

Stimulation of Geothermal Energy Resources



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STIMULATION OF GEOTHERMAL ENERGY RESOURCES

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INTRODUCTION

For more than a decade, geothermal heat has been considered as a most promising source of energy, and yet relatively little utilization has occurred since the demonstration of its conversion to electric power at Lardarello, Italy, in 1904. Although the upper 10 km of the earth's crust may contain more than 3×10^{26} cal of heat, the energy is too diffuse to be exploitable as a world-wide energy resource. However, many deposits of geothermal heat are concentrated at attainable depths, in adequate volumes, and at temperatures sufficient for commercial exploitation. The characteristics of commercial resources as described by White (1973) are reservoirs with fluid temperature in excess of 180°C, depth of less than 3 km, volume in excess of 5 km³, and with sufficient productivity to sustain adequate flow rates over the field amortization period.

The world's major commercial geothermal reservoirs used for electric power generation are high-quality hydrothermal convection systems producing high-enthalpy geofluids. Unfortunately, these characteristics have been found at only a few places on earth. Other geothermal energy resources occur in a variety of geological systems and in a variety of thermal and chemical qualities. The development of these abundant but lower quality geothermal resources may depend on the attainment of stimulation technology in the forms of increased energy extraction, increased conversion efficiency, and increased resource utilization.

The need for stimulation technologies is apparent from a comparison of the world's developed capacity for electric power production and the estimated potential. Table 1 shows the electric power generating capacity

from geothermal energy by nation in 1973. More than 75% of this capacity results from vapor-dominated hydrothermal systems which produce dry or super-heated steam directly usable in low-efficiency steam turbines. The remaining capacity results from high-quality water-dominated hydrothermal systems in which the geofluids are flashed on production and only the separated steam is used for electric power generation. The liquid fraction is either wasted or injected into the ground. These systems are less desirable because only a fraction of the hot water flashes to steam, thermal efficiencies are low, and plant operational problems are more severe. Unfortunately, liquid-dominated hydrothermal systems are believed (e.g., Barnea, 1972) to be many times more abundant than vapor-dominated systems. Other forms of geothermal resources, such as geopressured basins, magmatic deposits, and impermeable hot rock massives, may be many times more abundant than hydrothermal resources (Muffler and White, 1972).

Many estimates have been published of the potential of geothermal energy resources for electric power production. A range of forecasts for the United States is given in Table 2. The potential capacity is expressed in equivalent numbers of 1000 MWe nuclear reactors and in the equivalent consumption of oil in millions of barrels per day. The pessimistic estimates are from many sources; the optimistic forecast of Hickel (1972) represents some 13% of the forecast U.S. capacity in 1985. The national goal of achieving some 20,000 to 30,000 MWe of geothermal electric power is clearly a compromise between what is worth a national effort and what can be realistically achieved. The potential for replacing the equivalent of some 25 nuclear power reactors or the conservation of some million barrels of oil per day is clearly an incentive to accelerate the developme

of a geothermal industry in the United States. Table 1 notes that the entire world-wide electric power generating capacity from geothermal energy is equivalent to just one modern 1000 MWe nuclear power plant. Clearly the stimulation of geothermal energy resource development could add important energy supplies to many nations of the world.

Stimulation of geothermal energy resources in the industrial sense requires the development of three complementary components: (1) an adequate resource, (2) the technology for its economic utilization, and (3) the institutional means for widespread acceptance. Stimulation of a geothermal industry would suggest simultaneous efforts to develop these three components at an accelerated rate. It has been noted that the present commercial geothermal energy industry has focused on the high quality types of geothermal resources, and these were developed only with slow acceptance of the resource extent, existing low-efficiency conversion technology, and burdensome institutional problems. For development of lower quality resources, many problems remain to be solved. Some of these are summarized in Table 3. The variability of geothermal resources is perhaps the key parameter in the geothermal energy cycle from exploration to utilization. The problems of extraction and conversion of dry-steam reservoirs, although not fully resolved, have been developed sufficiently to be commercially attractive. These problems for hot water reservoirs are more difficult, and for hot brines, geopressured basins, and hot dry rock formations, they are not yet developed for commercial utilization. These latter types of potential geothermal energy resources have great promise if stimulation methods can be developed to exploit the energy in these formations.

