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Surface Containment for Geothermal Brines

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SURFACE CONTAINMENT FOR GEOTHERMAL BRINES

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FOREWORD

When energy and material resources are extracted, processed, converted, and used, the related pollutional impacts on our environment and even on our health often require that new and increasingly more efficient pollution control methods be used. The Industrial Environmental Research Laboratory-Cincinnati (IERL-Ci) assists in developing and demonstrating new and improved methodologies that will meet these needs both efficiently and economically.

Heat and chemical constituents in geothermal brines could be very damaging in an uncontrolled release to the surface environment. This report provides a preliminary evaluation of the probability of unplanned brine releases from geothermal power plant operations and describes measures that may be used to contain such releases.

Further information on the subjects of this report can be obtained from the Power Technology and Conservation Branch, Industrial Environmental Research Laboratory, Cincinnati, Ohio 45268.

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ABSTRACT

Planning is currently underway for approximately ten power plants in the United States, utilizing liquid-dominated geothermal resources. The extraction of heat from these geothermal brines will inevitably produce a large quantity of spent fluid that requires safe and economical disposal. Because of the large volume and potentially toxic nature of the spent fluid, environmental degradation may occur from rupture of the transport mechanism. The objective of this study has been to determine measures to minimize environmental damage from unplanned or accidental surface release of geothermal brine. These measures primarily involve methods of containing releases in time and area.

Six types of geothermal energy conversion systems were considered initially and three were selected for detailed analysis. These are:

- a 360°F (182°C) double flash system;
- a 360°F (182°C) brine binary system;
- a 550°F (288°C) multiflash binary system.

Flow rate and component sizes in these systems were selected for consistency with the requirements of a 50 MWe power plant. Maximum brine flow rates range from 4000 lpm (1000 gpm) to 53,000 lpm (14,000 gpm) in the well-to-plant piping. Accordingly, the rate of flow in an inadvertent release could range from a trickle to approximately 53,000 lpm (14,000 gpm), depending upon the component failure mode that causes the release.

The probability of an inadvertent brine release ranges from about one in 500 that a large spill will occur during a 40 year plant life to a virtual certainty that trickle spills will occur during the 40 years.

There are three means of containing an inadvertent release and minimizing the resultant environmental damage: minimizing the potential for component failure, limiting release duration, and limiting the affected area.

Minimizing the potential for component failure is a matter of:

- using materials of good engineering design, incorporating component redundancy, and minimizing the number of components;
- proper maintenance and component replacement; and
- security to prevent wanton damage.

Release time can be minimized with an adequate brine shut-off system. Automatic flow or pressure-actuated shut-off systems could limit brine release to a few hundred or thousand gallons, but such systems are complex and expensive. Given the relatively low probability of a major release, a shut-off system requiring manual closure of appropriate valves appears more attractive. If an adequate alarm system is present and free movement of personnel is assured through the plant in event of a release, alert and well-trained plant operators could manually close wellhead valves in an estimated maximum time of two hours. Accordingly, a maximum release could spill approximately 6,300 cubic meters (5 acre-feet) of brine.

Ponding can limit the areal extent of a brine release. Environmental damage would be minimized by locating the pond within the plant perimeter. Since significant spills to this pond will be rare and only temporary, unused portions of the plant site and non-critical areas such as parking lots could serve as locales. Since a 50 MWe geothermal plant will occupy approximately 40,000 square meters (10 acres), 6,300 cubic meters (5 acre-feet) of brine could be accommodated in most circumstances. Accordingly, areal containment will involve constructing a dike with its location and dimensions dependent upon available plant area and the grading profiles of the plant site.

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SECTION 1

INTRODUCTION

The major commercial development in geothermal energy in the United States is The Geysers dry steam field, operated by Pacific Gas and Electric Company for electric power production. Commercial development of the much more prevalent liquid-dominated geothermal resources can be expected within the next five to ten years. Approximately ten power plants using liquid-dominated resources are now under construction or being planned.

The extraction of heat from geothermal fluids will inevitably produce a large quantity (several million gallons a day at each site) of spent fluid. The most likely method of liquid disposal will be subsurface injection. Because of the large flow and potentially toxic nature of the spent brine, environmental degradation may result from rupture of the brine distribution system.

The objective of this study is to determine the measures necessary to minimize environmental damage from unplanned or accidental surface releases of geothermal brine. These measures primarily involve methods of preventing releases and containing those that do occur. Particular emphasis has been placed on power generation systems expected to be operational within the next five years.

SECTION 2

CONCLUSIONS

The conclusions that can be drawn from this study follow:

- In their chemical make-up, geothermal liquids in the United States range widely from nearly pure water to high salinity brines. Dilution of escaped geothermal liquid may occur by mixing with natural waters to limit the extent of damage, (although the damaged area may sometimes be increased), depending on the fluid characteristics and the local hydrological conditions.

- The conversion systems that are most likely to be used in the next five to ten years for generating electricity from geothermal liquids are flash and binary systems or a combination of these. In these systems, the geothermal liquid will be brought up from wells, passed through flash chambers or shell-and-tube heat exchangers, and returned to the subsurface by injection wells. The plant components that handle brine above ground will be comparatively few, simple, and of standard design. Independent units producing about 50 to 100 MWe from brine flows of 114,000 l/min (30,000 gpm) or less, depending on the fluid temperature, will be common. Escape rates in the event of a serious accident will be limited to about 53,000 l/min (14,000 gpm), if the brine flow is split into two parallel flows for engineering or safety reasons.

- Using individual component failure rates taken from nuclear safety studies, it is estimated that the overall probability of one large brine spill during 40 years operation of a 50 MW plant is about 1 in 500, or 0.2 percent. (The probability of two or more spills is very much less). A major portion of this risk is from failures in flash chambers, steam separators, heat exchangers or flow lines; wellhead failures are not included. The estimated probability that one wellhead will release brine during 40 years operation ranges downward from 0.8 percent, depending on the number of wells needed to produce 50 MWe; the probability decreases with decreasing number of wells.

- The successive lines of defense against brine spills are:

  - Good design and materials selection in building the plant, together with systematic monitoring and maintenance.

  - Systems to limit the duration of spills with automatic pressure-drop alarms and shut-off or bypass valves utilized where possible.

- Dikes to contain spills, designed to keep the largest expected spill within a small area inside the plant perimeter. Moderate spills will obviously be contained, if containment facilities are designed for the largest potential spill. Impervious ponds with clay, bentonite, or other lining material should be used for containment of spills within a plant facility.

SECTION 3

RECOMMENDATIONS

Recommendations arising from this study are as follows:

- Geothermal plant designers and operators should be caused to recognize the possibility of environmental damage resulting from a brine spill, and means of minimizing this damage should be routinely included in plant design and operations. Guidelines for materials, equipment, maintenance and special containment measures should be established to secure a uniformly low risk of spill-induced environmental damage. Given the wide variation in fluid chemistry at different sites and the generally small probability of large spills resulting from normal operations, numerical standards may not be appropriate.

- Given the lack of geothermal plant operating experience in the United States, estimating failure rates for geothermal components has required reliance upon nuclear data. Although these data are considered adequate for this preliminary estimate, it is recommended that confirmation of these estimates be made as early as possible from actual geothermal operating experience.

- With the lack of operating experience in geothermal hot water plants in the United States, data for establishing proper plant maintenance procedures, schedules and costs are not readily available. In particular, the workover requirements for long-term operation of geothermal wells are not defined. Maintenance data are available in other countries with data on the Cerro Prieto development in Mexico being perhaps the most available. Collecting, analyzing and applying these data to United States conditions are suggested.

- Most working fluids favored for use in geothermal binary conversion systems are flammable when mixed with air. Accordingly, an inadvertent spill of these materials could cause significant environmental damage as well as presenting a severe safety hazard. Additional investigation of the consequences of releasing working fluid into the environment is suggested.

SECTION 4

ENERGY CONVERSION SYSTEM AND COMPONENT CHARACTERIZATION

ENERGY CONVERSION SYSTEM DESCRIPTIONS

Many energy conversion system configurations can be applied to geothermal energy and the optimum configuration for any single generating plant depends upon the characteristics of the geothermal fluid, the cost, and the degree of experimentation that the plant owner is willing to include in the facility. The conversion systems that are now finding application fall into two general types, flash and binary, or combinations of these types. The detailed workings of these systems have been described in detail in the geothermal literature.

A flash system involves bringing geothermal brine, which is residing in the subsurface reservoir at a pressure above saturation, to the surface whereupon the pressure is lowered and steam is separated from the brine. The steam is then passed through a turbine coupled to an electric generator. Multiple flash stages may be used wherein steam is separated more than once from the brine residual and expanded through lower pressure turbine stages.

A binary system involves transferring thermal energy from the geothermal brine to a working fluid, commonly isobutane, in a series of heat exchangers. High pressure working fluid vapor is then expanded through a turbine/generator. Binary systems may be designed to maximize conversion efficiency by including economizers and regenerators. Both flash and binary systems condense the vapor (steam or working fluid) at the turbine exhaust and both systems usually inject the spent brine back into the subsurface.

There are no full-scale operating geothermal plants yet in the United States that are based on liquid geothermal resources. The most specific and realistic designs currently available for United States conditions are conceptual, including some detail at the component level, for plants at particular sites, using particular geothermal fluids.

The optimum energy conversion process and equipment for a given geothermal field will be closely related to the characteristics of the geothermal fluid The most important parameters are temperature, pressure and concentration of dissolved solids. Three conversion systems have been selected for detailed analysis in that they have received enough attention to make them likely candidates for power plants within the next 5 to 10 years. The selected systems are:

System 1. Double flash, 180°C (360°F) reservoir temperature.

System 2. Brine binary, 180°C (360°F) reservoir temperature.

System 3. Multiflash binary, 290°C (550°F) reservoir temperature.

Any type of conversion system will include wellhead assemblies on the production and injection wells. Each assembly is comprised of a concrete structure, usually below ground level, containing a complement of valves and pipes. The assembly allows well shutdown, redirection of the fluid flow, restricting the flow, and the insertion of probes into the well. The assembly is subject to stresses caused by thermal expansion and contraction as the geothermal wells are flowed and shut down. Excessive thermal cycling can cause ruptures in the valves and piping assembly.

The well layouts, piping layouts, and component arrangements for all of these systems have many similarities with the main differences being in the number of wells required for a given power output. In each of the systems, there is an appropriately valved bypass line from the production wells to the injection wells. The valves are opened in case of a power plant failure or the flow rate being too high for the power demanded of the system. As typical, a 50 MWe plant has been selected for analysis for a number of reasons:

- it represents the installation of minimum size that would be of interest to a large utility;

- design work on such units has been widely reported in the literature;

- the components and equipment are, in general, commercially available; and

- estimates can be made on failures and failure rates and prevention measures.

As will be discussed further below, this analysis assumes a production well flow of 3785 l/min (1000 gpm) from each well and a production to injection well ratio of two to one. Accordingly, each injection well flow is 7570 l/min (2000 gpm). Reference 1 contains the rationale for these flow rates and for the number of wells per system.

All production and injection wellheads are assumed to be located in a drilling island. The wells are bottomed on an approximate 25-acre spacing with producers and injectors located in a pattern approximating the five-spot pattern commonly used in petroleum development. Drilling from a drilling island is costlier than in a dispersed field because wells are slant-drilled. Slant drilling, however, offers definite advantages, such as minimizing the overland piping and allowing containment of a brine spill in a small area. The economic trade-offs of the two alternatives are not obvious and were not investigated in this study.

The geothermal field, as assumed here, will be developed around a centrally located power plant and energy center. Production and injection wellheads will be manifolded into aboveground brine supply and injection piping systems. Other components such as double block valves, bleed valves, bypasses, relief valves, expansion loops, pipe anchors and pipe supports, containment trenches, curbs, pits and sumps are included as good design practice to minimize thermal stresses, pressure surges, mechanical or material failures, or to allow access to the system during maintenance operations.

System 1. Double Flash

A double (two-stage) flash power generation system is shown schematically in Figure 1. The diagram shows flash and turbine redundancy and a direct contact condenser. A similar system could be constructed without redundancy and/or with a surface condenser.

System 1 includes distribution lines, separators, demisters, turbines, condensers, cooling towers and generators. The possibility of failure and consequent brine spill exists in all of the components in the brine loop and in the connecting pipes, joints, and valves. The condensers, while not in the brine loop, merit special attention because non-condensible gases, that are separated with the steam from the geothermal brine, must be removed to prevent back pressure build-up and a deterioration in turbine performance. The non-condensible gas is mostly CO_2, a relatively innocuous compound. However, other gases, making up to 10 percent of the total, include toxic compounds such as H_2S, NH_3, and SO_2. Currently, the most common recognized problem is H_2S, a major pollutant that even in small amounts can cause serious impacts, including deterioration of habitability (from noxious odors) in the area and corrosion of metal surfaces.

