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FINAL PROJECT REPORT

Improved Silica Removal for Enhanced Geothermal Plant Performance

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PREFACE

The California Energy Commission's (CEC) Energy Research and Development Division supports energy research and development programs to spur innovation in energy efficiency, renewable energy and advanced clean generation, energy-related environmental protection, energy transmission, and distribution and transportation.

In 2012, the Electric Program Investment Charge (EPIC) was established by the California Public Utilities Commission to fund public investments in research to create and advance new energy solutions, foster regional innovation, and bring ideas from the lab to the marketplace. The EPIC Program is funded by California utility customers under the auspices of the California Public Utilities Commission. The CEC and the state's three largest investor-owned utilities—Pacific Gas and Electric Company, San Diego Gas and Electric Company, and Southern California Edison Company—were selected to administer the EPIC funds and advance novel technologies, tools, and strategies that provide benefits to their electric ratepayers.

The CEC is committed to ensuring public participation in its research and development programs that promote greater reliability, lower costs, and increase safety for the California electric ratepayer and include:

- Providing societal benefits.
- Reducing greenhouse gas emission in the electricity sector at the lowest possible cost.
- Supporting California's loading order to meet energy needs first with energy efficiency and demand response, next with renewable energy (distributed generation and utility scale), and finally with clean, conventional electricity supply.
- Supporting low-emission vehicles and transportation.
- Providing economic development.
- Using ratepayer funds efficiently.

Improved Silica Removal for Enhanced Geothermal Plant Performance is the final report for EPC-19-029 conducted by Barr Engineering Co., Pacific Northwest National Laboratory, and TradeWind Services LLC. The information from this project contributes to the Energy Research and Development Division's EPIC Program.

For more information about the Energy Research and Development Division, please visit the CEC's research website (www.energy.ca.gov/research/) or contact the Energy Research and Development Division at ERDD@energy.ca.gov.

ABSTRACT

The purpose of this project was to develop and demonstrate the capability of geothermal mesofluidic enhanced particle separator (GMEPS) technology for removing silica precipitate in geothermal plants in the Salton Sea Geothermal Field. Silica management in geothermal plants is a costly process that limits the flexibility of geothermal plant operations. GMEPS technology would reduce the costs of operating geothermal plants and provide more flexibility than conventional silica management technologies to use geothermal power in areas with load-following grid operation. A project team consisting of Hell's Kitchen Geothermal (a subsidiary of Controlled Thermal Resources), Pacific Northwest National Laboratory, and Barr Engineering collaborated to demonstrate GMEPS technology as an effective and less costly method of silica removal in geothermal plants. Project goals included demonstrating silica removal from flowing geothermal brine at laboratory and pilot scales, gathering scaling factors to assist in design of larger scale demonstration or commercial plants, and developing a techno-economic analysis to show economic and operational advantages of using GMEPS over traditional silica removal technologies. Laboratory and pilot scale testing results have shown that GMEPS devices effectively remove silica from geothermal brine, can run at a maximum flow rate 10.6 times greater than the device's minimum flow rate (10.6x dynamic range), can separate and concentrate silica particles by size, can operate at brine flow rates of 10 gallons per minute, can operate uninterrupted for 30 hours, and have been estimated to be less costly to install and operate compared to traditional silica removal methods.

Keywords: Geothermal, silica removal, solids concentration, precipitation, mesofluidic separation

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Background

Geothermal energy is a renewable energy source drawn from hot well water called geothermal brine (due to the presence of high concentrations of dissolved minerals). As heat is removed from the brine, the dissolved minerals precipitate as solid particles, causing corrosion and fouling inside pipes and equipment used for geothermal plant operations. A major component of these precipitated minerals is silica. Removing silica from the brine is a key part of ensuring geothermal plants run efficiently, as built-up silica can lead to an increase in maintenance costs for cleaning the silica out of equipment, or an increase in capital costs for replacing corroded equipment and piping. Existing silica removal methods require expensive equipment and additional chemical additives and prevent geothermal plants from being able to operate with more flexibility, limiting the use of geothermal power.

Pacific Northwest National Laboratory has developed a new cost-effective and flexible method for removing silica from geothermal brines called geothermal mesofluidic enhanced particle separator technology, also known as GMEPS. This new technology removes silica from brine by using pillars and settling channels inside a device to drive larger-sized particles toward an outlet that concentrates silica particles for removal. Particles are separated by these devices by size, so specific minerals can be targeted to potentially produce value-added mineral products, such as lithium. Compared to traditional methods, GMEPS devices can operate more flexibly at a wider range of flow rates, can be manufactured inexpensively using 3D printing, and do not require additional costly chemical additives to manage silica in geothermal plants.

Implementing GMEPS technology for silica removal in geothermal plants would provide the following benefits:

- More flexible geothermal plant operations, expanding and improving renewable energy opportunities in California and allowing geothermal power to be used in tandem with solar and wind power for load-following grid operations
- Reduced costs to build and operate geothermal plants for utility companies by reducing the labor, materials, and required footprint for silica removal, which would reduce geothermal energy costs for ratepayers
- Reduction of carbon dioxide emissions by using more geothermal power as a renewable energy source
- Facilitation of the production of value-added minerals recovered from geothermal brine, including critical minerals such as lithium

Project Purpose and Approach

The purpose of this project was to develop and demonstrate GMEPS technology as an effective method for removing silica from geothermal brine in geothermal plants in the Salton Sea

Geothermal Field in Southern California. These geothermal brines are rich with other minerals such as lithium, and other critical minerals from which the silica must be separated.

The project team for this effort included:

- Hell's Kitchen Geothermal (a subsidiary of Controlled Thermal Resources), grant prime for the project. Controlled Thermal Resources is a geothermal power company and owner of the Hell's Kitchen Geothermal pilot plant in Salton Sea, California
- Pacific Northwest National Laboratory, the developer of GMEPS technology
- Barr Engineering, an engineering firm providing process design and economics expertise to the project

The project team's goals for demonstrating GMEPS technology for this application were to:

- Demonstrate silica removal from flowing geothermal brine at laboratory and pilot scales
- Gather scaling factors to assist in design of larger scale demonstrations or commercial plants
- Provide a techno-economic analysis for commercial scale operations and quantify GMEPS technology's potential benefits of reducing geothermal energy costs, enabling more flexible geothermal power generation, and facilitating improved minerals extraction from geothermal brines

The project team developed and tested various GMEPS device designs in the laboratory and in the field throughout the course of this project. The team gathered data related to particle separation, particle sizes recovered from the brine, and flow rate information to show GMEPS technology can handle dynamic ranges of brine flows.

Key Results

Lab Scale Testing Results

During laboratory scale trials, the team tested the impacts of flow rate on GMEPS device performance, particle separation from brine, separation of silica and iron particles from brine, particle separation by size, and operational flexibility by varying the brine flow rates with a dynamic range of 10 times. The team also tested the impact of operating devices in parallel or in series on total system performance. In all tests, the team demonstrated effective particle separation from synthetic geothermal brine.

The team found that increasing flow rate through a GMEPS device increases the pressure drop quadratically across the device, and increasing the flow rate decreases the volumetric fraction of solid particles recovered from the brine. The team demonstrated separation of silica particles from an iron-rich brine; however, the iron particles remained suspended in solution and remained in the brine passing through both device outlets, so further investigation into further separating the iron out of the solution is recommended. The team also demonstrated the separation of particles based on size using particles of 310 microns, 212–300 microns, and 45–90 microns in diameter. The team tested particle separation at varying flow rates ranging from 0.34 gallons per minute to 3.60 gallons per minute, or a dynamic range of 10.6 times, and demonstrated particle separation and thus operational flexibility of GMEPS technology. During these tests, configurations of devices in parallel demonstrated improvement in total system flow rate without increasing pressure drop, and configurations of devices in series demonstrated improvements in particle concentration or particle size separation ranges depending on how the devices are configured.

Pilot Testing Results

During pilot testing, the team performed trials using GMEPS device configurations within a pilot plant to test GMEPS performance using actual Salton Sea geothermal brine, operation with feed flow rates of 10 gallons per minute or greater, and uninterrupted operation for more than 30 hours. Pilot sites for testing with Salton Sea geothermal brine included the Hell's Kitchen Geothermal pilot plant and the Cyrq Hudson Ranch geothermal plant, and field testing using synthetic geothermal brine was performed at Barr Engineering's Salt Lake City office. The team demonstrated removal and concentration of larger sized particles from both Salton Sea and synthetic geothermal brines and demonstrated the pilot plant operating uninterrupted for 30 hours at flow rates greater than 10 gallons per minute.

Additional Results and Implications

In addition to GMEPS device testing, the project team developed a scaled-up engineering design for a commercial geothermal plant using GMEPS technology for silica removal, along with a techno-economic analysis of this design compared to traditional silica removal methods. The findings from the analysis show that capital and operational costs of geothermal plants using GMEPS devices are lower than those using traditional silica removal methods. The test results along with these findings show that GMEPS technology would reduce energy costs for utilities and ratepayers and would provide the operational flexibility needed to expand the use of geothermal energy as a renewable energy source for California.

Knowledge Transfer and Next Steps

The project team recommends designing and implementing a complete process with an actual system using GMEPS technology for silica removal, along with a corresponding demonstration of the fully scaled system in an operational environment. Knowledge transfer activities to date included conference presentations, securing intellectual property, commercialization efforts, and briefing government officials on the technology.

CHAPTER 1: Introduction

The purpose of this project was to develop and demonstrate the capability of geothermal mesofluidic enhanced particle separator (GMEPS[1]) technology for removing silica precipitate in geothermal plants in the Salton Sea Geothermal Field (SSGF). Geothermal power plants generate electricity by drawing hot geothermal brine[2] from underground and removing heat from the brine to drive a steam-powered turbine. The brine temperature decreases during this process, causing dissolved minerals to precipitate out of the brine as solid particles and collect as scale deposits inside pipes and equipment. A significant portion of these particles are silica. This silica scale reduces the efficiency of geothermal plant operations and can cause equipment damage, leading to increased energy costs for utilities and consumers.

Managing and removing silica precipitate is a key challenge and major cost for geothermal plant operations. Geothermal plants typically use crystallizer-reactor-clarifier[3] (CRC) technology to remove silica, which involves growing particles in the brine for removal via large settling tanks. The CRC process is costly to operate due to requiring additional chemical inputs and costly to install due to high capital equipment costs and requiring a large footprint. Clarifiers operate in a limited dynamic range of flow rates, which prevents them from being used in load-following grid operations. GMEPS technology is a potential solution to these issues.

GMEPS devices separate particles from solution as they flow mesofluidically[4] through offset posts or settling channels that drive larger particles to one side of the device for removal through a separate outlet. These devices can run at a wide variety of flow rates and do not require additional chemicals, so they have more operational flexibility and are less costly to operate. GMEPS devices can recover silica of specific sizes and filter out other particles by size, potentially generating pure silica product streams that can be sold instead of sent to waste. In summary, GMEPS technology can potentially provide more flexible options for geothermal energy, reduce capital and operational costs for utility providers, produce value-added products from recovered pure silica, and reduce the cost of energy produced from geothermal plants for consumers.

At the start of this project, GMEPS technology had been demonstrated at a technology readiness level (TRL) of 3/4, experimental proof/demonstration of concept. To demonstrate GMEPS technology as an effective means of removing silica from geothermal brines, the technology needed to advance to TRL 6/7, demonstration of a system prototype in a

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1 Previously known as geothermal micropillar enhanced particle separator technology. Current GMEPS device designs do not all use micropillars; the common trait shared by all GMEPS devices is the use of mesofluidic flow behavior to separate particles by size.

2 Water that is highly concentrated with salts and other minerals.

3 A clarifier is a settling tank that settles and removes suspended solids, such as precipitated silica, from geothermal brine. Clarifiers are currently the preferred equipment used for particle separation in geothermal plants.

4 Mesofluidic flow is defined as microfluidic flow at industrial scale flow rates.

relevant/operational environment. The project goals for advancing GMEPS technology to TRL 6/7 and demonstrating GMEPS technology as an effective and less costly method for removing silica from geothermal brine included:

- Demonstrate silica removal from flowing geothermal brine at laboratory and pilot scales.
- Gather scaling factors to assist in design of larger scale demonstrations or commercial plants.
- Provide a techno-economic analysis for commercial scale operations and quantify GMEPS technology's potential benefits of reducing geothermal energy costs, enabling more flexible geothermal power generation, and facilitating improved minerals extraction from geothermal brines.

The team developed and tested various GMEPS device designs in the laboratory and in the field throughout the course of this project to achieve these goals and gauged project success based on metrics including:

- GMEPS device particle separation efficiency
- Particle size distribution in GMEPS device outlet streams
- Split fraction of particles in GMEPS device outlet streams
- Dynamic range of geothermal brine flow rates through GMEPS devices
- Consistent flow rate over time to demonstrate steady-state operation

Device designs developed throughout the project took manufacturability into consideration, and ultimately the team developed devices that can be easily 3D printed. The team also developed a commercial scale 140-megawatt geothermal plant design along with a techno-economic analysis to show the economic advantages of using GMEPS technology over traditional silica removal methods.

CHAPTER 2: Project Approach

The California Energy Commission awarded a grant to Hell's Kitchen Geothermal, LLC (HKG), a subsidiary of Controlled Thermal Resources, to perform a project to demonstrate GMEPS technology as a new method to separate silica particles from geothermal brines. HKG partnered with Pacific Northwest National Laboratory (PNNL) on GMEPS device development and testing, and with Barr Engineering Co. on process design support.

