# Final Abstract

Final Report Approved on November 2, 2026

## M.L. 2023 Project Abstract

For the Period Ending June 30, 2026

**Project Title:** Environment-Friendly Decarbonizing of Steel Production with Hydrogen Plasma

**Project Manager:** Uwe Kortshagen

**Affiliation:** U of MN - College of Science and Engineering

**Mailing Address:** University of Minnesota, Department of Mechanical Engineering 111 Church Street SE

**City/State/Zip:** Minneapolis, MN 55455

**Phone:** (612) 625-4028

**E-mail:** kortshagen@umn.edu

**Website:** https://cse.umn.edu/

**Funding Source:**

**Fiscal Year:**

**Legal Citation:** M.L. 2023, Chp. 60, Art. 2, Sec. 2, Subd. 07e

**Appropriation Amount:** $739,000

**Amount Spent:** $739,000

**Amount Remaining:** -

**Sound bite of Project Outcomes and Results**

The project developed a fossil-fuel-free ironmaking technology using microwave hydrogen plasma, potentially reducing air pollution and emissions and energy-intensive pelletization. The process rapidly converts Minnesota iron ores and mining waste into iron. This innovation positions Minnesota to reduce industrial air pollution and conserve natural resources through future sustainable mining practices.

**Summary of Project and Outcomes**

Conventional ironmaking relies heavily on fossil fuels for both energy and chemical processing. In Minnesota, producing 30–40 million metric tons of iron ore pellets annually requires intense thermal energy and leaves behind significant quantities of low-quality ore and tailings as environmental waste.

To address these energy and waste challenges, we developed an innovative ironmaking technology using microwave hydrogen plasma. Powered by electricity and hydrogen, this process eliminates dependence on fossil fuels and bypasses the traditional, energy-intensive ore pelletization step.

Our primary project outcomes showed that hydrogen plasma reduces iron ores up to 100 times faster than other hydrogen-based approaches, achieving 80–90% metallization within seconds. We successfully processed standard Minnesota magnetite and hematite ores, fine particles under 5 microns, and low-grade iron ore waste materials. To lay the foundation for commercial scale-up, we established system scaling laws, validated a chemical kinetic model with over 100 reactions, and conducted techno-economic supply-chain analyses. These models identified Minnesota as a strategic priority region for early deployment due to its vast iron ore reserves and proximity to existing manufacturing infrastructure.

Overall, this project demonstrates that Minnesota can efficiently transform legacy mining waste into high-value iron while dramatically boosting production speed and energy efficiency. The models provide resource managers and industry leaders with actionable strategies to modernize iron production. Crucially, this ENRTF-funded research enabled our team to secure a competitive follow-on grant from the U.S. Department of Energy (ARPA-E) to advance the technology toward pilot-scale testing.

**Project Results Use and Dissemination**

Project results were broadly shared through peer-reviewed journal publications (including Journal of Physics D and Industrial & Engineering Chemistry Research) and presentations at major technical conferences such as SME Minnesota in Duluth, AISTech, ISPC-26 in Minneapolis, and MRS Fall Symposia. Results were also integrated into decision-making models for regional supply chain decarbonization. Findings from this ENRTF-funded project directly positioned our team to secure a major ARPA-E grant from the U.S. Department of Energy to further scale up the technology. All publications and presentations acknowledge ENRTF support per guidelines.

# Environment and Natural Resources Trust Fund

M.L. 2023 Approved Final Report

## General Information

**Date:** November 3, 2026

**ID Number:** 2023-171

**Staff Lead:** Lisa Bigaouette

**Project Title:** Environment-Friendly Decarbonizing of Steel Production with Hydrogen Plasma

**Project Budget:** $739,000

## Project Manager Information

**Name:** Uwe Kortshagen

**Organization:** U of MN - College of Science and Engineering

**Office Telephone:** (612) 625-4028

**Email:** kortshagen@umn.edu

**Web Address:** https://cse.umn.edu/

## Project Reporting

**Final Report Approved:** November 2, 2026

**Reporting Status:** Project Completed

**Date of Last Action:** November 2, 2026

**Project Completion:** June 30, 2026

## Legal Information

**Legal Citation:** M.L. 2023, Chp. 60, Art. 2, Sec. 2, Subd. 07e

**Appropriation Language:** $739,000 the first year is from the trust fund to the Board of Regents of the University of Minnesota to investigate the use of microwave hydrogen plasma to reduce fossil fuel use, carbon dioxide emissions, and waste and enable the use of alternative iron resources, including lower quality iron ores, tailings, and iron ore waste piles, in the iron-making industry. This appropriation is subject to Minnesota Statutes, section 116P.10.

**Appropriation End Date:** June 30, 2026

## Narrative

**Project Summary:** Conventional ironmaking requires massive amounts of fossil fuels and generates significant waste and CO2 emissions. Our microwave hydrogen plasma ironmaking eliminates fossil fuel use and CO2 emissions while reducing waste.

**Describe the opportunity or problem your proposal seeks to address. Include any relevant background information.**

Producing iron and steel - our most important industrial metals - carries an enormous environmental footprint. Globally, iron and steel making accounts for 8-10% of total carbon dioxide emissions. Each year, Minnesota produces 30-40 million metric tons of heat-consolidated blast furnace pellets for the iron and steel industry, which contributes roughly three million metric tons of CO2 emissions to the atmosphere. In addition, significant amounts of poor quality ore and tailings containing unused minerals are discharged into the landscape as waste products. The global steel industry aims to reduce CO2 emissions by 50% by 2050, creating an urgent need for disruptive technologies that will decarbonize the iron and steel production process. It is also critical that new decarbonization technologies can efficiently process alternative iron resources like the low-quality ores and tailings that are currently regarded as waste. The proposed project aims to create a disruptive technology that can efficiently use a broad spectrum of iron ores and eliminates the energy-intensive pelletization process and its associated emissions. This technology will dramatically reduce CO2 emissions and allow for the efficient use of alternative iron resources that are currently being discarded as waste and tailings.