The steam is usually separated in vessels in which the well fluid is injected tangentially to the wall. The resulting centrifugal action improves the separation efficiency with the steam moving to the center. Since the well fluid usually carries solid particles, the points of impact on the wall must be protected from abrasion that could cause perforation.

System 1 is assumed to require 28 production wells and 14 injection wells with a layout as shown in Figure 2. The brine-carrying components of System 1 are as follows:

- Two first stage flash tanks with valves, pipes, and fittings necessary for bringing brine from the production wells, conducting brine to the second stage flash tanks, and conducting steam to the demister and turbine.

- Two second stage flash tanks with the valves, pipes, and fittings necessary for bringing brine from the first stage flash tanks, conducting brine to injection lines, and conducting steam to the demister and low-pressure turbine.

- Three branch lines with pumps, valves, and fittings required to carry brine from the second stage flash tanks to the main line to the injection wells. In this system and in Systems 2 and 3, one of the fluid conveyance pumps can handle one-half of the total flow and one is on standby.

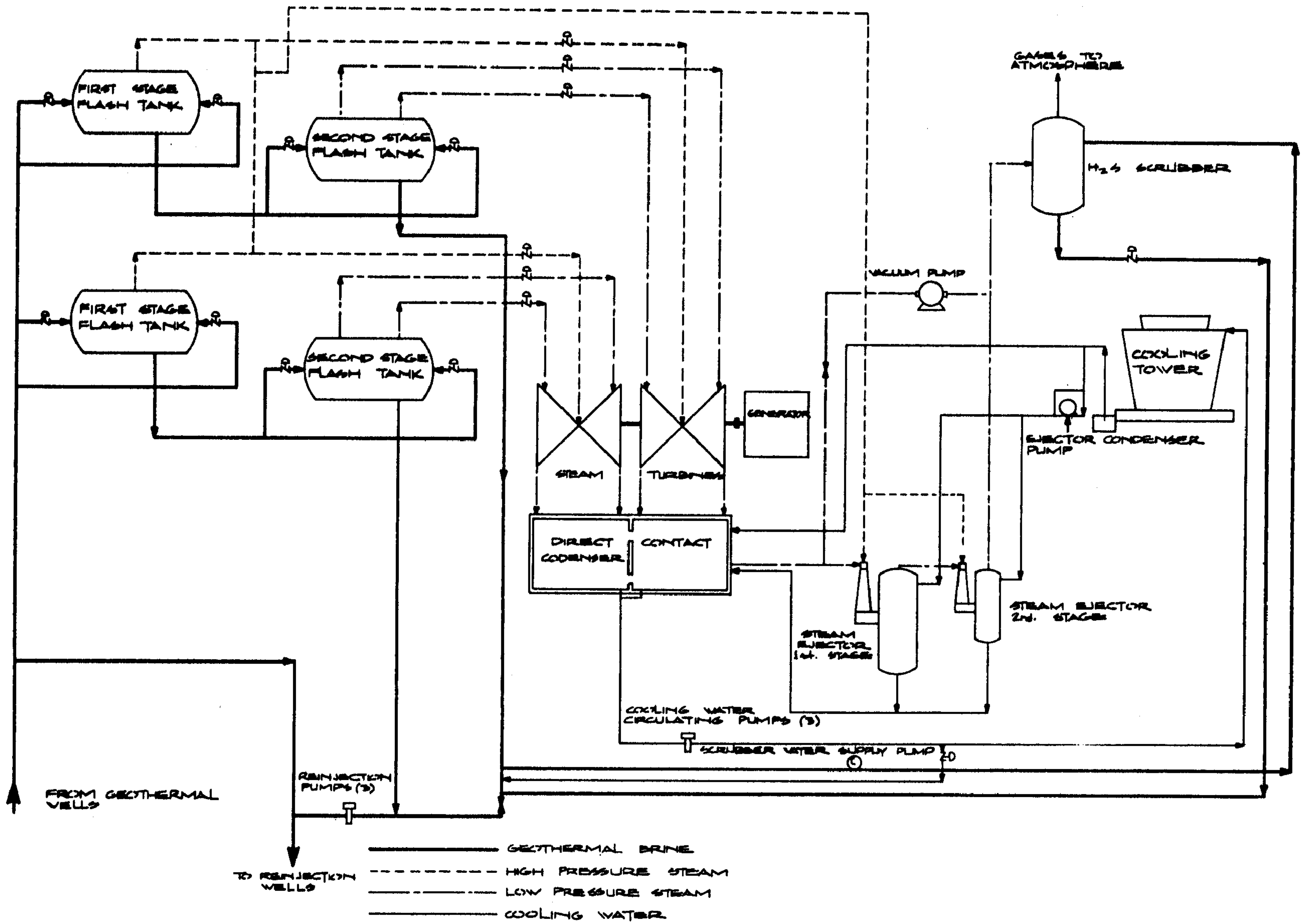


Figure 1. Double flash energy conversion system diagram - system 1.

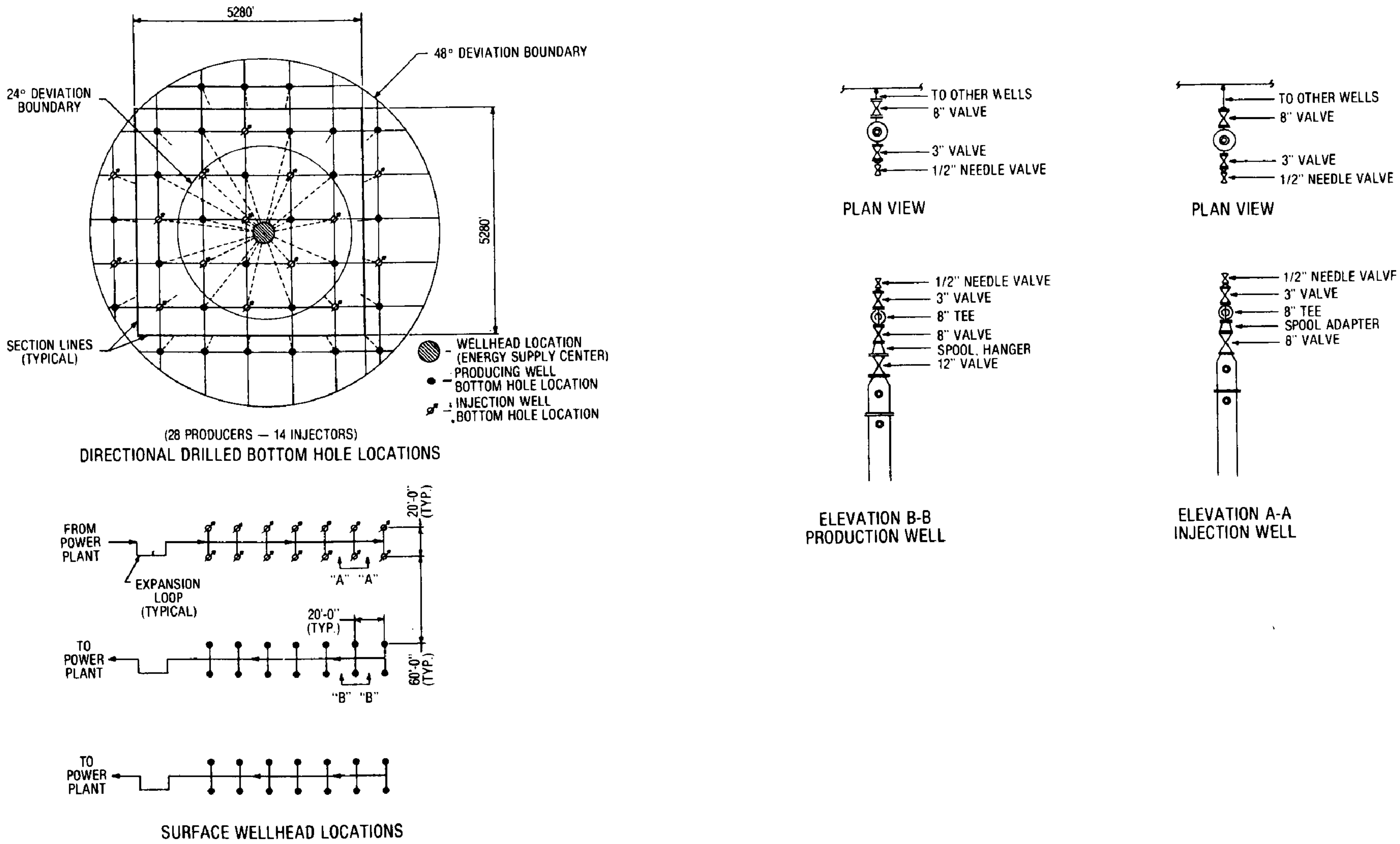


Figure 2. Well layout - system 1 (flash).

The cooling water loop, including the cooling tower and condensers with associated components, does not carry brine. Among the noncondensable gases removed from the condenser, H_2S is a serious pollutant. A two-stage ejector, and auxiliary vacuum pump and an H_2S scrubber with steam, vapor and water lines, valves and fittings are the usual requirements for handling these gases.

System 2. Brine Binary

A binary system (Figure 3), System 2, involves transferring thermal energy from the geothermal brine to a working fluid, commonly isobutane, in a series of heat exchangers. High pressure working fluid vapor is then expanded through a turbine/generator and recirculated. Both the brine and the working fluid flow in closed systems. The brine is maintained under pressure from production through injection so that flashing is prevented.

Binary systems are subject to the possibility of brine loop component failure and consequent brine spill in the same manner as flash systems. Here, however, the heat exchangers warrant special attention because, when the geothermal brine contains large amounts of dissolved solids, deposition (scaling) will occur in the heat exchanger tubes. To minimize this, acid (hydrochloric is most commonly used) may be added to the brine, but it may be corrosive to the materials used in the heat exchangers and pipes. Material must be resistant to corrosion from both brine chemicals and additives.

The favored working fluids for binary systems are flammable when mixed with air. These fluids, if inadvertently released, would pose a major hazard both to the environment and to the safety of personnel and equipment.

System 2 is assumed to require 25 production and 13 injection wells (Figure 4). The wells house downhole pumps to pressurize the brine and prevent flashing in either the supply pipes or the heat exchangers. Only sensible heat is removed from the brine which stays in the liquid phase throughout the process as illustrated in Figure 3. After exiting the preheater/economizer units, the brine is discharged to injection wells. Again, a drilling island is assumed.

- Two boiler-superheaters with the associated valves, pipes, and fittings. As assumed here, the boiler-superheaters and the preheater-economizers are tube-and-shell heat exchangers with brine flowing through the tubes and working fluids flowing through the shell.

- Two preheater-economizers with valves, pipes, and fittings to carry the brine from the boiler-superheater and to the injection lines.

- Three branch lines, two from economizers and one from brine main, with pumps, valves, and fittings to transport the brine to the main injection line and wells.

Nearly all pollutants will stay in the brine as it passes through the system and will be injected. Noncondensable gases cannot be released.