STIMULATION OF GEOTHERMAL ENERGY PRODUCTION

There are several ways to stimulate the production of geothermal energy; they involve the increase of efficiency through (1) modes of utilization, (2) technology for energy conversion, and (3) methods of extraction.

Increased Utilization Efficiency

The general modes of utilization of geothermal resources are summarized in Table 4. Planning for the development of geothermal fields generally considers the characteristics of the geofluids, the gathering and steam-water separation facilities, the turbine and generator equipment, the cooling cycle, the well productivity, spacing, and schedules, environmental impacts, and condensate disposal methods. Such planning assumes that electric power generation is the sole purpose of the field development. It may turn out, however, that very significant savings of fossil and nuclear fuels may result from the total utilization of the geothermal resource. Hydrothermal fluids with low temperature or enthalpy for economic electric power production might be useful for water and mineral sources and for industrial, agricultural, and municipal heating. For such utilization, it is interesting to note in Table 5 the engineering criteria for thermal water utilization suggested by Makarenko and Kononov (1970) in which geothermal fluids at temperatures of 25°C are considered to be of commercial value. However, since major interest in geothermal energy lies in the production of electric power, the combined or total utilization may help make geothermal resources that are submarginal in power production become economically feasible. Thus, research for methods of stimulating geothermal resource utilization in all forms appears to be well warranted.

Increased Conversion Efficiency

The general methods for producing electricity from geothermal fluids are summarized in Table 6. The choice of optimum conversion cycle is generally dependent on the thermodynamic and chemical properties of the produced fluids. Present commercial plants utilize low-salinity hydrothermal systems with steam or water at temperatures above about 200°C. It is generally accepted that hydrothermal systems with fluid temperatures below 200°C will be more abundant. Thus improved technology to utilize lower-quality geothermal fluids for electric power production is urgently needed.

Investigations are underway to develop alternate conversion systems; among them are single and multiple flash low-pressure steam turbines, single and multiple stage binary cycle systems, and hybrid systems combining these two. An example of the binary system is the Magmamax power cycle, shown in Figure 1, which uses a downhole pump to prevent flashing and an isobutane secondary fluid in a closed cycle (Anderson, 1973). Downhole pumps and heat exchanger systems are key components of such systems. For example, development of several types of downhole pump is underway, with design concepts which use (1) in-situ geothermal heat to operate a closed steam-generator-turbine to drive the pump, (2) a high-speed, high-temperature, high length-to-diameter electric-motor driven pump, and (3) a hydraulically driven unit with hydraulic power from the surface. Heat exchanger concepts include fluidized sand beds to enhance heat transfer rate and maintain clean surface, and liquid-liquid systems with (a) direct contact of immiscible fluids, (b) tray-tower contactors, (c) subcritical power cycles, or (d) supercritical power cycles.

A novel system for binary fluid energy conversion was described by Moskvicheva and Popov (1970) in which an experimental 750 kWe plant was used both to test Freon as a secondary fluid and to utilize mixed geofluids and cooling water for agricultural heating. Figure 2 shows a schematic drawing of this combined utilization.

