

Geothermal Technical Working Paper No. 5: Produced Fluids

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CONTENTS

1.	Introduction	1-7
2.	Technical Description.....	2-9
2.1	Technology Overview	2-9
2.1.1	Definition and Purpose	2-9
2.2	Technical Features.....	2-13
2.3.1	Process Steps	2-13
2.3.2	Resource Requirements	2-24
2.3.3	Associated Equipment	2-46
2.3.4	Characterization of Geothermal Power Production Wastes.....	2-47
3.	Environmental Impacts and Permitting Issues	3-49
3.1	Potential Environmental Impact Elements	3-49
3.2	Potential Environmental Consequences	3-50
3.2.1	Resource Elements Not Carried Forward for Further Analysis	3-52
3.2.2	Resource Elements Potentially Affected by Management of Produced Fluids	3-56
3.3	Permitting Requirements and Issues	3-67
3.3.1	Geothermal Drilling Permitting Process	3-67
3.3.2	Contingency Plans	3-68
3.3.3	Conditions of Approval	3-69
3.3.4	Relevant Regulatory Framework.....	3-70
4.	Potential Mitigation Measures.....	4-72
4.1	General Mitigation Measures/Conditions of Approval	4-72
4.1.1	Groundwater	4-72
4.1.2	Well Abandonment.....	4-74
4.2	Water Quality Management Plan	4-74
4.3	Best Management Practices.....	4-74
5.	Future Considerations and Conclusion.....	5-76
6.	References	6-77

LIST OF FIGURES

Figure 1-1. Implementation of technology in the geothermal power project	1-8
Figure 3-1. Simplified schematic of a flash steam geothermal power plant.....	3-58

LIST OF TABLES

Table 2-1. Total Mud and Cuttings Volume by State, 1981 to 1985.....	2-26
Table 2-2. Chemicals Used During Well Stimulation Activities.....	2-27
Table 2-3. Summary of Geothermal Scale Formation Mechanisms and Mitigation Options for Silicon Dioxide	2-39
Table 2-4. Summary of Geothermal Scale Formation Mechanisms and Mitigation Options for Metal Sulfides	2-40
Table 2-5. Summary of Geothermal Scale Formation Mechanisms and Mitigation Options for Calcium Carbonate.....	2-41
Table 2-6. Water Technologies for Removing Salt Content.....	2-45
Table 3-1. Environmental Resource Elements Potentially Affected by Management of Produced Fluids.....	3-51
Table 4-1. Best Management Practices for Produced Fluids	4-75

GLOSSARY

Acronyms and Terms	Definition
BLM	U.S. Bureau of Land Management
DCMD	Direct contact membrane distillation; a method of treatment of makeup water used in cooling towers
EGS	Enhanced geothermal systems; refers to a geothermal resource in which the subsurface reservoir has been artificially engineered or enhanced.
Geothermal Fluid (Geo-Fluid)	Any fluid that occurs naturally in rock formations, beds, or strata and refers to the fluid in the subsurface geothermal reservoir. A geo-fluid is a type of produced fluid .
Hydraulic Fracturing	Also called “hydro-fracturing” or “fracking,” this is a technique used primarily to fracture sub-surface rock formations for oil and natural gas recovery and extraction by injecting fluids under high pressure. This process is not meant to alter formation permeability but rather enhance wellbore contact with the permeable formation increasing the flow into/out of the production well or injection well .
Hydraulic Shearing	Also called “hydro-shearing” or “hydraulic assisted shear activation,” this refers to a technique used to increase pore pressure along existing zones of weakness by injecting stimulation fluids under moderate pressure (less than in hydraulic fracturing), such that the existing <i>in situ</i> stresses can create shear failure or shear movement along these planes. By enhancing permeability, this process can help to create flow paths between injection well and production well(s) .
Hydraulic Stimulation	This process involves the injection of fluids through a well into a subsurface formation to stimulate and re-open pre-existing fractures in order to increase permeability. The two main types of hydraulic stimulation are hydraulic fracturing and hydraulic shearing . In geothermal applications, hydraulic stimulation is intended to create pathways for fluid to circulate through heated subsurface rock formations for purposes of power production.

Acronyms and Terms	Definition
Injection Well	This is a well used to inject geothermal fluid from the surface power plant back into the geothermal reservoir.
Make-Up Fluid	This fluid replenishes any fluids lost during the operation of a geothermal power plant, including the geothermal fluid. The make-up fluid consists of water, tracers, corrosion inhibitors, and scaling inhibitors.
NCG	Non-condensable gas refers to any type of gas that does not readily change to a liquid phase upon cooling. Examples include CO₂, H₂S, CH₄, and NH₃.
NEPA	<i>National Environmental Policy Act of 1969</i>
NF	Nano-filtration is a pressure-driven treatment process for makeup water.
Produced Fluid	This is fluid stream generated during any phase of a geothermal project. The vast majority of produced fluid used during operations is used to generate electricity.
Production Well	The well through which geothermal fluid flows to the surface that is then utilized to generate electricity.
RO	Reverse osmosis is a pressure-driven treatment process for makeup water.
Scale	A type of solid that precipitates from the geothermal fluid onto pipes and other equipment. Common types of scale include barium/strontium sulfates, lead sulfides, and other mixed sulfides.
Scaling	The formation of scale on pipes and equipment during a geothermal project.
Scaling (Scale) Inhibitor	These chemical compounds—often acidic in nature—are intended to halt (inhibit) the formation of scale onto pipes and other equipment. Examples of scaling inhibitors are polyacrylic acid and polymaleic anhydrides.
Total Dissolved Solids (TDS)	The amount of solid minerals, specifically salts dissolved in a fluid; dissolved salts may include Na (sodium), Ca (calcium), K (potassium), Cl (chlorine), SiO ₂ (silicon dioxide), SO ₄ (sulfate), and HCO ₃ (bicarbonate).

EXECUTIVE SUMMARY

The U.S. Department of Energy's (DOE's) Geothermal Technologies Office (GTO), in collaboration with the U.S. Department of the Interior's (DOI's) Bureau of Land Management (BLM), has committed to develop and implement a formalized working agreement that will facilitate a technical evaluation of environmental impacts of geothermal technologies. This analysis forms a compendium reference document, which is available as an analytical tool for future agency *National Environmental Policy Act of 1969* (NEPA) documents. The analysis is in the form of a series of technical working papers (TWPs) that will be integrated into the NEPA processes of participating agencies via internal mechanisms. Examples of such internal mechanisms could include BLM issuance of an Instruction Bulletin/Memorandum and DOE guidance documents to Program and Field Offices. The U.S. Forest Service (USFS) and the U.S. Department of Defense (DoD) will implement through their respective agency-specific methods as well.

This analysis and reference document will focus on providing a baseline of knowledge to the agencies on specific technology areas associated with geothermal power production. These papers assume a general knowledge of geothermal activities and focus on giving a detailed description of the features of the specific working paper technology. The technology areas would include those that have previously been identified as contentious and/or are technologically complicated issues to address in the NEPA processes. The goal of this effort is to encourage federal NEPA practitioners to use a technically sound and consistent approach during their environmental reviews to ensure that their NEPA processes are streamlined and efficient. The intention is not for these papers to be regulatory; however, they can be used as reference for BLM and other federal and state agencies when completing a regulatory review.

DOE commissioned these technical working papers with input from technical and NEPA experts. While each paper contains a thorough description of its topic technology, it is not possible, nor was it DOE's intention, to define and address all geothermal-related terminology and regulations. Instead, the goal is to link industry practices with BLM regulations under a common understanding and set of terminology to give guidance for future NEPA and regulatory reviews.

1. INTRODUCTION

Geothermal power taps the heat of the interior of the Earth and uses the hot water and steam found in subsurface reservoirs to generate electricity. This is achieved through a system of wells that bore into permeable subsurface rock formations deep underground. The wells and the rock formation create a loop that brings a fluid stream mixture of heated water, steam, and small amounts of other compounds to the surface for the purpose of converting the heat into electricity. These mixtures are known as “produced fluids,” and they are the focus of this paper. Section 2, in particular, provides an overview of the technology associated with the use of produced fluids.

There are four major phases in the development of a geothermal power project:

- **Exploration:** Geothermal exploration is carried out to help define a geothermal resource in terms of its geometry, boundaries, permeability, temperature distribution, and fluid flow paths.
- **Development:** After a site-specific viable reservoir has been determined, the next phase is to develop the site for commercial operation, including development of the subsurface reservoir and the surface power plant facilities.
- **Production/Utilization:** This phase involves reservoir sustainability through operation, management, maintenance, and repair of all components of the geothermal system and the generation of electricity.
- **Reclamation:** Once a site is no longer viable, all facilities and infrastructure related to the geothermal power project are decommissioned and the project site is reclaimed.

Produced fluids are associated with the first three phases of a geothermal project, including exploration, development, and production /utilization. In focusing on produced fluids, this paper considers these phases and their accompanying processes, and it provides information about the associated activities, equipment, environmental impacts and mitigations, and permitting issues. This paper has a special focus on wells drilled after the geothermal resource has been proven and the site is being developed for commercial operation. Figure 1-1 shows the geothermal power project phases where produced fluids commonly occur.

Geothermal Power Project Phases

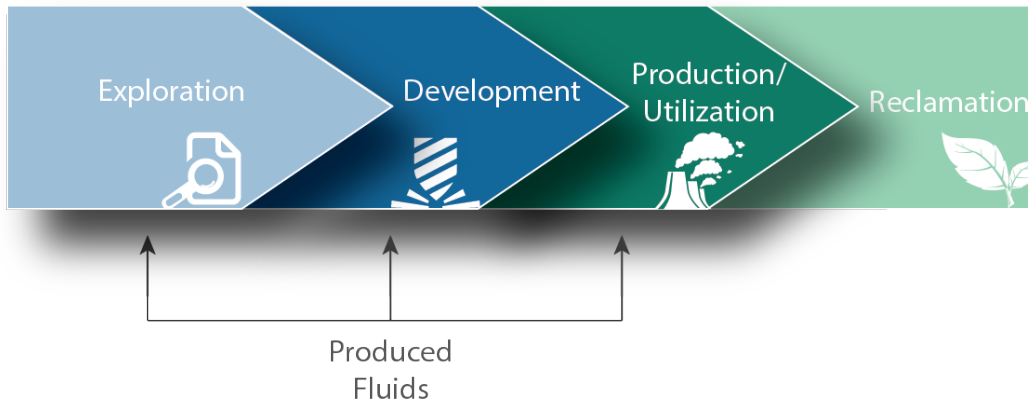


Figure 1-1. Implementation of technology in the geothermal power project

2. TECHNICAL DESCRIPTION

This section provides a technical overview of produced fluids, identifies typical treatment technologies, and discusses produced fluid management strategies across the geothermal development and production life cycle. The appropriate management approach will vary depending on the life cycle stage, as well as the amount of and the physical and chemical characteristics of the produced fluids.

2.1 TECHNOLOGY OVERVIEW

2.1.1 Definition and Purpose

Produced fluids refer to the mixture of fluids produced on-site during geothermal energy exploration, development, and production /utilization activities. Broadly speaking, produced fluids include any fluid that comes out of a well and subsequently must be managed on the surface. These fluids can include water and fluids used to drill geothermal wells; fluids used to stimulate wells in Enhanced Geothermal Systems (EGSs); fluids from the subsurface reservoir (called geothermal fluids or “geo-fluids”) that enter the power plant and transfer heat for electricity generation; and recondensed fluids that originated from the subsurface reservoir and that are used for cooling during the operational stage.

The proper characterization of these fluids is critical because they usually require specialized handling and management, and thus, they have important environmental implications. For purposes of this TWP, waste streams, such as lubricants, hydraulic fluids, solvents, paints, and sanitary wastes, are not considered “produced fluids” if they *are not* exempt from consideration as a hazardous waste under federal hazardous waste rules at 40 Code of Federal Regulations (CFR) §261.4(b)(5). Furthermore, this document does not discuss these waste streams. Many of the waste streams that *are* exempt from consideration as a hazardous waste include fluids that are considered to be “produced waters;” for the purposes of this document, these “produced waters” are somewhat similar to exempt wastes streams from the exploration and production activities in the oil and natural gas industry.

2.1.1.1 General Lifecycle of Produced Fluids

Produced fluids occur in all stages of geothermal energy production from pre-production or exploratory drilling to the operation of a geothermal power plant. They include many of the waste streams that are exempt from hazardous waste rules under 40 CFR §261.4(b)(5), and they are similar to exempt wastes from the oil and gas exploration and production industry and include the following:¹

- Drilling fluid additives (including caustics)

- Drill cuttings/solids
- Drilling fluids/muds
- Cement slurry returns and cement cuttings
- Produced sand
- Produced water
- Produced water constituents removed before disposal
- Well completion, treatment, stimulation, and packing fluids
- Pit sludges and contaminated bottoms from storage or disposal of exempt wastes
- Tank bottoms and basic sediment from storage facilities that hold exempt waste (including accumulated materials such as solids, sand, and production impoundments)
- Workover wastes (e.g., blowdown, swabbing, and bailing wastes).

Additional geothermal-related produced fluids include fluids from geothermal reservoirs; scale; flash tank solids; precipitated solids resulting from the treatment of brine; hydrogen sulfide (H₂S) wastes; and cooling tower-related waste. ²

Figure 2–1’s depiction of a typical geothermal power plant is helpful for identifying where produced fluids can occur during geothermal power plant development and operations.

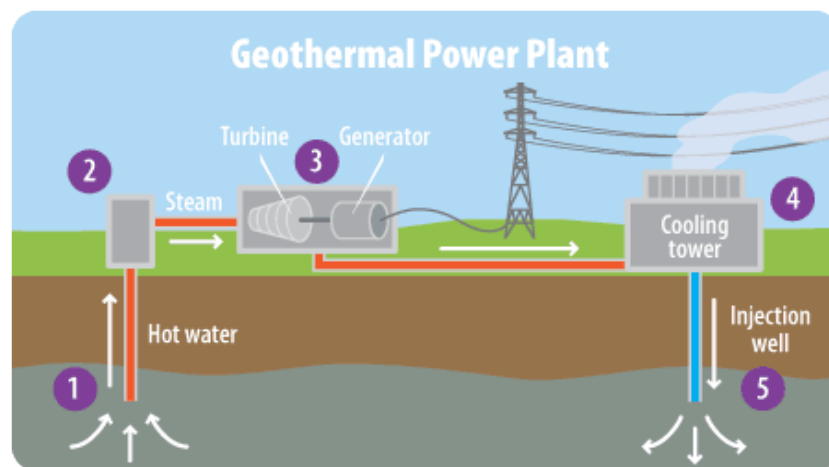


Figure 2-1. Schematic representation of a geothermal power plant³

During construction of a well (step 1 in Figure 2-1), produced fluids are generated from drilling and cementing as a result of conveying drill cuttings and cement cuttings to the surface. These produced fluids must then be managed and treated on the surface.

For EGS geothermal projects, hydraulic stimulation of the well must also occur to enhance the subsurface reservoir. During hydraulic stimulation, pressurized water is injected underground to increase permeability of the rock formation (see *TWP No.4: Hydraulic Stimulation*). Certain chemicals such as gel proppants, tracers, and diverters are sometimes added to the injection fluid to aid in this task. Flow tests and circulation tests—which are common among all geothermal projects and essential in an EGS one to confirm connectivity of the formation—return these fluids to the surface, where they may subsequently receive treatment to remove these additives.

Finally, during operation of the geothermal power plant, produced fluids are present when the geo-fluid is used as makeup and/or cooling water. In a conventional wet-cooled geothermal power plant, cooling water is used to help condense the steam in the cooling tower (step 4 in Figure 2-1) after it exits the turbine and generator (step 3 above). Additionally, makeup water in the form of reservoir enhancement is occasionally used to address declining geo-fluid water volume in the formation.

2.1.1.2 Produced Fluids from Well Drilling Activities Definition and Purpose

During the drilling process, drilling fluids or “muds” are used to lubricate and cool the drill bit, to modulate corrosivity, to maintain downhole hydrostatic pressure (thus preventing blowouts and stabilizing the wellbore), and to convey drill cuttings from the bottom of the hole to the surface.⁴ To accomplish these tasks, drilling muds contain chemicals and constituents to control factors such as density and viscosity, and to reduce fluid loss to the formation. For a single 2-km deep geothermal well with a 32-inch surface diameter casing, the estimated drilling mud volume needed is approximately 845 cubic meters or 223,225 gallons.⁵ This is roughly one-third the volume of an Olympic-size swimming pool. In practice, a geothermal project will consist of many such wells (both pre-production and production) over the course of its life. Thus, during the well-drilling stage alone, the volumes of produced fluids that must be managed for a geothermal power plant are likely to run into the millions of gallons.

2.1.1.3 Produced Fluids from Stimulation Activities and Flow and Circulation Testing Definition and Purpose

For EGS projects, stimulation may occur at one or more wells to improve water circulation through a geothermal resource by expanding existing fractures or creating new ones. Stimulations in geothermal energy projects can either be hydraulic or chemical in nature. The characteristics of fluids produced from stimulation activities will depend both on the constituents of the downhole fluids and the characteristics of the reservoir. For more information on downhole fluids, see *TWP No. 3: Downhole Fluids*.

In hydraulic shear stimulation, fluid is injected at sufficiently low pressures such that the least horizontal principal stress is not exceeded, and the rock formation is sheared rather than fractured.⁶ The lower pressures ensure that the propagation of shear displacement occurs along

the existing fracture plane. This approach avoids the use of proppants, which may be difficult to employ in thermal reservoirs because of the increased solubility of silica. Hydraulic shear stimulation typically uses whatever water source is most readily available. A recent analysis of 10 geothermal projects conducted by Argonne National Laboratory found that five used groundwater for stimulation fluid; two used surface water; one used treated wastewater; one used condensate; and one used storm water.⁷

Chemical stimulation typically involves the use of acid with a goal of mobilizing and removing acid-soluble materials from the well hole or from fractures in close proximity to the well. There are two types of chemical stimulation operations: *matrix acidizing* and *fracture acidizing*.

In matrix acidizing, the acidic stimulation fluid is injected at a low enough pressure to prevent fracturing. In the case of fracture acidizing, the technique involves injecting an acidic fluid into the formation at sufficient pressure to cause a wellbore pressure buildup, which results in an increase in fracture length and width.⁸ Chemical stimulation has been used in multiple geological settings including sandstone in the Groß Schönebeck Project in Germany and granite at the Soultz-sous-Forêts Project in France.⁹ Chemical stimulation is used when a geothermal project is having technical issues with its production and injection wells. It is often seen as a last resort for removing scale and other precipitates before a well is completely abandoned.

In addition to stimulating an EGS reservoir, there are several tests that must take place to verify enhancement and circulation. Circulation and flow testing is the physical means by which many of the additives used in the drilling phase end up on the surface and must subsequently be managed and/or treated, and thus they are relevant to this discussion of produced fluids. Each of these tests requires the addition of water. These include pre-stimulation and post-stimulation tests for an individual well; a short-term circulation test once a doublet or triplet production and injection well system has been installed; and a long-term circulation test once the series of doublet or triplet wells have been installed at commercial scale.¹⁰

Some estimates of typical water volumes, flow rates, and lengths of time of steps for long-term circulation have yet to be verified with commercial-scale EGS development.¹¹ Although consumption estimates assume that no water is reused, it may be possible for water recovered from one test to be used for another test. In this way, these fluids can be “produced” more than once. Finally, during circulation and flow testing, chemical additives known as tracers are added to the downhole fluid. These chemicals help characterize the way water flows through the underground formation during EGS testing. Tracers used at the Newberry Volcano EGS Demonstration Project included naphthalene sulfonates, rhodamine WT, lithium, cesium, rubidium, fluorescein, and safranin T.¹²

2.1.1.4 Produced Fluids from Operational Activities: Definition and Purpose

The vast majority of produced fluid used during operations is used to generate electricity. This fluid (chiefly water) is extracted from the geothermal resource and is commonly referred to as the geo-fluid. Geo-fluid is produced from a geothermal reservoir and directed into the geothermal power plant to produce electricity.

