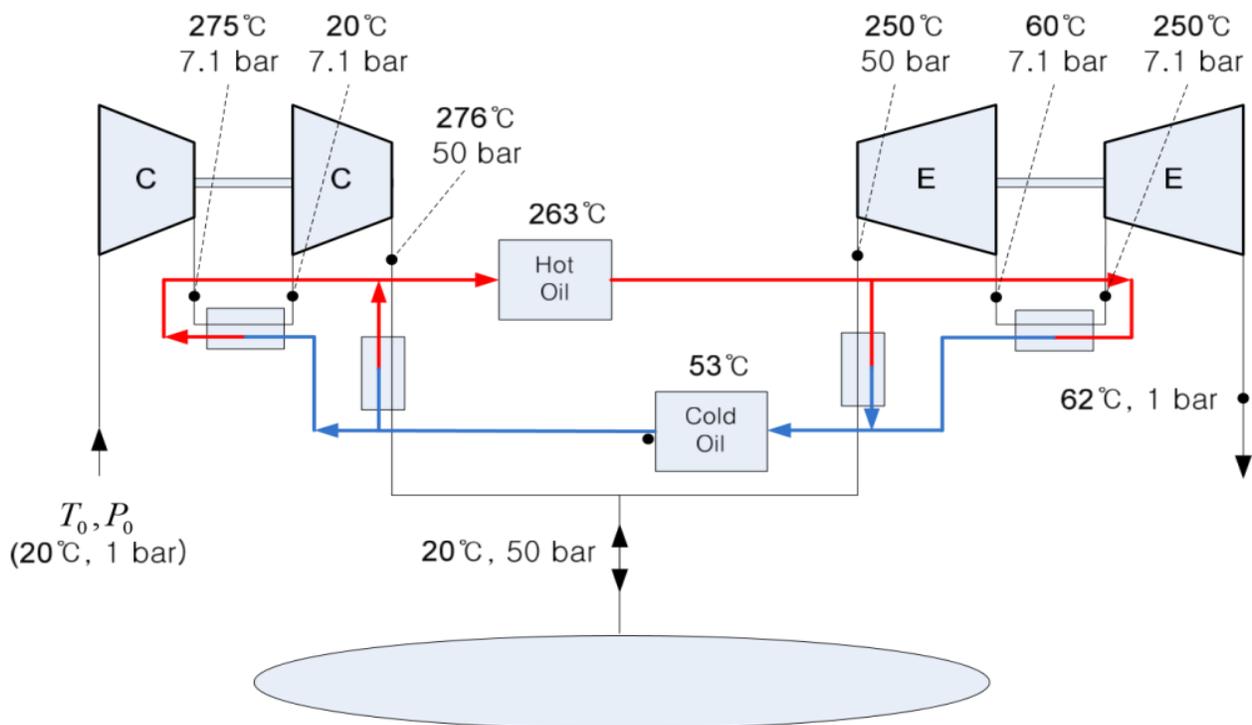
Advanced CAES technologies are emerging technologies, and at the present time, no full-scale facilities are in operation. Several facilities are planned, and at least three commercially viable systems are in development with goals of being viable for deployment in the next decade. Section 3.3 provides more in-depth information on these sites and specific technologies. Within the heading of Advanced CAES, several distinct technologies exist and are described below.

#### *Adiabatic CAES*

In general, an adiabatic CAES facility seeks to improve the efficiency of the compression/expansion processes by storing the heat generated during compression in a thermal energy storage system (TES) and using this stored thermal energy to heat the air during the expansion process, thus avoiding the need for burning fossil fuels. Two methods to accomplish this are being designed and developed: low temperature adiabatic and high temperature adiabatic. These processes are briefly described below.

### Low temperature adiabatic

A schematic of a “low temperature adiabatic” plant is shown in Figure 3.3-3, where C and E represent compression and expansion stages, respectively. This design is similar to a conventional diabatic plant in that it uses multi-stage compression and expansion, but the thermal energy of compression is not dumped to the atmosphere but is stored and used during the expansion. No combustor or additional heat source is used. The thermal energy storage system collects thermal energy from the intercoolers and the aftercooler in a thermal oil that is pumped from a low temperature tank through the intercoolers and aftercooler and stored in a high temperature tank. When the expansion/generation process is going on, a reverse process takes place; the hot oil is pumped to heat exchangers in the multistage expansion process giving up its heat to the expanding air, and the oil is collected back in the cool tank. The round trip efficiency for this type of system has been predicted to be around 60% (Freund et al., 2012). Although no CAES plant using this design has been built, the technology needed to build these units is well known. The disadvantage of this technology is that it is more complex than the diabatic option, and it has higher capital costs.

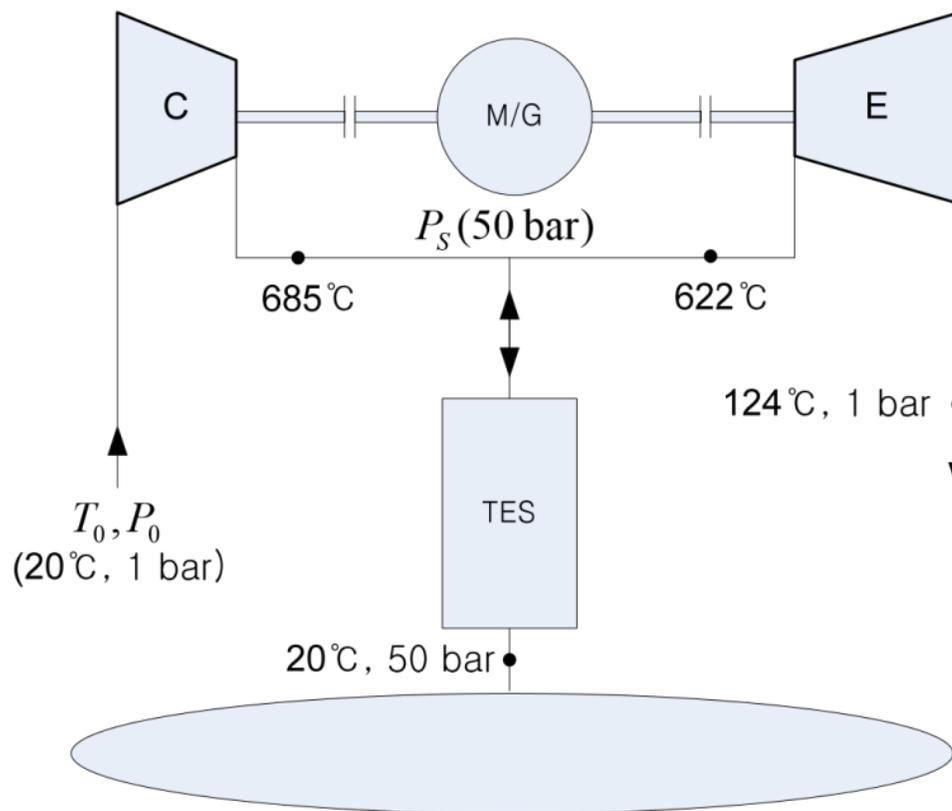


**Figure 3.3-3.** Schematic drawing of a “low temperature adiabatic” CAES plant (Kim et al., 2012).

### High temperature adiabatic

Another advanced adiabatic technology is schematically shown in Figure 3.3-4, where C and E represent compression and expansion stages. M/G is the motor/generator and TES is thermal storage system. This technology is referred to as high temperature adiabatic CAES.

No intercooling is used in this process, and the temperature of the air at the end of compression is quite high. The high temperature air flows through a thermal energy storage device giving up its thermal energy to the stone or ceramic used as a heat exchange material. The air enters the storage vessel at a temperature near ambient. When the air is released from the pressure vessel, it regains the heat that it has given up to the stones or ceramic and is expanded through the turbines. Although no plants have been built using this technology, round-trip efficiencies of up to 70% are predicted. A schematic of this design is shown in Fig. 3.3-4. A plant using this technology is slated for construction in Germany (Department of Energy Storage Database, 2014).



**Figure 3.3-4.** Schematic of high temperature adiabatic CAES (Kim et al., 2012).

### *Isothermal CAES*

Isothermal CAES or, as it has been more appropriately called, near-isothermal CAES, is being developed on several fronts, and the stage of its development is from the conceptual to the near-commercial (EPRI, 2015). An Isothermal CAES facility seeks to improve the efficiency of the compression/expansion cycles by keeping air temperature constant during compression and expansion stages. The innovations are focused on technologies for rapid heat exchange processes that occur within the compressor/expander and provide the ability to hold the air at a near-constant temperature (Yan et al., 2015; McBride et al., 2013; LightSail.com, n.d.). Because the air temperature is kept low, higher pressures can be achieved compared to conventional CAES, and the systems can avoid design of special high temperature components. Isothermal CAES innovators are also incorporating cost-effective above-ground air storage and do not rely on fossil fuel combustion in power generation. Efficiency goals are around 50-70% (EPRI, 2015).

At present time, no Isothermal CAES facilities exist, and a limited number of vendors are developing utility scale systems. In Section 3.3, more information is provided on these emerging companies and details on their Isothermal CAES platforms.

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**Section 3.4:  
Survey and Analysis of Existing or Planned CAES Plants**

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## **SURVEY AND ANALYSIS OF EXISTING OR PLANNED CAES PLANTS**

This section provides a summary of characteristics for existing or planned CAES facilities and technologies. This chapter is not a comprehensive survey and includes only sites that are in operation or facility/technologies that are in final stages of commercial development. Projects that are in early planning phases or feasibility phases are not included. The sources of this information are from the published literature, website, and other communications. The first plants to be reviewed are Conventional CAES plants. These are hybrid plants, being part storage and part power plant. The last reviews are Advanced CAES plants. These are true storage systems that store both compressed air and the heat of compression.

### **Huntorf CAES Plant**

The Huntorf CAES (Fig. 3.4-1) is the first utility scale compressed air storage facility in the world. The facility is located in Bremen, Germany, designed by Brown and Boveri, and owned by E.ON SE energy in Germany (Clean Energy Action Project, 2012; Brown Boveri Review, 1986). It was commissioned in 1978. The plant produced 290 MW. It was upgraded in 2006 and now produces 321 MW for over two hours. The plant was designed to provide full power very quickly (Clean Energy Action Project, 2012). This facility is a conventional CAES plant. The plant has two solution mined salt caverns of 140,000 m<sup>3</sup> and 170,000 m<sup>3</sup>, totaling 310,000 m<sup>3</sup> at a depth of 650 to 800 m from the ground surface. Although the plant could have been designed with a single large cavern, having two independent caverns adds to the reliability of the plant. The normal operating pressure of the cavern range is 43-70 bar (624 to 1015 psi) (Crotagino et al., 2001). The plant is a single shaft design with a single synchronous motor/generator connected with clutches to the compressor and turbine trains. It is reported that the gas turbine generator can be started rapidly and reach full speed within six minutes. The plant not only takes advantage of price arbitrage but can participate in ancillary markets for peak shaving and for black start services (Brown Boveri Review, n.d.; Brown Boveri Review, 1986; E.On, 2015).



**Figure 3.4-1.** Image of Huntorf CAES facility (E.On, 2015).

### **McIntosh CAES Plant**

McIntosh Alabama plant (Fig. 3.4-2) was commissioned in 1991. It is a 110 MW plant with 26 hours of storage. The design is based on the German Huntorf plant. The turbo machinery was manufactured by Dresser-Rand (Department of Energy Global Energy Storage Database, 2015). Air storage is achieved in a single solution mined salt cavern. The cavern is about 238 feet in diameter and about 900 feet long, yielding a volume of about 40,000,000 ft<sup>3</sup> or 1,100,000 m<sup>3</sup>. The cavern pressure range is from 45 to 76 bar (650 to 1,100 psi) (Department of Energy Global Energy Storage Database, 2015).

The plant is a single shaft design with a single motor/generator connected through clutches to the compressor and the generator. It uses multi-stage compressors with intercoolers and an aftercooler. The turbine train has both a high and low pressure turbine with each turbine preceded by a gas fired combustor. One of the differences between this plant and the Huntorf plant is that this plant is equipped with a recuperator that preheats the air going to the high pressure combustor using waste heat from the low pressure turbine. With the addition of the recuperator, efficiencies of around 54% can be reached. Being able to run efficiently at 10 to 25% of full-load capacity, the plant can also be used as spinning reserve. The plant can start up in 15 minutes. The plant is used for arbitrage, frequency regulation, and spinning reserve (Department of Energy Global Energy Storage Database, 2015; PowerSouth Energy, 2014; Dresser-Rand, 2010).

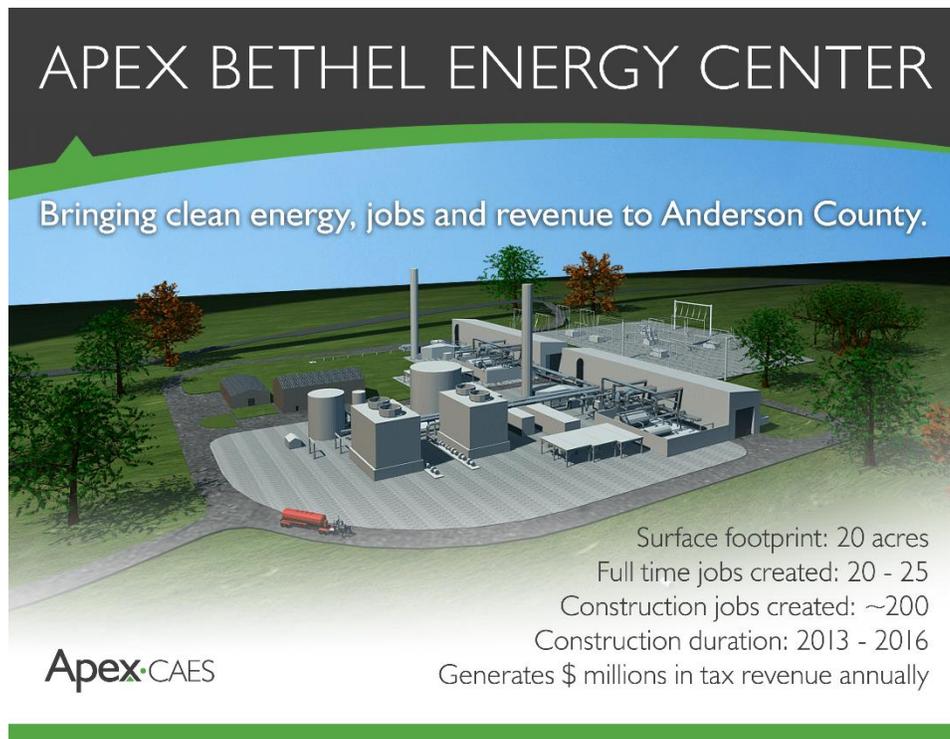


**Figure 3.4-2.** McIntosh CAES plant (Department of Energy Global Energy Storage Database, 2015).

### **APEX Bethel Energy Center, LLC (APEX)**

The Apex Bethel Energy Center (APEX) is designed and ready for construction (Fig. 3.4-3). Its proposed site is located at Tennessee Colony, Anderson County, Texas. The construction is now on hold with a decision to begin construction to be made in the summer or fall of 2015 (Industrial Info Resources, 2015). The proposed APEX plant is a 317 MW that can run at full power for approximately 100 hours (EPRI, 2014a). The compression and expansion equipment will be supplied by Dresser-Rand (St. John, 2013). The proposed storage cavern will be in a solution mined salt dome; the mining is expected to take 700-800 days. The cavern will be at a depth of about 3,750 feet. The operating pressure of the cavern will be 1,900 to 2,830 psi (131 to 195 bars); APEX Bethel Energy Center, 2012).

The Apex CAES plant will have two multi-stage compressors trains and two expansion/generation trains. The compressor and expansion/generation trains will be completely separate and able to work independently. Each of the compressor trains will be powered by a 150 MW synchronous motor. The motors will be connected to the compressor trains by a clutch that can be disengaged so that the disengaged motors can act as synchronous condensers used for grid voltage control and ancillary service. Because of the high pressure available in the cavern, an additional high-pressure turbine was able to be added to the standard 136 MW expansion trains, increasing the maximum power of each train to 158 MW and the total plant power to 317 MW. The plant as a whole will be able to run efficiently at 10% of its total capacity, and an economic analysis predicts that the plant will run at from 10 to 20% of its full load for much of the time, thus being able to sell its service as regulation or spinning reserve, and at other times, the same analysis sees the plant running at full power (APEX Bethel Energy Center, 2012).



**Figure 3.4-3.** Apex Bethel Energy Center conceptual image (Department of Energy Global Energy Storage Database, 2014a).

### **New York Power Authority CAES**

This proposed CAES facility is an above-ground plant that would be built in the New York City Area. The size of the facility is planned at 10.5-12 MW for 4.5 hours. The plant would be a second generation CAES plant (see Section 3.3). It would use the exhaust from a stand-alone combustion turbine to heat the compressed air before it enters the CAES expansion turbine (EPRI, 2014a). The output of the plant would be a combination of the gas turbine plus the output waste heat of the expansion turbine.

The air would be stored in large diameter steel pipes similar to those used by the gas pipeline industry. Although the storage is called above ground, the pipes would actually be buried in trenches with about two feet of soil covering them. Burying the pipe in trenches avoids the added expense of racks to hold the pipes; it also allows the pipe to come under the American Petroleum Institute (API) codes instead of the ASME codes for above ground storage pipe, which are more stringent. Approximately 12,000 feet of pipe would be used and have a volume of 85,000 ft<sup>3</sup> or 2,400 m<sup>3</sup> (EPRI, 2014a,b). This plant could be used for arbitrage, spinning reserve, frequency regulation, and black start (Kou, 2012). As of September 2014, the plant was at a go/no-go decision point (EPRI, 2014c).

### **Adele CAES Project**

Adele is the first adiabatic CAES project to be constructed. Adiabatic indicates that the heat that is created during air compression is stored onsite, and then returned to the air during air expansion. The facility is located in Staßfurt, a city in Sachsen-Anhalt, Germany and has a design rated power output of 200 MW for five hours (Department of Energy Global Energy Storage Database, 2014b). The project is a joint effort between RWE, General Electric, Zueblin, and the German Aerospace Center (RWE Power, 2010). Literature suggests that plant construction began in 2013, but no operational information or photographs were located; therefore, it is assumed that the project is still under construction (Department of Energy Global Energy Storage Database, 2014b).

### **SustainX CAES**

SustainX is a U.S.-based high-technology company focused on developing a commercially viable isothermal CAES system. SustainX completed a 1.5 MW, 40-minute prototype factory test plant at their corporate headquarters in Seabrook, Vermont. This plant became operational in December 2013. The test plant uses above ground storage in large diameter gas-line piping (Fig. 3.4-4). The full-scale system is still in its development phase, and all the details of the system are not yet published. The combined compressor/expander of the SustainX system is derived from a marine diesel reciprocating engine. The compressor/expander will be connected to variable speed permanent magnet motor/generator that then connects to the grid through a solid state converter-inverter. These components of the system are mature technologies; however, to make their system as close to isothermal as possible, efficient and rapid methods of heat transfer are needed and have been the focus of research and development within the company (Department of Energy Storage Database, 2014c). SustainX has reported innovative solutions to heat transfer by using a proprietary water-based foam that is injected into the cylinders during the compression and expansion processes (McBride et al., 2013). The company says that the heat of compression is stored and later transferred to the expansion process. The high pressure air will be stored above ground in natural gas type pipes; however, these pipes could be buried in shallow trenches near the surface. The air will be stored at 207 bar (3,000 psi). The system has very fast ramp rates going from cold start to full power in less than 60 seconds. The capital costs of the system are expected to be about \$500/kWh in the 2015 time frame and decreasing from there in the future.

SustainX has recently abandoned its plans to use above ground storage and announced a merger with General Compression, a former competitor in CAES focused on coupled development of wind energy/storage system, forming a new enterprise called GCX Energy Storage. This new enterprise will use underground storage in salt domes (St. John, 2015a).



**Figure 3.4-4.** Image of SustainX prototype facility (Department of Energy Global Energy Storage Database, 2014c).

### **LightSail Energy CAES**

LightSail Energy is a high-technology company based in Berkeley, California actively working to develop scalable isothermal compressed air energy storage. Limited published information is available detailing the technologies in development. Much of the research focus is on development of heat transfer technologies using water mist. The approach is used to quickly remove heat from the compression process and in the same way add heat back into the system during expansion. LightSail is also developing above ground storage approaches that are also easily scalable. LightSail website indicates power unit sizes of 250 KW and storage units with energy storage of 750 KWH (LightSail, 2015; St. John, 2015b).

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**Section 3.5:  
Development of Preliminary Engineering Design Parameters  
to be Considered in Planning and Design of a CAES Plant**

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## **OVERVIEW OF CAES FACILITY DESIGN PROCESS**

This section is a summary of the salient parameters, variables, and design guidance that should be considered in site selection and design of a CAES facility. The information provided below is gathered from available literature and publications.

### **Motivation for Developing Energy Storage. Why build?**

Construction of a large CAES facility is a major undertaking with many associated risks. Like all large infrastructure projects, the development process involves engaging public and private stakeholder groups; developing financial/business plans; hiring engineering services across a range of technical disciplines, conducting environmental assessments, permitting, and monitoring; and carrying out construction, commissioning and operation. The development of a CAES facility obviously needs to meet an identified need within the power transmission system and have financial viability.

The Facilities Team considered this issue from the perspective of the local industry/municipality, the regulated utility, and the regional transmission operator (RTO).

### **Local Industry/Municipality**

Large scale industries and communities may have need for energy storage. For example, communities located in remote or isolated regions may benefit from having local storage to ensure electricity is available and affordable in times of need. Some common motivations for this scale of CAES facility include:

- Backup energy supply to protect against loss of transmission system in remote regions (e.g., island communities or remote communities);
- Direct linkages to intermittent renewable energy generation such as wind energy plant or solar plant; and
- Communities or organizations seeking carbon free energy and energy storage.

In general, smaller scale CAES will not impact on the distribution or transmission system in a significant way. In other words, CAES facilities on the order of 10 MW with less than ~10 hours of storage will not impact the operation of the electric transmission system or offer ancillary services to the system. Therefore, the value of such systems may be realized in the environmental value of the technology (carbon-free) or the ability of the technology to provide back-up to intermittent sources when no other back-ups exist.

### *Regulated Utilities*

Electric utilities often operate in service areas of substantial size and are impacted by and have impact on the distribution and transmission systems. As a utility seeks to balance generation and load within its system, it may identify energy storage as an opportunity. Privately owned electrical energy storage (EES) by utilities is a major area of development (Byrne et al., 2012).

Some reasonable motivations of CAES facilities include:

- Intermittent energy sources exist in service area and there is a need to provide balancing during periods of no wind or sun;
- Energy storage is valued in the energy market and ancillary services can be accessed with the storage technology; and
- There is anticipated growth of load, load centers and this growth will impact currently owned transmission system.

The primary electric utility operating in northern Minnesota is Minnesota Power. Minnesota Power is a large utility that operates conventional generation and renewable generation across the region serving over 144,000 customers and a region 26,000 mi<sup>2</sup> (Fig. 3.5-1; Minnesota Power, 2015a).



**Figure 3.5-1.** Minnesota Power Coverage Map (Minnesota Power, 2015a).

In North Dakota, Minnesota Power operates 500 MW of wind energy. Minnesota Power recently acquired a 465 mile direct current 250kV transmission line that extends from Center, ND to Duluth, MN to bring energy from Minnesota Power's Bison Wind Energy Center to the city of Duluth, MN. The line was purchased to provide transmission capacity to meet the anticipated growth of Minnesota Power wind generation in eastern North Dakota (Renewable Energy World, 2010).

Minnesota Power is currently pursuing a new power purchase arrangement with Manitoba Hydropower through which a 500kV transmission line will be constructed between Grand Rapids, MN to the Manitoba/Minnesota border. The Great Northern Transmission Line will provide capacity up to 883 MW of renewable energy to Minnesota Power customers and help Minnesota Power meet corporate goals and state requirements for renewable energy. Minnesota Power presently has approximately 500 MW of wind energy from projects located in North Dakota. The Manitoba Hydropower agreement will provide additional capacity and balancing capabilities when wind generation is low (Minnesota Power, 2015b). The Great Northern Transmission Line is targeting operation design in 2016, with an in-service target of 2020.

Minnesota Power has aggressively pursued opportunities to diversify its energy generation portfolio and continues to develop transmission capacity in its system. The agreement with Manitoba Hydropower also provides Minnesota Power balancing capabilities and access to quickly-deployed stored energy through hydropower.

### *Regional Transmission Operator*

Regional Transmission Operators such as Midcontinent Independent System Operator (MISO) have a critical role in defining value structure for energy storage. The markets and market rules create the environment that motivates electrical energy storage. Work by Sandia National Laboratories concludes that grid scale EES “...are uniquely suited to address the variability of renewable generation and to provide other valuable grid services” (Byrne et al., 2012). However, there is variability in markets and market rules throughout the county and the planning of a CAES facility must take care to define and integrate into the design every opportunity to fully participate in the energy market. Examples of the types of considerations that must be carried out include:

- The operational characteristics of CAES technologies have financial value in the energy and ancillary services markets in MISO; and
- Specific geographical locations within the grid that will benefit from grid-scale CAES, and these are valued in the ancillary services or capacity market.

### **CAES Facility Sizing**

One could choose to construct a CAES of virtually any size ranging from one to hundreds of MWs of power and one to hundreds of hours of dispatch. Determining the most profitable and useful storage facility size is an iterative design exercise when developing a CAES facility and requires a careful study incorporating economic dispatch modeling of the facility within the specific region planned for development. We note that this project is looking within the service area of MISO. Past projects have conducted analysis of the historic performance of the local transmission system, local electric price variability, energy arbitrage, and the specific market rules that pertain to various energy services offered by energy storage. The specifics of these

market rules are not directly the focus of the Facilities Team nor is this project tasked with such a detailed study. We note, however, that there is a direct connection between facilities design and energy economics in determining the appropriate energy capacity and power of the CAES facility.

#### *Determining CAES Facility Size*

1. What are the load and pricing characteristics of the transmission system within the potential site locations or service node(s)?
2. What duration of time is available for recharging (pressurizing) the cavern?
3. What duration of time would be ideal for discharging the cavern? When is pricing high and for how long?
4. Evaluate charging at night and discharging during the day. Evaluate charging on the weekend and discharging during the week. Evaluate multiple charge/discharge cycles within a single day;
5. For conventional plants that will use gas-turbines, evaluate gas price fluctuations (monthly time scale); and
6. If applicable, evaluate benefits from ancillary services (spinning reserves, black start services, and frequency regulation) and capacity credit.