Flash and binary systems are useful in large power plants with capacity in excess of 50 MWe. They require complexes of multiple-well field development and extensive networks of gathering lines. Innovative conversion systems are also being considered in which small power plants, in sizes from 1 to 15 MWe, are installed at individual wells. These systems may involve a total flow concept in which both the thermal and kinetic energy of the geofluids are used for production of electricity. One of these is the impulse turbine (Austin et al, 1973) in which the thermal energy is converted to kinetic energy through a converging-diverging nozzle. The high-velocity output drives a hydraulic impulse turbine operated at low backpressure. A schematic design for this concept to utilize the hot brine resources of the Imperial Valley, California, is illustrated in Figure 3. Cost estimates for a 220 MWe plant using Salton Sea geothermal brines of 225°C temperature, 360 psia pressure at a production flux of 8.8×10^6 kg/hr/m² producing a power output of 474 MWe/m² are about \$180/kWe. Research is currently underway at the Lawrence Livermore Laboratory on the design of the appropriate nozzles and rugged, corrosion-erosion resistant materials for the impact turbines.

Another concept is the helical rotary screw expander (McKay and Sprankle, 1975) based on the Lysholm gas compressor machinery developed in the 1930's. The helical screw expander, shown in Figure 4, can expand

continuously the vapor from hot saturated liquids during pressure reduction in the machine, creating in essence an infinite series of flashing stages. A small model of a 62.5 kV prototype plant has been tested successfully with moderate salinity geofluids with indications that it can accept the total flow of untreated mineralized geofluids. Development of a prototype of a 1250 kWe system is underway.

Another concept being investigated is the bladeless turbine, in which a series of closely spaced circular disks are placed on a shaft with nozzle introduction of geofluids, housed to provide narrow channels between the disks. The rotary force results from viscous drag between the adjacent disks. Although the concept seems simple and self-cleanable with hot brines, the overall efficiency may be small.

Increased Extraction Efficiency

The potential for increased extraction of heat from hydrothermal and hot dry rock geothermal reservoirs can be evaluated from requirements of steam production for electric power generation. The energy aspects of hydrothermal systems have been estimated by Ramey et al (1973) for steam turbines operating at an inlet steam pressure of 100 psia. Table 7 shows the available energy content of a reservoir with assumed characteristics of 500°F, 1000 Btu/lb enthalpy, 25 percent porosity, produced by pressure reduction from the initial saturation pressure of 681 psia at 500°F to the abandonment pressure of 100 psia. The table summarizes the available energy content for both dry-steam and hot-water reservoirs of low salinity and without fluid reinjection. Two general observations are noted. First, although the latent heat of vaporization for steam is large with respect to the sensible heat in water at the same temperature, the hot-water

reservoir contains considerably more heat than the steam-filled reservoir because of the much larger mass of water. However, in both systems the mass of the rock formation is large compared to the mass of the fluid, and thus most of the heat available is stored in the rock formation. It is clear that extraction processes for recovery of the heat stored in the rock, as well as the heat in the fluid, would be of significant economic interest. Extraction of the heat in the rock formation may be achieved by flashing the geothermal liquid to steam within the formation or by recycling colder fluids back into the formation.

Table 8 shows the potential recovery of mass and energy for the steam and hot-water reservoirs. It is apparent that although the recovery of fluid is about the same for both types of hydrothermal systems, the recovery of energy from the hot-water reservoir is much greater.

Two of the world's most important geothermal fields are of the dry-steam type. Production occurs essentially by the isothermal process of pressure reduction. Since energy can be recovered from the rock formation only by a process that reduces the temperature of the rock, increased extraction efficiency for dry-steam reservoirs can be achieved only with some form of liquid-reinjection method.

For the hot-water reservoir, however, production by pressure reduction is not an isothermal process, since flashing of the water in the formation would be accompanied by a reduction in the temperature of the rock. The steam produced by flashing in the reservoir could remove most of the total available energy. For the assumed reservoir conditions, the usable steam available for electric-power generation would be some 20 times greater

than the total steam content in the steam reservoir. Thus, in-place boiling or colder-water injection become of major interest for increased extraction efficiency of hydrothermal systems.