For flash systems, the geo-fluid is flashed to vapor to drive a steam turbine and then passed through a condenser to recover fluid for cooling prior to reinjection into the reservoir. A portion of the fluid that remains in the liquid phase is also reinjected. The vapor that was not condensed enters the cooling tower and is lost via evaporation or drift. In binary systems, the geo-fluid is completely reinjected into the reservoir. In addition to electricity generation, the fluid (usually water) is used to condense vapor for (1) reinjection as a geo-fluid, or (2) in the case of binary systems, for reuse as the working fluid. Produced fluid is also used in normal operations to manage dissolved solids and minimize scaling.¹³

2.2 TECHNICAL FEATURES

2.3.1 Process Steps

Produced fluids are a result of drilling, stimulation, and operational activities within a geothermal power plant. This section discusses the process steps involved with the produced fluids of each activity.

2.3.1.1 Produced Fluids from Drilling and Stimulation Activities: Process Steps

Management of produced fluids and their interaction with the surface environment is extremely important during geothermal energy development. As noted earlier in this document, the law requires operators to manage most kinds of produced fluids according to specific state and federal guidelines and regulations.

Geothermal-related drilling muds and drill cuttings can be retained in on-site reserve pits or trucked to an off-site disposal location. In the last century, according to the U.S. Environmental Protection Agency (EPA), if regulatory thresholds were exceeded, drilling muds were sampled and trucked off-site for disposal in a licensed landfill.¹⁴ If thresholds were not exceeded, wastes were placed in an on-site reserve pit designed with a 2-ft-thick clay liner having a permeability of 10^{-6} centimeters (cm)/second. EPA also describes a land farming option while mentioning that such a disposal method was controversial because of the high chloride content of drilling waste in some locations.¹⁵

General water management activities, of which produced fluids are a subset, related to drilling on public lands generally conform to standards given in a reference book published by the BLM in 2007 entitled *Surface Operating Standards and Guidelines for Oil and Gas Exploration and*

*Development.*¹⁶ This book is more commonly called the “Gold Book” and serves as a standard for general drilling guidelines and for the management of water during these activities.¹⁷ Geothermal energy development falls within the purview of these guidelines.

For drilling, the Gold Book recommends that a reserve pit be excavated on each well pad for the temporary storage of drilling muds, flow test fluids, and drill cuttings. The capacity of the reserve pit depends on the extent of the drilling and can range up to more than a million gallons.¹⁸ It is recommended that reserve pits be constructed away from areas with shallow groundwater and not near natural watercourses such as wetlands, streams, or lakes.¹⁹ The reserve pits should be lined with either synthetic liners or materials such as bentonite or clay to minimize the contamination of on-site soils and groundwater.²⁰ Reserve pits should also be appropriately fenced to deter people, livestock, and wildlife.²¹ Finally, the management of storm water on and away from the well pad site is also important to consider.

Reserve pit reclamation, and subsequent disposal of produced water, is another area in which the Gold Book offers guidelines. Disposal of produced water often requires permits from EPA, in addition to authorization by the BLM under Onshore Order No. 7.²² The reserve pit must be reclaimed to a “safe and stable condition,” which includes disposing of the produced water; dealing with liquid and solid wastes that may have accumulated in the pit; removing the pit liner; and filling in the pit to blend in with the rest of the reclaimed well pad area.²³ The disposal of hazardous substances in the reserve pit must be in accord with federal and state waste management regulations.

A 2006 survey of waste-handling practices used in oil and gas exploration and production may be relevant for understanding the proper handling of geothermal exploration and development waste. The authors surveyed many states with known geothermal resources. They found that oil and gas drilling muds were disposed of both on-site in specially prepared reserve pits and off-site in commercial landfills. The authors also found that the handling of liquid exploration and development wastes included permitted discharge to surface waters, discharge to publicly owned treatment works, or underground injection at commercial facilities.²⁴

One form of bio-remediation technology was used for handling the drilling mud and drilling cuttings obtained from drilling five geothermal wells at the San Jacinto Tizate geothermal project in Nicaragua.²⁵ The approach involved mixing drilling mud and cuttings with soil amendments (manure and fertilizer), periodically mixing the treated materials, and then vegetating the modified soil mixture with specially selected grasses.

The Gold Book does not offer specific guidelines for water management during stimulation of EGS projects. However, many of the existent drilling guidelines could be used in these projects.

In addition to guidelines from the BLM there is also *the Pollution Prevention Act of 1990*, under which EPA supports pollution prevention technology by encouraging the appropriate use of

synthetic-based drilling fluids in place of traditional water- and oil-based drilling fluids.²⁶ Their use will generally lead to more efficient and faster drilling as well as a reduction in non-water-quality environmental impacts.²⁷

2.3.1.2 Produced Fluids from Operational Activities Process Steps

Following the extraction of heat for the production of electric power, the geo-fluid is reinjected into the rock formation. Additionally, at some geothermal power plants, other fluids associated with operation such as condensate and cooling water blowdown are injected along with the geo-fluid.²⁸ As previously discussed, these produced fluids can contain high levels of total dissolved solids (TDS), heavy metals, non-condensable gases (NCGs), and other constituents, any of which may exceed primary drinking water standards or health advisory levels.^{29, 30}

The characteristics of produced fluids vary by location and change over time. Different locales have different climates, regulatory or legal structures, and degrees of existing infrastructure. As a result, no single treatment technology is used at all locations. Many different technology options are available that can be employed at specific locations. Selection of a management option at a particular site will vary and depends upon the following factors:³¹

- Chemical and physical properties of the water
- Volume, duration, and rate of water generation
- Desired end use or disposition of the water
- Treatment and disposal options allowed by state and federal regulations
- Technical and economic feasibility of any particular option, including transportation and logistics
- Availability of suitable infrastructure for disposal
- Willingness of companies to employ a particular technology or management option that includes issues such as concerns about potential liability
- Costs involved in meeting the requirements and restrictions set by the regulatory agency.

Operators must manage produced fluids in a cost-effective manner that minimizes environmental impacts and complies with federal and state regulatory requirements. The primary management options include reinjection back into the geothermal reservoir; disposal to a nearby surface water body or evaporation pond; reuse or recycling for agricultural, industrial, and/or hydrological purposes; and treatment for the recovery of other valuable resources (e.g., minerals or fresh water). This paper discusses environmental impacts and mitigation measures in Section 3 and relevant regulations in Section 4.

2.3.1.3 Onsite Surface Disposal

Many types of industrial wastewater are discharged to streams, rivers, and other surface water bodies. The federal *Clean Water Act* (CWA) requires authorization for all discharge of pollutants to surface waters. A permit issued by state agencies under the National Pollutant Discharge Elimination System (NPDES) program grants this authorization. In order to meet CWA goals and requirements for produced water discharges, NPDES permits must consider two types of effluent limits: technology-based and water quality-based. The permit must then be based on the more stringent of these two approaches. In general, technology-based effluent limits can be found in EPA and state regulations. For example, EPA and many state agencies have adopted effluent limitations guidelines (ELGs) for numerous industries. However, no ELG exists at present for geothermal energy operations. Thus, in the absence of applicable national technology-based limits for industrial wastewater or pollutant discharges, permits are based on best professional judgment to identify technology-based limitations on a case-by-case basis.³²

Discharging produced fluids directly from a well site presents various challenges. For example, produced water typically contains high levels of TDS (a measure of salinity) and other constituents that would require treatment and compliance with federal and state water quality standards and regulations.

Another potential on-site disposal option involves storage, sedimentation, and/or evaporation in specially designed ponds.^{33, 34} This process would be particularly applicable to arid climates by taking advantage of natural conditions such as humidity, sun, and wind. By contrast, it would not be practicable in humid climates. However, even in arid climates, this technique has a number of drawbacks. First, ponds have large land requirements.³⁵ Second, the potential for water recycling is lost, increasing the water supply budget. Third, this process can take several years to complete before the sediment is sufficiently dense enough to allow blending and capping, allowing open ponds to become an on-site hazard.³⁶ Finally, there is the potential to create future air quality issues and salt deposition problems.³⁷

2.3.1.4 Reuse and Recycle

Due to the growing potential of water shortages and resulting arid farming land, it is increasingly important to find ways of recycling wastewater. Geothermal produced water can be considered a potential resource for industry and agriculture, as well as for supplying drinking water to displace demand on existing potable water supplies. However, it is important to note that the reuse of produced fluids could impact the long-term sustainability of a geothermal reservoir unless fluids are being replaced.

Research has found that turning produced water into a drinking water resource entails knowledge not just of the techniques to remove dissolved organic and inorganic compounds from the waters but also a broader understanding of the environmental and economic

implications of doing so. By contrast, treatment of geothermal water and condensate for beneficial use only (that is, not for drinking water) involves only the removal of inorganic components.³⁸ Beneficial use applications may include agricultural, industrial, and others (e.g., vehicle washing, firefighting, and dust control on gravel roads).³⁹

The processes used for ensuring that geothermal water treatment meets water standards greatly depends on the source constituents but does include the following:

- Desilication of the waters to produce marketable minerals
- Removal of dissolved solids by membrane or evaporation
- Blending, augmenting, or diluting with fresh water
- Removal of arsenic by oxidation/precipitation
- Removal of boron by various methods, including ion exchange.⁴⁰

Agricultural Use: Treated produced waters could have agricultural uses such as irrigation and livestock and wildlife watering.⁴¹ These applications could especially benefit arid areas—although the water may still need to be treated.

Use of such produced water in managed/constructed wetlands would provide a natural form of treatment. It would also provide the added benefits associated with wetlands, including the creation of a good habitat for wildlife. The downside to this option would be its large space requirements and its need for extensive oversight and management.⁴² Depending on the contaminants originally in the water, this option may also require some special degree of pretreatment prior to wetland application.

Industrial Use: The oil and gas industry can substitute produced water for fresh water supplies in the making of new drilling fluids or hydraulic fracturing (“fracking”) fluids. To be successfully used, the water may need treatment to meet operational specifications, and there must be a new well close by waiting to be drilled or stimulated in order to avoid long-term water storage.⁴³

Cooling towers are an essential part of power-generating facilities and require large quantities of water for continuous operation. To meet the high water demands, cooling towers use makeup water from various sources such as the sea, lakes, rivers, irrigation ditches, and groundwater, which, in some cases, is trucked to the geothermal facility. Reclaimed and recycled water has also been used as a makeup water source. Treatment is often required, and the quality of the makeup water dictates the number of possible cycles in the cooling tower.⁴⁴ Other drawbacks include the large volumes needed, which could result in huge collection and transportation costs, depending on the distance between extraction wells and power plants.⁴⁵

Currently, advanced membrane separation technologies are some of the more promising technologies for the treatment of cooling-tower water. Pressure-driven membrane processes [e.g., reverse osmosis (RO) and nanofiltration (NF)] have already been shown to be an effective method for producing high-quality water for reuse. RO and NF separation technologies remove dissolved impurities from water through the use of a semi-permeable membrane. NF separation technologies primarily remove divalent ions (e.g., Ca^{2+} , Mg^{2+}); whereas RO removal rejects divalent ions along with monovalent ions (e.g., Na^+). RO removal can be a high-energy process because the applied pressure for removal of ions must be greater than the osmotic pressure created by the high-salinity feed solution on the active side of the membrane and the high-purity (permeate) stream on the support side of the membrane. Because of the potential for high energy requirements in RO removal, NF may be a more desirable process. NF is a much less energy-intensive process that will still produce high-quality water.⁴⁶

One of the major problems associated with operation of RO and NF is membrane fouling and scaling. Membrane fouling refers to the formation of deposits on the membrane surface that can cause loss of flux and membrane damage, resulting in increased capital and operating costs. To reduce the occurrence or severity of fouling, the amount of contaminant loading in NF/RO systems needs to be lowered. Pretreating the source water to remove suspended solids typically accomplishes this reduction.⁴⁷

Cooling tower basins can be coated with epoxy resin to minimize these biofouling and corrosion problems. A biocide or a combination of bleach and trichloroisocyanuric acid can control biofouling. Another approach is to add caustic soda to control concrete dissolution by increasing the water pH from about 7 (the natural pH of water) to about 8. This treatment program is designed to control microbiological fouling of heat exchangers and cooling towers, regulate the pH of the water for mitigation of concrete dissolution, and abate H_2S gas emissions from the water to the atmosphere.^{48, 49}

Another option for the treatment of cooling tower water is direct contact membrane distillation (DCMD). DCMD is a thermally driven separation in which warmer feed water is in contact with the active side of the membrane and a cooler water stream is in direct contact with the support side. The driving force for mass transfer in DCMD is the vapor pressure difference across the membrane induced by the temperature difference across the membrane. Because increased concentrations of dissolved salts only have a minimal effect on the partial vapor pressure of water, DCMD has the potential to be an ideal treatment method for highly saline feeds.⁵⁰ Both NF and DCMD have been found to be effective treatments for geothermal brines. Because of the high turbidity and silt density index (SDI) of the blowdown water, pretreatment has been determined to be a necessary step. Pilot testing of the NF system showed that high-quality water could be produced at high recovery (60 %). In one reported case, the system operated for 100 hours with a flux decline that could be partially recovered after cleaning. This mini-pilot DCMD was able to operate with limited flux decline. However implementation at either pilot or full-

scale would require waste heat in order to be economically feasible. It is believed that DCMD would be a logical and effective choice for treating superheated geothermal brines.⁵¹

Domestic Use: Over the years, a number of efforts have been made to either produce fresh water directly from geo-fluids or use geothermal energy as an energy source for desalination. While produced water has low salinity and may be suitable for reuse with little or no treatment, this is not typically the case.⁵² For high-saline-produced waters, thermal distillation processes can be used to produce very clean water. After passing through the treatment unit, the water is segregated into a freshwater stream and a concentrated brine stream. The concentrated brine stream is hauled off-site for disposal at a commercial disposal facility while the clean water can be reused.⁵³

Although this process has been proven to be a technically feasible option, particularly for communities in arid areas, attempts to produce freshwater have run into high operating costs and other challenging economics.^{54, 55}

Another domestic application of geothermal fluids involves the heating of cold groundwater that is piped into a town's central heating system.^{56, 57} This is being done at the Nesjavellir geothermal field in Reyjavik, Iceland. The first step of treatment is to separate geothermal water and steam. The water and steam are piped separately to a powerhouse where steam turbines generate electricity. The excess water is partly disposed of in a shallow well in a nearby lava field and partly into on-site reinjection wells. The steam is condensed in a tubular condenser and cooled to approximately 55°C with cold groundwater, and then it is piped through heat exchangers for final heating to 87°C using the 192°C geothermal water from the separators. By degassing under vacuum in the deaerators, the dissolved oxygen is removed from the heated water. The final treatment before the water is pumped to Reykjavík for district heating is to inject some geothermal steam, which acts to remove the last traces of dissolved oxygen (via reaction with the H₂S in the steam) and adjust the water to pH 8.5.⁵⁸

Reuse for Hydrological Purposes: Reuse for hydrological purposes includes stream flow augmentation. In this case, the produced fluid is treated to meet allowable discharge standards to help augment declining water levels in streams. Some interstate rivers are subject to compacts that require upstream states to provide a minimum flow level for the downstream states. However, this use requires treatment to meet allowable discharge standards.⁵⁹

2.3.1.5 Mineral Extraction and Recovery

Geothermal fluids have had intimate and lengthy contact and interaction with the layers of crust through which they have flowed, resulting in dissolution of minerals and metals from the host rocks and solution into the hot water.⁶⁰ Potential products present in geo-fluids include silica, zinc, lithium, and precious metals.⁶¹ Some of these aqueous solutions can be rich in these materials, while others are relatively dilute.⁶² This mineral content may be considered more a

nuisance than an asset; however, if produced fluid from a particular formation contains sufficient concentrations of desirable compounds, it can be a cost-effective feedstock for the extraction of these minerals as marketable by-products. As a result, in addition to energy production, geo-fluids have long been looked at as potential sources of other valuable resources, particularly as minerals and metals.

In the early history of geothermal resource development, boric acid, sulfur, and ammonium salts were recovered commercially until they lost economic competitiveness to other mining processes.⁶³ Much effort was also historically focused on the production of potassium chloride (used for fertilizer production), carbon dioxide for industrial purposes, and a range of industrial metals [e.g., zinc, lead, iron, magnesium, silver, and manganese]. None of these efforts proved economically viable over extended periods. Major challenges included high operating costs and changes in the market price of the product.^{64, 65} A survey of historical literature on the extraction of minerals from geothermal brines identified at least 14 projects that attempted to economically produce a range of minerals from geothermal brines, including lithium, zinc, manganese, magnesium, sodium chloride, potassium chloride, calcium chloride, silica, and borax.⁶⁶ Of these projects, very few were more than a temporary commercial success.

Reasons for failure varied, but they included changes to underlying commodity prices and high operating costs resulting from high temperatures, scale and corrosion, and challenging separation processes due to complex brine chemistry. In addition, requirements for reinjection of spent brine to preserve the resource and minimize subsidence severely limit its use in many current geothermal systems.⁶⁷

In general, resource removal optimally takes place after or near the end of the energy extraction process but prior to reinjection. Separation processes historically used or proposed for the extraction of minerals and metals from geothermal brines primarily included evaporation and crystallization. Another option for dissolved species involves photo-assisted oxidation, followed by subsequent removal through precipitation/co-precipitation.⁶⁸

Other processes have included enrichment through RO and extraction using ion exchange resins or functionalized carbon/silica aerogels.⁶⁹ It appears that systems utilizing selective ion exchange or similar processes may have the most potential in these cases. Modern materials engineering may allow for the development of cheaper and more selective ion exchange resins that can better withstand the harsh conditions present in geo-fluids.⁷⁰

One of the general problems encountered with the extraction of metals from aqueous solutions involves changes in pH associated with the exchange of metal ions for hydrogen ions in ion exchange reactions. This causes a progressive lowering of the pH, which in turn impedes the efficiency of the process. Attempts to solve this problem have been reported, but their success has been limited.⁷¹

A significant advantage of mineral extraction from geo-fluids compared with other brines is that much of the difficult heavy lifting of well drilling and pumping have already been done for energy production, lowering the bar for economic production. However, the economics of mineral extraction are driven by numerous factors such as geo-fluid chemistry; product quantity and quality; market price, size and accessibility; recovery cost; and operational challenges (e.g., scale and corrosion).^{72, 73} Thus, the potential for mineral extraction from extracted water will be highly site-specific.

While it is possible, and even likely, that there will be formations that have favorable conditions for mineral extraction, these will probably be the exception rather than the rule. This conclusion is made based on the past history of mineral extraction from brines.⁷⁴ Based upon this (limited) analysis, products with the greatest economic potential are silver, potassium, lithium, manganese, silica, and zinc.⁷⁵ This result is consistent with the past history of geo-fluid mining. However, this history also shows that large economic potential does not in any way guarantee that the resource can be exploited profitably.⁷⁶

Most of the work in this field has focused on extraction of silica, lithium, zinc, and manganese, the resources that have the greatest potential to be economically extracted. Therefore, these materials are the focus of a more detailed review provided in the sections below, with other materials such as sulfur and types of salts noted at the end.

