Pacific Northwest
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PNNL-38895

Improving Lithium Recovery and Production of Value-Added Minerals from Geothermal Brines with Controlled Precipitation and Precision Separation (CRADA 635) Final Report

December 2025

U.S. DEPARTMENT OF ENERGY

Prepared for the U.S. Department of Energy
under Contract DE-AC05-76RL01830

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Prepared for the U.S. Department of Energy under Contract DE-AC05-76RL01830

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Cooperative Research and Development Agreement (CRADA) Final Report

Report Date:

In accordance with Requirements set forth in the terms of the CRADA, this document is the CRADA Final Report, including a list of Subject Inventions, to be provided to PNNL Information Release who will forward to the DOE Office of Scientific and Technical Information as part of the commitment to the public to demonstrate results of federally funded research. **PNNL acknowledges that the CRADA parties have been involved in the preparation of the report or reviewed the report.**

Parties to the Agreement: Hell's Kitchen Geothermal (HKG)

CRADA number: 635

CRADA Title: Improving Lithium Recovery and Production of Value-Added Minerals from Geothermal Brines with Controlled Precipitation and Precision Separation

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Sponsoring DOE Program Offices:

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Joint Work Statement Funding Table showing DOE funding commitment:

	Funding Amounts			
CRADA Parties	**DOE Funding**	**Funds-In**	***In-kind**	**Total**
HKG	$0	$0	$100,000	$100,000
DOE Funding to PNNL	$276,991	N/A	N/A	$276,991
Total of all Contributions	$276,991	$0	$0	$376,991

Provide a list of publications, conference papers, or other public releases of results, developed under this CRADA:

N/A

Provide a detailed list of all subject inventions, to include patent applications, copyrights, and trademarks:

No subject inventions were generated under this CRADA.

Executive Summary of CRADA Work

The purpose of this project is to design, build, and demonstrate a system for mineral extraction from geothermal brines by selectively precipitating minerals and then removing them with mesofluidic devices, sometimes termed a Geothermal Micropillar Enhanced Particle Separator (GMEPS) or Micropillar Enhanced Particle Separator (MEPS). This combination of a new particle separation technology and selective precipitation chemistry to recover valuable minerals from geothermal brines will provide an improved feed stream for lithium recovery processes. Metals this project focused on include iron (representative of coarse materials), manganese (hard minerals), and zinc (soft minerals) from the Salton Sea Geothermal field. By removing these minerals, lithium can be more readily processed and the removed precipitates may be value-added. Li is a relatively nonreactive and highly soluble ion that is typically inert to many of the precipitation reactions that strongly impact the more reactive minerals, allowing lithium to pass through precipitative processes that remove other minerals from solution. Precipitation is a proven, cost-effective industrial process widely used in mining and treatment of large volumes of water. DOE funding provides the essential resources to develop, optimize, and integrate the different component technologies into a flexible novel system that allows the recovery of valuable minerals from geothermal brines (and other solutions) containing critical minerals.

This is a 2-year effort that succeeded in:

- developing and demonstrating a new mineral recovery precipitation process that is applicable to wide range of critical minerals.
- developing and demonstrating new MEPS devices for improved mineral particle separation. Improvements provide better mineral recovery with compact inexpensive.
- Advancing the system from Technology Readiness Level (TRL) 3 to TRL 5.
- Preparing for pilot plant scale efforts and potentially a field demonstration in Salton Sea area.

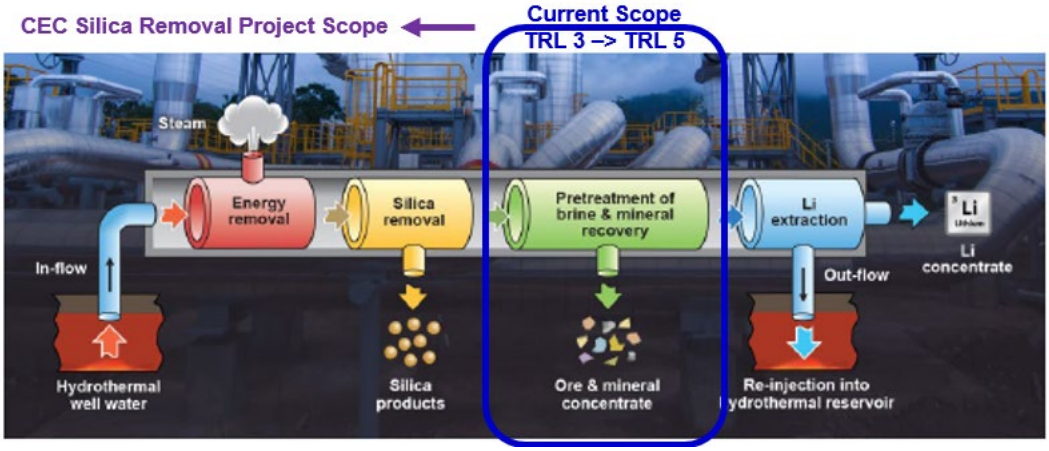

Figure 1. Conceptual process flow diagram showing that, after silica is removed from geothermal brines, the remaining minerals become accessible.

Specifically, PNNL invented mesofluidic technology, which provides inexpensive particle/mineral separation from fluids over a large range of flow rates. PNNL has successfully developed the technology from concept to over 100 gpm scale for solutions and applications ranging from

nuclear waste slurries to trace mineral recovery from acid solutions. PNNL leveraged a $3M California Energy Commission (CEC) program to develop mesofluidic devices to remove silica from geothermal solutions. Although silica removal is a key step in the overall process, as shown in Figure 1, silica removal lies outside this scope. This project develops a multi-stage pretreatment process that follows the silica separation stage, using chemically controlled precipitation to enable the precision separation of value-added minerals and a cleaner feed stream for lithium separation methods.

Problem

The extraction of lithium and other elements is complicated by coarse minerals, including iron, soft minerals, including Zn, and hard minerals, including Mn. By removing these minerals, lithium can be more readily processed, and the removed precipitates may be value-added. Li is a relatively nonreactive and highly soluble ion that is typically immune to many of the precipitation reactions that strongly impact the more reactive minerals, allowing lithium to pass through precipitative processes that remove other minerals from solution.

Solution

The solution explored in this effort combines one proven technology (chemical precipitation) organized for mineral recovery from Salton Sea geothermal brines with a second brand-new technology (mesofluidics) constructed using additive manufacturing (3D printing) to create a novel, inexpensive process that provides selective separation and recovery of minerals from solutions.

Mesofluidic systems separate solid precipitate particles based on their size[1] as they flow through sequential devices. This effort herein acknowledges that precipitation will happen. Unlike previous efforts, this project directs and controls the precipitation processes, not fighting them. PNNL and partners are preparing the devices, verifying the precipitation reactions, and evaluating the techno-economic aspects of the proposed process, as reported below.

Project Objective

The general objective of this project is to develop and demonstrate a new particle separation technology that, when coupled with selective precipitation chemistry, provides cost-effective recovery of valuable minerals from geothermal brines while providing an improved feed stream for lithium recovery processes. This effort developed and demonstrated mesofluidic technology and customized precipitation chemistry for this application, along with initial engineering studies, and then refined the process chemistry in order to prepare a technoeconomic analysis for a full-scale system.

This report summarizes project accomplishments that indicate successful project completion. Milestones achieved in the first budget period include the following.

- 3.1 Complete initial process and physical design of mesofluidic devices

[1] Some mesofluidic devices herein also separate by density.

- 4.1 Demonstrate selective removal of precipitates (synthetic brines)
- 4.2 Demonstrate sequential extraction processing with mesofluidic devices
- 4.3 Demonstrate bench scale selective removal of precipitates
- 5.1 Complete initial engineering designs and economic analysis

Milestone 4.3 addresses and constitutes the go/no-go decision. Together, these accomplishments satisfied the go criteria of the go/no-go decision point.

Milestones achieved and completed in the second budget period include the following.

- 1.1 Bi-annual participation in Lithium RD&D Virtual Center
- 1.2 Annual participation in critical materials RD&D coordination meeting
- 6.1 Demonstrate improved performance of mesofluidic devices
- 7.1 Demonstrate better Li feed streams through reduction of minerals
- 8.1 Complete evaluation of operational lifetime for brines
- 9.1 Issue preliminary report on system engineering design
- 10.1 Issue final TEA report
- 11.1 Issue final report on laboratory results and engineering studies

Milestones removed from scope but which were completed during the project period before change of scope (i.e., completed before January 2025) include the following.

- 2.1 Initiate outreach and Hold all Hands meeting on diversity, equity, inclusion, and accessibility
- 2.2 Secure Student for PNNL internship
- 2.3 Hold STEM workshop with partners

Please see Appendix A for a summary of these including a report on seminar outcomes accomplished.

These milestones satisfy the completion of the entirety of the project and are highlighted in remaining sections. The final status is given below.