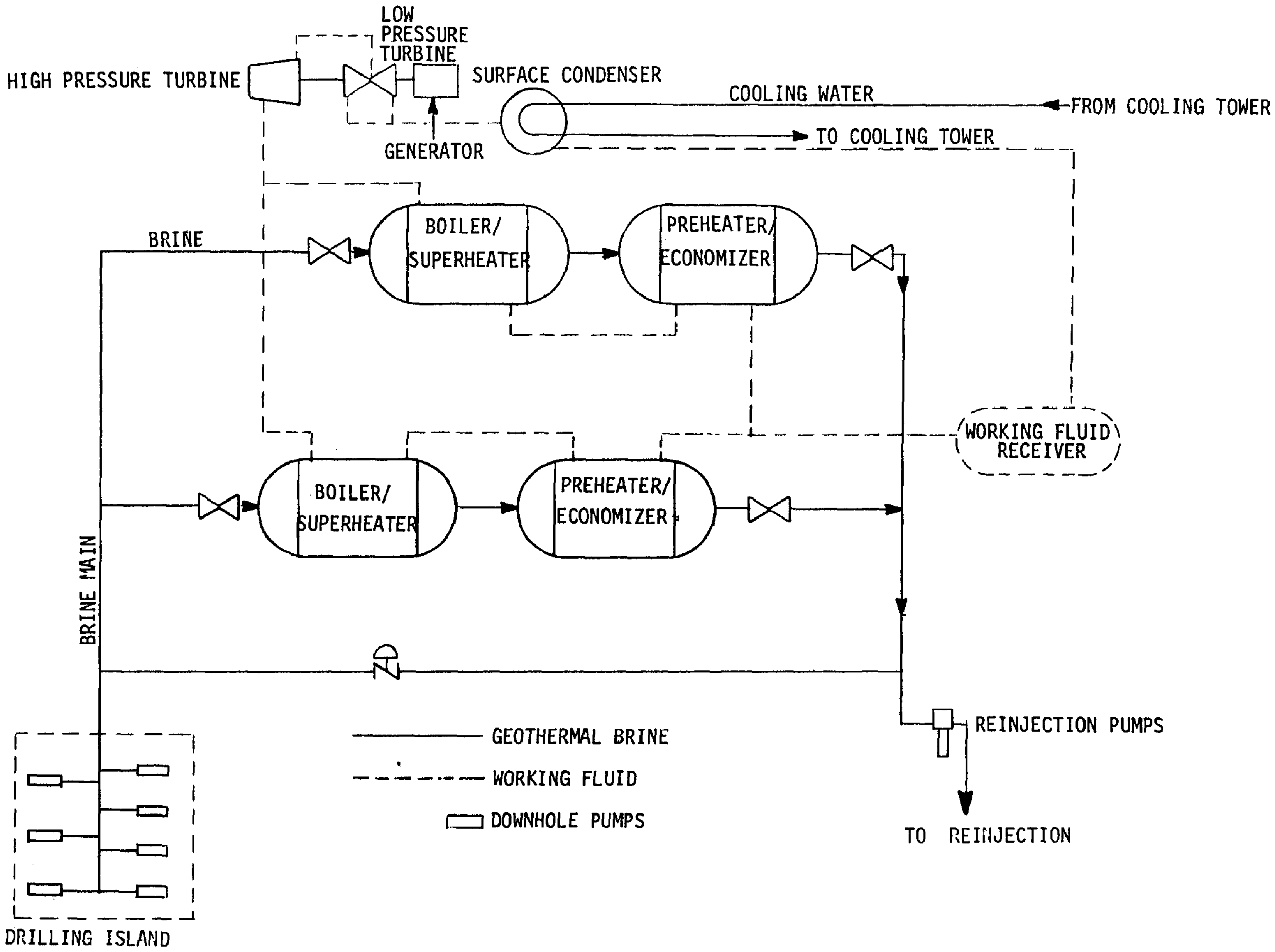


Figure 3. Brine binary energy conversion system diagram - system 2.

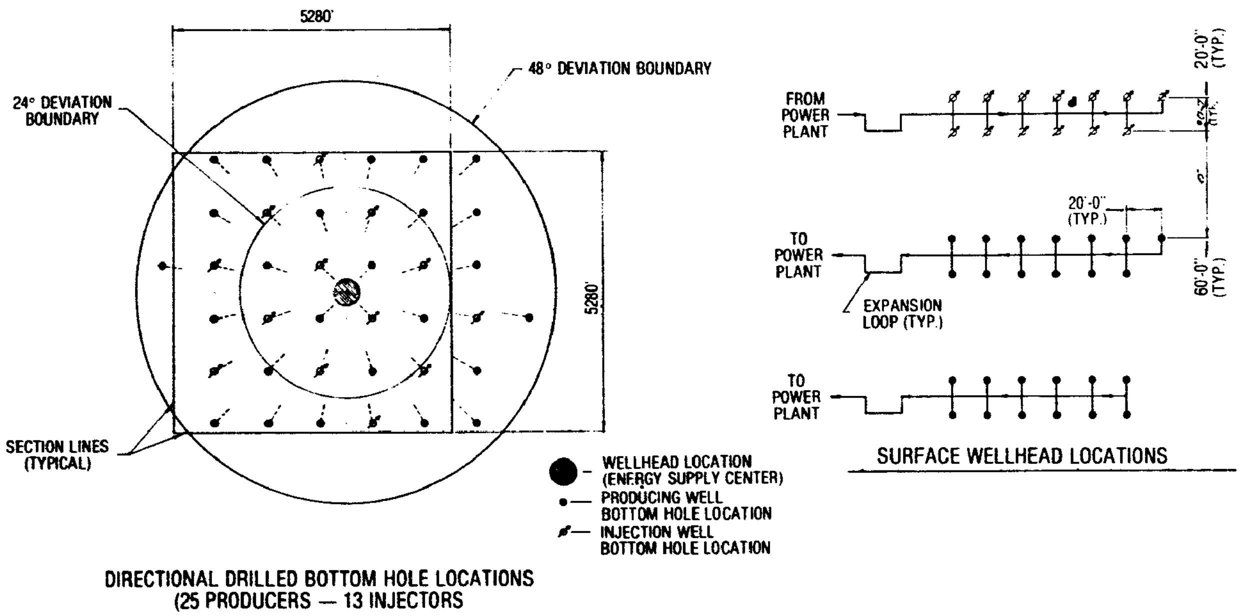


Figure 4. Well layout - system 2 (binary).

System 3. Multiflash Binary

The multiflash binary system (Figure 5), of System 3, is similar to the brine binary system except that the geothermal fluid is flashed prior to heat exchange with the secondary fluid. The intent is to prevent scaling in the heat exchangers that would occur if the brine were passed directly through the exchangers.

System 3 is designed for use in the Salton Sea geothermal area of California, a resource in which temperature and salinity are very high. While the characteristics of this resource may be unique in this country and the characteristics of the applicable conversion system may also be unique, the great power generating potential of the area attracts special attention and warrants inclusion of the system in this study.

In System 3, as shown in Figure 5, the brine vaporizes and condenses in a series of chambers operating at successively lower pressures. The produced steam condenses over tubes located in the upper part of the chamber and the working fluid flows through the tubes absorbing the heat of condensation. Accordingly, the brine remains at the constant temperature corresponding to the pressure in each chamber. The condensate falls and mixes with the brine. The net effect is that the brine salinity remains nearly constant throughout the process and the brine does not come in contact with the heat transfer surfaces.

System 3 is assumed to require 8 production wells and 4 injection wells as shown in Figure 6.

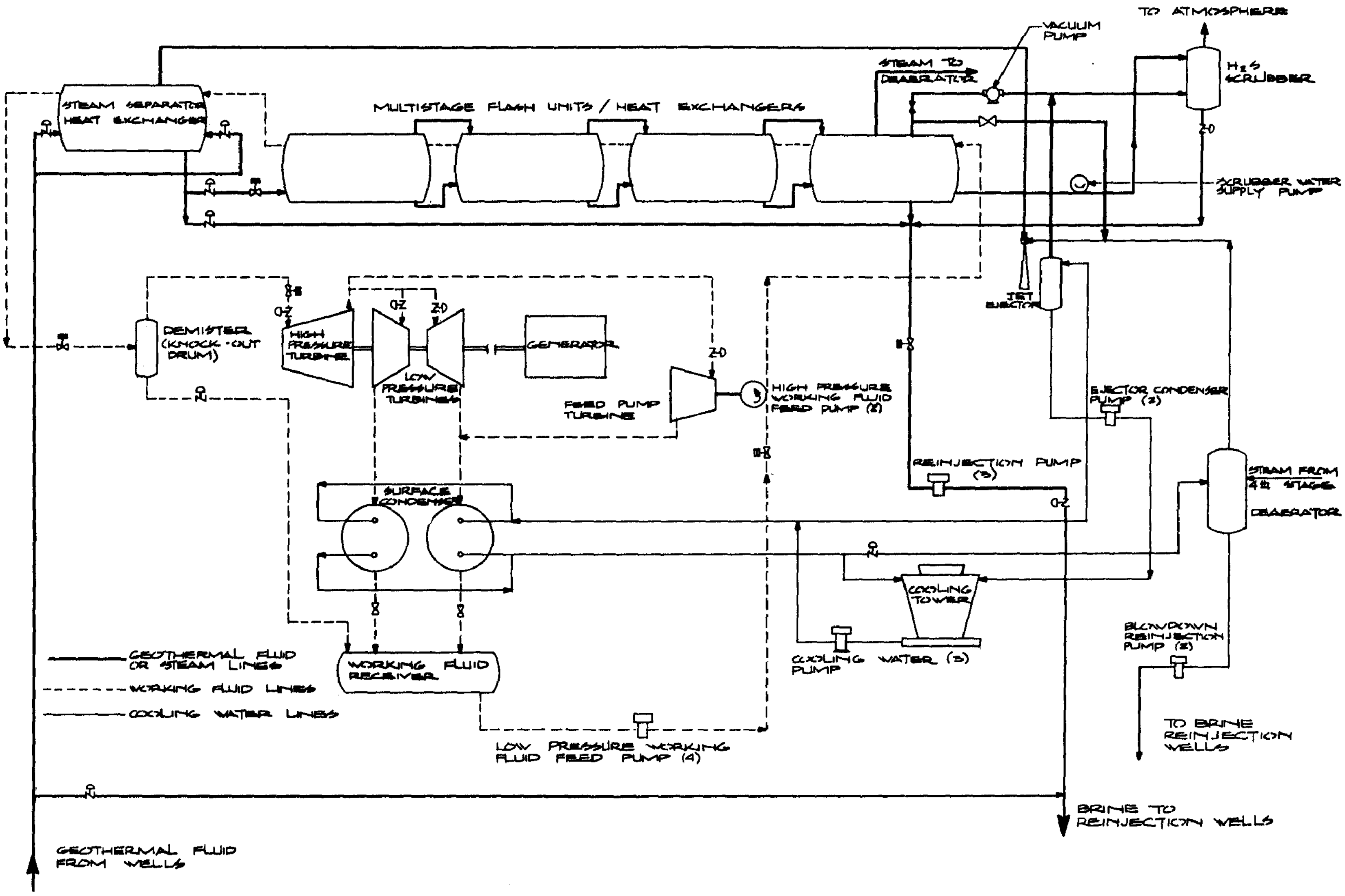
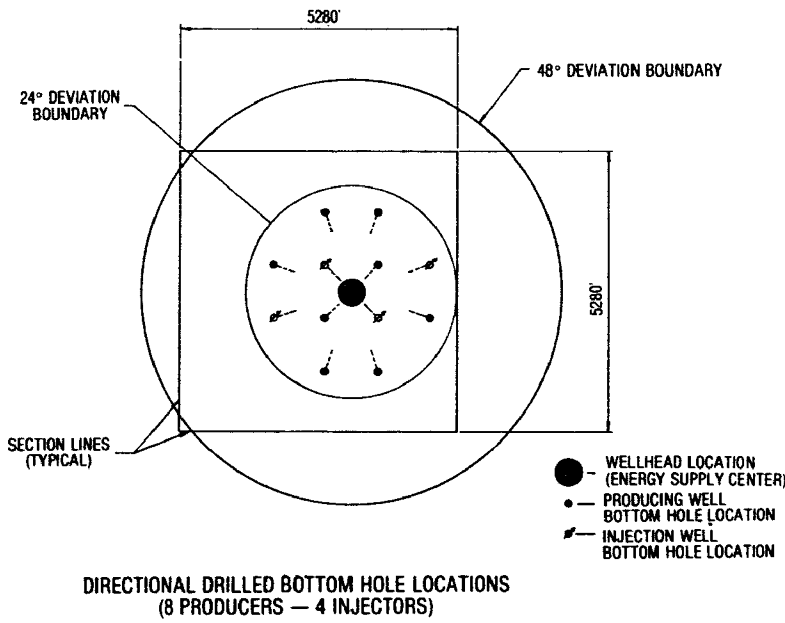


Figure 5. Multiple flash binary energy conversion system diagram - system 3.



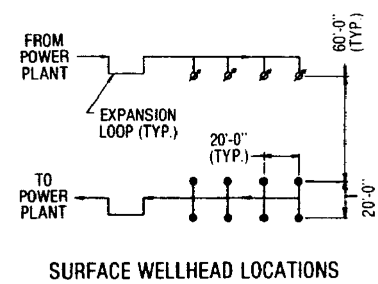


Figure 6. Well layout - system 3 (multiflash/binary).

Specific brine-carrying components of System 3 are:

- One steam separator-heat exchanger with the valves, pipes, and fittings necessary to transport brine from the production wells, conduct brine to the multistage flash units, and conduct high pressure steam to the jet ejector. A high pressure steam line is included.

- Four multistage flash tanks operating in series, with valves, pipes, and fittings necessary to conduct brine from the separator/heat exchanger, to interconnect the tanks for the transfer of brine and steam, and to remove brine and low pressure steam from the last stage tank. The brine is moved to the injection lines, with a small fraction first going to an H_2S scrubber. Steam flow rates are small when compared to the total brine flow since most of the steam is condensed and mixed with the brine in each of the tanks.

- Three branch lines with the valves and pumps required to carry brine to the injection wells.