The overall project objectives included the following:

- Develop and demonstrate the efficacy of GMEPS technology for removal of silica from geothermal brines at laboratory scale.
- Demonstrate scale-up of the GMEPS design to pilot scale for field demonstration up to 10 gallons per minute (GPM).
- Demonstrate flexible flow operations over a 10x dynamic range while maintaining effective silica particle separation.
- Acquire parametric test data to define the range and effectiveness of GMEPS operating on in-field flowing geothermal brine.
- Demonstrate steady-state, uninterrupted operation for at least 30 hours.
- Demonstrate that GMEPS facilitates production of value-added minerals from geothermal brine, such as high-quality silica, iron particles of controlled size, and clean brine flow conducive to downstream recovery of minerals such as lithium.
- Demonstrate scalable and cost-effective manufacturing methods for GMEPS technology.
- Produce engineering designs for optimal GMEPS use and scaling of technology for commercial scale operation.
- Complete a techno-economic analysis demonstrating the relative economic advantages of GMEPS over existing silica removal systems.
- Calculate reduced geothermal energy costs and impacts to ratepayers.

GMEPS Device Development

A GMEPS device has one inlet and two outlets, with one outlet called the express lane for the separated particles and a second outlet called the permeate lane for the filtered permeate[5] solution. Initial GMEPS device designs separated particles from solution using an array of offset micropillars; current GMEPS device designs separate particles from solution by particle diameter as the particles flow mesofluidically through offset posts or settling channels that

[5] Permeate refers to the solution that has had particles removed through filtration, in this case via the GMEPS device. The term permeate suggests a membrane was used for filtration; however, a GMEPS device does not use a membrane for filtration.

drive the larger particles to one side of the device for removal through the express lane outlet as a particle concentrate,[6] and the remaining solution flows freely through the permeate lane.

GMEPS Design Criteria

The project team at PNNL developed iterations of the GMEPS device design based on the following design parameters:

- Volumetric flow rate of geothermal brine
- Silica particle sizes in SSGF geothermal brine
- Particle concentrations in SSGF geothermal brine

The project team performed testing on prototype GMEPS devices to determine the impact of these design parameters on performance variables, such as pressure drop and particle separation efficiency. The team also performed particle size analysis at the HKG pilot site to determine silica particle sizes and overall composition of the brine at the pilot site.

Types of GMEPS Devices

PNNL tested the following three types of GMEPS devices throughout the project:

- GMEPS Separator: Separates particles from solution via an array of offset pillars set in a pipe or channel that push larger particles toward the express lane while allowing smaller particles to flow through the posts to the permeate lane.
- GMEPS Fractionator: Separates particles from solution with one or more rows of lateral, diagonally offset pillars that drive larger particles toward the express lane while allowing smaller particles to flow through the posts to the permeate lane. The target particle sizes for a fractionator are greater than those of a GMEPS separator.
- GMEPS Avalanche Settler: Separates particles from solution using thin channels set at angles with respect to gravity. Particles settle to the bottom of the channel to be collected at the express lane. Avalanche settlers can separate smaller sized particles from solution compared to a GMEPS separator.

Figure 1 shows the particle size ranges the three types of devices can separate from solution. Different GMEPS devices can be configured in series in various combinations to target different ranges of particle sizes for separation, or they can be configured in parallel arrangements to increase total operating flow rate. The final configuration for an industrial scale silica removal process is still to be determined.

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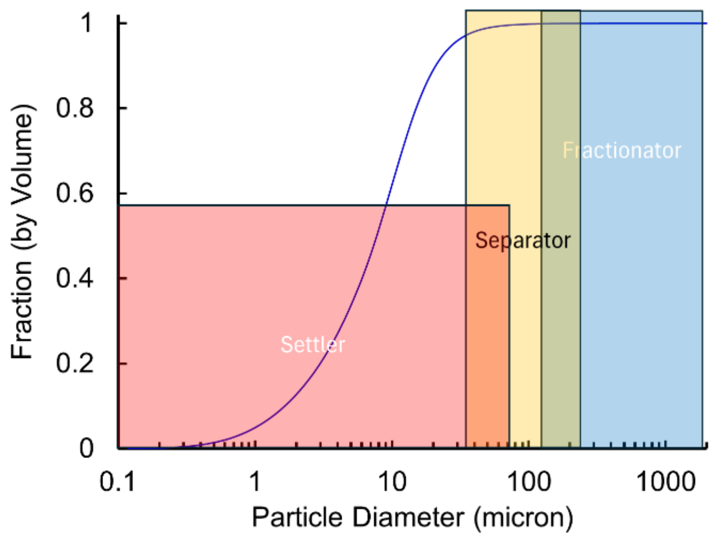
6 Concentrate refers to multiple particles that have formed together into a larger mass.

Figure 1: Particle Size Ranges of GMEPS Device with Process Stream Particle Distribution



Operational ranges of the GMEPS fractionator, separator, and avalanche settler are represented. Note that the ranges shown are approximate, as testing has shown that settlers can separate particles greater than 100 microns in diameter. The particle distribution was determined during particle size testing performed at the pilot site.

Source: PNNL (2024)

PNNL developed the original prototype GMEPS separator[7] outside the project's scope and funding; however, they tested this separator in laboratory scale tests during this project. The team developed and tested iterations of GMEPS separator designs during this project. The GMEPS avalanche settler[8] and GMEPS fractionator[9] were also invented and patented outside this project's scope and funding but were tested for and applied to the silica removal application.

Figure 2 shows images of the original prototype separator, and Figure 3 shows a plastic separator developed and tested during this project. Separator devices are labeled based on their nominal cutoff[10] diameter and their nominal maximum particle size, in this case 40–100 and 100–300 for the metal and plastic devices respectively. The team developed additional

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[7] Burns, Carolyn A., Timothy G. Veldman, Jason Serkowski, Richard C. Daniel, Xiao-Ying Yu, Michael J. Minette, Leonard F. Pease (Pacific Northwest National Laboratory). January 2021. "Mesofluidic separation versus dead-end filtration," *Separation and Purification Technology*, Volume 254. Article number 117256. https://doi.org/10.1016/j.seppur.2020.117256.

[8] Pease, Leonard F., Michael J. Minette, Carolyn A. Burns, R. Shane Addleman, Jason E. Serkowski (Pacific Northwest National Laboratory). April 2024. "Material Separating Assemblies and Methods," U.S. Patent Application Serial No. 18/649,076 and PCT Patent Application Serial No. PCT/US24/26794.

[9] Pease, Leonard F., Michael J. Minette, Carolyn A. Burns, Jason E. Serkowski, Nathan R. Phillips (Pacific Northwest National Laboratory). April 2024. "Systems and Methods for Separating Components of a Mixture," U.S. Patent Application Serial No. 18/649,674 and PCT Patent Application Serial No. PCT/US24/26871.

[10] Cutoff diameter is the particle diameter in microns at which 50 percent of particles are separated from the solution.

GMEPS device designs throughout the project; however, these two devices represent the preferred separator design used in early testing.

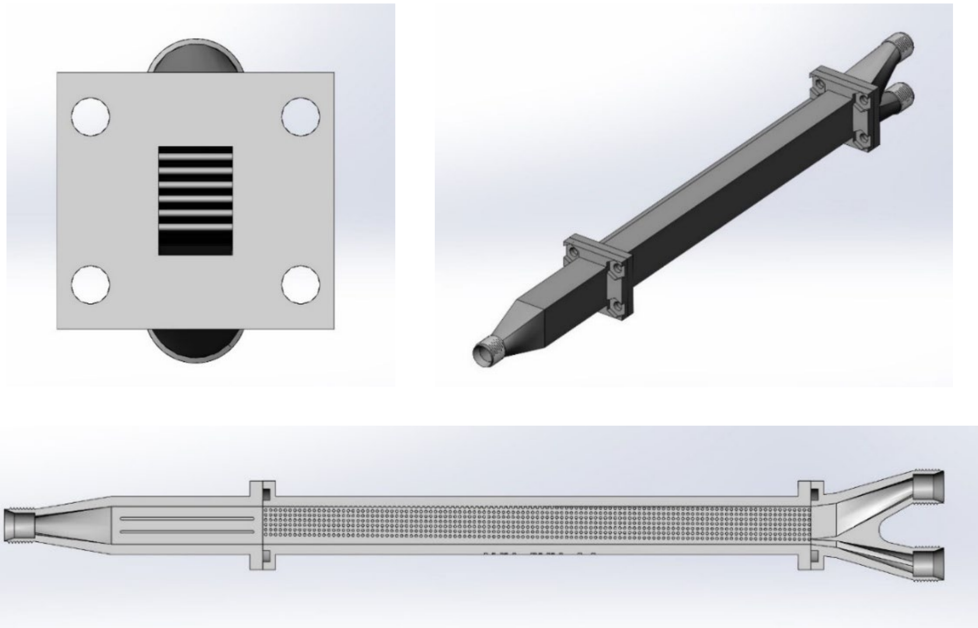
Figure 2: Metal 40–100 GMEPS Separator

Images representing perspectives of metal GMEPS separators used in laboratory testing with a nominal cutoff particle diameter of 40 microns and nominal maximum particle size of 100 microns. The devices have a diameter of 1 centimeter. The permeate lane is the wider outlet on the upper-right side of the device, and the express lane is the smaller outlet on the lower-right side. Last image courtesy of American Society of Mechanical Engineers (ASME) (FEDSM2022-87708).[11]

Source: PNNL (2024) and ASME (2022)

[11] Pease, Leonard F., Judith Ann Bamberger, Carolyn A. Burns, Michael J. Minette (Pacific Northwest National Laboratory). August 2022. "Concentrating Slurries Mesofluidically for Nuclear Waste Processing." Proceedings of the ASME 2022 Fluids Engineering Division Summer Meeting. Volume 2: Multiphase Flow (MFTC); Computational Fluid Dynamics (CFDTC); Micro and Nano Fluid Dynamics (MNFDTC). Paper number FEDSM2022-87708, V002T04A017. https://doi.org/10.1115/FEDSM2022-87708.

Figure 3: Plastic 100–300 GMEPS Separator

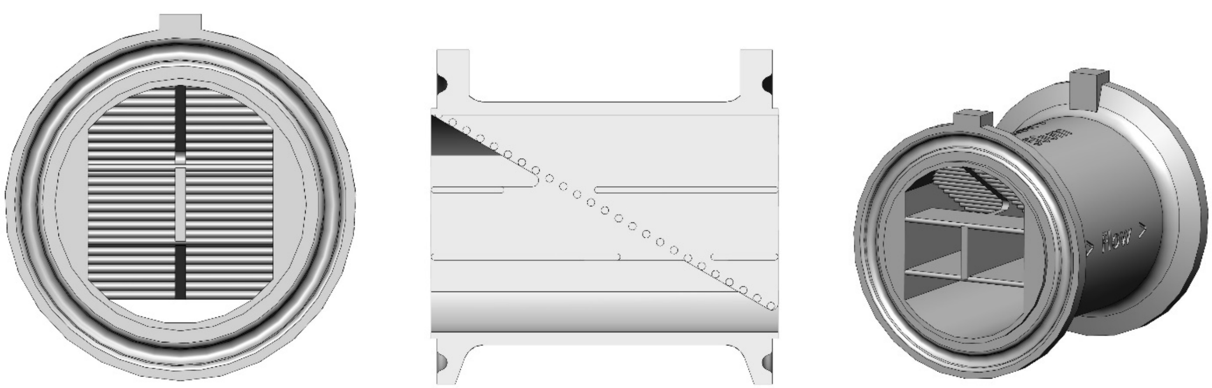


Images representing perspectives of the plastic GMEPS separator with a nominal cutoff particle diameter of 100 microns and nominal maximum particle size of 300 microns. Note this is the first version of this device; the second version of this separator was the version that was tested.

Source: PNNL (2024)

Figure 4 shows a model of a GMEPS fractionator, and Figure 5 shows an as-built pipe insert fractionator. Testing has shown a fractionator can separate particles greater than 120 microns in diameter from solution. Simplifying the design from a pillar array to only one row of pillars also simplifies device manufacturing; the as-built fractionator in Figure 5 was made using a 3D printer.

Figure 4: GMEPS Fractionator Design



Source: PNNL (2024)

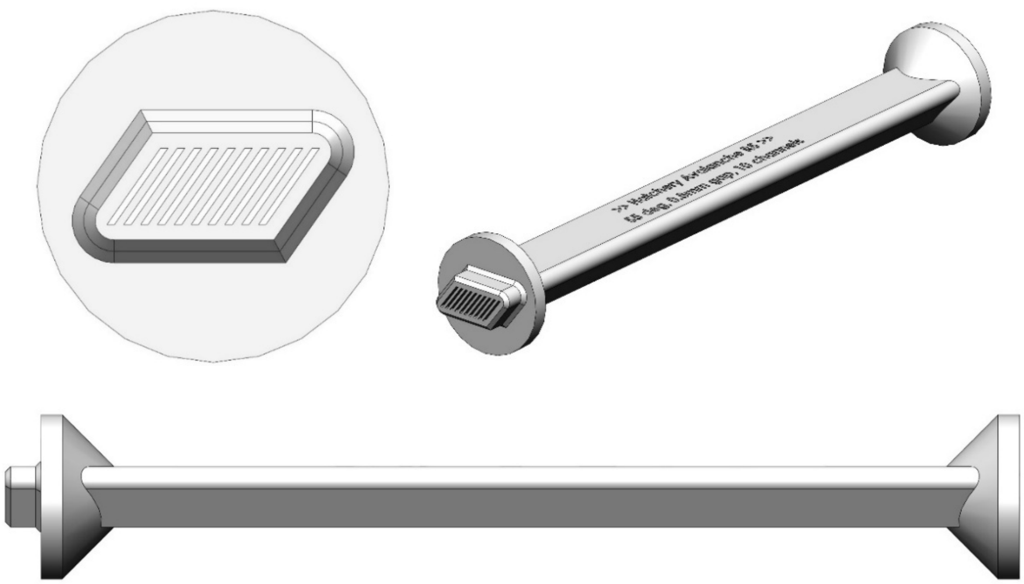
Figure 5: GMEPS Fractionator

This fractionator has one row of posts and is approximately 2 inches long and approximately 2 inches in diameter.