Final SOPO Table 1. Metrics and Targets for Integrated Mesofluidic System Operating in Geothermal Power Plants with Mineral-Rich Brines

Objective/Goal	Metric	End of Project Minimum	End of Project Stretch Target	Baseline Performance	Current Status
Provide Cleaner Brine to Li extraction Process(es)[a]	% Removal of reactive (transition) metals	90%	99%	0	≥99%[f] of Cu, Ag, and Pb
Co-production of Mn[b]	% Removal into concentrate	95%	99%	0	~98%[f]
Co-production of Zn[b]	% Removal into concentrate	95%	99%	0	99%[f]
Reduce Waste Disposal Costs[c]	% Reduction in mineral precipitates sent to waste disposal	50%	80%	0	100%
Reduce Operating Costs[d]	% Reduce baseline line operating costs (OC)	20% OC	30% OC	N/A*	21%
Reduce Capital Costs[e]	% Reduction of plant capital costs (CC)	20% CC	30% CC	N/A	57%
Reduce Plant Generator Down Time	% Increase in operations	2% (175 h)	3% (263 h)	Existing Up Time	2%

*no existing process; anticipated processes have not become operational to facilitate comparison

a. No mineral removal pretreatment systems are presently in commercial use. This includes all reactive minerals in transition series, both waste and valuable minerals. Note removal of these minerals will provide greater lithium extraction efficiency and higher lithium product first-stage separation. Specific values will depend on the specific process and feed brines used. These metrics will be evaluated at the end of the project.

b. Marketable metals present in high concentration in Salton Sea geothermal brines Mn (~450 ppm) and Zn (~1200 ppm) are representative economically valuable minerals that can be recovered with known precipitation chemistry at high efficiencies.

c. Presently all mineral precipitates from geothermal plants are disposed of as waste. By reclaiming valuable minerals, we will significantly reduce the waste volume produced. New geothermal plant designs exist to produce minerals but are not operational. This technology applied upstream to silica (out of scope) would have resulted in additional cost savings.

d. The existing mixer-settler systems used to remove mineral precipitates require significant maintenance efforts and plant downtime (~20%/year) and are estimated to be ~20-30% of plant operating costs cost (MEPS devices, running in parallel, will eliminate these costs).

e. Minerals precipitated are presently removed using multiple expensive large mixer-settling systems (>$100k each) which increase plant capital costs. MEPS devices will be a small fraction of this cost, possibly less than $2k/stage, resulting in large cost savings.

f. Assumes two consecutive devices and 95% precipitation efficiencies.

Although this has been developed for geothermal brines. The proposed technology has a full range of applications to brines and other challenging solutions (e.g., waste water, hard rock mine tailings, hydrometallurgy, produced waters from hydrocarbon extraction, etc.). Following the

above 10 gpm system, the next phase of development will be 100 gpm run in a PNNL high bay that has the capabilities to receive and process external (mobile) vessels as a demonstration of its onsite potential and scalability.

Summary of Research Results

The following table summarizes each of the milestones and their status.

Table 1. Table of milestones.

Milestone	Criteria	End Date	Status
1.1 Bi-annual participation in Lithium RD&D Virtual Center	Participation as requested in Lithium RD&D Virtual Center event	Q1 FY26	Participated As Requested
1.2 Annual participation in critical materials RD&D coordination meeting.	Participation as requested in critical materials RD&D coordination meeting	Q1 FY26	Participated As Requested
3.1 Complete initial process and physical design of mesofluidic devices	Present a working system comprising a mesofluidic device in the loop that can be used on subsequent milestones	Q3 FY24	Achieved
4.1 Demonstrate selective removal of precipitates (synthetic brines)	Significant progress toward selective removal of one or more Fe, Mn, or Zn precipitates	Q4 FY24	Achieved
4.2 Demonstrate sequential extraction processing with mesofluidic devices	Remove two different particles from two sequential mesofluidic devices	Q1 FY25	Achieved
4.3 Demonstrate bench scale selective removal of precipitates (Go/No Go)	Bench-scale demonstration of process/technology, meaning precipitation process chemistry with mesofluidic technology with a plan for additional success for Task 6	Q2 FY25	Achieved
5.1 Complete initial engineering designs and economic analysis	Evaluate progress toward initial metrics of success in Statement of Project Objectives (SOPO) Table 1	Q2 FY25	Achieved
2.2 Secure Student for PNNL internship	Identify a promising student	Q2 FY25	Achieved
6.1 Demonstrate improved performance of mesofluidic devices	Improved performance toward target minerals/mineral classes (e.g., Fe, Mn, Zn)	Q3 FY25	Achieved
7.1 Demonstrate better Li feed streams through reduction of minerals	Quantify other potentially interfering species in Salton Sea geothermal process brines and evaluate potential for their removal using chemistry and system of Task 4 or 6	Q4 FY25	Achieved

Milestone	Criteria	End Date	Status
8.1 Complete evaluation of operational lifetime for brines	The potential impact of materials on operational lifetimes of the devices and cleaning methods during plant operations	Q1 FY26	Achieved
9.1 Issue preliminary report on system engineering design	Reporting issued on system engineering design to achieve metrics in SOPO Table 1	Q1 FY26	Achieved
10.1 Issue final TEA report	Final evaluation of TEA metrics relevant to SOPO Table 1	Q1 FY26	Achieved
11.1 Issue final report on laboratory results and engineering studies	Summary of laboratory results and engineering studies performed as part of this project	Q1 FY26	Achieved
2.1 Initiate outreach and Hold all Hands meeting on DEIA	Meeting held for key staff on DEIA issues in local disadvantaged communities with invited speaker from local community impacted by the project	Q2 FY24	Achieved then removed from scope
2.2 Secure student for PNNL internship	Work with the appropriate office to secure a student for the PNNL internship	Q1 FY25	Achieved then removed from scope
2.3 Hold STEM workshop with partners	Hold at least one community-based workshop with educational institutions.	Q3 FY25	Achieved ahead of schedule then removed from scope

[1]As updated in AOP. The end date is the scheduled end date; some milestones were completed ahead of schedule.

Summary of Tasks

Tasks highlighted in this report include the following.

Task 3 – Design Mesofluidic Devices for Mineral Precipitation Separation from Brines: This task designed mesofluidic devices to separate mineral precipitates from brine. Variables and features important to the design included device geometry, ease of insertion into plant processes, ability to accommodate a wide range of flow rates, manufacturing complexity, and potential to resist mineral scaling and corrosion.

Milestone 3.1 – Complete initial process and physical design of mesofluidic devices: Present a working system comprising a mesofluidic device in the loop that can be used on subsequent milestones.

Please see Select Highlight 1, which summarizes progress satisfying Milestone 3.1 "Complete initial process and physical design. The metric of success is a working system with a mesofluidic device in the loop that can be used on subsequent milestones." Process and/or design improvements may be identified in Tasks 4-9.

Task 4 – Demonstrate Precipitation and Removal (synthetic geothermal brines): The core of this effort has been to carefully control precipitation chemistry to form mineral particles that can then be removed with mesofluidic devices. For the purpose of developing a multistage industrial process, we have evaluated and combined processes and operations, including preferred precipitation chemistries and removal/selective recovery of gross precipitates/valuable minerals (Mn, Zn, etc.) from synthetic brines using mesofluidic devices. This task is comprised of three milestones as given below.

Milestone 4.1 – Demonstrate selective removal of precipitates (synthetic brines): Significant progress toward selective removal of one or more Fe, Mn, or Zn precipitates.

Please see Select Highlight 2 addressing this milestone.

Milestone 4.2 – Demonstrate sequential extraction processing with mesofluidic devices: Remove two different particles from two sequential mesofluidic devices.

Milestone 4.3 – Demonstrate bench scale selective removal of precipitates (Go/No Go): Bench-scale demonstration of process/technology, meaning precipitation process chemistry with mesofluidic technology with a plan for additional success for Task 6.

Please see Select Highlight 3 satisfying these milestones (Select Highlight 2 focuses on a separation of an Mn-rich precipitate, and Select Highlight 3 focuses on the Fe-rich precipitate). Plans for Task 6 as required for Task 4 include the following. Task 6 calls for demonstrating the use of mesofluidic devices to separate mineral precipitates from real Salton Sea geothermal brines. To that end, we will use slurry samples from the Salton Sea Geothermal Field that have

been provided by Hell's Kitchen Geothermal (HKG) as a meaningful portion of their cost-share. Their permits for geothermal wells expired in 2024. In anticipation thereof, several gallons of mineral brines were captured, sealed, shipped, and stored at PNNL specifically for use in Task 6. These brines will be used in the mesofluidic devices to confirm that this process works well with actual brines from the Salton Sea Geothermal Field. Task 6 will further improve the process by further refining process chemistry including species interactions and by further refining flow conditions. This analysis and highlights address Milestones 4.2-4.3 and the corresponding Go/No Go.

Task 5 – Conceptual Engineering Design and Initial Technoeconomic Analysis (TEA) of Process: This task used laboratory data obtained across year 1 efforts to generate initial engineering designs for the chemical process and to prepare initial economics. These results provide insights into gaps and opportunities for development in year 2 and after this project is complete.

Milestone 5.1 – Complete initial engineering designs and economic analysis: Evaluate progress toward initial metrics of success in SOPO Table 1.

The final SOPO table is given in the Executive Summary.

Task 6 – Demonstrate Mesofluidic Devices to Separate Mineral Precipitates from Real Salton Sea Geothermal Brines: This task utilized year 1 results to improve upon the chemical process as well as separation devices as necessary. We demonstrated mesofluidic devices to separate mineral precipitates from synthetic or real Salton Sea geothermal brines.

Milestone 6.1 – Demonstrate Improved Performance of Mesofluidic Devices: Improved performance toward target minerals/mineral classes (e.g., Fe, Mn, Zn).

Please see Select Highlight 4 addressing this milestone.

Task 7 – Demonstrate Improved Feed Stream for Li Recovery Methods: This task demonstrated mesofluidic processing of real Salton Sea geothermal brines provides improved feed streams for Li recovery technologies. Improved feed stream means lower particle levels and much lower reactive mineral content. Unfiltered particles and/or reactive minerals are typical very detrimental to the performance of any lithium recovery technology. The silica in these brines will have been removed prior to implementation here similar because the silica will have been removed upstream using the CEC funded pre-treatment process (see Fig. 1).

Milestone 7.1 – Demonstrate better Li feed streams through reduction of competitive and interfering minerals from real Salton Sea geothermal brines: Quantify other potentially interfering species in Salton Sea geothermal process brines and evaluate potential for their removal using chemistry and system of Task 4 or 6.

Please see Select Highlight 5 satisfying this milestone.

Task 8 – Evaluate Methods to Extend Mesofluidic Device Operational Lifetimes: Devices operating in geothermal brines face a hostile environment with temperature extremes, corrosive solutions, and solutions laden with minerals that can precipitate out and plug up the system. Devices on this project were designed to function in these conditions but what will be the potential impact of materials on operation lifetimes? This task explored the potential impact of materials on device operational lifetime.

Milestone 8.1 – Complete evaluation of operational lifetime for brines: The potential impact of materials on operational lifetimes of the devices and cleaning methods during plant operations.

Please see Select Highlight 6 satisfying this milestone.