POTENTIAL BRINE LOSS POINTS

Virtually every component in the system, with the exceptions noted below, is a potential brine loss point in that there is some possibility of failure (albeit very small) associated with each of these components. The most significant potential loss points are pipe joints, either sleeve fittings or flanges, and points where the brine flow impinges directly on a metal surface, such as pipe elbows and tees. Since the input and output of every component requires a pipe joint and since lengthy straight runs of pipe are rare in a conversion system, the potential for loss exists at many points in the system.

Components that are not potential loss points are:

- Downhole pumps - failure will cause a reduction in produced brine in System 2 but, in all reasonable failure modes, effects will be contained in the wellbore with no brine escape.

- Heat exchanger tubes - System 2 and 3 consider the brine to pass through the tubes of conventional shell-and-tube heat exchangers. The working fluid passes through the shell. Accordingly, in the event of tube failure, the brine will be contained by the shell and will not escape into the environment. Of course, mixing the brine and working fluid would necessitate shutting down that portion of the system, but brine spillage would not ordinarily occur. However, for conservatism, heat exchangers are included in the failure rates discussed in the next section.

- Brine treatment - pretreatment of spent brine is sometimes required prior to injection. This would constitute a potential brine loss point and subsequent containment may be required. However, the need for brine treatment is dependent largely on the salinity of the geothermal fluid under investigation. Geothermal fluids with salinity less than 5000 mg/l will most likely not require any pretreatment prior to subsurface injection.

Potential loss points and associated interconnections for the three systems of interest are indicated in the networks of Figures 7, 8, and 9. Table 1 shows the length of pipe and the numbers of valves, elbows, and flanges required by the three systems analyzed. System 1 contains the greatest number of brine-carrying components and System 3 contains the least.

The cooling water loop, including the cooling tower and condensers with associated components, does not carry brine. Among the noncondensable gases removed from the condenser, H_2S is a serious pollutant. A two-stage ejector, and auxiliary vacuum pump and an H_2S scrubber with steam, vapor and water lines, valves and fittings are the usual requirements for handling these gases.

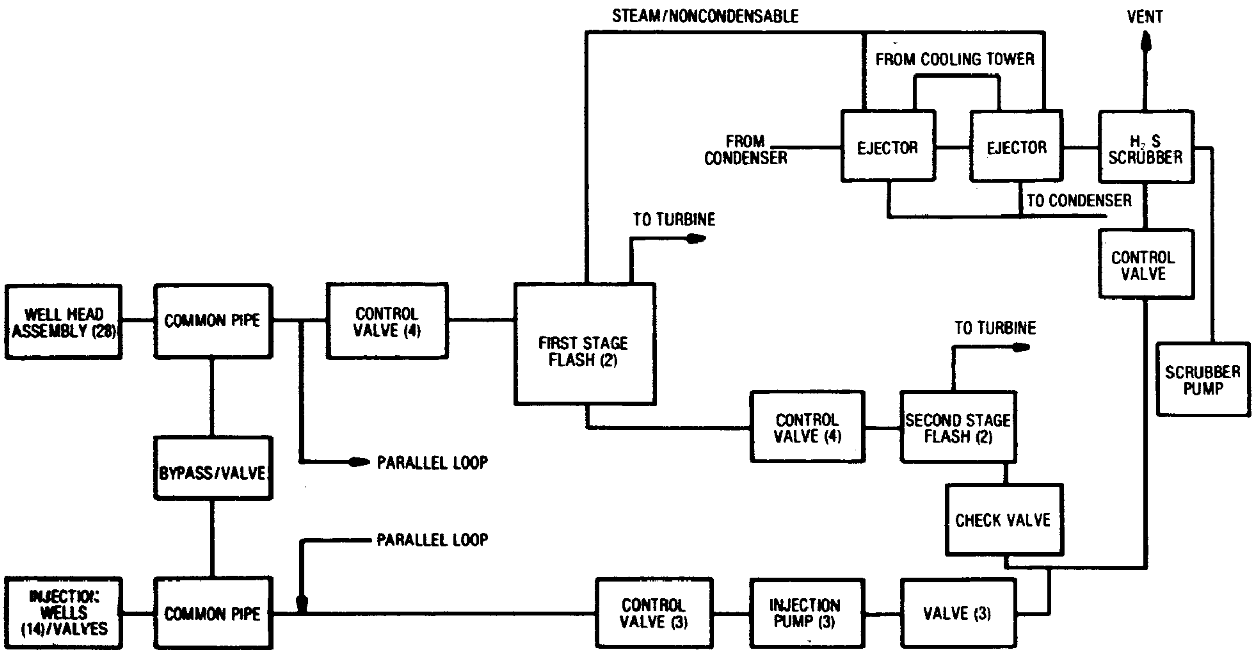


Figure 7. Potential brine loss points - system 1.

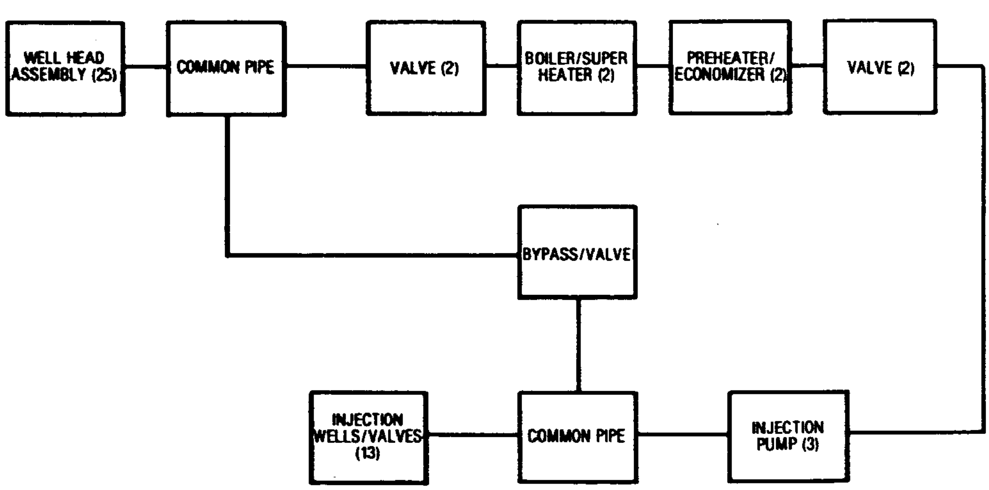


Figure 8. Potential brine loss points - System 2.

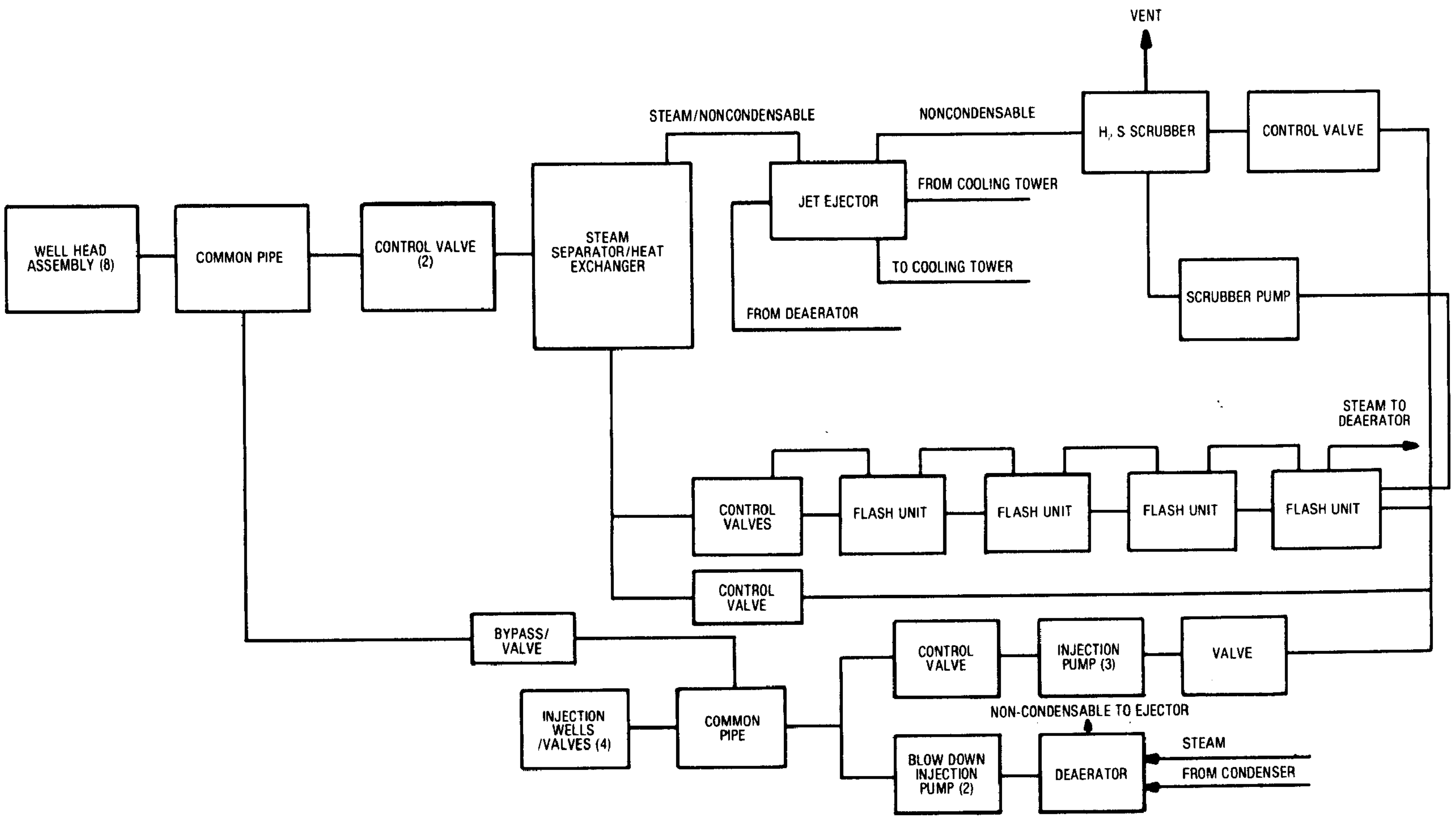


Figure 9. Potential brine loss points - system 3.

TABLE 1. NUMBERS OF BRINE TRANSPORTING COMPONENTS

Item	System 1	System 2	System 3
No. of production wells	28	25	8
No. of injection wells	14	13	4
Feet of piping			
8"	1680	1520	480
16"			140
30"			220
34"	1050	980	
No. of valves			
1/2"	168	152	48
3"	168	152	48
8"	112	101	32
12"	42	38	12
No. of elbows			
8"	126	114	36
16"			4
30"			4
34"	12		
No. of flanges			
3"	374	342	108
8"	84	76	64
12"	84	76	24
20"	42	38	12
No. of tees			
8"	42	38	12
No. of stub-ins			
3" to 12"	168	152	48
8" to 16" - 34"	42	38	12

SECTION 5

FLUID RELEASE ANALYSIS

FLUID RELEASE CAUSES

The various potential causes of fluid release are described in the following, together with the means of minimizing the chances of release:

Blowouts

Geothermal production wells can blow out, i.e., flow uncontrolled, when proper drilling, casing, or completion practices are not followed. There are several reasons for blowouts as described in Reference 2.

- Unconsolidated earth blowouts may occur when the well penetrates soft, unconsolidated rock (identified as "Punky" in the reference), reservoir pressures exceed hydrostatic, and surface casing is not long enough. The pressure is sufficient to force the brine through the rock to discharge on the surface at some unpredictable point away from the wellhead.

- Landslide blowouts may occur when the well is located in unstable soil. The soil slips, the casing shears, and the brine reaches the surface, either along the slippage zone or some other route. Here again, the brine may discharge on the surface at some unpredictable point away from the wellhead.

- Wellhead blowouts may occur when the wellhead assembly is incorrectly installed. Vibration and temperature cycling may fracture the wellhead assembly or crack surface casing cement, allowing brine access to the surface through the wellhead.

- Improper downhole casing and/or cementing blowouts may occur when defective casing is used and/or the casing cement is permeable. Brine may infiltrate the cement either through defects in the casing or from below the casing shoe, reaching the surface through the permeable cement or the surrounding rock. The brine may discharge on the surface either at the wellhead or at some unpredictable point away from the wellhead.

- Seismicity may cause blowouts where the well crosses an active fault.

The brine discharge rate in a blowout is the flow rate generated by downhole pressure and flashing in the wellbore. Geothermal wells in the East Mesa area of California typically flow at a few hundred lpm at brine temperatures above 300^{o}F, Reference 3. Flow rate can be expected to increase with increasing temperature, but natural flow rates of more than 3785 lpm (1000 gpm) are likely to be relatively rare.