#### **Air Storage/Subsurface/Geology**

The primary design variable for a CAES facility is the storage facility. For utility scale facilities (100s of MW of power), a substantial volume of space must be available to hold the pressurized air. The location of the cavern, and therefore, the location of the surface facility, is set by the near surface geology. In all cases of published facility design, the identification and engineering verification, and design of underground storage is the critical first step of the project. As an example of the importance of this subsystem, the 270 MW Iowa Stored Energy Park was terminated after the geologic investigation identified unfavorable subsurface conditions (Schulte et al., 2012).

#### *Determining the physical location of the underground storage cavern*

1. Where are viable locations of subsurface geologic formations (latitude, longitude, depth and extent)?
2. What are the quality, character, and coherence of subsurface geology?
3. Estimate the subsurface rock permeability considering rock structure, fractures, faults, and joints. Will the rock hold pressurized air?

4. Determine proximity of viable subsurface rock bodies to desirable surface features, such as:
  - a. available real estate, hard and soft costs for acquiring/leasing land;
  - b. distance and size of transmission service, interconnection points;
  - c. distance to surface water for cooling, volume of reservoir water and water quality; and
  - d. surface water for pressure regulation in the subsurface cavern.
5. Cavern volume potential: Does the rock body have the potential to be developed, with respect to design volume of the system and to the design pressures and duty cycle of the designed system? and
6. What is the hydrogeologic situation at the potential site? What is the general flow field? Is their potential for contaminant transport through ground water flow?

### **Above Ground Works**

The bulk of a CAES plant is located above ground and has similar elements as a conventional power plant. The size of the facility will be determined by the generating capacity and the technology schema selected. The design of the facility will be unique to the plant, but the primary features will include the following:

1. Office space, conference room for facility personnel;
2. Spare parts and operation and maintenance storage areas;
3. Shop space for tools and repair and facility vehicles;
4. Communication systems telephone and high-bandwidth network connections;
5. Facility space for primary compressed air energy equipment:
  - a. Compressors;
  - b. Expanders;
  - c. Heat exchanger;
  - d. Valves and fluid flow meters;
  - e. Piping;
  - f. Motor/generator; and
  - g. Control systems;
6. Electrical interconnection equipment including appropriate feeder lines, station power, switch gear and transformers; and
7. Conventional CAES will require natural gas piping sized to meet the requirements of the facility.

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**Section 3.6:  
Review of Important Energy Market Regulation  
and Rules Affecting Facility Design and Operation**

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## FACILITIES TEAM PERSPECTIVE ON ENERGY ECONOMICS FOR CAES

CAES facilities participate in financial markets with the ability to participate in the wholesale energy and reliability services markets. Section 3.5 highlighted the importance for strategic planning for how a CAES facility fits into the complex puzzle of energy markets and transmission system reliability. In this section, a brief summary of the main markets and services that are associated with electrical energy storage, and specifically CAES, is provided.

### Regional Transmission Organization

The Midcontinent Independent System Operator (MISO) is responsible for reliability, planning, and market operations within its service area (Figure 3.6-1). The state of Minnesota is included in this region. Because market rules vary from region to region, the following discussion is from a northern Minnesota perspective, but the information is applicable to other regions as well.



**Figure 3.6-1.** Midcontinent Independent System Operator U.S. market area (MISO Energy, 2014).

### Energy Market Structure

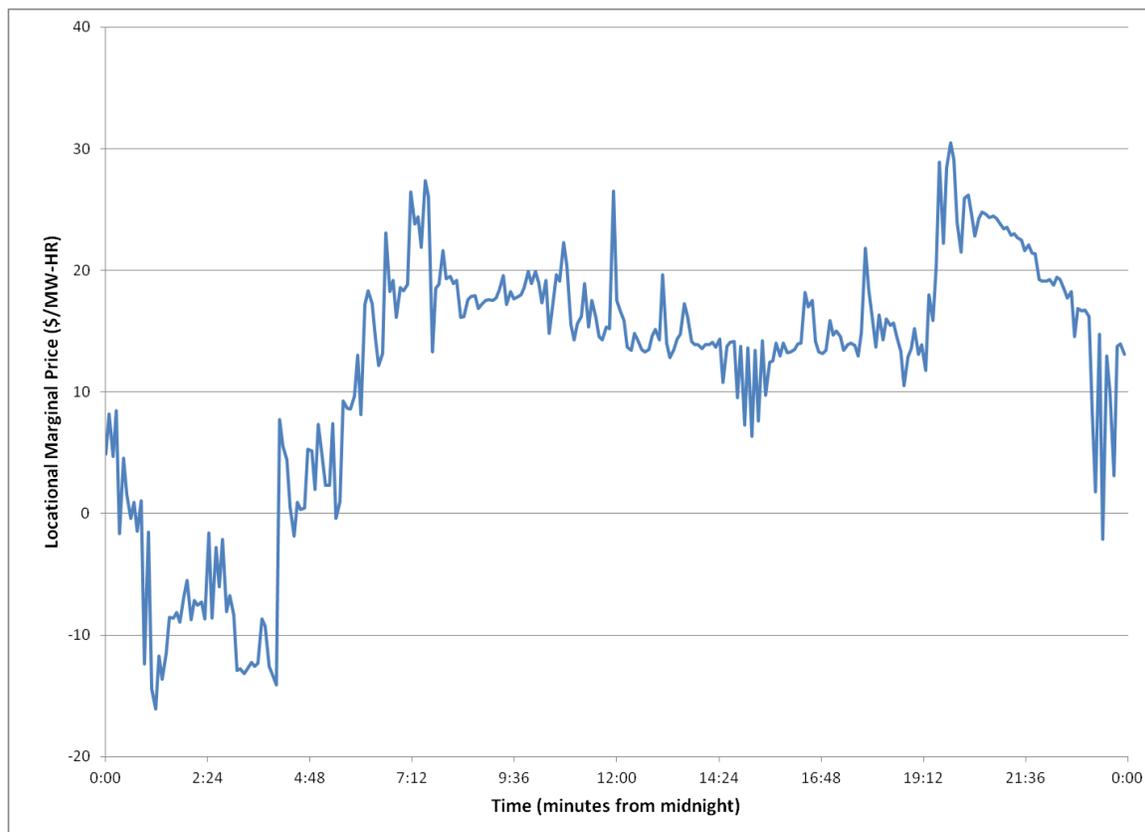
The regional energy market is managed by Independent System Operators or Regional Transmission Organizations following rules and guidelines of National Electrical Reliability Council and Federal Energy Regulatory Commission. Energy markets are controlled and managed through wholesale energy markets and reliability services markets.

### Wholesale market

These markets include the *day-ahead market* and the *real-time market* and include direct bidding and sale of electricity. In simplest terms, the day-ahead market is an “auction market” and energy producers/facilities provide price-quantity information, i.e., bids, to the ISO for tomorrow’s energy. The ISO selects bids and determines the day ahead energy generation forecast and load forecast, and locational marginal pricing (LMP) is determined (Paine et al., 2014).

The real-time market works in conjunction with the day-ahead market but, as the name suggests, works real-time to match the day-ahead generation schedule to actual generation and actual load. The pricing of real-time market couples the day-ahead bids with actual performance and provides the mechanisms to compensate for energy production commitment and actual performance (Paine et al., 2014).

The LMP varies in time and location and is a function of day-ahead and real-time supply/demand. Figure 3.6-2 is a plot of the LMP for a 24-hr. period of time at a node in northern Minnesota. Price arbitrage, which is mentioned throughout this report, is the potential difference in LMP over a storage cycle, e.g., charge and discharge of a CAES facility. Price arbitrage is often cited as the primary financial strategy of CAES facilities.



**Figure 3.6-2.** Plot of locational marginal price for a 24-hour period in northern Minnesota. Data source is MISO.

### *Reliability services markets*

ISOs are responsible for providing system reliability, efficiency, and contingency planning within their service area and do so, in part, by providing value for certain reliability and ancillary services. The specific mechanisms or services are common; however, the rules for how they are accessed by generating facilities vary with RTO/ISO. Work by the North American Electric Reliability Corporation (NERC) categorizes reliability services into three building blocks: *Load and Resource*, *Voltage Support*, and *Frequency Support* and within each of these are specific services that are necessary to provide reliability for bulk power systems (NERC, 2014).

Ancillary services are a subset of reliability service and are the core services necessary for reliable system operation. Table 3.5-1 summarizes ancillary services including required/desired attributes of each for response speed, duration, and cycle time.

### *Ancillary Services*

*Regulating reserve* – a generating resource that can be dispatched remotely by the operator to quickly meet load demand. Estimated required response times are on the order of one minute. Large CAES facilities have the ability to provide regulatory reserve; however, they may be limited based on the size of energy storage capacity.

*Load following* – generating resources that are slower than regulating reserve but, again, can be dispatched by the operator and help meet changes in load. Response speed is ~10 minutes. Again, CAES facilities may be able to provide this service but may be limited by power and capacity of the facility.

*Spinning reserves* – generating reserves that are available to immediately be utilized if there is a major failure of another generating facility in the system. Spinning reserves are generators that are synchronized to the grid and can output power very quickly. Response speed is short (seconds to <10 minutes). CAES facilities could be designed with synchronous generators.

*Non-spinning reserve* – generating reserves are similar to spinning reserves; however, the generators need to be started and run-up until they are synchronous to the grid and then can immediately output power. Response time is <10 minutes. Large CAES facilities are fully capable of providing non-spinning reserve.

*Supplemental reserve* – generating facilities that take longer to get online but are reserved in case failures occur. Once supplemental reserves are online and are producing power, spinning and non-spinning reserves are put back into reserve status. Response time is <30 minutes. Large CAES facilities are fully capable of providing supplemental reserve.

*Black start* – generating facilities capable of starting without any additional power from the grid. Generators are able to be spun up to synchronous speed and generation of power can begin. CAES facilities are certainly capable of black start services but may need to be supplemented with additional systems to complete. Huntorf has one cavern dedicated to black start.

**Table 3.6-1.** Summary of Ancillary Services (Kirby, 2007).

Service	Service Description				
	Response Speed	Duration	Cycle Time	Market Cycle	Price Range* (avg./max.) \$/MW-hr.
<b>Normal Conditions</b>					
Regulating Reserve	Online resources, on automatic generation control, that can respond rapidly to system-operator requests for up and down movements; used to track the minute-to-minute fluctuations in system load and to correct for unintended fluctuations in generator output to comply with Control Performance Standards (CPSs) 1 and 2 of the North American Electric Reliability Council (NERC 2006).				
	~1 min.	Minutes	Minutes	Hourly	35-40 200-400
Load Following or Fast Energy Markets	Similar to regulation but slower. Bridges between the regulation service and the hourly energy markets.				
	~10 minutes	10 min. to hours	10 min. to hours	Hourly	-
<b>Contingency Conditions</b>					
Spinning Reserve	Online generation, synchronized to the grid, which can increase output immediately in response to a major generator or transmission outage and can reach full output within 10 min. to comply with NERC's Disturbance Control Standard (DCS).				
	Seconds to <10 min.	10 to 120 min.	Hours to Days	Hourly	6-17 100-300
Non-Spinning Reserve	Same as spinning reserve, but need not respond immediately; resources can be offline but still must be capable of reaching full output within the required 10 min.				
	<10 min.	10 to 120 min.	Hours to Days	Hourly	3-6 100-400
Replacement or Supplemental Reserve	Same as supplemental reserve, but with a 30-60 min. response time; used to restore spinning and non-spinning reserves to their pre-contingency status.				
	<30 min.	2 hours	Hours to Days	Hourly	0.4-2 2-36
<b>Other Services</b>					
Voltage Control	The injection or absorption of reactive power to maintain transmission-system voltages within required ranges.				
	Seconds	Seconds	Continuous	Year(s)	\$1-\$4/kvar-yr.
Black Start	Generation, in the correct location, that is able to start itself without support from the grid and which has sufficient real and reactive capability and control to be useful in energizing pieces of the transmission system and starting additional generators.				
	Minutes	Hours	Months to Years	Year(s)	-

### **CAES and Ancillary Services**

It is well documented that CAES facilities need to be able to access both the wholesale market, i.e., arbitrage, as well as ancillary services markets to be financially viable (Kirby, 2007; Paine et al., 2014; EPRI, 2014). For example, Kirby (2007) compared a 100 MW hypothetical gas-fired generation plant with energy sales only and then with energy sales and ancillary services. The model showed that profits of the facility could be increased by 17-250% with ancillary services. Financial viability is also dependent on the location of the facility and the market rules of the system operator. Paine et al. (2014) showed through modeling that a large pumped

hydro facility, simulated in two different ISO regions, had a 240% difference in weekly operating profits. CAES facilities differ from Pumped Hydro Energy Storage, but the importance of region is the same.

In the following section, the analysis turns to focus on three specific sites where CAES facilities are conceptually designed. The energy economics discussed briefly in this section will be applied in the feasibility of these sites.

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**Section 3.7:**  
**Preliminary Design of Three CAES Sites Selected in Northern Minnesota**

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## **SITE EVALUATIONS: SUMMARY**

The project team conducted conceptual design and feasibility evaluation of three CAES facilities. Two facilities are located in northern Minnesota within the Mesabi Iron Range, and the third facility is located on the Cuyuna Range in central Minnesota. The goal of this exercise is to provide an overview of technology, facility configuration, and financial model for operation.

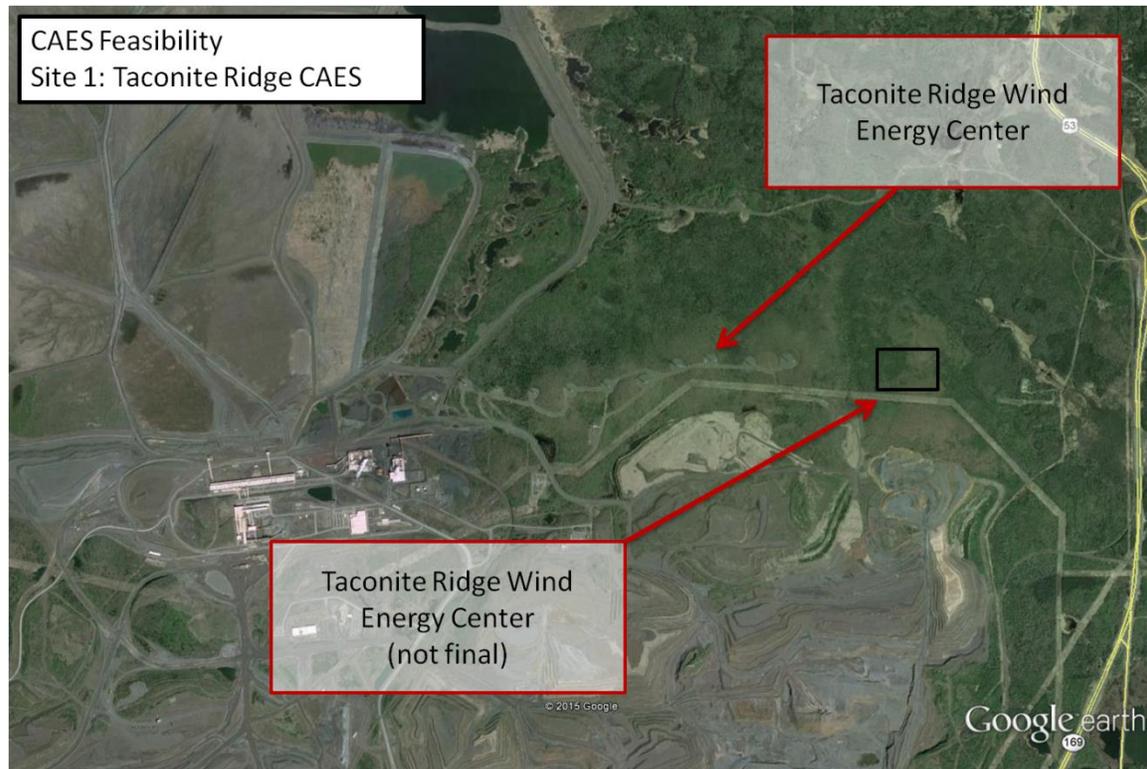
### **Site 1: Taconite Ridge**

#### *Site description and location*

Site 1 is named Taconite Ridge CAES and is associated with an existing 25 MW wind plant owned and operated by Minnesota Power. The wind plant, called Taconite Ridge Wind Energy Center (TR), is comprised of ten, 2.5-MW Clipper Liberty C96 wind turbines with a total nameplate capacity of 25 MW. The site was commissioned in 2008 and is interconnected into Minnesota Power's transmission system. The location of the wind plant is four miles north of Mountain Iron, MN in St. Louis County (Latitude: 47° 34' 22.2"; Longitude: -92° 36' 0.6").

Electricity produced by TR is transmitted to the local electrical distribution and transmission systems through a substation located to the south of the wind plant. There are no special operational protocols for the site other than to produce electricity when the wind resource is available. The site was created to help Minnesota Power achieve a company goal of 1/3 energy from renewable sources. It is noted that there are times when the locational marginal price for energy in this region of northern Minnesota becomes extremely low or negative, suggesting that there may be opportunity for storing energy during these times. See Fig. 3.5-2 for LMP for a single day in April 2015.

The actual location of the CAES facility is not specified here and would require a siting analysis. The property in the region is owned by U.S. Steel Corporation. The actual CAES technology for this site (discussed below) will not use underground storage, and therefore is not tied to a specific location as would be the case with an underground storage cavern. Figure 3.7-1 is a location map showing the Taconite Ridge Wind Energy Center as well as a hypothetical location for the CAES facility. Estimates for facility footprint ranges between 1.0-3.5 acres for above ground facilities in the size range of 45-55 MWh (EPRI, 2014a). The location shown in Fig. 3.7-1 is owned by the local mine and would need to be leased or purchased for the facility.



**Figure 3.7-1.** Location map for Site 1: Taconite Ridge CAES.

### *Basis for design*

The desired goal of this site was to evaluate an Advanced CAES facility that was coupled with wind energy production. The project team sought to select a technology that could be designed with above ground air storage and non-fossil fuel power generation. As a starting point, the capacity and duration of the CAES facility was chosen to be 30% of the Taconite Ridge Wind Energy Center's generating capability (7.5 MW) and a storage duration of five hours, which was chosen based on typical durations for similar sized projects and is the same approximate duration of daily peak demand.

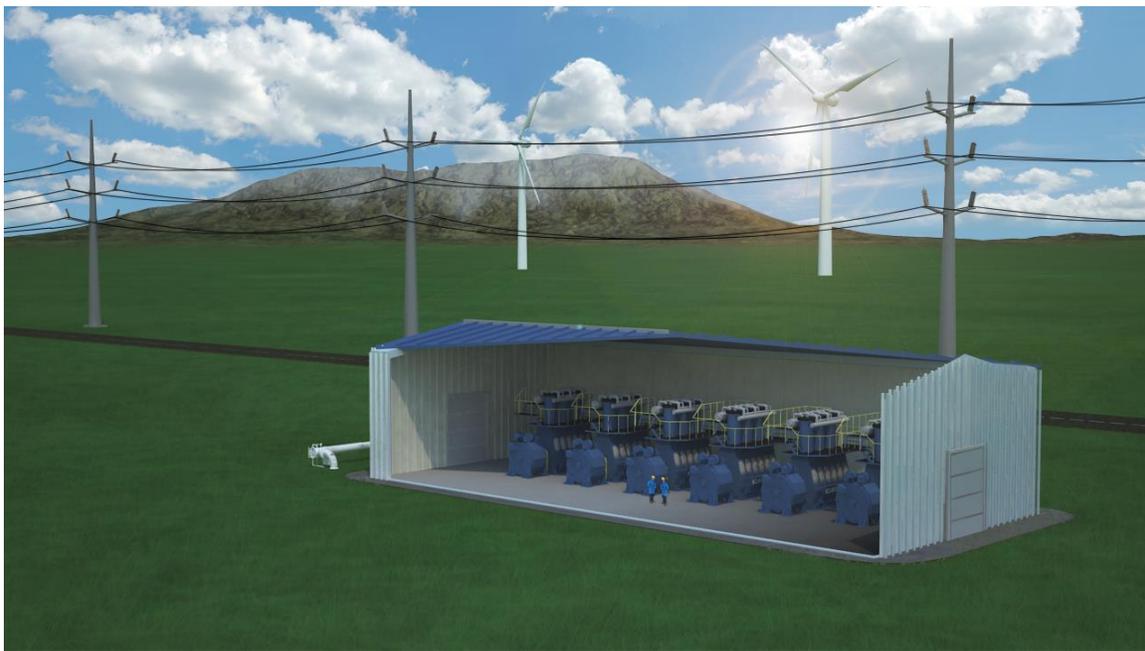
Section 3.4 provided a summary of existing and emerging advanced CAES technologies, which include adiabatic and isothermal approaches. Presently, there are no Advanced CAES facilities in operation today. Several facilities are in design and various stages of construction planning, and a small number of new emerging technologies are available for consideration (LightSail, General Compression, SustainX, Dresser-Rand Adiabatic).

For this site, the facilities team chose to design for an isothermal CAES schema and specifically using the SustainX systems. We note that a recent press release suggest SustainX has merged with General Compression and formed a new entity GCX Energy Storage (St. John, 2015). Since no further information is available on this restructure, our design is based on published information on SustainX technology.

The facility design seeks to optimize profitability by taking advantage of wholesale energy markets and ancillary markets as much as possible. The SustainX system provides these capabilities and is discussed in more detail below.

### *Facility design*

The Taconite Ridge CAES facility conceptual design is an above ground facility with capacity of 7.5 MW and duration of five hours. Total energy of the facility is 37.5 MWh. Using available literature for Advanced CAES and other above ground storage sites, the Facilities Team developed this conceptual design (Fig. 3.7-2).



**Figure 3.7-2.** Rendering of SustainX CAES facility (SustainX Inc., 2015a).

### Generator and Crankshaft

The site will use five 1.5MW compressor/expander modules. The single reciprocating piston module serves as both compressor and expander. This module is coupled to a 1.5 MW permanent magnet motor/generator which can run at variable speeds by virtue of the solid state electrical power converter. The unit will operate with six large pistons as a two-stage compressor/expander – three pistons used for low pressure and three for high pressure (SustainX Inc., 2015b; EPRI, 2014b).

This is an isothermal system which attempts to minimize the work needed to compress the air through a near-isothermal compression and maximize the expansion process. These two processes are achieved by the use of a foam, which is injected directly into the cylinders. This

foam serves as a heat transfer fluid removing heat during the compression and adding heat during the expansion (McBride, 2013). The advantages of this system include high round trip efficiencies; the ability to deliver higher pressure air into storage at near ambient temperatures; reduction in capital costs due to the use of a single unit for both the compression and expansion; and the elimination of intercoolers and aftercoolers.

### Air Storage

Air storage will be achieved with above ground storage within large diameter pipes. The facilities team adopts the concept from a similar sized project by the New York Power Authority (NYPA), which is currently in design. The NYPA CAES plant is 10.5MW and 4.5-hour duration using above ground storage in over 2 miles of 3-ft. diameter metal pipe. Since size of the facilities are so similar, the Facilities Team chose an identical design approach herein. The pipe will be buried several feet underground to allow for smaller pipe-wall thickness, and temperature control in the shallow-underground environment, which lowers costs of systems. (EPRI, 2014b). The NYPA Project estimates 12,000 feet of pipe total to provide 4.5 hours of storage. The SustainX system is capable of much higher compression than conventional CAES systems – an advantage of isothermal compression and, therefore, the required volume of storage is much less. Assuming NYPA pressures are in the range of 80 bar (1,160 psi) and SustainX is 200 bar (2,900 psi), a 40% reduction of storage volume is required.

In summary, the air storage design for the Taconite Ridge CAES is for 12,000-ft. of 3-ft. diameter API 5L steel pipe buried 0-5 feet below the ground surface. Total volume of storage is 85,000 ft<sup>3</sup> (2,407 m<sup>3</sup>). The max storage pressure is 200 bar (2,900 psi).

### Heat Storage

The SustainX design is a near-isothermal compression/expansion. An open question with the technology is what is done with the heat removed during compression; the process is not clear in available literature. The technology may a) utilize open-air ponds to modulate temperature of the thermal aqueous foam solution up or down to ambient temperature; b) thermal energy may be stored in a thermal storage systems much like is being planned for the Adele CAES in Germany (See Section 3.4); or c) some other process. The Facilities Team has selected for conceptual design of Site 1 based on an open-air pond for thermal fluid storage and heat exchange with atmosphere. In concept, the surface pond will serve to modulate thermal aqueous foam solution back to ambient temperature by storing the fluid in an open tank with large surface area. During compression, hot fluid will enter the ponds and cool toward ambient temp. During expansion chilled fluids will enter pond and warm toward ambient. No further design is done on this system.

## *Costs summary*

### Capital Costs

Very little information is available in the literature on the capital costs for this technology. Estimates by SustainX range from \$400-\$500 /KWh (EPRI, 2015), which equates to \$15M-\$19M. This estimate incorporates an above ground storage system.

Above ground air storage costs are described in EPRI (2014a) for the 10.5-MW 4.5-hr NYPA facility. The air storage component of the system is estimated at \$600/kW-\$1750 /kW. Applying this rate to the Taconite Ridge CAES facility results in a cost of \$4.5M-\$13.1M storage. Note that the higher pressure storage of SustainX results in 40% of the required volume needed for an 80 bar (1,160 psi) (conventional) storage system.

### Other

Below is summary of additional costs associated with the development of Taconite Ridge CAES:

- Acquisition of property (purchase or long-term lease);
- Site evaluation, environmental impacts (air, water, subsurface, human), and permitting; and
- Interconnection of the CAES facility to the substation as well as development of interconnection and power purchase agreements.

### *Facility operational plan*

The conceptual operational plan for this facility is to maximize its profitability through its participation in the energy and ancillary markets operated by MISO.

### Wholesale energy – Arbitrage

The Taconite Ridge CAES facility will study historic behavior of nodal load marginal price (LMP) and determine when it is most advantageous to compress and store air (low price) and when to discharge electrical energy. It is assumed that the CAES facility is interconnected separately from the wind plant and therefore operational decisions are made independently of that asset. The LMP price is affected by electrical energy production from all generating facilities including 600 MW of wind throughout Minnesota Power's systems (Minnesota Power, 2015). The relative size of this CAES facility is small and will have a negligible impact on the LMP but can still take advantage of price differential. The plant will operate on an approximately diurnal cycle of compression during the late evening and discharge during peak demand.

SustainX estimates a charge cycle duration of 8-hr. is required for 6-hr. discharge cycle (EPRI, 2015).

### Ancillary Services

The Taconite Ridge CAES facility will attempt to access ancillary services markets of MISO. SustainX technologies claim high ramp rates as the primary ancillary benefits service of the technology with the ability to go from cold start to full power in less than one minute (EPRI, 2015). Because the facility is relatively small, it will be limited in what ancillary services markets are available. The following services are potential relevant:

- Regulation reserve;
- Contingency reserve, spinning;
- Contingency reserve, supplemental; and
- Black start.