Silica: The silica in geothermal fluids interferes with traditional extraction methods because of its tendency to cause equipment fouling. Thus, the removal of silica is a necessary precursor to extracting other valuable dissolved elements from geothermal fluids. Moreover, by purposefully precipitating silica as a high-surface area, porous material with properties similar to those of commercially precipitated silica, the initial silica-scaling problem is not only solved, but a marketable by-product is produced. Other possible side benefits from this process include additional energy extraction that would not otherwise be economically feasible due to scaling and recycling of the low-TDS permeate for use in cooling processes.^{77, 78} Researchers are evaluating whether silica can be used as a cement substitute in building blocks.⁷⁹ Salton Sea geo-fluid treatment residuals have been used as beneficial building materials.⁸⁰

Many methods have been used to precipitate silica as a commercial-grade commodity, along with other valuable metals, from geothermal fluids. One common technique uses an RO separation unit to concentrate the brine and create a freshwater stream, which could be used for evaporative cooling.^{81, 82, 83, 84} The concentrated brine is then pumped into a reactor where an agglomerating agent or flocculant is added to enhance precipitation before the silica is extracted.^{85, 86} As a case in point, the addition of a base (e.g., soda ash [Na_2CO_3], lime, and hydroxides) that raises pH to 8.0 ± 0.5 can increase the buffering capacity of the fluid and enhance water desilication, resulting in undersaturation with respect to amorphous silica.⁸⁷ A salt (e.g., magnesium chloride), which dissolves into active cations, or synthetic polymer electrolytes can

also be added to a geo-fluid to increase polymerization rates and facilitate agglomeration of silica.^{88, 89} Depending on the particle size, filtration, settling, or centrifugation can remove silica particles from the solution. Modern ultrafiltration membranes have been incorporated into silica extraction processes.^{90, 91}

Geothermal silicas can be of very high purity, greater than 98 weight percent for untreated silica, and about 99.6 weight percent for acid-rinsed silica. These compositions compare favorably with commercial-precipitated silica that often have 1– 5 weight percent impurities. The precipitate sometimes contains measurable arsenic; however, the arsenic is less enriched in the silica precipitate than in the bulk fluid. The silicon to arsenic ratio of the fluid is about 800:1 while it is 70:1 in the silica precipitate. If necessary, a simple acid rinse could be used to reduce the arsenic levels by approximately two-thirds in the silica precipitate final product.⁹²

The silica-free concentrate would then be pumped through another process for extraction of other valuable materials. Example processes for the extraction of potentially economic concentrations of minerals and metal, which have become enriched in geo-fluid brine, typically include the use of an ion exchange reagent or other functionalized material (e.g., aerogels).^{93, 94} These exchange recovery systems generally involve contacting the aqueous metal-containing solution with an exchange reagent that becomes impregnated with the metal, which is subsequently stripped to produce a more concentrated metal-containing solution. The resulting metal-loaded strip solution is of controllable composition or purity, and the metal values can be directly recovered—most generally by electrolysis.⁹⁵ The final waste fluid is pumped to a surface pond and re-injected into the subsurface.⁹⁶

Lithium: The technology to extract lithium from produced water exists, and, in situations where brine lithium concentrations are sufficiently high, it may also be considered profitable. At the beginning of the extraction process, geothermal fluid is extracted from the production well and steam and brine are separated. The steam generates electricity, then cools and mixes with waste brine, which is sent on for lithium extraction.⁹⁷ Generally, the lithium is either extracted by direct precipitation as lithium salts or captured using ion exchange resins. In addition, the treatment of waters with a combination of magnesium and iron can precipitate hectorite (i.e., a lithium-rich clay mineral of the montmorillonite group).⁹⁸ In this process, zinc and manganese can also be recovered with lithium.⁹⁹

Zinc: The extraction of zinc from brine is usually through various combinations of ion exchange or solvent extraction and electrochemical stripping.¹⁰⁰ In general, these processes begin with the mixing of brine with an immiscible anionic organic solvent or ion exchange bed that is selective to the extraction of zinc chloride.^{101, 102} The zinc chloride-loaded anionic extractant is eluted to produce an impure zinc chloride solution. Iron, arsenic, and lead are also extracted in the process but are subsequently removed by oxidation, followed by solids removal. The zinc is then contacted with a cationic extractant that is also selective for zinc. After removal of the zinc-

depleted aqueous phase, the zinc-loaded extractant is rinsed and then stripped with a sulfuric acid solution. Zinc is recovered as metallic zinc by conventional electrowinning.^{103, 104}

Manganese: Manganese is usually extracted in the form of electrolytic manganese dioxide (EMD). Perhaps the most common process today for extracting manganese starts with mixing the manganese-containing material with sulfuric acid to form a manganese sulfate electrolyte. Precipitation and filtration then separates this intermediate from other metals. Thereafter, the manganese sulfate is subjected to solvent extraction and electrowinning.¹⁰⁵ Another method involves a liquid-liquid anoxic extraction of manganese (and iron) from brine, followed by oxidation to cause the iron to precipitate (the precipitate is thereafter removed). Electrolysis of the chloride (or sulfate) liquor is then performed to extract the EMD, which is deposited on the cathode.¹⁰⁶ Other work has shown that a solvent extraction method utilizing diethylhexyl phosphoric acid and a quaternary amine shows good selectivity for manganese over other metals present in the brine.¹⁰⁷

Sulfur: Purification of steam containing H₂S can also recover sulfur. This is done by passing the steam through a reactor packed with activated carbon in the presence of a stoichiometric amount of oxygen, which oxidizes the H₂S to elemental sulfur that is adsorbed on the bed. The carbon can be recycled after the sulfur has been recovered by vacuum distillation, inert gas entrainment, or solvent extraction. This process of purifying geothermal steam is very suitable if the steam contains some other NCGs.¹⁰⁸

Other By-Products: Geothermal fluids could be used to produce some inexpensive salts such as sodium chloride, sodium sulfate monohydrate, and calcium chloride.¹⁰⁹ Although these materials are not of high value, they may be produced as by-products of the processes that produce other, more valuable solids and may add to the profitability of geothermal co-production. Another potential by-product is high-surface area-precipitated calcium carbonate, which has unique properties that make it useful in applications such as paper filler and allows it to command a much higher price than limestone.^{110, 111} Researchers in Brazil are also studying the economic feasibility of extracting sodium carbonate (i.e., sodium ash) from produced water.^{112, 113}

Geothermal reservoirs often contain precious metals such as gold and silver. To extract these metals, a pregnant solution is pumped through activated charcoal, which absorbs gold and silver, at the process plant. Cyanide solution is pumped to a holding basin where lime and cyanide are added to repeat the leaching process. Gold-bearing charcoal is chemically treated to release the gold and is reactivated by heating for future use. The resultant gold-bearing strip solution, which is more concentrated than the original pregnant cyanide solution, is treated at the process plant to produce bars of impure gold.¹¹⁴

Specialty chemicals, such as cesium and rubidium, can also be enriched in geothermal fluids and because of their high value could be extracted at a profit. Cesium and rubidium are used

interchangeably in applications in thermionics, as oxygen-getters in vacuum tubes, and in alloys used in photocells. The hydroxides of cesium and rubidium are the strongest known bases. Cesium and rubidium can be separated using high-cross-linkage ion exchange resins.¹¹⁵ Novel methods utilizing crown ethers have also been investigated.¹¹⁶

In geothermal water, boron is present as boric acid and its dissociated anion, borate. Special ion exchange resins and borate-selective media have proven successful in removing boron from geothermal fluids.^{117, 118} Boron is recovered as borax at the Lardello geothermal field in Italy at the rate of 12,000 tons per year, and iodine and bromine are recovered from Cheleken thermal waters in Russia.¹¹⁹

The production of clays has also been a subject of research. In laboratory reactions, kerolite clay (a disordered form of talc) was precipitated upon treating synthetic and field waters with magnesium at 130°C, whereas, under similar conditions, sodalite and Zeolite P (various forms of gismodine) were precipitated upon treatment with aluminum hydroxide or sodium aluminate.¹²⁰

For kerolite production in the field, magnesium chloride is added at slightly above stoichiometric proportions (3 Magnesium: 4 Silicon) and caustic soda or lime increases the pH to ~10.0 with caustic soda or lime. The crystallizer and clarifier include sludge recirculation to maximize the “seed crystal” effect, thus providing a high surface area for precipitation. After precipitation, the water is clarified, possibly treated further to meet industrial water specifications, cooled to pipeline specifications, and finally sent to a pipeline for transport to the industrial site. The kerolite sludge is dewatered using a filter, as discussed earlier. The dewatered sludge can be dried in a steam-heated kiln or in an arid but cool environment at the power plant. Dried kerolite is transported off-site for commercial refining and use.

For zeolite manufacture in the field, sodium aluminate is used as both the aluminum and base source. Hectorite and saponite (a magnesium-rich clay mineral of the montmorillonite group) are made in a similar fashion by treating water with magnesium (Mg^{2+}) and iron (Fe^{2+}) salts and a base.¹²¹

2.3.2 Resource Requirements

2.3.2.1 Produced Fluids from Drilling Activities

Operators formulate drilling muds on-site and alter the recipe according to the physical conditions and chemical properties of the site and the changing conditions during drilling.¹²² Muds are screened to remove cuttings brought to the surface, and periodically, they are changed during drilling in response to fluctuating conditions. The mud remaining in the circulation system after drilling may either be disposed of or regenerated for future use.¹²³

Water-based muds are commonly used, although oil-based muds are common in high-temperature drilling for thermal stability. However, oil-based muds generally require additional handling and treatment.¹²⁴ Geothermal drilling can involve high temperatures and a corrosive environment.¹²⁵

Drilling mud is typically a mixture of bentonite clay and chemical additives in a water base. Composition of a typical mud, as developed by ChemTech,¹²⁶ includes bentonite, soda ash, Gelex polymeric dispersant, high-temperature stabilizer, and modified lignite or resin. The dominant material by several orders of magnitude is bentonite.¹²⁷

Bentonite is a natural, impure clay material consisting largely of montmorillonite that can seal off permeable formations. It is often referred to as “gel” because during pumping it flows easily, but once under static conditions, it forms a hard structure (gel) that resists flow (a property referred to as thixotropism). Soda ash (sodium carbonate) has a similar function. It acts as a bridging agent, sealing off large holes in the formation to maintain static pressure. The other components aid in preventing clumping of the drilling mud (polymeric dispersants), lubricating and cooling the drill bit (high-temperature stabilizers), and maintaining low fluid pH and viscosity (lignite and resin).¹²⁸ The drilling mud is often pumped from a tank down the drill string and then up through the annulus.

Used drilling muds can be processed by circulating the mud through additional equipment, such as hydroclones and centrifuges (to remove some of the drill cuttings) and cooling towers or tanks if the fluid needs to be cooled before reuse. Once the mud is processed in this manner, it can be recycled back into the drilling operation.¹²⁹

The total volume of drilling muds depends on the volume of the borehole and the physical and chemical properties of the formation. As a result, predicting the volume for a typical drilling project can be challenging.¹³⁰ Since geothermal wells can be installed to significant depths ranging from one to several kilometers in extent, drilling activities can be expected to generate a large amount of drill cuttings and drilling muds.

Past estimates in the literature characterize drilling fluid volumes to be approximately 845 cubic meters (223,225 gallons) per well drilled.¹³¹ Similarly, a single 2,000-meter well with a variable boring radius (22 to 81 cm) could generate 294 cubic meters of drill cuttings.¹³² A DOE study referenced by EPA considered 50 wells drilled in the Imperial Valley of California and reported that about 600 metric tons of drilling mud and cuttings could be produced from drilling a typical 1,500-m well.¹³³ This number must, of course, be multiplied by the number of geothermal wells needed on a project, so in the end, considerable volumes (i.e., on the order of a million gallons) of produced drilling mud and drill cuttings may need treatment and management.

In a 5-year period (1981–1985), EPA estimated that the waste volume of mud and cuttings generated by drilling activities associated with exploration and development of geothermal

resources in the U.S. totaled about 592,000 barrels. Table 2-1 provides a state-by-state breakdown for that period.

Table 2-1. Total Mud and Cuttings Volume by State, 1981 to 1985¹³⁴

State	Total Mud and Cuttings Volume in Thousands of Barrels				
	1981	1982	1983	1984	1985
California	97.3	103.8	51.2	198.9	109.3
Nevada	7.2	1.0	2.0	1.0	1.5
Idaho	0.6	NA	0.3	NA	NA
Montana	NA	0.1	0.1	NA	NA
Wyoming	NA	NA	NA	NA	NA
New Mexico	2.8	1.4	NA	NA	NA
Oregon	0.3	0.1	0.1	NA	0.1
Washington	0.2	0.1	NA	NA	NA
Utah	NA	2.3	1.2	2.3	NA
South Dakota	NA	NA	NA	NA	NA
North Dakota	NA	NA	NA	NA	NA
Hawaii	5.1	2.5	NA	NA	NA
Total U.S.	113.5	111.3	54.9	202.2	110.9

Until recently, water-based muds did not require treatment and could be discharged directly into the environment. However, in many areas, government regulations now prohibit a number of components in these muds, such as chrome-containing lignosulfonates.¹³⁵ Tight restrictions are also imposed on substances such as chlorides, nitrates, and potassium salts, or more generally, on the total electrical conductivity of the mud.¹³⁶

2.3.2.2 Produced Fluids from Stimulation and Flow- and Circulation- Testing Activities

Hydraulic stimulation can involve the use of water (“waterfrac”), gel-proppant frac, or a combination of both fluids known as “hybrid frac.” EGS geothermal reservoirs in the U.S., which to date are all located in igneous formations, have been stimulated with waterfracs.¹³⁷ Outside of the U.S., EGS geothermal reservoirs also have been stimulated with waterfracs, while gel-proppant frac have been used to stimulate geothermal reservoirs in both sedimentary rock

(at Groß Schönebeck, Germany) and igneous rock (Bad Urach, Germany, and Fjällbacka, Sweden).^{138, 139}

Reservoir engineers tend to select the fluid type used for stimulation and the injection pressure used to introduce the fluid into the reservoir formation on the basis of the nature of the geological formation. This includes the rock type (i.e., sedimentary, igneous, or metamorphic), the presence and orientation of natural or intrinsic fractures, and the natural tendency for fracture propagation during stimulation.¹⁴⁰

The fluids and additives used during well stimulation are relevant because during circulation and flow testing, they end up on the surface and must subsequently be managed and/or treated. If the fluid is produced from the same well, it is likely that the fluid has the characteristics of the fluid pumped downhole. For a more in-depth look at these additives, see Table 2-2. It should be noted that not all of these chemicals inevitably appear in the produced fluid during a circulation or flow test, but they may. For an expanded analysis of some of these substances, please refer to *TWP No. 2: Production Drilling*.

Table 2-2. Chemicals Used During Well Stimulation Activities¹⁴¹

Chemical	Purpose
Acids	Acidizing calcareous and sandstone formation Dissolution of drilling muds and clays
Chelating Agents	Formation cleanup, especially in formations that could be damaged by acids Dissolution of iron, calcium, magnesium, and aluminum
Bases	Dissolution of wellbore silica and near-wellbore formation silicates
Tracers	Use in helping to characterize the formation
Diverters	Interval isolation in the formation
Additives	Corrosion and scale inhibitors Proppants that help keep fractures open

2.3.2.3 Produced Fluids from Operational Activities

Ranges of Chemical Constituents of Geo-Fluids: The chemical composition of geo-fluids varies widely between geothermal fields, within geothermal fields, and even (in some cases) over time within the same geothermal well.¹⁴² The exact chemical makeup of the geo-fluid can have

important implications for both the design and operation of a geothermal plant and its potential environmental impact.

Figure 2-2 and Figure 2-3 show the distribution of pH values and TDS values in the Argonne Geothermal Geochemical Database (AGGD), a composite database created from the merger of five smaller component databases on the chemical characteristics of geo-fluids.¹⁴³ The histograms in both figures represent all samples in the dataset with temperatures greater than 90°C.

The pH values appear to be normally distributed around a median of 7.3, with most values falling between 5 and 10. The range varies from as low as 0.9 to as high as 11.8, showing the broad range of characteristics that are common among geo-fluids.

TDS values are less neatly distributed, with 80% of the samples having a value less than 5,000 milligrams per liter (mg/L) and 10% of samples having a value greater than 200,000 mg/L. The mean and median TDS values for high-temperature geo-fluids (>150°C) are approximately 81,000 mg/L and 2,500 mg/L, respectively; for moderate-temperature fluids (90–150°C), the reported mean and median TDS value are about 8,200 mg/L and 1,100 mg/L, respectively.

Although researchers found that the majority of TDS measurements were clustered between 500 and 5,000 mg/L, some reservoirs have TDS values outside this range.¹⁴⁴ On the lower end, the Soultz-sous-Forêts EGS reservoir reported TDS readings at 95 mg/L,¹⁴⁵ and The Geysers in California reports ranges from 130–340 mg/L.¹⁴⁶ On the higher end, the EGS project at Desert Peak in Nevada reported a geo-fluid TDS value of 7,000 parts per million (ppm),¹⁴⁷ and the Hudson Ranch I and II Geothermal Projects in California have average estimated brine concentrations of around 260,000–280,000 mg/L TDS.^{148, 149}

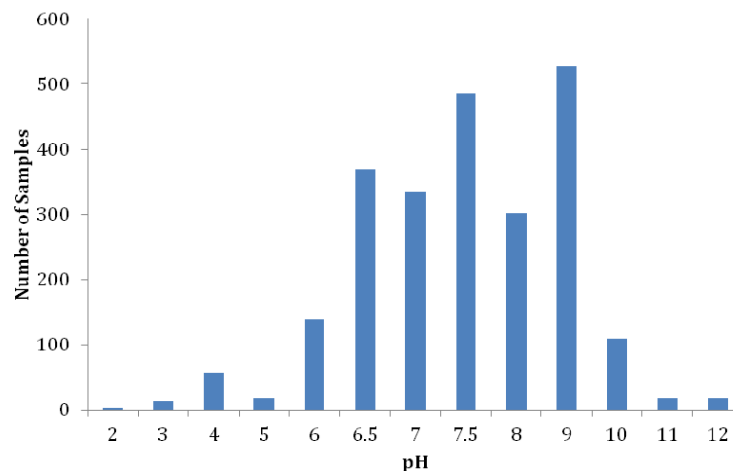


Figure 2-2. Distribution of pH measurements for U.S. geothermal sources with temperatures >90°C¹⁵⁰

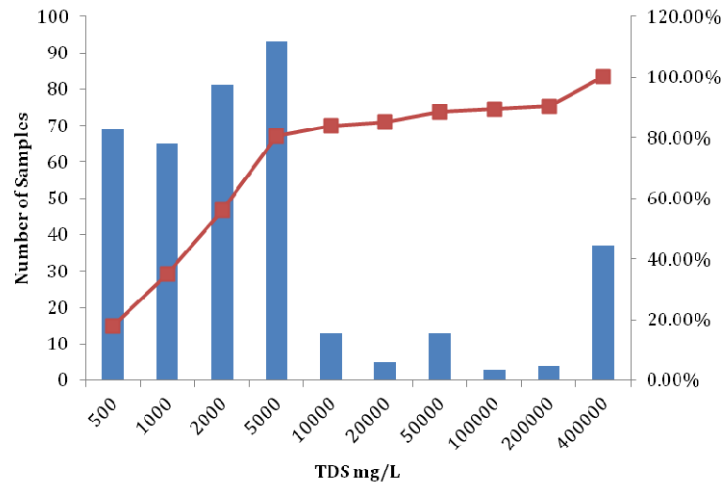


Figure 2-3. Distribution of TDS measurements for U.S. geothermal sources with temperatures > 90°C¹⁵¹

Figure 2-4 is a box plot representing the distribution of concentrations of major chemical constituents found in the data for samples with temperatures greater than 90°C. The dissolved solids in most geo-fluids are predominantly sodium chloride, followed by bicarbonate, sulfate, silica, calcium, and potassium.¹⁵² The concentration of a constituent can vary by at least an order of magnitude between the 25th and 75th percentile, and by as many as five or more orders of magnitude between the extremes of the distribution.