**What is your proposed solution to the problem or opportunity discussed above? Introduce us to the work you are seeking funding to do. You will be asked to expand on this proposed solution in Activities & Milestones.**

Conventional iron ore processing is energy- and carbon-intensive, using fossil fuel for both heat and chemical reduction. We propose a fossil fuel-free iron ore reduction process using microwave hydrogen plasma (an ionized gas), which is a technology recently developed in the High Temperature and Plasma Laboratory at the University of Minnesota (provisional patent filed 5/9/2022). The proposed process eliminates both carbon-intensive reduction and energy-intensive pelletization steps in conventional iron ore processing. Hydrogen plasma reduction is a fully electric technology and, when operated with renewable electricity and "green" hydrogen produced by electrolysis, completely obviates the need for fossil fuels and thus has the potential to decarbonize the ironmaking process. Our plasma technology has already demonstrated over 90% reduction of magnetite and other iron ores (hematite) and may enable the utilization of lower quality ores, as well as existing tailings and waste piles. In addition, as a virtually instant on-off technology without significant thermal inertia, hydrogen plasma is exceptionally compatible with intermittent renewable electricity supplied by renewable sources. Finally, hydrogen plasma reduction occurs up to one hundred times faster than reduction using other carbon-free hydrogen approaches, which will ultimately lead to significant advantages in efficiency and economics.

**What are the specific project outcomes as they relate to the public purpose of protection, conservation, preservation, and enhancement of the state's natural resources?**

- Development of a fossil fuel free ironmaking technology based on hydrogen plasma that can utilize lower quality alternative iron resources and iron ore waste piles
- Demonstration of potential for scale up by continuous operation for more than 10 hours with less than 5% variation of process conditions and product quality
- Estimation of CO2 emission reductions by replacing iron ore pelletization with hydrogen plasma reduction
- Preliminary techno-economic analysis of the proposed process with scale up assessment
- Early-stage anticipatory life cycle study focused on scale-up potential for the plasma technology

## Project Location

**What is the best scale for describing where your work will take place?**

Statewide

**What is the best scale to describe the area impacted by your work?**

Statewide

**When will the work impact occur?**

During the Project and In the Future

## Activities and Milestones

### Activity 1: Fundamental Evaluation of the Hydrogen Plasma Reduction System

**Activity Budget:** $273,166

**Activity Description:**
Research in Activity 1 will be focused on generating baseline data for the hydrogen plasma reduction system using reagent grade iron minerals – magnetite, hematite, and goethite. Hydrogen plasma reduction of iron minerals has been demonstrated by the High Temperature and Plasma Laboratory on a benchtop size reactor, demonstrating more than 90% reduction of reagent grade magnetite and hematite with ore particles passing through the hydrogen plasma in less than one tenth of a second. This activity will investigate the following important questions: 1) What is the impact of iron mineralogy on hydrogen plasma reduction? 2) What are the characteristics of the input and exhaust streams of the reactor? 3) What is the energy budget of the hydrogen plasma process? 4) How do these metrics scale with larger reactor size?

The ultimate goal of Activity 1 is to better understand how changing the iron mineralogy will impact the performance of the hydrogen plasma system – from the mass and energy balance, through product quality. This baseline data will be compared to work using lower quality alternative iron ore resources and iron ore waste materials. A thorough characterization of the feed and product materials will be undertaken.

**Activity Milestones:**

| Description | Approximate Completion Date |
|---|---|
| Exploration of optimal conditions for the reduction of different iron mineral types | June 30, 2024 |
| Analysis of input and exhaust streams and energy efficiency of hydrogen plasma | June 30, 2025 |
| Determination of scaling laws with larger scale reactor | June 30, 2026 |
| Publication of results of the activity; preparation of final report. | June 30, 2026 |

### Activity 2: Evaluation of the Hydrogen Plasma Reduction System using Iron Ore Concentrates

**Activity Budget:** $233,916

**Activity Description:**
Research in Activity 2 will be focused on assessing the response of the H2 plasma reduction process relative to baseline operating conditions determined in Activity 1. The activity will use existing iron ore concentrates and potential iron ore concentrates produced from Minnesota iron ore waste.

Iron ore concentrates for Activity 2 will be acquired from industry partners and beneficiated from lower quality alternative iron ore resources and iron ore waste materials. A series of experiments will be conducted under baseline conditions, established in Activity 1, using magnetite, hematite, mixed magnetite-hematite, and hematite-goethite-magnetite concentrates. This will inform on the H2 Plasma reduction systems response to gangue materials present with the iron minerals. A series of follow-up experiments will be conducted to improve the efficiency of H2 plasma reduction of the various ore types. A thorough characterization of the feed and product materials will be undertaken.

**Activity Milestones:**

| Description | Approximate Completion Date |
|---|---|
| Acquire iron ore concentrates that are representative of current industry standards | June 30, 2024 |
| Beneficiate lower quality Minnesota iron ores and iron ore waste materials to produce a concentrate | June 30, 2024 |
| Compare performance of the reagent grade material to iron ore concentrates | June 30, 2025 |

| | |
|---|---|
| Determination of optimal operating conditions for iron ore concentrate reduction | June 30, 2025 |
| Explore reduction conditions, input & exhaust streams, energy efficiency for scaling up | June 30, 2026 |
| Publication of results of the activity; preparation of final report. | June 30, 2026 |

## Activity 3: Techno-Economic-Environmental Analysis of Hydrogen Plasma Reduction System

**Activity Budget:** $231,918

**Activity Description:**

To assess the viability of the proposed technology, we will perform a comprehensive techno-economic-environmental analysis (TEEA) of the whole system. To this end, we will first combine first-principles knowledge and the experimental data obtained in Activity 1 to build a hybrid model of the plasma-based iron ore reduction process, which will then be integrated with models for the upstream green hydrogen production and the downstream metal processing processes to form the full manufacturing system. The design of the system will be optimized with respect to its economic and environmental performance metrics, where the latter will focus on CO2 emissions evaluated via life cycle assessment. The TEEA will be performed for plants of different scales. Importantly, our model will incorporate intermittent renewable energy input and the corresponding operational constraints, which will enable adequate sizing of the process units and additional energy and product storage capacities. Moreover, we will analyze a potential deployment of the proposed technology in Minnesota at the supply chain level. Our geographically explicit supply chain model will allow us to determine the most suitable locations for such plants and the best logistics strategy for distributing the products to customers in and out of the state.