Source: PNNL (2024)

Figure 6 shows a GMEPS avalanche settler, and Figure 7 shows an as-built pipe insert avalanche settler. Brine flows through channels set at an angle with respect to gravity to accelerate particle settling. Separating particles smaller than 10 microns in diameter is possible using a GMEPS avalanche settler if enough time is given for the particles to settle. Like the fractionator, the team 3D printed the as-built avalanche settler in Figure 7.

Figure 6: GMEPS Avalanche Settler Design



Source: PNNL (2024)

Figure 7: GMEPS Avalanche Settler

This avalanche settler has ten channels set at a 55-degree angle and is approximately 11¼ inches long and approximately 1¾ inches in diameter at the ends.

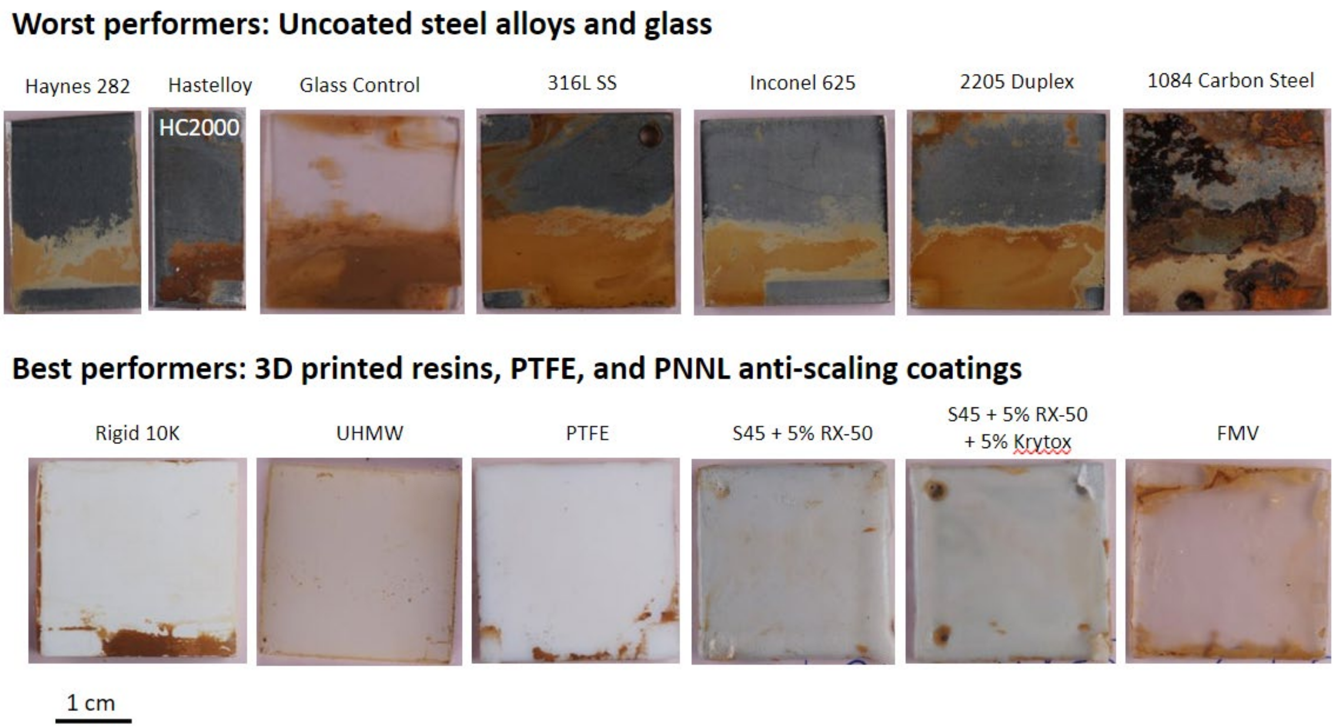
Source: PNNL (2024)

Materials and Manufacturing

An additional design consideration for GMEPS devices was the material of construction. GMEPS devices must be able to effectively separate particles from SSGF brine while withstanding the high temperatures and corrosive environment of the brine. They also must be economically and technically feasible to produce, as devices require micro-scale resolution to be able to separate particles only microns in size. Most GMEPS separator devices developed during the project were made from different metal alloys using direct metal laser sintering (DMLS) technology to manufacture devices with micro-scale resolution. Some separator designs and the GMEPS fractionator and avalanche settler designs were made from polymer composites using 3D printing technology.

3D printing GMEPS devices with polymer composites is much less costly than manufacturing metal devices with DMLS, but 3D printing technology does not have as high a resolution as DMLS technology. The team overcame this limitation by using GMEPS fractionators and avalanche settlers in testing configurations that required much less demanding resolution to manufacture. Additionally, PNNL tested various metals and polymer composites at the HKG pilot site for mineral fouling in SSGF brines and found metals generally performed worse than polymer composites; Figure 8 shows the results of some of the tested materials. Since metal devices cost more to manufacture compared to 3D printing a polymer device, the team selected a glass fiber reinforced thermopolymer composite for GMEPS devices to use in field testing.

Figure 8: Materials Tested for Mineral Fouling in SSGF Brines at the HKG Pilot Site



Source: PNNL (2024)

GMEPS Lab Scale Testing

Lab Testing Objectives

Lab scale testing objectives included:

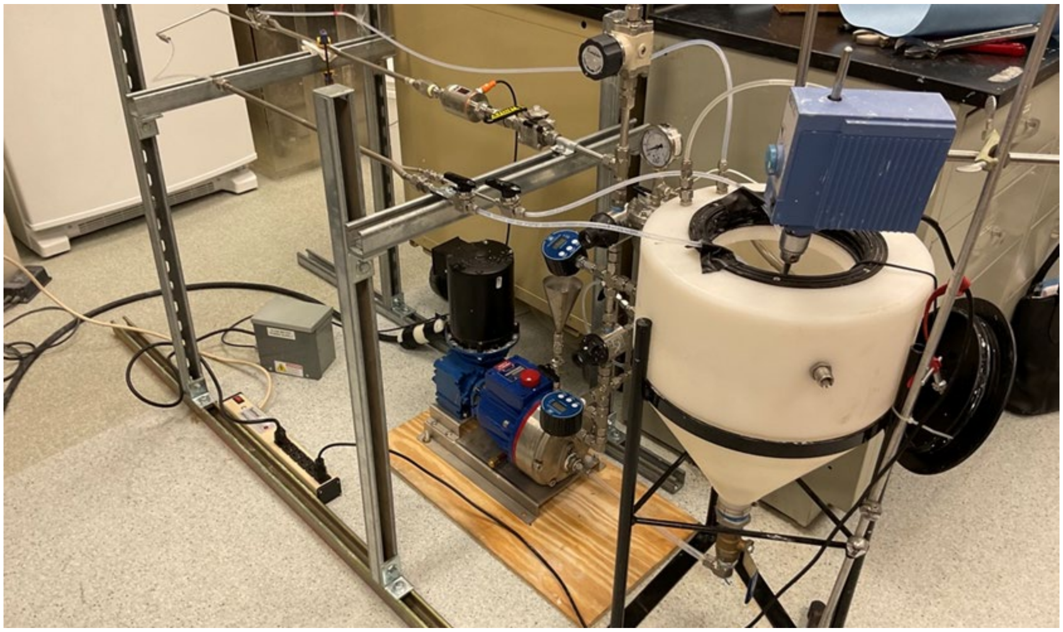
- Demonstrating particle separation from geothermal brine
- Determining the impact of flow rate on GMEPS device performance
- Demonstrating separation of silica and iron particles from geothermal brine
- Demonstrating particle separation based on size
- Demonstrate turndown[12] capability of GMEPS devices by operating at varying flow rates

Lab Scale System

Figure 9 and Figure 10 show the testing systems for the metal 40–100 and plastic 100–300 GMEPS separators respectively. The setup for the metal separator included two separators in parallel. The project team added silica beads of various sizes to the testing solution to simulate silica particles in geothermal brine. PNNL tested these two systems to determine the impact of flow rate on device performance variables.

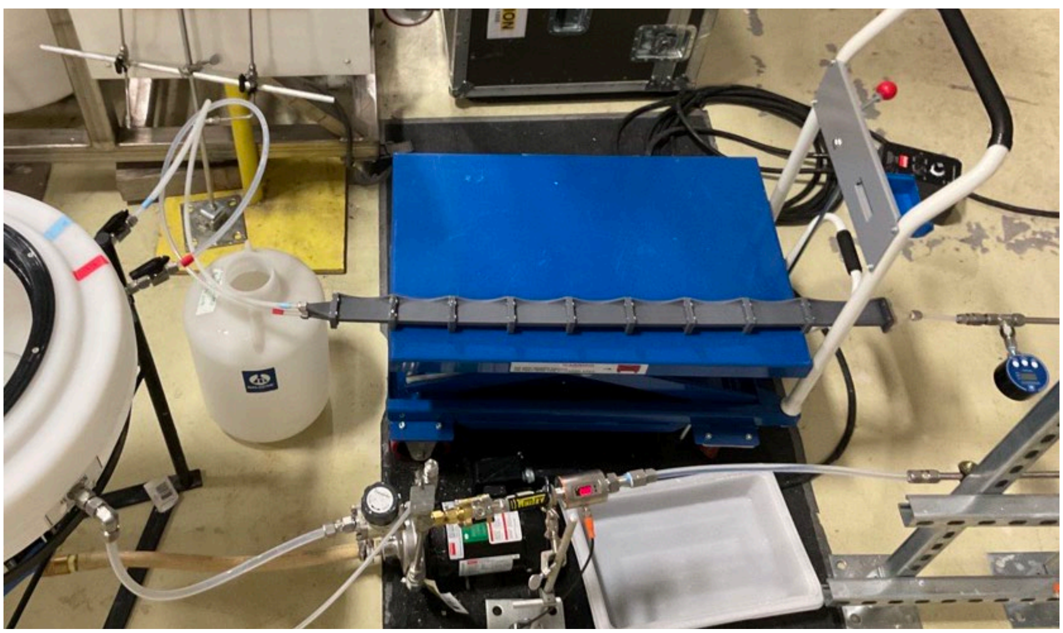
[12] Turndown refers to being able to operate at lower flow rates for more flexible operation.

Figure 9: Metal 40–100 GMEPS Separator Testing System



Source: PNNL (2024)

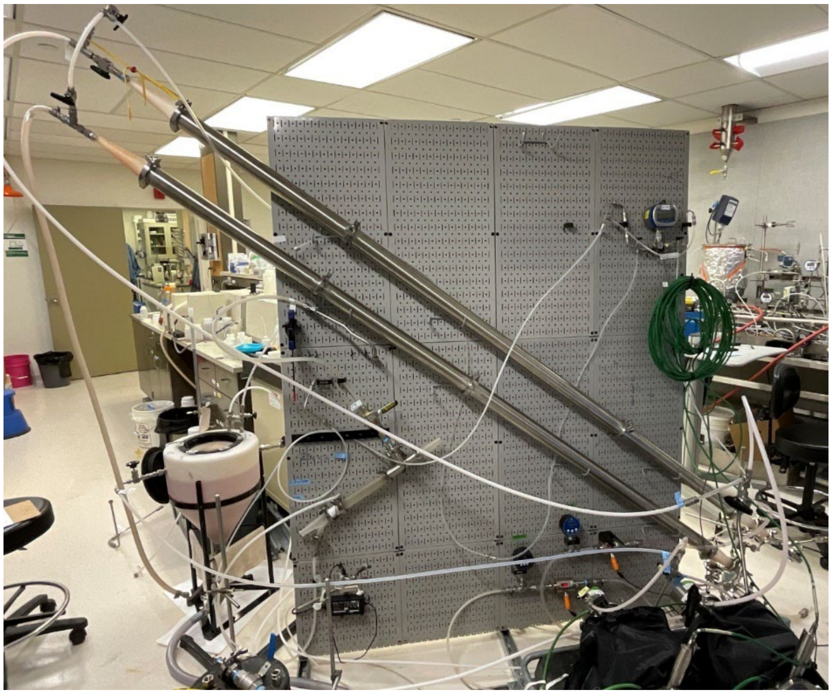
Figure 10: Plastic 100–300 GMEPS Separator Testing System



Source: PNNL (2024)

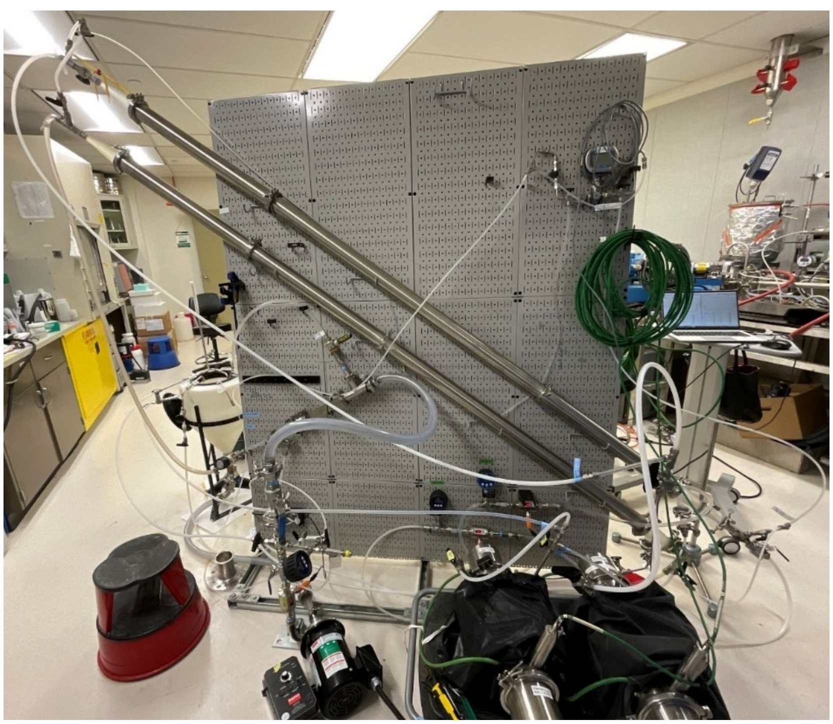
The project team tested the particle separation capabilities of GMEPS devices with two testing systems using GMEPS settlers and fractionators. The system shown in Figure 11 used two GMEPS settlers in series to demonstrate the separation of silica particles from ferric oxide particles in a simulated brine solution. The system shown in Figure 12 used a GMEPS fractionator and two GMEPS settlers in series to demonstrate the separation of different-sized silica particles from each other in simulated brine solution and to demonstrate the scalability of GMEPS devices for varying flow rates.