Task 9 – System Engineering Designs for Full-Scale Operation: This task updated the year 1 engineering analysis and designs with year 2 laboratory data with actual Salton Sea geothermal brines. The study has the best possible estimated cost and performance of a full-scale engineered system. This engineering design will show how this technology can be utilized and integrated into geothermal plants.

Milestone 9.1 – Issue preliminary report on system engineering design: Reporting on system engineering design to achieve metrics in SOPO Table 1.

Please see below for the Final SOPO Table 1: Metrics and Targets for Integrated Mesofluidic System Operating in Geothermal Power Plants with Mineral-Rich Brines. Please see Select Highlight 7 satisfying this milestone.

Task 10 – Complete Final TEA of Process: This task updated the year 1 TEA based on year 2 laboratory data with actual Salton Sea geothermal brines and the results from Task 9 (on the estimated cost and performance of a full scale engineered system). The TEA addressed issues involving mineral production and waste minimization. The TEA incorporated lifecycle assessments to provide comprehensive cradle to grave economics. This TEA was key in determining when and how this technology should be profitably applied to a range of geothermal plants.

Milestone 10.1 – Issue final TEA report: Final evaluation of TEA metrics relevant to SOPO Table 1

Please see the Executive Summary for the Final SOPO Table 1: Metrics and Targets for Integrated Mesofluidic System Operating in Geothermal Power Plants with Mineral-Rich Brines. Please see Select Highlight 8 addressing this milestone.

Task 11 – Complete Design for Integrated Future Field Demonstration: This task will provide a clear path forward to mature and demonstrate the developed technology by reporting on the results of Tasks 9-10. The design may be a portable “skid” mount platform for a system that would easily be transported to specific geothermal plants and tested on-site.

Milestone 11.1 – Issue final report on laboratory results and engineering studies: Summarize laboratory results and engineering studies performed as part of this project.

This report satisfies this milestone. Please see Select Highlight 9 describing lessons learned to be implemented in pilot scale and future work.

Summary of Research Highlights

The remainder of this report provides select highlights and milestone accomplishments.

Select Highlight 1: Design of Mineral Separation Process

The purpose of this project is to design, build, and demonstrate a system for mineral extraction from geothermal brines by selectively precipitating minerals and then removing them with a mesofluidic separator. The extraction of lithium and other elements is complicated by the presence of other reactive minerals (i.e., iron, Zn, and Mn in Salton Sea geothermal brines). By removing these minerals, lithium can be extracted more readily, and many of the removed precipitates can provide value added products or new critical material sources.

Table 2 lists the most common mineral species found in the Salton Sea geothermal brine (Stringfellow and Dobson, 2021) in order from most concentrated species to least concentrated species. The table shows that Fe, Mn, and Zr (along with Sr, B, and Ba) are present at higher concentrations than Li. At the highest concentrations, Fe, Mn, and Zn are the priority minerals for removal. Table 2 further suggests which species are soluble (sol. in table) and which are insoluble (insol. in table) (https://en.wikipedia.org/wiki/Solubility_chart, downloaded 6/17/2024) at 1 atm and 25°C. Species that are insoluble are assumed therein to leave <0.1 g/L in solution. The fourth column of the table suggests the amount of material that would be removed via precipitation at these conditions. These values are preliminary to testing described below. These values are reasonably close to but shy of the target asserted for Mn and Zn (see Table 3). We recognize that the composition of the Salton Sea geothermal brines (and HKG plants) may be meaningfully different and that process conditions are also meaningfully different from 1 atm and 25°C (e.g., 65-115°C), which will affect these initial percentages. Nevertheless, this initial solubility analysis suggests that a significant fraction of the minerals can be removed via this process.

Table 2. Estimated Concentrations and Solubility of Most Common Salton Sea Geothermal Brine Species.

Element	Target	Conc mg/L	Approximate Remove (Insoluble <100 mg/L)	CO_3^{-2}	OH^-	CN^-	Oxides	S^{-2}	Cl^-	$C_2O_4^{-2}$
Cl	No	142015								
Na	No	49249								
K	No	25684								
Fe	Target	1347	>93%	Insol.	Insol.	Sol.	Insol.	Insol.	Sol.	Sol.
Mn	Target	1201	>92%	Insol.	Insol.	Sol.	Insol.	Insol.	Sol.	Insol.
Zn	Target	463	>78%	Insol.	Insol.	Insol.	Insol.	Insol.	Sol.	Insol.
Sr	No	434								
B	No	298								
Ba	No	205								
Li	Target	202		Sol.	Sol.	Sol.	Sol.	Sol.	Sol.	Sol.

Table 3. Target Concentrations for Mineral Species.

Objective/Goal	Metric	Minimum	Stretch Target	Baseline Performance
Provide Cleaner Brine to Li extraction Process(es)	% Removal of reactive (transition) metals	90%	99%	0%
Co-production of Mn	% Removal into concentrate	95%	99%	0%
Co-production of Zn	% Removal into concentrate	95%	99%	0%

Figure 2 shows an initial representation of a process flow diagram for the process. The top image represents a mineral rich geothermal flow from which energy is removed, then the silica is removed in preparation for the removal of minerals of interest and then lithium. We note that the removal of water as steam should significantly concentrate the remaining minerals relative to the concentration of those in the Salton Sea geothermal brines (Stringfellow and Dobson, 2021), though those concentration enhancements have not been measured for the purposes of this project. The bottom image in Fig. 2 represents a process flow diagram with flow streams. The concentrations in these flow streams are represented in Table 4 for the ideal case (Salton Sea geothermal brine concentrations instead of within plant concentrations, standard temperature and pressure, equilibrium solubilities, and perfect particle removal). The actual concentrations are not likely to be ideal but determining these values is a core aspect of the subsequent steps. Working through the chemistries in Tasks 4-9 determine how many separators will be necessary to achieve project goals.

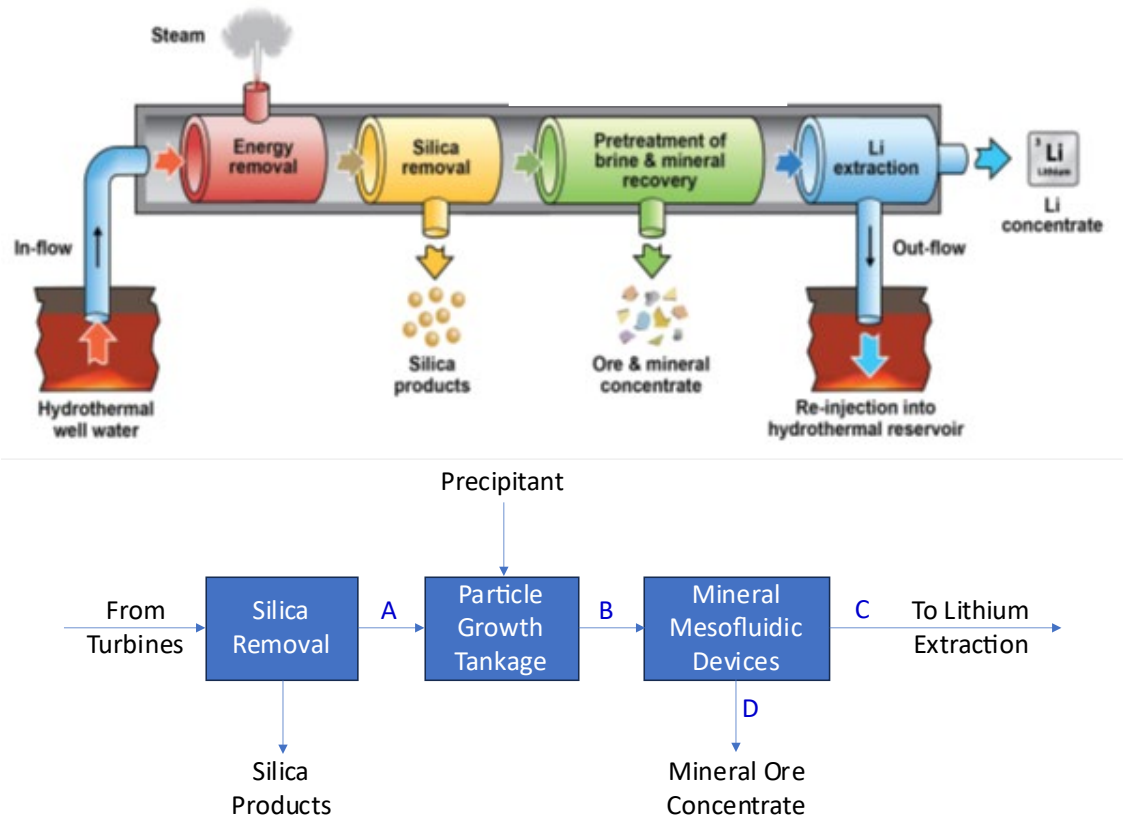

Figure 2. (top) Representation of the sequential separation process as initially envisioned. Removal of valuable and interfering minerals occurs after bulk silica removal and before Li extraction. (bottom) Block representation of process at unit operation level for individual classes of minerals. The sequence could be repeated multiple times for different classes of minerals by adjusting and coordinating the chemistry. The product is a mineral ore concentrate that can be sold directly to minerals refiners.

Table 4. Ideal species concentrations corresponding to locations indicated in Fig. 2.

Species	Stream A	Stream B	Stream C	Stream D
Free Fe	1.35 g/L	0.10 g/L	0.10 g/L	0.10 g/L
Free Mn	1.20 g/L	0.10 g/L	0.10 g/L	0.10 g/L
Free Zn	0.46 g/L	0.10 g/L	0.10 g/L	0.10 g/L
Precipitated Fe	0.00 g/L	1.25 g/L	0.00 g/L	1.25 g/L
Precipitated Mn	0.00 g/L	1.10 g/L	0.00 g/L	1.10 g/L
Precipitated Zn	0.00 g/L	0.36 g/L	0.00 g/L	0.36 g/L
Flow	0.95 L/min	1.00 L/min	0.90 L/min	0.10 L/min
*Concentrations from Stringfellow and Dobson (2021), 0.05 L NaOH/1 L inlet flow (assumes ~2% concentration), assumes perfect particle separation and 90:10 flow split.				