**Activity Milestones:**

| Description | Approximate Completion Date |
|---|---|
| Build preliminary hybrid model of the plasma-based iron ore reduction process | June 30, 2024 |
| Build preliminary model for the whole system and perform design optimization | December 31, 2024 |
| Update model with new experimental data and perform update design optimization | June 30, 2025 |
| Perform life cycle assessment for the whole system | December 31, 2025 |
| Perform supply chain optimization and life cycle assessment considering the State of Minnesota | June 30, 2026 |
| Publication of results of the activity; preparation of final report. | June 30, 2026 |

## Project Partners and Collaborators

| Name | Organization | Role | Receiving Funds |
|---|---|---|---|
| Peter J. Bruggeman | University of Minnesota - College of Science and Engineering | Professor Bruggeman is an expert in plasma technology and co-inventor of the hydrogen plasma reduction. He will work on further developing the process. | Yes |
| Qi Zhang | University of Minnesota - College of Science and Engineering | Prof. Zhang's research in the area of process systems engineering lies at the intersection of chemical engineering and operations research, focusing on computational discovery and decision making in complex process systems. He will lead the techno-economic analysis of the process. | Yes |
| Rodney Johnson | University of Minnesota - Duluth - Natural Resources Research Institute | Dr. Johnson holds the Endowed Taconite Chair. He is respected geologist, mineralogist, and geometallurgist with over thirty years of experience in exploration, mining, research, and mineral processing and will lead efforts in production of iron ore concentrates and product characterization. | Yes |
| Brett Spigarelli | University of Minnesota - Duluth - Natural Resources Research Institute | Dr. Spigarelli, Metallurgical Engineer at the NRRI Coleraine labs, received his Ph.D. in Chemical Engineering from Michigan Technological University. He will work on iron ore concentrates and product characterization. | Yes |
| Pat Schoff | University of Minnesota - Duluth - Natural Resources Research Institute | Dr. Schoff teaches in the Biology Department and Integrated Biosciences graduate program at UMD. Current research includes studies on the effects of chemicals and other stressors on the early developmental stages of fish and amphibians, endocrine disruption, and recently, sustainable development. He will lead the environmental life cycle analysis. | Yes |

## Dissemination

**Describe your plans for dissemination, presentation, documentation, or sharing of data, results, samples, physical collections, and other products and how they will follow ENRTF Acknowledgement Requirements and Guidelines.**
All team members are active members of their scientific and engineering communities. As such, they routinely disseminate results of their research through the publication of peer-reviewed research papers in scientific journals, conference papers and presentations, and seminar presentations at other universities and companies. We will particularly focus on conferences on iron and steel making, including that annual SME Minnesota Conference and the AISTech Conference. The SME Minnesota conference is a great venue to inform the Minnesota mining industry of our research. AISTech is the largest North American iron and steel conference. The Environment and Natural Resources Trust Fund will be acknowledged through use of the trust fund logo or attribution language on project print and electronic media, publications, signage, and other communications per the ENTRF Acknowledgment Guidelines.

## Long-Term Implementation and Funding

**Describe how the results will be implemented and how any ongoing effort will be funded. If not already addressed as part of the project, how will findings, results, and products developed be implemented after project completion? If**

**additional work is needed, how will this work be funded?**

The proposed research will help establish the full potential of the hydrogen plasma iron ore reduction technology. Once this is achieved, we expect that there will be significant interest both by federal funding agencies and by industry. The team will pursue research funding from the Advanced Research Projects Agency-Energy (ARPA-E), the Department of Energy, and the National Science Foundation. The University is already seeking patent protection for the technology and the team will pursue collaborations with NRRI's industrial partners in the iron and steel processing field.

## Other ENRTF Appropriations Awarded in the Last Six Years

| Name | Appropriation | Amount Awarded |
|---|---|---|
| Develop Solar Window Concentrators for Electricity | M.L. 2018, Chp. 214, Art. 4, Sec. 2, Subd. 07a | $350,000 |

## Budget Summary

| Category / Name | Subcategory or Type | Description | Purpose | Gen. Ineligible | % Benefits | # FTE | Classified Staff? | $ Amount | $ Amount Spent | $ Amount Remaining |
|---|---|---|---|---|---|---|---|---|---|---|
| **Personnel** | | | | | | | | | | |
| Uwe Kortshagen | | Principal Investigator / Project Manager (UMN-TC) | | | 25% | 0.15 | | $50,882 | - | - |
| Peter Bruggeman | | co-Principal Investigator: plasma technology, UMN-TC | | | 25% | 0.15 | | $29,568 | - | - |
| Qi Zhang | | co-Principal Investigator, economic analysis, UMN-TC | | | 25% | 0.15 | | $22,168 | - | - |
| Rodney Johnson | | co-Principal Investigator, Endowed Taconite Chair, UMD NRRI | | | 25% | 0.11 | | $16,972 | - | - |
| Brett Spigarelli | | Metallurgical Engineer, iron ore processing, UMD NRRI | | | 25% | 0.24 | | $30,566 | - | - |
| Pat Schoff | | Research Associate, Environmental life cycle analysis, UMD-NRRI | | | 25% | 0.12 | | $10,149 | - | - |
| Stephen Monson Geerts | | Geologist, iron ore processing, UMD NRRI | | | 25% | 0.09 | | $9,519 | - | - |
| Julie Mutchler | | Chemical Lab Supervisor, UMD NRRI | | | 22% | 0.06 | | $3,798 | - | - |
| Laboratory technicians | | 3 lab technicians, UMD NRRI | | | 22% | 0.45 | | $36,975 | - | - |
| Graduate Student Researchers | | 3 graduate student researchers, 2 in Mechanical Eng., 1 in Chem. Eng. Mat. Sci, UMN-TC | | | 43% | 3.75 | | $428,675 | - | - |
| Research Project Manager | | Research Project Manager UMD NRRI | | | 25% | 0.15 | | $15,832 | - | - |
| | | | | | | | **Sub Total** | **$655,104** | **$655,104** | **-** |
| **Contracts and Services** | | | | | | | | | | |
| University of Minnesota - Materials Characterization Facility | Internal services or fees (uncommon) | Materials characterization is required to determine the amount of iron ore reduction by the hydrogen plasma. Services will include X-ray diffraction, transmission electron micrsocopy and others. | | | | 0 | | $31,393 | $31,393 | - |
| | | | | | | | **Sub Total** | **$31,393** | **$31,393** | **-** |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Equipment, Tools, and Supplies** | | | | | | | | | | |
| | Equipment | Scaled up plasma reactor | A larger version of the current plasma reactor will be built to explore scaling laws | | | | | $20,000 | $20,000 | - |
| | Tools and Supplies | Process gases, glass ware, filters, general laboratory supplies | Items are needed for operation of hydrogen plasma process | | | | | $30,938 | $30,938 | - |
| | | | | | | | **Sub Total** | **$50,938** | **$50,938** | **-** |
| **Capital Equipment** | | | | | | | | | | |
| | | | | | | | **Sub Total** | **-** | **-** | **-** |
| **Acquisitions and Stewardship** | | | | | | | | | | |
| | | | | | | | **Sub Total** | **-** | **-** | **-** |
| **Travel In Minnesota** | | | | | | | | | | |
| | Miles/ Meals/ Lodging | Travel of project participants between UMN-Twin Cities and UMD NRRI | Travel to discuss project progress, visit partner sites, participate in off-campus research | | | | | $1,476 | $1,476 | - |
| | | | | | | | **Sub Total** | **$1,476** | **$1,476** | **-** |
| **Travel Outside Minnesota** | | | | | | | | | | |
| | | | | | | | **Sub Total** | **-** | **-** | **-** |
| **Printing and Publication** | | | | | | | | | | |
| | Publication | Cost of publication charges | Cost of article preparation fees in open access scientific journals | | | | | $89 | $89 | - |
| | | | | | | | **Sub Total** | **$89** | **$89** | **-** |
| **Other Expenses** | | | | | | | | | | |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | **Sub Total** | **-** | **-** | **-** |
| | | | | | | | **Grand Total** | **$739,000** | **$739,000** | **-** |

