Environment and Natural Resources Trust Fund

M.L. 2023 Approved Work Plan

General Information

ID Number: 2023-171

Staff Lead: Mike Campana

Date this document submitted to LCCMR: May 22, 2023

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

Project Budget: $739,000

Project Manager Information

Name: Uwe Kortshagen

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Project Reporting

Date Work Plan Approved by LCCMR: June 22, 2023

Reporting Schedule: April 1 / October 1 of each year.

Project Completion: June 30, 2026

Final Report Due Date: August 14, 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 CO_2 emissions. Our microwave hydrogen plasma ironmaking eliminates fossil fuel use and CO_2 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 CO_2 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 CO_2 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 CO_2 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 CO_2 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
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%	0.27		$42,387
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%	0.18		$20,149
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	**$690,519**
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.				-		$11,000
							Sub Total	**$11,000**

Equipment, Tools, and Supplies								
	Equipment	Scaled up plasma reactor	A larger version of the current plasma reactor will be built to explore scaling laws					$15,000
	Tools and Supplies	Process gases, glass ware, filters, general laboratory supplies	Items are needed for operation of hydrogen plasma process					$12,481
							Sub Total	**$27,481**
Capital Expenditures								
							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					$6,000
							Sub Total	**$6,000**
Travel Outside Minnesota								
							Sub Total	**-**
Printing and Publication								
	Publication	Cost of publication charges	Cost of article preparation fees in open access scientific journals					$4,000
							Sub Total	**$4,000**
Other Expenses								
							Sub Total	**-**
							Grand Total	**$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
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....

Optional Attachments

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

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 agree travel expenses must 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 agree to the UMN Policy.

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

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