Blowouts are of particular concern because of potential difficulties in controlling them. Oilfield blowout preventers (BOPs) are routinely used in geothermal well drilling and required by regulation. While BOPs are useful in controlling the large, abrupt pressure surges that are typical of oilfield blowout occurrences, their application to geothermal drilling, where pressure surges need not be as great or abrupt, is less well defined. Many of the blowouts encountered to date in geothermal operations could not have been controlled by BOPs.

In a geothermal blowout, if the brine is discharging through the wellhead and is uncontrolled by the BOP, it may be possible to fasten a cap or closing valve to the assembly stub. However, if the brine is discharging away from the wellhead, flow may be stopped by one of two methods, i.e., cooling or flow-inhibiting materials can be injected directly into the wellbore, or coolant can be injected into the reservoir very near the uncontrolled wellbore through a relief well. The first possibility may be impractical in that the brine discharge may be located so that there is no access to the wellhead and the second possibility, requiring a special well, is expensive. Either of these control methods will be time-consuming in that special supplies, equipment and personnel must be obtained and transported to the drill site. Accordingly, while the rate of brine discharge in a blowout may not be great, the flow can continue for a significant length of time and the volume of discharged brine can be large. As an example, Well Thermal 4 in The Geysers dry steam field blew out while drilling in 1957 because of inadequate casing and a minor landslide. To date, this well is still only partially controlled. It has been estimated that from 1957 to 1972 the well emitted more than 9 million tons of steam, about 4,000 tons of H_2S, 5,000 tons of NH_3, and 6,000 tons of CH_4, Reference 4. The Geysers is the only operational geothermal field in the United States. Over 100 wells have been drilled there with four blowouts.

Blowouts have also occurred at Beowawe, Nevada, where three capped wells, drilled between 1959 and 1965, were dynamited by vandals. Strong ejections of steam and water resulted and these wells are still uncontrolled but adequate control measures have not been applied. The discharged water is of low salinity and is currently used for pasture irrigation.

Outside the United States, blowouts have occurred at Cesano in Italy, Cerro Prieto in Mexico and Wairakei in New Zeland. In the Cesano field, the first exploratory well blew out in January, 1975. The well flowed uncontrolled and then geyser-type eruptions occurred. The well eventually spewed both mud and water and, after 10 hours, closed itself by scale blocking valves and drilling equipment.

At Cerro Prieto, over 40 wells have been drilled, with two blowouts, in 1961 and 1972. The 1961 blowout was controlled by directional drilling and injection of cement, while the 1972 blowout was eventually controlled after blowing wild for four months, following a violent eruption.

At Wairakei, of the 100 geothermal wells drilled, three have been subject to blowouts. One of these resulted in a large crater which emitted steam for several years.

Corrosion

Components in a geothermal power plant can fail because of corrosive effects that are functions of the material used, physical characteristics of the brine, chemical composition of the brine, the presence of entrained solids or gases in the brine, and the time involved. It is important to note that the presence of oxygen in the brine will increase corrosion rates in nearly all metals. Data is currently being compiled on rates of corrosion versus metal type; Reference 5 contains such typical data.

General corrosion occurs by removal of material over the entire exposed surface. The result is a diminishing of wall thickness with a consequent structural weakening of the component. Products derived from corrosion can also "jam" movable parts such as valves.

Physical factors which affect corrosion and corrosion control are temperature, volocity of fluid flow, changes in flow direction and velocity, and contact with a second metal. As a general rule, higher temperatures generate higher corrosion rates, higher velocities usually increase corrosion rates, and bimetallic contact intensifies corrosion of one of the metals.

Extreme temperatures are the greatest accelerators of corrosion in iron and steel plumbing systems in that the higher the temperature, the more rapid is the rate of chemical reaction. In general, for each 25°C (45°F) rise in water temperature, the rate of corrosion doubles. An increase in flow velocity induces higher frictional resistance on the pipe; hence the potential for stress corrosion is generally increased. This is particularly true for aggressive waters in which high velocities are conducive to rapid pipe deterioration.

Bimetallic contact is the usual cause of galvanic corrosion. When two metals are in contact, as in the case of coupling copper to iron pipes, the difference in electrochemical potential results in current flow. The iron becomes the anode and corrodes to protect the copper (the cathode). The cathodic metal is said to be protected at the expense of the anode. In general, the rate of galvanic corrosion is increased by greater differences in potential between the two metals; large areas of cathode relative to the anodes; by proximity of the two metals; and increased mineralization or conductivity of the water.

Failures also can occur in materials subjected to stress over a long period of time while exposed to brine and the failure stress can be much smaller than would be expected from straightforward considerations. Some materials are prone to pitting, and deep penetration can occur in a short time. Intergranular corrosion is a localized type occurring at grain boundaries within a metal. There are, however, several types of corrosion that are particularly important in geothermal facilities and these are discussed in the following.

Stress corrosion cracking can occur when a metal under tensile stress is exposed to a specific corrosive environment; for example, carbon steels and aluminum alloys, commonly used in geothermal power plants, can be affected by sea water and marine and industrial atmospheres as well as other solutions. Copper alloys can be affected by hydrogen sulfide. Stress corrosion cracking can be prevented by cathodic polarization.

Corrosion fatigue can occur when a metal in a corrosive medium is subjected to repeated stresses. There are many corrosive fluids that can cause this failure and they are not necessarily specific for a given metal. Hydrogen embrittlement occurs when metal is exposed to hydrogen gas although one type is evidently the result of hydrogen being in solid solution in the steel lattice. It is marked by delayed failure under low temperature, long term load conditions; failure occurs at loads less than the expected. Hydrogen embrittlement is more prevalent in high strength materials.

Erosion-corrosion is very important in areas of high brine velocity, especially when a directional change in the flow occurs. Here, protective films are continuously removed by impingement of the fluid and the corrosion rate is accelerated. Entrained solids in the stream accentuate the problem. A similar mechanism is fretting-corrosion, where small mechanical displacements (due for instance, to a vibrational load) cause the protective films to be continuously removed and fresh metal exposed.

The corrosive effects of geothermal brines have been and continue to be the subject of much attention within the geothermal community. Since the physical and chemical characteristics of brine can vary significantly between and within reservoirs, extensive analyses and tests of brine-induced corrosion have been and are being conducted. Past work has been summarized by Banning and Oden (Reference 6). Other studies pertaining to specific geothermal reservoirs have been documented by Miller (Reference 7) and the Bureau of Reclamation (Reference 8). Much of this investigation has been oriented toward materials selection, i.e., identifying the construction material that is least susceptibe to corrosion by determining the amount of material lost per time (commonly in millimeters per year) through corrosion under the test conditions. Table 2, as derived by Shannon (Reference 9), indicates typical test results. The materials investigated are usually metals, although concretes and elastomers have also been examined. Kukacka (Reference 10) and Hirasuna (Reference 11) conducted studies in these areas. Still other studies, such as that by the Lawrence Berkeley Laboratory (Reference 12) have examined methods of treating the brine to control corrosion of a given material.

Based on the above and many similar studies, there appears to be a complex correlation between corrosion and component failure rate but quantitive correlations have yet to be established.

Abrasion

Flowing brine can abrade the inside walls of brine carriers; suspended particulate matter increases the abrasion rate. The effect is to reduce the carrier wall thickness with a consequent lessening in a structural strength. Soft, elastomer valve seats are particularly vulnerable to abrasion with the result that the valve will not close properly.

TABLE 2. CORROSION RATES (MM/YR) OF VARIOUS ALLOYS VERSUS BRINE COMPOSITION*

Alloy	1% NaCl	5% NaCl	10% NaCl	20% NaCl
A570	0.30	0.90	1.10	2.80
A53B, Heat 1	0.30	0.60	0.90	2.80
A53B, Heat 2	-	0.40	0.60	3.20
C75	0.20	0.40	0.20	2.00
1010	0.40	1.00	1.00	3.50
4130	-	-	0.20	2.30
2 1/4	0/08	0.60	0.30	1.80
410, Heat 1	0.08	0.10	0.80	3.50
410, Heat 2	-	0.20	0.50	3.80
E-Brite 26-1, Heat 1	0.05	0.01	0.02	0.08
#-Brite 26-1, Heat 2	-	0.02	0.02	0.02
Hastalloy C-276	0.02	0.03	0.04	0.04
Inconel 625	0.01	0.01	0.01	0.02
Inconel 600	0.02	0.02	0.05	0.04
Incoloy 825	0.01	0.01	0.01	0.05
29Cr-4-2	0.08	0.01	0.02	0.01
6X	0.01	0.01	0.01	0.03

*Test Conditions: T = 250°C; P = 68.9 Bar (1000 psi); Oxygen = <0.01 ppm; pH = 4.6 to 4.8

Since the most common source of particulate matter is the production reservoir (rock particles are commonly entrained in the produced brine), components at and near the production wellheads are most affected by abrasion.

Scaling

Scale can form on the inside surfaces of pipes and other brine carriers. It is formed, in part, by an oxidation reaction wherein a metal component in the system is dissolved and redeposited as an oxide. Also, in addition, reactions will occur to form insoluble compounds which precipitate on exposed surfaces under changing temperature, pressure, fluid composition and velocity conditions. The most common of the latter types are sulfates and carbonates of calcium, magnesium and sodium and also metallic sulfides.

Saturation index (S.I.) is normally used to measure the corrosiveness or scaling potential of a water. This index is based on the concentration of the carbonate and calcium ions exceeding the solubility product as a criteria for deposition. Since the index is dependent upon the law of mass action between the two ions, the effect of dissolved oxygen on corrosion rates is not considered. In general, when S.I. is positive, scaling or deposition of calcium carbonate will occur. An S.I. >0.5 indicates excessive scale formation. When S.I. is negative, the water is corrosive and scale will dissolve in solution.

Ideally, to prevent corrosion, the water should have a S.I. of zero at all times. In reality this is not possible because of the dynamic system; the general rule of thumb is, therefore, to maintain the S.I. slightly positive (0.1 to 0.3) so that a protective film of calcium carbonate is always there to minimize corrosion effects.

While the scale itself does not present a significant problem in brine release, the scale will constrict flow channels either reducing the flow in a fixed pressure delivery system or, under certain special circumstances, cause an increase in pressure in the system. This pressure increase combined with structureal weakness caused by corrosion or erosion could cause failure. When the scale breaks loose, it can clog valve seats causing valves to freeze open allowing fluid to pass with possibilities of fluid release. A case in point would be the failure of a relief valve to reseat due to scale on the seat and continuing to discharge fluid to the atmosphere.

A variation of this can take place in the injection process. A very high brine injection rate is desirable to minimize the number and cost of injection wells. Precipitation can occur in the reservoir in the vicinity of the wellbore, necessitating a rise in injection pressure which, again in combination with other factors, could cause a filaure in the system.

Similar to corrosion, the subject of scaling is receiving much attention by the geothermal community and many tests of scaling in geothermal systems have been and are being conducted. These studies involve both examining the mechanisms of scale accumulation, of which Makrides (Reference 13) is an example, and methods of removing the scale after it is formed, exemplified by Daedalean Associates (Reference 14).

The three foregoing processes, corrosion, erosion and scaling, are potential failure mechanisms that have a high probability of occurrence in geothermal systems. Minimizing the effects of these requires good engineering practices, periodic inspections during operations, and an adequate maintenance program. Good engineering practices would include proper choice of materials and components (e.g., some valves are more resistant to abrasion than others), inclusion of inspection ports in vessels, and, to minimize abrasion, use of long radius elbows, heavy walled elbows and expendable components such as replaceable impingement baffles used in vessels at Cerro Prieto and Westmorland.

Improper Design/Poor Workmanship

Proper design of a system, good workmanship in the installation, and the use of good materials are normally expected in any piping and equipment system such as refineries, power plants and chemical plants. Design, installation, and materials necessary to assure a reliable geothermal system are all within the state-of-the-art. Design inadequacies that may allow failures and ruptures and consequent brine release include pressure build-ups between shut-off points with no relief valves, improperly selected pumps (shut-off heads exceeding allowable stresses), and inadequate flexibility in piping to allow for temperature growth. Improper selection of class or rating as well as materials of seals, gaskets, bonnets, seats of valves and equipment is possible if the designer is not thoroughly familiar with the system and all its extremes. Poor workmanship with improper or non-existent inspection and testing can result in loose leaking joints. A check valve or a relief valve installed backwards can have disastrous effects with leaking brine and/or complete rupture of pipe or equipment. Pumps have been installed backwards as well as binary vessels, such as exchangers, having connections reversed.

Designs should be reviewed by competent, knowledgeable individuals, similar to building and safety and environmental engineers. Construction should be inspected to assure compliance with the plans and specifications of the design. Each system and subsystem within a geothermal loop should be tested under controlled conditions prior to operation.