## Classified Staff or Generally Ineligible Expenses

| Category/Name | Subcategory or Type | Description | Justification Ineligible Expense or Classified Staff Request |
|---|---|---|---|

## Non ENRTF Funds

| Category | Specific Source | Use | Status | $ Amount | $ Amount Spent | $ Amount Remaining |
|---|---|---|---|---|---|---|
| **State** | | | | | | |
| | | | **State Sub Total** | **-** | **-** | **-** |
| **Non-State** | | | | | | |
| | | | **Non State Sub Total** | **-** | **-** | **-** |
| | | | **Funds Total** | **-** | **-** | **-** |

# Attachments

## Required Attachments

### *Visual Component*

File: 5f5de6f8-6b7.pdf

### *Alternate Text for Visual Component*

The image demonstrates carbon-free iron ore reduction, using renewable energy to produce hydrogen from electrolysis and power the hydrogen plasma. Ground iron ore and existing mining waste of lower quality ores are fed into the plasma, which converts them to pure iron and water....

## Supplemental Attachments

### *Capital Project Questionnaire, Budget Supplements, Support Letter, Photos, Media, Other*

| Title | File |
|---|---|
| Letter of Endorsement | 31e62286-a5d.pdf |
| Background Check Certification Form | 778bf4f6-d28.pdf |
| Environment-friendly Decarbonizing of Steel Production with Hydrogen Plasma | c0207064-1c3.pdf |
| In-flight iron ore reduction and nanoparticle formation in an atmospheric pressure hydrogen microwave plasma | 954343e5-de5.pdf |
| Experimental and thermodynamic limits of dissociative metal oxide reduction using microwave hydrogen plasma | cc2ac65a-4b8.pdf |
| Operando Characterization of Iron Ore Reduction by MW Ar-H2 Plasmas | 368f33b6-107.pdf |
| Transition Toward a Decarbonized Steel Industry: A Supply Chain Analysis for the United States | 1cae5120-e07.pdf |
| Bimetallic (Ni–Fe) and Trimetallic (Ni–Fe–Cr) Nanoalloys from Metal Oxides Using a Microwave Hydrogen Plasma | ca219675-31a.pdf |
| Mechanism of H2 plasma-enabled reduction of hematite thin films | f7d2784d-36e.pdf |
| List matching Outcomes to Publications/Reports | 195722e2-648.pdf |

# Difference between Proposal and Work Plan

### *Describe changes from Proposal to Work Plan Stage*

We provided additional information on dissemination and updated/verified all information, as requested. We adjusted the budget to the recommended funding by reducing funds for equipment, publication fees, materials and supplies and services, and travel. Industrial project partners want to remain anonymous and have not been listed.

## Additional Acknowledgements and Conditions:

The following are acknowledgements and conditions beyond those already included in the above workplan:

**Do you understand and acknowledge the ENRTF repayment requirements if the use of capital equipment changes?**

N/A

**Do you understand that travel expenses are only approved if they follow the "Commissioner's Plan" promulgated by the Commissioner of Management of Budget or, for University of Minnesota projects, the University of Minnesota plan?**

Yes, I understand the UMN Policy on travel applies.

**Does your project have potential for royalties, copyrights, patents, sale of products and assets, or revenue generation?**

Yes

**Do you understand and acknowledge IP and revenue-return and sharing requirements in 116P.10?**

Yes

**Do you wish to request reinvestment of any revenues into your project instead of returning revenue to the ENRTF?**

No

**Does your project include original, hypothesis-driven research?**

Yes

**Does the organization have a fiscal agent for this project?**

Yes, Sponsored Projects Administration

**Do you understand that a named service contract does not constitute a funder-designated subrecipient or approval of a sole-source contract? In other words, a service contract entity is only approved if it has been selected according to the contracting rules identified in state law and policy for organizations that receive ENRTF funds through direct appropriations, or in the DNR's reimbursement manual for non-state organizations. These rules may include competitive bidding and prevailing wage requirements**

N/A

# Work Plan Amendments

| Amendment ID | Request Type | Changes made on the following pages | Justification For Amendment Request (word limit 75) | Date Submitted | Approved | Date of LCCMR Action |
|---|---|---|---|---|---|---|
| 1 | Amendment Request | • Other<br>• Budget - Professional / Technical Contracts<br>• Budget - Capital, Equipment, Tools, and Supplies<br>• Budget - Travel and Conferences<br>• Budget - Printing and Publication | We request changes to our budget from our original request: An increase of Professional/Technical contracts due to higher than anticipated expenses for materials characterization. A decrease in capital equipment because another piece of equipment became available from another source to perform the proposed work on scaling laws. An increase in non-capital equipment due to higher than anticipated costs in this category. The overall total budget request remains unchanged. | April 2, 2025 | Yes | May 2, 2025 |
| 2 | Amendment Request | • Budget - Professional / Technical Contracts<br>• Budget - Capital, Equipment, Tools, and Supplies<br>• Budget - Travel and Conferences<br>• Budget - Printing and Publication<br>• Attachments | Our expenses for services and subcontracts were higher than originally budgeted. We anticipate lower expenses in printing and publication, and adjusted the budget accordingly. This is reflected in the current amendment request. | October 1, 2025 | Yes | November 10, 2025 |
| 3 | Amendment Request | • Budget<br>• Budget - Personnel<br>• Budget - Professional / Technical Contracts<br>• Budget - Capital, Equipment, Tools, and Supplies<br>• Attachments | Personnel costs have been lower than expected due to the retirement of two team members. Expenses for materials and supplies and characterization facility services were higher than originally budgeted, necessitating the current budget amendment. The original line item for equipment was restored because a piece of equipment that is required to complete the experimental studies broke. | April 1, 2026 | Yes | April 23, 2026 |
| 4 | Amendment Request | • Budget<br>• Other<br>• Budget - Personnel | Personnel costs have been lower than expected due to the retirement of two team members. Travel expenses and | October 23, 2026 | Yes | October 23, 2026 |