The initial results for iron hydroxide precipitates (in advance of Task 4) suggest that the particle sizes (by volume) span from 10-50 microns up to 300 microns. This result suggests that the preferred devices to separate small particles may be the 40-100 metal mesofluidic separator device or the 45-175 plastic mesofluidic separator device in the flow loops shown in Fig. 3. Alternatively, if a lower particle size cutoff is needed, the mesofluidic settler device in the flow loop

shown in Fig. 4 may be preferred. In both cases, material testing at the Salton Sea Geothermal Field has shown that the materials that these devices are constructed of are preferred to minimize fouling and corrosion in mineral-rich brine. By numbering up these devices (which are stackable), they can accommodate a wide range of flow conditions at industrial scale for easy insertion into plant process. The next step is to evaluate the performance of these devices with one or more precipitates.

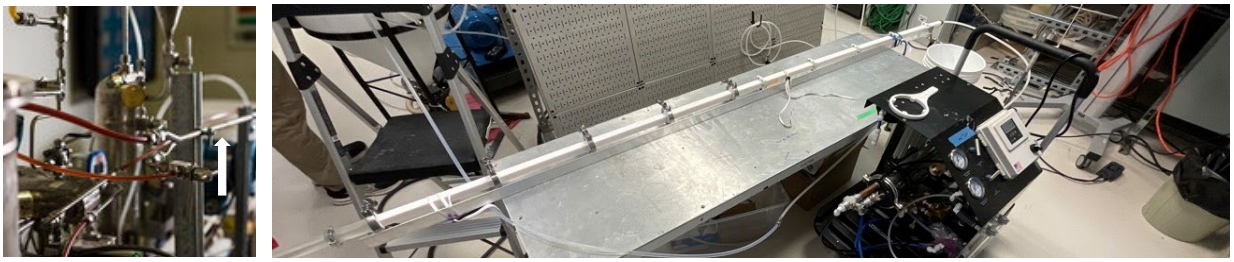

Figure 3. The (left) 40-100 metal mesofluidic separator device and (right) 45-175 white plastic mesofluidic separator device in flow loops.



Figure 4. Mesofluidic settler device within a metal pipe in the loop.

Reference: Stringfellow, W.T., and P. F. Dobson. 2021. “Technology for Lithium Extraction in the Context of Hybrid Geothermal Power.” 46th Workshop on Geothermal Reservoir Engineering, Stanford University.

Select Highlight 2: Initial Particle Separation

The purpose of this project is to design, build, and demonstrate a system for mineral extraction from geothermal brines by selectively precipitating minerals and then removing them with a

mesofluidic separator. The extraction of lithium and other elements is complicated by the presence of coarse minerals including iron, soft minerals including Zn, and hard minerals including Mn. By removing these minerals, lithium can be extracted more readily, and the removed precipitates may be value added.

The first separation was performed using a device from the mesofluidic suite of technologies. A flow loop was used including the mesofluidic separator, rotary lobe pump, and a Malvern Insitec inline particle analyzer with cell pathlength of 1 mm, along with assorted flow meters and pressure sensors (Fig. 5b). A manganese hydroxide precipitate (Fig. 5a) was used for these tests. This precipitate was prepared by adding 3.58 mmol of manganese chloride, 0.005%w/v of a nonionic polyacrylamide (Lubon), and 7.15 mmol of NaOH to a beaker with a brine solution[a] at pH 5.5. After supernatant decanting, approximately 100 g of the concentrated slurry was added to a 1 gallon tank and diluted with synthetic brine.

$$2\ NaOH + 1MnCl_2 \text{ ----> } 2\ NaCl + Mn(OH)_2$$

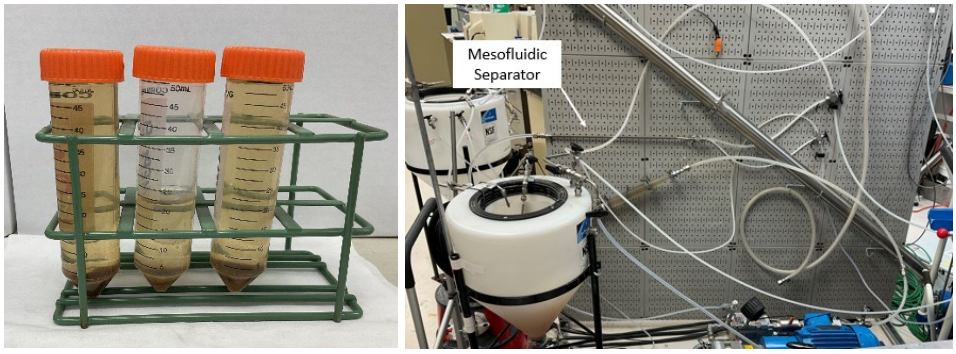

Figure 5. (a) Examples of manganese hydroxide precipitates separated. (b) The flow loop used in testing.

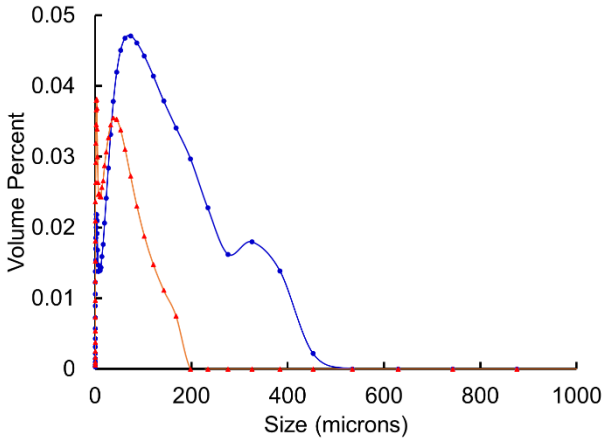

Figure 6. Size distributions of particles separated in a mesofluidic separator exiting either the express lane, which should be enriched in large particles, and the permeate, which should be depleted in the same.

This separation was performed at 0.13 gpm. Figure 6 shows a clear partition of larger particles. The data presented above demonstrate that separation can be achieved with this technology in completion of Milestone 4.1 Selective Precipitate Removal.

[a]Other species in the brine include the following approximate amounts: 65 mg/L of Ba, 32,490 mg/L of Ca, 70 mg/L of Mg, 19,445 mg/L of K, 61,150 mg/L of Na, and 170,304 mg/L of Cl, all in 250 mL at pH 5.5.

Select Highlight 3: Sequenced Separation Processes

The purpose of this project is to design, build, and demonstrate a system for mineral extraction from geothermal brines by selectively precipitating minerals and then removing them with a mesofluidic separator. The extraction of lithium and other elements is complicated by the presence of coarse minerals including iron, soft minerals including Zn, and hard minerals including Mn. By removing these minerals, lithium can be extracted more readily, and the removed precipitates may be value added.

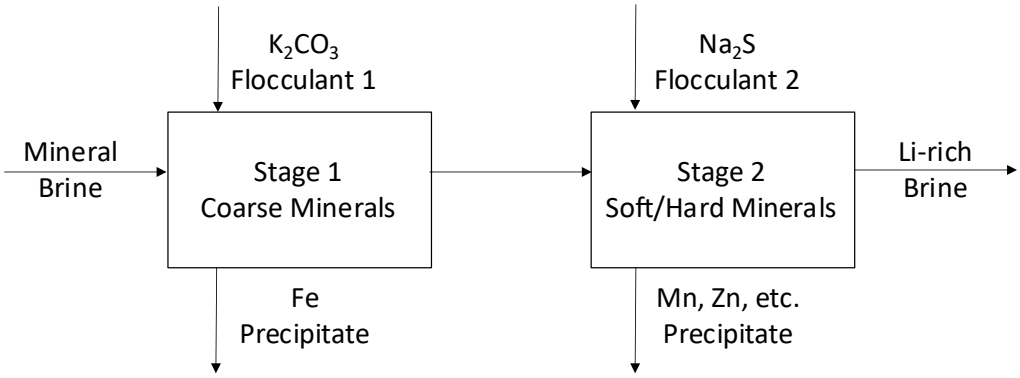

Figure 7. Mesofluidic settler device in the loop.

The schematic above (Fig. 7) depicts a two-stage process that requires two sequential mesofluidic devices. The first stage uses K_2CO_3 to precipitate coarse minerals including iron. The following recipe was used to prepare the precipitates at this first stage. Precipitation with Prepare brine solution with 1700 ppm Fe and 200 ppm Si as follows: Add 4941.6 mg $FeCl_3$ and 427.4 mg activated Si (1-10 micron SiO_2) to 1 L of brine, mix well and then adjust pH to ~5.5±0.1 with NH_4OH/HCl. Add 10.97 mL K_2CO_3 solution (from a stock of 9.90 g in 50 mL DI water) and mix well for ~5 mins or longer. Add 10 mL of 1%w/v of Lubon to make 0.01% Lubon in the solution and mix well ~10 minutes or longer until the particle suspensions appear uniform. Adjust pH to ~6.0-6.3.

$$2\ FeCl_3 + 3\ K_2CO_3 \text{ ----> } Fe_2(CO_3)_3 + 6\ KCl$$

The second stage uses Na_2S to precipitate hard and soft minerals, including Mn and Zn. The following recipe was used to prepare the precipitates at this second stage. Prepare brine solution with 1800 ppm Mn, 610 ppm Zn, 120 ppm Pb, 6 ppm Cu, and 0.6 ppm Ag as follows: Add with

6384.2 mg $MnCl_2$ x $4H_2O$, 1271.6 mg $ZnCl_2$, 161.1 mg $PbCl_2$, 12.7 mg $CuCl_2$ and 0.8 $AgCl_2$ to 1 L of brine, mix well and then adjust pH to ~6.15±0.1 with NH_4OH/HCl. Add 20.37 mL Na_2S solution (from a stock of 10 g in 50 mL DI water) and mix well for ~5 mins or longer. Add 10 mL of 1%w/v of Nalco 9907® to make 0.01% Nalco 9907® in the solution and mix well ~10 minutes or longer until the particle suspensions appear uniform. Adjust pH to ~7-8.

$$MnCl_2 + Na_2S \text{ ----> } MnS + 2\ NaCl$$

This recipe creates precipitate particles that then flocculate into larger precipitate particles. Figure 8 shows that these larger particles settle over time—a key property that allows the mesofluidic settler (Fig. 9) to remove them. The settling time influences device performance. Figure 10 shows that the particles partition and preferentially exit the express lane over the permeate for both the iron carbonate and the manganese sulfide in a single pass. Additional passes will improve the separation.