Figure 11: GMEPS Testing System with Two Avalanche Settlers



Source: PNNL (2024)

Figure 12: GMEPS Testing System with One Fractionator and Two Avalanche Settlers

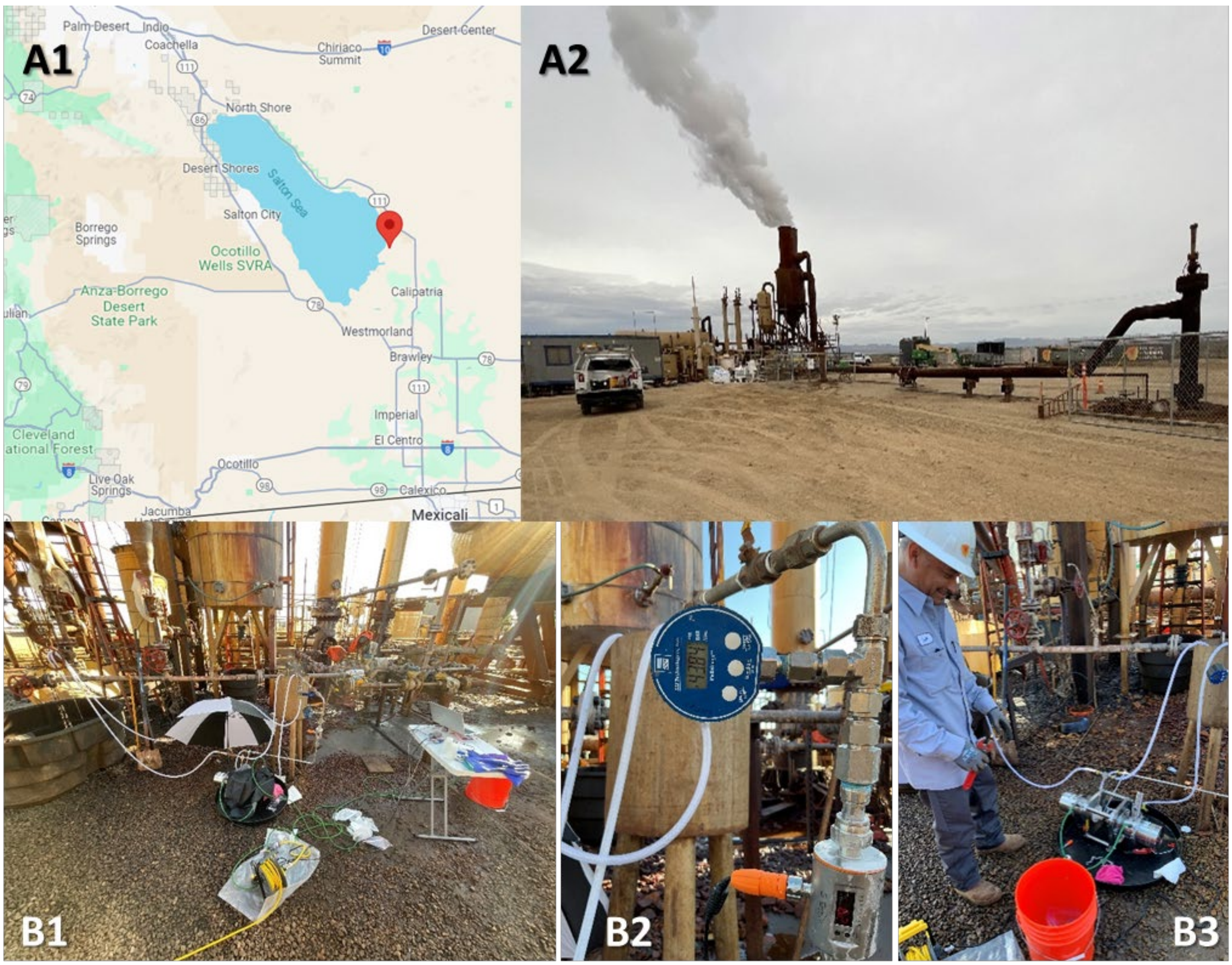


Source: PNNL (2024)

Particle Size Analysis – Salton Sea Brines

To guide GMEPS device design for pilot testing and beyond, PNNL and HKG collaborated to perform particle size and composition testing at the pilot site in the Salton Sea. Understanding the exact silica particle sizes and brine composition at the pilot site is key for GMEPS device design because GMEPS technology is being developed and demonstrated based on the actual particle sizes in the process flows at the pilot site. The project team at PNNL used dynamic light scattering (DLS) to measure particle sizes by measuring laser light reflected off particles in the process brine, as shown in Figure 13. The team also used scanning electron microscopy to analyze the elemental composition of the brine.

Figure 13: Hell's Kitchen Geothermal Pilot Site



Images of the HKG pilot site and the deployment of particle measurement equipment. The upper row shows the test location (A1) and a photo of the test site (A2) with wellheads at the center and right and processing equipment on the left. The lower row (B1–3) shows the particle size (DLS) measurement test system connected to HKG pilot site process piping at various locations.

Source: PNNL (2024)

Pilot Testing – Salton Sea Brines

Pilot Testing Objectives

Pilot testing objectives included:

- Demonstrating particle separation from actual SSGF brine
- Demonstrating operation at a feed flow rate of 10 GPM
- Demonstrating uninterrupted steady-state operation for at least 30 hours

Testing Host Site

The project team conducted pilot testing at three different pilot sites:

- HKG pilot plant in the SSGF, California
- Cyrq Hudson Ranch geothermal plant in the SSGF, California
- Barr Engineering office in Salt Lake City, Utah

Pilot System Design and Fabrication

PNNL conducted initial field testing at the HKG pilot site using GMEPS devices to separate particles from SSGF brine. The team tested a device train that included a GMEPS fractionator for filtering out larger sized particles and a series of downstream GMEPS avalanche settlers for filtering out smaller particles. The fractionator and the last settler each have an express lane to capture the particle concentrate separated from the brine. The team installed the devices in line with plant operations to use Salton Sea brine for testing. Figure 14 shows the testing arrangement at the HKG pilot site.

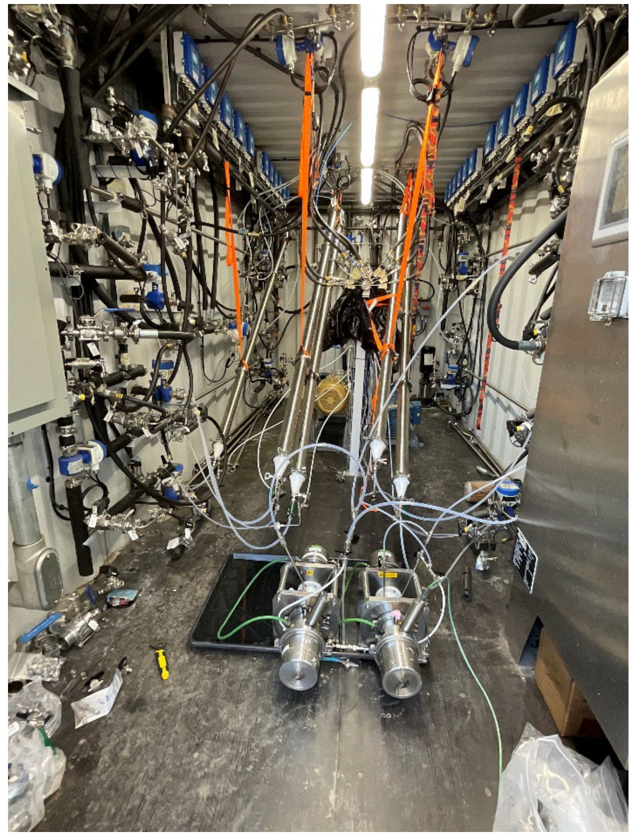
Figure 14: Hell's Kitchen Geothermal Pilot Testing System

Images of the GMEPS device train used for field testing at the HKG pilot site. Brine flows through the train with respect to gravity to promote settling. A fractionator is installed at the entrance at the higher end of the train to remove larger particles from the system to prevent clogging downstream settlers, and settlers are arranged in series to settle smaller particles for removal at the end of the train.

Source: PNNL (2025)

PNNL conducted additional field testing at the Cyrq Hudson Ranch geothermal plant in the SSGF and at Barr Engineering's Salt Lake City office. The team operated five of the GMEPS device trains used at the HKG pilot site in parallel to maintain a target flow rate of 10 GPM. Contractors built a mobile pilot plant for operating the five trains, and the team transported it between the two sites. The team installed the pilot plant in line with geothermal plant operations at the Cyrq plant to test Salton Sea brine, and in line with a mixing tank with synthetic brine at the Barr Engineering office. Figure 15 shows the GMEPS devices and the pilot plant used for testing at both sites.

Figure 15: Pilot Plant Testing Arrangement and Devices



Images of the GMEPS devices and the pilot plant used for field testing at the Cyrq plant and Barr pilot site. Five GMEPS device trains are arranged in parallel to achieve a 10 GPM flow rate.

Source: PNNL (2025)

CHAPTER 3: Results

Lab Scale Testing Results

PNNL performed tests using the device configurations shown in Chapter 2 to achieve the previously outlined testing objectives. Improvements to device designs are reflected in the change from using GMEPS separators in early tests to using GMEPS fractionators and avalanche settlers in later tests. Below is a summary of the tests performed:

- Impact of flow rate on particle separation and pressure drop using GMEPS separators
- Separation of silica and iron particles from geothermal brine using two GMEPS avalanche settlers in series
- Separation of silica by particle size using a GMEPS fractionator and two GMEPS avalanche settlers in series
- Demonstration of flow rate with a dynamic range of 10x using two GMEPS avalanche settlers in series

The results from these tests provided insight into how to improve GMEPS devices and configurations for field testing using actual SSGF brines. Below is a summary of the results:

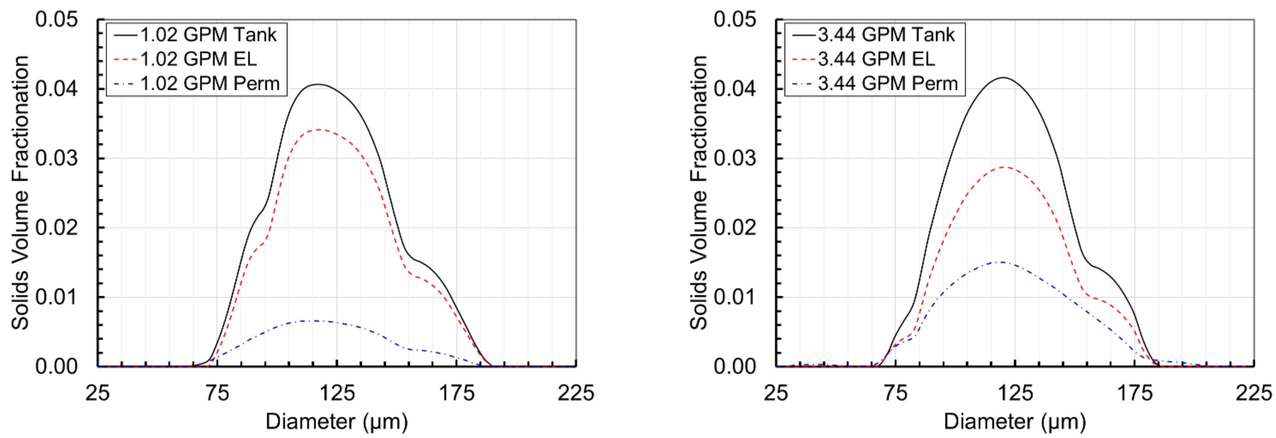
- GMEPS devices can remove silica particles from synthetic geothermal brine, with lower flow rates increasing the volumetric fraction of solid particles in the express lane.
- Pressure drop across a GMEPS device increases quadratically with flow rate.
- GMEPS devices can separate silica particles into distinct concentrates based on particle size.
- GMEPS devices can separate silica particles from iron-rich geothermal brine.
- GMEPS devices can operate at varying flow rates within a dynamic range of 10.6x, or a maximum flow rate 10.6 times greater than the minimum flow rate.
- GMEPS devices can operate in series to improve concentration of silica particles or in parallel to increase total flow rate.