| | | | | | | |
|---|---|---|---|---|---|---|
| | | • Budget - Professional / Technical Contracts<br>• Budget - Capital, Equipment, Tools, and Supplies<br>• Budget - Travel and Conferences<br>• Budget - Printing and Publication<br>• Attachments | publication charges were also lower than originally budgeted. Expenses for materials and supplies and for characterization facility services were higher than originally budgeted, necessitating the current budget amendment. All line items have been updated to reflect actual expenses. | | | |

# Status Update Reporting

## Final Status Update August 14, 2026

**Date Submitted:** October 23, 2026

**Date Approved:** October 23, 2026

**Overall Update**
Hydrogen Plasma Reduction: Demonstrated rapid, efficient reduction of various Minnesota iron ores (blast furnace and DRI grade). Common impurities do not significantly hinder the process. We established scaling laws demonstrating that higher power, smaller particle sizes, and closer proximity to the plasma maximize metallization and energy efficiency.

Process Optimization Model: Developed and experimentally validated a comprehensive Ar-H2 plasma kinetic model featuring over 100 reactions. This model successfully identifies the optimal power, gas flow, and reactive species concentrations needed to scale up reactor operations.

Techno-Economic & Policy Analysis: Created a long-term U.S. steel supply chain optimization model, specifically identifying Minnesota as a strategic priority region for early-stage decarbonization. We also built a bilevel optimization algorithm to model how government policies can most effectively incentivize stakeholders across the supply chain.

Dissemination & Scale-Up: Met all milestones, producing multiple peer-reviewed publications and conference presentations. Crucially, this ENRTF-supported research enabled the team to secure a competitive ARPA-E grant to further advance the technology's readiness level.

Attachment: "List matching Outcomes to Publications/Reports" maps the provided publications and reports to "Expected Outcomes" from the Narrative section.

**Activity 1**
Since the last update on April 1, 2026, we have continued our fundamental evaluation of the hydrogen plasma reduction system. This included operating the microwave plasma over a wide range of applied powers, powder feed rates, and hydrogen molar fractions from 10% to over 60%. The results indicate that iron oxide particles are reduced more rapidly as power and hydrogen percentage increase. The extent of reduction decreases with increasing powder feed rate. Hence, feed rate, hydrogen fraction, and power need to be optimized to achieve optimal energy efficiency.

Additional work focused on evaluating different iron ore mineralogies. While research is still needed, initial results suggest that the plasma process is largely agnostic to magnetite and hematite ores and that common impurities such as silica and alumina do not have a major impact on iron ore reduction. A manuscript exploring the mechanism of hydrogen plasma reduction of hematite was recently published.

Results from this activity have been partially published in journal papers and conference proceedings. Work is in progress to summarize the remaining results and prepare them for publication.
*(This activity marked as complete as of this status update)*

**Activity 2**
Since the last update, we have continued the development of a model for Ar-H2 plasmas to determine optimal reduction conditions. This model uses flow rates of Ar and hydrogen and input power as parameters to solve a reaction mechanism with over 100 reactions. Over the last three months, we focused on better modeling the energy input into the plasma volume, based on experimental measurements of the plasma emission.

The model now enables us to perform quickly perform parametric studies of plasma conditions relevant for iron oxide reduction when input parameters such as gas mixture, flow rates, and power are varied. The model has been validated against experimental measurements such as electron density in the plasma and gas temperature in the afterglow, where downstream iron ore reduction occurs. In general, good agreement has been found. A manuscript describing this model has been largely completed and will be submitted soon.
*(This activity marked as complete as of this status update)*

**Activity 3**
Since the last project update, we developed an algorithm that can learn the unknown objectives of different stakeholders given their past decisions. This is helpful in designing appropriate policies to drive a desired decarbonization pathway in a steel manufacturing supply chain, where different stakeholders make decisions based on their own objectives. Our approach is based on a bilevel optimization formulation that models the problem as a Stackelberg game, in which the leader is the government, which aims to determine optimal policies, and the followers are various actors in the steel supply chain, such as iron miners, steel producers, and consumers. We presented some preliminary results at the International Conference on Bilevel Optimization (ICBO) in August and are currently working on a larger case study and a manuscript to be submitted within the next few months.
*(This activity marked as complete as of this status update)*

**Dissemination**
Project participants continue to publish research papers resulting from this research. One paper about the mechanism of hydrogen plasma reduction of hematite was published during the report period. Another manuscript on the argon-hydrogen plasma model is about to be submitted to a journal.

As is usual with research grants, papers resulting from this work will still be published months after the grant end date. Moreover, Professor Kortshagen will present results of this research as an invited presentation at the upcoming Materials Research Society Fall Symposium in December 2026 in Boston, MA.

# Status Update Reporting

## Status Update April 1, 2026

**Date Submitted:** April 1, 2026

**Date Approved:** April 23, 2026

**Overall Update**
Since our last report, the project has made significant progress across all three activities, and we remain on track to meet all final milestones by the project end date of June 30, 2026.

In Activity 1, we have confirmed that magnetite and hematite are readily reduced in our system, and we are now characterizing the impact of impurities like silica and alumina. Our recent work suggests a potential universal scaling law that captures our data across varying plasma power and flow rates, providing a clear path for larger-scale reactor evaluation.

For Activity 2, we developed a comprehensive Ar-H2 plasma model featuring over 100 reactions to identify optimal gas temperatures and reactive species concentrations. This modeling effort is critical for defining the precise operating parameters necessary for efficient reduction as we move toward scaling up.