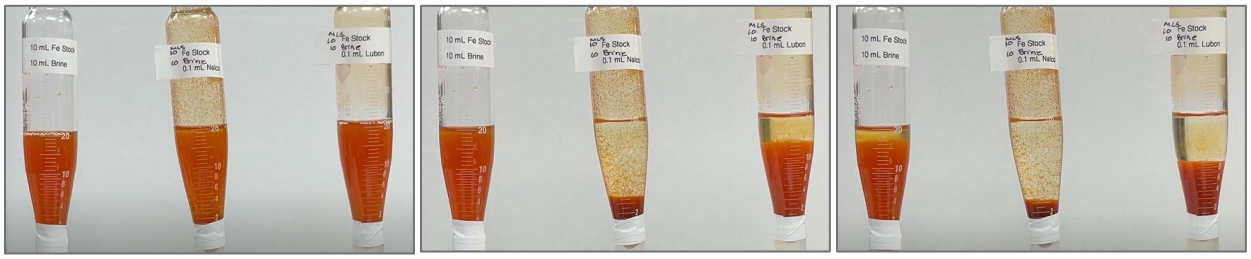

Figure 8. Precipitates immediately after suspending (left), after 90 s (center), and after 180 s (right) highlighting the influence of different flocculants (within image left: none, center: Nalco 9907®, right: Lubon) on iron carbonate precipitates in synthetic brine. The Lubon flocculant yields larger precipitates, while the Nalco 9907® yields smaller sticker precipitates.



Figure 9. Images of the mesofluidic settler and flow loop for testing.

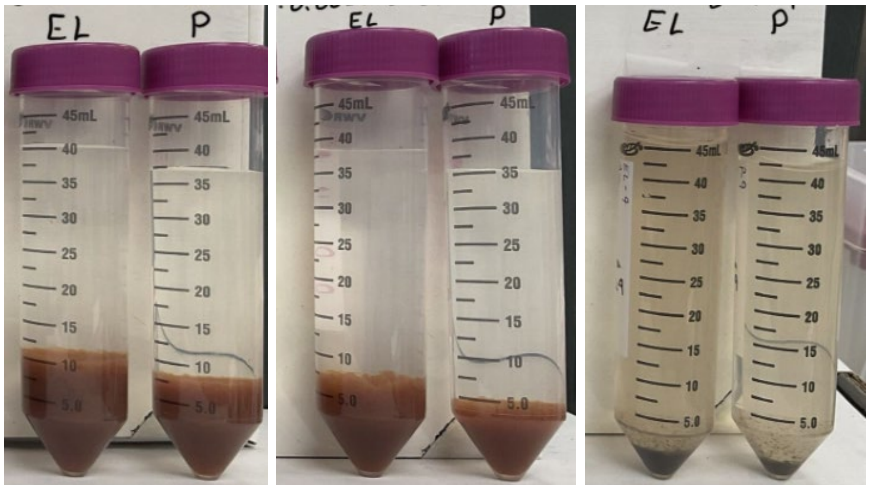

Figure 10. Examples of iron carbonate and manganese sulfide precipitates separated in the Fig. 9 flow loop (0.11-0.12 gpm). (left) Iron carbonate slurry diluted 1:1 with brine and flocculated with 0.0075 wt% Nalco 9907®. (middle) Iron carbonate slurry diluted 1:2 with brine and flocculated with 0.0125 wt% Lubon. (right) Manganese sulfide diluted 1:1 with brine and flocculated with 0.016 wt% Nalco 9907®. Samples collected for 10 s equally.

External research on sequential separation of silica particles using mesofluidic devices has been leveraged. An example of three consecutive mesofluidic devices in series is given in the figure below. These devices were used to separate two sizes of silica particles that had been mixed together in brine, namely a Potters MIL 6 particle 212-200 microns in size and a Potters MIL 13 particle 45-90 microns in size. The figure shows baseline resolution of the two particles achieved using sequential mesofluidic devices.

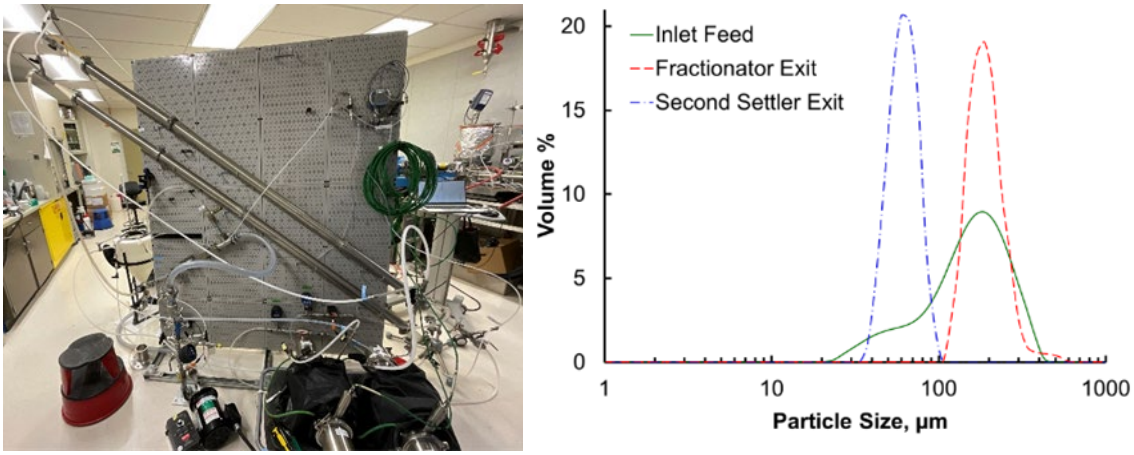

Figure 11. (left) Mesofluidic system assembling sequential mesofluidic devices. (right) Particle size distributions show a good split between two silica product streams from the sequential mesofluidic devices. (From Shelby, Tyler, Raymond S. Addleman, Debra Barnett, Carolyn Burns, Chad Haugen, Dan Palo, Leonard Pease. 2025. Improved Silica Removal for Enhanced Geothermal Plant Performance. California Energy Commission. Publication Number: CEC-500-2026-002.)

Select Highlight 4: Improved Separation

The purpose of this project is to design, build, and demonstrate a system for mineral extraction from geothermal brines by selectively precipitating minerals and then removing them with a mesofluidic separator. The extraction of lithium and other elements is complicated by the presence of coarse minerals including iron, soft minerals including Zn, and hard minerals including Mn. By removing these minerals, lithium can be extracted more readily, and the removed precipitates may be value added. Work above demonstrated that coupling precipitates with particle separation can remove significant amounts of undesirable minerals, but further optimization is necessary. The work of Task 6 included using slurry samples from the Salton Sea Geothermal Field that have been provided by Hell's Kitchen Geothermal (HKG), refining process chemistry, etc. This highlight describes further advances in process chemistry.

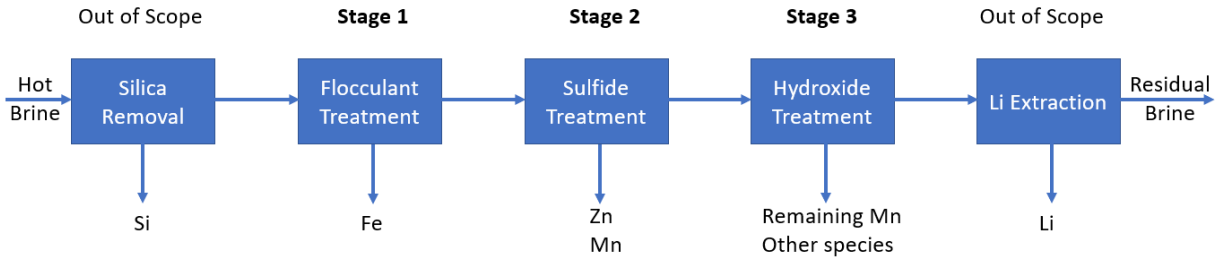

Figure 12. Proposed unit operation level representation of the sequential separation process to remove minerals that interfere with lithium extraction as a value-added product.

Table 5 shows the concentrations of Fe, Mn, and Zn at each of the three proposed stages (see Fig. 12). The first stage is designed to remove Fe with minimal removal of other minerals. The second stage is designed to recover multiple mineral sulfides. The third stage is designed to recover remaining Mn with a base.

Table 5. Total cumulative percent removal of common interfering metals with downstream Li processing.

Stage	Additive	Brine pH	Fe	Mn	Zn
1	Flocculant	~4.5-5.5	100%	5-6%	6% - 8%
2	Sulfide	~6.2-6.4	Removed in Stage 1	12%-17%	99-100%
3	Hydroxide	~9.5-10	Removed in Stage 1	94%-98%	Removed in Stage 2

As seen in the Table 5, the three-stage process achieves ≥99% removal of two target species, Fe and Zn. Stage 1 eliminates nearly all Fe and slightly removes Mn and Zn. Stage 2 increases Zn removal to ~99%, while Stage 3 raises Mn removal to 98%.

These results demonstrate that the proposed three-stage process does indeed remove interfering minerals, which is key to providing better Li feed streams through mineral reduction. This analysis satisfies Milestone 6.1 "Demonstrate Improved Performance of Mesofluidic Devices: Improved performance toward target minerals/mineral classes (e.g., Fe, Mn, Zn)" by quantifying these species in Salton Sea geothermal process brines and evaluating potential for their removal using

chemistry and system of Tasks 4 and 6. The implications of these findings will be evaluated in the TEA (see Milestone 10.1).