Key Findings

Performance of GMEPS Separators at Varying Flow Rates

PNNL used the metal and plastic GMEPS separator designs discussed in Chapter 2 to test and evaluate the impact of flow rate on various process variables, starting with the 100–300 plastic GMEPS separator to show the impact of flow rate on removing solid particle concentrate from solution. This testing used silica beads with a median particle diameter of 116 microns mixed in water to simulate geothermal brine. Results of this testing in Figure 16 show increased solids in the express lane at a lower flow rate, which is consistent with the initial separator design testing. Figure 17 shows that the pressure drop increases quadratically as the flow rate through the separator increases, a concern if devices are intended to operate at greater than 10,000 GPM; however, running devices in parallel to increase the total flow rate can circumvent this issue.

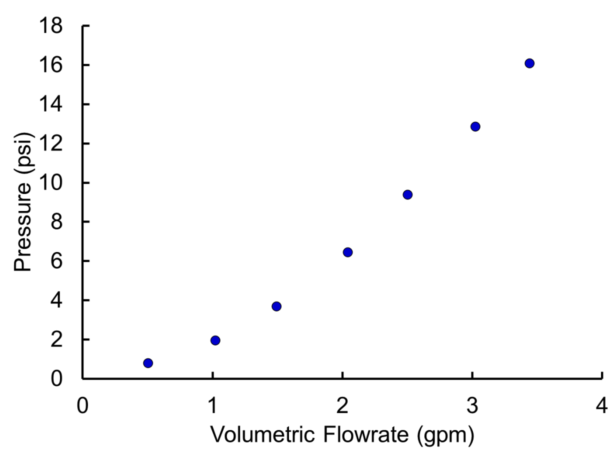
Figure 16: Solids Fractionation for Plastic 100–300 GMEPS Separator



Graphs show solids fractionation in inlet solution, permeate, and express lane as a function of particle diameter at 1.02 and 3.44 GPM for the plastic 100–300 GMEPS separator.

Source: PNNL (2024)

Figure 17: Pressure Drop Across Plastic 100–300 GMEPS Separator



Graph shows pressure drop across the plastic 100–300 GMEPS separator as a function of brine flow rate.

Source: PNNL (2024)

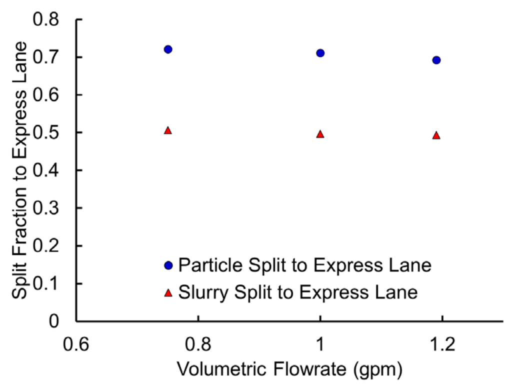
Performance of Separators Configured in Parallel and in Series

PNNL tested the metal 40–100 GMEPS separator performance in a parallel configuration to achieve desired flow rate targets of 0.8 to 1.2 GPM while maintaining pressure within system design limits. The tests evaluated the impact of varying flow rates on the split fraction of particles and total slurry that were separated from the brine permeate, the particle sizes leaving the permeate and express lanes, and the pressure drop across the separator. PNNL mixed two varieties of silica particles in a concentrated saline solution to simulate silica removal from a geothermal brine. The two silica particles had median particle diameters of 57.7 microns and 34.0 microns, and PNNL added the particles in a 7:4 ratio respectively to represent a broad particle size distribution. Figure 18, Figure 19, and Figure 20 show the following results of this test respectively:

- Seventy (70) percent of particles in the brine exited the device through the express lane as a particle concentrate, with little difference in performance across flow rates.
- Particle sizes in the express lane were greater than particle sizes in the permeate.
- The pressure drop across the separator increased as the brine flow rate increased.

These results show that GMEPS devices can separate silica particles from a brine solution and that they can be run in parallel to achieve greater system flow rates.

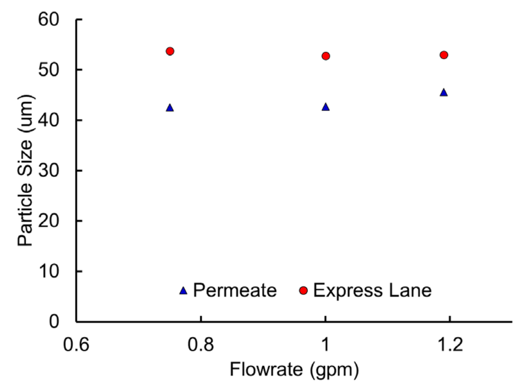
Figure 18: Split Fraction for Two Metal 40–100 GMEPS Separators



Graph shows split fraction of particles and slurry sent to the express lane as a function of flow rate for the two metal 40–100 GMEPS separators in parallel.

Source: PNNL (2024)

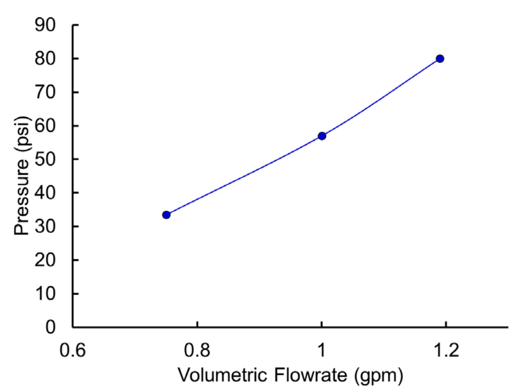
Figure 19: Particle Sizes for Two Metal 40–100 GMEPS Separators



Graph shows particle sizes in permeate and express lane particle concentrate as a function of flow rate for the two metal 40–100 GMEPS separators in parallel.

Source: PNNL (2024)

Figure 20: Pressure Drop for Two Metal 40–100 GMEPS Separators

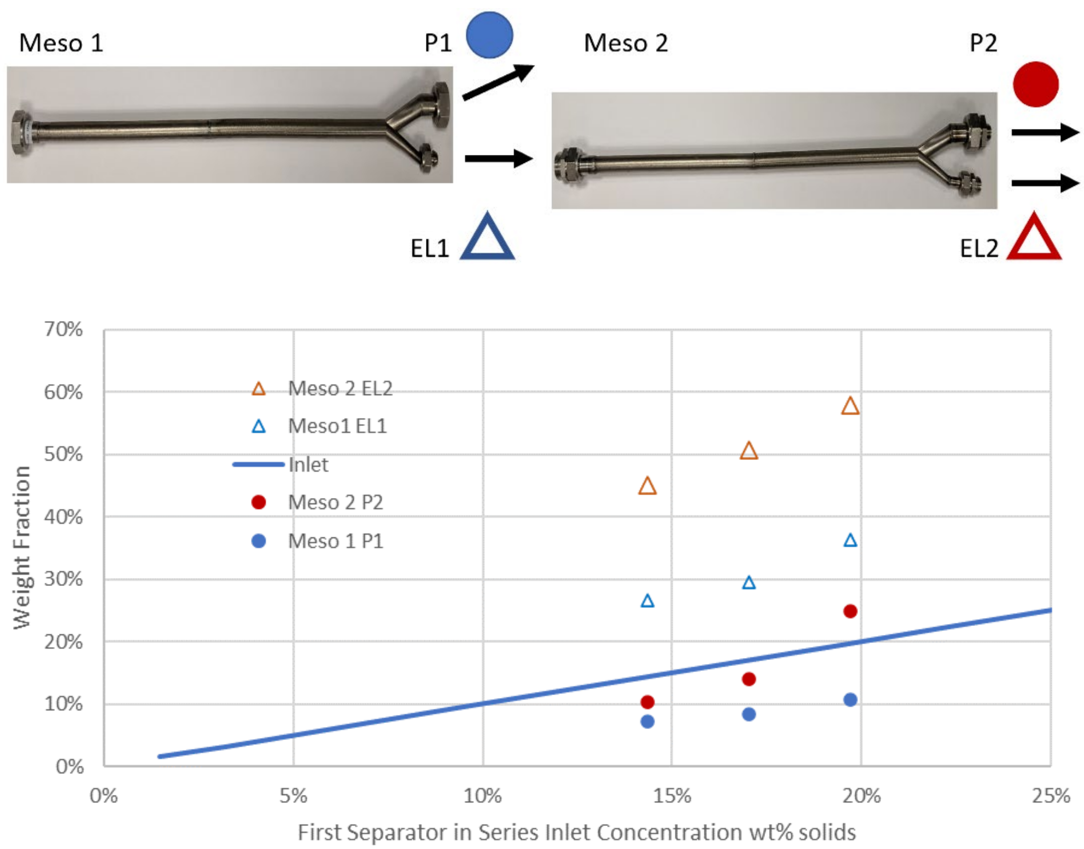


Graph shows pressure drop as a function of flow rate for the two metal 40–100 GMEPS separators in parallel.

Source: PNNL (2024)

PNNL performed testing in a previous effort with the same metal GMEPS separators configured in parallel to test the impact that running devices in series has on particle concentrations in the permeate and express lanes.[13] When installed in series, the first separator sends its particle concentrate in the express lane to the inlet of the second device to improve the recovery of the brine permeate and improve the concentration of particles leaving the second device's express lane. Figure 21 shows this arrangement of the devices along with the results of the testing. The results confirm that concentrate leaving the second separator's express lane has a much greater concentration of solid particles than the first separator's concentrate, thereby confirming the benefit of improved particle recovery and concentration by configuring GMEPS devices in series.

Figure 21: Particle Weight Fraction for Two Metal 40–100 GMEPS Separators in Series



Graph shows particle weight fraction as a function of inlet solids concentration for the two metal 40–100 GMEPS separators in series with device arrangement. Meso 1 is the first device and Meso 2 is the second device in the series. P1 and P2 are the permeate lanes, and EL1 and EL2 are the express lanes of the first and second devices respectively.
Figure courtesy of ASME (FEDSM2022-87708).

Source: ASME (2022)

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[13] Pease, Leonard F., Judith Ann Bamberger, Carolyn A. Burns, Michael J. Minette (Pacific Northwest National Laboratory). August 2022. "Concentrating Slurries Mesofluidically for Nuclear Waste Processing." Proceedings of the ASME 2022 Fluids Engineering Division Summer Meeting. Volume 2: Multiphase Flow (MFTC); Computational Fluid Dynamics (CFDTC); Micro and Nano Fluid Dynamics (MNFDTC). Paper number FEDSM2022-87708, V002T04A017. Available at https://doi.org/10.1115/FEDSM2022-87708.

Separation of Silica and Iron Particles Using GMEPS Settlers

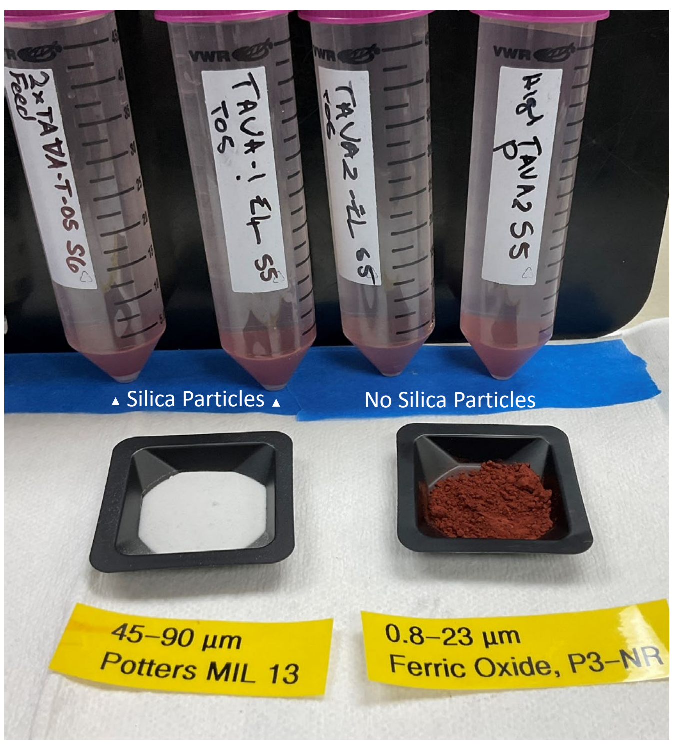
PNNL tested separating silica particles from a heterogeneous brine solution that included silica and iron particles by using the two-device GMEPS settler testing system discussed in Chapter 2, with the settlers configured in series so that the permeate from the first settler feeds the inlet of the second settler. Particle concentrate samples were collected from each settler's express lane.

The brine solution simulating geothermal brine contains silica particles ranging from 45 to 90 microns in diameter along with ferric oxide particles ranging from 0.8 to 23 microns in diameter. PNNL ran the brine solution through the two settlers then collected four grab samples shown in Figure 22. From left to right the samples are:

- Brine feed to the first settler
- Express lane output from the first GMEPS settler
- Express lane output from the second GMEPS settler
- Permeate output from the second GMEPS settler

The first two samples contained settled silica, indicating the first GMEPS settler successfully removed the larger silica particles. The last two samples contained a negligible amount of silica by comparison. All samples contained suspended iron particles due to the small size of the iron particles. These results prove GMEPS devices can remove silica from iron-enriched streams; however, separating the iron particles from solution will need to be investigated further.