In Activity 3, we have advanced our techno-economic-environmental analysis by implementing a bilevel optimization approach to model interactions between government policies and supply chain stakeholders. This follows our previous analysis, which identified Minnesota as a priority region for early-stage decarbonization.

Overall, the work is progressing well, and the team is focused on finalizing these results for the final report and upcoming publications.

**Activity 1**
Since the last update on October 1, 2025, we have continued our fundamental evaluation of the hydrogen plasma reduction system. We have conducted initial trials with ores of different mineralogy; while research is still in progress, initial results suggest that magnetite and hematite are readily reduced to iron in the hydrogen plasma, whereas impurities such as silica and alumina appear less affected and are not fully reduced.

We have also performed preliminary work exploring wide ranges of plasma power, hydrogen flow rate, and particle feed rates. These results suggest a potential universal scaling law that captures our data to date. However, additional work using iron ore fines of different particle sizes is currently in progress to finalize these conclusions before the June 30, 2026, milestone.

Cumulative progress is now focused on the final milestones: determining scaling laws with a larger-scale reactor and preparing the final report. The remaining work on the energy budget and exhaust streams is in progress and will be reported in the final update. We expect to complete all Activity 1 outcomes by the project end date.

**Activity 2**
Since the last update on October 1, 2025, we have developed a model for Ar-H2 plasmas to determine optimal reduction conditions. This model uses flow rates of Ar and hydrogen and input power as parameters to solve a reaction mechanism with over 100 reactions. This enables us to identify gas temperatures and concentrations of key reactive species, such as atomic and vibrationally excited hydrogen, to accurately model the system's iron ore reduction capabilities.

Work is underway to analyze which plasma conditions provide the optimal gas temperatures and reactive species concentrations to achieve the most efficient reduction of iron ore concentrates. This modeling effort supports our move toward scaling up by defining the operating parameters necessary for various ore types. We expect to complete this model by the project's end date of June 30, 2026. Results will be reported in the final update and are currently being prepared for publication in a journal paper. This work builds on our previous findings regarding particle size and distance effects to further refine process efficiency.

**Activity 3**

We previously conducted a techno-economic-environmental analysis of the U.S. steel supply chain with state-level resolution and developed a long-term planning model to determine a cost-effective strategy for transitioning toward a decarbonized U.S. iron and steel industry. The results from our analysis demonstrate a feasible decarbonization pathway that involves a phased retirement of blast furnace-basic oxygen furnace facilities, expansion of electric arc furnace capacity, and a widespread shift toward renewable electricity use. Minnesota and Michigan emerge as priority regions for early installation of electrolyzers and direct reduction shaft units, given their iron ore reserves and proximity to existing electric arc furnace plants. These findings highlight Minnesota’s strategic position in enabling early-stage decarbonization.

Currently, our work focuses on developing a model to optimize the necessary policies to drive a desired decarbonization pathway, as in our previous work. This requires consideration of interactions among stakeholders in the same supply chain who have competing objectives. We use a bilevel optimization approach to model the problem as a Stackelberg game where the leader is the government that aims to determine the optimal policies, and the followers are different actors in the steel supply chain, such as iron miners, steel producers, and consumers.

**Dissemination**

Over this report period, an additional paper acknowledging ENRTF support has been published. In this paper, we explored the ability of hydrogen microwave plasmas to form iron-based alloys by feeding iron ore and other metal oxide particles into the plasma. Fe–Ni particles were produced from a mixture of magnetite and nickel oxide particles having a size of around 30 μm. The composition of these particles could be tuned by varying the feed material composition. Furthermore, trimetallic Fe–Ni–Cr NPs are synthesized using chromium oxide ($Cr_2O_3$) as the third precursor, demonstrating the process’s flexibility in incorporating different metal oxides. A copy of the paper is included as attachment.

# Status Update Reporting

## Status Update October 1, 2025

**Date Submitted:** October 1, 2025

**Date Approved:** November 10, 2025

**Overall Update**

Over the past six months, our team has advanced the development of fossil fuel-free ironmaking technology using hydrogen plasma. In addition to earlier work with reagent-grade materials, we tested a range of realistic iron ores, extending our understanding of the impacts of particle size and impurities on process performance. We continue to pursue the goal of demonstrating long-term (10+ hours) stable operation. Results indicate that extended operation is an achievable target for downstream reduction following the plasma step, though full demonstration is still needed.

On the techno-economic front, our preliminary model has been refined, and we published a study, "Transition Toward a Decarbonized Steel Industry: A Supply Chain Analysis for the United States", which highlights the potential role of hydrogen plasma reduction within broader decarbonization pathways. Life cycle considerations and scale-up challenges remain a focus, and this work is providing critical insights for next-stage development.

The support provided by the ENRTF has positioned our team to make meaningful progress toward a scalable, low-carbon alternative for steelmaking and complements our ARPA-E–funded efforts to further increase technological readiness.

**Activity 1**

During this reporting period, we advanced baseline studies of the hydrogen plasma reduction system using reagent-grade and realistic iron ores. A comprehensive dataset was collected, including inputs of iron ore, hydrogen, argon (carrier gas), and electricity, enabling evaluation of mass and energy balances under varying process conditions. Reduction and metallization were quantified across a range of iron ores, providing insight into mineralogical effects on performance.

We observed a clear dependence of downstream reduction on distance from the plasma: iron ore particles located closer to the plasma exhibited higher reduction rates and greater degrees of metallization. To interpret these findings, we developed a plasma chemical model for an argon–hydrogen plasma. The model predicts that reducing species, especially atomic hydrogen, rapidly decrease with distance from the plasma due to recombination, consistent with our experimental results.

These results represent a significant step toward achieving the goals of Activity 1 of analyzing input and exhaust streams and improving energy efficiency. Ongoing work will refine energy budgets and continue characterization of product quality, providing critical data for scaling and for comparison with alternative and waste iron ore feedstocks.

**Activity 2**

Over the past six months, we evaluated the response of the hydrogen plasma reduction process using industry-derived iron ore concentrates and materials representative of Minnesota iron ore waste. Unlike the reagent-grade materials studied in Activity 1, these concentrates revealed a strong dependence of reduction kinetics on particle size. Particles smaller than 5 microns achieved more than 80% metallization within seconds, while larger particles (25–40 microns) required several minutes to reach comparable levels, resulting in lower overall energy efficiency.