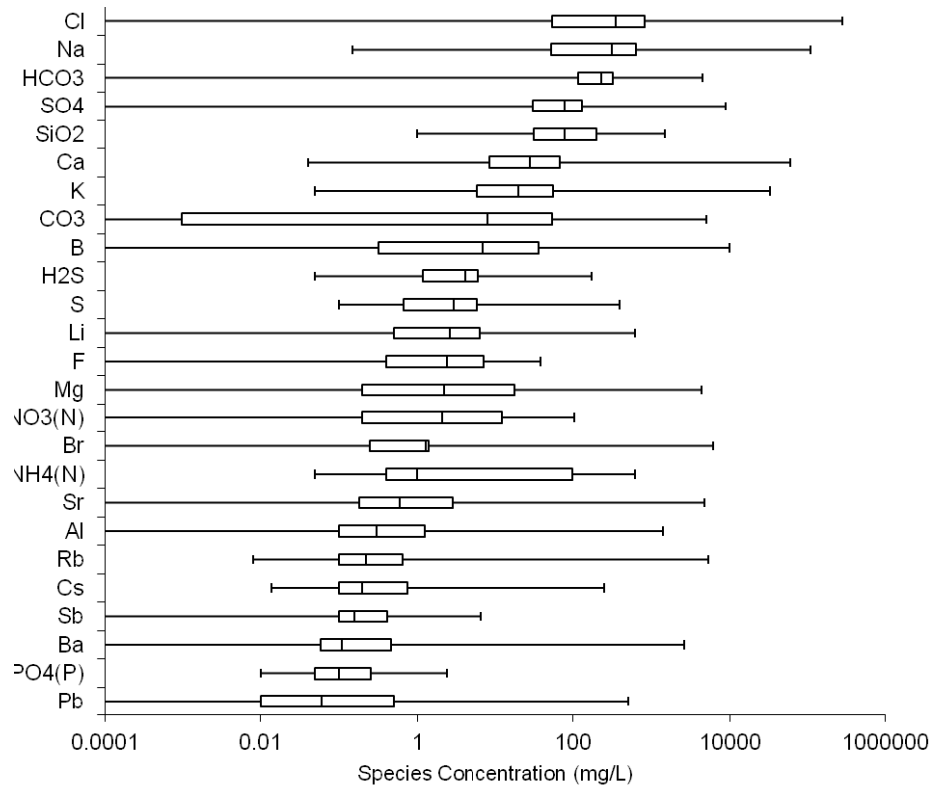


Figure 2-4. Geofluid composition box plots, major constituents¹⁵³

Constituents of Interest: Although there is wide variability in chemical constituents of geofluids, there are several constituents of interest that can affect geothermal power plant operations. These include NCGs, constituents associated with scale and corrosion, and naturally occurring radioactive material (NORM).

Non-Condensable Gases (NCGs) in Geo-Fluids: Geo-fluids contain a fraction of dissolved NCGs. These gases are released when steam is flashed and collect in the condenser of flash and steam systems. The release of NCGs does not occur in binary systems because the gases remain dissolved in the pressurized geo-fluid and are reinjected into the reservoir. In the case of EGS, experience and data are limited, but it is expected that NCG volumes will be highly dependent upon the energy conversion approach taken (i.e., binary vs. flash, or dry steam), the properties of the reservoir, and the rate at which fluid is circulated in the system.¹⁵⁴

Commonly encountered NCGs include nitrogen, carbon dioxide, H₂S, methane, and argon.¹⁵⁵ These gases are usually released into the atmosphere, except for H₂S, which must be scrubbed prior to release. Typical NCG concentrations range from 0.5%–1.0% of the steam generated,¹⁵⁶ although NCG concentrations observed at The Geysers geothermal field in California range from 0.2%–1.8% of the steam produced.¹⁵⁷

Gas composition data were incorporated into AGGD Version 2.0 after correcting for air contamination in the data.¹⁵⁸ Analysis of these data indicated that the composition of the NCG stream varies widely by location and is dominated by nitrogen and carbon dioxide. In most cases, one or the other of these gases dominates the composition, but there are cases where the two gases are mixed more equally.¹⁵⁹ Concentrations of H₂S, methane, oxygen, hydrogen, and argon are typically under 1% each but can reach as high as 10% in some cases.¹⁶⁰

Scale Formation and Corrosion from Geo-Fluids: Geo-fluids are chemically complex and can create extreme and harsh conditions that present difficult engineering challenges. Scale formation and corrosion are major operational considerations for geothermal plant design and operation.¹⁶¹ Both of these processes are directly related to geo-fluid characteristics. Scale results from solids in the geo-fluid precipitating out and attaching to the surfaces of pipes and equipment, whereas corrosion results from chemical interaction between the geo-fluid and the internal surfaces of process equipment, including well casing, pipes, and heat exchangers.¹⁶²

Failure to properly manage scale and corrosion can result in fouling of equipment and significant reductions in fluid production rates, through-plant flow rates, heat transfer efficiencies, and injection rates.^{163, 164, 165, 166} Periodic, and often costly, shutdowns of wells and surface facilities may be required for scale removal and corrosion control services. Therefore, high-impact reductions in operating and maintenance costs, plant downtime, and production declines can be achieved by reducing the amount or rate of scale formation and/or rendering the scale easier to remove during cleaning operations.¹⁶⁷ In some cases, however, scale can actually form a protective coating inside pipes, which in turn may help to inhibit corrosion.¹⁶⁸

The three most common species of scale in geothermal systems are silicon dioxide (silica), metal sulfides, and calcium carbonate (calcite).¹⁶⁹ These different forms of scale typically impact different stages of the process, with sulfides and calcium carbonate usually precipitating early and silica precipitating later in the process—like after the geo-fluid is concentrated through flashing or heat is removed in the heat exchangers.¹⁷⁰ Other minerals also contribute to scaling, including barite and fluorite.¹⁷¹

Scaling has been a significant issue for geothermal plants. For example, at the Soultz-sous-Forêts EGS Project, scale has collected on power plant equipment, such as the filters, pipes, and heat exchangers. The scale formed on-site most often included barium/strontium sulfates, lead sulfides, and other mixed sulfides, and it most commonly occurred in the cool part of the power plant owing to temperature decreases from the heat exchanger.¹⁷² Other scales, referred to as cuttings, were actually raised from the reservoir itself.

Silicon Dioxide: Silicon dioxide, or silica scaling, is of greatest concern to most geothermal facilities because silica is found in virtually all geothermal brine. Many geo-fluids leave their source in equilibrium with crystalline quartz. In a reservoir, dissolved silica exists in solution as

discrete silicic acid molecules, and their concentration is directly proportional to the temperature of the brine, with hotter water able to hold more dissolved silica. As brine flows through the well to the surface, the temperature decreases and the silica solubility decrease correspondingly, causing the brine phase to become over-saturated. During energy production, when pressure is dropped in the flash vessel, steam flashes and the temperature of the brine decreases further. In the flash vessel, the brine phase becomes more concentrated and the silica becomes even more unstable. Under these conditions, the excess silicic acid does not normally re-precipitate as quartz but instead precipitates as either amorphous silica or reacts with available cations (e.g., iron, magnesium, calcium, zinc) to form co-precipitated silica deposits.^{173, 174} These deposits are extremely tenacious and can occur throughout the production field, plant, and injection systems. It has been suggested that controlling silica scale may reduce other forms of scale because the silica acts as a substrate or nucleation site for other types of scale to form.¹⁷⁵

Metal Sulfide: Metal sulfide scale formation is more complex and less understood than the other two forms of scale. A wide range of metals will precipitate as sulfides with different solubilities. In order of increasing solubility, these include mercury, copper, lead, silver, iron, and zinc.¹⁷⁶ Sulfides of arsenic and antimony have also been observed at the Salton Sea geothermal field.¹⁷⁷ Sulfide scale formation is known to increase not just with decreasing temperature and increasing pH, but also under reduced (low-oxidation) conditions within the brine.¹⁷⁸ In general, most effort spent on controlling scale is targeted at calcite and silica because their constituents are usually found in much higher concentrations in geothermal brines.¹⁷⁹

Calcium Carbonate: Compared with metal sulfide precipitation, calcium carbonate scale formation is a simpler process. Unlike metal sulfides and silica, calcite increases in solubility as the temperature decreases; thus, the possibility of precipitation declines as energy is removed from the geo-fluid.¹⁸⁰ The major driver of calcium carbonate scale formation is related to the concentration of dissolved carbon dioxide. The removal of carbon dioxide from solution has two main influences on the likelihood of scale formation. First, it results in a sudden increase in pH, which favors the precipitate. Second, the removal of carbon dioxide from solution drives the dissociation equilibrium toward the precipitate.¹⁸¹

The unique mechanism for calcite scaling presents a major challenge for geothermal engineering. In many cases, geo-fluids are allowed to flash within the wellbore at the natural flash horizon. If conditions are ripe for calcium carbonate scale formation (i.e., high calcium concentration and high dissolved carbon dioxide concentration), scale will begin to form at the flash horizon and can result in a constriction within the wellbore, eventually choking off flow from the well.¹⁸² In general, binary systems have fewer issues with this kind of scaling because fluid is pressurized above the flash point.¹⁸³

The presence of cations such as Ca^{2+} in a geothermal reservoir can also be problematic in EGS systems. For example, because the solubility of these cations decreases with increasing

temperature, they tend to precipitate out of solution as the groundwater is injected for stimulation, and the temperature of the stimulation fluid increases as a result of contact with the reservoir. The temperature increase, combined with the pressure drops that occur during stimulation, can result in significant scaling problems on the geothermal power equipment as well as scaling along the well and fracture network that stimulation is meant to open and expand.¹⁸⁴

Corrosion: Corrosion results from chemical interactions between the geo-fluid and the internal surfaces of equipment, including well casing, pipes, and heat exchangers. It is a complex process that depends upon chloride concentration, pH levels, hydrogen sulfite partial pressure, and geo-fluid temperature.¹⁸⁵ Corrosion is usually managed through materials selection during the plant design process. Lining equipment with corrosion-resistant coatings or using corrosion-resistant alloys are two common approaches for addressing corrosion.¹⁸⁶

Failure to properly manage corrosion and scale can result in restricted flow from production wells, reduced injectivity of injection wells, costly plant shutdowns, and equipment failure.¹⁸⁷ Scale formation can produce an insulating effect, reducing the heat transfer coefficient to 30%–50 % of the original value.¹⁸⁸ This can be good for reducing thermal losses through transport pipes but bad for heat exchangers because it significantly reduces their effectiveness. Scale can also form a protective coating inside pipes, helping to inhibit corrosion. Consequently, certain approaches taken to mitigate scale formation, such as acidification, may result in increased corrosion.¹⁸⁹

Naturally Occurring Radioactive Materials (NORMs) in Geo-Fluids: NORMs are present in many of the geologic formations overlying geothermal resources and within the geothermal resources themselves. As a result, there is some potential for NORM to be present in waste streams associated with the exploration, development, and power-generation phases of a geothermal project. Furthermore, there is significant potential for the technologies used to obtain and use geothermal energy to concentrate the NORM that is present in secondarily generated materials such as scale. The presence of such technically enhanced NORM (also known as TENORM) in geothermal waste streams can be of particular concern because of the risk of worker exposure and the specialized and costly waste disposal requirements.

NORM in geothermal operations is caused by radium-226 and radium-228, which are daughter products of uranium-238 and thorium-232, respectively.¹⁹⁰ More specifically, radium is a chemical homolog of alkaline earth elements such as barium and calcium that are present in geo-fluids and that have a tendency to form scale in production and injection wells, geo-fluid transfer piping, and power production and pollution control equipment.¹⁹¹

The findings of Naturally Occurring Radioactive Materials (NORM) in Produced Water and Scale from Texas Oil, Gas and Geothermal Wells: Geographic, Geologic, and Geochemical

Controls are informative even though the study is Texas-specific and includes oil and gas wells.¹⁹² Elevated NORM levels occur where volcanic rock fragments are present in sandstone reservoirs. It is unclear if this finding is significant since many U.S. EGS projects are also located in volcanic formations. NORM was found to be associated with barite scale in both sludge and scale, and the potential for barite scale to precipitate increases with reservoir temperature. Although it was found that the radium activity of barite scale differs widely between major basins examined in the study, high radium activity [>200 picocuries per liter (pCi/L)] occurs only if the TDS content exceeds about 35,000 mg/L.¹⁹³

One can appreciate the impact of TENORM in the geothermal industry by considering geothermal power production near the Salton Sea. In this case, there were major concerns about worker exposure to alpha radiation, the potential for groundwater contamination caused by the presence of NORM in re-purposed solids, and impending regulation of NORM waste. As a result, operators experimented with introducing an inhibitor into the crystallizer/clarifier process to minimize or preclude the generation of barite scale.¹⁹⁴

Correlations have been observed between scale development and radionuclide concentrations at Soultz-sous-Forêts.¹⁹⁵ In a study of the plant's operations during 2010 and 2012, an increase in NORM was observed in parallel with increases in circulation volume, with the highest values found close to the reinjection point where the temperature is lower.¹⁹⁶

2.3.2.4 Scale and Corrosion Inhibitors

Scale formation and corrosion are significant issues affecting the technical and economic feasibility of geothermal plant design and operation. Both of these processes are directly related to the geo-fluid characteristics.

Scale inhibition and corrosion control methods employed in geothermal fields have generally been specific to brine chemistry and process conditions. Scale control programs typically involve the use of chemical inhibitors that retard or disrupt specific steps and/or change fluid chemistry to retard overall rates such that the fluid moves beyond scale-sensitive plant facilities before scale precipitates.¹⁹⁷ Some of the methods that prevent and treat scaling in geothermal wells include varying pressure, changing the temperature profile, altering brine pH levels, seeding, and using scale inhibitors. The use of some, more commonly practiced techniques to mitigate scale formation, such as acidification, may actually result in increased corrosion.¹⁹⁸ There is, therefore, interest in non-acid additives for scale control.¹⁹⁹

As previously discussed, the three most common species of scale in geothermal systems are silicon dioxide (silica), metal sulfides, and calcium carbonate (calcite).²⁰⁰ These different forms of scale typically impact different stages of the geothermal energy process. Discussion of the treatment options for these species is below.

Silicon Dioxide: Silica reactions have been studied for over a century. In general, silica scale precipitation is a multi-step process involving a nucleation-related induction period, aqueous polymerization, condensation of polymers to form colloids, and deposition onto a solid surface. Many chemical and physical variables (e.g., solubility and kinetics) influence the rates of these steps.²⁰¹ Common methods identified and previously employed to mitigate and control silica scaling in geothermal systems include the following:^{202, 203}

- Maintenance of brine flash pressures and temperatures to prevent silica oversaturation
- Exchanging brine heat to another working fluid without flashing (in binary system operations)
- Dilution with steam condensate or fresh water
- Adjustment of brine pH levels (e.g., decrease with acid or acid gases)
- Controlled precipitation of silica by cationic surfactants or metals
- Aging, evaporation/percolation, or pond retention
- Reducing-agent treatment
- Crystallization/clarification
- Dispersants and polymeric organic inhibitors
- Chelating agents, organic acids, sequestrants, and complexing agents.

Modification of Operating Conditions to Minimize Silica Precipitation: Maintaining brine flash pressures and temperatures to keep silica in solution is an effective means to mitigate scale formation. It is usually easier to avoid scale formation in binary systems because only the temperature is decreasing and there is no concentration of the brine through the loss of geo-fluid to steam.²⁰⁴ Flash systems typically require other treatment techniques.

pH Modification for Treating Silica: The pH level strongly influences the rate of scale formation. Scale formation is the most rapid in conditions of near-neutral pH. Thus, controlling pH levels can generally control silica scaling. At geothermal fields around the world today, pH modification processes appear to be the most common method researched and applied for controlling amorphous silica and silicate scale deposition. This is because pH is known to influence the rate of polymerization and scale formation.²⁰⁵

In general, for pH modification to be successful, the reactions responsible for scale deposition must be slowed to a time sufficient to allow brine to migrate deep into injection formations before significant polymerization occurs. Since the most rapid kinetics occur in conditions of near-neutral pH,²⁰⁶ it is not surprising that potential methods for controlling siliceous scaling from geothermal brines and other aqueous solutions includes treatment with acids or bases.

Although possible, no geothermal power plant is currently increasing the pH of brine.²⁰⁷ This is primarily due to potential formation of metal carbonates and hydroxides as by-products. In almost all cases, increasing the pH of a brine to control silica requires mitigation or controlled precipitation of the by-products.²⁰⁸ Thus, matrix acidizing is more commonly utilized to control scale deposition and extend brine-injection well life.

Research has shown that lowering pH levels both increases the induction time prior to the polymerization stage and decreases the polymerization rate.²⁰⁹ This chemical treatment involves the injection of a reactive fluid (normally an acid), typically downhole into the porous medium at a pressure below the fracturing pressure. The acid works through a process of dissolution of material deposited in some of the porous formations including carbonates, metal oxides, sulfates, sulfides or chlorides, amorphous silica, drilling mud, and cement filtrates from invasion.²¹⁰ This approach may, however, backfire in some cases, because the slowed precipitation may still occur in or around the injection well, impacting the permeability of the formation and reducing injectivity of the spent geo-fluid.²¹¹

Adjustment of pH levels can also be done at the power plant. For example, in a multi-flash power plant, the high-pressure separation pressure is chosen and controlled at a level that will maintain a brine temperature above the silica saturation temperature. As a result, the acid is added before any further pressure reduction.²¹²

Acids commonly employed in pH modification technology include hydrochloric, hydrofluoric, and sulfuric, although other acids such as acetic, nitric, and sulfurous may find application in the process. Acid selection depends on compatibility with brine.^{213, 214, 215} Hydrochloric acid is compatible with most geothermal brines. Sulfuric and sulfurous acids may not be compatible with brines containing significant alkaline-earth metals and must be used with caution to avoid by-product sulfate scale deposition. Hydrofluoric acids are typically avoided owing to by-product calcium fluoride scaling. Nitric acid is normally too oxidizing for practical use.

Typically, acid dosages are low and brine pH is decreased by less than two units (e.g., pH range of 5 to 6) to achieve good scale inhibition results, and slow the kinetics of silica polymerization without substantially increasing corrosion.^{216, 217, 218, 219}

However, results have also shown that the magnitude of the pH effect is different for different wells and depends on the other chemical variables as well, including the presence of natural chemical buffers (e.g., bicarbonate).^{220, 221} Thus, the employment of silica scaling rate prediction models and brine titration data often help to select target acid dosages and pH level.

In some pH modification applications, if acid dosages are small (e.g., a few tens of ppm), direct acid injection into brine may be feasible.²²² On the other hand, when the acid dosing requirement to achieve the target pH is significant, pre-dilution of acid with hot, nonaerated brine is advantageous.²²³ A standard acid treatment for wells scaled with amorphous silica during their

commercial operation has generally used a pre- and post-flush of 10% hydrochloric acid and a main flush of 10 % hydrochloric /5 % hydrofluoric combination.^{224, 225, 226} The HCl pre-flush can also dissolve carbonate minerals in the formation.²²⁷

The pH reduction technology offers an advantage because it is a relatively cheap, effective inhibitor that has a relatively small footprint, moderate equipment costs, reduced waste disposal, no ponding, no surface disposal of brine, and opportunities for continued improvements.²²⁸ In addition, it may be used in combination with other scale control methods such as non-pH-adjusting chemical additives, reducing agent treatment, or induced precipitation through seeding with silicate particles.

The uncertainties or limitations of acidizing are generally based on the following concerns: significant corrosion rates with the mineral acids at the temperatures encountered in geothermal wells; possible interference with surface processes; and placement problems resulting from large completion intervals.²²⁹ It has been noted that treatment volumes, injection rates, acid placement techniques, acid system selection, and the evaluation of the results of stimulation of geothermal wells follow the same criteria used for oil wells.²³⁰ However, the formation temperature is of particular importance because it influences the efficiency of corrosion inhibitors and reaction rates.

Non-pH-Adjustment Treatment Options for Silica: Some of the non-pH-adjusting chemical additives used for silica control in the precipitation-inhibition tests were polyoxyethylenes (i.e., any polymer of ethylene glycol having a general formula $\text{HO}-(\text{CH}_2\text{CH}_2\text{O})_n\text{-H}$), cellulose derivatives, imines (organic compounds containing the group $\text{C}=\text{NH}$ or $\text{C}=\text{NR}$, where R is an alkyl or other group), and organic acids.

Overall, the most promising group of non-pH-adjusting compounds arising from research tests is cationic nitrogen-containing compounds.²³¹ The presence of polyoxyethylenes in these compounds may improve, but is not necessary for their reactivity with silica. Four chemicals specifically identified for non-pH-adjusting chemical additives, which would probably be most effective in combination with a pH adjustor (such as HCl), include:

- Corcat P-18 (polyethylene imine), Q PAE-HCl (polyaminoethylene hydrochloride)
- Ethoquad 18/25 (polyoxyethylene octadecylammonium chloride)
- Mirapol A-15 (polydiquaternary ammonium chloride).²³²

Treatment of brines with reducing agents can also inhibit ferric and manganic silicates. Ferrous and manganous-rich amorphous silicas exhibit a higher solubility in aqueous solution than their higher-oxidation-state counterparts.²³³ A preferred reducing acid is formic acid (HCOOH) because it is strong enough to acidify brines at reasonable dosages, and the by-product of reaction is benign CO_2 .