Figure 22: Brine Samples Containing Silica and Iron Particles from GMEPS Settler Testing System



Source: PNNL (2024)

Separation of Silica Particles of Controlled Sizes Using GMEPS Fractionator and Settlers

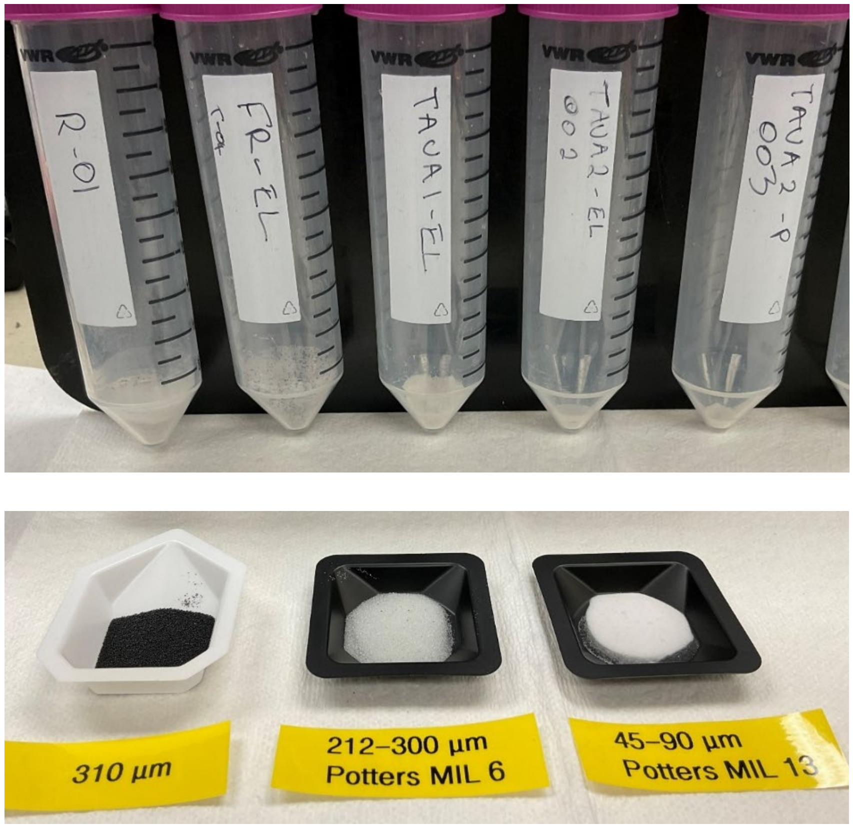
PNNL tested separating silica particles of particular sizes using brine solution that included silica particles of distinct sizes and tracer particles by using the three-device GMEPS settler and fractionator testing system discussed in Chapter 2. The fractionator and two settlers were configured in series so the feed enters the fractionator, then the fractionator permeate feeds the first settler, and then the first settler permeate feeds the inlet of the second settler. Particle concentrate samples were collected from the fractionator's and the two settlers' express lanes.

The solution simulating geothermal brine contained silica particles ranging from 45 to 90 microns in diameter, silica particles ranging from 212 to 300 microns in diameter, and black tracer particles sized at 310 microns in diameter. The team added the tracer particles to clearly demonstrate the system's capability of removing larger-sized particles from solution with the GMEPS fractionator. PNNL ran the brine solution through the fractionator and two settlers, then collected and dried five grab samples shown in Figure 23. From left to right, the samples contain particles from:

- Brine feed to the GMEPS fractionator
- Express lane output from the GMEPS fractionator
- Express lane output from the first GMEPS settler
- Express lane output from the second GMEPS settler
- Permeate output from the second GMEPS settler

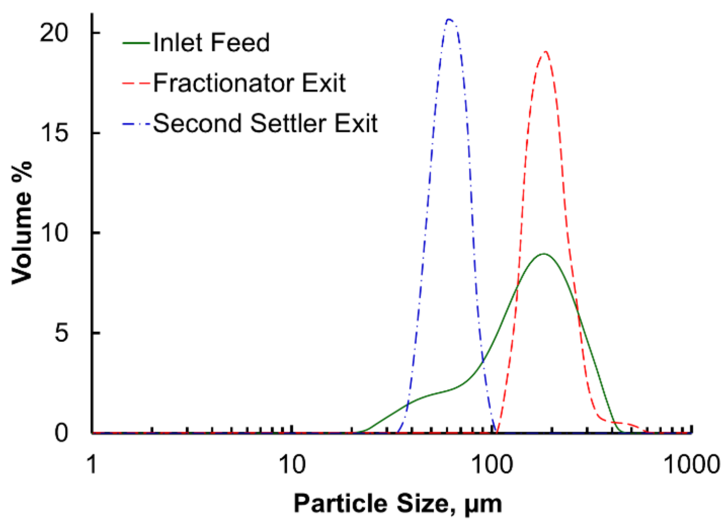
The sample from the fractionator express lane mostly contained the black tracer particles, and those same particles were absent from the samples leaving the settlers, indicating the fractionator successfully removed the large particles. Figure 24 quantifies the particle size distribution for the fractionator and second settler particle concentrates along with the feed, showing that this method of separation can produce two distinct product streams of different particle sizes.

Figure 23: Brine Samples Containing Silica and Iron Particles from GMEPS Settler and Fractionator Testing System



Source: PNNL (2024)

Figure 24: Particle Size Distributions from GMEPS Fractionator and Settler Testing System

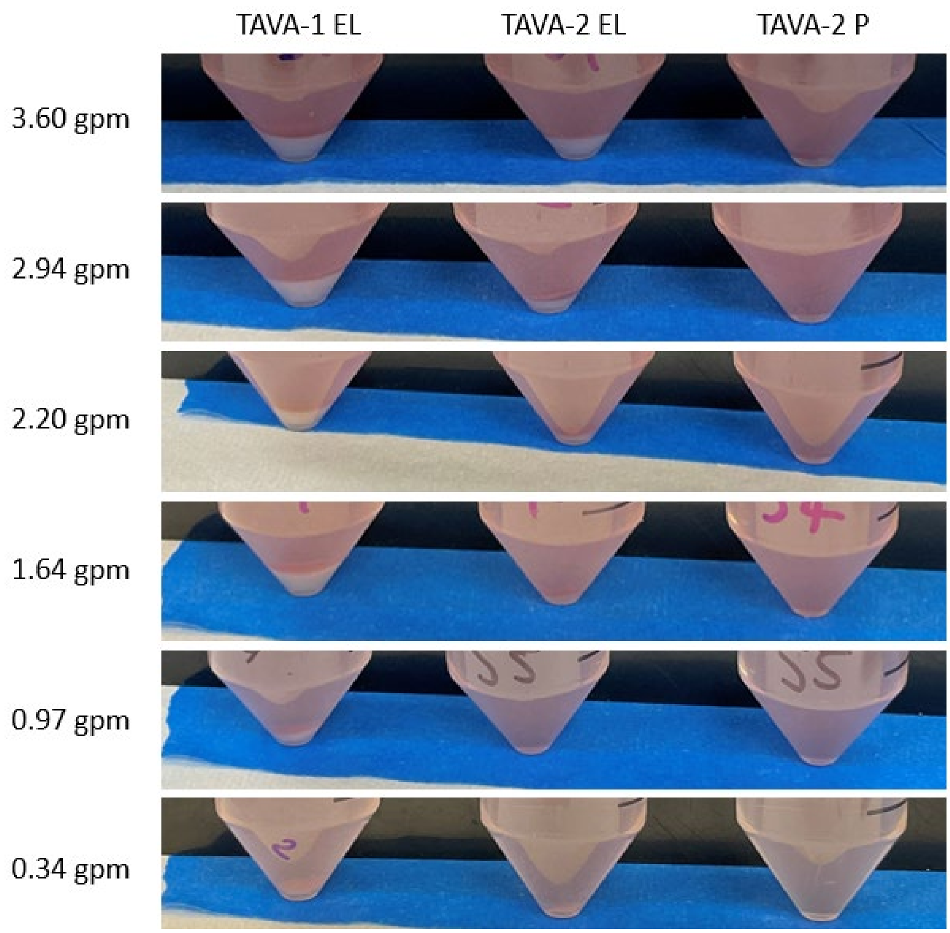


Source: PNNL (2024)

Demonstration of GMEPS Turndown Capability Using GMEPS Settlers

PNNL demonstrated the capability of GMEPS devices to operate at a wide, flexible range of brine flow rates using the same two-device GMEPS settler testing system used for the silica-iron separation testing. Figure 25 shows brine samples taken (from left to right) from the first settler express lane, second settler express lane, and second settler permeate lane at various flow rates ranging from 0.34 GPM to 3.60 GPM, representing a dynamic range of 10.6x for this GMEPS device arrangement. This result indicates GMEPS devices have expansive turndown capability, and running devices in parallel would provide additional flexibility in addition to scaling up operating flow rates.

Figure 25: Brine Samples from GMEPS Settler Outlets at Varying Flow Rates



TAVA-1 EL is first avalanche settler's express lane, TAVA-2 EL is second avalanche settler's express lane, and TAVA-2 P is second avalanche settler's permeate lane.

Source: PNNL (2024)

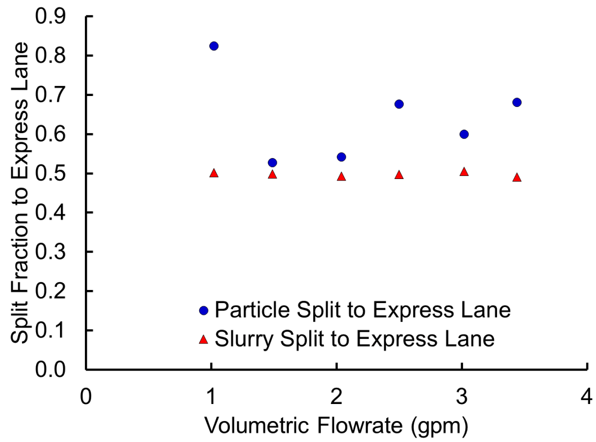
Barriers and Challenges

Device Materials

The team tested the impact of flow rate on the fraction of particles and slurry sent to the express lane using the plastic 100–300 GMEPS separator; however, the results shown in

Figure 26 did not show a consistent trend due to a swelling problem with 3D printing select resins discovered later. Other tests using different resins did not show this same variation.

Figure 26: Split Fraction for Plastic 100–300 GMEPS Separator



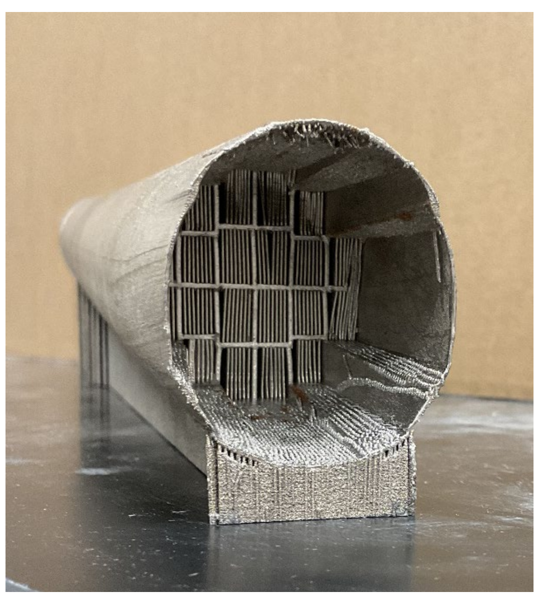
Graph shows the split fraction of particles and slurry sent to the express lane as a function of flow rate for the plastic 100–300 GMEPS separator.

Source: PNNL (2024)

Device Size and Manufacturing Methods

PNNL used data from GMEPS separator testing to develop additional separator designs, including the large metal separator shown in Figure 27. However, externally the pipe was not well formed, making connections difficult, and internally the posts were neither straight nor parallel, putting its ability to properly separate and remove particles from brine into question. The team suspended further evaluation of large metal GMEPS separators following this failed device and instead developed the testing systems using GMEPS settlers and fractionators.

Figure 27: Post-Printing Failure of Large GMEPS Separator Design



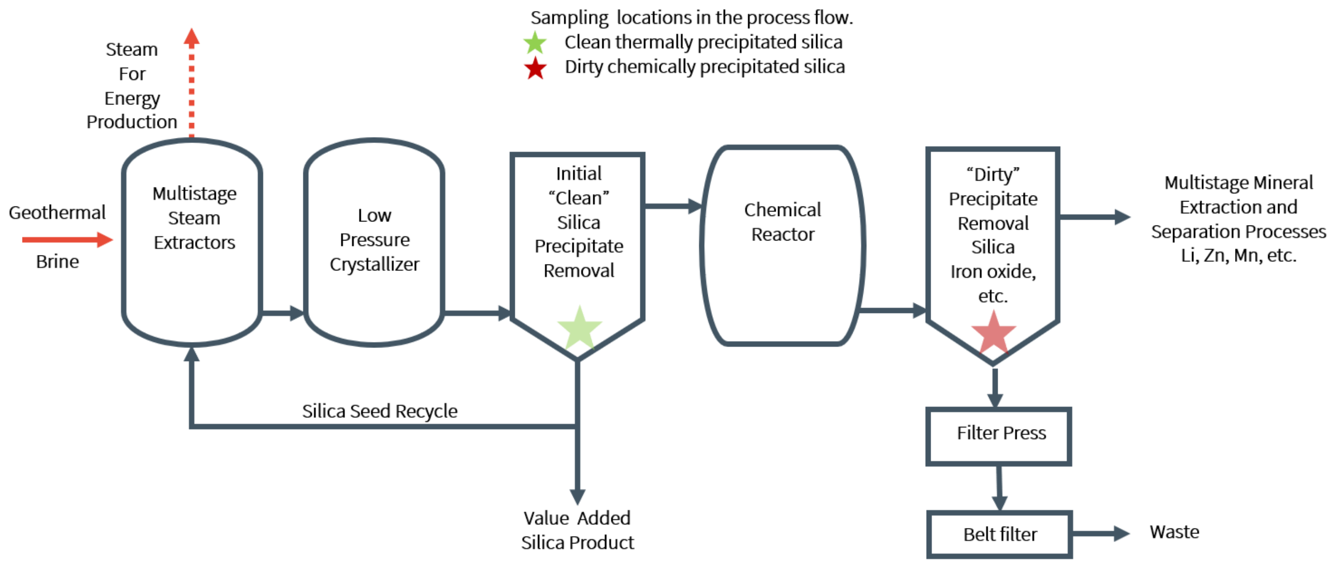
Source: PNNL (2024)

Particle Size Analysis Results

Key Findings

PNNL determined particle size distributions of flowing SSGF brine for two locations in the HKG pilot test plant process shown in the process flow diagram in Figure 28. The first location sample contained clean, thermally precipitated pure silica, and the second location sample contained silica precipitated by reacting with other minerals in the brine in addition to pure silica.