We also identified that the effect of particle size can be partially mitigated by decreasing the distance between the particle bed and the plasma, which enhances exposure to reactive species. Initial assessments show little variation in

reduction rates due to impurities, though this will be investigated further as more concentrate types are tested.

These findings directly address Activity 2 milestones by establishing clear differences in performance between reagent-grade and concentrate feedstocks, and by beginning to define operating parameters that improve efficiency. Continued work will refine optimal conditions for iron ore concentrate reduction and expand characterization of products to better understand the role of gangue and mineralogy in process performance.

**Activity 3**

We conducted a techno-economic-environmental analysis of the U.S. steel supply chain with state-level resolution and developed a long-term planning model to determine a cost-effective strategy for transitioning toward a decarbonized U.S. iron and steel industry. The model incorporates key parameters such as capital costs, iron ore availability, renewable electricity prices, and transportation costs for transporting iron ore and steel. It determines optimal plant siting, technology deployment, and material flows while satisfying emissions, capacity, and resource constraints over time.

We applied the model to explore the long-term transition to green hydrogen-based direct reduced iron and electric arc furnace (green H-DRI-EAF) systems, two of the most promising near-term decarbonization options. The resulting pathway shows a phased retirement of blast furnace-basic oxygen furnace facilities, expansion of EAF capacity, and a widespread shift toward renewable electricity use. Minnesota and Michigan emerge as priority regions for early installation of electrolyzers and direct reduction shaft (DRS) units due to the existence of iron ore reserves and proximity to existing EAF plants.

These findings highlight Minnesota's strategic position in enabling early-stage decarbonization. Current efforts focus on modeling the interactions between different stakeholders in the supply chain to make more realistic predictions of technology investment decisions.

**Dissemination**

Over the past six months, dissemination efforts have included publication, conference presentations, and journal submissions. A peer-reviewed article was published in Industrial & Engineering Chemistry Research: Jeong Y, Zhang Q. Transition toward a Decarbonized Steel Industry: A Supply Chain Analysis for the United States (Aug 2025). In June 2025, two presentations were delivered at the 26th International Symposium on Plasma Chemistry in Minneapolis, MN. The first, by Kumar et al., addressed the Experimental and thermodynamic limits of dissociative metal oxide reduction using microwave hydrogen plasma. The second, by Akinshilo et al., reported on Operando Characterization of Iron Ore Reduction by MW Ar-H2 Plasmas. In addition, two further manuscripts have been submitted to peer-reviewed journals and are currently under review. Together, these activities demonstrate strong progress in disseminating research findings to both the scientific community and broader stakeholders.

# Additional Status Update Reporting

## Additional Status Update March 25, 2025

**Date Submitted:** April 1, 2025

**Date Approved:** May 2, 2025

**Overall Update**
This additional status update was created by mistake. A regular update will be filed April 1.

**Activity 1**
This additional status update was created by mistake. A regular update will be filed April 1.

**Activity 2**
This additional status update was created by mistake. A regular update will be filed April 1.

**Activity 3**
This additional status update was created by mistake. A regular update will be filed April 1.

**Dissemination**
This additional status update was created by mistake. A regular update will be filed April 1.

# Status Update Reporting

## Status Update April 1, 2025

**Date Submitted:** April 1, 2025

**Date Approved:** May 2, 2025

**Overall Update**

Over the past reporting period, our team has made good progress on the development of a fossil fuel-free ironmaking technology based on hydrogen plasma. Initial steps have been taken to explore the utilization of lower-quality alternative iron resources and iron ore waste piles. The team has started evaluating input and output materials streams as well as energy consumption. This will help us assess the CO2 emission reductions by replacing iron ore pelletization with hydrogen plasma reduction. A preliminary model has been developed for the techno-economic analysis. This model will be refined and used to assess the scale-up of the proposed process. The team is also working towards the following goals that still need to be achieved:

- Early-stage anticipatory life cycle study focused on scale-up potential for the plasma technology
- Demonstration of potential for scale-up by continuous operation for more than 10 hours with less than 5% variation of process conditions and product quality

The support provided by the ENRTF has put our team in a position to successfully compete for funding from the Advanced Research Projects Agency-Energy (ARPA-E). An ARPA-E grant focused on further scale-up of the technology and raising the technological readiness level was received in July 2024.

**Activity 1**

Within the scope of this activity, the research team has worked to refine the approach for the previously defined 'downstream' treatment method. The team used a data-driven approach to inform optimization experimentation. The effect of critical parameters were systematically studied: hydrogen gas concentration and ore proximity to the plasma during treatment. Data for these experiments came from an in-situ Raman laser gas analyzer (RLGA) and an ex-situ x-ray diffraction (XRD) instrument. By correlating the data from these two techniques, real-time monitoring of the rate of iron ore reduction was achieved. Exhaust composition during the experiment was compared to the treated product composition. This yielded crucial information about the reduction rate and total reduction percentage. The input ore was also analyzed with XRD and separated into size ranges for experimentation to understand the effect of particle size. RLGA data enabled the analysis of the exhaust streams obtained from the downstream treatment process to estimate the percentage of hydrogen utilization and energy efficiency of the plasma system. In parallel with optimization, experiments were conducted to determine the effect of lower microwave power on the reduction rate and system efficiency. Overall, data-driven experimentation enabled further optimization and analysis of the system in operation.

**Activity 2**

The NRRI team has begun work on the beneficiation of iron ore waste materials to produce a concentrate. For the purpose of this update, “waste materials” are iron-bearing materials not currently being processed by the industry. A partially oxidized iron ore sample from the Mesabi Iron Range will be used as the feedstock for the study. The partially oxidized sample contains high concentrations of hematite (Fe2O3) and goethite (FeO(OH)), making it difficult to beneficiate via the traditional low-intensity magnetic separation technologies.

The team has started grinding the iron ore sample to determine the liberation size of the iron minerals. Once the liberation size is identified, the team will move on to bulk grinding to produce samples for bench-scale beneficiation. Bench scale beneficiation will consist of using a natural pH flotation process developed by NRRI. The product from the

flotation process will be a high hematite/goethite iron ore concentrate that is not currently generated by the iron ore industry.