Determining the value of these ancillary services to the facility is beyond the scope of this study. MISO market rules regarding stored energy resources (SER) are also changing rapidly and need to be assessed at the time of facility feasibility.

### Integration with Taconite Ridge Wind Energy Center

A motivation for a CAES facility at this site is the coupling of storage with the intermittent energy generation of the wind plant. The Facilities Team research could not determine a strong purpose for linking the CAES facility with the generation facility. Both would be interconnected separately from one another. The wind plant will produce and sell energy as the wind resource allows. The CAES facility will be designed and operated to maximize profits through the MISO markets and largely independent of the wind plant.

Minnesota Power seeks to balance power within its service area. One-third of Minnesota Power's generation is from renewable intermittent sources with 600 MW from wind. Storage may be able to add value by providing storage of energy when there is surplus energy. That said, the fact that the CAES facility is relatively small and Minnesota Power has access to large quantities of energy through their agreement with Manitoba Hydropower reduces the benefit of a new CAES facility.

### *Environmental considerations*

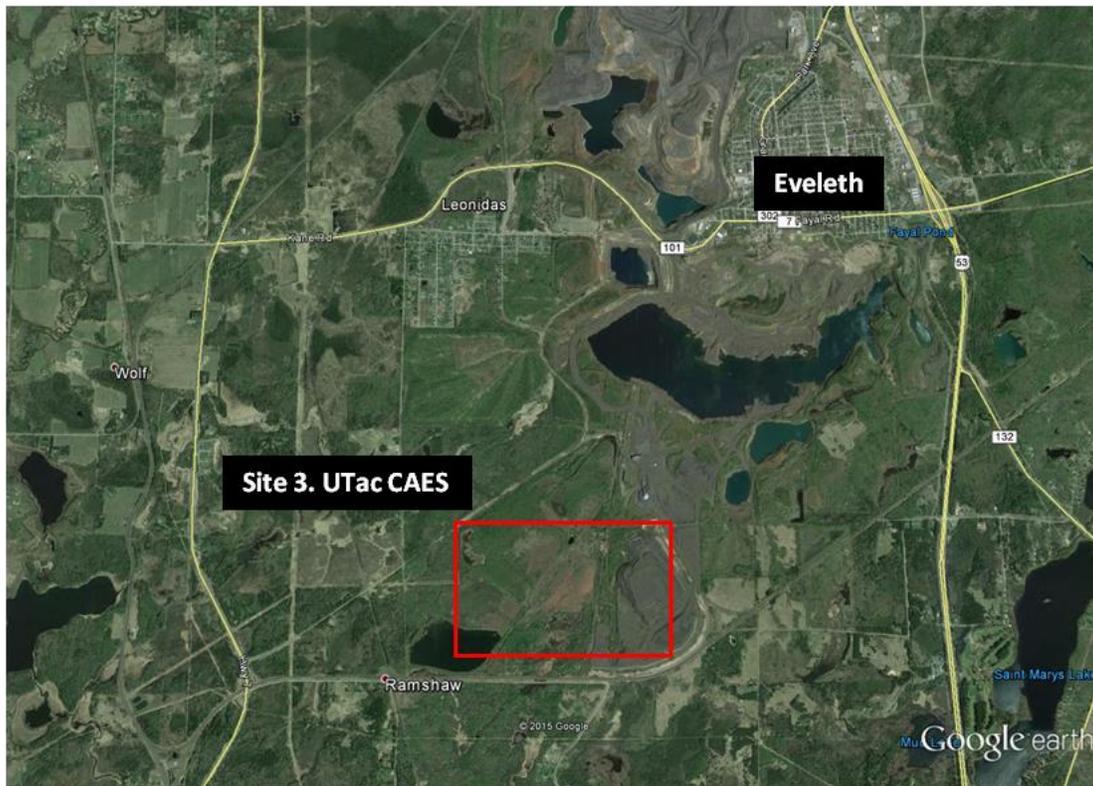
The Taconite Ridge CAES facility is proposed with an above ground air storage facility. The Facilities Team estimates an area less than four acres in size. Additional area may be required for relatively small surface ponds. The plant is designed with fuel-free, isothermal CAES process thus is cleaner than conventional CAES or energy generation plants. The main environmental considerations are listed below:

- Land acquisition – The plant is located near the Laurentian Continental Divide within the Superior National Forest and is considered a highly important environmental location;
- Surface water – no natural surface water will be used at the site. Engineered tanks will be incorporated into the design, which will store aqueous foam solution;
- Air quality – The compression process will intake air for compression and will discharge this air back to the atmosphere after it expands. The quality of air should remain high during the compression/expansion cycle since no fuel-combustion occurs; and
- Human impacts – The CAES facility will have impacts on humans through noise produced by the compression/expansion cycle. No information is available of the noise generated by the five modules.

### **Site 2: United Taconite CAES**

#### *Site description and Location*

Site 2 is named United Taconite Compressed Air Energy Storage Facility (UTac CAES) and the proposed location is two miles southwest of the Eveleth, MN (Fig. 3.7-3). The goal of this site is to explore development of a larger CAES facility in conjunction with the mining activities in the region. United Taconite is an active mine operation owned by Cliffs Natural Resources. The mine has been active since 1965 and produced over 184 million gross tons of useful magnetite ore (Cliffs Natural Resources, 2014). The mine will continue to operate for decades into the future.



**Figure 3.7-3.** Location of concept UTac CAES facility.

The CAES facility is designed with both above ground and subsurface structure. In particular, air storage will be accommodated by a single underground pressurized cavern. The United Taconite site was chosen as a site with known taconite ore at around 1,200-ft. depth. At this site the assumption was made that an underground mining technique would be used to extract taconite ore from the site and that the excavated cavern could then be used as a cavern for a CAES plant. Although in practice, the selection of both the above ground plant and the underground cavern is a very complicated process, some very general assumptions are made in order get an idea of what a CAES plant at this site might involve.

The city of Eveleth has a population of 3700 residents. The United Taconite mine employs over 500 workers from the surrounding communities and reports an annual electrical power purchase of \$31 million (Cliffs Natural Resources, 2014). Minnesota Power is the electrical utility serving this region of Minnesota and the transmission system and energy market is operated by the MISO.

### *Basis for design*

The desired goal of this site was to evaluate a larger CAES facility co-developed with an underground mine. The United Taconite site was selected as a possible location for a CAES plant

because the mine is active with a projected future of subsurface mining. This study examined the CAES facility and also explored coupling the development of creating an air storage cavern along with mining.

The CAES facility size was selected to be 136-MW for 10-hour or 1360 MWh and was determined with input from project advisors, Minnesota Power and Great River Energy, and from the Facilities Team's understanding of commercially available CAES technologies. This moderately sized facility is large enough to provide balancing capabilities for an electric utility. Facilities of similar size are described in various literature and reports, which was helpful in carrying out the study.

The design selected an underground storage cavern for the compressed air. Because an abandoned cavern does not exist in this area, the project team considered an approach in which the air storage cavern would be created during the process of mining ore. Once mining of the subsurface ore is completed, the cavern would be conditioned for high pressure storage of compressed air.

A conventional, fuel-supplemented CAES facility was selected for the above ground facility. Because advanced, fuel-free CAES technologies are still early-stage, it seemed most useful to examine conventional design for this facility.

A plant of this size (1360 MWh) would also be of benefit to the power utilities and MISO through power generation and through ancillary services such as regulating reserves, contingency reserves and other ancillary services. In the sections below, more detail is provided on participation in wholesale and ancillary services markets.

### *Facility design*

The conceptual design for the UTAC CAES Facility was for a conventional fuel-supplemented generation technology and subsurface storage. From available literature the following conceptual design was developed.

### Surface Facility

The facilities team looked at a number of options for compression/expansion and electric power generation. The example plant at United Taconite is based on the 136 MW Dresser-Rand SmartCAES plant similar to that proposed for the Seneca NY CAES facility described in the National Energy Technology Laboratory (NETL; 2012). Some changes will be made in the specifications of the compressor train to account for differences in the in cavern storage pressure. These changes will only be approximations to what the vendor might recommend. The expansion/generation train of the selected plant as set up at Seneca NY runs at an input pressure of 55 bar (800 psi). We will use this same turbine input pressure in our example case.

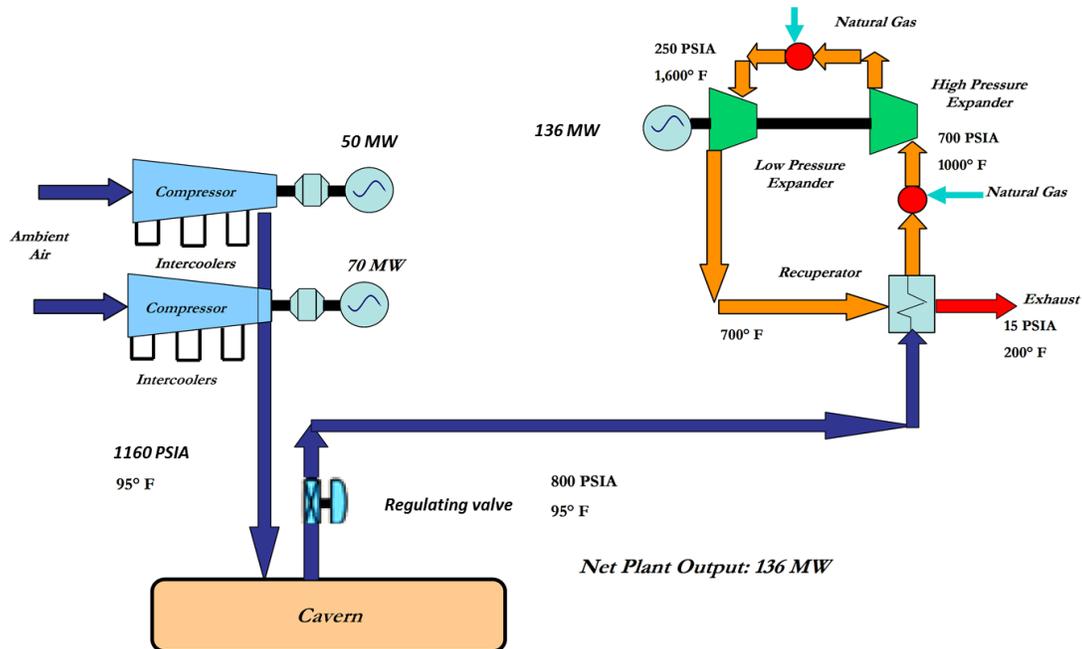
The New York State Electric and Gas Corporation Seneca Compressed Air Energy Storage Demonstration Project was first announced in November 2010, and over three years a substantial amount of project preliminary design and feasibility was conducted. In 2014 it was announced that the project was cancelled because "the economics of the project were not

favorable” (Department of Energy Global Energy Storage Database, 2014). The feasibility work published on the project is very useful for the UTac site as the size of the facilities are very similar. An overview of the main components are listed below:

- The compression process will utilize two separate compression trains, powered by synchronous motors. The compressors will be capable of filling the entire cavern from low pressure to high pressure in eight hours. Synchronous motors and compressors will be connected by clutches;
- The motors will be started with variable frequency drives to avoid placing starting transients on the transmission system. The compressors will have 3 stages with intercoolers between each stage and an aftercooler;
- The generation train will consist of a high pressure and a low pressure turbine connected to a common 136 MW synchronous generator. The high pressure turbine is preceded by a recuperator fed by the low pressure turbine exhaust. Both turbines will be preceded by natural gas combustors. The synchronous generator will be connected to the turbines with a clutch allowing the turbine to be used as a synchronous condenser when not producing power;
- The recuperator will be equipped with carbon monoxide (CO) and mono-nitrous oxides (NO<sub>x</sub>) reduction systems to meet local codes. The combustors will include demineralized water injection to reduce NO<sub>x</sub> emissions;
- Cooling for the intercoolers and aftercooler will be necessary. The cooling will be provided by air cooled intercoolers and aftercooler thus avoiding any thermal **pollution issues**;
- A natural gas fired emergency generator will be installed to provide black start capabilities in case of loss of grid power;
- An electrical substation at the CAES plant as well as a transmission line to the power grid will be built; and
- A natural gas pipeline from the plant site to the main gas source will be installed. Using findings from NETL (National Energy Technology Laboratory, 2012), it is estimated that the gas pressure at the high pressure combustor will be ~950 psig (~65 bar) and that at the low pressure combustor ~450 psig (~31 bar).

Figure 3.7-4 details the configuration of the hypothetical UTac CAES plant and is based on the proposed NYSEG Seneca facility. Compression is achieved by two independent compressors driven by A/C motors. One compressor is driven by a 50 MW motor and the second by a 70MW motor. The target pressure following compressing is 80 bar (1,160 psi), and this air is stored in the subsurface cavern discussed below. Each compressor train also has intercoolers which serve to remove heat generated during compression, which improved efficiency of this stage.

Compressed air is discharged out of the cavern to the generator train. A controllable regulator valve serves to regulate pressure of the exiting air and maintaining a pressure of 800 psi. Two air expanders are mechanically connected to a single electric generator with a design output of 136 MW. Prior to entering the first expander, the air is heated in a recuperator with heat derived from the combustion process. Natural gas is added and the fuel-air mixture is combusted prior to the first stage of expansion. A second inlet of heat through natural gas combustion takes place before the final expansion through the low pressure expander.



**Figure 3.7-4.** Facility schema selected for the UTac facility. Figure is modified from the NYSEG Seneca project (National Energy Technology Laboratory, 2012).

### Subsurface

As described earlier, a significant taconite ore seam exists at a depth of around 1,200 feet in the location of this site. It is assumed that this ore will be mined in the next 20 years and will result in a cavern sufficient to serve as a CAES pressure vessel. It is not possible to determine if it is feasible for the mining and CAES cavern development to have high-level of coordination (i.e., mining is performed in a way to achieve the goals of profitably extracting ore and developing a viable CAES cavern). Decisions on the geometry, location, and character of the cavern will ultimately be based on the geology, the technology, and the economic environment at the time the ore is mined. For the sake of this study, it is assumed that a taconite ore body at 1,200 feet depth will be mined, and will leave a cavern that can be used for the CAES pressure vessel.

### Cavern design

The plant is designed to run at a constant pressure of ~55 bar (800 psi). Constant pressure is a selected design attribute because constant pressure at the turbine allows the full turbine generating capacity to be used. Also, running at a constant pressure increases the overall efficiency of the generating plant and simplifies the system control (Succar and Williams, 2008). There are two primary approaches for providing constant pressure: Option 1 - by pressurizing the air in the cavern through a water column connected to an above-ground pond, or Option 2 - by pressurizing the cavern to a higher pressure and reducing the pressure delivered to the turbine with a throttling valve. A simple calculation reveals that the UTac cavern is not deep enough to achieve Option 1. A 1,200-ft. column of water produces a static pressure of only 520 psi, which is less than the 800 psi needed. For the throttled option (Option 2), a maximum pressure of 1,160 psi (80 bar) is selected, and throttle valves will be used to maintain an 80 psi inlet pressure at the gas turbine generator.

The analysis reviewed stability of the cavern under these pressures and results in the design requirement to line the cavern with a concrete to provide structural stability and prevent air leakage. A recent paper by Kim et al. (2012) states that the requirements of air tightness and cavern wall stability can be met in a relatively shallow mine if the mine is lined with an appropriate material (e.g., concrete), and the pressures in the cavern stay within the limits of 720 to 1,160 psi.

Having defined the cavern high pressure limit (1,160 psi), the low pressure limit (800 psi), the method of delivering the constant pressure air (throttling), and the desired MWh of electrical energy storage, the cavern volume can be determined using a method described in Succar and Williams (2008). Figure 3.7-5 is an important figure taken from Succar and Williams (2008). The y-axis is energy density of the cavern defined as the total design energy capacity of the facility over the volume of available storage. The x-axis is the high pressure limit in the cavern. The chart provides relationships for various ratios of high pressure limit to low pressure limit.

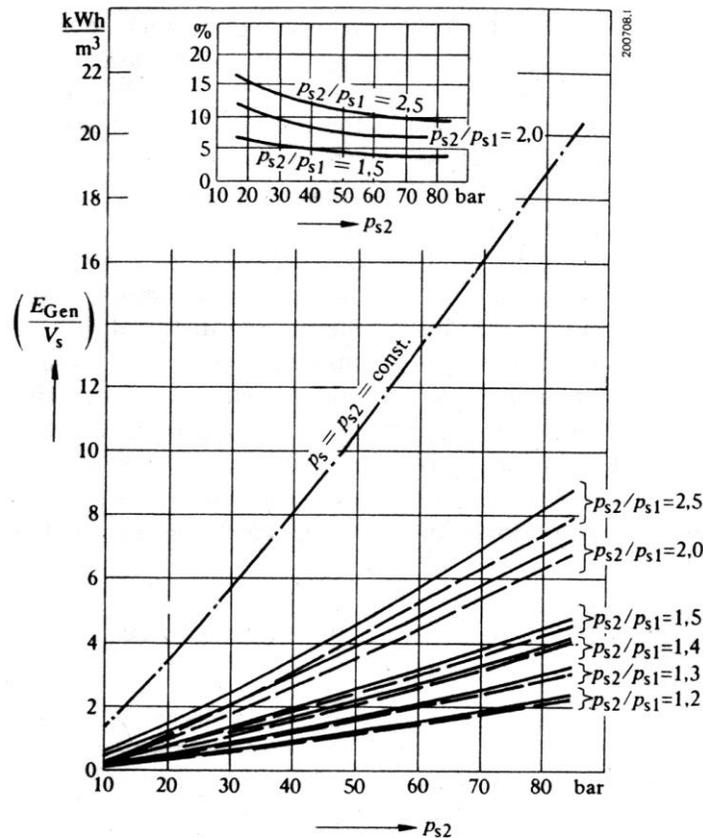


Fig. – Determining the size of the reservoir

- $E_{Gen}$  = Generator energy
- $V_s$  = Storage volume
- $p_{s2}$  = Upper storage pressure
- $p_{s1}$  = Lower storage pressure
- = Reservoir, case 1
- = Reservoir, case 2
- = Reservoir, case 3
- $T_{EHD} = 825 \text{ }^\circ K, T_{END} = 1100 \text{ }^\circ K$

**Figure 3.7-5.** Design chart relating energy density to maximum cavern pressure (Succar and Williams, 2008).

The chart is used to estimate cavern volume in the following way. First the pressure ratio  $P_2/P_1$  is determined. For this site  $P_2 / P_1 = 1160/800 = 1.45$  and  $P_2$  is 1160 psi or 80 bar. Entering the figure with this information, it is determined that the energy density is  $4.0 \text{ kWh/m}^3$ . The energy storage capacity of the site was selected to be  $136,000 \text{ kW} * 10 \text{ h} = 1,360,000 \text{ kWh}$ . The required volume is therefore determined to be  $340,000 \text{ m}^3$ .

## Cost Summary

The UTac CAES facility cost estimates are determined through review of available reports and literature of similar facilities. The NYSEG Seneca plant as well as other proposed facilities use a facility size of 136 MW for 8-10 hours of operation.

Estimates of capital costs for this size of facility range from 400-1000 \$/kW (Lou and Wang, 2013). Rastler (2009) suggests cost of 590-730 \$/kW. Akhil et al. (2013) published a cost of \$920/kW and Rastler (2010) published a cost of 1000 \$/kW. The range is substantial and for the UTac facility of 1,088 MWh, total costs of capital equipment ranges from \$ 54M to \$136M.

The costs reference above include the costs of creating the air cavern. Co-development of the air cavern with ore mining provides the opportunity to costshare the underground storage cost. Akhil et al. (2013) estimated costs of underground cavern creation to be \$16M, which was roughly 11% of the total facility cost. The cost of the UTac underground storage cavern was not specifically estimated here.

The costs above are for capital equipment. Additional facility costs involve design and contractors, professional engineering services, permits and licensing and other costs associated with implementation of the facility. These costs are significant. For example, the Seneca facility estimated an addition ~\$300k in costs over an above capital costs (National Energy Technology Laboratory, 2012).

## Facility operational plan

The conceptual operational plan for this facility is to maximize its profitability through its participation in the energy and ancillary markets operated by MISO. The various markets were discussed in Section 3.6. The UTAC facility is large enough that, conceptually, is able to provide energy and contingency services; however, the actual value of these services and a dispatch plan was not developed in this preliminary feasibility study.

The Seneca facility (National Energy Technology Laboratory, 2012) was a facility of identical size in terms of power and storage duration. The referenced feasibility study includes a relatively detailed analysis, including financial dispatch modeling, of the site. The Seneca facility was located in the New York Independent System Operator (NYISO) which has structures and financial market rules that differ from MISO.

One major finding of the Seneca study is the following statement (National Energy Technology Laboratory, 2012):

***The retirement of coal and other aging base load generation will require the addition of new generating capability which will largely take the form of natural gas peaking and combined cycle units. While some penetration of renewable energy will continue, the modeling clearly indicates that the majority of the new capacity additions will be natural gas fired.***

Because the UTac CAES is reliant on a natural gas combustion turbine technology, the price and availability of natural gas is critical to the financial and operational plan of the facility. As

coal plants are retired, new generating facilities will be better able to follow load resulting in narrowing of price arbitrage. Also the price of energy will be tightly bound with the price of natural gas. In short, as is suggested by NETL (National Energy Technology Laboratory, 2012), modeling suggests that future price arbitrage for CAES will shrink. In the case of the Seneca facility, the end results was that the facility was not financially viable and the project was ended. The natural gas price forecast was the primary reason cited.

For the UTac facility, the situation may or may not be similar. The Facilities Team has not examined retirement of coal facilities in the MISO region or impact of retirements/replacements on natural gas pricing futures. As discussed in Section 3.5, Minnesota Power is presently negotiating an agreement with Manitoba Hydro for access to hydropower energy, which they will use as an energy source and to balance load on their system.

### ***Co-developing ore mining and CAES underground storage***

Excavating a mine for the combined purposes of extracting valuable ore and creating a CAES cavern has never been done and what this process might entail is unknown. There may be benefit to additional study on the benefits of co-development, however, the following challenges were identified by the Facilities Team:

- Timing of ore mining is several decades into the future and mining methods, energy economics, mining economics will be different from today. Also, mining the ore will take many years to complete, and it is likely CAES cannot begin development until mining has left the area a caveat to this would be a cooperative program between the power company and mining company to specifically develop the cavern at an earlier stage;
- Ore mining techniques may or may not support CAES cavern development, and it may be too costly to deviate from standard mining methods, but geologic studies indicate that stable rock is available at the site and likely could be mined with conventional underground mining practices;
- Ownership of mine versus ownership of energy storage facility and legal/business relationship between these entities is important and undetermined; and
- MISO market rules change quickly and will need to be assessed when the project is closer to a start date.

### ***Environmental consideration***

The UTac CAES has several key areas for environmental evaluation and consideration. Here we summarize the above-ground and subsurface environmental issues.

### Air resources

The UTac plant will intake and discharge air during its processes. CAES plants typically are very clean and air quality control systems will be installed, if necessary, to meet the required air quality standards.

### Cultural and natural resources

Northern Minnesota has many surface water resources such as lakes, rivers and wetlands and the development of the surface site may have impact on these resources. The UTac plant will need a source of cooling. A dry cooling system (water free) will be used to limit impact on water resources (Giramonti et al., 1978).

The siting of the UTac facility was not determined in this study but an archeological and cultural survey will need to be conducted to assess archeological impacts prior to selection of the final site.

The site was previously evaluated in the PHES study previously undertaken by the current study team as noted previously. The geological characteristics do indicate a potentially viable ore source to help reduce the cost of cavern creation.

### Visual Impact

The UTac facility will be substantial in size with a multi-story building and a tall air discharge stack. As part of further feasibility a formal visual impact study will be required. The site will be very near (above) major ore mining operations, which will also have visual impact. The Facilities Team believes that the CAES facility will have no larger visual impact than the mine.

### Subsurface cavern

The subsurface cavern will be created during the mining and environmental impacts to surface and subsurface (groundwater, structural, safety) will be established during that phase of development. The CAES cavern will need to be designed such that it can operate safely under the design pressures without failure. Leakage from the cavern could release air or fluids into the groundwater and thus leakage may need to be investigated. The rock integrity for this location appears to be suitable for this type of cavern creation.

### **Site 3: Cuyuna Range: Armor 1 and 2**

#### *Site description and Location*

Site 3 is a proposed CAES facility utilizing the abandoned iron mines of the Cuyuna Range in northern Minnesota. The Cuyuna Range is located in north central Minnesota between the towns of Brainerd and Aikin. The specific sites proposed for study are north of Ironton, Minnesota - Armour No. 1 and Armour No. 2 (Figs. 3.7-6 and 3.7-7).

Both Armour No. 1 and Armour No. 2 were active mines in the early 1900s. The ore was located deep (800-ft.) below the surface and was accessed via underground mining. Both sites had a single main shaft that extended vertically to the level of the ore body. Horizontal cross-cut or drifts were then created, which accessed the ore body at various elevations (Figs. 3.7-8 and 3.7-9). More information on the mining and extents of these mines is addressed by the other teams. The project team identified Armour No. 2 as the most promising site in the Cuyuna Range and, in particular, focused on the shaft and underground cavern network.

In addition to the potential value of abandoned mine for compressed air storage, the location has other benefits summarized below:

- Two major electrical transmission line located four miles west (215 kV AC) and four miles north (115 kV AC) of the sites; and
- Surface water (open pit lakes) exist at the site and could be utilized for cooling water.

The site is located within the Minnesota Power service area, which participates in the MISO region. Great River Energy also has transmission lines that traverse the area.