Select Highlight 5: Improved Removal of Interfering Minerals

The purpose of this project is to design, build, and demonstrate a system for mineral extraction from geothermal brines by selectively precipitating minerals and then removing them with a mesofluidic separator. The extraction of lithium and other elements is complicated by the presence of coarse minerals including iron, soft minerals including Zn, and hard minerals including Mn. By removing these minerals, lithium can be extracted more readily, and the removed precipitates may be value added. Although removing coarse minerals, including iron, soft minerals, including Zn, and hard minerals, including Mn, facilitates lithium extraction, other species not previously evaluated as part of this effort can be interfering. These include Ag, Cu, and Pb inter alia. However, prior tasks in this project have not quantified the removal of these species. This gap is addressed below.

Table 6 presents the concentrations of Ag, Cu, and Pb at each of the three proposed stages, as outlined in Task 6. The first stage is specifically designed to facilitate the removal of Fe while minimizing the extraction of other minerals. The second stage is optimized for the recovery of multiple mineral sulfides, whereas the third stage focuses on Mn recovery in the presence of a base.

Table 6. Total cumulative percent removal of common interfering metals with downstream Li processing.

Stage	Additive	Brine pH	Ag	Cu	Pb
1	Flocculant	~4.5-5.5	0%	46% - 56%	8% - 30%
2	Sulfide	~6.2-6.4	86%-92%	98% - 100%	98-100%
3	Hydroxide	~9.5-10	100%	Removed in Stage 2	Removed in Stage 2

As seen in the Table 6, the three-stage process removes at least ~98% of these three interfering species. The first stage removes approximately half of the Cu and some of the Pb. The second stage brings removal rates to at least 90%, and the third stage brings removal to at least 99%. The concentration of the interfering metals before and after the removal process stages are shown in Table 7. This level of removal is notable, considering the process was optimized with Fe, Mn and Zn in mind.

Table 7. Concentration of common interfering metals in the pre- and post-removal process stages.

Metal	Pre-process concentration (ppm)	Post-process concentration (ppm)
Fe	~1350	0
Mn	~1410	~28
Zn	~450	~0.6
Pb	~87	0
Cu	~7.2	0
Ag	~1.6	0

These results demonstrate that the proposed three-stage process does indeed remove interfering minerals, which is key to providing better Li feed streams through mineral reduction. This analysis satisfies Milestone 7.1 “Demonstrate better Li feed streams through reduction of minerals” by quantify other potentially interfering species in Salton Sea geothermal process brines and evaluate potential for their removal using chemistry and system of Tasks 4 and 6. The implications of these findings will be evaluated in the TEA (see Milestone 10.1).

Select Highlight 6: Scaling Prevention

The purpose of this project is to design, build, and demonstrate a system for mineral extraction from geothermal brines by selectively precipitating minerals and then removing them with a mesofluidic separator. The extraction of lithium and other elements is complicated by the presence of coarse minerals including iron, soft minerals including Zn, and hard minerals including Mn. By removing these minerals, lithium can be extracted more readily, and the removed precipitates may be value added.

A key challenge in designing systems for operation in brines that have been processed through geothermal plants is scaling or adhesion of precipitates onto surfaces. To successfully leverage precipitation to selectively remove minerals as described above, these precipitates must not adhere to surface of mesofluidic devices or conduits as that could lead to blockages. Existing geothermal plants use stainless steel, for example, to reduce precipitation, but this is decidedly expensive. Alternative materials would be advantageous where available.

To evaluate the potential for precipitation, samples of several materials were selected. They were loaded into holders that were arranged serially inside of a conduit as shown below. The total conduit length was approximately 4 feet long, housing several samples. At the Salton Sea Geothermal Field, hot brines (~69°C) were then introduced into the conduits from a slip stream for approximately 8 hours. The brines partially submerged each of the samples. After the test, the conduit tube ends were bolted and returned to PNNL for analysis. The figure below highlights and compares the adhesion onto several candidate surfaces.

Because the inline samples were partially submerged, comparing the bottom (submerged) to the top provides a sense of the extent of precipitation. The carbon steel adsorbed many precipitates even with limited exposure. The 316 stainless steel did better. Remarkably, the Rigid 10k and the PTFE perform better at preventing scaling with very limited adhesion. Indeed, the Rigid 10K is the primary polymer used to form the devices in this effort.

These results demonstrate that the materials section plays a key role in both preventing precipitation on surface walls and subsequent rinsing/cleaning during operations under conditions that commensurate with the types and thermal conditions in actual pilot plant operations. By selecting materials such as Rigid 10K to generate devices, operational lifetimes can be extended. This analysis satisfies Milestone 8.1 “Complete evaluation of operational lifetime for brines: The potential impact of materials on operational lifetimes of the devices and cleaning methods during plant operations.” These results are operationally important because (a) precipitation into

particles instead of precipitation onto pipe and separator walls leads to better economics, and (b) arterial deposition can lead to complete occlusion of piping, shutting down plants that process geothermal brines for energy and materials extraction.

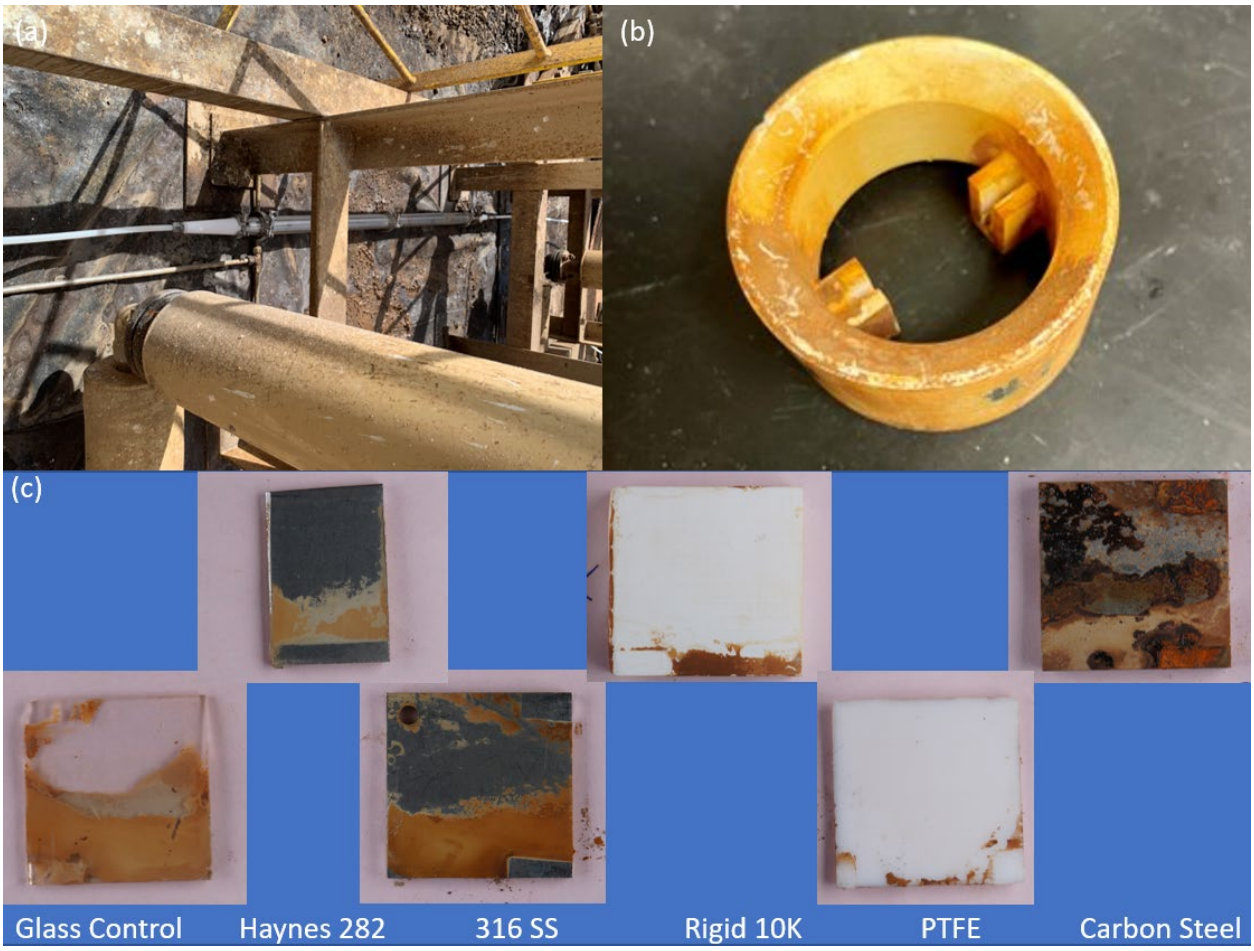

Figure 13. (a) Testing configuration attached to a geothermal well. (b) Coupon holder after coating with surface precipitation. (c) Test pieces after ~8 hrs in ~68-69ºC geothermal brine. Due to continual air entrainment, the test configuration containing the sample coupons was only half-filled throughout testing.

Select Highlight 7: System Engineering Design

The purpose of this project is to design, build, and demonstrate a system for mineral extraction from geothermal brines by selectively precipitating minerals and then removing them with a mesofluidic separator. The extraction of lithium and other elements is complicated by the presence of coarse minerals including iron, soft minerals including Zn, and hard minerals including Mn. By removing these minerals, lithium can be extracted more readily, and the removed precipitates may be value added.

PNNL and Barr Engineering collaborated to develop the process and engineering design for mineral recovery from Salton Sea Geothermal Field brines. The proposed full-scale design of the system utilizing Geothermal Mesofluidic Enhanced Particle Separator (GMEPS) technology for separation and concentration of target minerals was designed to be integrated into existing geothermal plant operations that utilize an upstream, out-of-scope silica removal process, and optionally additional downstream mineral extraction and lithium extraction processes that are also out of the scope of this design. A process flow diagram of the full-scale mineral recovery system is provided as Fig. 14.