Natural Disasters

The geographical correlation between geothermal resources and zones of tectonic activity is well known. Accordingly, geothermal power plants are inherently associated with areas of higher seismicity. In fact, locating areas with an unusually high level of micro-earthquake activity is an important geothermal exploration method, and determining the geometric shape of these areas is becoming an important geothermal reservoir development factor. Consequently, the possibility of earthquake damage appears greater during the life of a geothermal installation than the more conventional power plants. Damage can be minimized through proper design.

Flood, landslide, high wind and/or fire damage during the life of the power plant is a possibility. The probability of flood and slide damage can be minimized through proper siting, i.e., avoidance of flood plains and unstable slopes. The possibility of subsidence damage may be minimized by injection of spent brine back to the geothermal reservoir.

Vandalism/Terrorism

Terroristic attacks, wanton destruction and inadvertent damage caused by demonstrators for otherwise peaceful causes are becoming more of a problem, particularly for projects that are controversial. The mitigative action here is an adequate security system including controlled access to the facility, in addition to a realistic public information program.

Accidents/Personnel Errors

Accidents, such as a vehicle being driven inadvertently into a brine carrier, and personnel errors, such as the wrong valve being opened, are ever-present possibilities. A well trained, motivated work force is the best response to this. Protective structures and devices should be installed in higher risk areas.

BRINE RELEASE RATES

The rate of fluid release will be dependent upon failure mode. A leaking gasket in a flange will allow a trickle release. Failure of valve packing or pump seals may allow a few percent of the brine flow to escape. Brine release from perforations in the wall of steam separators or other vessels will range from a trickle to a few percent of the flow. Release from a burst pipe will depend upon the location and size of the break. A longitudinal split is the normal mode of failure. A small split on the upper surface of a level pipe may release a few tenths of a percent of the pipe flow while a large split on the undersurface of a sloping pipe may release the entire flow. Given this variability in potential brine release rates, a containment method should be designed for the worst case.

Table 3 indicates the flow rates in specific parts, comprising groups of potential loss points, depicted in Figure 7, 8, and 9, that have a common flow rate. The indicated flow rates are the maximum brine spillage rates that can occur within each group. The spillage rates associated with the production and injection manifolds are a function of where in the manifold the pipe bursts. The maximum potential release rate of 53,000 l/min (14,000 gpm) is found in System 1.

TABLE 3. BRINE FLOW RATES

Potential Loss Point Groups (m^3/min)

	Production wellhead	Common pipe (including manifold)	Steam separator/heat exchanger	Flash units	Common pipe	Injection manifold	Injection wellhead
System 1	4	4-53	--	53*	53*	8-53*	8*
System 2	4	4-49	49	--	49	8-49	8
System 3	4	4-30	30	30**	15**	8-15**	8*

* Less fluid flashing to steam
** Less noncondensables

FAILURE MODE ANALYSIS

A failure mode and effects analysis was performed on each identified component in the three systems of interest; results are tabulated in Table 4. Of primary interest were those components and failure modes that could contribute to brine spillage. Although the loss of working fluid in a binary system and the venting of non-condensable gases are hazardous, they are outside the scope of this study.

Failure Rate Data

There are no compilations yet of failure rate data that are specifically applicable to geothermal power conversion and there is no extended history of liquid-dominated geothermal operations in the United States upon which to base such compilations.

There is a growing body of data on the corrosion and scaling of materials when exposed to geothermal brines. While these data are no doubt influencing the design and selection of components for geothermal power plants with a consequent increase in overall reliability, extrapolating these data into quantitative failure rates at the present time would be pure speculation.

The source for the component failure rates used here is Appendix III of a commercial reactor safety study, the "Rasmussen Report" (Reference 15). This report contains failure rates that reflect both nuclear and non-nuclear industrial experience. The data were derived from Department of Defense data, NASA data and general industrial and commercial operating experience. Approximately 50 sources of failure data are cited. The operations that provide the basis for the failure rates involve high pressure, high temperature steam, and the components involved are of a physical size comparable to those used in geothermal power plants. The Rasmussen Report treats failure rates as random variables as opposed to single, best values and, consequently, provides failure rate in a variety of forms. These are summarized in Table 4 for several components that are applicable to geothermal power plants. The specific type of failure is also provided. It is important to note that failure rates are provided in terms of both failures per demand and failures per hour. The only data considered herein are failures per hour. Maximum and minimum failure rates obtained from raw industrial data, the median values of those data and entirely nuclear failure rates are listed. The failure rates used here are the median values and represent a combination of nuclear and non-nuclear data. While the study does not list entirely non-nuclear failure rates (and these are the failure rates that might be considered best applicable to geothermal usage), the Rasmussen Report does state (p. III-77) that, in the case of pipe failure (the single most controlling factor in determining the probability of brine release in a geothermal power plant), there is general agreement between nuclear and industrial data. Further, a comparison of the median values and the nuclear experience values indicates that, for a given component, the two are equivalent or the median failure rates are higher. Since these failure rates are implicitly valid for components and materials that meet good engineering practices for the conditions of temperature, pressure and chemical environment in which they operate, use of the median rates in assessing geothermal brine release probabilities appears valid.

TABLE 4. FAILURE RATE DATA

Components	Failure Rates - Rasmussen Report (Reference 15)		
	Extreme Range	Median	Nuclear Experience
Pumps			
Fail to start/d*	5×10^{-5} - 5×10^{-3}	1×10^{-3}	1×10^{-3}
Fail to run/hr**	1×10^{-7} - 1×10^{-4}	3×10^{-5}	1×10^{-6}
Valves, Motor Operated			
Fail to operate/d	2×10^{-4} - 7×10^{-2}	1×10^{-3}	1×10^{-3}
Plugged/d	6×10^{-5} - 3×10^{-4}	1×10^{-4}	3×10^{-5}
Leak/rupture/hr	---	1×10^{-8}	---
Valves, Solenoid Operated			
Fail to operate/d	2×10^{-5} - 6×10^{-3}	1×10^{-3}	1×10^{-3}
Valves, Check			
Fail to open/d	2×10^{-5} - 3×10^{-4}	1×10^{-4}	1×10^{-4}
Leak/rupture/hr	---	1×10^{-8}	---
Valves, Relief			
Fail to open/d	1.4×10^{-5} - 3.6×10^{-5}	1×10^{-5}	1×10^{-5}
Valves, Manual			
Plugged/d	---	1×10^{-4}	3×10^{-5}
Pipe			
Plug/rupture/hr			
≤3" diameter	2×10^{-9} - 5×10^{-6}	1×10^{-9}	1×10^{-9}
≥3" diameter	1×10^{-10} - 5×10^{-6}	1×10^{-10}	1×10^{-10}
Gaskets			
Leak/hr	---	3×10^{-6}	---

Failure Rates - RADC*** (Reference 16)	
Components	Failure Rate/Hr
Pumps	
Boiler feed	4.2×10^{-7}
Centrifugal	5.8×10^{-6}
Valves	
General	1.5×10^{-5}
Butterfly	1.3×10^{-6}
Solenoid	1.6×10^{-6}
Diaphragm	2.6×10^{-6}
Check	3.2×10^{-6}
Relief	1.6×10^{-6}
Gaskets	
General	1.3×10^{-6}
Packing	3.5×10^{-6}

LEGEND

* /d = per demand

** /hr = per hour

*** RADC = Rome Air Development Center

Additional failure rate data have been compiled in Table 4 from the Reliability Analysis Center, Rome Air Development Center, Reference 16. This document is a compilation of failure rates for nonelectronic parts for both military and commercial applications. Parts that are applicable for geothermal applications include pumps, valves and gaskets and pertinent data on the failure rates of these are also tabulated in Table 4. These rates, however, consider components generically and include failures from all causes; accordingly, comparison of data from this document and the Rasmussen Report is difficult. The only direct comparison is that of gaskets, and the failure rate is comparable. A comparison of other components that are not included in this geothermal examination, i.e., clutches, motors, relays, switches and power supplies, suggest that failure rates from entirely nuclear parts are higher than commercial and military counterparts.

The specific failure rates used in this analysis are tabulated in Table 5. The pipe rupture failure rate, as extracted from the Rasmussen Report, is applicable to a section of pipe where a section is defined as "an average length between discontinuities such as valves, pumps, etc. Each section can include several welds, elbows and flanges." The pipe rupture rate was also used as a basis for estimating the failure rates for other components. The rate for the boiler/superheater, preheater/economizer, separator/heat exchanger, multistage flash units and flash tanks were derived by applying a complexity factor of ten to the large diameter pipe failure rate. This factor was deemed appropriate due to the number of welds, joints, valves and flanges involved. Similarly, a complexity factor of five was applied to the injection pump section and a factor of two was applied to the hydrogen sulfide scrubber. Wellhead assembly failure rates were obtained by combining failure rates for an appropriate number of valves and pipe sections.

In relating the causes of fluid releases to the components in a geothermal brine system as shown in the matrix of Table 6, it becomes apparent that, except in the special cases of wells and gaskets, all components are subject to most of the generic causes of failure and/or rupture as shown. A matrix such as this can be used by the designer in the selection and design of the individual components in his attempts to minimize the number of spills of brine. Gaskets, with the lowest reliability, must be selected of the proper type and material, and close control of installation must be exercised. Proper maintenance is also indicated to prevent leaking. A leak is distinguished from a rupture, as used here, by the degree of fracture. A rupture is a major violation of the structural integrity of a component leading to the release of a significant quantity of fluid per unit time. A leak, on the other hand, is a minor violation of structural integrity and the quantity of fluid released per unit time is relatively small. From Table 5, although the failure rate of gaskets is high, the failure mode is leakage and not rupture; containment of brine from this cause and component is not warranted. Conversely, boiler/superheaters, and flash units, which have a relatively high failure rate, a number of uncontrolled failure causes, and a rupture failure mode, will require either positive brine physical containment methods or failure prevention methods, whichever is the more economical.

It should be recognized that the failure rates included here are measured rates that apply to specific component parts operating in specific environments.

TABLE 5. GEOTHERMAL BRINE RELEASE, FAILURE MODES AND EFFECTS

Item	Failure mode mechanism	Failure effect	Failure rate (failures/hour)
Wellhead assembly	Valve leakage Pipe rupture	Blow out Brine spill Control loss	8×10^{-10}
Valves	Failure to operate Leakage	Control loss Brine spill	1×10^{-8}
Piping	Leakage Rupture	Brine spill	1×10^{-10}
Boiler/superheater	Tube failure Nozzle leakage Rupture	Leakage	1×10^{-9}
Preheater/economizer	As above	As above	As above
Injection pump/valves/ piping	Blade defect Bearing wear Seal wear/leakage Rupture	Brine spill	5×10^{-10}
Injection wells/valves	Leakage Valve/piping rupture	Brine spill	8×10^{-10}
Separator/heat exchanger	Nozzle leakage Rupture	Reduced output Brine spill	1×10^{-9}
Multistage flash units	Nozzle leakage Rupture	Reduced output Brine spill	1×10^{-9}
Hydrogen sulfide (H_2S) scrubber	Leakage Rupture	Brine spill	2×10^{-10}
Flash tanks	Nozzle leakage Rupture	Reduced output Brine spill	1×10^{-9}
Gaskets	Leakage	Brine spill	3×10^{-6}

Accordingly, some of the causes of brine release discussed in the previous section may not be adequately represented. In particular, accidents and personnel errors will probably cause a significant percentage of the total fluid releases, but the above quantitative rates may not reflect this. Consequently, the cited failure rates and the conclusions drawn from them are probably conservatively low.

TABLE 6. GEOTHERMAL COMPONENTS AND FAILURE CAUSES

GEOTHERMAL COMPONENT		FLUID RELEASE CAUSES									
ITEM	FAILURE RATE (FAILURE/HR)	BLOWOUT	CORROSION	ABRASION/EROSION	SCALING	NATURAL DISASTER	VANDALISM/TERRORISM	ACCIDENTS	PERSONNEL ERROR	IMPROPER DESIGN	POOR WORKMANSHIP OR MATERIALS
Gaskets	3×10^{-6}			X						X	X
Valves	1×10^{-8}			X	X		X		X	X	X
Boiler/Superheater	1×10^{-9}		X	X		X		X	X	X	X
Preheater/Economizer	1×10^{-9}		X	X		X		X	X	X	X
Separator/Heat Exchanger	1×10^{-9}		X	X		X		X	X	X	X
Flash Units	1×10^{-9}		X	X		X		X	X	X	X
Flash Tank	1×10^{-9}		X			X		X	X	X	X
Wellhead Assembly	8×10^{-8}	X				X				X	X
Injection Wells	8×10^{-10}	X			X	X		X	X	X	X
Injection Pump	5×10^{-10}			X					X	X	X
H_2S Scrubber	2×10^{-10}		X			X		X	X	X	X
Piping	1×10^{-10}		X	X		X		X	X	X	X

FAILURE RATE ANALYSIS

Since design details on the three systems of interest are lacking, failure analysis has been done by groups rather than individual components, and complexity factors have been used to compensate for lack of detail. However, the detailed design data are not necessary in order to identify those areas requiring containment measures. As the design evolves and design specifications become available, a more detailed analysis would be beneficial in identifying areas requiring further attention. The categories of brine release considered here range from a single-point minor release to a critical release as the result of component rupture. Three categories of brine release have been defined for use in this study. These are:

- Critical release - a single-point rupture that can be controlled only by closing the wellhead valves;
- Major release - a single-point rupture that is controllable by valves other than the wellhead valves;

- Minor release - a single-point gasket or seal leak.