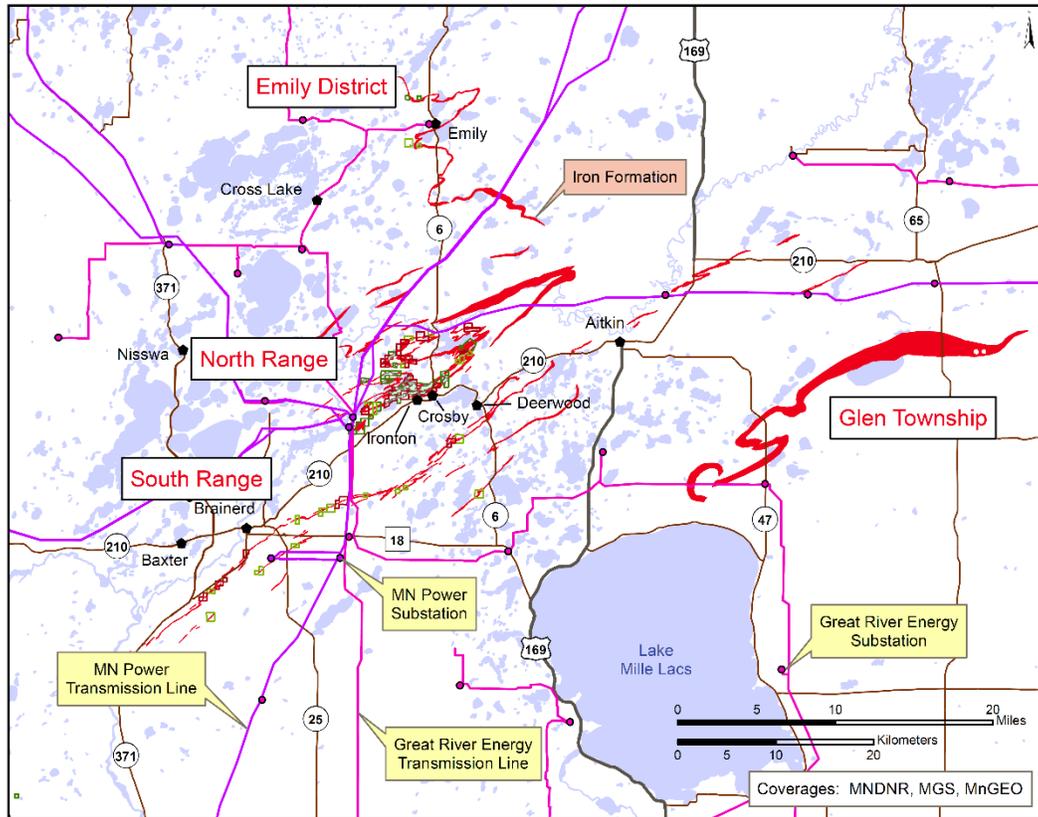


Figure 3.7-6. Location map of the Cuyuna Iron Range in northern Minnesota.

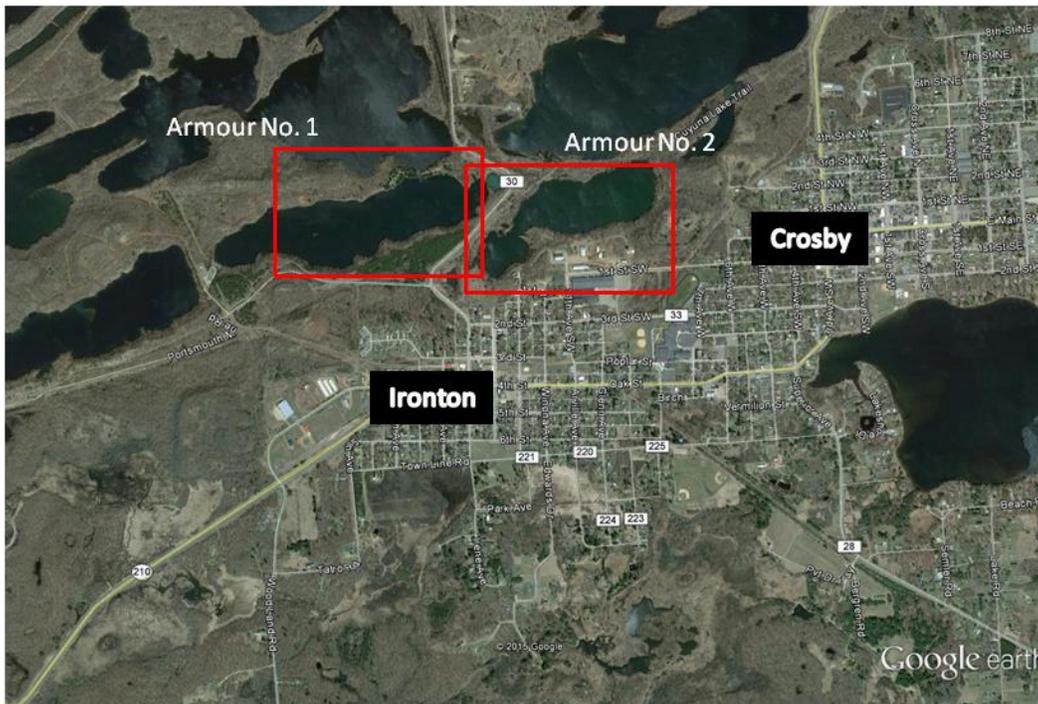
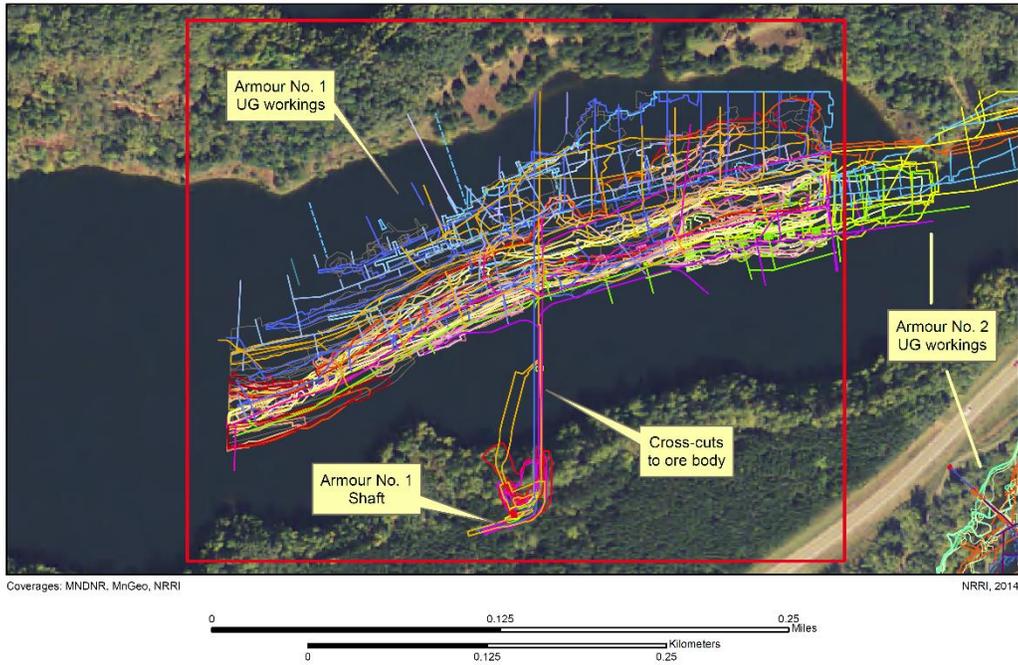
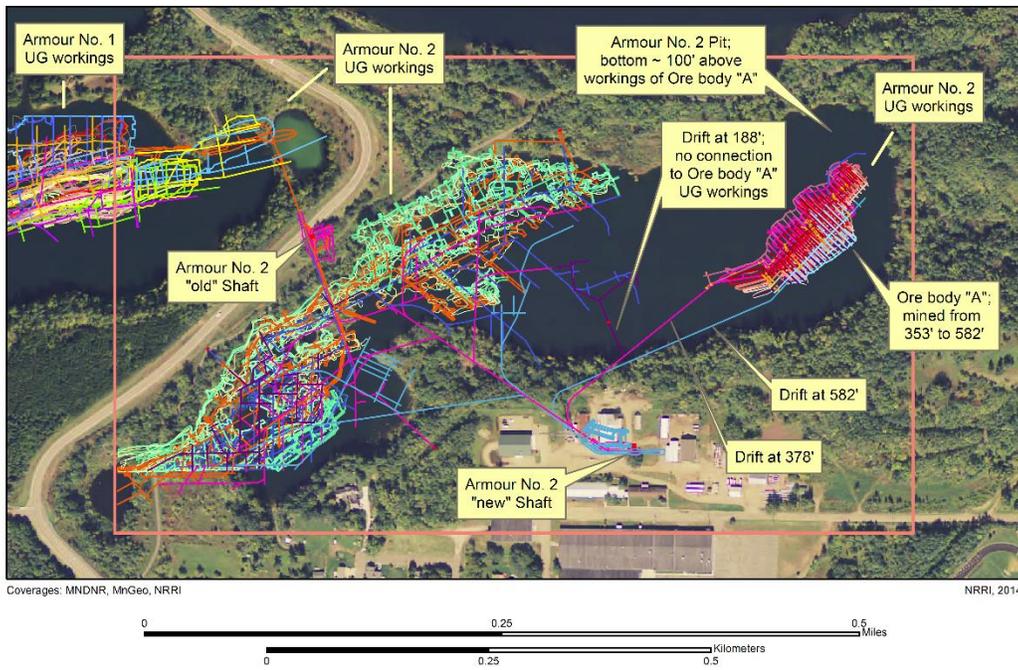


Figure 3.7-7. Location map of the two study sites, Armour 1 and Armour 2.



**Figure 3.7-8.** Detailed location map of Armour No. 1 showing mapped mine activity.



**Figure 3.7-9.** Detailed location map of Armour No. 2 showing mapped mine activity.

*Site 3: Basis for Design: Energy and economics*

The design goal for this site was to explore using an abandoned underground mine to restore and use for the subsurface component of the CAES facility. The team envisioned a facility on the order of the UTac or slightly smaller and employing conventional CAES (natural gas fired combustion turbines). Because the design goal specified “existing underground storage” location becomes critical in this case.

The Geotechnical Assessment Team conducted a thorough study of the Armour sites concluding that all sites would be extremely complex to use in underground air storage. At best, the primary 800-ft. shafts could be used but the actual storage volume available in these shafts is very small. Details of these investigations can be found in Geotechnical Assessment Team report.

Because the Armour mine was determined to be unviable, the goal of Site 3 cannot be met. Creating a new underground cavern was considered, but due to the costs associated with this effort and a lack of other motivating factors (e.g., economic and/or energy needs in the Crosby/Ironton region, energy balancing needs for Minnesota Power, or capturing and storing nearby intermittent renewable energy), no additional investigation was performed by the Facilities Team.

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## SUMMARY

The information provided in this report summarizes the Facilities Team's efforts focused on six core areas: 1) principles of CAES; 2) general CAES technology platforms; 3) CAES proposed and existing facilities; 4) design process for developing CAES facilities; 5) energy economics for CAES; and 6) feasibility of three hypothetical CAES facilities in northern Minnesota.

Compressed Air Energy Storage is a major energy storage technology that has been in discussion for several decades but only a small number of conventional systems exist today. CAES is a promising technology that offers scalable, clean, and flexible electrical energy storage but has market barriers resulting from gaps in technology, policy, and energy economics. The need for underground storage caverns compounds the complexity of a project because it severely limits sites to specific locations and engineering of underground structures is expensive.

Advanced CAES technologies are still in the development phase. Adiabatic CAES is developing by incorporating both standard and novel methods for storing and using the heat of compression. Isothermal CAES is advancing through the development of new heat transfer technologies. Technology leaders are working on scalable above ground compressed air storage systems which would free CAES from geographical restriction. These advances will open up new possibilities for CAES.

The energy economics of CAES must be considered from local, regional and national perspectives. CAES plants seek to have financial models that are sustainable. The selection of the type of CAES platform (i.e., conventional versus advanced) is an iterative process that must consider engineering design, electrical transmission system, plant dispatch model and economics as well as the environmental resource impacts of the facility. The participation of the CAES facility in energy markets is very dependent on the local and regional location of the facility. Basic questions that need to be considered include: 1) Does the electric utility operating the transmission systems in the area have a need for energy storage, and what services are needed? and 2) What are the specific markets and market rules available to the facility via the Independent System Operator? Understanding the energy storage needs of a region and understanding the market opportunities for specific energy and ancillary services are key factors to establishing the primary design and operational goals of the CAES facility.

Three hypothetical CAES facilities were examined. The three sites were selected to illustrate the range of CAES application. Site 1 is the Taconite Ridge CAES facility and is a small facility with capacity of 7.5 MW for five hours using a near-isothermal CAES technology. Site 2 is the UTAC CAES facility with a capacity of 136 MW for eight hours using conventional CAES. The underground cavern for the site will be co-developed during the mining of a large ore body located ~1,200-ft. below the surface. Site 3 is the Cuyuna CAES facility utilizing an existing but abandoned mine works located at 800 ft. below the surface. The first two sites demonstrate possible feasibilities and the range of complexities involved in CAES design. The third situation was not found to be feasible with the complex nature of the shafts and drifts involved in the two mines considered.

At this point in time, it does not appear that a large-scale CAES facility is viable in northern Minnesota. Minnesota Power has developed transmission infrastructure and balancing capabilities to meet their current and future needs. There are no obvious existing underground

caverns available, and the co-development of a cavern along with ore-mining is possible but will be a challenging endeavor that will involve active cooperation between the power developer and the mining company. Advanced CAES technologies are still developing and because of their scalability (small to large) and use of above ground storage, they remain a possible future technology for very site-specific applications. For example, a community or industry that has very localized energy surplus or deficit could take advantage of a small CAES plant. Presently, no commercially available Advanced CAES facilities exist, and stakeholders will need to continue to monitor this area of high-technology. Northern Minnesota does possess competent rock strata that could allow creation of an underground compressed air storage system, but economics and policy considerations need to become more favorable and renewable energy portfolios for the state likely have to reach much higher levels than the current 25% target that is set for the state.

**CHAPTER 4:****AN ENVIRONMENTAL ASSESSMENT FOR A COMPRESSED AIR ENERGY STORAGE FACILITY IN  
HARDROCK CAVERNS ON THE CUYUNA AND MESABI IRON RANGES IN MINNESOTA****Environmental Team**

Dr. Rebecca Teasley, Civil Engineering, UMD  
Ms. Kathryn Sinner, Civil Engineering, UMD (Undergraduate Student)  
Ms. Kyrstyn Haapala, Civil Engineering, UMD (Undergraduate Student)

Synopsis

Chapter 4 reviews various potential environmental impacts associated with constructing a Compressed Air Energy Storage (CAES) facility on the Cuyuna or Mesabi Iron Range. The general site locations evaluated include Armour Mine Nos. 1 and 2 on the Cuyuna Range near Ironton, Minnesota, as well as the Taconite Ridge Energy Center near the Mesabi Range. All site proposals are previous hardrock mining locations. This environmental report serves as a foundation for public or private parties interested in developing a CAES facility on the Cuyuna and Mesabi Iron Ranges in central and northeast Minnesota, respectively. Each environmental review independently considers impacts to the Cuyuna or Mesabi Range caverns. Following the environmental review, the report includes preliminary models for cavern pressurization.

The report concludes with a summary of permit requirements and procedures.

**Section 4.0:  
Executive Summary**

**Dr. Rebecca Teasley, Civil Engineering, UMD  
Kathryn Sinner, Civil Engineering, UMD (Undergraduate Student)**

**EXECUTIVE SUMMARY**

The intent of this environmental impact report is to provide interested private and public parties with a preliminary scope of the environmental concerns associated with the implementation of a CAES facility using above-ground facilities or existing hardrock caverns in Minnesota. The two sites evaluated include the Mesabi Iron Range in northeastern Minnesota and the Cuyuna Iron Range in north central Minnesota.

Section 4.1 overviews the impacts of a CAES facility on various environmental factors such as geology, soil, greenhouse gas emissions, and biological and water resources. The report also evaluates a CAES project in terms of regional resources, including agricultural, aesthetic, cultural, population and housing, noise, and air quality. A summary table of the concerns addressed and their recommended mitigation measures concludes Section 4.1. Section 4.2 includes environmental modeling for existing hardrock caverns with MODFLOW to examine potential impacts on the regional and local groundwater table. The model explores the use of various facility design factors through the choice of different parameters.

Significant environmental impacts depend on the specific type of CAES facility implemented but are likely to predominantly occur during the construction phase. Site location and facility design choice will allow for the creation of specific mitigation measures and management plans.

**Section 4.1:  
General Environmental Issues and Concerns for a CAES Project**

**Dr. Rebecca Teasley, Civil Engineering, UMD  
Kathryn Sinner, Civil Engineering, UMD (Undergraduate Student)  
Kyrstyn Haapala, Civil Engineering, UMD (Undergraduate Student)**

Section 4.1 provides a preliminary environmental review of the scope of environmental issues and regional concerns associated with the construction of a CAES facility. The general environmental issues addressed include geology and soil, soil erosion, seismicity, ground water quality, surface water quality, and biological resources. General regional concerns addressed include agricultural resources, cultural resources, aesthetic resources, recreational resources, population and housing, air quality and noise, greenhouse gas emissions, and hazardous materials. The chapter concludes with a summary table of the issues addressed, as well as their recommended mitigation measures and associated missing data.

## **GEOLOGY AND SOIL**

Construction and operation of a facility may affect geological formations in either the Cuyuna or Mesabi Range locations. Glacial activity from over 10,000 years ago created the landforms in both regions. According United States Geological Survey report, the general geologic features of the Cuyuna Range include tightly folded Precambrian rocks consisting of argillite, slate, phyllite, and iron-formations (Schmidt, 1963). Volcanic tuff, flows, and lesser amounts of coarser clastic rock are also present. Pleistocene glacial drift covers the bedrock anywhere from 15 to 200 feet across the Range, leaving few outcrops. Specifically, the North District section of the Cuyuna Range, an area approximately 12 miles long and 5 miles wide, contains Armour Mine No. 1 and Armour Mine No. 2. This district is the focus of Schmidt's report.

The Mesabi Range also consists of bedrock from the Precambrian and contains granite, quartzite, iron-formations, argillite, and gabbro (Fosnacht et al., 2011). The glacial till drift covering the bedrock on the Mesabi Range ranges 0 to 300 feet. Most of the drift exceeds 100 feet in thickness (Winter, 1972).

## **SOIL EROSION**

Regardless of site location, the construction of the CAES facility carries the greatest risk of soil erosion. Project development plans should incorporate soil erosion and sedimentation control plans, specifically for areas during the construction phase particularly affected by soil and rock alteration and removal.

## **SEISMICITY**

Concerns concerning seismic activity of the proposed site location, as well as the potential of CAES operations, regard seismic events generated through cavern pressurization. A National Research Council committee produced a report on energy technology-induced seismicity in June, 2012 upon request from the U.S. Department of Energy (Hintzman, 2012). The committee found seismicity associated with fluid injection or withdrawal is most likely to occur due to pore fluid pressure changes and/or "change in stress in the subsurface in the presence of faults with

specific properties and orientations and a critical state of stress in the rocks” (Hitzman, 2012). According to the report, net fluid balance is the driving factor in energy technology-induced seismicity.

To safely prevent seismic activity related to CAES standard operations, further geologic and environmental analyses must be performed upon selection of a specific site. Environmental assessments and project plans should incorporate analyses into preventative measures. Tables 4.1-1. and 4.1-2 highlight regional historic seismic activity (U.S.G.S., 2009).

**Table 4.1-1.** Recorded historical earthquakes affecting Minnesota (adapted from U.S.G.S., 2009).

Date	Severity of the Shock	Quake Center	Area Affected in Minnesota
1860	Fairly strong	Central Minnesota, US	Entire state
Sept. 3, 1917	Intensity VI	Central Minnesota, US	Entire state
Nov. 15, 1877	Strong shock	Eastern Nebraska, US	SW Minnesota
May 26, 1909	Intensity VII	Illinois, US	SE Minnesota
Feb. 28, 1925	--	Quebec, Canada	Slightly felt in Minneapolis, MN
Nov. 1, 1935	Strong	Timiskaming, Canada	Slightly felt in Minneapolis
Nov. 9, 1968	Intensity I-IV	South-central Illinois, US	Austin, Glencoe, Mankato, Minneapolis, Rochester, MN

**Table 4.1-2.** Additional historical earthquakes affecting Minnesota (Chandler, 1994; pers. comm., Nov. 8, 2011).

#	Epicenter (nearest town)	County	Mo./Day/Yr.	Lat. (deg.)	Long. (deg.)	Depth (km)	Km <sup>2</sup>	Intensity	Magnitude
1	Long Prairie	Todd	1860-61	46.10	94.90	---	---	VI-VII	5.0
2	New Prague	Scott	12/16/1860	44.60	93.50	---	---	VI	4.7
3	St. Vincent	Kittson	12/28/1880	49.00	97.20	---	---	II-IV	3.6
4	New Ulm	Brown	2/5- 2/12/1881	44.30	94.50	---	v. local	VI	3.0-4.0?
5	Red Lake	Beltrami	2/6/1917	47.90	95.00	---	---	V	3.8
6	Staples	Todd	9/3/1917	46.34	94.63	---	48,000	VI-VII	4.3
7	Bowstring	Itasca	12/23/1928	47.50	93.80	---	---	IV	3.8
8	Detroit Lakes	Becker	1/28/1939	46.90	96.00	---	8,000	IV	3.9-3
9	Alexandria	Douglas	2/15/1950	46.10	95.20	---	3,000	V	3.6
10	Pipestone*	Pipestone	9/28/1964	44.00	96.40	---	---	---	3.4
11	Morris*	Stevens	7/9/1975	45.50	96.10	---	82,000	VI	4.8-4.6
12	Milaca*	Mille Lacs	3/5/1979	45.85	93.75	---	---	---	1.0
13	Evergreen*	Becker	4/16/1979	46.78	95.55	---	---	---	3.1
14	Rush City*	Chisago	5/14/1979	45.72	92.90	---	---	---	0.1
15	Nisswa*	Crow Wing	7/26/1979	46.50	94.33	---	v. local	III	1.0
16	Cottage Grove	Washington	4/24/1981	44.84	92.93	---	v. local	III-IV	3.6
17	Walker	Cass	9/27/1982	47.10	97.60	---	v. local	II	2.0
18	Dumont*	Stevens	6/4/1993	45.67	96.29	---	69,500	V-VI	4.1
19	Granite Falls*	Yellow Medicine	2/9/1994	44.86	95.56	---	11,600	V	3.1
20	Alexandria*	Douglas	4/29/2011	45.99	95.53	15.6	---	---	2.5
*	Asterisks denote earthquakes that were recorded instrumentally.								

## WATER QUALITY

With the assumption of air storage cavern impermeability, the greatest potential for water quality impacts include the initial cavern dewatering, construction-related runoff, the use of water as a system coolant, and issues related to the use of a water curtain. Overall, the greatest impact to water quality will occur during the construction phase. Standard, daily CAES operations will have little to no ground and surface water interaction.

Specific facility design decisions will impact water quality mitigation measures. If the facility employs the use of a water curtain, consideration must be given to ensure minimal adverse impact to facility equipment. In addition, the facility may require water use as an equipment coolant. If the cooling process is not a closed system, the water must be hauled offsite and disposed at a permitted facility.

Initial site-specific environmental assessments must also take into consideration the effect of geology and mineralogy on both ground and surface water quality.

Groundwater impact concerns depend on the location and depth of the storage cavern. Primary concerns include cavern dewatering, the potential for air escape into the local groundwater reservoir, and the use of a water curtain.

Research shows the primary flow of groundwater within the Mesabi Iron Range flows south-southeast from the Laurentian Divide through fractures, faults, and joints (Fosnacht et al., 2011). Fosnacht et al. (2011) highlighted the Biwabik Iron Formation (BIF) and stratified glacial drifts as the most productive aquifers on the Mesabi Iron Range.

In general, groundwater within the Cuyuna Iron Range flows north-northwest toward the Mississippi River. A majority of the Cuyuna Range aquifers are artesian in nature and can produce water yields up to 2,000 gallons per minute. Other aquifers are water table-based aquifers that range 2 to 50 feet in thickness (Minnesota Department of Natural Resources, 1995).

## **SURFACE WATER**

Primary surface water concerns are likely to occur during the construction phase. Although impacts to surface water during general operation are likely to be minimal, both phases should incorporate mitigation plans for potential surface water impacts related to stormwater, soil erosion, and sedimentation control.

## **BIOLOGICAL RESOURCES**

Biological resources include plant and wildlife communities potentially adversely affected due to CAES construction and operation. The United States Fish and Wildlife Service (USFWS) and the Minnesota Department of Natural Resources (MN DNR) have designated threatened and endangered species under each individual jurisdiction. Species may have both state and federal status, differentiated by legislation discrepancies. In addition to “threatened” and “endangered,” Minnesota includes a third designated status of “special concern.”

### **Federally Designated Species**

The USFWS categorizes endangered and threatened species by counties in each state. The two counties for the CAES proposals in the Cuyuna and Mesabi Iron Ranges include Crow Wing County and Saint Louis County, respectively. The proposed endangered Northern long-eared bat, *Myotis septentrionalis*, which hibernates in caves and mines, resides in both counties and is Crow Wing County’s only federally-listed species. The proposed CAES sites in Saint Louis County additionally overlap with the threatened Canada Lynx, *Lynx canadensis*, populations (USFWS, n.d.-a).

## **State Designated Species**

The MN DNR and United States Forest Service (USFS) developed an Ecological Classification System (ECS) based on the National Hierarchical Framework of Ecological Units. Minnesota contains 26 subsections of the ECS, defined by unique “glacial deposit processes, surface bedrock formations, local climate, topographic relief, and the distribution of plant species, especially trees” (Minnesota Department of Natural Resources, n.d.-b). The MN DNR has worked to identify species of greatest conservation need and relative ecological issues in each subsection.

The facility proposals in Crow Wing County lie within the Mille Lacs Uplands ecological subsection of the Laurentian Mixed Province. The document, “Mille Lacs Uplands Subsection Profile,” developed in 2006 by the MN DNR, states 57 federal or state endangered, threatened, or special concern wildlife species exist within the 3.38 million acres (Minnesota Department of Natural Resources, 2006). In addition, the document highlights this subsection as a major migratory corridor for water birds. Some of these species of concern within this subsection include the spotted salamander, red-shoulder hawk, and Blanding’s turtle.

The two proposed locations on the Mesabi Range in Saint Louis County lie within the Nashwauk Uplands Subsection that includes 38 species of greatest concern. According to the 2011 PHES report, an EIS prepared for the PolyMet NorthMet mine site listed nine plant species and seven federal and state wildlife species to be of particular concern (Fosnacht et al., 2011).

Cavern dewatering in the Cuyuna Range will likely affect fish species such as bass, northern, trout, sunfish, crappie, and walleye.

Excavating a new cavern may incur the greatest potential for adverse effects to biological communities. Utilizing existing caverns for CAES is likely to minimize impacts, unless the loss of habitat that currently exists in a pre-mined cavern occurs and is ultimately accessible.

## **IMPACTS COMMON TO CAES FACILITY CONSTRUCTION**

### **Agricultural Resources**

All CAES facility proposals are likely to have minimal impact on agricultural resources. Armour Mine No. 1 and Armour Mine No. 2 near Ironton, Minnesota are located in the Cuyuna Country State Recreation Area and Ironton Industrial Park, respectively. The locations of the proposed facilities on the Mesabi Range coincide with mining and energy production, therefore having little to no impact to agricultural resources in the area.