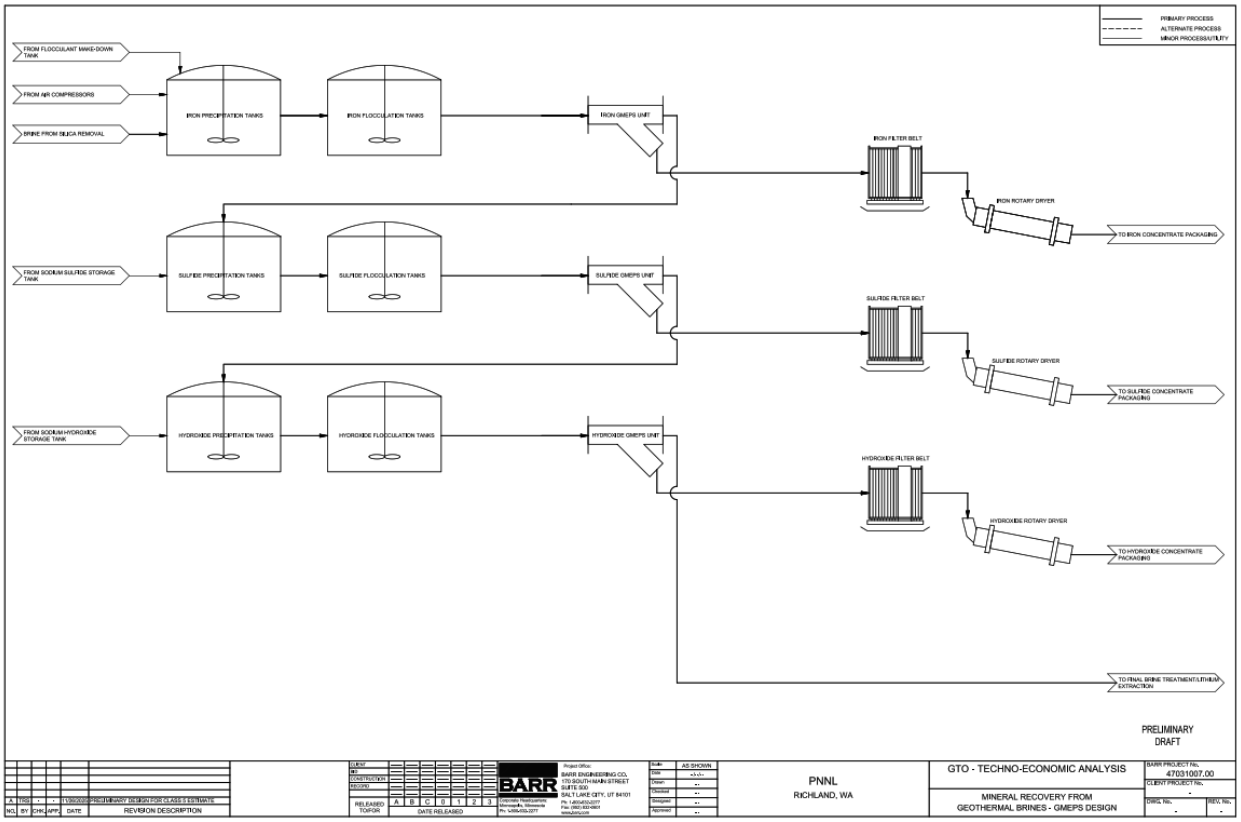

Figure 14. Proposed process flow diagram.

The full-scale system design assumes that the inlet geothermal brine has undergone a silica removal process that removed all silica from the brine. The brine will pass through three circuits of precipitation reactions and flocculation: precipitations via aeration to precipitate all iron from the brine as iron (III) hydroxide, precipitation using sodium sulfide to remove the bulk of the target minerals as sulfides, and precipitation using sodium hydroxide to remove most of the remaining manganese hydroxide. Each circuit will contain a series of reaction and flocculation tanks that are sized for 1-hour residence times, a GMEPS device series (or unit) to separate concentrated precipitate from the brine, a belt filter to dewater the mineral concentrate into a cake, and a rotary dryer to further dry the concentrate to prepare it for packaging. The full-scale system design also includes additional ancillary systems, such as reagent storage and handling to supply sodium sulfide and sodium hydroxide to the precipitation circuits, a flocculant make-down tank for mixing

and supplying flocculant to the precipitation circuits, air compressors, dust collectors, vent scrubbers, and packaging equipment.

The process flow for each circuit will start with brine and the precipitation reagent added to the mixing tanks, then proceed to flocculating tanks to suspend the precipitate. The brine and precipitate will pass through the GMEPS unit, where concentrate will be removed from the brine and sent to the belt filter, and the brine will exit the GMEPS unit as permeate and enter the next circuit. The concentrate will then be dewatered by a belt filter and dried by a rotary dryer before being packaged for sale. The brine leaving the final GMEPS unit will either be sent to downstream non-precipitation mineral extraction or lithium extraction processes, or prepared for reinjection into the wellfield, all of which are out of the scope of this design.

This analysis addresses key aspects of Milestone 9.1 “Issue preliminary report on system engineering design: Reporting on system engineering design to achieve metrics in SOPO Table 1.” The SOPO Table results are to be found at the end of this document.

Select Highlight 8: Technoeconomic Analysis

The purpose of this project is to design, build, and demonstrate a system for mineral extraction from geothermal brines by selectively precipitating minerals and then removing them with a mesofluidic separator. The extraction of lithium and other elements is complicated by the presence of coarse minerals including iron, soft minerals including Zn, and hard minerals including Mn. By removing these minerals, lithium can be extracted more readily, and the removed precipitates may be value added.

Barr Engineering Co. (Barr) developed a techno-economic analysis (TEA) on the full-scale industrial design of the mineral recovery process described in Task 9 to evaluate the potential revenue of the recovered minerals and to determine if the scaled-up process is economically viable. The goal of recovering the target minerals, including manganese, zinc, silver, and more, is to create new revenue streams for geothermal power plants in the Salton Sea Geothermal Field (SSGF) while simultaneously pretreating brine for downstream direct lithium extraction (DLE) processes. The TEA evaluates the revenue of the recovered minerals based on bench testing results for the proposed recovery process and literature values for SSGF brine mineral concentrations. The TEA also evaluates the full-scale designs using either Geothermal Mesofluidic Enhanced Particle Separator (GMEPS) technology for separating and concentrating precipitated minerals from the brine or using traditional clarifiers and thickeners to compare the economic viability of using GMEPS to existing technologies.

The evaluation of the mineral recovery process developed and tested by PNNL found that the annual revenue of these minerals is nearly $120 million. For this TEA, minerals were priced as metals or their most commonly traded commodity due to uncertainty in pricing out the concentrates. Refining and shipping cost assumptions were applied to account for the evaluation of the refined minerals instead of the mineral concentrates, and it was assumed that all minerals recovered from the brine can be separated and refined into their respective metals or commodities

and sold regardless of external market forces. The bulk of the revenue comes from manganese, zinc, and silver. Rare earth elements, uranium and other critical or strategic elements are present in the brine in small quantities and do not provide a significant source of revenue but may be a potential limited domestic source. The TEA model assumed wellfield mineral concentrations and recoveries are constant, however it is understood that the brine chemistry can be variable and recoveries and, thus, revenue could be lower due to this variability.

Using the full-scale design developed for Task 9 as a basis, Barr developed a Class 5 cost estimate for the capital expenses (CAPEX) and an estimate for operating expenses (OPEX) required to install and operate the mineral recovery process in an existing geothermal power plant located in the SSGF. The scope of the capital and operating costs was strictly the mineral recovery process and did not include any upstream or downstream processes in the costs. The estimates also assumed a silica removal process would be present upstream to pretreat the brine upstream into mineral recovery. The total CAPEX for a process using GMEPS was estimated to be $54.1 million, and for a process using clarifiers and thickeners to be $124.4 million. The cost difference is primarily derived from the difference in GMEPS and clarifier unit costs. Estimated OPEX costs, including reagents, equipment operation and maintenance, and the assumed refining and shipping costs totaled $56.2 million for the GMEPS design, and $70.9 million for the clarifier design, with the difference again coming from the decreased costs of operating and maintaining GMEPS units versus clarifiers.

Using the revenue, total CAPEX, and total OPEX, it was found the GMEPS design has a return on investment (ROI) of 78% and a net present value (NPV) of $282.5 million, and the clarifier design has an ROI of 21% and an NPV of $117.8 million. These results show that mineral recovery from SSGF brines is economically viable, and far more economically favorable to install and operate the process using GMEPS compared to using clarifiers and thickeners. Further developing GMEPS technology for geothermal applications would provide a greater chance of this process being economically viable. It is worth noting that various assumptions applied to the TEA model would need to be verified in future efforts, including pilot-scale testing of the mineral recovery process, investigating refining of the mineral concentrates, performing market analyses on the mineral products and raw materials needed for the process, and investigating other mineral extraction opportunities for out-of-scope salts and metals in the brine.

This analysis addresses key aspects of Milestone 10.1 “Issue final TEA report: Final evaluation of TEA metrics relevant to SOPO Table 1.” The SOPO Table results are to be found at the end of this document.

Select Highlight 9: Future Field Demonstration Design

The purpose of this project is to design, build, and demonstrate a system for mineral extraction from geothermal brines by selectively precipitating minerals and then removing them with a mesofluidic separator. The extraction of lithium and other elements is complicated by the presence of coarse minerals including iron, soft minerals including Zn, and hard minerals including

Mn. By removing these minerals, lithium can be extracted more readily, and the removed precipitates may be value added.

The techno-economic analysis (TEA) performed on the full-scale process design for the proposed mineral recovery process found that the process is economically viable if Geothermal Mesofluidic Enhanced Particle Separator (GMEPS) devices were used in place of clarifiers and thickeners for recovering and concentrating solids precipitated from Salton Sea geothermal brine. The mineral recovery rates used for the bulk of the minerals were determined from bench testing with a brine simulant, and various TEA assumptions require validation, so additional testing at pilot-scale using real geothermal brines will be needed to verify the process is both effective and scalable.