A critical release will result in the spillage of large amounts of brine, ranging from 4000 to 56,000 liters per minute. A major release will allow spillage rates ranging from approximately 40 to 4000 liters per minute, depending upon the size of the component that ruptures. A minor release will usually involve less than 40 liters per minute.

Each system under consideration was diagrammed (Figures 7, 8, and 9) to highlight the potential fluid release sections within the system. The most likely areas of concern, i.e., a critical release, would be at the brine entry side of the plant. As the flow progressess through the plant, more faults (or failures) are required for critical brine release. Critical fluid releases and major fluid release probabilities were computed for both an assumed forty-year design life and at a five-year point. The numbers reflect the probability that at least one fluid release would occur during the designated time periods. For example, the probability that at least one critical fluid release will occur in the double flash system during the forty-year design life is 3.7×10^{-5}. It can be seen, from the table, that approximately an order of magnitude decrease in the probability of a brine release can be realized by substituting a comprehensive preventive maintenance program, i.e., essentially renewing the system at five-year intervals.

The overall probability of a major fluid release somewhere in the system, as shown in Table 6, is about the same for all three systems, approximately 2×10^{-3}, or one chance in 500 during 40 years operation of a plant. This figure excludes wellhead ruptures, which are discussed below.

So that the possibility of inducing additional failures by rapid flow reduction is reduced, consideration should be given to having the capability to bypass all brine from the production wells to the reinjection wells. Such a bypass line is shown in the system configurations of Figures 1, 3, and 5. A review of Table 6 clearly shows that the major contributor to the overall plant critical brine release probability is the well-to-plant sections. Adding a valve at the well-to-plant section to facilitate isolation of that section would change the well-to-plant critical release probability from 3.5×10^{-5} to 3.5×10^{-8} and, consequently, the overall system critical fluid release probability would decrease significantly.

Production well brine release probabilities vary with the number of production wells required in each system. The limited historical data available suggests that approximately two percent of geothermal wells will blow out during drilling. Each wellhead contains eight valves and associated piping/connections that are potential rupture release points. Based upon data presented previously, the probabilities of a wellhead rupture during the forty-year design life are: System 1 - 7.8×10^{-3}; System 2 - 6.9×10^{-3}; and System 3 - 2.2×10^{-3}.

Minor leaks are to be expected. Based upon available gasket failure data, each gasket in the system would be expected to fail at least once during the assumed forty-year design life.

TABLE 7. BRINE RELEASE PROBABILITIES

System/section	Critical: 5-Year inspect refurbish	Critical: 40-Year design life	Major: 5-Year inspect/ refurbish	Major: 40-Year design life
System 1 - total	4.6×10^{-6}	3.7×10^{-5}	2.2×10^{-4}	1.8×10^{-3}
Well-to-plant	4.4×10^{-6}	3.5×10^{-5}	4.4×10^{-6}	3.5×10^{-5}
First stage flash	1.8×10^{-7}	1.4×10^{-6}	8.8×10^{-5}	7.0×10^{-4}
Second stage flash	3.5×10^{-10}	2.8×10^{-9}	8.8×10^{-5}	7.0×10^{-4}
H_2S scrubber	3.5×10^{-14}	2.8×10^{-13}	8.8×10^{-6}	7.0×10^{-5}
Injection	1.8×10^{-10}	1.4×10^{-9}	2.2×10^{-5}	1.8×10^{-4}
Plant bypass	8.8×10^{-9}	7.0×10^{-8}	4.4×10^{-6}	3.5×10^{-5}
Plant-to-well	7.0×10^{-17}	5.6×10^{-16}	4.4×10^{-6}	3.5×10^{-5}
System 2 - total	4.6×10^{-6}	3.7×10^{-5}	2.1×10^{-4}	1.7×10^{-3}
Well-to-plant	4.4×10^{-6}	3.5×10^{-5}	4.4×10^{-6}	3.5×10^{-5}
Boiler/superheater	8.8×10^{-8}	7.0×10^{-7}	8.8×10^{-5}	7.0×10^{-4}
Preheater/separator	8.8×10^{-8}	7.0×10^{-7}	8.8×10^{-5}	7.0×10^{-4}
Injection	8.8×10^{-11}	8.8×10^{-10}	2.2×10^{-5}	1.8×10^{-4}
Plant bypass	8.8×10^{-9}	7.0×10^{-8}	4.4×10^{-6}	3.5×10^{-5}
Plant-to-well	8.8×10^{-12}	7.0×10^{-11}	4.4×10^{-6}	3.5×10^{-5}
System 3 - total	4.5×10^{-5}	3.6×10^{-5}	2.7×10^{-4}	2.1×10^{-3}
Well-to-plant	4.4×10^{-6}	3.5×10^{-5}	4.4×10^{-6}	1.4×10^{-3}
Separator/heat exchanger	8.8×10^{-8}	7.0×10^{-7}	4.4×10^{-5}	7.0×10^{-5}
Flash unit	3.5×10^{-10}	2.8×10^{-9}	1.8×10^{-4}	1.4×10^{-3}
H_2S scrubber	1.8×10^{-11}	1.4×10^{-10}	8.8×10^{-6}	7.0×10^{-5}
Injection	4.4×10^{-14}	3.5×10^{-13}	2.2×10^{-5}	1.8×10^{-4}
Flash unit bypass	8.8×10^{-12}	7.0×10^{-11}	4.4×10^{-6}	3.5×10^{-5}
Plant bypass	8.8×10^{-9}	7.0×10^{-8}	4.4×10^{-6}	3.5×10^{-5}
Plant-to-well	8.8×10^{-18}	7.0×10^{-17}	4.4×10^{-6}	3.5×10^{-5}

SECTION 6

CONTAINMENT METHODS AND FLUID RELEASE CAUSES

GENERAL CONTAINMENT EVALUATION

The previous section describes the causes and probabilities of a geothermal brine release and points out that the volume and rate of brine released can be extremely variable and unpredictable and that the location of release and the direction of brine emission from the release point is also unpredictable. Accordingly, the containment measures described in this section are in keeping with good engineering practice and consider the worst case release condition.

There are no firm guidelines to indicate when a containment system should be incorporated in a geothermal facility and so the criteria for including a containment system is to minimize environmental damage from a brine spill. It should be recognized, however, that in some cases, environmental damage from spills could be minimal where geothermal brines are relatively low in salt content and the area is extremely arid. Accordingly, the spilled water flowing over the terrain might be beneficial to plant and animal life. A containment system appears to be most desirable in those facilities utilizing a brine with a high salt content and where flow from a large spill would cause erosional damage. Further, thermal pollution from a large spill can be mitigated by a containment system with delayed release of the brine into the environment. Decisions as to the use of a containment system and the type of system to be used will be judgmental, based on trade-offs between cost and the positive and negative environmental impacts of a spill.

Measures or methods for containing surface releases of geothermal brine fall into three general categories, (1) minimizing release possibility; (2) minimizing release duration; and (3) minimizing release area. Table 8 has been developed to indicate the applicability of these three containment methods to the causes of fluid release identified and discussed in the previous section. It is quite obvious that the number of failures and resulting brine releases can be reduced by good design practices and by use of proper operating and maintenance techniques but it must be realized that failures and releases cannot be totally eliminated. Accepting that spills will occur, it then becomes a question of reducing the quantity of brine released and minimizing the area affected by the spill. This will, in turn, minimize the environmental impact resulting from the spill. Correct operating procedures, inclusion of alarms in the design and proper personnel training programs are necessities if the time of brine flow through a rupture (and, therefore, the quantity of brine released) is to be minimal. Establishing procedures and personnel training are inexpensive and should be part of routine operations at any power plant.

TABLE 8. SURFACE BRINE RELEASE CONTAINMENT METHODS

FLUID RELEASE CAUSES	TO MINIMIZE NUMBER OF FAILURES									TO REDUCE TIME DURATION OF RELEASE				TO REDUCE AFFECTED AREA OF RELEASE				
	OPTIMUM MATERIAL USE	COMPONENT & SYSTEM DESIGN	SEISMIC DESIGN CONSIDERATIONS	PRESSURE RELEASE	MINIMUM NUMBER OF COMPONENTS	MAINTAINABILITY	EFFECTIVE MAINTENANCE PROGRAM	OPERATING PROCEDURES & TRAINING PROGRAM	PHYSICAL SECURITY SYSTEM	AUTOMATIC SHUT-OFF AT WELL	MANUAL SHUT-OFF AT WELL	WELL REWORK	EMERGENCY PROCEDURES & TRAINING PROGRAM	SYSTEM REDUNDANCY	SHUT-OFF REDUNDANCY	EMERGENCY PROCEDURE & TRAINING PROGRAM	LOCAL DIKED AREA	TOTAL PLANT DIKED AREA
BLOW OUTS			X				X	X				X		X			X	
CORROSION	X	X			X	X	X			X	X		X		X	X	X	X
ABRASION	X	X			X	X	X			X	X		X		X	X	X	X
SCALING	X			X	X	X	X			X	X		X		X	X	X	X
NATURAL DISASTERS		X	X							X	X		X			X		X
VANDALISM/TERRORISM								X	X	X	X		X		X	X		X
ACCIDENTS								X	X	X	X		X	X	X	X		X
PERSONNEL ERROR				X	X			X		X	X		X			X		X

The methods, or combinations of methods, that are optimal for reducing the duration of release and the area affected is a function of the cause of release and this is discussed in the following by reference to Table 8.

Blowouts

Blowouts are best prevented by employing good operating procedures and proper equipment during drilling. An effective maintenance program involving periodic inspection and reworking of the wells will detect and repair those factors, e.g., corroded casing or failed cement that may generate blowouts during the life of the well. Proper rework of the cement can also increase the probability of post-blowout brine flow being contained in the wellbore so that capping is expedited and the duration of release is reduced. Since geothermal wells are inherently located in seismically-active areas, seismically-induced failure of casing and wellhead equipment may become a problem and including seismic considerations in the well design may be desirable. An example of this might be more prevalent use of uncemented hung liner that would be more amenable to lateral longitudinal motion than would be cemented casing. Areal effects of a blowout-caused spill could be reduced by diked areas, but this is probably not generally practicable.

Corrosion and Abrasion

Containment methods useful for corrosion and abrasion-caused releases are essentially identical. Minimizing the probability of failure through these causes is a matter of employing good design practices including the use of optimal materials, minimizing the number of components used and directly applying the necessary design techniques such as specifying increased wall thicknesses where abrasion in piping could be significant. Proper maintenance including periodic inspections is a requirement for minimizing failure probability during the plant life. Reducing the time duration of release due to these causes is a matter of a shut-off system (either automatic or manual) being available at the wellhead, having emergency procedures defined and having a well-trained work force available to implement these procedures. It is interesting to note that these factors are also applicable to reducing the time duration of release from any of the causes. Areal effects are reduced by including several points of shut-off in the system, again having procedures and trained personnel available and using diked areas of a size appropriate to the expected worst-case release.

Scaling

Scaling-caused release containment is very similar to that of corrosion and abrasion except that including scaling effects in design considerations is less practical and the use of pressure release components at appropriate places in the system becomes mandatory. Areal containment methods are also very similar to those of corrosion and abrasion.

Natural Disasters

The releases induced by natural disasters such as quakes promise to be worst-case in nature so that larger diked areas may be necessary. Design techniques for limiting seismic effects on piping systems are well known and could be employed to minimize spills from this cause.

Vandalism and Accidents

Methods of minimizing failures caused by vandalism and accidents are similar in that the necessary operating procedures plus a well-trained work force to implement these procedures are required. Further, a physical security system that would monitor the presence of intruders, both purposeful and accidental, within the plant boundaries is necessary. Areal limitation of resulting spills is a function of having multiple shut-off locations available, the necessary procedures and trained people being available, and appropriate diking.

Personnel Errors

Releases through personnel errors can be reduced primarily by employing a trained, motivated staff. Using the minimum of components and appropriate pressure release mechanisms (to be used in event that a valve is mistakenly actuated and a pressure buildup is generated) are also significant. Areal containment is primarily a function of appropriate diking.