### **Cultural Resources**

Impacts to cultural resources pertain to historical, architectural, and archeological properties within the proposed site’s potential area of impact, as defined by Minnesota Statute 166 and the National Historic Preservation Act of 1966 (Fosnacht et al., 2011). To determine cultural impacts, local, state, and tribal authorities should be consulted prior to site designation.

In addition, project authorities should consult the Minnesota Historical Society. Site proposals in existing caverns are the least likely of all the areas considered to reveal potential cultural impacts.

### **Aesthetic Resources**

The primary concern regarding aesthetic resources involves the proposed Cuyuna Range mine caverns. Both Armour Mine No. 1 and Armour Mine No. 2 proposals lie within one mile of Ironton, Minnesota's Chamber of Commerce. In addition, both mines may affect tourism in Ironton and the surrounding area due to their existence in and adjacency to the Cuyuna Country State Recreation Area (Minnesota Department of Natural Resources, 2014a). Armour No. 1 lies completely within the recreation area, and Armour No. 2 is less than a mile from the boundary. Potential dewatering of Armour No. 1 and Armour No. 2 caverns may impact the water levels of adjacent water bodies, which may have significant impact on the aesthetic value for the Ironton community and tourism. Further site-specific studies on cavern location, water levels, and connectivity of cavern water to adjacent bodies will determine the full extent of water-related aesthetic impact for a facility located on the Cuyuna Iron Range.

The proposed site locations on the Mesabi Range are likely to have less negative aesthetic impact than the Cuyuna Range sites due to their proximity to current industrial activity and associated facilities.

### **Recreational Resources**

Out of all project location considerations, the Cuyuna Range proposals have the greatest potential for adverse impact to recreational resources due to their location in and near the Cuyuna Country State Recreation Area, one of Minnesota's newest State Recreation Areas (SRAs). Over 118,000 tourists visit the Cuyuna Country State Recreation Area annually to hike, bike, ski, camp, fish, scuba dive, and swim (Minnesota Department of Natural Resources, 2014a). The recreation area boasts one of the state's top rated mountain bike trail systems, which includes over 25 miles of trails. Site proposal Armour No. 1 lies entirely within the recreation boundaries and adjacent to the mountain bike trail system. Although Armour No. 2 is outside recreation area limits, it is still less than one mile from both the town of Ironton and the SRA limits. Additionally, a paved state bike trail, the Cuyuna State Trail, bisects the two site locations.

The proposed mine pits in northeastern Minnesota hold little recreational value due to their proximity to previous or current energy extraction and production. The construction of CAES facilities at either of these locations is likely to have minimal present and future recreational impact.

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## **Population and Housing**

The potential impacts of a CAES facility to population and housing depend on site location and facility type. The PHES report (Fosnacht et al., 2011) references a 2010 study by GEI consultants (2010) regarding population growth. The report outlines two ways a project significantly may influence housing and population: directly or indirectly induce substantial population growth and/or require housing construction through displacement (Fosnacht et al., 2011).

A 100 MW facility employment is not likely to significantly impact a region's local population and housing. A report prepared by the United States Department of Energy for a projected 300 MW CAES facility in California predicts employment of approximately 475 temporary employees during the construction phase and 25 permanent employees during standard operations (Nuhfer and Medeiros, 2013). Based on Nuhfer and Medeiros's projections, a proposed 150 MW facility is not likely to employ more than 500 permanent and temporary employees.

## **Air Quality and Noise**

The greatest impacts to air quality will occur during the construction phase for a CAES facility. Such impacts will be temporary and are not expected to exceed state and federal regulations. Emissions during construction are likely to include dust, combustion emissions from vehicles and equipment, and potential volatiles from the well-testing phase (Nuhfer and Medeiros, 2013).

Noise impacts during construction will result from machinery operation and potential cavern excavation. During operation, the generator and air compressor system will be the primary sources of noise.

The proximity to residential areas increases the adverse impact of both air quality and noise for the installation and operation of a CAES facility. As the Armour Mines exists within a mile of Ironton, Minnesota and are adjacent to the Cuyuna Country State Recreation Area, these locations are likely to have the greatest overall impact.

## **Greenhouse Gas Emissions**

Overall, CAES facilities use less fossil fuels to drive production than typical energy facilities, such as natural gas and coal power plants. The quantitative use of fossil fuels ultimately depends on the type of CAES facility implemented.

## **Hazardous Materials**

The presence of hazardous materials associated with a CAES facility will likely occur during construction and maintenance of the facility. Hazardous materials, otherwise known as

“hazmats,” may include particles in solid, liquid, and gaseous states. A few examples of hazmats include lead, mercury, polychlorinated biphenyls (PCBs), and asbestos. If daily operations incorporate hazardous materials, mitigation measures, as well as environmental, health, and safety plans, should be developed and implemented.

**Table 4.1-3.** General environmental issues and concerns summary.

Potential Environmental Impacts	Level of Significance	Potential Mitigation Measures	Missing Data
<b>Potential impacts to developing and operating a CAES project</b>			
Impacts to geology and soil			
Soil Erosion	Potentially significant	Sedimentation and runoff control, best construction practices, effective stormwater mitigation and management	Site and design specific
Seismicity triggered by reservoirs	Not significant	Best construction practices, management plans for cavern pressurization	Site and design specific
Impacts to surface water resources			
Impacts incurred during construction	Potentially significant	Best construction practices, stormwater and runoff mitigation and management	
Impacts incurred during general operation	Not significant	Stormwater and runoff mitigation and management	
Impacts to groundwater resources			
Impacts to water table (if a cavern is excavated)	Potentially significant	Site selection	Site and design specific
Water curtain use	Not significant	Site selection, best construction and management practices, cavern pressurization and management plans	Site specific groundwater information
General groundwater quality	Not significant		Site specific groundwater information
General groundwater quantity: availability to wells, wetlands, rivers, and lakes in surrounding area	Not significant	Cavern pressurization and management	Site specific groundwater information
Impacts to biological resources			
General plant communities	Not significant	Best construction practices to minimize plant community disturbance	Site specific
Special Concern (ETSC) plant and wildlife species	Not significant		Site specific
Fish communities in caverns	Potentially significant	Consult Minnesota DNR regarding fish removal	Site specific
<b>Impacts common to large facility construction</b>			
Agricultural resources	Not significant	Not needed	Site specific
Cultural resources	Potentially significant	Site specific	Site specific
Aesthetic resources	Potentially significant	Site specific	Site specific
Population and housing	Not significant	Not needed	None
Air quality and noise	Not significant	Best construction practices	
Greenhouse gas emissions (construction and operation)	Potentially significant	Best construction practices	
Hazardous materials	Potentially significant	Best construction practices, management of materials during operation	Site and design specific

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**Chapter 4.2:  
Federal and State Permitting Requirements for  
Compressed Air Energy Storage in Minnesota**

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## INTRODUCTION

The federal and state permitting chapter of the environmental report offers a generalized outline for CAES permit requirements in Minnesota. On a global scale, two CAES facilities operate as of 2014, one in Alabama and the other in Germany. Few current CAES project proposals exist in the United States, none of which include Minnesota. The scarcity of CAES facilities in comparison with similar renewable energy technologies leaves few well-documented parameters for federal and state permitting applications. The recommendations presented in this document serve as a baseline resource for the permitting process. Rather than delving into precise detail, this chapter will instead provide permit information, as well as the documentation references for additional permit procedures.

Agencies at both the federal and state level operate by law to permit and regulate energy facilities. Applications and timelines vary greatly depending on agency, permit type, and site location. Many permit applications require environmental impact information. Completing an initial site assessment prior to the application process will prove a beneficial investment.

In general, state public utility commissions (PUCs) serve as the primary regulatory agencies for CAES facilities in the United States. A CAES facility in Minnesota will require a majority of its construction and operation permits from state agencies. Federal agencies, such as the Aviation Administration and the United States Fish and Wildlife Service, may also impose permit applications. CAES facilities must also adhere to environmental assessment regulations stated in the National Environmental Policy Act.

In Minnesota, the Minnesota Public Utilities Commission (MPUC) authorizes permits for CAES project construction and facility operation. The Minnesota Pollution Control Agency (MPCA), which regulates state standards in addition to federal standards designated by the United States Environmental Protection Agency, approves air and water quality-related permits. Additional state permitting through the MN DNR may also be required.

## FEDERAL PERMITTING

On a federal level, the agencies requiring permits for a compressed air energy storage site depend on policy nuances regarding sustainable energy storage and production. Overall, federal permits pertain to potential air, water, and wildlife impacts. Many state agencies, such as the MPCA, operate as a designated body to enforce both federal and state regulations.

### **United States Federal Aviation Administration (USFAA)**

Construction of a CAES facility exceeding 200 feet in height or proximity of a facility to an airport may require permits through the USFAA, according to Federal Regulation Title 14 Part 77 (USFAA, 2012). Both temporary and permanent structures apply to this policy. The USFAA requires submission of notice at least 45 days prior to construction of the proposed site (2012).

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**United States Fish and Wildlife Service (USFWS)**

Section 10 of the Endangered Species Act regulates a range of activities affecting federally designated threatened and endangered species and their habitats. Governed by this act, the USFWS may issue Incidental Take Permits when non-Federal facility activities might result in the take of threatened or endangered species (USFWS, n.d.-b). Initial assessment of a specific site location must determine the possibility of adverse effects to federal and state designated threatened or endangered species. Note: state and federal endangered species may differ, resulting in permit applications at both levels.

The Incidental Take Permit application requires a Habitat Conservation Plan (HCP), which assures the proposed project minimizes and mitigates impacts to the species addressed (USFWS, n.d.-b). In issuing an Incidental Take Permit, the USFWS must comply with the National Environmental Policy Act (NEPA), and conduct an environmental assessment. If the potential impact to listed species is “minor or negligible,” the project may be exempt from the USFWS-related NEPA assessment.

**STATE AND LOCAL PERMITTING****Minnesota Public Utilities Commission (MPUC)**

The Minnesota Public Utilities Commission (MPUC) regulates electric and natural gas public utilities and has oversight for large energy facilities. Minnesota State Statute 216E, known as the “Power Plant Siting Act” guides the PUC’s permitting process for large energy storage facilities (Minnesota Revisor of Statutes, 2014). While Statute 216E does not explicitly mention jurisdiction of CAES, it does administer permits for energy generation, transmission lines, and wind power operations, all of which may apply to a CAES facility.

*MPUC Permitting Overview*

Statute 216E.2 Section 2 grants jurisdiction to the MPUC to site and route large energy facilities. Policy deems a “large electric generating power plant” as one capable of producing 50 megawatts of energy and a “high voltage transmission line” to be capable of operation at nominal voltage of at least 100 kilovolts and greater than 1,500 feet in length (Minnesota Public Utilities Commission, n.d.). The applicant must apply for both siting and routing permits and propose at least two options for the facility’s location and two route options for the high voltage transmission line. As defined in Statute 216E, state policy requires the siting of electric power facilities to minimize potential adverse human and environmental impact while efficiently and reliably utilizing energy resources.

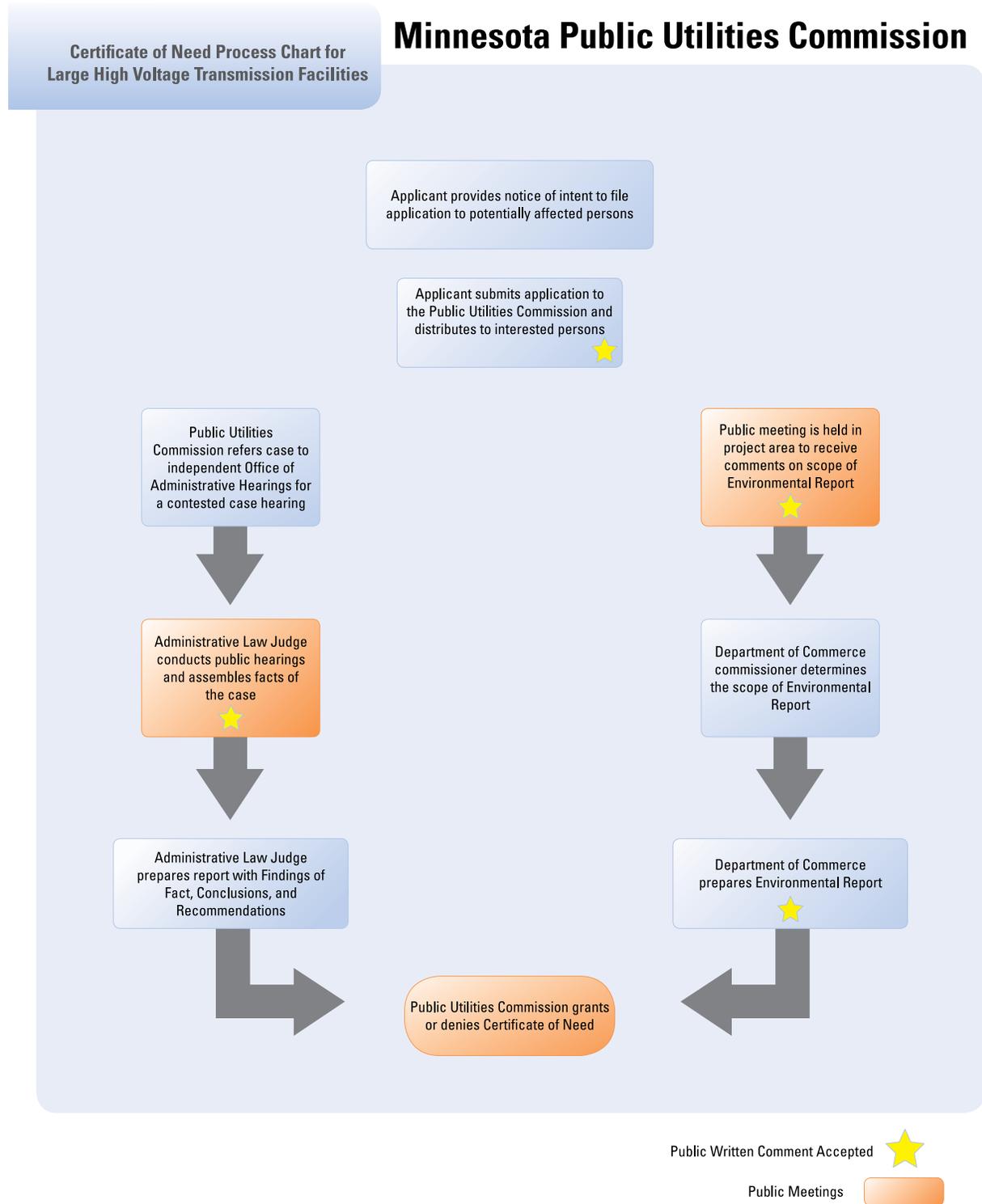
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### *Certificate of Need Process*

A CAES facility may also require a Certificate of Need (CON) in conjunction with the siting and routing permit application. Statute 216B.243 provides details and exemptions regarding a CON, which requires the proposed facility to be in the best interest of Minnesota’s citizens (Minnesota Public Utilities Commission, n.d.). If a CON is required, the Minnesota Department of Commerce (MN DOC) initiates an Environmental Review Process, and the PUC and Office of Administrative Hearings initiate a contested case process. The MN DOC must also hold a public meeting within 40 days of a submitted application. At this meeting, participants may call into question and suggest alternatives for the proposed environmental review. The MN DOC must allow 20 days following the public meeting for individuals to provide written comments on the application. Further details regarding the CON process can be found on the MPUC website (Minnesota Department of Commerce, n.d.). Figure 4.2-1 summarizes the CON process for large high voltage transmission facilities.

### *Application Process and Timing*

Statute 316E.03 outlines additional details regarding the application process for a proposed CAES facility. Statute 316 provides details concerning the notification of local governments and property owners prior to application, the public hearing process, and consideration of site selection by the PUC. After the PUC designates an application as complete, a final decision on permit requests must be made within one year. This PUC may extend the deadline up to three months for just cause. See Figure 4.2-2 for a summary of the alternative application process pertaining to high voltage transmission line routing and siting.

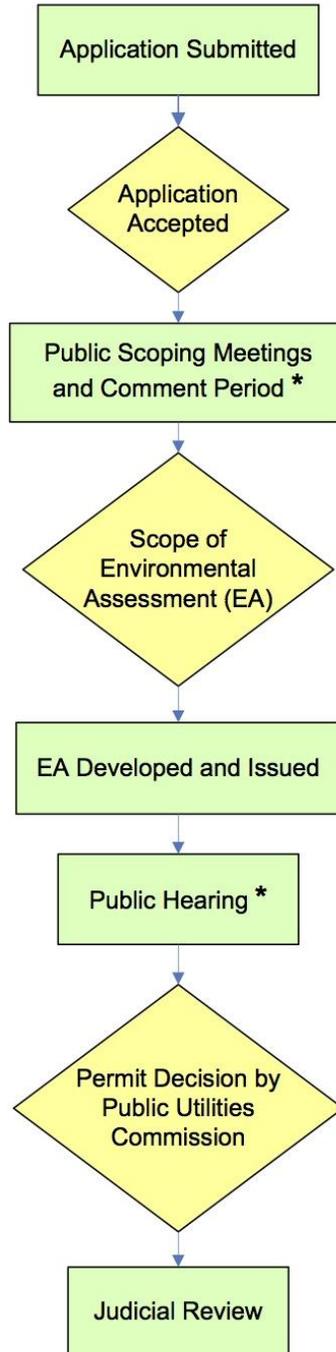


**Figure 4.2-1.** Minnesota Public Utilities Commission Certificate of Need Process Chart (Minnesota Public Utilities Commission, n.d.).



**HVTL Routing and Power Plant Siting  
Alternative Permitting Process**

**Minnesota Rules 7850**



**Timeline**  
Time from application acceptance to permit decision = 6 months

\* Public Participation Opportunities

**Figure 4.2-2.** Minnesota Public Utilities Commission full review permit process (Xcel Energy, n.d.).

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## **Minnesota Pollution Control Agency**

Construction and operation of a compressed air energy storage facility in Minnesota requires both air and pollution discharge permits from the Minnesota Pollution Control Agency (MPCA). Both permit types comply with federal regulations required by the Environmental Protection Agency.

### *Air Permits*

The MPCA operates as a delegated state agency to grant air permits according to federal regulations. Two air permits encompass both state and federal regulatory guidelines. Initially, a Prevention of Significant Deterioration (PSD) Permit must be obtained for site construction. A PSD Permit assures minimal air quality degradation from the addition of a CAES facility and incorporates recent rulings regarding greenhouse gas emissions (Minnesota Pollution Control Agency, 2014). General CAES operation requires a Part 70 Permit, also known as a Title V Permit. The MPCA website provides guidelines and applications for both permits.

### *National Pollutant Discharge Elimination System (NPDES) Permit*

The MPCA oversees the EPA's Industrial NPDES permit program, as authorized by the Clean Water Act. The NPDES permit program regulates wastewater discharges into lakes, streams, wetlands, and other surface waters (Minnesota Pollution Control Agency, 2009). Depending on site location and the type of CAES facility, three applications may be required for the overall CAES facility permitting process and include permits pertaining to industrial process wastewater, miscellaneous waste types, and construction stormwater. The Industrial Process Wastewater application concerns wastewater that "comes into direct contact with, or is left over from production of a raw material, intermediate product, finished product, byproduct, or waste product" during manufacturing or processing (Minnesota Pollution Control Agency, n.d.). The Miscellaneous Waste Types application concerns groundwater pump-outs and non-contact cooling water, both of which may pertain to CAES facility operations. Finally, the construction stormwater permit applies to water runoff during the project's construction phase.

## **Minnesota Department of Natural Resources**

### *Public Waters Work Permit*

Depending on the site location, water-related permits may be needed from the MN DNR. If the site occurs on public land and affects the "course or current of public water," a public waters work permit will be required by the MN DNR (Minnesota Department of Natural Resources, n.d.-a). This permit concerns projects constructed below the "ordinary high water level" (OHWL) and pertains to activities such as diking, dredging, draining, filling, excavating,

and placing structures in public waters or public wetlands (Easter and Perry, 2011). As defined by the MN DNR, the OWHL references the highest water level maintained over a significant period of time (Minnesota Department of Natural Resources, n.d.-a). The MN DNR website provides a list of local area hydrologists who determine OWHL for specific bodies of water. A public water work permit also observes Minnesota’s Wetland’s Conservation Act, which establishes a policy of “no net loss in the quantity, quality, and biological diversity of Minnesota’s existing wetlands” under Statute 103A.201 (Easter and Perry, 2011).

### *Wildlife Permits*

The MN DNR requires fishery permits to remove or transport fish species in various settings. Dewatering of a public land cavern for CAES facility construction may require a fishery permit application depending on site location, land ownership, and MN DNR regulations.

In addition, if a proposed CAES facility adversely impacts species listed as endangered or threatened in Minnesota that are not federally listed, the project must obtain a permit from the MN DNR. Permit requests must be submitted in the form of a letter to the MN DNR (Minnesota Department of Natural Resources, 2014b). The permit request must document detailed information regarding potentially impacted species in addition to project and site information. If the MN DNR determines there are no feasible alternatives to the taking of impacted species, compensation may be required. Further information regarding the MN DNR endangered species permits may be found on the MN DNR’s website.

## **SUMMARY**

In general, the permitting process for any proposed energy facility is time intensive and costly. As a CAES facility in the United States has not been constructed for over 20 years, applicants for CAES permits may encounter unforeseen hindrances. Environmental assessments of a proposed site location and facility will significantly benefit the applicant throughout the application and permitting process.

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**Section 4.3:  
Groundwater Modeling**

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## INTRODUCTION

### GROUNDWATER MODELING

Compressed Air Energy Storage (CAES) is an innovative technology used to store energy from intermittent renewable sources, i.e., wind and solar, and integrate it into the grid. CAES uses power generated by renewable sources to pump air into a storage space. When energy is needed, the compressed air is released to flow through a turbine and generates electricity.

There are two main processes for CAES operation: isothermal or adiabatic compression. In isothermal compression, the air is prevented from heating up, while adiabatic compression can result in the air heating up to extremely high temperatures. For underground storage to have a minimal impact, isothermal CAES can be used. Other project partners will determine the most efficient cavern size for isothermal CAES operation (see Chapter 3, this paper).

This project looks into using existing underground caverns as a site for CAES. The Iron Range of Minnesota has multiple abandoned underground mines that can be considered for storage sites (see Chapter 1, this paper). Current open pit mines on the Mesabi Range may make it unfeasible to use nearby existing mines because of blasting concerns. Abandoned underground mines on the Cuyuna Range may be a more realistic option, although many are converted to open pit mines or are now flooded (see Chapter 1, this paper). Future precious metal mining operations in the Duluth Complex may be another option to consider converting into CAES storage facilities after underground mining operation is complete.

### MODEL CONFIGURATION

A series of models were developed using MODFLOW in Groundwater Vistas to examine the best approach to modeling an underground cavern holding compressed air. Models are set up with specific objectives of determining the effect of a water curtain, the possibility of air leakage, the area of influence from dewatering an abandoned mine, and the potential influence of using a reservoir to maintain constant pressure in the cavern. More thorough modeling should be completed once a physical site is selected and field collection of physical parameters.

In order to set up an effective model, it is necessary to choose layer elevations, grid spacing, boundary conditions, cavern size and location, and model parameters that could represent a specific site. Modeling is done to determine how each component of the model could affect future models at a chosen site.

### LAYERS

Layer elevations are chosen based on assumptions for how deep the cavern should be, and how the cavern can be altered based on cavern depth requirements. In models used to represent a water curtain, extra layers are used in order to simplify placement of the water curtain. In a model assuming a mine drift at a depth of 300 ft. and a water curtain about 50 ft. above the cavern, the layers can be represented as shown in Table 4.3-1. These values are a

basic representation of the mines in the region studied, and these values need some adjustment based on the stratigraphy of a site, and whether a water curtain is used.

**Table 4.3-4.** Typical layer distribution with water curtain.

Layer	Description	Top Elevation (ft.)	Thickness (ft.)
1	Sand and gravel	500	100
2	Bedrock	400	100
3	Water curtain in bedrock	300	1
4	49' between cavern and water curtain	299	49
5	Mine drift in bedrock	250	50
6	Bedrock	200	200
	Bottom of model	0	

## GRID

Grid spacing is typically determined based on the area of interest. Grid refinement in key areas, i.e., at the cavern location, can be used to increase the accuracy of the model in these areas, at the expense of lower accuracy at the edges of the model grid (Rumbaugh and Rumbaugh, 2011). When using refinement, the “smooth grid” command can be used to limit the grid change ratio (maximum 1.5 typical) to allow for better results. In the preliminary models, grid spacing is chosen based on cavern size to allow for ease of setting up the model. Distance to lateral boundaries is at least three times the depth of the flow system; after that, increasing the distance has only slight influence on the model (Lehn Franke et al., 1987). For example, if a cavern has a depth of 300 ft. and the model extends 200 ft. below it for a total model depth of 500 ft., the distance to lateral boundaries can be about 1,500 ft.

## CAVERN SIZE/LOCATION

The depth of the cavern used for preliminary models is initially chosen based on data from existing underground mine shafts in the Cuyuna Range. “While there are a few that are 12' by 16' x 800', most are likely to be somewhat smaller area-wise and probably 300' in depth. The idea was to start with this and then extend out horizontally into mine drifts to attain the volume required” (J. Oreskovich, pers. comm., 2013). The size of the shaft is assumed to be 10 ft. by 15 ft., with a depth of 300 ft. The drifts are assumed to be about 50 ft. wide by 50 ft. high by 400 ft. long, to give a cavern size of approximately 101,300 ft<sup>3</sup>. The facilities group has determined that the cavern will most likely need to be at least 100 m (328 ft.) underground.

## **BOUNDARY CONDITIONS**

Boundary condition considerations include changes in system flow and distance of boundary conditions from flow system. If the stress on a flow system causes changes in a natural boundary, e.g., head drawdown from a new well, the boundary is no longer physically reasonable (Lehn Franke et al., 1987). Therefore, further field investigation is necessary when using a constant head boundary at the edge.

Properties of the regional water table are useful in determining which boundary conditions to use at the edge of the model. The preliminary models use either a constant head boundary or a general head boundary to give a baseline representation of the water table for modeling purposes. A water table depth of about 20 ft. is assumed as a value that is typically found in the region.

For effective air storage, water at the cavern boundary should flow toward the cavern or have no flow. Outwards movement of water is possible at the bottom of the cavern, so to prevent air from leaking, the cavern bottom should be saturated with water or lined (Liang and Lindholm, 1994). To model groundwater flow, there must be a boundary condition to represent the air water interface at the edge of the cavern. This boundary needs a better technical understanding for modeling and will be affected by design decisions such as physical geology of selected location, cavern lining, cavern dimensions, and operating air pressure. Two simplified boundary conditions are selected for modeling: a constant head boundary and a water curtain. If a constant head boundary is assumed, it implies an infinite supply of water in the nearby area, and no changes in head will occur at the boundary. The second boundary condition is a water curtain that is used for providing a pressurized boundary condition in unlined caverns.