**Activity 3**

We developed a multiperiod supply chain optimization model with state-level resolution to design cost-effective roadmaps for decarbonizing the U.S. iron and steel industry. The model is formulated as a mixed-integer linear program and incorporates key parameters such as capital costs, iron ore availability, renewable electricity prices, and transportation between states. It determines optimal plant siting, technology deployment, and material flows while satisfying emissions, capacity, and resource constraints over time. We applied the model to explore long-term transitions to green hydrogen-based direct reduced iron and electric arc furnace (green H-DRI-EAF) systems, one of the most promising near-term decarbonization options. The resulting pathways show a phased retirement of blast furnace-basic oxygen furnace facilities, expansion of EAF capacity, and a widespread shift toward renewable electricity use. Minnesota and Michigan emerge as priority regions for early installation of electrolyzers and direct reduction shaft (DRS) units due to the existence of iron ore reserves and proximity to existing EAF plants. These findings highlight Minnesota's strategic position in enabling early-stage decarbonization. Future work will build on this framework to evaluate additional technology pathways for achieving deep emissions reductions in the steel sector.

**Dissemination**

In the past reporting period, we published a peer-reviewed paper:
Xiong, Z., Kumar, S., Held, J., Bruggeman, P., Kortshagen, U., 2024. In-flight iron ore reduction and nanoparticle formation in an atmospheric pressure hydrogen microwave plasma. J. Phys. D: Appl. Phys. 57, 355201. https://doi.org/10.1088/1361-6463/ad5027

The paper Jeong, Y. & Zhang, Q. (2024). Transition toward a decarbonized steel industry: A supply chain analysis for the United States, was presented at the AIChE Annual Meeting, San Diego, Oct. 27-31, 2024.

The paper Uwe Kortshagen, Sachin Kumar ,Zichang Xiong, Julian Held, Peter Bruggeman (2024) In-Flight Reduction of Iron Ore Particles in an Atmospheric Pressure Hydrogen Microwave Plasma was presented at the Materials Research Society Meeting in Boston, MA, Dec. 1-6, 2024

# Status Update Reporting

## Status Update October 1, 2024

**Date Submitted:** September 28, 2024

**Date Approved:** October 1, 2024

**Overall Update**
This status update is waived per guidance from LCCMR staff provided on August 13, 2024.

**Activity 1**
This status update is waived per guidance from LCCMR staff provided on August 13, 2024.

**Activity 2**
This status update is waived per guidance from LCCMR staff provided on August 13, 2024.

**Activity 3**
This status update is waived per guidance from LCCMR staff provided on August 13, 2024.

**Dissemination**
This status update is waived per guidance from LCCMR staff provided on August 13, 2024.

# Status Update Reporting

## Status Update April 1, 2024

**Date Submitted:** March 29, 2024

**Date Approved:** May 23, 2024

**Overall Update**

This project comprises three activities to achieve the proposed project outcomes. All activities have made good initial progress and are on track to reach the first project milestones. Under Activity 1, we have demonstrated hydrogen plasma reduction of iron ores, which can be a carbon-free technology if operated with renewable electricity and "green hydrogen." Different modes of iron ore reduction have been explored, and several types of iron ore materials have been treated. The preliminary results have been promising, with the plasma showing potential to treat iron ore particles of different compositions and sizes, as well as disks fabricated from iron ore pellets. Under Activity 2, different Minnesota-specific iron ores with varying quality grades were procured and prepared for hydrogen plasma treatment. Under Activity 3, a computational model was developed that captures the production process as well as costs and constraints related to the distribution of raw materials and produced steel. A first manuscript has been prepared and submitted, and a conference presentation will be made at the 2024 SME Minnesota Conference.

**Activity 1**

Under this activity, the research team has investigated two modes of treating iron ore particles: 1) a "downstream" treatment, in which iron ore particles were exposed to the effluent of the hydrogen plasma, and 2) an "in-flight" treatment in which particles are injected directly into the plasma and carried through the plasma by the gas flow.

For the downstream treatment, iron ore particles were found to be reduced within a few seconds, depending on their size. Compared with treatment with hot hydrogen gas in a furnace, the plasma treatment was about three to four times faster, suggesting that excited plasma species such as atomic hydrogen or hydrogen ions play a significant role in the reduction. Work is currently underway to reveal the role of particle size in the reduction kinetics.

In-flight reduction is a newer approach that initially has shown promising results. However, more work is needed to understand the role of particle size, gas flow velocities, and particle residence time in the plasma. Work on this approach will be continued in the next report period.

**Activity 2**

To evaluate the suitability of the plasma process for different types and quality grades of iron ore, various samples were procured and prepared by the NRRI team and shipped to the UMN-Twin Cities team for hydrogen plasma treatment. Four samples representing a range of iron ore concentrate quality were selected for the plasma reduction. The samples include DR (Direct Reduced) grade concentrate, blast furnace grade concentrate, hematite concentrate, and partially oxidized mixed magnetite-hematite-goethite concentrate. Identification of the minerals present using X-ray diffraction is complete. The mineral abundances have been quantified using Rietveld refinement. Polished mounts of the four samples have been prepared for reflected light microscopy. Splits of the four samples have been submitted to the NRRI Coleraine Laboratory for Total Fe, Fe++, Satmagan Fe, SiO2, Phos, and sieve analysis to determine the particle size distribution of each sample.

**Activity 3**

To be able to compare the economic and environmental performance of the proposed steel manufacturing process involving plasma-based iron ore reduction with other promising sustainable alternatives at the systems level, we have been working on a benchmark focusing on the most prominent sustainable steelmaking path, namely the use of hydrogen-based direct reduction and electric arc furnace powered by renewable electricity. We have developed a

computational model that captures the production process as well as costs and constraints related to the distribution of raw materials and produced steel. Using this model, we can optimize for a given region, e.g. the State of Minnesota or the entire United States, where, when, and to what extent we deploy the new technology over the coming years in order to achieve given emission reduction targets. Applying the proposed model to different scenarios, our preliminary results show how we can potentially transition to a decarbonized steel industry over the next 30 years using this particular alternative process, and how much that would cost.

**Dissemination**

A manuscript describing some of Activity 1's preliminary results has been prepared and submitted to a scientific journal. The team is working on addressing reviewer comments.

A presentation entitled “Microwave Hydrogen Plasma Reduction of Iron Ore” was submitted to the Society for Mining, Metallurgy & Exploration Inc. (SME) Minnesota 2024 meeting, to be held in Duluth, MN. The presentation has been accepted and will be given on April 17, 2024.