Figure 28: Geothermal Power Plant Process Flow Diagram with Brine Sample Collection Locations



Source: PNNL (2024)

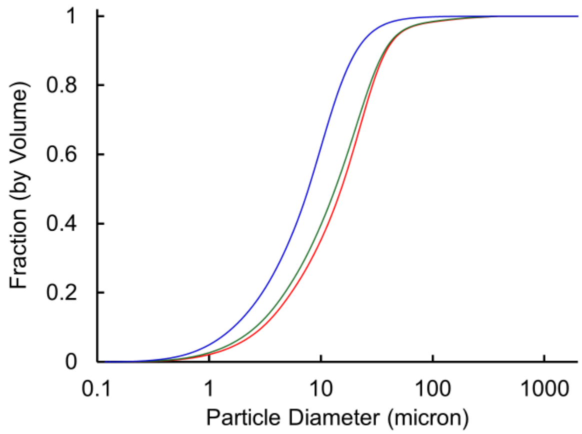
Figure 29 shows the in-situ[14] particle size distributions of silica measured from the two sample locations, including the distribution for brine collected directly from the SSGF. The particle size distributions generally are:

- Bottom 5 percent: 1.0 to 1.8 microns
- Median: 7.8 to 15.3 microns
- Top 5 percent: 27.9 to 51.4 microns

The particle size distribution results show a particle range of roughly 1 to 50 microns in diameter and that silica particles grow as they spend more time in the process. Process temperatures impact these results by governing particle solubility, so particle sizes at different points in the process may vary from these results.

[14] "In-situ" refers to particles suspended in geothermal brine.

Figure 29: Particle Size Distributions for SSGF Brine Samples from Pilot Site



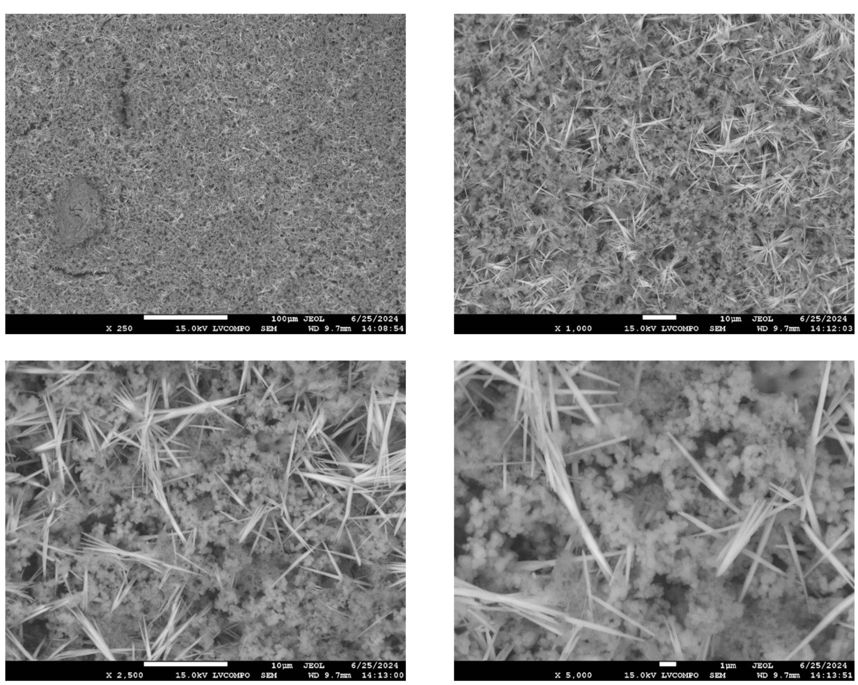
The blue curve represents brine directly sampled from the SSGF, the green curve represents brine sampled from the process directly downstream from the low-pressure crystallizer, and the red curve represents brine sampled from the process directly following chemical precipitations.

Source: PNNL (2024)

PNNL visualized the particle samples using DLS shown in Figure 30 and then analyzed the elemental compositions of the samples via energy dispersible spectrometry shown in the elemental maps in Figure 31. The results are qualitative due to uneven surfaces on the samples, and the findings include the following particles identified in the samples:

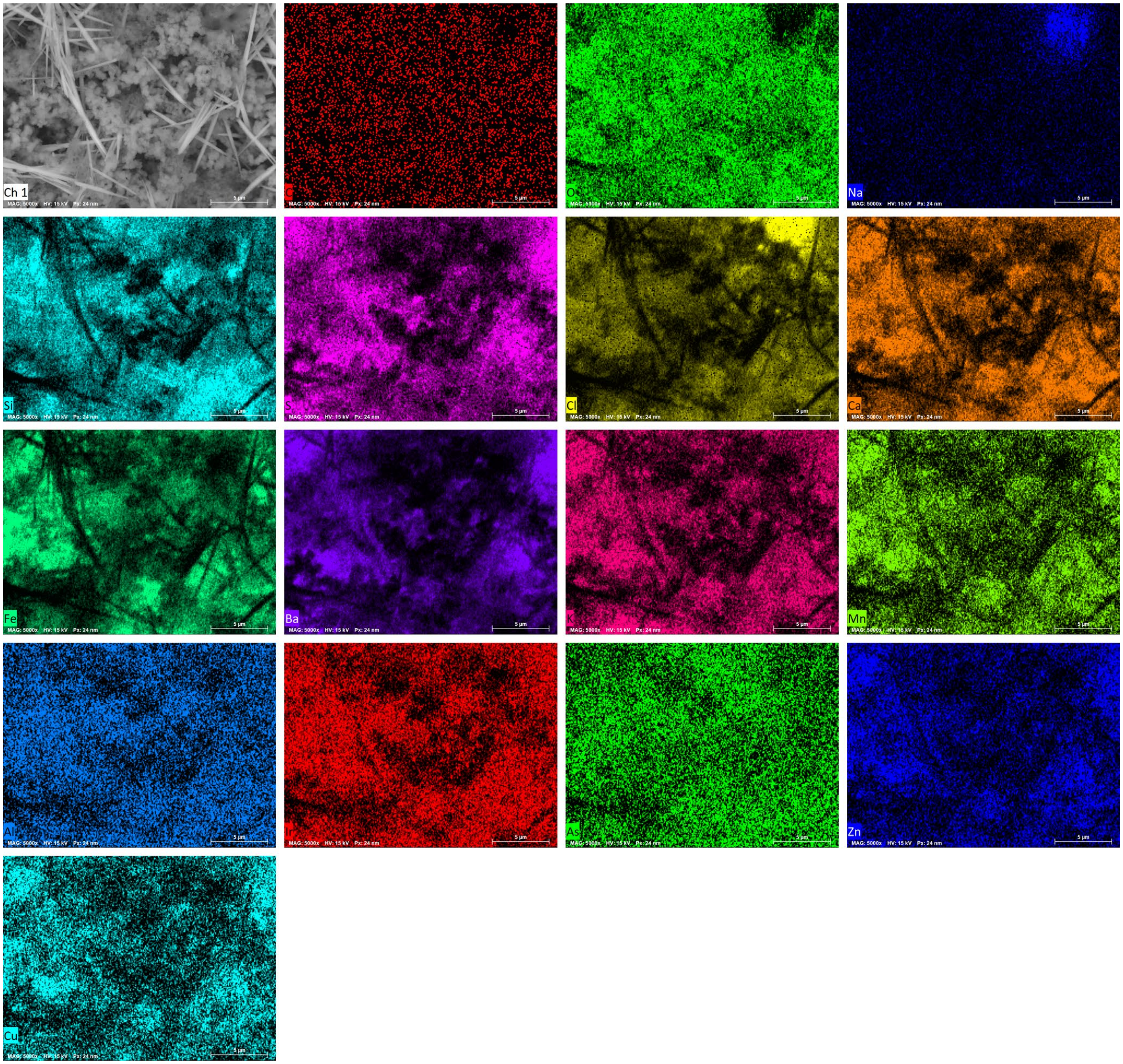
- Sodium and barium chloride crystals
- Calcium fluoride crystals
- Wide variety of oxide particles

Figure 30: DLS Particle Images from SSGF Brine Samples Collected from Pilot Site



Source: PNNL (2024)

Figure 31: Elemental Map from SSGF Brine Samples Collected from Pilot Site



Source: PNNL (2024)

Pilot Test Results

PNNL performed tests using the GMEPS device train and pilot plan shown in Chapter 2 to achieve the previously outlined pilot testing objectives. Below is a summary of the tests performed:

- Operation of a GMEPS device train consisting of a fractionator and avalanche settlers using SSGF brine at the HKG pilot site
- Operation of the pilot plant with five GMEPS device trains in parallel, each consisting of a fractionator and avalanche settlers using SSGF brine at the Cyrq plant

- Operation of the pilot plant with five GMEPS device trains, each consisting of a fractionator and avalanche settlers using synthetic geothermal brine at the Barr Engineering pilot site

The results from field testing support the advancement of GMEPS technology to TRL 6/7. Below is a summary of the results:

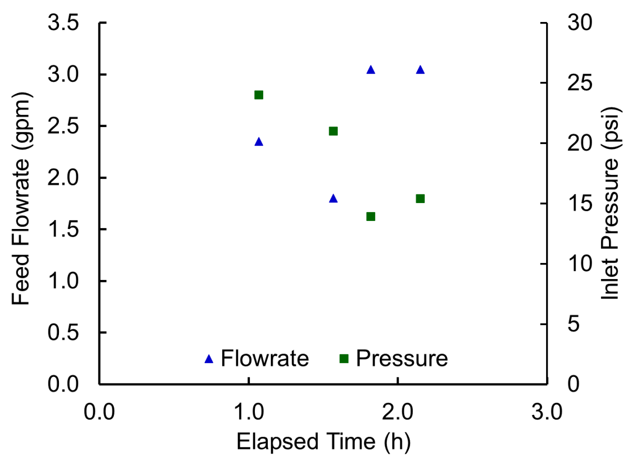
- GMEPS devices can separate and concentrate solid particles from SSGF brine in an operational environment.
- GMEPS devices can maintain uninterrupted steady-state operation for more than 30 hours in a relevant environment.
- GMEPS device trains in parallel can operate at feed flow rates greater than 10 gallons per minute.
- GMEPS devices can operate at varying feed flow rates and temperatures in relevant and operational environments.

Key Findings

Cyrq Hudson Ranch Field Testing

The team operated the pilot plant for two days at the Cyrq plant. The pilot plant operated for a maximum runtime of 5.5 hours on the first day of field testing and managed to run at a maximum brine feed flow rate of 11.4 GPM. The pilot plant operated for more than 2 hours on the second day, and the team measured feed flow rate, pressure, and particle sizes during this test period. Figure 32 shows the data points measured for feed flow rate and pressure during the operating period on the second day, showing the pilot plant was able to achieve steady state operation at approximately 2 hours into data collection.

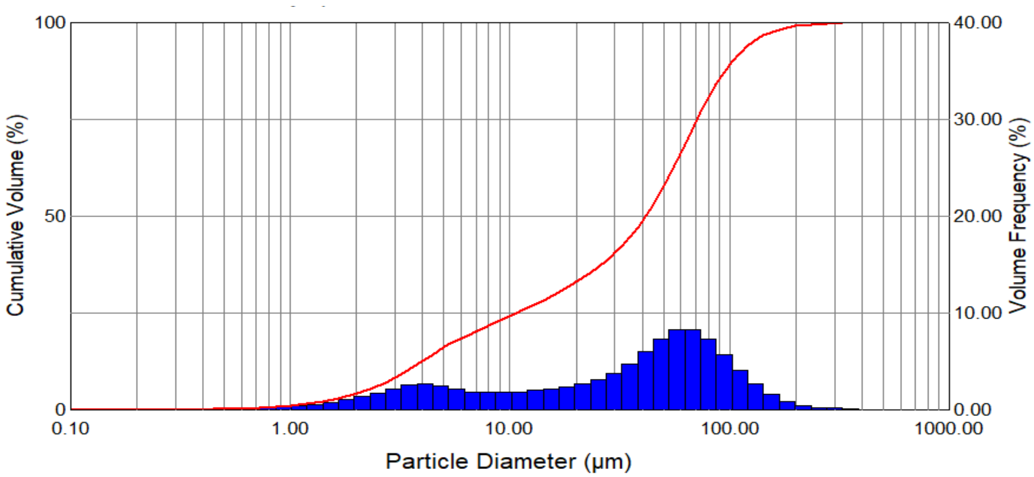
Figure 32: Feed Flow Rate and Pressure of Brine During Cyrq Field Testing



Source: PNNL (2025)

The team collected and analyzed the particle concentrate from the express lanes of the pilot plant device trains to determine if the GMEPS device train separated the larger particles from the brine. Figure 33 shows the particle size distribution of the express lane concentrate, showing a greater concentration of larger-sized particles in the concentrate and therefore demonstrating GMEPS devices effectively separating particles from SSGF brine.