Recommendations

Examination of Table 8 indicates that certain containment methods are essentially common to all release causes once fluid has been released. These methods are: the availability of a shut-off system, either automatic or manual, at the wellhead, an appropriate diking system, the existence of emergency operating procedures and a work force that is sufficiently trained and motivated to exercise these procedures on demand.

SPECIFIC CONTAINMENT EVALUATION

As stated above, there are three general categories of containment methods, i.e., minimizing the possibility of brine release, containing a release in time, and containing a release in area. These are evaluated in the following discussion. Finally, a step-by-step procedure for determining containment designs and specifications is presented.

Minimizing Brine Release Possibilities

The most significant factor in minimizing the possibility of brine release is the use of good engineering practices in the design and operation of the geothermal energy conversion system. The possibility of brine release should be considered from the onset of the program. Some specific practices to lessen effect on brine release possibility are discussed below. (It should be recognized that other system considerations may be sufficient to negate the actual use of some of these practices).

- The facility should be designed so that components are visible and accessible. Piping should be above ground, pipe insulation should cover flanges, and pressure gauges should be located for easy viewing.

- Redundance should be incorporated into the design. Systems 1 and 2, described previously, have fully redundant brine loops. (System 3 is more experimental and is patterned closely to a specific installation). Incorporating redundancy in a system is now a good, standard design practice. Subsequent examination of the failure rate data for these systems shows no obvious need for more redundancy than has been used.

- The numbers of components should be minimal while keeping with the redundancy principle. This is an obvious desirability, also reflecting into system costs.

- Optimum materials should be used. Existing facilities rely heavily on carbon steel but a body of data on the corrosive effects of geothermal brine on various materials is being generated and other, probably more expensive materials may find application. Titanium heat exchanger tubes are now commonly accepted.

- The facility design should recognize the relatively higher seismicity of geothermal areas, and pipe supports and other installations should be so designed and installed. Unstable soil areas should be identified and avoided.

- Blowout preventers should be used when drilling and casing and cement should be selected to withstand high temperatures.

Another significant factor in minimizing brine release probabilities is an adequate maintenance program during facility operation. The failure analysis in the previous section points this out. The program should have an adequate budget and the importance should be recognized. However, the data necessary for devising a complete maintenance program does not now exist. While data pertaining to brine carrying and power conversion components are available, as discussed in the previous section, wells present a more formidable problem. There is not yet sufficient experience in this country to determine the workover procedures and schedules necessary to keep production and injection wells operating in an optimum manner. Experience along these lines does exist in other countries. A large body of well maintenance data exists for the Cerro Prieto field in Mexico. A program of collecting and analyzing maintenance data from these sources is suggested.

Finally, security of the area should be considered. The system designs considered here are inherently secure in that the facility is limited in size and it will be well lighted and manned around the clock. Other systems that utilize vertical drilling will occupy a larger area and a longer perimeter fence and, perhaps, patrols will be required.

Brine Release Containment in Time

The time during which brine is released should be minimized, thereby minimizing the volume spilled. Accordingly, flow through the loss point should be shut off quickly. There are several means of doing this, as follows:

- A fully-automatic shut-down system may be used. A brine release will generate a pressure loss that can be sensed and used to trigger valve actuators at appropriate places in the system. One configuration of this system would have automatically-actuated valves on the production wellheads that would close upon signal. Another configuration would use a bypass producer-to-injection line, as shown in the systems previously described and automatically-actuated valves would open this line while closing the lines to the conversion system. This would present some advantages in allowing the wells to continue to flow. The actuating time of motor-driven valves is measured in seconds and the maximum brine spillage, associated with the maximum flow rate of 53,000 l/min, (14,000 gpm) would be less than 8,000 liters (2,000 gallons). Fully-automatic systems are complex and expensive. An eight-inch motor-driven valve will cost approximately $6,000 installed and the cost of so equipping 28 wellheads would be approximately $170,000. A 36-inch motor driven valve, such as would be used in the bypass configuration, would cost approximately $30,000 installed and two of these would be required. A data processing unit as well as switching units will also be required. In summary, designing, procuring and installing such a fully-automatic system would cost approximately $250,000, a significant cost figure. This cost refers to the systems of interest here where electrical power can be easily supplied to the wellheads. In systems utilizing vertical wells, the cost of supplying power to the dispersed wellheads would make the automatic feature more expensive.

- A semi-automatic system may be used where a pressure loss, signalling a brine release, is presented as an alarm to the plant operator who manually triggers the actuators. Here, the volume of brine released is a function of the reaction time of the operator, which will be, in turn, a function of his training and alertness. A maximum reaction time of two minutes might be expected, resulting in a maximum spill of approximately 106,000 liters (28,000 gallons). This system has some advantages in eliminating the data processing system, about 15 percent of the cost, and in reducing the possibility of false alarms.

- A semi-manual system may also be used in which a pressure loss alarm is presented to the plant operator who informs and instructs other operational personnel. These personnel then operate the required valves manually. The brine release will be determined by the time required to locate and inform the proper personnel, for these personnel to access the appropriate valves and to operate them. A maximum total reaction time of two hours might be expected, resulting in a maximum spill of approximately 6.4 million liters (1.7 million gallons).

This system requires personnel to be able to approach and operate the correct valve hand wheels without being significantly deterred by the escaping hot fluid and steam. This implies that there must be several routes of access to the valves, that at least some of the valves must be elevated above potential surface fluid flows and that valve stems must be extended so that hand wheels lie behind protective bulkheads. This system could be implemented in the three conversion systems of interest for approximately $8,000, assuming two low-lying catwalks, pressure detectors with alarms, and a wooden bulkhead near the production wellheads with valve stems extended to pass through it.

- Still another system would be completely manual with the pressure detectors eliminated and operating personnel being required to visually detect a brine release and to operate the valves necessary to control it.

Of these time-containing systems, the semi-manual system, backed up by visual release detection by operating personnel, appears the most likely to be implemented.

Brine Containment Dikes

Areal containment of brine release involves locating, designing and constructing a pond of a size to hold the maximum potential volume of released brine. If used only for spill containment, factors to be considered will be the potential spill volumes and the fluid retention time required. Should the pond be constructed for other purposes in addition to spill containment, water treatment for example, factors pertaining to these other purposes would have to be considered also.

The maximum expected release of 6.8 million liters (1.7 million gallons) of brine is equivalent to approximately 5.2 acre-feet. Since a 50 MWe geothermal power plant of the systems of interest here occupies approximately ten acres, a maximum expected release would cover the entire plant site to a water depth of approximately 15 cm (six inches).

It is desirable to cause the spilled brine to flow away from the wellheads and conversion system so that water damage may be minimized and repairs may be speeded. Accordingly, the plant site should be graded to drain to an appropriately placed pond. The desired surface area of the pond, and the resulting length and height of the berm, will be a function of the plant layout. It seems that, given the rarity of significant spills, areas of the site not occupied by facilities or planned operations would be available for containment pond usage. Such areas might normally serve as parking lots. If one-third of the ten acre-site is available for the pond and if the pond bottom is formed by a single-slope grade to the perimeter fence an average dike height of approximately one meter (three feet) will be required to contain the maximum potential spill. The dike length, along the perimeter fence, would be a function of the shape of the available land area. This type of containment has the advantages of reduced cost and adding very little environmental damage to that already incurred by constructing the plant.

There may be situations in which grading the site to route the released brine into a nearby holding pond is necessary. Reference 17 presents investment costs for such holding ponds; a pond with one-half acre of surface area and ten-foot dikes would cause environmental damage during construction and would cost approximately $25,000. The perimeter dike discussed above would cost approximately one-tenth of this figure.

Under ordinary circumstances, the containment will act as a settling pond with the brine eventually disappearing through evaporation and percolating into the subsurface. Under conditions of very saline brine and rigid environmental protection requirements, where contamination of ground water aquifers is feared, percolation into the subsurface may not be allowable and the containment pond may require lining. This would add substantially to the costs.

Step-by-Step Procedures

- From the system design, locate the component having the greatest brine flow and note the flow.

- Compute costs of automatic and semi-automatic brine shutoff systems.

  - Valves and actuators
  - Supplying power to actuators
  - Pressure sensors
  - Signal conditioning and processing unit
  - Switching units

  (Costs should include engineering, installation and maintenance over the life of the plant).

- Collect information on local environmental effects, regulatory requirements, community attitudes and political climate regarding a brine spill.

- Decision: Is automatic/semi-automatic shutoff system feasible and desirable?

  If yes, no containment area is necessary.

  If no, implement manual system and proceed to the next step.

- From plant layout, around-the-clock staffing plans and internal plant communications and transportation plans, determine maximum reaction time for personnel to access and operate wellhead valves upon alarm. Influence communications and transportation plans to reduce reaction time.

- Multiply steps to determine maximum volume of an expected brine release. Convert to acre-feet.

- From the plant layout, determine areas within the plant perimeter where temporary submergence by a containment pond is tolerable. Include non-critical facility areas such as parking lots.

- From the areas defined in the preceding step, determine the average berm height and the berm length, as located on the site perimeter, to contain the maximum expected brine release volume.

- From the areas defined previously and site grading plans and profiles, determine actual berm heights, approximating the desired average, around the site perimeter. Compute the volume of fluid that will be contained by this berm. Influence site grading plans to maximize this volume.

- Decision: Will the pond contain the maximum expected brine release volume?

  If yes, go to the next-to-last step.

  If no, proceed to next step.

- Locate topographically feasible areas outside plant perimeter into which the pond can be expanded with minimum environmental damage, compute berm height and length necessary to contain the maximum expected brine release volume.

- From the brine characteristics and the local environmental requirements determined previously, determine if the brine settling into the subsurface is satisfactory. If not, add a bottom liner to the pond area.

- Influence construction schedules so that the berm is constructed simultaneously with plant site grading.

REFERENCES

1. TRW, Incorporated. Experimental Geothermal Research Facilities Study. TRW Final Report 26405-6001-RU-00. Redondo Beach, California, 1974.

2. Campbell, G.E. Geothermal Well Drilling and Completion Practices in California Including Casing and Abandonment Programs and Examples of Blowouts. Publication of the Geothermal Unit, California Division of Oil and Gas.

3. TRW, Incorporated. Study of the Geothermal Reservoir Underlying the East Mesa Area, Imperial Valley, California. TRW Final Report 28859-6001-RU-00. Redondo Beach, California, 1976.

4. Final Environmental Statement for the Geothermal Leasing Program, Volume 1. United States Department of the Interior, 1973.

5. Miller, R.L. Results of Short-Term Corrosion Evaluation Tests of Raft River. Idaho National Engineering Laboratory. Report TREE-1176, 1977.

6. Banning, L.H. and Oden, L.L. Corrosion Resistance of Metals in Hot Brines - A Literature Review. U.S. Bureau of Mines Report IC-8601, 1973.

7. Miller, R.L. Results of Short-Term Corrosion Evaluation Tests at Raft River. Idaho National Engineering Laboratory Report TREE-1176, 1977.

8. Status Report, Geothermal Resource Investigations, East Mesa Test Site, Imperial Valley, California. U.S. Bureau of Reclamation, 1977.

9. Shannon, D.W. Corrosion of Iron-Base Alloys Versus Alternate Materials In Geothermal Brines. Battelle Pacific Northwest Laboratories Interim Report PNL-2456, 1977.

10. Kukacka, L.E. et.al. Alternate Materials of Construction for Geothermal Applications. Brookhaven National Laboratory Progress Report BNL 50834, 1978.

11. Hirasuna, A.R. et.al. Geothermal Elastomeric Materials. L'Garde Inc. Progress Report SAN/1308-1, 1977.

12. Lawrence Berkeley Laboratory. A Study of Brine Treatment. Electric Power Research Institute Report ER-476, 1977.

13. Makrides, A.C. et.al. Study of Silica Scaling from Geothermal Brines. EIC Corporation Report COO-2607-5, 1978.

14. Daedalean Associates Inc. The Results of the Initital Feasibility Program on Cavitation Descaling Techniques for Pipes and Tubes Used in Geothermal Energy Plants. Daedalean Associates Report HCP/T2289-01.

15. Reactor Safety Study. United States Department of Commerce Report WASH-1400 (NUREG 75/014), 1975.

16. Fulton, D.W. Non-electronic Parts Reliability Data. Rome Air Defense Center Report NPRD-1, 1978.

17. Sung, R. et.al. Preliminary Cost Estimates of Pollution Control Technologies for Geothermal Developments. EPA Contract No. 68-03-2560, T-5004, U.S. Environmental Protection Agency, Cincinnati, Ohio, 1979. 131 pp.

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16. ABSTRACT

This report examines the probability of significant releases of geothermal brine to the surface environment through unplanned or accidental events. It then evaluates the containment measures that may be used to prevent environmental damage. The results indicate that major spills are likely to be very rare and that simple warning systems and diked containment areas should provide adequate protection.

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