Oxygen scavengers are also acceptable reducing agents in this application. Precautions must be taken to ensure that by-products of oxygen scavenging and metal ion reduction agents are compatible with other brine constituents. The reducing agents are known to precipitate silver, gold, antimony, and arsenic from geothermal brines by a cementation reaction, which may or may not be desirable.^{234, 235}

An alternative method of controlling silica scale is to induce precipitation of scale-forming materials, notably silica, from the brine in the flashing stage by contacting the flashed brine with silica or silica-rich seed crystals.^{236, 237, 238} Preferably, the seed crystals are introduced into the high-pressure flashing vessel, which may then be referred to as a high-pressure flash crystallizer, wherein the brine first becomes supersaturated in scale-forming materials. When the silica saturation level in the brine is exceeded, the silica leaving the solution will deposit onto the seed crystals. Not only do the micron-sized seed crystals introduced into the flashing stage provide a larger surface area than the exposed surfaces of the flashing vessels, but the silica from the brine also tends to preferentially deposit onto the seed crystals. The crystallization process, while starting in the high-pressure flash crystallizer, continues in successive lower-pressure flashing vessels in which the brine typically again becomes supersaturated with silica. This approach results in the majority of the supersaturated silica precipitating onto the seed crystals instead of precipitating as scale onto vessel walls or equipment walls or in injection wells. In a downstream reactor-clarifier, the siliceous precipitate is separated from the brine as slurry, which can contain about 30% by weight of silica.²³⁹

Other research has suggested that aging geothermal wastewater in a retention tank, which allows the monomeric silica in excess of amorphous silica solubility to form polymers, can also considerably lower the silica scaling potential of such waters. The size of a retention tank is determined by the rate of silica polymerization. If the wastewater has a pH value between 7 and 8, the polymerization time is at a maximum, requiring the smallest retention tank; this method is not suited for geothermal waters with pH lower than 6 at 80°C because of slow polymerization rates.²⁴⁰ However, enhancing the rate of silica polymerization (e.g., by increasing ionic strength) will also increase the rate of silica deposition and risk of scaling. Therefore, this method is not likely to be suitable for geothermal waters of high salinity because of the high silica deposition rate that would result.²⁴¹ A summary of likely methods for mitigating silica scale formation is presented in Table 2-3.

Table 2-3. Summary of Geothermal Scale Formation Mechanisms and Mitigation Options for Silicon Dioxide ²⁴²

Chemical Species	Drivers of Scale Formation	Mitigation Options
Silicon dioxide (silica)	↓ temperature pH close to neutral ↑ dissolved silicon dioxide concentration	Modification of system operating conditions to minimize oversaturation Modification of geo-fluid pH via acidification Modification of geo-fluid using non-pH-adjusting compounds or reducing agents

Metal Sulfides: A wide range of metals will precipitate as sulfides with different levels of solubility in geothermal brines. In order of increasing solubility, these include mercury, copper, lead, silver, iron, and zinc.²⁴³ Sulfides of arsenic and antimony have also been observed.^{244, 245} Some of the metallic sulfides tend to deposit near the wellbore, but most of these sulfides intermix with silicates and form a scale mixture.²⁴⁶

Sulfide scale formation is known to increase not just with decreasing temperature and increasing pH but also under reduced (low-oxidation) conditions within the brine. This is a particular problem in binary plants, as they often run at lower temperatures than flash plants and with retained gas in the process fluid. The deposition of metal sulfides can cause a reduction in heat transfer in the heat exchangers that reduces the power output of the plant.²⁴⁷

Current treatment options include mechanical removal, chemical dissolution with a caustic, and periodic dissolution by changing the on-line process pH conditions.²⁴⁸ Partial oxidation of brine or combined oxidation and acidification have also been proposed as possible approaches for managing sulfide precipitation.²⁴⁹ Alternatively, some researchers suggest that metal sulfate scales are strongly controlled by dissolved hydrogen sulfate concentrations and are triggered by the release of gas from solution at the flash point.^{250, 251} Research is ongoing to try to develop an organic antiscalant that can inhibit deposition, particularly for stibnite.²⁵² A summary of likely methods for mitigating metal sulfide scale formation is presented in Table 2-4.

Table 2-4. Summary of Geothermal Scale Formation Mechanisms and Mitigation Options for Metal Sulfides²⁵³

Chemical Species	Drivers of Scale Formation	Mitigation Options
Metal sulfide	↓ Temperature ↑ pH ↓ Oxidation state ↓ Dissolved H ₂ S concentration	Oxidation of geo-fluid Acidification of geo-fluid

Calcium Carbonate: Almost all geothermal systems contain dissolved carbon dioxide (CO₂) in an aqueous solution at equilibrium. According to Henry’s Law, the amount of CO₂ present is proportional to the partial pressure of the gas in contact with the solution. The major driver of calcium carbonate scale formation is related to the concentration of dissolved CO₂. The low pH of the fluids under reservoir conditions caused by the presence of the CO₂ in solution keeps calcite scaling from occurring in the reservoir. However, as fluid is produced and CO₂ comes out of solution, the pH increases, liquid volume decreases, and the solubility of various ions in solution changes, favoring the precipitation of calcium carbonate scale.^{254, 255, 256} The removal of CO₂ from solution also drives the dissociation equilibrium toward the precipitate.^{257, 258}

Calcite solubility increases as temperature decreases; thus, the possibility of precipitation declines as energy is removed from the geo-fluid. However, if conditions are ripe for calcium carbonate scale formation, scale will begin to form at the flash horizon within the wellbore, eventually choking off flow from the well.²⁵⁹

In general, binary systems have fewer issues with calcium carbonate scaling because fluid is pressurized above the flash point throughout the process. However, calcium precipitates have been observed in some cases at locations where there is a pressure drop such as across pumps.^{260, 261} It is hypothesized that pressure drops result in local evolution of CO₂, which can temporarily create conditions conducive to calcite scale formation.^{262, 263}

A method has been developed to prevent calcium carbonate scaling that involves use of scale inhibitors, typically specialized and proprietary polymers. With this method, the scale-control options include: (1) limiting production so that the drop in pressure is not sufficient to induce precipitation; (2) injecting trace concentrations of inhibitors in the surface equipment; (3) injecting trace concentrations of inhibitors down-well to pressurize the fluid above the flash point; and (4) squeezing inhibitor into the formation so that the inhibitor will be released slowly when production begins.^{264, 265, 266}

The use of downhole pumps can also prevent scaling within the wellbore; however, the thermodynamics of this method typically favor binary systems over flash systems.^{267, 268}

Acidizing with hydrochloric acid has also been found to remove damage effectively from calcium carbonate scaling both in the wellbore and the reservoir formation. Acidizing is more effective at removing scale after a mechanical wellbore cleanout since the acid will have had more contact with the formation.²⁶⁹ In other research, wells damaged by calcite scaling were treated using a main flush of 12% hydrochloric/3% hydrofluoric acids.²⁷⁰ Table 2-5 presents a summary of likely methods for mitigating calcite scale formation.

Table 2-5. Summary of Geothermal Scale Formation Mechanisms and Mitigation Options for Calcium Carbonate²⁷¹

Chemical Species	Drivers of Scale Formation	Mitigation Options
Calcium carbonate (calcite)	↑ Temperature ↑ pH ↓ Dissolved CO ₂ concentration	Pressurization of geo-fluid in the wellbore Injection of specialized scale inhibitors Acidification of geo-fluid

NORM and Barium Sulfate: NORM refers to radionuclides that occur naturally in the environment (e.g., in subsurface formations), which can become concentrated in certain geothermal production and processing waste streams including scale deposits, produced fluids, contaminated equipment, and biofilm deposits. Studies of this contamination issue have generally focused on methods either to dissolve or inhibit NORM deposition.

Research has shown that attempts to dissolve or leach NORM from sludges with either water or a variety of chemical solvents are not particularly successful. Acids and bases have also been found to be ineffective in dissolving NORM. By contrast, commercially available barium sulfate dissolvers (chelates and converters in basic solution) were somewhat successful in leaching about 25% of NORM and barium sulfate from sludge, but only under very rigorous reaction conditions (i.e., high temperatures, long leach times, stirring, etc.).²⁷²

The petroleum industry has successfully used a variety of scale inhibitors (generally, highly charged polymeric organic compounds) to inhibit barite and fluorite deposition in wells, piping, and produced water-handling equipment. When barite is properly inhibited, NORM deposition is also to be mitigated. Inhibitors that have found application in control of barium sulfate scales include phosphonates, polyacrylates, and polymalates.²⁷³ Unfortunately, there is little agreement

and inadequate understanding concerning the effectiveness of these inhibitors, optimum dosage requirements, and reaction mechanisms involved in these inhibition reactions.^{274, 275}

In general, these scale inhibitors impart charges on particles that result in dispersion of solids. Inhibitors will generally increase the negative charge on the geothermal solids owing to their anionic character, causing increased dispersion and poor settling (upsets) in clarifiers. In this regard, flocculants are injected into clarifiers to gather and settle suspended solids for the polishing of injectate brines. Inhibitors that disperse the siliceous precipitates are expected to affect flocculated clarifier operation deleteriously. Thus, a method is needed that prevents or inhibits radioactive geothermal scale/sludge from precipitating without interfering with crystallizer-clarifier operation and the action of the flocculants used to settle slowly precipitating silicate species.²⁷⁶

The more promising inhibitors for barium sulfate and NORM contained phosphonate and acrylate functionality. As expected, most of the inhibitors dispersed the clarifier solids. To combat the adverse reaction of the inhibitors on the suspended solids, various flocculant formulations were also tested in jar experiments. Several mildly cationic flocculants were able to overcome the additional negative charge imparted on the suspended solids by the anionic, dispersing inhibitors. This latter result suggests that injecting an inhibitor upstream of the low-pressure crystallizer (just before NORM, barium sulfate, and calcium fluoride begin to precipitate) while also injecting a cationic flocculant into the secondary clarifier could control NORM deposition without adversely affecting the silicate crystallization-clarification process.²⁷⁷

Corrosion: Corrosion is initially managed during the plant design phase through selection and use of corrosion-resistant alloys or application of corrosion-resistant coatings suitable for use in geothermal fluids at high temperatures and other hostile environments.²⁷⁸ However, these materials are typically more costly than materials such as carbon or lower-grade stainless steels. Since there is such wide variability in geo-fluids from location to location, the recommendation is that materials be chosen only after testing them with the specific geo-fluid to be used.²⁷⁹

Internal treatment methods for corrosion control during operations depend upon the group of corrosive species (e.g., H₂S or oxygen) that must be reduced or removed from the system.²⁸⁰ Aeration, wherein air is bubbled through the water, can remove H₂S and other dissolved gases (e.g., CO₂). Yet, this process has the disadvantage of adding oxygen to the system, which itself becomes a corrosive, dissolved constituent. The addition of sulfite or hydrazine to reduce the oxygen can then accomplish the removal of oxygen. The treatment of brines with reducing agents also decreases corrosion.²⁸¹

2.3.2.5 Non-Condensable Gases (NCGs)

Geothermal brines and steam generally contain NCGs such as nitrogen, carbon dioxide (CO₂), H₂S, methane, argon, and oxygen. These gases are usually purged into the atmosphere, except for H₂S, which must be scrubbed prior to release.

Increasing concerns over greenhouse gas emissions may require limiting emissions in the future. Thus, in the case of CO₂, compressing the NCGs and reinjecting them into the reservoir with the spent geo-fluid is an option for limiting emissions from resources with higher CO₂ concentrations. This process, however, would result in additional parasitic power consumption.²⁸² Targeting reservoirs with lower CO₂ concentrations is another option for limiting these emissions.²⁸³

Some of the more common methods of H₂S abatement are caustic scrubbing followed by oxidation, adsorption, and catalytic conversion to elemental sulfur.²⁸⁴ However, hydrogen gas could be separated and collected for use on-site or sold into the market as an additional energy and revenue stream.²⁸⁵ For example, H₂S in vent gas could be utilized to generate sulfurous acid and sulfuric acid for use in pH modification processes and acidizing activities. In the field, a pilot burner-scrubber,²⁸⁶ and a sulfur-oxidizing bacteria bioreactor²⁸⁷ have been tested for this application. In a similar process, H₂S in vent gas may also generate an inorganic acid solution that can be reused in the geothermal brine acidification treatments.²⁸⁸ In this process, a geothermal vent gas containing H₂S is fed through a bed of halogen containing oxidizing-agent granules. In the absence of significant moisture, the H₂S reacts with the oxidizing agent to yield elemental sulfur and a hydrogen halide gas. The elemental sulfur deposits on the oxidizing-agent particles, and the produced hydrogen halide gas (e.g., HCl) is sparged (bubbled) into the brine, steam condensate, or water. The acid gas dissolves in aqueous solution to yield an inorganic acid solution, which may decrease brine pH levels for silica, carbonate, or metal sulfide scale control in order to restore productivity and stimulate the wells.²⁸⁹ Use of HCl to reduce NCG surging can result in a sufficient decrease in the surges to allow longer or continuous operation of that well.²⁹⁰

Air pollution control systems in place for treating geothermal steam can also result in the generation of significant power production-related wastes. Steam from a geothermal field can contain a number of NCGs including CO₂, H₂S, ammonia, methane, nitrogen, and hydrogen.²⁹¹ H₂S can be released by well drilling and testing, steam venting during power plant start-ups, condenser off-gas operation, or cooling tower drift.²⁹² In the case of The Geysers, a significant waste stream results from treating steam emissions for H₂S content. At The Geysers complex, exhaust steam exiting the turbine is condensed, pumped to a cooling tower, and then cooled. In effect, the cooling tower acts as a concentrating unit for any dissolved solids present in the condensate. Abatement chemicals are added at the geothermal units to remove H₂S. As a result, fine particles of sulfur accumulate in significant amounts in cooling-tower basins.²⁹³

2.3.2.6 Metals

As already noted, with low pH values, lower temperatures, and the presence of H₂S, heavy metals in brines can precipitate as sulfides. For example, antimony in the form of stibnite and arsenic in the form of orpiment have been found in scale.^{294, 295} In addition, the silica in geofluids can react with available metal cations (e.g., iron, magnesium, calcium, and zinc) to form metal-silica deposits.^{296, 297} Other metal precipitation comes in the form of copper-arsenide and silver-antimony scales in pH-adjusted Salton Sea brines.²⁹⁸ Similar scales have also been observed in low-TDS brines where the reductive deposition occurs on freely corroding carbon steel.

When these deposits are coherent, they protect the underlying steel, but when they are not coherent, recent experience has indicated that rapid localized corrosion can result.²⁹⁹ Additional formation damage may result from invasion of suspended solids (primarily iron silicate particles) present in injection brine precipitates into permeable sections of the reservoir.³⁰⁰

One option described for precipitating heavy metals naturally present in geothermal brines involves adding a base to the silica removal process.³⁰¹ The base, which is selected from a group consisting of ammonia (preferred), sodium hydroxide, calcium hydroxide, sodium sulfide, and sodium polysulfide, increases the pH of the brine-base mixture to between about 6.2 and about 6.6 and reacts with at least some of the heavy metals, notably iron and/or lead, which are naturally contained in the brine. Finely divided, relatively insoluble heavy metal compounds are precipitated from the brine, forming seed material onto which the supersaturated amount of silica precipitates or deposits. When ammonia is used, the base process preferably also includes combining a flocculating agent (e.g., cationic polymer) with the brine and base mixture so as to enhance flocculation of the insoluble siliceous material formed by contacting the brine with ammonia.³⁰²

Another treatment used to polish brines and collect metal scale deposits at the surface just prior to injection consists of passing brine (with a pH of 5) through a conduit packed with coiled, galvanized poultry wire for a time sufficient to precipitate thereon a significant amount of iron silicate and heavy metal scales.³⁰³ The wire packing serves to filter some siliceous suspended solids from the brine while simultaneously removing and recovering a small amount of silver, copper, antimony, and arsenic by a cementation reaction. This greatly reduces scale deposition and appears to extend the useful life of injection wells.³⁰⁴

Arsenic removal from spent geothermal fluids has also been studied. One technique considered viable for removing traces of arsenic from condensate or from water is ozone oxidation followed by iron co-precipitation or catalyzed photo-oxidation processes.³⁰⁵ The photo-oxidation process consists of sparging (bubbling) air through the photo-adsorber-treated fluid and then irradiating it with ultraviolet lamps or exposing it to sunlight to oxidize trivalent arsenic (As³⁺) to pentavalent

arsenic (As^{5+}).³⁰⁶ Residual arsenic in the precipitate may be slurry-injected into a water disposal well or fixed/stabilized for land disposal. Another arsenic treatment method involves using strong-base anion exchange resins that remove traces of arsenic in geothermal fluids provided that the amorphous silica is decreased below its saturation point or the water is stabilized against silica scaling by acidification.³⁰⁷ Chloride-rich water, which had been treated with lime and filtered to reduce amorphous silica to well below its saturation point, successfully regenerated the resin. The ion exchange alternative to arsenic removal by oxidation/precipitation has proven successful in reducing the concentrations of this element to below the limits set for drinking water standards.³⁰⁸

Electro-coagulation treatment is another method for arsenic removal from separated geothermal water.³⁰⁹ Electro-coagulation is an electrochemical process that uses direct current to remove a wide range of contaminants from wastewater. In general, aluminum or iron can be utilized as sacrificial electrodes. The application of a voltage results in the release of charged aluminum or iron ions, depending on the electrode material being used. The ions subsequently hydrolyze to aluminum hydroxide or iron hydroxide. The metal hydroxides agglomerate the colloidal and monomeric silica and the solid mass also adsorbs arsenic. Then, any suitable separation technology can easily separate the flocculants.³¹⁰

Mercury is another metal sometimes found in geothermal fluids. Mercury emissions are usually discharged as gaseous species (Hg^0) and reach the atmosphere with the NCG fraction.³¹¹

2.3.2.7 Total Dissolved Solids (TDS)

The concentration of TDS is a key parameter in determining the feasibility of a number of water treatment technologies. In many instances, the term TDS reflects salinity since these ions are typically in the form of salts. In general, treatment becomes more difficult and expensive as TDS increases.

Table 2-6 lists treatment technologies designed to remove salt and other inorganics from produced fluids.³¹²

Table 2-6. Water Technologies for Removing Salt Content³¹³

Technology	Subcategory	Pros	Cons
Membrane processes	Microfiltration, ultrafiltration, and nanofiltration	<ul style="list-style-type: none"> • Good pretreatment steps for more advanced processes such as reverse osmosis • Operate at lower pressure and lower cost than reverse osmosis 	<ul style="list-style-type: none"> • Cannot remove most salinity • Potential for membrane fouling • Sensitivity to fluctuating water quality

Technology	Subcategory	Pros	Cons
	Reverse osmosis	<ul style="list-style-type: none"> Reverse osmosis can remove salinity (up to about 50,000 mg/L TDS) The membrane allows water to pass through but blocks 98% of the salts 	<ul style="list-style-type: none"> Requires pretreatment and regular membrane cleaning Not suitable for high-salinity water Potential for membrane fouling Sensitivity to fluctuating water quality
Thermal treatment	Distillation	<ul style="list-style-type: none"> Can process high-salinity waters Generates very clean water (which can be reused) as one product 	<ul style="list-style-type: none"> High energy usage and cost Generates concentrated brine stream that requires separate disposal Potential for scaling
	Evaporation/crystallization	<ul style="list-style-type: none"> Can treat to a zero liquid discharge standard 	<ul style="list-style-type: none"> High energy usage and cost Limited usage in oil field applications Potential for scaling Challenges in disposing of salt residue
Ion exchange	None	<ul style="list-style-type: none"> Successfully treats low- to medium-salinity water 	<ul style="list-style-type: none"> Large acid usage; resins can foul Challenges in disposing of rinse water and spent media (resin) Also ineffective on high-salinity produced waters
Capacitive deionization	None	<ul style="list-style-type: none"> Low energy cost 	<ul style="list-style-type: none"> Limited to treating low-salinity waters Limited usage in oil-field applications, but could have a role in treating extracted water with low to medium TDS

2.3.3 Associated Equipment

2.3.3.1 Geothermal Operational Waste Handling

Different types of wastes result from geothermal operations, and they may be handled in a variety of ways. Among the types are solid wastes from treating geothermal brines, untreated geothermal wastes used on a once-through basis, and residuals from pollution control of H₂S. In

some cases, geo-fluids may be discharged to the surface and must also be treated as a waste (refer to Section 2.1.1). Handling practices at several facilities are described by way of example.