Figure 33: Particle Size Distribution of Particle Concentrate During Cyrq Field Testing

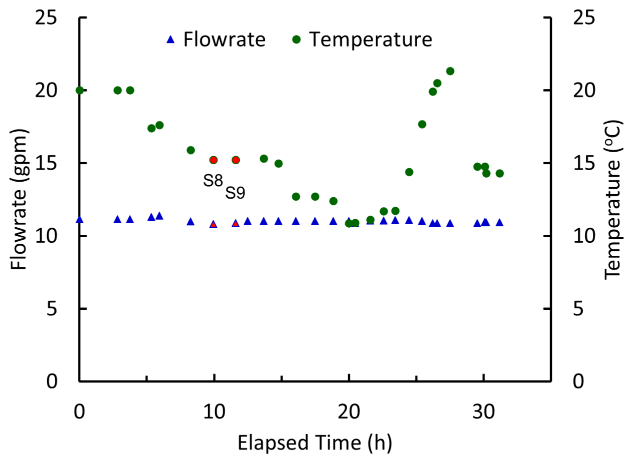


Source: PNNL (2025)

Barr Engineering Pilot Site Field Testing

The team operated the pilot plant at the Barr Engineering site for more than 30 hours at a consistent flow rate of approximately 11 gallons per minute of synthetic geothermal brine, demonstrating steady-state, uninterrupted operation for at least 30 hours. Figure 34 shows the flow rate of the synthetic brine along with ambient air temperature measurements collected during the operating period. The flow rate remained stable despite fluctuating ambient air temperatures.

Figure 34: Feed Flow Rate of Synthetic Brine During Barr Field Testing



Graph shows the feed flow rate of synthetic geothermal brine and ambient temperature during Barr Engineering pilot site field testing. The red points in the figure marked S8 and S9 are specific points where the team added solid particles to test particle separation.

Source: PNNL (2025)

After confirming steady-state operation, the team added two different-sized solid particles, nominally 8 to 12 microns and 55 to 60 microns in diameter, to the brine mixing tank to be run through the pilot at times S8 and S9 shown above in Figure 34 to test particle separation. The team collected brine samples from the permeate and express lanes of the GMEPS device trains in the pilot plant to determine the efficacy of particle separation and concentration. The team also performed particle size analyses using DLS on the express lane, permeate, and inlet feed brines to develop particle size distributions.

Table 1 shows the results of the particle separation tests. The results show the concentration of particles was greater in the express lane than in the permeate and that the median particle size was also greater in the express lane than in the permeate. These results are consistent across both tests and demonstrate that the GMEPS device trains in the pilot plant separate and concentrate larger particles from the brine in the express lane so they do not proceed into the permeate.

Table 1: Particle Concentrations of Permeate and Express Lane Brines Collected During Barr Field Testing

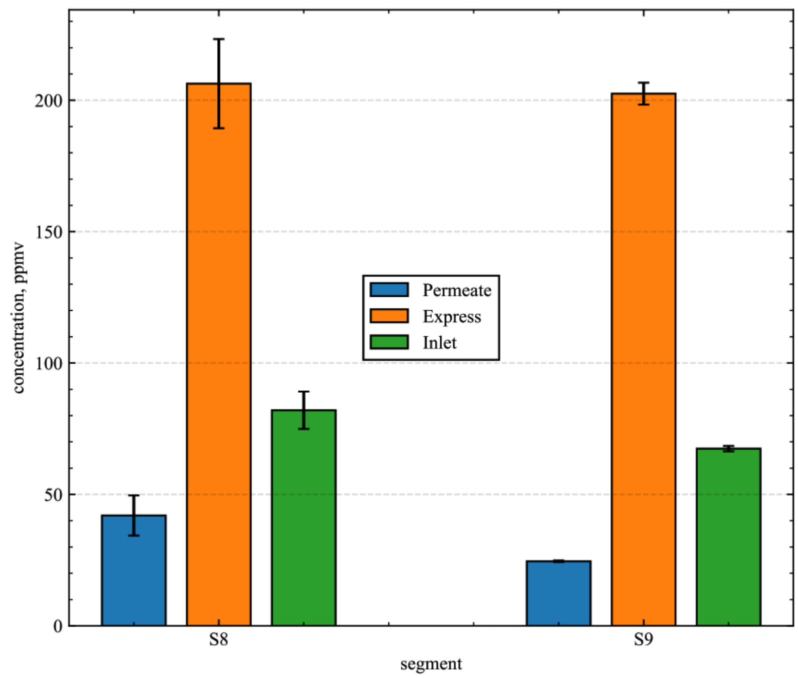
Parameter	S8	S9
Feed Flow Rate (GPM)	10.8	10.9
Train Pressure (psig)	5.6	5.6
Permeate Flow Rate (GPM)	8.17	8.24
Express Lane Flow Rate (GPM)	2.63	2.62
Permeate Particle Concentration (ppmv)	42	24.6
Express Lane Particle Concentration (ppmv)	206.3	202.5
Permeate Median Particle Diameter (microns)	13.9	8.5
Express Lane Median Particle Diameter (microns)	54	54.2
Particle Production Rate (milliliter/minute)	2.06	2.01

Particle production rate refers to the volume of particles exiting the GMEPS device train via the express lanes. [unit definitions: gallons per minute (GPM), pounds per square inch gage (psig), parts per million by volume (ppmv)]

Source: PNNL (2025)

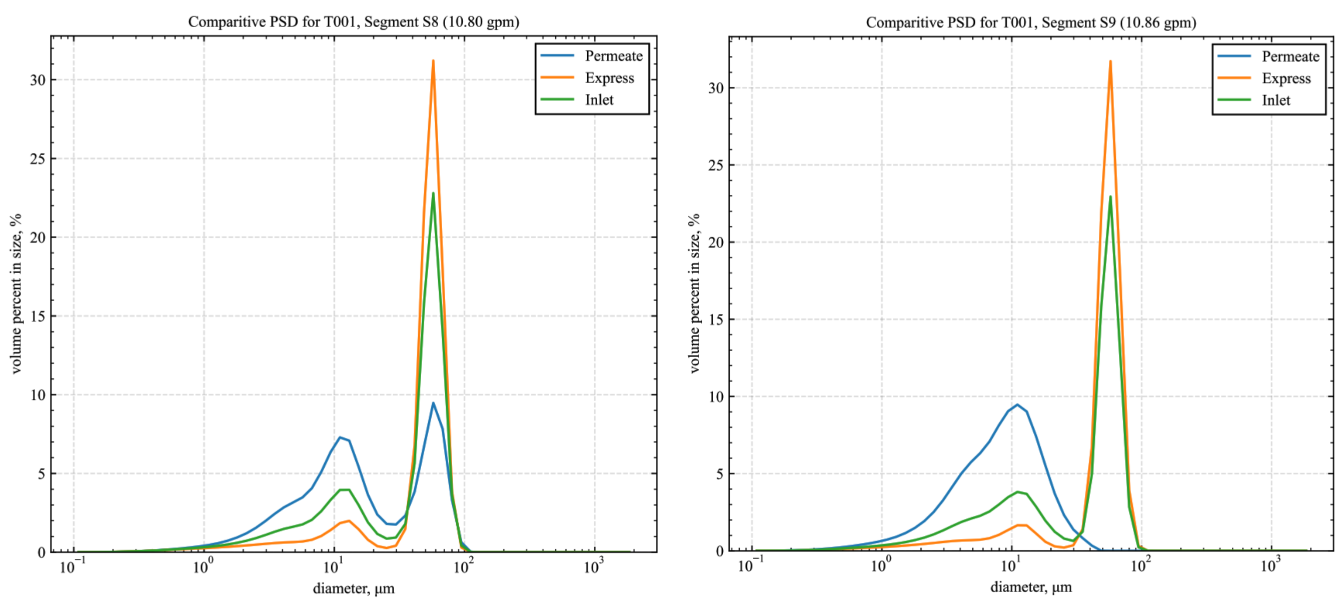
The results in Table 1 are visualized in Figure 35 and Figure 36. Figure 35 visualizes the difference in particle concentration between the inlet feed, permeate, and express lane brines during the particle testing periods outlined in Table 1. The results show that the concentration of particles in the express lane is much greater than the inlet concentration, and the concentration of particles in the permeate is less than the inlet concentration in both test periods. Figure 36 shows the particle size distributions the team developed for each test period during steady-state operation. The results show a greater concentration of larger particles in the express lane than the inlet and permeate, demonstrating particle separation by size.

Figure 35: Particle Concentrations of Inlet, Permeate, and Express Lane Brines During Barr Field Testing



Source: PNNL (2025)

Figure 36: Particle Size Distributions of Inlet, Permeate, and Express Lane Brines During Barr Field Testing



Source: PNNL (2025)

Overall, pilot plant field testing results support the advancement of GMEPS technology to TRL 6/7 by demonstrating operation in relevant and operational environments and show that GMEPS devices separate particles from solution to provide a cleaner permeate to be used in downstream lithium extraction processes.

Barriers and Challenges

The team experienced challenges testing SSGF brines due to variability and differences in the brine composition compared to the results from the particle size analysis performed at the HKG pilot plant, leading to inconclusive results during field testing at the same site. Geothermal brines are dynamic chemical environments so variability within the process is to be expected and will be accounted for in future studies targeting advancement of GMEPS technology to TRL 8.

CHAPTER 4: Conclusion

Benefits of GMEPS Technology to California

GMEPS technology enables more dynamic geothermal plant operations due to its improved turndown capability compared to traditional silica removal methods, allowing geothermal plants to be used for load-following grid operations. GMEPS devices can separate silica particles from geothermal brine based on size to produce potential value-added products. A techno-economic analysis performed on a 140-megawatt geothermal plant using GMEPS technology for precipitate management shows reduced capital costs of approximately $10.5 million and reduced operational costs of approximately $6.3 million per year, a 22 percent reduction in operational costs, for constructing and operating a geothermal plant compared to a facility using traditional CRC silica removal technologies. Further details are available in the Final Engineering Report and Techno-Economic Analysis Report.

The potential benefits of GMEPS technology based on these improvements include:

- More flexibility in operating conditions to build and operate geothermal plants by providing an effective silica removal system with a wide dynamic flow range, expanding and improving renewable energy opportunities in California and allowing geothermal power to be used in tandem with solar and wind power for load-following grid operations.
- Reduced costs to build and operate geothermal plants for utility companies by reducing the labor, materials, and required footprint for silica removal, in turn reducing geothermal energy costs for consumers.
- Reduction of carbon dioxide emissions by using renewable energy resources such as geothermal energy in tandem with solar and wind power.
- Increased energy security by expanding access to geothermal resources.
- Production of value-added minerals from high-purity silica and other minerals removed from geothermal brine.
- Increase in revenue and new job opportunities for Californians by expanding geothermal operations and developing more lithium production facilities in the Salton Sea.

Future Development and Market Opportunities

GMEPS Manufacturing Materials and Methods

Current GMEPS device material options include various polymer composite resins and metal alloys. The team designed and tested GMEPS devices made of various materials throughout the process and found a polymer composite that could be 3D printed into the current GMEPS fractionator and avalanche settler designs for a low cost. The team also explored ceramics as a potential GMEPS material due to their chemical and thermal durability; however, current manufacturing methods for ceramic devices are unable to provide the resolution required for separating particles only microns in size. As 3D printing technology improves, sintered ceramics may become an option for manufacturing GMEPS devices. Alumina ceramics performed well during material tests conducted at the pilot site and may be the ideal material for GMEPS devices in the future.

Mineral Separation

GMEPS technology can potentially recover other in-situ minerals from SSGF brines in downstream processes following silica removal to produce valuable product streams and a cleaner brine feed for lithium extraction. Critical minerals such as manganese and zinc are present in the brine at high quantities and can be recovered as value-added products using GMEPS technology. The proposed HKG geothermal plant will recover lithium from SSGF brines, and GMEPS technology providing cleaner brine to lithium extraction processes in development should improve process economics and effectiveness, yielding cheaper lithium. These potential product streams may further improve the economics of geothermal power and provide a clean, domestic source for critical minerals.

Recommendations

The project outcomes show that GMEPS technology has advanced to TRL 6/7 by demonstrating a system prototype in relevant and operational environments, meaning GMEPS technology is now ready for the next stage of scale-up. The project team recommends designing and implementing a complete process with an actual system and corresponding demonstration of the fully scaled system in an operational environment with end-use qualification to satisfy TRL 8. To that end, further research is required to develop GMEPS device designs capable of handling industrial scale flow rates as high as 1,000 to 10,000 GPM and to determine the appropriate configuration of devices for optimal particle separation and concentration. Based on lessons learned during field testing, the team also recommends the following improvements for future systems using GMEPS devices to remove silica from geothermal brines:

- The pilot plant system successfully controlled the pump, but there is an opportunity for more complete process control, data acquisition, and data sharing. The team recommends the GMEPS system be fully instrumented for fully automated operation and data analysis with refined calibration.
- The glass fiber reinforced thermopolymer composite used for the current GMEPS fractionator and avalanche settler designs allow for simple desktop 3D printing to manufacture devices. These materials performed well in geothermal brine environments and were resilient to various testing conditions; however, the team recommends building the junctions, exits, and entrances between devices out of metal to reinforce joints that sustain additional stresses.
- Flush lines available for field testing did not have controls for temperature or other process variables, leading to variable performance during flushing operations. The team recommends controlling the temperature and particle composition of the flush lines to improve on-site performance of GMEPS devices..

GLOSSARY AND LIST OF ACRONYMS

Term	Definition
ASME	American Society of Mechanical Engineers
CRC	crystallizer-reactor-clarifier
DLS	dynamic light scattering
GMEPS	geothermal mesofluidic enhanced particle separator
GPM	gallons per minute
HKG	Hell’s Kitchen Geothermal
PNNL	Pacific Northwest National Laboratory
SSGF	Salton Sea Geothermal Field
TRL	technology readiness level

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Project Deliverables

Project deliverables are available upon request by submitting an email to pubs@energy.ca.gov.

- Final Engineering Report
- Techno-Economic Analysis Report
- Final Project Fact Sheet
- Final Technology/Knowledge Transfer Report
- Production Readiness Plan