The value for the constant head boundary used for the cavern is found assuming an operating air pressure of 1,150 psi. This value converts to 2,538 ft. of water head. A constant head within the cavern may not be accurate, depending on the configuration of the system. CAES operation requires cyclic compression and decompression of the air within the cavern. In order to actually keep a constant head in the cavern, a reservoir is needed to be used that compensates for the change in air pressure within the cavern. Therefore, since the constant head boundary is used to represent the cavern, a reservoir location should probably be accounted for in the models. Just using the constant head boundary is an oversimplification of what would have to occur in order to keep the cavern at a constant pressure.

If a lined cavern is used, the boundary condition at the cavern would just be a no-flow boundary in Groundwater Vistas. In the case of a lined cavern being used, the potential for air escape through the lining has to be considered. However, representing the detailed boundary condition is beyond the scope of the modeling that was accomplished using Groundwater Vistas.

## **MODEL PARAMETERS**

Assuming the geology of the Cuyuna Range, values for Storage, Specific Yield, Porosity, and Hydraulic Conductivity are selected. Storage coefficients ranging from -0.00005 to 0.005 are selected for confined aquifers. Porosity is typically less than 0.01 and decreases with depth, and

Specific Yield is a function of Porosity. These values (Table 4.3-5) are selected to represent a reasonable physical range found in the region (Todd and Mays, 2005).

**Table 4.3-5.** Typical values of Storage (S), Specific yield (Sy), and Porosity (P).

Zone	S	Sy	Porosity
1	0.01	0.009	0.01
2	0.005	0.005	0.008
3	0.002	0.002	0.005

## MODELS AND RESULTS

Using the methods explained in the previous section, Groundwater Vistas is used in producing a series of models. These models are developed to examine various aspects of the project. The specific models are listed in Table 4.3-6. In this section, each model is described in depth in order to give an understanding of the purpose of each model and how the results can be useful in future models.

**Table 4.3-6.** Specific Groundwater Vistas models.

Model Name	Description
Sensitivity 1	Sensitivity to hydraulic conductivity
Sensitivity2	Sensitivity to storage parameter
Sensitivity3	Sensitivity to specific yield and porosity parameters
Water curtain	Water curtain with 1 AE well
Gridspace1	General head boundary (825 ft. from cavern to head boundary)
Gridspace2	Constant head boundary (725 ft. from cavern to head boundary)
Gridspace3	Constant head boundary (825 ft. from cavern to head boundary)
Gridspace4	Water curtain (1500 ft. from cavern to head boundary)
Gridspace5	Dewatering (2000 ft. from cavern to head boundary)
Gridspace6	Dewatering (2500 ft. from cavern to head boundary)
Grid100	Varying ratio of hydraulic conductivity
Refining1	Water curtain with 14 Analytic Element (AE) wells
Refining2	Dewatering with well boundary condition
Pressures	Water curtain flow rates with varying operating pressure
Dewater	Dewatering with well boundary condition, varying hydraulic conductivity (K)

## SENSITIVITY MODELS

Three models are created to determine the sensitivity of the model output to changes in model input. This method identifies which physical parameters need careful measurement once a site is selected to ensure realistic results from the groundwater model.

### Sensitivity1

The sensitivity1 model has four layers ranging from 0 to 300 ft. Elevation (in ft.) 0, 100, 150, 200, 300). The grid is made of thirty-nine 15 ft. rows and twenty-nine 10 ft. columns. The cavern is located in the center of layer 3, and is 50 ft. wide by 50 ft. high by 405 ft. long. The cavern is modeled as having a constant head of 2,538 ft. (to approximate a constant pressure of 1,100 psi within the cavern). The first layer has a constant head boundary set at 290 ft. along both edges.

Sensitivity1 is used to determine how varying the hydraulic conductivity (K), while holding all other parameters constant, affects the model. This calculation is accomplished by starting out with constant horizontal hydraulic conductivity ( $K_h$ ) and vertical hydraulic conductivity ( $K_z$ ) values in all of the layers. Each layer is assumed to have an anisotropy ratio of  $K_z/K_h=0.1$ . Then, the first layer is kept at the initial K values, and for the rest of the layers K values are reduced. Next, the first and second layers are held constant, while reducing layers 3 and 4. Finally, the model is run with all four layers set at different K values, as shown in Table 4.3-7.

**Table 4.3-7.** Sensitivity1 hydraulic conductivities.

Layer	Kh (ft./day)	Kz (ft./day)
1	0.001	0.0001
2	0.0001	0.00001
3	0.00001	0.000001
4	0.000001	0.0000001

The storage, specific yield, and porosity parameters are all kept at a constant value of 0.01 throughout all layers of the sensitivity1 model.

Reducing the hydraulic conductivity over each layer gives the most intuitive results, which is expected since hydraulic conductivity decreases with depth underground (Todd and Mays, 2005). Using these values, the model is altered by varying hydraulic conductivity in the cavern. As hydraulic conductivity with the cavern is increased, the final heads increased and a larger area in the model is affected.

From this sensitivity model, it is apparent that the hydraulic conductivities used in a Groundwater Vistas model have a large effect on the model results.

## Sensitivity2

The sensitivity2 model is set up similarly to the sensitivity1 model, using the same layers, grid layout, and boundary conditions, but different model parameters. The sensitivity2 model has four layers ranging from 0 to 300 ft. (Elevation (in ft.) 0, 100, 150, 200, 300). The grid is made of thirty-nine 15 ft. rows and twenty-nine 10 ft. columns. The cavern is located in the center of layer 3, and is 50 ft. wide by 50 ft. high by 405 ft. long. The cavern is modeled as having a constant head of 2,538 ft. The first layer has a constant head boundary set at 290 ft. along both edges.

Sensitivity2 is used to determine how varying the storage parameter affects the model. Hydraulic conductivities for each layer are as shown in Table 4.3-8, with the cavern having  $K_h=0.00001$  ft./day and  $K_z=0.000001$  ft./day. Storage values for each layer are changed similarly to how K values are altered in the first model, and there is no visible difference resulting from the variation of S.

**Table 4.3-8.** Sensitivity2 model parameters.

	$K_h$ (ft./day)	$K_z$ (ft./day)	S	$S_y$	Porosity
Layer 1	1.0E-03	1.0E-04	0.010	0.01	0.01
Layer 2	1.0E-04	1.0E-05	0.005	0.01	0.01
Layer 3	1.0E-05	1.0E-06	0.001	0.01	0.01
Layer 4	1.0E-06	1.0E-07	0.0001	0.01	0.01
Cavern	1.0E-05	1.0E-06	0.0001	0.01	0.01

The storage value in the cavern is also varied, and there is no effect on final heads with this variation. Storage does not seem to have much effect on this model.

## Sensitivity3

The sensitivity3 model is set up similarly to the other two sensitivity models, again using the same layers, grid layout, and boundary conditions, but different model parameters. The sensitivity3 model has four layers ranging from 0 to 300 ft. (Elevation (in ft.) 0, 100, 150, 200, 300). The grid is made of thirty-nine 15 ft. rows and twenty-nine 10 ft. columns. The cavern is located in the center of layer 3, and is 50 ft. wide by 50 ft. high by 405 ft. long. The cavern is modeled as having a constant head of 2,538 ft. The first layer has a constant head boundary set at 290 ft. along both edges.

Sensitivity3 is used to determine how varying specific yield and porosity affects the model. These two parameters are varied at the same time because specific yield is a portion of porosity. Porosity is assumed to be less than 0.01 because of values found in the book *Groundwater Hydrology* (Todd and Mays, 2005). Table 4.3-9 shows the specific values used for all of the model parameters. This model is run with various  $S_y$  and porosity values, similarly to

how the previous models are varied for K and S. There is no evident effect on the final heads from varying specific yield and porosity.

**Table 4.3-9.** Sensitivity3 model parameters.

	<b>Kh (ft./day)</b>	<b>Kz (ft./day)</b>	<b>S</b>	<b>Sy</b>	<b>Porosity</b>
Layer 1	1.0E-03	1.0E-04	0.01	0.01	0.01
Layer 2	1.0E-04	1.0E-05	0.005	0.009	0.01
Layer 3	1.0E-05	1.0E-06	0.001	0.005	0.008
Layer 4	1.0E-06	1.0E-07	0.0001	0.002	0.005
Cavern	1.0E-05	1.0E-06	0.001	var	var

## WATER CURTAIN

The water curtain model is set up to get an idea of what type of boundary works the best to represent a water curtain. This model has five layers going from 0 to 400 ft. (see Table 4.3-10). The grid is made of thirty-nine 15 ft. rows and twenty-nine 10 ft. columns, as in the sensitivity models. A 50x50x405 ft. cavern is located in the center of layer 4, and has a constant head of 2,538 ft. The first layer of the model has a general head boundary of 350 ft. along the right edge. A water curtain area is located above the cavern, in layer 2 of the model. MODLFOW AE (Analytical Element) wells are used with a steady state pumping rate of 2,600 ft.<sup>3</sup>/day into this 1 ft. layer. Hydraulic conductivity values for the water curtain model are shown in Table 4.3-10, and all other model parameters (storage, specific yield, porosity) were set at 0.01 throughout the model. The decision not to vary storage, specific yield, and porosity is based on results from a sensitivity analysis conducted by the team that showed that demonstrated that these parameters have no effect on the model. These results are not included in this report.

**Table 4.3-10.** Water curtain model properties.

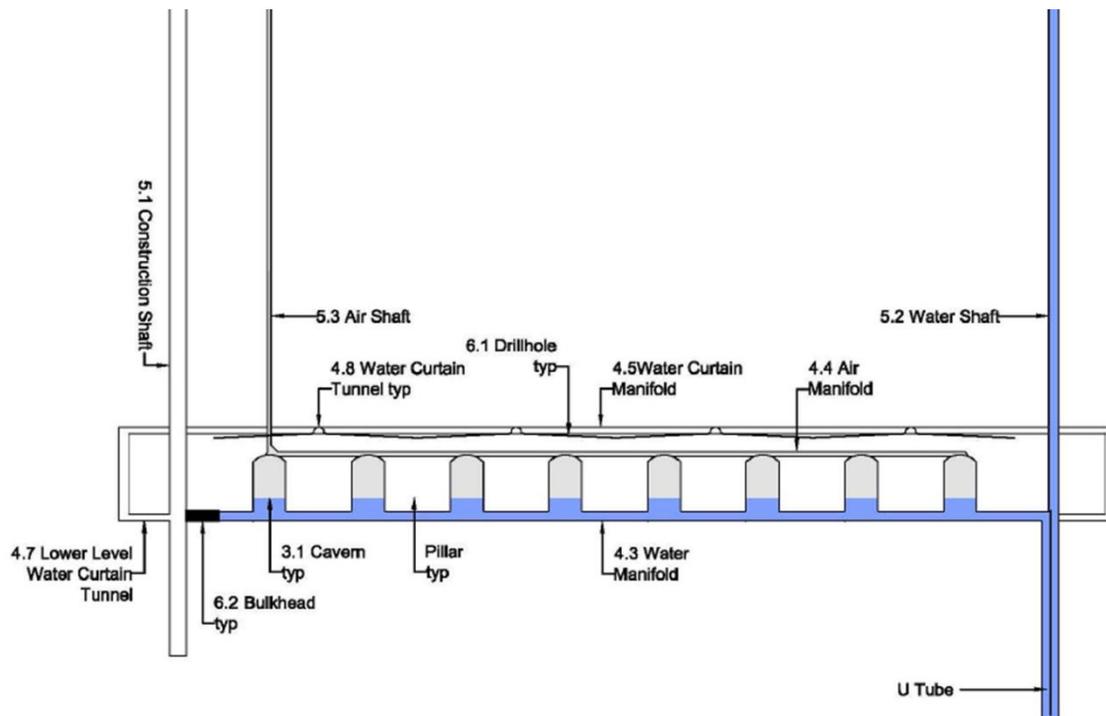
<b>Layer Number</b>	<b>Top Layer Elevation (ft.)</b>	<b>Horizontal Hydraulic Conductivity K<sub>h</sub> (ft./day)</b>	<b>Vertical Hydraulic Conductivity K<sub>z</sub> (ft./day)</b>
1	400	100	10
2	200	100	10
3	199	50	5
4	150	10	1
5	100	10	1
Cavern		1	0.1
Water curtain		1	0.1

For the model, a water curtain is installed 40 to 50 ft. above the top of a cavern to provide a pressure that is greater than the pressure in the cavern. This pressure gradient is accomplished by placing boreholes spaced at about 10 ft. along the length to allow the water curtain to at least cover the roof of the cavern (see Figure 4.3-3). Flow for an 855 pounds per square inch gage (psig) curtain is about 13.5 gallons per minute (gpm), or 2.600 ft.<sup>3</sup>/day (Bauer et al., 2012).

### Gridspace1

The gridspace1 model is made up of five layers ranging from 0 to 500 ft. as presented in Table 4.3-11. The grid has 20 rows and 18 columns, which started at a 100 ft. by 100 ft. spacing and are refined down to 50 ft. rows by 25 ft. columns. The cavern is located in the center of layer 4, and is 50 ft. wide by 50 ft. high by 400 ft. long. The cavern is modeled as having a constant head of 2,538 ft. The first layer has a general head boundary (GHB) set at 480 ft. along the left edge, with the distance to the cavern to the head boundary set at 200 ft. This spacing provides a total distance of 825 ft. from the cavern to the head boundary.

The hydraulic conductivity values for the gridspace1 model are shown in Table 4.3-11, and all other model parameters (storage, specific yield, porosity) are set at 0.01 throughout the model.



**Figure 4.3-3.** CAES cross-section with water curtain (Bauer et al., 2012).

**Table 4.3-11.** Gridspace1 layer and cavern properties.

Layer Number	Layer Top Elevation (ft.)	Horizontal Hydraulic Conductivity $K_h$ (ft./day)	Vertical Hydraulic Conductivity $K_v$ (ft./day)
1	500	300	30
2	300	300	30
3	299	20	2
4	250	20	2
5	200	20	2
Cavern		0.05	0.05

### Gridspace2

The gridspace2 model was set up similarly to gridspace1 but has a larger model size. The layers were set up the same as in gridspace1, as seen in Table 4.3-12. The grid has 22 rows and 20 columns that started at a 100 ft. by 100 ft. spacing and are refined down to 50 ft. rows by 25 ft. columns. The cavern is located in the center of layer 4 and is 50 ft. wide by 50 ft. high by 400 ft. long. The cavern is modeled as having a constant head of 2,538 ft. The first layer of the gridspace2 model has a constant head boundary set at 480 ft. along the left edge. The gridspace2 model has a distance of 725 ft. from the cavern to the head boundary, which is less than that of the gridspace1 model.

The hydraulic conductivities are the same as the previous model, as shown in Table 4.3-12. Storage, specific yield, and porosity were again set at 0.01 throughout the model.

**Table 4.3-12.** Gridspace2 layer and cavern properties.

Layer Number	Top Layer Elevation (ft.)	Horizontal Hydraulic Conductivity $K_h$ (ft./day)	Vertical Hydraulic Conductivity $K_z$ (ft./day)
1	500	300	30
2	300	300	30
3	299	20	2
4	250	20	2
5	200	20	2
Cavern		0.05	0.05

### Gridspace3

The gridspace3 model is similar to the previous two models, but with another increase in model size. The layers are set up the same as in gridspace1, as seen in Table 4.3-13. The grid has 24 rows and 22 columns, which start at a 100 ft. by 100 ft. spacing and are refined down to 50 ft. rows by 25 ft. columns. The cavern is located in the center of layer 4 and is 50 ft. wide by 50 ft. high by 400 ft. long. The cavern is modeled as having a constant head of 2,538 ft. The first layer of the gridspace3 model has a constant head boundary set at 480 ft. along the left edge. The gridspace3 model has a distance of 825 ft. from the cavern to the head boundary, which is the same as that of the gridspace1 model. This spacing allows for a comparison between using the general and constant head boundaries.

The hydraulic conductivities are the same as the previous model, as shown in Table 4.3-13. Storage, specific yield, and porosity are again set at 0.01 throughout the model.

**Table 4.3-13.** Gridspace3 layer and cavern properties.

Layer Number	Top Layer Elevation (ft.)	Horizontal Hydraulic Conductivity $K_h$ (ft./day)	Vertical Hydraulic Conductivity $K_z$ (ft./day)
1	500	300	30
2	300	300	30
3	299	20	2
4	250	20	2
5	200	20	2
Cavern		0.05	0.05

### Gridspace4

The gridspace4 model has the same layer properties as the previous three models, with a change in grid size and cavern model parameters as shown in Table 4.3-14. The grid has 40 rows and 36 columns, which start at a 100 ft. by 100 ft. spacing and are refined down to 50 ft. rows by 25 ft. columns. The cavern is located in the center of layer 4 and is 50 ft. wide by 50 ft. high by 400 ft. long. The cavern is modeled as having a constant head of 2,538 ft. An area above the cavern in layer 2 is designated as the water curtain, and has a constant head boundary of 2,538 ft. The first layer of the gridspace4 model has a constant head boundary set at 470 ft. along both sides of the model. The distance from the cavern to the head boundary is 1,500 ft. on each side.

The hydraulic conductivities of the layers are kept the same, but the hydraulic conductivity of the cavern is increased from the previous gridspace models. The water curtain area has a hydraulic conductivity of 0.0001. Storage, specific yield, and porosity are set at 0.01 throughout the model.

**Table 4.3-14.** Gridspace4 layer and cavern properties.

Layer Number	Top Layer Elevation (ft.)	Horizontal Hydraulic Conductivity $K_h$ (ft./day)	Vertical Hydraulic Conductivity $K_z$ (ft./day)
1	500	300	30
2	300	300	30
3	299	20	2
4	250	20	2
5	200	20	2
Cavern		1000	1000

### Gridspace5

The gridspace5 model has the same layer properties as all of the other gridspace models (see Table 4.3-15). The grid has 50 rows and 46 columns, which starts at a 100 ft. by 100 ft. spacing and is refined down to 50 ft. rows by 25 ft. columns. The cavern is located in the center of layer 4 and is 50 ft. wide by 50 ft. high by 400 ft. long. The cavern is modeled as a well boundary condition with a pumping rate of -1000 to simulate dewatering the cavern. The first layer of the gridspace5 model has a constant head boundary set at 470 ft. along both sides of the model. The distance from the cavern to the head boundary is 2,000 ft. on each side. The hydraulic conductivities of the layers are kept the same, but the hydraulic conductivity of the cavern is changed from the previous gridspace models. Storage, specific yield, and porosity are again set at 0.01 throughout the model.

**Table 4.3-15.** Gridspace5 layer and cavern properties.

Layer Number	Top Layer Elevation (ft.)	Horizontal Hydraulic Conductivity $K_h$ (ft./day)	Vertical Hydraulic Conductivity $K_z$ (ft./day)
1	500	300	30
2	300	300	30
3	299	20	2
4	250	20	2
5	200	20	2
Cavern		1	1

### **Gridspace6**

The gridspace6 model again has the same layer properties (see Table 4.3-16). The grid has 60 rows and 56 columns, which starts at a 100 ft. by 100 ft. spacing and is refined down to 50 ft. rows by 25 ft. columns. The cavern is located in the center of layer 4 and is 50 ft. wide by 50 ft. high by 400 ft. long. The cavern uses the same boundary condition as gridspace5 and is modeled as a well boundary condition with a pumping rate of -1000 to simulate dewatering the cavern. The first layer of the gridspace6 model has a constant head boundary set at 470 ft. along both sides of the model. The distance from the cavern to the head boundary is 2,500 ft. on each side. The hydraulic conductivities of the layers are kept the same, but the hydraulic conductivity of the cavern is changed from the previous gridspace models. Storage, specific yield, and porosity are again set at 0.01 throughout the model.

**Table 4.3-16.** Gridspace6 layer and cavern properties.

<b>Layer Number</b>	<b>Top Layer Elevation (ft.)</b>	<b>Horizontal Hydraulic Conductivity <math>K_h</math> (ft./day)</b>	<b>Vertical Hydraulic Conductivity <math>K_z</math> (ft./day)</b>
1	500	300	30
2	300	300	30
3	299	20	2
4	250	20	2
5	200	20	2
Cavern		100	100

The gridspace models are set up to determine what effect grid spacing has on the model. All of the gridspace models use the same layer elevations and hydraulic conductivities. Boundary conditions at the edge of the model vary with each of the models as the total model size is increased (Table 4.3-17).

**Table 4.3-17.** Gridspace model sizes and boundary conditions.

<b>Gridspace Model</b>	<b>Total Area</b>	<b>Boundary Condition</b>
1	1820000	GHB (left side)
2	2400000	CH (left side)
3	3060000	CH (left side)
4	10540000	CH (both sides)
5	18040000	CH (both sides)
6	27540000	CH (both sides)

Gridspace4 had 1,500 ft. from the cavern to the head boundary on each side of the model, gridspace5 has 2,000 ft., and gridspace6 had 3,000 ft. When making a larger grid, the constant head boundary is effectively moved further from the cavern and causes a change in the final heads of the model.

### **Grid100**

The grid100 model has five layers ranging from 0 to 500 ft. (see Table 4.3-18). The grid has 14 rows and 12 columns, which start at a 100 ft. by 100 ft. spacing and are refined down to 50 ft. rows by 25 ft. columns. The cavern is located in the center of layer 4 and is 50 ft. wide by 50 ft. high by 400 ft. long. The cavern is modeled as having a constant head of 2,538 ft. The first layer has a constant head boundary set at 480 ft. along the left edge of the model. Storage, specific yield, and porosity are set at 0.01 throughout the model.

**Table 4.3-18.** Grid100 layer elevations.

Layer	Top Elevation (ft.)
1	500
2	300
3	299
4	250
5	200

The grid100 model is used to determine how the rate of change in hydraulic conductivity affects the final heads. Maximum and minimum head results are recorded for each layer while varying hydraulic conductivity values. After a few trials, it is noticed that runs with a similar rate of change in hydraulic conductivity have the same head values, as seen in Table 4.3-19.

**Table 4.3-19.** Head results with ratio of hydraulic conductivity.

Layer	K <sub>h</sub>	K <sub>v</sub>
1 & 2	1	0.1
3 to 5	0.2	0.02
ratio	5	
Head Results		
Layer	Min	Max
1	480	648
2	618	871
3	800	1206
4	1059	2538
5	1335	1423

Layer	K <sub>h</sub>	K <sub>v</sub>
1 & 2	50	5
3 to 5	10	1
ratio	5	
Head Results		
Layer	Min	Max
1	480	648
2	618	871
3	800	1206
4	1059	2538
5	1335	1423

Layer	K <sub>h</sub>	K <sub>v</sub>
1 & 2	10	1
3 to 5	1	0.1
ratio	10	
Head Results		
Layer	Min	Max
1	480	572
2	546	703
3	717	1091
4	976	2538
5	1257	1348

Layer	K <sub>h</sub>	K <sub>v</sub>
1 & 2	1	0.1
3 to 5	0.1	0.01
ratio	10	
Head Results		
Layer	Min	Max
1	480	572
2	546	703
3	717	1091
4	976	2538
5	1257	1348

More trials were run to see how the ratio between the hydraulic conductivity of the top two layers and the hydraulic conductivity of the bottom three layers affected the head in the model. From this model, it is determined that increasing the ratio in K values between the layers tends to decrease head values in model (Figure 4.3-4). Actual K values do not impact heads as much as the rate of change in K with depth.

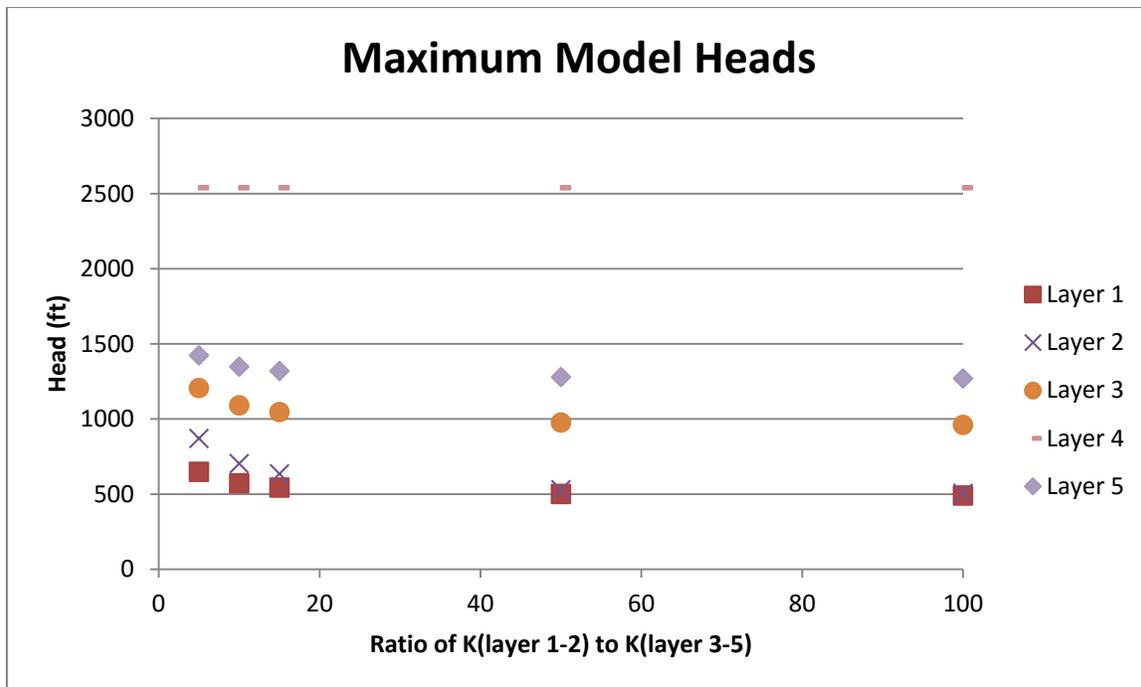


Figure 4.3-4. Maximum model head with ratio between hydraulic conductivities of layers.

**Refining1**

The refining1 model has six layers, with the range of elevations going from 0 to 500 ft. The grid for the refining1 model starts with 100 ft. spacing for both columns and rows and is refined down to 15 ft. rows by 10 ft. columns at the cavern. A 50x50x405 ft. cavern is located in the center of layer 5, with a mine shaft that is 10 ft. by 15 ft. located at the edge of the cavern going up to the first layer. The cavern and shaft areas are considered to be a continuous region by keeping their properties consistent throughout modeling and have a constant head boundary of 2,538 ft. A water curtain area is designated above the cavern, in layer 3. Constant head boundaries are used at both edges of the first layer, with heads of 480 ft. The hydraulic conductivity in each of the layers is shown in Table 4.3-20, while the hydraulic conductivity of the cavern and water curtain area is varied. Storage, specific yield, and porosity are set at 0.01 throughout the model.