The Kizildere, Turkey power plant in the 2003 time frame discharged about 7.4 million tons of wastewater per year to the Buyuk Menderes River.³¹⁴

The residuals from treating the hypersaline brine used at sites located in the Imperial Valley of California, such as the Salton Sea facility, are disposed off-site.³¹⁵ Evaporation basins have also been used for the handling of geothermal brines in Imperial County, California. In 2011, the California Regional Water Quality Control Board issued an order to Unocal Corporation concerning an 85-acre site located in Imperial County.³¹⁶ The facility has 65 acres of evaporation ponds that have been used (or are being used) to manage geothermal brines. Evaporation ponds also handle residual brine from the Cerro Prieto Geothermal Field. Disposal of about 88% of the residual brine production (5,600 tons per hour) is in a 19-square kilometer evaporation pond.³¹⁷

Accumulated sludge from the H₂S pollution control process at The Geysers is periodically trucked to a solids removal facility for processing using a vertical chamber filter press. Filtrate from the filter press is re-injected into the reservoir. Disposal of the dewatered sludge occurs off-site in a California hazardous-waste landfill.³¹⁸

2.3.4 Characterization of Geothermal Power Production Wastes

Extracting heat for the purposes of geothermal power generation can require the processing of significant volumes of geo-fluid. For example, generating 240 Megawatts electric from a liquid-dominated steam flash plant can involve the processing of over 175,000 cubic meters of brine.³¹⁹ As stated previously, geothermal production fluids show a wide range of TDS concentrations (i.e., from less than 500 mg/L to more than 200,000 mg/L), with averages around 81,000 mg/L for high-temperature geo-fluids and 8,200 mg/L for moderate-temperature geo-fluids (refer to Section 2.2.2.3 for further details).³²⁰

Specifically for silica, from a mass balance standpoint, 3 million pounds per day pass through the world's geothermal plants. Thus, a significant amount of that silica flux must be removed as waste to preserve the commercial viability of the geothermal resource.³²¹ Geo-fluid containing environmentally significant NCGs such as H₂S must also be treated, resulting in the generation of large volumes of air pollution control-related waste. The generation of solid wastes by the geothermal power production industry can vary significantly from plant to plant. Characteristics of a few power production-related waste streams are described by way of example.

While not typical, at the Salton Sea geothermal complex, the removal of silica from processed geo-fluids occurs prior to reinjection by the use of crystallizer/clarifiers. About 600 mg of sludge per kg of brine is generated. At one time, the Salton Sea Geothermal Plant clarifiers generated about 45 tons per day of sludge. About 65% of the sludge is iron-rich silica. Fluorite and barite

make up about 3% and 31% of the sludge, respectively. However, in an effort to address the creation of NORM scale in the clarifiers, an inhibitor was introduced into the sludge-handling process. The inhibitor reduced the amount of NORM in the filter cake sludge and reduced generation of sludge by about 40%.³²² This dated information suggests that, at least at the time, the Salton Sea geothermal complex generated about 27 tons per day of solid waste as a result of treating geo-fluids prior to re-injection.

As discussed, the treated brines consist of iron-rich silica, fluorite, and barite. Salton Sea brine also can contain a number of environmentally significant inorganic constituents, which could also be present in the clarifier sludge. For example, arsenic, copper, and lead have been detected in the brine at concentrations of 12, 5.5, and 91 milligrams (mg)/ kilogram (kg), respectively.³²³

The Cerro Prieto plant in Mexico generates up to 50,000 tons of silica waste yearly.³²⁴ This waste is composed of amorphous silicon dioxide, sodium chloride, potassium chloride, and oxides of calcium, sodium, potassium, and titanium.³²⁵

Abatement chemicals were added to condensed geothermal steam used to operate 19 geothermal units at The Geysers resulting in the accumulation of pollution control-related sludge. About 160–570 tons of sludge containing 12%–20% solids are removed from a cooling tower during the blowdown cycle. There is no information available regarding the frequency of the blowdown cycle.³²⁶

3. ENVIRONMENTAL IMPACTS AND PERMITTING ISSUES

This section considers the environmental impacts and accompanying permitting issues associated with geothermal energy development, including the handling of produced fluids. Section 3.1 defines environmental impact elements, including criteria. Section 3.2 describes potential environmental consequences, including impacts on these resources' elements resulting from management of produced fluids. Finally, section 3.3 explains permitting requirements and issues

3.1 POTENTIAL ENVIRONMENTAL IMPACT ELEMENTS

Environmental impact criteria qualitatively evaluate activities associated with geothermal technologies. For more information on these criteria, see Appendix A, “Environmental Resource Element Impact Criteria” in *TWP No. 1: Exploratory Drilling*. The bases for these criteria are often specific environmental resource protection laws. The criteria describe conditions that would lead to potentially significant environmental effects should the activity be implemented. This evaluation includes an assessment of expected impacts based on the type of technology employed—realizing that the assessment's intention is not to address a specific location or actual project.

Impacts may consist of direct or indirect effects. The definition of direct impacts is those impacts caused by the action and occurring at the same time and place. Examples include habitat destruction, soil disturbance, air emissions, and water use. The definition of indirect impacts is those impacts caused by the action, but occurring later in time or farther removed in distance from the action. Examples include changes in surface water quality resulting from soil erosion and alteration of wetlands resulting from changes in surface water quantity.

Additionally, when considering environmental impacts, one must consider all connected, similar, and cumulative actions. A connected action is one that closely relates to the project; an action that cannot or would not proceed unless another action is taken previously or simultaneously; or an action that is an interdependent part of a larger action and depends on the larger action for its justification. For example, treatment and disposal of geothermal wastewater may require construction of a new wastewater treatment plant. Similar actions have similarities with the proposed action that provide a basis for evaluating their environmental consequences together, such as common timing, geography, or purpose. Similar actions can also qualify as connected and cumulative actions. Cumulative actions can have cumulatively significant impacts when viewed with other proposed actions that occur within the same temporal and spatial boundaries. A proposed road-building action by some other agency or entity in the same general areas as the geothermal project would be a cumulative action.

These potential effects can often be mitigated or reduced, but at a cost, and often not completely eliminated.

3.2 POTENTIAL ENVIRONMENTAL CONSEQUENCES

Most of the TWPs in this series have evaluated the potential environmental impacts associated with various geothermal technologies by using the accepted practice of developing and evaluating a hypothetical, representative project. However, discussion of potential environmental consequences for the technology of produced fluids, in a manner similar to that given in *TWP No. 3: Downhole Fluids*, uses a more general approach rather than attempting to develop a hypothetical, representative project. This more general approach is required given how widely the characteristics of the fluids (whether downhole or produced fluids) can vary.

In the case of produced fluids, as described in Section 2 of this paper, the range is quite broad, and it might not be unusual for a geothermal project to involve the use of most—or even all—of the described types. However, the characteristics of these fluids can be so different that management approaches at one site may have little applicability at another. Accordingly, attempting to discuss potential impacts associated with management of specific produced fluids using an assumed set of specific characteristics would likely have limited value, and hence, the more general approach is preferable. However, by the same token, some project-related boundaries are required so that the extent of the necessary discussion is clear.

During the exploration and development phases of a geothermal project, large quantities of produced fluids, including drilling muds, stimulation fluids, or even geothermal fluids, could be managed on the surface at the project site. This document addresses the management of such produced fluids, but it does not address the potential impacts associated with constructing or installing the infrastructure and facilities that would be used in managing these fluids. Rather, it is assumed such infrastructure and facilities are already in place. Similarly, with regard to the production phase, this document discusses potential impacts from managing the various produced fluids that might be present, but it does not discuss the impacts of building, installing, or otherwise using the facilities that would be part of an operating geothermal system. It may be noted in a couple of instances that the produced fluids described in this document consist largely of fluids addressed in *TWP No. 3: Downhole Fluids*. That paper, however, focuses on the initial formulation of the fluids and their intended subsurface use.

Consistent with implementing regulations and guidance for the *National Environmental Policy Act of 1969* (NEPA), as amended (42 U.S.C. §§ 4321 et seq.), environmental analyses must focus on topics with the greatest potential for significant environmental impact. For the reasons discussed in Section 3.2.1, management of produced fluids would not be expected to have any measurable effects on certain resource elements; therefore, these resources would not be carried forward for further analysis. Section 3.2.2 provides a more detailed discussion of the resource

elements that could be affected by the management or reuse of produced fluids. Table 3-1 provides a summary of which environmental resource elements potentially could be affected by the action and the ones for which there is no expectation of adverse effects.

Table 3-1. Environmental Resource Elements Potentially Affected by Management of Produced Fluids

Environmental Resource Elements	Potentially Affected	Not Affected
Cultural and historic		x
Air quality	✓	
Climate change	✓	
Water resources (surface and groundwater)	✓	
Floodplains and wetlands	✓	
Coastal zone management		x
Geology and soils	✓	
Land use		x
Biological	✓	
Transportation		x
Health and safety	✓	
Noise and vibration		x
Natural hazards		x
Hazardous materials and waste	✓	
Intentional destructive acts		x
Recreational resources		x
Visual		x
Socioeconomics		x
Environmental justice		x

Environmental Resource Elements	Potentially Affected	Not Affected
Utilities		x
Cumulative	✓	

3.2.1 Resource Elements Not Carried Forward for Further Analysis

Every aspect of a project site should be considered when evaluating the potential impacts of a specific project. After the appropriate consideration, it can be decided whether an individual resource element can be dropped from detailed analysis in the NEPA document. This section briefly describes why the produced fluid elements of a geothermal project would likely not affect some resource elements. However, the basis for the reasoning provided is only what might be considered a typical project; an actual geothermal project will have its own unique characteristics that may not fit the patterns described in this section.

3.2.1.1 Cultural and Historic Resources

There would be no expectation that the management of produced fluids would have any direct effect on cultural or historic resources in the area. Most activities would be confined to the already constructed and occupied well pad or power production facilities, so there would be no additional land disturbance and no potential for additional impacts beyond those that may already have been experienced from the original construction actions.

As with all other resource elements not carried forward for detailed analysis, the justifications provided in this paper are based on general expectations, which may not be appropriate for a specific site or project. In the case of cultural or historic resources, a local population or tribal group with ties to the land may have a strong reaction to any intrusive action including any component within a larger project.

3.2.1.2 Coastal Zone Management

The *Coastal Zone Management Act of 1972* encourages appropriate development and protection of the nation’s coastal and shoreline areas and gives the states the primary role in managing those areas. The act requires participating coastal states to develop management programs, and once their programs obtain federal approval, the states have review authority over certain federal agency actions. In such cases, the individual state has authorization to determine whether federal projects, federally funded projects, or activities requiring federal licenses or permits are consistent with the state’s coastal zone program.

Management of produced fluids, and geothermal projects in general, would be fully subject to *Coastal Zone Management Act* requirements if their location is in a state’s designated coastal

zone. However, being subject to and meeting such requirements would be similar to meeting permitting requirements. There is no expectation of adverse impacts; rather, the state's review to ensure that projects are meeting its coastal zone management requirements would be expected to result in either a status quo or a reduction in the potential for adverse impacts.

3.2.1.3 Land Use

Activities associated with the management of produced fluids generally would not be expected to involve a change in the effects on land use from those already being experienced from the existing geothermal project. Under the assumption that infrastructure and facilities are already in place and that this evaluation does not address them, there would be no new areas of land disturbance. However, as with other resource elements discussed in this section, projects involving produced fluids could affect land use in some instances. For example, if an EGS project was implemented to expand or enhance a geothermal system already in production, the facility may no longer have the infrastructure to handle a volume of produced fluid that may have been required during production drilling. That is, capacity, such as that provided by a sump pond described in *TWP No. 2: Production Drilling*, could be needed at least temporarily and could involve a notable change to the site's existing land use. As noted previously, for each project, all resource elements must be considered for potential impacts. To reiterate an earlier point, putting a resource element in a category that does not require a detailed analysis, as is done in this paper, is only a generality based on a set of hypothetical assumptions.

3.2.1.4 Transportation

Vehicle traffic associated with management of produced fluids would be expected to be minor unless it was to include transporting large volumes of fluids or treatment residues off-site for disposition or reuse. Water needed to support a geothermal project (and which often becomes produced fluids after being used in actions such as drilling and stimulation) could potentially involve transportation needs, but such needs were addressed in *TWP No. 2: Production Drilling* and *TWP No. 4: Hydraulic Stimulation* and are assumed to be outside the scope of this document.

Additives used in conditioning geothermal fluids or in treating other produced fluids before disposition would be brought on-site via existing roads and would be expected to represent only a minor amount of additional traffic to the geothermal project site. With regard to transporting produced fluids or treatment residues off-site, it is expected that such actions would not be primary options during project planning, particularly if they involved large volumes of materials. However, depending on the project and its location, such actions could be necessary, and potential impacts to area transportation would have to be addressed as an element of managing produced fluids.

3.2.1.5 Noise and Vibration

Management of produced fluids would not be expected to involve any unusual sources of noise or vibrations. Although it is recognized that moving large quantities of water into or out of the subsurface can be associated with seismic events, induced seismicity associated with hydraulic stimulation is addressed in *TWP No. 4: Hydraulic Stimulation* of this series and is not considered to be within the scope of this document. Similarly, noises generated from well drilling or, in most cases, from operating a power production plant are considered independent of how produced fluids are managed. It is recognized, however, that significant noise elements of a power plant operation, including the steam turbine operation and occasional steam venting, are directly related to the use of geothermal fluids. For this discussion, it is assumed such noise is better evaluated as part of overall plant operations rather than as an element of produced fluid management, but such an evaluation, whatever the context, would be necessary for an actual project. Pumping fluids to and from the subsurface, even at the high pressures involved in hydraulic stimulation, or moving and mixing fluids at the surface would not be expected to involve noise or vibrations notably different than other elements of the geothermal project.

3.2.1.6 Natural Hazards

Management of produced fluids would not be expected to aggravate on-site natural hazards. As noted, the induced seismicity associated with hydraulic stimulation actions is not considered to be within the scope of this document.

3.2.1.7 Intentional Destructive Acts

DOE considers intentional destructive acts (i.e., acts of sabotage or terrorism) in its NEPA documentation.³²⁷ Management of produced fluids would not involve the transportation, storage, or use of radioactive, explosive, or toxic materials. Minor exceptions to this would arise if radioisotopes were brought to the site for use as a tracer or if naturally occurring radioactive material (NORM) residues were accumulated from treatment or cleaning actions. Tracers would most likely be used during flow testing of a subsurface reservoir, but they could also be used at other times in the project to characterize how the reservoir is working. One of the benefits of using radioisotopes in tracer tests is that they can be detected at such low concentrations. The amounts of these materials that might be at a geothermal site would not be expected to present an attractive target for sabotage or terrorism.

3.2.1.8 Recreational Resources

The management of produced fluids at a well pad or at an operating geothermal power plant would not be expected to have any direct effect on recreational resources beyond those already experienced from the original construction and operation of the facilities.

3.2.1.9 Visual Resources

Management of produced fluids would not be expected to involve impacts to visual resources beyond those already experienced from other elements of the geothermal project. A possible exception would be steam plumes that could occur occasionally during development actions and, depending on the design of the power plant, during power production. Similar to the noise and vibration discussion above, steam plumes may be considered a result of the management of produced fluids, specifically, geothermal fluids, but for purposes of the current discussion, their impact is attributed to overall plant operations. Again, an evaluation of potential visual impacts, such as might occur from the presence of a steam plume, would be necessary for an actual project.

3.2.1.10 Socioeconomics

Although management of produced fluids, specifically geothermal fluids, is a key element in the operations of a geothermal power plant, it is not reasonable to associate possible socioeconomic impacts with just that element. As with many of the other environmental impact elements, the evaluation of potential socioeconomic impacts is best done at the project level.

3.2.1.11 Environmental Justice

Executive Order 12898, *Federal Actions to Address Environmental Justice in Minority Populations and Low-Income Populations*, directs federal agencies to identify and address the potential for their activities to cause disproportionately high and adverse impacts to minority or low-income populations. Environmental justice is another example of an issue difficult to address except on the basis of the entire project. It is also wholly site-specific. It is unlikely that management of produced fluids could affect minority or low-income populations beyond those effects, if any, already being experienced as a result of the overall geothermal project. However, even if unlikely, impact elements such as air quality, water resources, or visual resources could be affected by produced fluids-related actions at different or more distant sites than by other geothermal project actions. The potential for a low-income or minority population to be subjected to disproportionately high and adverse impacts as a result would have to be evaluated on a case-by-case basis. An evaluation of an actual project would have to consider the potential for such impacts to occur.

3.2.1.12 Utilities

If the geothermal project were in the vicinity of a community, management of produced fluids could potentially affect water and wastewater utilities. Water needed to support a geothermal project (which, as described previously, may become or contribute to produced fluids) could potentially be supplied by a nearby community, but such needs were addressed in this TWP

series for *TWP No. 2: Production Drilling* and *TWP No. 4: Hydraulic Stimulation* and are assumed to be outside the scope of this document.

A wastewater treatment plant operated by a nearby community may be considered an option for the disposal of some produced fluids. The volume of the fluid requiring disposal and the distance to the wastewater treatment plant or one of its collection lines would likely be important considerations in determining the feasibility of such an option. If a local utility was being considered, it would be appropriate to evaluate potential effects by comparing the treatment plant's capacity to existing system demands to ensure the project's needs could be met without affecting the plant's ability to meet its own discharge requirements. The evaluation would also consider the plant's treatment system for compatibility with the specific produced fluid, again to ensure the treatment plant could provide whatever treatment was necessary and still meet its discharge requirements. If the produced fluid wastewater were to be discharged to a collection line, the evaluation would need to address the carrying capacity of the lines to ensure it could handle the new discharge along with existing flows.

An evaluation of potential impacts to utilities, as briefly described above, would be both project- and site-specific. As with other impact elements in this section “not carried forward for further analysis,” the potential impacts to utilities are not analyzed in this paper because the element would not typically be adversely affected and a more detailed evaluation would be site-specific. However, if management of produced fluids involved local water utilities, a complete evaluation of the consequences of such involvement would be appropriate.

3.2.2 Resource Elements Potentially Affected by Management of Produced Fluids

3.2.2.1 Air Quality

The primary concern for air emissions associated with the management of produced fluids would be through the loss or degassing of naturally occurring NCGs from the geothermal fluid. As described in Section 2.4.2, geothermal fluids brought up to the surface during well drilling and testing or for power production often contain NCGs such as nitrogen, CO₂, H₂S, methane, and argon, but they also may include small amounts of ammonia, hydrogen, and sulfur dioxide.³²⁸ H₂S is generally considered the air pollutant of primary concern for geothermal projects. By contrast, there are usually no attempts to capture other gases, and they are simply released to the atmosphere. Emissions of CO₂ and methane as greenhouse gases are discussed in the next section while the discussion in this section primarily deals with H₂S.

H₂S's distinctive “rotten egg” odor can be detected by most people at low concentrations (about 30 parts per billion),³²⁹ and it can have toxic and even lethal effects at higher concentrations. The Occupational Safety and Health Administration (OSHA) has set 20 parts per million of H₂S as the acceptable ceiling limit for the work place³³⁰ and identifies levels above 100 ppm as being “Immediately Dangerous to Life and Health”.³³¹

H₂S and other NCGs can be released from geothermal fluids whenever they are exposed to the atmosphere, such as locations where geothermal fluids naturally come to the surface or in geothermal projects where the fluids are discharged during flow tests. During well drilling and testing actions, there may be no practical means to capture NCGs that may come to the surface with geothermal fluids, but the potential for H₂S to be present in those fluids can present a hazard to workers. As described in *TWP No. 2: Production Drilling*, the safety hazard posed by H₂S requires the use of additional detection and alarm equipment with mandated monitored during drilling operations. Response to alarms, depending on the levels detected, could involve such actions as curtailment of activities, donning of personal protective equipment, or even evacuation.