Pilot-scale testing of the mineral recovery process would focus primarily on verifying the process chemistry, including the precipitation reactions, precipitate flocculation, and precipitation residence times, and determining the efficacy of GMEPS devices in separating and concentrating the precipitate. A 10 gallons per minute (gpm) brine flow rate is recommended for reasonably sizing the tanks and GMEPS devices, noting that the full-scale design assumes a 10,000 gpm brine flow rate. The process flow diagram (PFD) of the full-scale process using GMEPS included as Fig. 14 applies to the pilot-scale process, excluding the belt filter and dryer as they are not necessary for validating process chemistry or GMEPS device efficacy. The equipment and systems required for pilot-scale testing include:

- Flocculant makedown and dosing system
- Air compressor for first precipitation stage
- Mixing and dosing systems for sodium sulfide and sodium hydroxide precipitating reagents
- Mixing tanks with agitators for precipitations and flocculation; two per stage for six total, estimated 600-gallon size for one hour residence time at 10 gpm
- GMEPS devices for the three precipitation stages, generally arranged as trains in parallel
- Ancillary pumps and instrumentation

Given the size and amount of equipment and number of stages, it is unlikely that this pilot system would be able to fit on a portable skid and would need to be constructed as a small pilot plant within a geothermal power plant at the Salton Sea Geothermal Field. The TEA currently assumes that silica in the brine was removed prior to the first stage of precipitation, so when testing with geothermal brines an additional pretreatment step would likely be required, potentially using additional GMEPS devices. Silica removal using GMEPS was explored in a prior effort.

The following tests can be run in varying stages and built out further by starting with a simulant at the first precipitation and moving forward with the additional process steps after dialing in the previous step. When using real geothermal brine, the composition of the brine needs to be evaluated prior to testing to understand how the process may be impacted and adjusted accordingly. Testing can be conducted for the following:

- Reagents: compare recovery rates at higher scale to bench testing results using the same chemistry for simulant and test if chemistry is effective with real geothermal brines. Can also test different residence times by adjusting flow.
- Flocculant: test the bench scale concentration to see how well it scales for simulant and test how the flocculant performs in real geothermal brine. Can also test different residence times by adjusting flow.
- GMEPS: test for particle separation by comparing particle size distributions of solids in permeate and concentrate leaving the device trains. Can also arrange devices of different particle size targets to try and create more purified concentrate streams depending on if there is a significant difference in sulfide and hydroxide particle sizes.

Future work that can be performed beyond the scope of this mineral recovery process to validate the TEA assumptions and further explore uses for GMEPS technology include the following:

- Investigate the refining of mineral concentrates recovered from geothermal brine and verify if the mineral concentrates are easily separable and economically viable to refine.
- Perform a market analysis on recovered minerals to determine if they can be sold and used domestically given existing market forces.
- Perform a raw material availability study to determine if required reagents are available to be used in the Salton Sea Geothermal Field. If necessary, determine economic viability of producing sodium sulfide and/or sodium hydroxide on site.
- Investigate additional mineral recovery for other metals and salts in the brine to determine if extracting those additional minerals are economically viable, and for further developing pretreatment processes for improved lithium extraction.
- Explore additional applications for GMEPS technology, such as wastewater treatment, mine tailings handling, hydrometallurgy, and mineral recovery from solutions produced from hydrocarbon extraction.

This analysis addresses key aspects of Milestone 11.1 “Issue final report on laboratory results and engineering studies: Summarize laboratory results and engineering studies performed as part of this project.”

Appendix A

Task 2 and Report on Seminar Outcomes

After January 2025, Task 2 was removed from scope with its corresponding milestones. This appendix presents the accomplishments that satisfy the milestones that were accomplished prior to January 2025.

Task 2 – Diversity, Equity, Inclusion, and Accessibility (DEIA): The team involved in this project is committed to including and creating opportunities to include all. To this end, the team has developed a number of activities that occur throughout the duration of the project to enhance the interaction with students from underrepresented backgrounds, particularly in the local community. These accomplishments are described below.

Milestone 2.1 – Initiate outreach and Hold all Hands meeting on DEIA: Meeting held for key staff on DEIA issues in local disadvantaged communities with invited speaker from local community impacted by the project.

In Q2 of FY24, PNNL held a "hold all hands" meeting with project partners to emphasize DEIA as called for in this project. Specifically, Milestone 2.1 called for a meeting to be held for key staff around DEIA opportunities in disadvantaged communities with an invited speaker from a local community to be impacted by the project. Please see the agenda below. The meeting was successful by all accounts, particularly the contributions from both Lauren Rose and Priscilla Lopez, who are from the local community in Imperial County, CA, around the HKG facility, satisfying the milestone. An important aspect of this milestone is that it assisted in developing relationships that will support the STEM (science, technology, engineering, and mathematics) workshop(s) of the project (see Milestone 2.3).

HOLD ALL HANDS MEETING AGENDA

MEETING GOALS

- Enhance DEIA, improve scientific progress, and advance diversity of the field.
- Initiate outreach (M2.1).
- Secure student for internship at PNNL (M2.2).
- Start planning STEM workshop (M2.3).

MEETING INVITEES

- All key staff working on the project in the spirit of an "all hands" meeting.
- Priscilla Lopez, Director of Imperial County Workforce and Economic Development.
- Alexandra Prisjatschew, DOE.
- Additional interested staff.

1:10 PM WELCOME **Leonard Pease, PNNL**

- Meeting objectives, review agenda
- Context setting
  - Project Overview
  - Acknowledge differences and perspectives - this is an initial session to discuss issues, ideas, and concerns in a safe environment.

1:13 PM INTRODUCTIONS All: 1-2 Minutes Each

- Name / Organization(s)
- Current understanding of your role for the project
- Personal hopes for this project / questions you'd like answered

1:20 PM DEIA ENGAGEMENT Will Osborn/Lauren Rose, HKG

- Review of HKG community outreach and future planning
- Community representative speaking about impacts of geothermal energy and DEIA issues to/for their community: Priscilla Lopez, Director of Imperial County Workforce and Economic Development

1:50 PM PLANNING COLLEGE-LEVEL INTERSHIP AND STEM WORKSHOP

Leonard Pease, PNNL

- Student recruiting (HKG and Barr engagement, early engagement with educators, PNNL's Office of STEM Education) and opportunities local to HKG accounting for DEIA
- STEM Workshop options for consideration
  - Career pathways seminar
  - Student participation component: "mini projects", data analysis from the project, student presentations
  - Connecting the project to the community (https://www.youtube.com/watch?v=QPyHQqolN7Y)
  - Coordination with a local college to engage, inform, and educate students on our project's goals, objectives, and internship opportunities with the project team.

2:00 PM ADJOURN Leonard Pease, PNNL

Milestone 2.2 – Secure Student for PNNL internship: Identify a promising student.

The project team is a strong supporter of STEM, with multiple interns (ranging from high schoolers to post-docs) working under its direction at any given time. For this project specifically, a STEM intern (a non-white male) was identified and has been supporting the experimental work of Milestones 4.1-4.3. He is an undergraduate and intends to go to graduate school at least partially based on the positive experiences he has had by working on this project. The team is further

working to identify other students who can also participate. This selection process involved reaching out to multiple institutions supporting students with diverse backgrounds. These included the local area near Imperial County, CA, an economically disadvantaged area where Hell's Kitchen Geothermal is located.

Milestone 2.3 – Hold STEM workshop with partners: Hold at least one community-based workshop with educational institutions.

In FY24, project partner CTR held workshops to allow students (and educators) an opportunity to learn more about the project. The workshop was in-person, included project team members, and had a student participation component. Please see the Report on Seminar Outcomes below.

CTR

Deliverable/Milestone 2.3: STEM Workshop with Partners

San Diego State University STEM Day Event – May 31, 2024

On May 31, 2024, San Diego State University led a community-based STEM workshop at the Calexico campus, in collaboration with local high schools and the Controlled Thermal Resources team. This event was designed to provide students and educators with a hands-on introduction to the project's scientific and technical components, as well as to promote awareness of career pathways in STEM fields related to geothermal energy and lithium extraction.

The workshop featured four distinct activity stations, each led by Laboratory, Engineering, and Geology professionals.



Figure 1. Students learn about density and use laboratory filtering techniques.



Figure 2. Students learn about minerals found in rocks and brine and test for hardness and other physical properties.

These stations allowed students to engage directly with experiments and demonstrations that illustrated key concepts in geothermal energy, mineral extraction, and their real-world applications. Additionally, a dedicated station focused on the Hell's Kitchen project, connecting the hands-on activities to the broader context of sustainable energy development in the region.

A unique aspect of this event was its focus on serving students from Imperial County schools, which are predominantly located in underrepresented communities. The majority of participants were of diverse backgrounds including females, first-generation students, Spanish

speakers or Latino, reflecting the project's commitment to diversity, equity, and inclusion. Students were encouraged to ask questions, participate in experiments, and discuss their interests with project team members, fostering both engagement and a sense of belonging in STEM fields.

Imperial County STEM Festival – November 7, 2024



Figure 3. Discussing the Salton Sea fault lines and geothermal activity in the Salton Sea region.

In a separate but related effort, Controlled Thermal Resources participated in the Imperial County STEAM Festival, held in collaboration with the Imperial County Office of Education at the Imperial Valley Fairgrounds on November 7, 2024. This event targeted middle school students in grades 6th-8th grade providing them with an early introduction to STEM concepts and careers.

As with the SDSU event, the Laboratory, Engineering, and Geology teams each hosted interactive stations, offering hands-on activities that demonstrated the relevance of STEM to everyday life and potential future careers. The festival format encouraged students to explore, ask questions, and interact with professionals from diverse backgrounds while providing hands-on activities, exposure to tools, equipment and techniques used in the field.
The STEAM Festival also emphasized community engagement, a critical component for establishing STEM's relevance and meaning for youth, especially in underserved areas. By involving a wide range of professionals and providing opportunities for direct student participation, the event supported the development of curiosity and opportunities in science among young attendees.



Figure 4. Students learn about the rock formations, laboratory equipment and practice measuring techniques using glassware and pipettes.

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