**Table 4.3-20.** Refining1 layer properties.

Layer No.	Top El. (ft.)	Kh (ft./day)	Kz (ft./day)
1	500	300	30
2	400	0.003	0.0003
3	300	0.003	0.0003
4	299	0.003	0.0003
5	250	1.00E-06	1E-07
6	200	1.00E-06	1E-07

The refining1 model is used in an attempt to model the water curtain using analytic element (AE) wells. Fourteen AE wells are placed in layer 3 and spread across the length of the cavern. A steady-state pumping rate is used to give reasonable heads in the model. The hydraulic conductivities of the water curtain area and the cavern area are modified, and it is found that decreasing K in the water curtain results in a drastic increase in heads when using the same pumping rate.

## **Refining2**

Although the refining2 model uses the same grid and layer layout as refining1, no water curtain is used in this model. Six layers ranging from 0 to 500 ft. have the same properties as the refining1 model, as shown in Table 4.3-21. The grid for the refining2 model starts with 100 ft. spacing for both columns and rows and is refined down to 15 ft. rows by 10 ft. columns at the cavern. A 50x50x405 ft. cavern is located in the center of layer 5 with a mine shaft that is 10 ft. by 15 ft. and is located at the edge of the cavern going up to the first layer. The cavern and shaft area are considered to be a continuous region by keeping their properties consistent throughout modeling. Storage, specific yield, and porosity are set at 0.01 throughout the model. Constant head boundaries are used at both edges of the first layer, with heads of 480 ft.

**Table 4.3-21.** Refining2 layer properties.

Layer No.	Top El. (ft.)	Kh (ft./day)	Kz (ft./day)
1	500	300	30
2	400	0.003	0.0003
3	300	0.003	0.0003
4	299	0.003	0.0003
5	250	1E-06	1E-07
6	200	1E-06	1E-07

A well boundary condition is used in the cavern to simulate dewatering of an underground mine. The pumping rate necessary to effectively dewater the mine is dependent on the hydraulic conductivity. For the mine  $K_h = 10^{-9}$  and  $K_z = 10^{-10}$ , a  $Q = -0.0105$  is required for dewatering. When the mine  $K = 100$ , a  $Q = -900$  was required.

## PRESSURES

This model is used to find the effect of varying the cavern operating pressure and to determine what flow rate into the water curtain is necessary to keep air contained for each pressure. Operating pressures that are considered are 900 psi, 1100 psi, 1600 psi, and 2000 psi. Corresponding head values that are used are in Table 4.3-22.

**Table 4.3-22.** Potential operating pressures and head values.

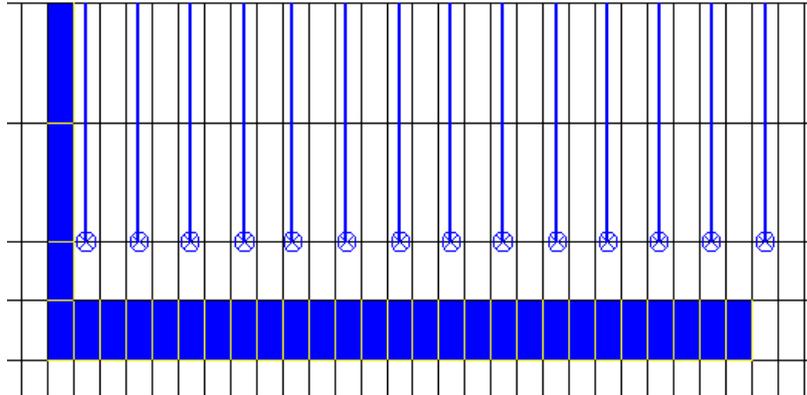
Operating Pressure (psi)	Water Head (ft.)
900	2077
1100	2538
1600	3692
2000	4615

The pressures model consists of six layers ranging from 0 to 500 ft. A grid with 65 rows and 44 columns started with 100 ft. spacing and is refined down to 15 ft. rows and 10 ft. columns at the cavern. A 50x50x405 ft. cavern is located in the center of layer 5 and has a constant head boundary condition that is varied to model each operating pressure. Constant head boundaries are used at both edges of the first layer, with heads of 480 ft. Fourteen AE wells are placed in layer 3 and spread across the length of the cavern. Hydraulic conductivity values for the pressures model are presented in Table 4.3-23. Storage, specific yield, and porosity are set at 0.01 throughout the model.

**Table 4.3-23.** Pressures model properties.

Layer No.	Top El. (ft.)	$K_h$ (ft./day)	$K_z$ (ft./day)
1	500	300	30
2	400	0.003	0.0003
3	300	0.003	0.0003
4	299	0.003	0.0003
5	250	1E-06	1E-07
6	200	1E-06	1E-07
Cavern		1	0.1
Water curtain		0.1	0.01

The water curtain is modeled in MODFLOW as a series of analytic element (AE) wells (Figure 4.3-5). The modeling shows that for operating pressures ranging from 900-2000 psi, the current model is requiring injection rates of 45-120 ft.<sup>3</sup>/day to achieve pressures greater than cavern operating pressures. The project team must determine if this is a reasonable setup for the CAES project.



**Figure 4.3-5.** Cavern model with multiple AE wells for a water curtain.

## DEWATER

This model is used to simulate the effect of dewatering a cavern. It consists of six layers going from 0 to 500 ft. The grid (similar to gridspace4) has 40 rows and 36 columns, which start at a 100 ft. by 100 ft. spacing and are refined down to 50 ft. rows by 25 ft. columns. The cavern is located in the center of layer 5, is 50 ft. wide by 50 ft. high by 400 ft. long, and has a mine shaft going from the edge of the cavern up to the first layer. A well boundary condition using various pumping rates is set within the cavern and mine shaft area. Constant head boundaries of 480 ft. are set along both edges of the first layer. Hydraulic conductivity values for the layers of the dewater model are presented in Table 4.3-24. Storage, specific yield, and porosity are set at 0.01 throughout the model.

**Table 4.3-24.** Dewater model layer properties.

Layer No.	Top El. (ft.)	Kh (ft./day)	Kz (ft./day)
1	500	300	30
2	400	0.003	0.0003
3	300	0.003	0.0003
4	299	0.003	0.0003
5	250	0.003	0.0003
6	200	0.003	0.0003

Various pumping rates and hydraulic conductivity values of the well are used to see how the model would be affected. From basic hydrology principles, it makes sense that for a constant pumping rate, there has to be a higher change in head in order to have a lower hydraulic conductivity. When looking at results from the dewatering model, the head in the cavern area should be lower than the elevation of the bottom of the cavern in order to have effectively dewatered the cavern.

## REMAINING QUESTIONS

To complete the model of regional groundwater flow, a few questions must be answered. A site must be selected so that the geology is well known including further field investigations. The modeling has shown that the model is sensitive to values of hydraulic conductivity. Additionally, boundary conditions must be characterized including the local geology, the surrounding water table depth, the operating pressures, and how the air will be contained (lining or a water curtain). The geometry and layout of the cavern are also important parameters for the model and finally, existing groundwater data must be used to calibrate the model.

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**CHAPTER 5:****ECONOMIC AND POLICY IMPLICATIONS OF CAES ON IMPLEMENTATION IN  
NORTHERN MINNESOTA USING UNDERGROUND MINE WORKINGS****Economic and Policy Team**

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Synopsis

The potential implementation of CAES in the northern Minnesota using underground mine working has various economic and policy implications. The work by the Econ and Policy team focused on developing a key understanding of the issues associated with potential implementation and on the economic and other beneficial impacts as new opportunities for the storage technology in the electricity market evolves. An overview of this chapter will be described next. Section 5.0 reviews the regulatory environment such as federal law and state policy, FERC order and market rule in MISO, as well as examines these factors in other parts of the country. It also covers policy barriers and opportunities for promoting CAES and explains the critical part planning models play. Section 5.1 provides regulatory and socio-political criteria for assessment guidelines. Since this criterion depends on CAES site selection, general permitting process is explained by the Minnesota Public Utilities Commission (PUC). Section 5.2 identifies stakeholders related to CAES and investigates socio-political factors affecting CAES implementation through literature review. Section 5.3 covers economic factors affecting CAES implementation. Key economic issues for CAES implementation are outlined.

**Section 5.0:  
Policy and Economic Environment for CAES Development**

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## INTRODUCTION

The policy environment for compressed air energy storage (CAES) is interactive: CAES could play a role in achieving certain policy goals (such as increasing the percentage of renewable power in Minnesota), and policy would play a role in whether CAES projects are built and how they are operated. Regulation would strongly influence whether CAES is chosen as the least cost alternative for a utility to meet its reliability, quality, and environmental objectives. It would also influence site selection, design, and operation of a CAES project. To explore these inter-relationships: the first part presents relevant state and federal legislations and reviewed incentives for storage technology development and CAES relevant legislation, the second part describes policy barriers and opportunities for promoting CAES, and a third part describes the role planning models play in valuing energy storage projects.

## OVERVIEW OF REGULATORY ENVIRONMENT

Characterization of the economic and policy environment for CAES has included research into relevant laws and regulations, criteria for potential site decision and incentives in ISO, land and mineral ownership, and potentially land use conflicts. This falls into federal and state regulation as well as incentives in MISO, the regional transmission organization. We have examined relevant state and federal legislation and reviewed incentives for storage technology development and CAES relevant legislation specifically.

### **Federal Law and State Policy**

The need for energy storage is re-iterated in many pieces of legislation. The Energy Policy Act of 2005, Energy Independence and Security Act of 2007, and the American Recovery and Reinvestment Act of 2009 all underscore the critical role that energy storage can play in the electrical transmission system. Additionally, many efforts have been made to promote legislation supporting investment in storage technologies, many proposing Investment Tax Credits, much like the Production Tax Credit that has been so helpful for supporting wind power. While legislation has been proposed in Congress, e.g., the STORAGE Act of 2011 or the Clean Energy Standard Act of 2012, no legislation has yet been passed, and the current political gridlock in Washington appears to make passage unlikely.

At the state level, renewable portfolio standards require generation from renewable sources of electricity, but the role of energy storage in renewable portfolio standards is varied, but most focus on generation technologies, not storage capabilities. For example, California have mandated that by 2024, California's three investor-owned utilities must invest in 1.325 GW of energy storage capacity. In Minnesota, there has not been specific legislation promoting storage. However, if a CAES project were to be developed in conjunction with wind development, applicable policies related with renewable energy would also be important. In Minnesota, the Renewable Energy Production Incentive (Minn. Statute 216C.41 Subdivision 1-Definitions): "Qualified wind energy conversion facility" 1.0 cent per kw-h until December 31,

2018, the Renewable Energy Standard (Minn. Statute 216B.1691) and the Energy Policy Goal (Minn. Statute 216C.05 Subd.2): 25% of total energy used in the state should be derived from renewable energy resources by 2025, are all important pieces of legislation shaping the policy environment.

### **FERC Order and Market rule in MISO**

After 2007, the Federal Energy Regulatory Commission has issued new Order for storage technologies. Table 5.0-1 explains how the FERC ordered RTOs for storage technology in details.

**Table 5.0-1.** Summary of FERC Order for storage technology (Source: <https://www.ferc.gov/whats-new/comm-meet/2013/071813/E-22.pd>).

<b>FERC Order</b>	<b>Year</b>	<b>Contents</b>
FERC Order 755 Frequency Regulation Compensation in the Organized Wholesale Power Markets	Issued October 20, 2011  Effective 60 days after publication in the Federal Register	Order 755 requires regional transmission organizations and independent system operators to adopt a two-part market-based compensation method for frequency regulation services – a capacity payment reflecting opportunity costs and a market-based performance payment – rewarding faster-ramping resources, such as batteries and flywheels.
FERC Order 784 Third-Party Provision of Ancillary Services; Accounting and Financial Reporting for New Electric Storage Technologies	Issued July 18, 2013  Effective 120 days after publication in the Federal Register	Order 784 requires high-voltage interstate transmission operators to recognize the value of energy storage systems that can quickly and precisely dampen potentially dangerous disturbances in electrical frequencies.
FERC Order 792 Small Generator Interconnection Agreements and Procedures	Issued November 22, 2013  Effective 60 days after publication in the Federal Register	Order 792 added energy storage to the category of resources eligible to interconnect with the electric grid. Thus, energy storage can receive rates, terms and conditions for interconnection with public utilities that are just and reasonable and not unduly discriminatory.
FERC Order 890 Preventing Undue Discrimination and Preference in Transmission Service	Issued February 16, 2007  Effective 60 days after publication in the Federal Register	Order 890 required ISOs to develop tariffs, market rule, and control algorithms, to open markets for non-generation energy storage technologies to provide ancillary services.

Another important policy consideration is regional *de facto* policy through regional transmission organizations (RTOs), both through their planning activities and in market design. RTOs also recognize the benefits from storage plants and FERC Order 755, 784, 792 and 890 helps to address this issue by rewarding speed and accuracy through pay-for-performance requirements and by creating new market for storage.

Midcontinent Independent System Operator (MISO) defines Stored Energy Resource (SER) as eligible to provide Regulating Reserves. In the regulation reserves market, a storage plant deserves to receive payment for mileage because of its fast ramping rate. In Oct 2011, Federal Energy Regulatory Commission (FERC) issued Order 755 that required the organized wholesale power markets to also provide compensation for generation movement in response to regulation dispatch. In December 2012, MISO added a regulation “mileage” product to financially compensate generators for providing regulation capacity. See Table 5.0-2. This is important for the value of CAES projects.

**Table 5.0-2.** MISO Frequency Regulation Compensation (Source: MISO Frequency Regulation Compensation FERC Order 755, Market Subcommittee December 4, 2012).

Regulating Capacity (Cleared Reg MW)	Regulating mileage
Compensated at regulating reserve MCP Prepaid mileage = $a \cdot (\text{Cleared Reg MW}) / \text{Interval}$ a is per dispatch interval ratio	AdditionalRegMileage = $\max(0, (\text{Regulating Mileage Target}) - a \cdot \text{ClearedRegMW})$ UndeployedRegMileage = $\max(0, (a \cdot \text{ClearedRegMW} - \text{Regulating Mileage Target}))$

Additionally, CAES projects are affected by government protocols shaping facility siting. Environmental permitting and approvals by state and federal entities which will impact how CAES technologies are developed and deployed. As CAES plants store compressed air in subsurface rock formations, the geologic characteristics of the site are paramount for facility operation. Candidate sites are currently being investigated by the Geology Team (see Section 1.1), and the Economic and Policy team is working closely to better understand how geologic data will affect plant design and potential operation. Site selection will affect economic characteristics that will impact facility costs and the cost of electricity. Infrastructure costs, such as access to the high-voltage electric transmission network and easy delivery of natural gas, will affect the financial viability of CAES.

Finally, the ability of CAES projects to be constructed on the Mesabi Range remains dependent on access to land and mineral rights. Earlier work on the viability of the CAES project in Mesabi and Cuyuna Ranges (Fosnacht et al., 2011) on the Mesabi Range addressed this issue, “The largest mineral rights owner and a major landowner is the State of the Minnesota. Purchasing the land to build a CAES facility is complicated by the fact that property rights may be severed, which means that landowner may not hold the mineral rights.” These issues remain important for any CAES development.

## **Minnesota Public Utilities Commission**

As a key regulatory entity in the state of Minnesota, the Minnesota Public Utilities Commission (MPUC) is a permitting authority for any future CAES plant. However, MPUC does not provide a specific guideline for CAES facility because this authority is still investigating the CAES facility. Instead, they provide general guideline for any large energy facility proposed. General process of permitting is explained in Section 5.2.

## **OTHER STATES**

### **California**

The California Public Utilities Commission (CPUC) has been the first of all states to make a regulatory requirement to require a certain amount of energy storage to be procured by its investor-owned utilities. To fulfill the requirements of CA Bill 2514, Rulemaking 10-12-007 sets out the requirements (California Public Utilities Commission, 2013). Investor owned utilities; Southern California Edison, Pacific Gas & Electric, and San Diego Gas & Electric, are required to install a total of 1,325MW of storage by 2020. The ruling splits up the requirement between the three utilities and lays out possible procurement targets in three different storage grid domains; transmission, distribution, and customer. The PUC defines the benefits of storage in three guiding principles:

- “1) The optimization of the grid, including peak reduction, contribution to reliability needs, or deferment of transmission and distribution upgrade investments;
- 2) The integration of renewable energy; and
- 3) The reduction of greenhouse gas emissions to 80 percent below 1990 levels by 2050, per California goals.” (California Public Utilities Commission, 2013)

It should also be noted that CPUC has already implemented two demand side programs that energy storage can participate in: Permanent Load Shifting and Self Generation Incentive Program (California Independent System Operator, 2014). Being demand side management programs, these are both dealing with storage installed on the customer side of the meter, yet these programs show the value CPUC is putting on energy storage technology to meet long-term energy goals. California Independent System Operator (CISO), along with CPUC and the California Energy Commission, have developed an extensive roadmap looking at any issues or roadblocks that need to be resolved going forward with a grid that fully supports energy storage integration (California Independent System Operator, 2014).

### **Texas**

Texas is another area of the country with interesting developments in addressing energy storage technology. The Electric Reliability Council of Texas (ERCOT), the independent grid

operator for the state of Texas, is looked to incorporate a “pay for performance” regulation which in effect would be similar to the FERC order 755 requirements (Electric Reliability Council of Texas, 2013). This is significant, as ERCOT is not required to follow the FERC ruling, thus they are choosing to incorporate this type of service in their market rules. ERCOT’s “pay-for-performance” is part of a bigger effort ERCOT is currently undertaking to redesign its ancillary services market (Electric Reliability Council of Texas, 2013). They are initiating this process in response to the fact that new resources respond in ways that bring challenges for them as operators as well as some resources also bring new benefits they want to take advantage of. ERCOT foresees a redevelopment of the ancillary services market as the way to better utilize these new capabilities and support a more efficient way of operating the grid.

The Public Utility Commission of Texas (PUCT) is making headway on rulings for energy storage which helps investors know how to plan for future investments. They have ruled that energy storage will pay wholesale price, settled at the node when they are in the charging stage, and energy storage will not be subject to ancillary costs (Public Utility Commission of Texas, 2012).

Oncor Electric Delivery Company, a Transmission and Distribution Service Provider (TDSP) located in Texas, had a study completed by The Brattle Group last year (Brattle Group, 2014). The Brattle study found that up to 5,000 MW of energy storage could be cost effective across the ERCOT territory. Yet, the advantageous economics for deploying energy storage is from totaling the benefits from both the transmission and distribution (T&D) market and the wholesale market. From this study, Oncor has proposed to install up to 5,000 MW of battery energy storage throughout the ERCOT area (Husch Blackwell, 2015). This would require a legislative change in order for a TDSP to deploy generation assets since T&D providers are not allowed to compete in the wholesale market.

## **New York**

In New York City, Con Edison and the New York State Energy Research and Development Authority (NYSERDA) have created a Demand Management program which gives monetary incentives for developers of energy storage projects (Con Edison, 2015). Projects are required to be operational by June 1, 2016 and reduce peak demand by at least 50 kW and projects receive bonus incentives for reducing peak demand by 500 kW. Figure 5.0-1 shows the current rate for incentives (Con Edison, 2015). Although this program is for the New York City area and does not directly affect future compressed air projects, it is interesting that this program is a large demand-side program for energy storage, instead of looking to deploy storage on the utility side of the meter. This is a type of program other states—or, specifically, large cities—might be interested in replicating, so all forms of energy storage should be interested in the effects it creates.

<b>Con Edision of New York: Demand Management Program</b>	
<b>Project Type</b>	<b>Incentives</b>
Thermal Storage	\$2,600/kW
Battery Storage	\$2,100/kW
Chiller/HVAC/BMS/Controls	\$0.16/kWh + \$1,250/kW
Lighting/LED	\$0.16/kWh + \$800/kW
DR Enablement	\$800/kW
Fuel Switching: Non-Electric A/C*	\$500 - \$1,000/kW
*Incentives will be offered for installing steam or natural gas A/C rather than electric A/C.	

**Figure 5.0-1.** New York ConEdison energy storage incentives.

Going forward, the New York Public Service Commission (NYPSC) has commenced an initiative called “Reforming the Energy Vision” where they are extensively examining New York State’s energy industry and regulatory practices (New York Public Service Commission, 2015). The outcomes will certainly directly affect future energy storage projects in the state even though it is still an ongoing process.

The procedural and market developments in each of these states show how quickly and dramatically the landscape is changing for energy storage projects. In general, the overwhelming time and resources going towards quantifying the grid and public value of energy storage shows that storage will play a large role in the future of the electric grid. Yet, these are all developments that energy storage investors and researchers would be wise to pay close attention to, as market rules and regulation can drastically change the possible value of a storage project. As has been shown by Paine et al. (2014) for a pumped hydro project, market rules can greatly affect the profits from deploying energy storage.

## **POLICY BARRIERS AND OPPORTUNITIES FOR PROMOTING COMPRESSED AIR ENERGY STORAGE**

Despite CAES technologies having the potential to create benefits for the power system<sup>1</sup>, there are currently numerous barriers to their deployment. Price is clearly a barrier, with CAES technologies significantly more expensive than the alternatives that are currently in use, but there are also regulatory barriers that could be addressed to incentivize deployment of compressed air energy storage. Some of these potential regulatory changes, such as creating electricity markets where price is a function of power quality, as well as power quantity, are longer term issues, but there are other regulatory barriers to storage that could be addressed now.

<sup>1</sup> Eyer and Corey (2010) suggests the following benefits of energy storage for the electricity grid: (1) Electric Energy Time-shift, (2) Voltage Support, (3) Avoided Transmission and Distributed Energy Losses, (4) Electric Supply Capacity, (5) Transmission Congestion Relief, (6) Electric Service Reliability, (7) Reduced Generation Fossil Fuel Use, and so on.

Compressed air energy storage coupled with wind farm could be made eligible to receive renewable energy credits under Minnesota’s Renewable Energy Standard, similar to its treatment in Michigan. Michigan grants 20 percent of a renewable energy credit for each MWh of electricity that is generated from a renewable energy system during off-peak hours, stored by a CAES facility, and resold during peak hours (Michigan Clean, Renewable, and Efficient Energy Act, Section 460.1039; Michigan Legislature, n.d.). This renewable energy credit incentive reflects the mixed impact of CAES on greenhouse gas emissions. CAES in some scenarios could reduce the cost of integrating large amounts of wind resources into the power system and displace natural gas.

As new FERC Orders encourage ISOs to create new AS market for storage facilities, MISO is expected to allow CAES facility to participate in Ancillary Service Market. For example, NY-ISO allows storage to provide voltage control service, which CAES can also provide. At the present, high market entry barriers prevent CAES from seeking additional revenue in the market even though CAES has ability to provide various ancillary services. In cooperation with the Facilities Team, a matrix of potential ancillary services for the market are identified in Table 5.0-3.

Finally, MISO could consider the impact of energy storage facilities when doing transmission planning studies and treat CAES on a comparable basis with transmission build-outs for purposes of qualifying for transmission price incentives and participation in regional transmission plans. CAES projects might also be classified as Multi Value Projects in the transmission planning process, which would give them advantages in cost allocation for grid interconnection.

The future viability of CAES will depend on the extent to which public utility commissions and electricity market operators establish rules that internalize system-wide costs, looking at CAES as a part of a resource portfolio that serves a range of valuable functions.

**Table 5.0-3. Potential ancillary service market for CAES facility**  
 (Source: [https://mitel.mit.edu/system/files/Electric\\_Grid\\_AppendixB\\_Electric\\_Power\\_System\\_Basics.pdf](https://mitel.mit.edu/system/files/Electric_Grid_AppendixB_Electric_Power_System_Basics.pdf)).

	Function	Timing Constraints	Ancillary Services
<b>Normal Conditions</b>			
Regulation and Frequency Response	Provide balance between scheduled demand and actual demand	Fast acting with seconds, controlled by the Balancing Authority through Automatic Generation Control (AGF)	Since it provides regulation up and down, generally, storage level needs to be stay at mean level. Faster acting than it provides load following.
Load Following	Provide balance between scheduled demand and actual demand	Slower acting within 10 minutes	Combustible turbine is not appropriate to provide load following service because of heat rate. However, round efficiency of CAES is appropriate to provide load following service.
Reactive Supply and Voltage Control	Regulates the supply and demand of reactive power caused by a change in system voltage	Fast acting needs to be controlled by BA	
<b>Contingency Conditions</b>			
Operating Reserve-Spinning	Online partially loaded generators that can increase power production or decrease power usage in response to a major generation or transmission outage	Response time less than 10 minutes	To provide this service, storage level should be at minimum.
Operating Reserve-supplemental	Same as spinning reserve but need not be online still capable of full response within 10 minutes	Response time less than 10 minutes	
Backup Supply	A contingency service that can be online within 30 minutes	Less than 30 minutes	
Energy Imbalance (EIM)	A market for contingency ancillary services across multiple Balancing Authorities		

## ENERGY PLANNING MODELS

Software modeling is an important part of any electric grid planning process. There are a range of models looking at very short time frames to decades-long time frames. The long-range models are assessing generation capacity expansion needs for 15 to 30-plus years out. Some examples of this type of model are EGEAS from EPRI, and System Optimizer or Strategist from Ventyx. When looking at shorter time frames, models such as PSS\E are used to assess power flow and dynamic conditions of the grid in static snapshots and evaluate for operational robustness. Other short-term models evaluate economically how a specified portfolio of generation resources will perform. The complexity of these models, such as PROMOD or PLEXOS, requires long run times (50-plus hours) to examine individual scenarios. There are also other models that have been created solely for evaluating energy storage systems.

Generation capacity expansion models, also known as production cost models, are designed to continually assess all the possible options given as a set of resources they can choose from to meet future needs. From the given set of resources they find the options that are least-cost over the time period of the study. What this means is that they generally do not model most energy storage options accurately because the simulation does not allow detailed analysis.

Although production cost models can capture some of the value and costs of energy storage resources, more so with large scale options such as hydro or compressed air, they cannot account for all of the characteristics of storage. One of the reasons for this is these types of models are based on hourly supply and demand time-stamps, not any smaller, as well as the models do not run in chronological order. Spatial considerations are also not modeled in production cost models. Below are some limitations for production cost modeling using the EGEAS model as an example (EPRI, 2014):

- The sequencing of charging versus generating may not line up correctly as this is time-dependent although the model will try to minimize this possibility;
- Storage cannot be modeled as being matched with a specific generation source such as a renewable resource;
- Time-dependent losses cannot be modeled; and
- The full benefits of storage providing ancillary services such as frequency regulation or spinning reserves cannot be modeled.