If the geothermal project moves to the development and production phases, the design of the power plant must address long-term management of NCGs, particularly H₂S. The potential for the emission of gases in the geothermal fluid depends on the type of power plant and the plant's design for using the fluid in generating electricity. For purposes of this document's discussion, the assumption is that this element of the power plant design fits within the scope of "managing produced fluids"; however, it is understood that when selecting the type and design of the power plant for deployment, one must take into consideration many factors in addition to the management of produced fluids.

In typical geothermal power plants where steam from the geothermal reservoir drives a turbine, such as the flash plant depicted in , most of the NCGs are separated from the rest of the geothermal fluid at the condenser and must be vented or otherwise removed in order to avoid pressure buildup. In systems like that shown in Figure 3-1, the condensed fluid may be sent through a cooling system and recycled back to provide cooling of the condenser before being re-injected into the subsurface formation. If the cooling system is an open cooling tower, this may represent another emission source for any H₂S mixed with the condensed liquid.

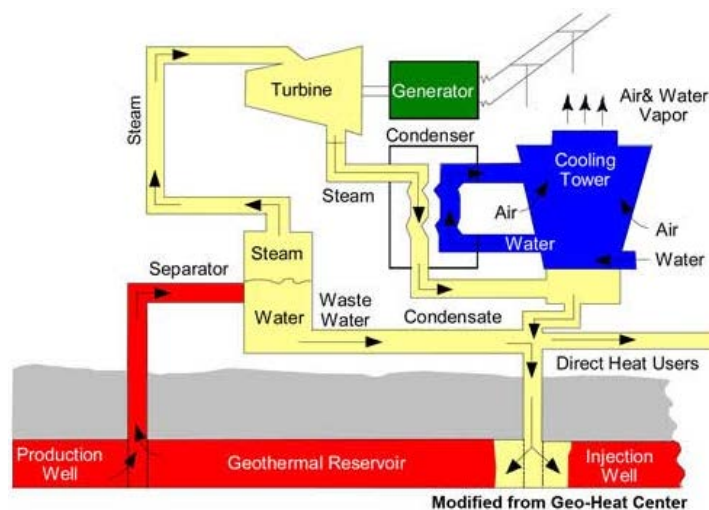


Figure 3-1. Simplified schematic of a flash steam geothermal power plant³³²

The amount of H₂S in geothermal fluid can vary greatly by site and, in cases, by well within a site. A report by DOE's National Renewable Energy Laboratory (NREL) describes H₂S emissions from geothermal flash plants as being in the broad range of 0.5 to 6.4 kg (1.1 to 14.1 pounds [lbs]) per megawatt-hour of electricity produced.³³³ As a result, the potential for emissions of H₂S to be an environmental concern can vary greatly by location as well as by the number and type of production facilities. The need for pollution control equipment also depends on the environmental, safety, and health requirements of the specific location.

If air pollution control equipment is needed to reduce H₂S emissions from the plant, it would typically be in the form of a unit designed for the vent stream at the condenser and could involve chemical treatment or scrubbing to remove the gas. Section 2.4.2 briefly described several different treatment and recovery options. Alternatively, the design of the power plant could be such that NCGs vented at the condenser are collected, recompressed, and injected back into the subsurface with the spent geothermal fluid. The cooling system for the condenser could also be designed such that it did not use the geothermal fluid (for example, either by using only fresh water or being designed as an air-cooled system), so there would be no secondary emission source for the H₂S. In summary, emissions of H₂S from the geothermal fluid are a potential concern for geothermal projects, but a generalization of the severity of such impacts is not practical. Instead, the air permitting process for a new power plant requires specific assessments, which would have to consider all other air emission sources associated with the power plant as well.

Other air emissions associated with the management of produced fluids would be limited to treatment approaches that generated dry materials. The materials include those that could be sources of dust or particulate emissions when moved or otherwise handled or if subjected to wind erosion. Treatment actions such as the use of evaporation ponds for drilling fluids or removal of minerals from geothermal fluids could result in generation of dry materials that could become airborne. These types of air emissions, if potentially part of a geothermal project, could generally be easily controlled through typical best management practices for dust suppression, but they would need to be recognized and addressed in an environmental evaluation.

Conformity: Section 176(c)(1) of the *Clean Air Act* requires federal agencies to ensure that their actions occurring in nonattainment or maintenance areas conform to an implementation plan for achieving and maintaining ambient air quality standards. Specifically, federal agencies must ensure such actions do not contribute to new violations of the standards, increase the frequency or severity of existing violations, or delay timely attainment of standards in the action area.³³⁴ If the assumption is that the geothermal project was in a nonattainment or maintenance area and was a federal action (that is, federally implemented, funded, permitted, or otherwise supported), then it would have to be reviewed for conformity as described in 40 CFR Part 93, Subpart B.

These regulations [40 CFR § 93.153(b)] set specific criteria pollutant threshold emission values that vary depending on whether the site is a nonattainment or maintenance area and, in the former case, the severity of nonattainment. These threshold values can be as low as 10 tons per year for volatile organic compounds or nitrogen oxides in extreme nonattainment areas, but in most instances are in the 50–100 ton per year range (except that lead has a threshold value of 25 tons per year in all nonattainment or maintenance areas). Formal conformity determinations are required only of actions involving air emissions that would equal or exceed any of the threshold values.

Management of produced fluids would not be expected to involve any actions that would equal or exceed threshold values for a conformity determination, but as noted previously for air permits in general, conformity requirements for an actual project would have to be addressed based on the entire geothermal project including the potential release of NCGs from the geothermal fluid.

As examples of implementing these requirements, DOE guidance states that the conformity determination and NEPA public participation processes should be integrated to the fullest extent possible.³³⁵ It is further DOE policy guidance that if the conformity review process concludes that a formal determination is not required, then the NEPA documentation should include such results. DOI/BLM guidance notes that combining conformity and NEPA analyses may be efficient and convenient in some cases, but that such a link is not required (that is, the conformity requirements can be met outside of the NEPA process).³³⁶

3.2.2.2 Climate Change

As discussed in Section 3.2.2.1, NCGs are generally present in natural geothermal fluids, and they include the greenhouse gases CO₂ and to a lesser extent methane. Other than the long-term use of geothermal fluids in the power plant, emissions of NCGs from the management of produced fluids would be relatively minor and temporary. With regard to power plant operations, records of greenhouse gas emissions from geothermal power plants have been evaluated and compared to similar emissions from power plants that burn fossil fuel to generate electricity. On a comparable basis of greenhouse gases emitted per kilowatt-hour of electricity produced, one study described CO₂ emissions from geothermal power plants as being a full order of magnitude less than CO₂ emissions from coal- or oil-fired power plants and about 15% of that emitted by natural gas-fired power plants.³³⁷ Another evaluation described typical greenhouse gas emissions from geothermal power plants as being even smaller in comparison to fossil fuel-fired power plants, specifically, as being less than 5% of those from coal-fired plants and less than 10% of those from natural gas-fired plants.³³⁸ Both evaluations noted that binary power plants, where the geothermal fluid is only put through a heat exchanger before being re-injected, produce no greenhouse gases.

NREL performed an evaluation of lifecycle greenhouse gas emissions from geothermal power plants in which it developed estimates of emissions from various stages of a typical flash steam power plant project.³³⁹ For the operations phase, NREL used an estimated 9.7 grams of greenhouse gases emitted per kilowatt-hour of electricity produced. This emission rate means, for example, that a 10-megawatt flash steam geothermal plant operating at full capacity for a full year (and thus producing 87,600 megawatt-hours or, equivalently, 87,600,000 kilowatt-hours of electricity) would emit about 850 metric tons (940 tons) of greenhouse gases. Using the same emission rate, a 100-megawatt power plant could potentially emit 10 times that quantity. These emissions may appear large, but they are well below the 25,000-metric-ton-per-year trigger set by the EPA for reporting requirements of greenhouse gases (40 CFR Part 98).

Based on the air emission estimates in these examples, it is reasonable to characterize geothermal power plant operations as relatively minor sources of greenhouse gases. If the regulation of greenhouse gases becomes more stringent, however, these emission levels could be associated with more restrictions in the future than at present.

An environmental impact evaluation of the entire geothermal project could address the potential benefits that would result from the overall project. This could be done (as above) by citing reference materials, or by generating project-specific estimates. The Emissions & Generation Resource Integrated Database (eGrid) developed by EPA (available online at <http://www.epa.gov/egrid>) includes air emissions data for almost all electric power generated in the United States. Using this information, which is available by region, estimates can be made of the amount of greenhouse gases that the geothermal plant would avoid when compared to what electric power plants burning fossil fuels would have otherwise produced. The amount of greenhouse gases produced during the upfront phases of the geothermal project (e.g., exploration, production drilling, construction, etc.) would be minor compared to the long-term offsets that would be gained during power production.

3.2.2.3 Water Resources

Potential impacts to water resources, including both surface water and groundwater, from the management of produced fluids would consist primarily of the possibility of contaminating clean water resources with discharges or inadvertent losses and depleting clean resources as a result of the need to supply, replenish, or cool produced fluids. As described in the discussion of transportation impacts (see Section 3.2.1.4), water needed to support a geothermal project may become, or contribute to, produced fluids after being used in actions such as drilling and stimulation. However, the potential environmental impacts of such water needs were addressed in other TWP for those actions (see *TWP No. 2: Production Drilling* and *TWP No. 4: for Hydraulic Stimulation*) and are not repeated in this document.

The term “clean water resource” used in this section refers to surface water or groundwater resources that the geothermal project is investigating or tapping but that are not part of the geothermal fluid reservoir. Since it is assumed that the infrastructure used in managing produced fluids is already in place, this document does not address runoff and erosion-type issues typically associated with new land disturbance.

As Section 2.2 described, naturally occurring geothermal fluids typically have high mineral contents, contain dissolved gases, and can be acidic or alkaline in nature. As a result, these fluids typically are not considered potential drinking water sources. However, there may be clean water resources in close proximity, including overlying aquifers that have to be penetrated to reach the geothermal reservoir. Section 2.2 also describes characteristics of drilling fluids (“muds”) that would be produced from drilling actions and the types of chemicals that could be added to stimulation fluids or for flow or circulation testing and which subsequently would be managed as produced fluids. Additives may include a wide range of materials that can include acids, bases, various tracers, chelating agents, drilling muds, and drilling mud additives. These additives may not be considered highly toxic, particularly in the concentrations used, but it is reasonable to assume that most would not be considered acceptable for uncontrolled release to a drinking water source, either surface water or groundwater.

In an actual project, of course, options for the management of produced fluids would depend on the specific constituents they contained and their concentrations. If discharge to surface water or groundwater was being considered, options would also have to consider the quality and uses of the receiving waters in the area, as well as the regulatory requirements that would be applicable to such a discharge.

Management of produced fluids typically involves periods, for at least parts of a geothermal project, when large volumes of fluids need to be managed at the site. Drilling fluids or muds are formulated and staged in holding ponds or tanks awaiting use in drilling and as they come back up from the drill hole for separation or settling of cuttings. In instances where makeup water is required during power plant operations, tanks or ponds may be needed to mix additives before injection. Hydraulic stimulation, already addressed in TWP No. 4, is another example of an action where above-ground fluid handling capacity would be required. Although the fluid managed in these examples would consist primarily of water, it is assumed they would be managed in tanks or lined pits or ponds due to the additives or natural constituents in geothermal fluids.

Any action to discharge these fluids as wastewater, with or without interim storage, would require the appropriate permits and authorization. Under these conditions, expected environmental effects of the management of produced fluids would be minor. Environmental evaluations also would need to address the effects of accidental releases of these fluids, where they could travel, and what they could impact.

As described in Section 2.2, management of produced fluids could also involve the addition of chemicals to the geothermal fluid or to makeup water to control corrosion or scale formation as the fluid is cycled between the reservoir and the power plant. As described in *TWP No. 3: Downhole Fluids*, environmental evaluations need to identify the specific constituents to be added to the fluids, their concentrations, any associated toxicity information, and their expected fate in the downhole environment. Characterization information collected on the geothermal reservoir should provide key information on where the groundwater is believed to move.

The evaluation would also need to address the potential for well casing failures and possible release of fluids to areas above the geothermal reservoir. This could even involve releases to aquifers at higher elevations that are known to be drinking water sources. This discussion would include the requirement contained in standard geothermal drilling permits to isolate zones of fresh water, usable aquifers, and mineral resources from the geothermal well. This is done through placement of cement in the annulus between the casing and the bore hole. Also under terms of the permit, the adequacy of the isolation must be verified via cased hole cement bond logging with remediation of any zones not having an adequate cement bond. The evaluation needs to include any deviations from these types of requirements; these include providing additional or less protection.

The evaluation of constituents added to geothermal fluids returning to the subsurface reservoir or to other produced fluids that could be accidentally released during management on the surface may represent a “worst case” type of evaluation in which very conservative assumptions are made as to the fate of the fluid, the exposures that could result, and the impacts of those exposures. Screening levels for chemical contaminants at superfund sites posted by [EPA](#)¹ or similar information from the specific state may help in evaluating the risks associated with produced fluid additives in these types of worse-case evaluations.

3.2.2.4 Floodplains and Wetlands

The proponent of a geothermal project would be expected to avoid floodplains and wetlands areas if only to reduce costs and minimize regulatory requirements. With the ability to use directional drilling, avoiding such areas would generally not be difficult, unless floodplains or wetlands were very large or there were some other issues that prevented avoidance. However, were the project located in a floodplain or wetlands area, certain requirements and potential effects can be described in the manner that follows.

Floodplains: Floodplains are lowland and flat areas adjoining inland and coastal waters. These areas are often prone to flooding and the amount of adjacent land inundated depends on the

¹ <https://www.epa.gov/risk/regional-screening-levels-rsls-generic-tables-may-2016>

magnitude of the flooding event. The National Flood Insurance Program administered by the Federal Emergency Management Agency (FEMA) has set the 100-year flood as the national standard for purposes of requiring the purchase of flood insurance and regulating new development.³⁴⁰ A 100-year flood is a magnitude of flood with a statistical probability of occurring, on average, once every 100 years, or restated, a flood with a 1% chance of occurring during any single year. FEMA has developed Flood Insurance Rate Maps for most of the U.S. that show areas prone to inundation by 100-year floods.

Management of produced fluids during exploration or development phases of a geothermal project would be relatively temporary (short-term) and unlikely to be affected by flooding or to impact flood zone boundaries unless the project was in a very flood-prone location. However, during the production/utilization phase, produced fluid management actions would be expected to involve more permanent facilities and equipment and be designed or enhanced to incorporate appropriate flood protection measures. This could include making the facilities and equipment more resistant to flood damage and keeping at least the operating levels of structures above flood levels. It is reasonable to assume such actions would be taken because they protect the value of the facility and would likely be required by building permits as well as insurers.

If in a floodplain, any facility components below the flood level would take up space that would otherwise be available for flood water. The action would therefore change the height and area of inundation for a given magnitude flood. Depending on the characteristics of the flood zone and the proximity of other facilities, flood level changes could adversely affect other facilities. Local agencies responsible for issuing building permits would consider these types of concerns and would be expected to deny building permits or require mitigation measures if potential effects to flood levels were significant.

If the project was part of a federal action or if it was, in whole or in part, federally funded, the applicable federal agency would be required to adhere to requirements of Executive Order 11988, *Floodplain Management*, which requires federal agencies to take actions to reduce the risk of flood damage; minimize the impact of floods on human safety, health, and welfare; and restore and preserve the natural and beneficial values served by floodplains.

Wetlands: Wetlands are areas periodically or permanently inundated by surface water or groundwater that support vegetation adapted for life in saturated soil. For a location to qualify as a wetland, it must have hydric soils, hydrology indicators, and wetland vegetative species.³⁴¹

If there is the potential for wetlands to be present in the area, qualified personnel need to undertake a survey to determine the presence of wetlands in any project areas. If a wetland is present, a tentative determination also needs to be made as to whether it is a jurisdictional wetland (that is, associated with a traditional navigable “waters of the United States” or a relatively permanent tributary to one) and regulated by the U.S. Army Corps of Engineers

(“Corps”) under Section 404 of the *Clean Water Act*. A determination through a survey effort can only be tentative because the Corps must make the formal determination.

If it is a jurisdictional wetland and if it cannot be avoided, any action involving discharge of dredge or fill materials into the wetland would have to obtain a permit from the Corps to do so. Such a permit could be accompanied by a requirement to establish, or contribute to the establishment of, replacement wetland at some other location. If a wetland is present, but it is an isolated, non-jurisdictional wetland, there may still be permit requirements if the applicable state regulates such wetlands. Also, in many states, any wetland action that requires a Section 404 permit from the Corps must also obtain certification from the state pursuant to Section 401 of the *Clean Water Act*. If applicable, the certification often dictates best management practices and possibly monitoring and assessment plans to ensure project actions associated with the wetlands area comply with state water quality standards. If there was any question about the applicability of a Section 404 permit, discussion with the Corps would be the appropriate course of action.

In the unlikely event that either floodplains or wetlands were present in the project area, permitting requirements and anticipated building restrictions would minimize the potential for any serious environmental consequences.

3.2.2.5 Geology and Soils

Since it is being assumed that all infrastructure is in place for the management of produced fluids (and, therefore, not in the scope of this document), there would be little potential for adverse impacts to soils other than those associated with accidental releases (addressed in the discussion of water resources) and from subsidence (addressed in this section).

Most geothermal projects and power plants are located in tectonically active areas such as volcanic regions and fault zones and, as a result, are in areas where subsidence may occur naturally. There are, however, examples, such as the Cerro Prieto geothermal field in Baja California, Mexico, where subsidence attributed to the geothermal project itself has occurred.³⁴²

The extraction of large volumes of water from the subsurface geothermal reservoir without replenishment causes such subsidence. Removing the water causes a reduction in the formation’s pore pressure and reduces the formation’s ability to support itself and the overlying rock, potentially resulting in a slow downward deformation of the overlying materials. Reinjecting the geothermal fluid or injecting makeup water reduces the potential for subsidence to occur.

If management of produced fluids did not involve cycling geothermal fluids back to the subsurface reservoir, with makeup water as necessary, then the potential for subsidence would need to be evaluated. The potential for subsidence would depend on site-specific characteristics including the depth of the reservoir and the geology at and above the reservoir.

3.2.2.6 Biological Resources

Management of produced fluids could have effects on biological resources in a couple of areas beyond the existing geothermal project. The first area includes potential concerns that are basically the same as those discussed with respect to water resources, namely, the potential for accidental release of produced fluids. Contaminants in the produced fluids would most likely affect the flora and fauna in nearby receiving waters (i.e., stream, ponds, and/or reservoirs). The expectation is that the evaluation of potential impacts would focus on the likelihood of a release to occur and the proximity of any receiving water if it did occur. Project water demands could affect flora and fauna in springs and other surface waters as discussed in *TWP No. 3: Downhole Fluids*, but as described previously, project water demands are assumed to be outside the scope of the current discussion.

The second area of potential concern involves any open pits, sumps, or ponds possibly used in the management of produced fluids. These types of structures might be required for the management of drilling muds, geothermal fluids from flow testing, or other produced water and generally are lined with plastic or clay to prevent seepage and vegetation growth. These structures could impact wildlife by providing a catch basin for rainwater, but they could also contain minerals and chemicals from produced fluids that could be toxic to wildlife. Furthermore, some species may fall into the pits or go into them intentionally for water, and then be unable to get out because of the slick liner. This latter concern might be mitigated by installing some type of wildlife escape structure like those developed for watering troughs and other water structures.³⁴³ Such a structure may be no more than a climbable, low-angle surface that extends down to the bottom of the pond. Whether an escape structure would be appropriate would depend on the site, the accessibility of the pond to wildlife, and the wildlife that could be affected. Depending on the specific wildlife, or even livestock, that could be affected, fencing as described in Section 2.3 may also be an appropriate protective measure.

Of course, these identified concerns become more serious if there are threatened or endangered species or state species of concern that the project could negatively impact.

3.2.2.7 Health and Safety

Because they are hot and generally at high pressures, geothermal fluids and their proper management represent some of the primary worker health and safety concerns associated with a geothermal project. However, management of these fluids is a primary consideration of geothermal power plant design and procedures development for all stages of a geothermal project.

Although there are unique health and safety concerns associated with the management of produced fluids, they are also thoroughly integrated into overall geothermal activities, and they are best evaluated in terms of the entire geothermal project.

Risks to public health and safety from management of produced fluids would be similar to those posed during other elements of the geothermal project. The well pads typically constructed for development activities (such as production drilling) are large (5 acres in size in the case of the Newberry Volcano EGS Demonstration Project) and by themselves provide a physical buffer between the work actions and any member of the public during those operations.

An adequate buffer space would also be an expected element of any power plant's design and construction. It is assumed directional drilling would be pursued if necessary to provide an adequate safety buffer between members of the public and operations on the well pad or subsequent power plant operation.

The potential for adverse effects to aquifers and drinking water sources would represent a public health and safety concern; the water resources discussion addressed these effects.

3.2.2.8 Hazardous Materials and Waste

The produced fluids described in this document are primarily water. Drilling muds, in spite of all the solids used in their makeup, are still predominantly water. Other than the produced fluids themselves, the hazardous materials and waste directly associated with the management of those fluids would be the additives and possibly treatment residues or extracted constituents described in Section 2. Additives would be expected to include both liquids and solids and likely would be stored to some extent on-site pending their use. Minimum requirements would specify the use of secondary containment for any storage tanks or drums containing hazardous liquids.

As was described in other TWPs (in particular, *TWP No. 2: Production Drilling and TWP No. 4: Hydraulic Stimulation*), project operations during construction, including any management of produced fluids, would be subject to a general NPDES permit for storm water discharges. This would also include adherence to the Storm Water Pollution Prevention Plan required as terms of the NPDES permit. These requirements include measures to ensure the proper management of any hazardous materials, to minimize the potential that runoff could carry any hazardous materials off-site, and to maintain procedures and equipment in order to respond to and clean up any inadvertent spills or leaks.

A geothermal power plant is not one of the industrial categories that automatically requires, per federal regulations, a NPDES permit during operations, but the specific state in which the plant is located may have additional requirements. In any case, best management practices should dictate the appropriate management of any hazardous materials stored on-site, and the appropriate equipment and procedures should have been established during construction actions when they were required measures.

Should any produced fluids not be injected to the geothermal reservoir and require disposal, they would likely represent one of the more significant waste streams, at least by volume, to be

disposed of by the geothermal project. Depending on the specific site, the applicable regulatory agency could possibly agree to and issue a permit for the discharge of a wastewater to a surface drainage, but it is very unlikely that such a discharge would be allowed before the wastewater could be tested and verified to have acceptable discharge characteristics (including heat and any naturally occurring contaminants). It is assumed that the well pad sump or sumps would be available to hold this wastewater pending its characterization and appropriate disposition.

As described previously, disposal of wastewaters in a local community's wastewater treatment system may be an option at some locations. This is provided that the project's wastewater was compatible with the treatment system and would not cause the treatment plant to exceed its discharge limits.

As described in Section 2.1, the produced fluids addressed in this TWP are those considered to qualify for the hazardous waste exclusion of 40 CFR § 261.4(b)(5). However, it is important to note that although these produced fluids are not, by definition, hazardous waste, their management is still regulated under other environmental regulations including those established under the *Clean Water Act* and the *Safe Drinking Water Act*. Also, unused additives that might be considered (as described above) hazardous materials would be fully subject to hazardous waste regulations, as applicable, if designated as waste.

3.2.2.9 Cumulative Impacts

As was described in Section 3.1, typical environmental evaluations would address other proposed actions that may occur within the same temporal and spatial boundaries as the primary action being evaluated and which, therefore, may result in cumulative impacts. Since this paper is intended to address only a specific element of an overall project, there is no basis for a discussion of cumulative impacts in this instance. At a minimum, an evaluation of environmental consequences from the management of produced fluids would have to be in the context of the overall geothermal project. That is, produced fluids would be part of, and in a sense cumulative with, a larger project. The evaluation of an actual geothermal project would include the management of produced fluids as well as other related or non-related proposed actions that could involve cumulative impacts.

3.3 PERMITTING REQUIREMENTS AND ISSUES

3.3.1 Geothermal Drilling Permitting Process

Before a geothermal well may be drilled through a federally managed geothermal lease, a Geothermal Drilling Permit (GDP) (BLM Form 3260-2) must have been submitted and approved by the BLM and the appropriate state agency. The individual state agencies' permits that are required prior to GDP approval vary widely. Detailed information on federal, state, and local permitting is available at the Geothermal Regulatory Roadmapping website on OpenEI:

<http://en.openei.org/wiki/GRR>. Each GDP application requires information on the drilling plan, mitigation measures to protect the environment, and contingency plans.

3.3.2 Contingency Plans

Contingency Plans are safety plans that apply to a geothermal drilling project. They are included as an appendix of the GDP and include plans specific to produced fluids. These include (1) Hydrogen Sulfide Contingency Plan; (2) Spill Containment and Notification Plan; and (3) Blowout Action Plan. The Conditions of Approval (COAs) specific to the submitted drilling and operation programs may also be attached to the approved GDP. Those listed and described below are specific to produced fluids handling and storage.

3.3.2.1 Blowout Contingency Plan

BOPE is to be kept in operating condition and tested in compliance with BLM regulations, Oregon Department of Geology and Mineral Industries requirements, and industry standards. In addition, cold water and barite will be stored at the well pad for use in the killing of (i.e., preventing the continued flow from) the well in case of an emergency. In the event of an emergency such as a blowout, immediate efforts will be taken to shut surface valves and activate the blowout preventer system. If the means to shutting or controlling the flow from the well are lost, the Blowout Contingency Plan contains procedures that shall be implemented to completely contain the well and initiate steps to return the area to its normal state prior to the blowout or fluid flow.

3.3.2.2 Spill or Discharge Contingency Plan

In the event of discharge of formation fluids, drilling muds, petroleum products, or construction debris, the person responsible for the operation shall make an immediate investigation and then contact the drilling supervisor and advise him or her of the spill. The drilling supervisor shall, in turn, release equipment, regulate field operations, and/or do other work, as appropriate, for control and clean-up of the spill.

The Spill or Discharge Contingency Plan contains specific procedures for responding to geothermal fluid, drilling mud, and petroleum product spills. These include the following:

- For geothermal fluid spills: Contain spillage with dikes, if possible, and haul the fluid to a disposal site by vacuum or water trucks, or otherwise dispose of it in an acceptable manner.
- For drilling muds: Repair any broken sump and/or contain with dikes, and haul the fluid to another sump, available tanks, or approved disposal site.

- Petroleum products: Contain spill with available manpower. Use absorbents and dispose of these in approved disposal area. If a spill occurs, clean up any surface staining on soil on a regular basis.

In all cases, the applicant must notify agencies and regulatory bodies and will also advise the local population and affected property owners if a spill affects residents or property. The applicant must have the source of the spill repaired at the earliest practical time, and will continue to utilize work crews and equipment on cleanup activities until all concerned agencies are satisfied.

3.3.2.3 Hazardous Gas Contingency Plan

All personnel must be trained in warning signs, signals, first aid, and responsibilities in case of the release of hazardous gases. The site will have two briefing areas situated in such a way that one is always upwind from the well and containment basin. Before drilling or testing commences, all personnel will be advised of escape routes. Weekly drills must be conducted. In addition, automatic H₂S detectors must be stationed around the rig. Safety precautions will take into account the possibility (as noted within a nearby well log) of encountering natural gas during drilling. Lower explosive limit meters must be installed on the drill rig to monitor natural gas levels.

The Hazardous Gas Contingency Plan also contains emergency procedures that will be followed in the event that hazardous gas is detected. This plan will be submitted to BLM prior to the commencement of project activities and amended at the discretion of the agency.

3.3.3 Conditions of Approval

COAs include special provisions applied to any GDP or Geothermal Sundry Notice (Form 3260-3) approval. The engineering and geologic staff typically develop COAs during an on-site inspection and environmental review for the operations and drilling plans. The on-site inspection is conducted with the participation of the BLM and surface management agency representatives, the operator (or permitting agent), and those parties associated with processing the permit application, which may include the operator's contractors, agency resource specialists, surveyors, and utility/pipeline company representatives. If the project is on split estate lands, the surface owner will be invited to participate in the on-site review.

Site-specific COAs will be identified and may be negotiated during the on-site inspection phase of GDP processing. In addition, discussions and decisions of which best management practices are suitable to mitigate those impacts will be incorporated within the approved permit.

3.3.4 Relevant Regulatory Framework

3.3.4.1 Safe Drinking Water Act

Geothermal reinjection requires a Class V Underground Injection Control (UIC) permit. The Class V system is regulated under authority of Part C of the *Safe Drinking Water Act*.³⁴⁴ Depending on the state and whether the well is located on state, federal, or private land, state agencies, the BLM, and/or EPA regional offices will issue the permits.³⁴⁵ In general, the permits establish requirements and oversight for the design, construction, operation, and monitoring of these wells, including mechanical integrity testing, financial responsibility, and end-of-life plugging and abandonment.³⁴⁶

UIC regulations in 40 CFR §146.5(e) define Class V wells to include “injection wells associated with the recovery of geothermal energy for heating, aquaculture, and the production of electric power.”³⁴⁷ These wells may inject three types of fluid: (1) spent geothermal fluids; (2) condensate and other operationally produced fluids from the power plant; and (3) supplemental water.³⁴⁸ A total of 234 documented electric power geothermal injection wells existed in the United States as of 2007 when the EPA published a report on their operations.³⁴⁹ These injection wells are typically drilled to a greater depth and use thicker casings than most other Class V wells.

As part of receiving a UIC well permit, these injection wells are monitored on a continuous or periodic basis (e.g., every one to five years) as a routine condition of injection management activities.³⁵⁰ This monitoring ensures that the fluid is consistently reaching the intended injection zone. Other forms of continuous monitoring include the monitoring of injection pressure, flow rates, and volume changes, which may signal a leak in the well tubing and/or casing.³⁵¹ Because injected fluids recharge the geothermal reservoir underground and thus will appear at some point in the future in the production wells (as produced fluids), plant operators have an incentive to make sure that the fluids injected underground will not compromise plant operations at a later date.³⁵²

3.3.4.2 Geothermal Steam Act

At the federal level, the BLM regulates use of geothermal resources on federal lands administered by the Department of the Interior or the Department of Agriculture.³⁵³ The BLM can issue geothermal resource operational orders pertaining to nationwide requirements, notices to lessees about statewide or regional requirements, and other orders or instructions specific to a field or area.³⁵⁴

These rules establish general standards that apply to all drilling operations. These can include all environmental and operational standards, the prevention of unnecessary impacts to surface and subsurface resources, the conservation of geothermal resources by minimizing waste, and the

protection of public health and safety. On an operational level, these standards include keeping the well under control at all times, conducting training during operation to ensure competence of personnel, providing a system to control geo-fluid temperatures, providing BOPE, and providing a casing and cementing program.³⁵⁵

3.3.4.3 State and Local Regulations

State and local authorities can also have overlapping jurisdiction with other federal geo-fluid management programs. States can each provide their own regulations and requirements for managing geo-fluid return-flow wells. This is done in a variety of ways. California, for example, has a Memorandum of Agreement between EPA and the California Division of Gas and Oil. In addition, Regional Water Quality Control Boards may prescribe requirements for discharge of waters within the state.³⁵⁶ In Hawaii, the Department of Health also regulates geothermal injection wells and requires a state-level permit.³⁵⁷ Finally, Nevada requires that geothermal injection wells obtain a separate permit in addition to the Class V UIC requirements.

4. POTENTIAL MITIGATION MEASURES

The BLM requires that decisions be implemented in accordance with the appropriate NEPA decision document (i.e., Decision Record/Finding of No Significant Impact). Monitoring is needed to ensure that actions taken comply with the terms, conditions, and mitigation measures identified in the decision. The BLM will fulfill this responsibility by monitoring the implementation of mitigation measures adopted as COAs to the submitted Operations Plan and GDPs, as well as any stipulations attached to the geothermal lease.

4.1 GENERAL MITIGATION MEASURES/CONDITIONS OF APPROVAL

The mitigation and monitoring measures described below for groundwater represent those identified during the analysis conducted during an EA as part of the GDP approval process:

4.1.1 Groundwater

- Excavation into native soil during construction of well pad reserve pits will be minimized to the maximum extent possible.
- Drill pad reserve pits will compact during construction, and settled bentonite clay from drilling mud will accumulate on the bottom of the drill pad reserve pits to act as an unconsolidated clay liner, thus reducing the potential for drilling fluid to percolate to groundwater.
- A BLM-approved cementing and casing program for the drilling of observation wells will prevent water quality effects on groundwater during or after completion of the wells.
- Borehole geophysics analyses (i.e., cement bond logs) will document that well casing and cementing activities provide an effective seal isolating the geothermal aquifer from shallow alluvial aquifers, thereby minimizing potential impacts on surface springs or streams.
- The use of BOPE during drilling and the installation of well casing cemented into the ground will ensure that any geothermal fluid encountered during the drilling will not flow uncontrolled to the surface.
- Any well on the leased land that is not in use or demonstrated to be potentially useful will be promptly plugged and abandoned in accordance with lease stipulations. No well will be abandoned until it has been demonstrated to the satisfaction of the BLM that the well can no longer produce commercial quantities, and that it will not serve any other useful purpose such as injection of geothermal fluids, monitoring of the geothermal reservoir, or groundwater. No water wells will be installed within a 5,000 foot radius of existing water wells on BLM lands.

As part of the mitigation measure, the wellbore would be drilled using non-toxic, temperature-stable drilling mud composed of a bentonite clay-water or polymer-water mix for all wells. Specific materials and quantities to be used would be determined based on conditions encountered during drilling. Variable concentrations of additives would be added to the drilling mud as needed to prevent corrosion, increase mud weight, and prevent mud loss. Additional drilling mud would be mixed and added to the mud system as needed to maintain the required quantities.

Full-size wells would undergo short-term well testing. Each test, lasting approximately four days, would consist of flowing the well while monitoring geothermal fluid temperatures, pressures, flow rates, chemistry, and other parameters.

Geothermal steam and NCGs would be separated from produced geothermal fluid and discharged to the atmosphere through a rock muffler (if used) or steam separator. A surface-booster pump would pump the residual produced geothermal fluid through a temporary 8–10-inch diameter pipeline to route the produced fluid in one or more of the following ways:

- To the constructed reserve pit(s)
- Into one or more tanks, such as 500 barrel (bbl) Baker Tanks contained on the well pad
- Into one of the other geothermal wells drilled within the project area.

An “injectivity” test may also be conducted by injecting the produced geothermal fluid from the reserve pit back into the well and the geothermal reservoir. The drill rig would not be moved from the well site following completion of these short-term test(s).

One or more long-term flow tests of each full-size, drilled well would likely be conducted following the short-term flow tests to determine more accurately the productivity of the long-term well and geothermal reservoir. Each long-term flow test could last as long as 10 days.

Geothermal fluids would not be discharged to the ground under normal operating conditions, except as identified in Section 4.2. Furthermore, geothermal wells are cased to minimize the risks of comingling of the geothermal fluids with underground aquifers. A Spill or Discharge Contingency Plan is provided in the Operations Plan (see Section 3.3.2.2).

Each well would be equipped with controls and alarms for detecting and warning of hazardous gas emissions such as H₂S from deep geothermal fluids. A Hazardous Gas Contingency Plan (discussed in Section 3.3.2.3) is provided in Appendix A, subpart C of the Operations Plan. The BLM requires these measures for geothermal well drilling (refer to 43 CFR § 3262.10 & § 3262.11).

The reserve pit shall be fenced in conformance with the *Gold Book*.³⁵⁸

4.1.2 Well Abandonment

A well with no commercial potential may continue to be monitored but will eventually be plugged and abandoned in conformance with the well abandonment requirements of the BLM and the appropriate state agency. Abandonment typically involves filling the wellbore with clean, heavy abandonment mud and cement until the top of the cement is at ground level. The well head (and any other equipment) will then be removed, the casing cut off deep below ground level, and the well hole backfilled to the surface.

4.2 WATER QUALITY MANAGEMENT PLAN

The purpose of a water quality management plan (WMP) for the site is to identify any potential impacts to both surface and groundwater. Geochemical data should be collected prior to stimulation on the groundwater in shallow aquifers; on the groundwater in all geothermal production, monitoring, and observation wells; and on any geothermal features in the immediate area to establish a baseline. Recommended analysis in addition to geochemistry should include water resistivity (conductivity), pH, temperature, and hydrostatic head pressure in non-flowing wells.

A WMP is an essential component of any drilling operation. The plan must be specifically designed for the hydrological basin in which the project is planned and address both surface and ground waters. The plan should include an understanding of the applicable federal and state laws, regulations, and policies governing both surface and groundwater use. This includes the *Clean Water Act*, and the implications of state water laws for the acquisition and use of water for the project.

Consultation and outreach with surface and water rights holders should be initiated early in the planning process for the project and development of the WMP. There should be an application of best management practices (BMPs) within the WMP.³⁵⁹ While most of the BMPs developed were specifically for oil and gas, they are applicable to the development of geothermal resources. The application of a particular BMP is evaluated during the NEPA process to develop mitigation measures and altered to reduce or eliminate site specific impacts.

4.3 BEST MANAGEMENT PRACTICES

A number of BMPs can be implemented to increase protection of drinking water and the environment. These offer the added bonus of improving the safety and cost performance of the geothermal well. EPA developed the BMPs in Table 4-1. EPA provides more detail regarding these BMPs in its report, *The Class V Underground Injection Control Study Volume 17: Electric Power Geothermal Injection Wells*.³⁶⁰

Table 4-1. Best Management Practices for Produced Fluids³⁶¹

Design and Construction	To protect groundwater, wells should be designed with casing that runs from the surface to a depth below drinking-water formations.
Operating Pressure and Injection Rate	Maintaining proper injection pressure is critical so as to avoid excessive pressure buildups, which can cause injection-induced seismic activity. These, in turn, can stress injection well equipment and cause failures that have the potential to contaminate drinking water sources. Continuous monitoring of injection pressure is therefore important in avoiding these issues.
Maintenance	Using site-specific materials is an important part of well maintenance. Some environments are extremely corrosive, and care must be taken to ensure that corrosion of well equipment does not result in leaks.
Mechanical Integrity	Well integrity should be monitored continuously as a routine part of injection management activities. It should include monitoring of injection pressure, flow rate, and volume for changes that may signal a leak in the injection casing. Testing may involve performing hydraulic pressure tests or mechanical well logging to confirm that the well is functioning correctly and fluid injected is confined to the correct zone.

5. FUTURE CONSIDERATIONS AND CONCLUSION

Utilizing the Earth's geothermal heat reserves for widespread commercial usage will require continued improvements to various technologies related to drilling and the types of fluids used to stimulate geothermal reservoir productivity. Successful, widespread geothermal energy production will also require the effective management of the produced fluids resulting from the drilling, stimulation, and surface power plant operations. As discussed in this paper, these fluids must be properly characterized because they frequently require specialized handling and management at the surface to ensure they do not adversely impact the environment. This is true for the drilling muds as well as the geothermal fluids returning via production wells. Issues of on-site surface disposal must be addressed through federal, state, and local clean water statutes and regulations. In addition, while reuse and recycling of certain produced fluids represents a possible resource for industry, agriculture, and even domestic use, as well as recharging the hydrological cycle, any such efforts must continue to meet stringent environmental and human health standards. In this way, effectively managing produced fluids is as important a future consideration as any other issue related to geothermal energy development.

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