Long-term models are only one type of simulation software used for electric grid planning. As mentioned above, there are many other models that can analyze systems in much greater detail including spatial and chronological considerations. Whether using information developed from running snapshot views of the system or individual generation mix scenarios, a user can develop a basis for certain inputs such as O&M costs that can then be fed into the long-term models. It is ultimately a mixture of all the models together that inform decision makers as to what generation and transmission resources to develop. MISO has standardized a seven step planning process that combines data brought together from all the above mentioned modeling types that are completed on an annual cycle.

There are also stand-alone models which were designed specifically to evaluate the value of different energy storage options. It should be pointed out that these models' attributes vary

greatly, and this type of analysis is not necessarily evaluating storage options for least-cost in concert within an array of other non-storage options. Some of them evaluate just specific storage scenarios. A recent example of the value of this approach is seen in the CPUC Rulemaking 10-12-007 on energy storage procurement targets for their IOUs. CPUC had input into their proceedings from both EPRI (EPRI, 2013) and DNV KEMA Energy and Sustainability (Fioravanti et al., 2013), who each used their in-house stand-alone energy storage modeling tools to evaluate different scenarios. EPRI's model is called the Energy Storage Valuation Tool (ESVT) and DNV KEMA has a suite of models KERMIT, ESBAM, OpenDSS, and MGO that they paired with PLEXOS to do simulations. One model, EPRI's ESVT, was simulating just storage scenarios to understand how to optimize the technology itself, whereas the other model, DNV KEMA's suite of tools, was simulating specified energy storage implementation within the current long-term grid plan for California.

MISO has also been proactive with researching a best approach to use that evaluates energy storage appropriately in their planning process. EPRI conducted phase one of a study (MISO, 2012) for MISO to evaluate just that question. The two models that were examined were EPRI's EGEAS tool and PLEXOS; both models that are already used in MISO's seven step planning process. The first phase of this process found that EGEAS could help identify potential cases that storage might be beneficial, but that PLEXOS was then the appropriate model to analyze these cases further. MISO is still continuing this work.

Appropriately valuing energy storage in software modeling is a key factor in future storage development. The models are an integral part of how utilities or other stakeholders are able to optimize for risk in a highly complex assortment of options. Potential CAES projects will need to not only show that their project has value but be able to show that in a way that can be inputted into the models used by the appropriate regulating body for that area.

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**Section 5.1:  
Regulatory and socio-political criteria for assessment guidelines**

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Regulatory and socio-screening criteria for CAES site assessment include the following factors and depend on CAES site selection. Once potential sites are selected, we will examine the following: current land use, patterns of property ownership (surface and mineral), and permitting considerations.

## **CURRENT LAND USE AND OWNERSHIP**

For permitting process and community acceptance, the following factors need to be reviewed and surveyed: residential population density, current industry activities, ecological features, and recreational uses of the potential site.

## **PERMITTING**

### **Federal**

**The Federal Energy Regulatory Commission (FERC)** is an independent federal agency that regulates the interstate transmission of electricity, natural gas, and oil. FERC also reviews proposals to build liquefied natural gas (LNG) terminals and interstate natural gas pipelines as well as licensing hydropower projects.

### **State**

**The Minnesota Department of Commerce, Energy Facility Permitting (EFP) unit** conducts the environmental review required for proposed energy facilities in Minnesota (Minnesota Department of Commerce, 2014). This unit serves as technical staff to the Minnesota Public Utilities Commission (MPUC) in its permitting of energy facilities. These facilities include power plants, transmission lines, wind farms, and pipelines. The type of environmental review varies with facility type and size, e.g., the review for a large transmission line would be an environmental impact statement and include a contested case hearing.

**The Minnesota Public Utilities Commission (MPUC)** has permitting authority for any future CAES plant in Minnesota. It oversees electric utilities' resource plans to serve Minnesota customers and approves proposals to construct large energy facilities in the state. In determining whether to grant a Certificate of Need for a new large scale energy facility such as a CAES project, the MPUC considers how the project would affect the reliability, adequacy, and efficiency of the energy supply, whether a more reasonable and prudent alternative is available, and what effects the project would have on natural and socioeconomic environments (Minn. Rules 7849.0120; Minnesota Revisor of Statutes, 2013). The MPUC considers the cost of the proposed plant, as well as the cost of energy it would supply in comparison with alternatives. In the case of CAES, the MPUC would probably consider a combined cycle gas turbine (CCGT) plant as a reasonable alternative to CAES. The MPUC also implements the Renewable Energy Standard (RES) passed by the legislature in 2005 and tracks utilities' compliance with the RES

requirements. The MPUC would make a determination as to whether and to what extent CAES is an eligible energy technology for the purpose fulfilling the RES requirements, and consider the role of CAES in integrating more intermittent wind power into a company's overall resource portfolio. Under the Power Plant Siting Act (Minn. Statute 216E) in the review process, an environmental impact statement (EIS) on the project and a contested case hearing are conducted (Minn. Rules Chapter 7850; Minnesota Revisor of Statutes, 2009).

### *Permitting process*

Under the Power Plant Siting Act (Minn. Statute 216E), a site permit from the Minnesota Public Utilities Commission (Commission) is required to build a large electric power generating plant (LEPGP). An LEPPG is a power plant and associated facilities capable of operating at a capacity of 50 megawatts or more. The rules for the administration of power plant site permits are found at Minnesota Rules Chapter 7850 (Minnesota Revisor of Statutes, 2009; See Appendix 5.1-I).

### Full Review

For the full review permitting process, an applicant must identify in its application a preferred site for the power plant and one alternative site. As part of the full review process, the Minnesota Department of Commerce, Energy Facility Permitting unit prepares an EIS on the project, and a contested case hearing is conducted by an administrative law judge. The Commission has up to one year from the time the application is accepted to complete the process and make a decision on the permit (Minn. Rules 7850 (Minnesota Revisor of Statutes, 2009); See Appendix 5.1-II).

### Alternative Review

An alternative review permitting process is available for certain smaller-sized power plants identified in Minnesota Statute 216E.04. For the alternative review process, the Minnesota Department of Commerce EFP unit prepares an environmental assessment (EA) for the project, and a public hearing is conducted by an administrative law judge. The Commission has up to six months from the time the application is accepted to complete the process and make a decision on the permit (Minn. Rules 7850 (Minnesota Revisor of Statutes, 2009); See Appendix 5.1-III).

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## Local Review

For certain projects, the applicant can elect to seek authorization from local units of government rather than from the Commission. Qualifying projects are identified in Minnesota Statute 216E.05 (Minn. Rules 7850.5300).<sup>2</sup>

### *Environmental Assessment Worksheet*

New power plants under 50 megawatts but over 25 megawatts do not require a Commission site permit but do require an Environmental Assessment Worksheet (EAW) under the Minnesota Environmental Policy Act (Minnesota Statute 116D) and Minnesota Rules 4410.4300 (Minnesota Revisor of Statutes, 2015). The Environmental Quality Board oversees these EAWs. New power plants under five megawatts are exempt from any state environmental review, and plants between 5 and 25 megawatts are subject to discretionary review.

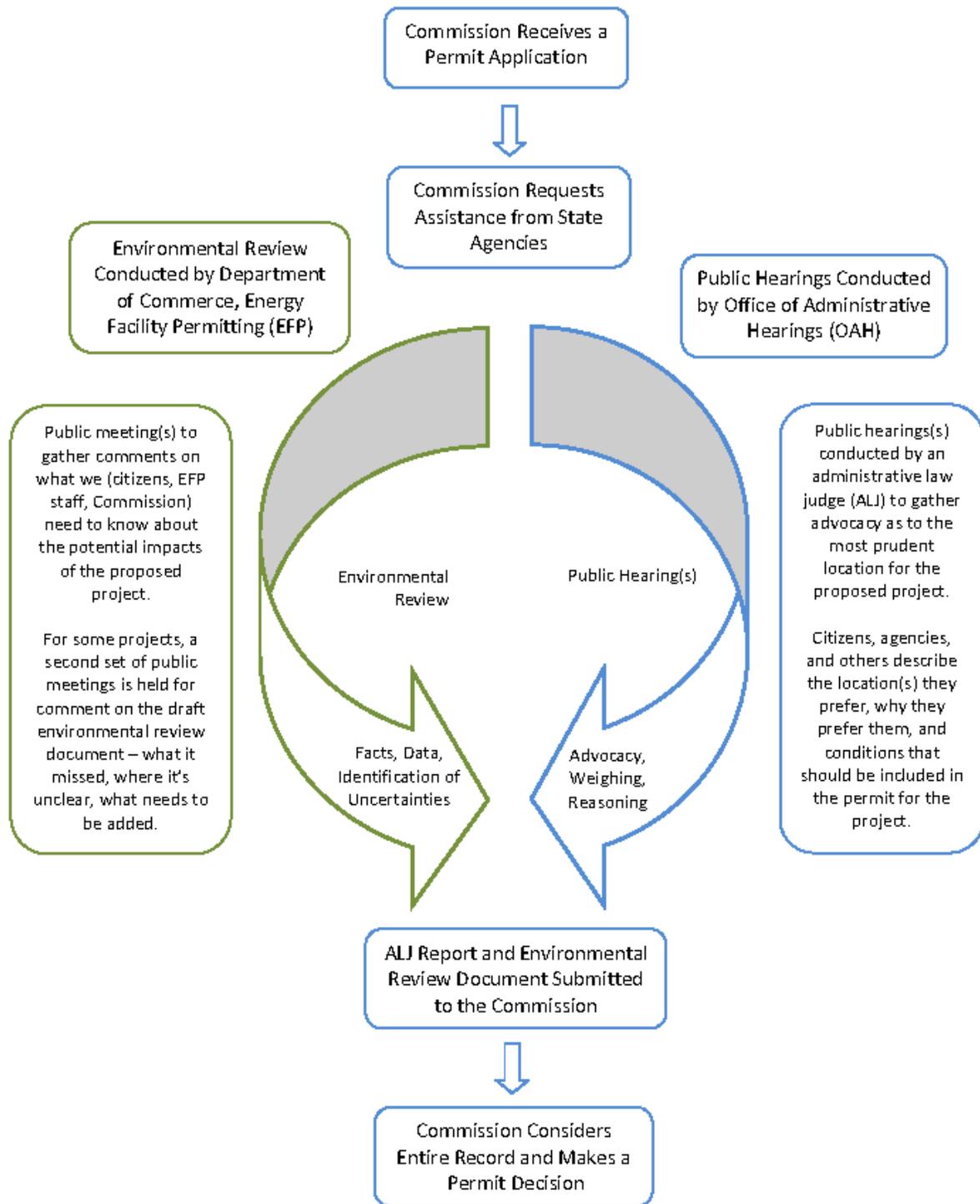
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<sup>2</sup><http://mn.gov/commerce/energyfacilities/documents/Local%20Review%20-%20A%20Guide%20for%20LGUs%20and%20Proposers,%2010.24.11.pdf>

**Appendix 5.1-I. Permitting process except for wind farms.**

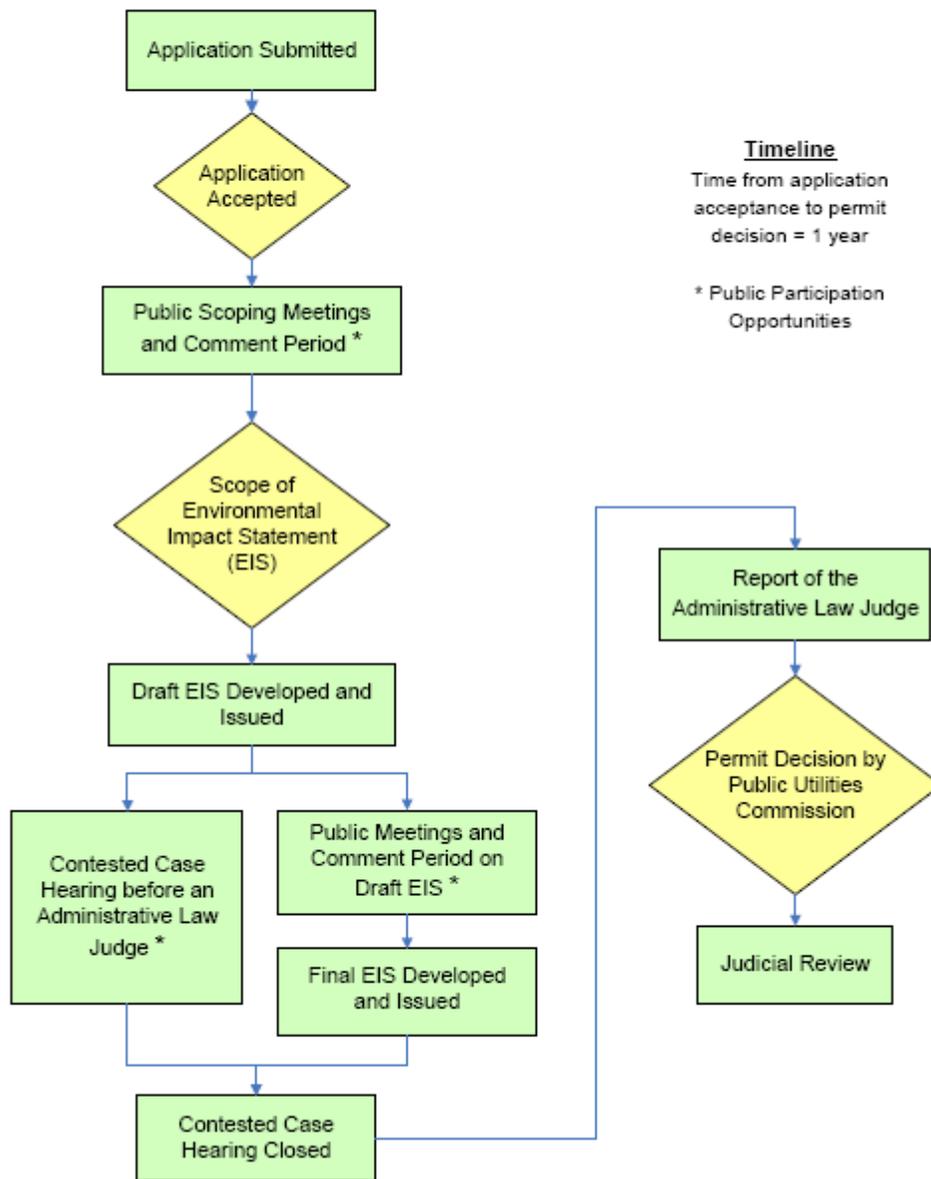


**Appendix 5.1-II. HVTL routing and power plant siting full permitting process.**



**HVTL Routing and Power Plant Siting Full Permitting Process**

**Minnesota Rules 7850**



**Timeline**

Time from application acceptance to permit decision = 1 year

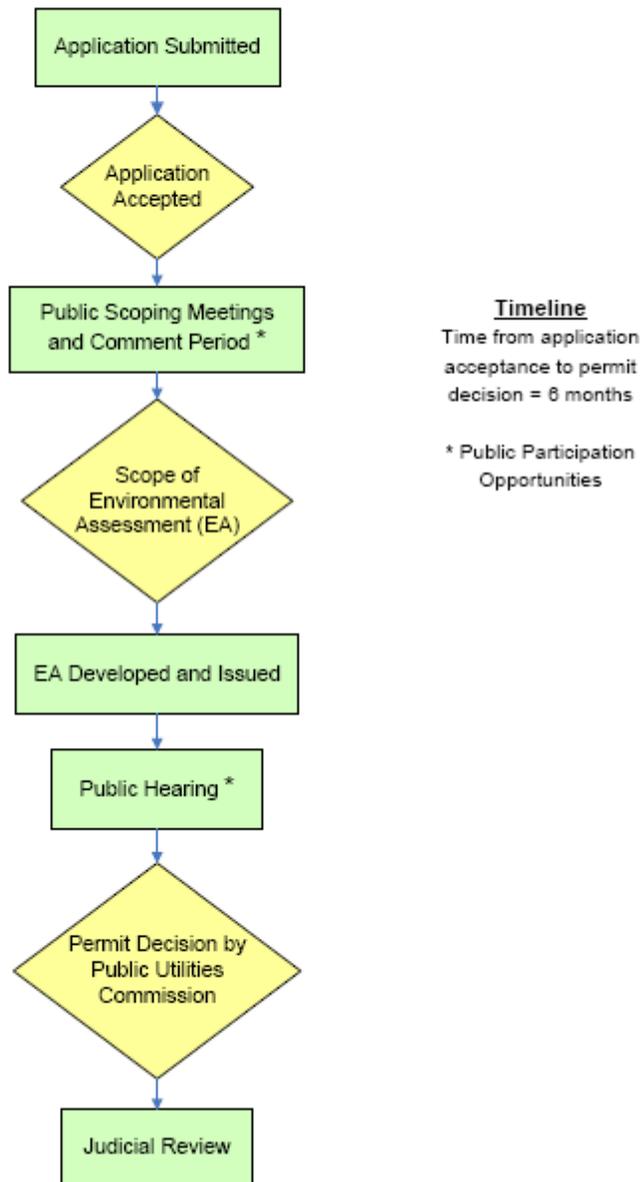
\* Public Participation Opportunities

**Appendix 5.1-III.** HVTL routing and power plant siting alternative permitting process.



**HVTL Routing and Power Plant Siting  
Alternative Permitting Process**

**Minnesota Rules 7850**



**Section 5.2:  
Socio-political factors affecting CAES implementation**

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## SUMMARY

CAES stakeholders include both direct beneficiaries (facility owners, electric utilities, system operators, owners of variable electricity sources) and indirect beneficiaries (residential, commercial, and industrial customers). Additionally, gatekeeper organizations include regulators (Minnesota Pollution Control Agency (MPCA), Minnesota Department of Natural Resources (MN DNR), Public Utilities Commission (PUC), Federal Energy Regulatory Commission (FERC)), economic development agencies, e.g., Iron Range Resources and Rehabilitation Board (IRRRB), as well as nearby residents of communities in the vicinity of potential CAES sites. Other stakeholders include private landowners, recreational users, mine owners and mineral rights holders, and environmental non-profit organizations.

Drawing from the literature, our research has identified several socio-political factors with the potential to affect CAES implementation, including: increasing prices for iron ore and non-ferrous minerals; shifting natural gas prices; Minnesota state renewable portfolio standards; and decreased support for national greenhouse gas (GHG) emission limits or national renewable energy standards. In specific terms, when a CAES facility is coupled with a wind farm, the CAES facility qualifies to obtain a renewable energy production incentive (Minn. Statute 216C.41; Minnesota Revisor of Statutes, 2009).

Compatibility with present and future mining is a key objective in siting and designing advantages for a CAES project, including preexisting mining space that could be used as a cavern, hard rock area that facilitates to building an acceptable cavern. For example, Iowa CAES plant was abandoned after geological surveys of the selected sandstone structure. Some potential sites, however, can have challenges because widespread mineral deposits make land valuable, and mining operations can affect large areas. This paper outlines a framework for assessing the compatibility of potential CAES sites with present and future mining. The premise is that: 1) CAES plants would need to be insulated from the effects of current and future mining; 2) engineering techniques are available that could achieve this insulation in many cases; and 3) building a CAES project that can coexist with mining will require additional land and engineering beyond what's needed for power production.

Nearby mining could harm a CAES project primarily through blasting or the possibility of leakage. For example, Moutoux (2007) pointed out that Colorado also abandoned hard rock mines because using a mine as a CAES reservoir adds significant financial risk due the possibility of leakage that takes considerable time and money to correct. Permitting processes will likely require that these types of potential impacts be addressed. Should such damages occur, legal remedies could be sought, but lawsuits are costly and holders of mineral rights typically have precedence. Selecting a site that would never fall within the area of influence of current or future mining would be ideal, but this is unrealistic in northern Minnesota because mineral deposits are widespread. A more feasible and secure approach is to site and design the plant so it is insulated from nearby mining.

Geo-engineering to insulate a CAES project from blasting and leakage would be site specific, with two focuses. Minimizing blast vibration damage might be achieved through inclusion of a blast buffer (size according to the geologic properties of the site). Blast buffers on the range of 2,000 to 3,000 feet are reported in the LVP (Laurentian Vision Partnership, 2002). Where active mining or future mining could approach closer than the necessary buffer, techniques such as

pre-splitting could be utilized, as was proposed in Barr Engineering's (1999) Giant's Ridge Report.

The site-specific options for insulating a plant from blasting and leakage will determine the additional costs associated with designing a CAES project to coexist with mining in northern Minnesota. Two categories of additional costs must be estimated, both based on the preferred geotechnical options to minimize impacts from blasting and dewatering: 1) the costs of additional design and construction work (described above); and 2) the costs of additional property acquisition. CAES projects in northern Minnesota will need to buy or lease surface and mineral rights for both for the project footprint, encompassing the reservoirs and surface facilities, and for a buffer zone needed to insulate the project from current or future mining. The size of the buffer will be site specific, determined by proximity to mineral deposits and by the geo-engineering options chosen to prevent damage to the CAES project from blasting and leakage.

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**Section 5.3:  
Key economic factors affecting CAES implementation**

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The following section provides a literature review and discusses key economic factors. In conjunction with the policy work, this will allow us to better understand the implications and value of CAES development. The type of implementation for CAES varies depending on whether it is independent CAES or coupled with a wind farm. In addition, the difference of on-peak price and off-peak price, the price of natural gas, location, and ownership impact the value of CAES. Various factors will impact revenue from CAES implementation and these include: arbitrage revenue and revenue from ancillary service market.

## **LITERATURE REVIEW ON COMPRESSED AIR ENERGY STORAGE**

The economic and policy literature on CAES can be divided into two classes. The first class of articles focuses on the value of independent CAES. The second class deals with the value of CAES with wind integration.

### **The value of independent CAES**

Several studies estimated the value of electricity storage. First, Sioshansi et al. (2009) analyzed the arbitrage value of pricing taking storage devices in PJM Interconnection LLC, a regional transmission organization (RTO) which is part of the Eastern Interconnection grid and was operated as an electric transmission system from 2002 to 2007 with welfare effects. They pointed out that the difference between on-peak price and off-peak price and the volatility of price for natural gas and electricity have raised interest in the potential economic value for electricity storage. In addition, the impact of load shifting for larger amounts of storage and reductions in arbitrage can threaten the economic value for plants. However, it will be offset by increases in social welfare due to an increase in consumer surplus. Yucekaya (2013) also emphasized that the fluctuation of prices for electricity and natural gas impacts the revenue of CAES directly. Based on 100 simulations in the Turkish market, the author showed that the investment to CAES would be economically feasible for the given market prices and could be implemented. Second, Sioshansi et al. (2009) and Jenkin and Weiss (2005) also noted that depending on its location, storage can have some transmission-related benefits. Third, regarding ownership, Sioshansi et al. (2011) suggested that a private sector investor may not have incentive to invest CAES plants in a restructured market such as PJM, and treating storage as a regulated asset like transmission or distribution infrastructures would be better considering potential benefits from storage such as congestion relief, deferred transmission, and better grid and asset utilization. Fourth, the authors also showed that compared with pure storage devices, the CAES device purchases 44% less energy, choosing from lower cost hours. Lastly, Drury et al. (2011) estimated the value of CAES considering both operating reserves revenue and arbitrage revenue in several U.S. markets. They found that conventional CAES systems could earn an additional \$23±10/Kw-yr. by providing operating reserves, and adiabatic CAES systems could earn an additional \$28 ±13/Kw-yr. They also found that arbitrage-only revenues are unlikely to support a CAES investment in most market locations, but the addition

of reserve revenues could support a conventional CAES investment in several markets. Adiabatic CAES revenues are not likely to support an investment in most regions studied.

### **The economics of CAES with wind integration**

Most studies on CAES with wind integration suggested that the CAES plant is likely to be unprofitable unless specific additional incentives become available. Denholm and Sioshansi (2009) suggested that the advantage of co-location of wind and storage is a decrease in transmission requirements, but the disadvantage of it is a decrease in the economic value of energy storage compared to locating energy storage at the load. Fertig and Apt (2011) showed that for various price scenarios, most CAES plants are unprofitable, considering revenue from regulation markets raises the value of CAES slightly. Even though the social benefits of CAES with wind integration include the avoidance of the construction of new generation capacity, improved air quality during peak times, and increased economic surplus and subsidy from government is considered, the private cost of the CAES system will not be covered. Mauch et al. (2012) also tested whether a wind farm with CAES can survive in the day-ahead market. They found that annual income for the wind/CAES plants would not offset annualized capital costs, even considering the market prices with a carbon price at the current time. Madlener and Latz (2013) also analyzed the economic feasibility of CAES with various capacity scenarios. The feasibility of CAES plants depends on entering both the spot market and the reserves market. Without the revenue from reserves market, building CAES plants is not viable. An independent CAES plant is found to be more profitable than a CAES with integration. In the Madlener and Latz (2013) study, diabatic CAES is more profitable than adiabatic CAES.

### **KEY ECONOMIC ISSUES AFFECTING CAES IMPLEMENTATION**

Based on previous studies related with CAES, the operating cost, including the price of natural gas and electricity, potential project profitability in the electricity market and the optimal duration of the operating cycle impacts the value of CAES plants. In particular, considering CAES has a relatively high operation cost per kW installed and the major revenue of CAES are from arbitrage and ancillary service revenues, major key issues affecting the value of CAES plants are the following: 1) natural gas price; 2) the type of plant – Independent CAES plant or Coupling CAES plant with wind farm; and 3) uncertainties in the price of electricity. Technical factors affecting the value of CAES are heat rate, energy ratio (energy efficiency factor), power ratio (power efficiency factor), ramp rate, response time, and storage duration period. Financing factors affecting the value of CAES are capital costs, real estate and taxes, construction, and permitting period.

The profitability of a CAES facility is strongly linked to the volatility of electricity prices, which change over time (seasonally and through the decades), and with location on the electric grid. The CAES facility captures arbitrage value by storing low-cost energy and selling that energy during the high-price peak demand periods. The arbitrage value of storage depends on the price spread and the efficiency of the CAES facility.

A number of factors would affect the arbitrage value available to a CAES facility. For example, trends in the price of natural gas will impact the arbitrage value of storage due to the fact that natural gas sets the price during peak periods. Also, changes in the generation mix will impact price spreads. The integration of more wind into the power system and the retirement of coal plants will increase price volatility and produce more arbitrage opportunities for storage.

Ultimately, the value of energy storage technologies must be judged at both the facility scale and for their impact on total system costs. The impact of CAES on total system costs would be a function of the level of wind or solar deployment, curtailment patterns, and whether or not there is a climate policy that places a price on greenhouse gas emissions. Within the system as a whole, the impact of energy storage technologies like CAES will depend on the value of the energy services they provide compared to alternatives. The adoption of the technology will be both policy dependent and revenue dependent based on the conditions in a given state on how the technology is integrated into the renewable energy portfolio.

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