The extraction efficiency of energy from impermeable hot dry rock formations is extremely small. Yet hot dry rock deposits in the upper 10 km of the earth's surface represent an important potential resource of geothermal energy. The volumetric energy extractable from hot dry rock may be estimated by

$$H = L\rho(1-\phi)VC\Delta T$$

where L = heat recovery factor

ρ = rock density

ϕ = porosity

V = fractured rock volume

C = heat capacity

ΔT = temperature

For a rock massive with the assumed properties of $\rho = 2.6 \text{ g/cm}^3$, $\phi = 0.31$ cal/g°C, extraction of heat for $L = 0.1$ with a temperature reduction of 200°C would be 10^{15} cal/km³ or 1.2×10^9 kWh/km³ of fractured rock. The volumetric power extraction would be 1.4 MW/km³ for 1 century. The technical challenge is the ability to fracture such volumes of hot rock massives and achieve an extraction efficiency of the order of 10 percent.

Stimulation methods may be used to increase permeability, to fracture deposits around wellbores, or to increase wellbore diameter. Stimulation effects may be useful in many types of geothermal reservoirs. In vapor-dominated systems, stimulation may be useful to restore declining pressure or to connect dry holes in known steam fields to producing sections.

In liquid-dominated systems lacking sufficient productivity for power plant amortization, stimulation may be useful to provide a large wellbore diameter for increased flowrate, greater surface area for heat transfer, or to fracture deposits of silica, calcite, or other minerals decreasing formation porosity or permeability near the well. In dry geothermal systems, stimulation is needed to provide large fracture volumes for heat transfer to an artificial convective extraction system. Fracturing methods under study include hydraulic fracturing, thermal stressing, and chemical and nuclear explosive fracturing. Hydraulic and explosive fracturing methods have already been proven successful in the stimulation of natural gas reservoirs.

FRACTURING OF GEOTHERMAL RESERVOIRS

Hydraulic Fracturing

Hydraulic fracturing, which has become an established technology for stimulation of hydrocarbon production, is described in detail by Howard and Fast (1970). They report that this method of well stimulation has been used more than half a million times. Hydraulic fracturing is defined as the creation and preservation of fractures in reservoir rocks by the injection of a suitable fluid. Although the process in the laboratory is relatively simple, transfer of the hydraulic energy pumped at the wellhead to a deep hot hard-rock formation may be difficult. Losses in energy result from frictional pressure drop in the well, viscous pressure drop through the fracture, and leakage from the fracture into the formation.

The mechanics of hydraulic fracturing are not fully understood. The concepts that require fundamental assumptions include the mechanics of

rock failure, elasticity vs. plasticity, the effects of fluid penetration, and homogeneity and isotopy vs. heterogeneity. Several theories have been advanced concerning the mechanics of failure to rock subjected to internal fluid pressure. The general problem is the need to understand two aspects of rock fracturing, one involving theories of strength and deformation and the other involving theories of fracture mechanisms. The sparsity of sub-surface data, such as the type of fracture formed at the well and its orientation in the formation, accentuates the problem.

Hydraulic fracturing for the recovery of natural gas in deep low-permeability reservoirs was suggested by Holditch and Morse (1973) as an alternate to the use of nuclear explosives. Stimulation of natural gas production by hydraulic fracturing is achieved by altering the flow geometry; fluids surrounding a fracture flow normal to it, allowing rapid depletion of the formation adjacent to the fracture and fluids beyond the fracture flow radially to the fracture ends. To develop hydraulic fracturing as a means of reservoir stimulation for geothermal energy, several technology advances are needed; among them are the demonstrations that appropriate fractures and transmissivity can be achieved in a reservoir and that the fracturing process does not unduly alter the reservoir formation.

A method involving both hydraulic and thermal stress fracturing for recovery of geothermal energy from hot dry rock formations has been proposed by Smith et al (1973). The method is being tested by the Los Alamos Scientific Laboratory in New Mexico with the proposed experimental system illustrated in Figure 5. In this concept a vertical crack is hydraulically created at the bottom of a bore hole in the geothermal formation. A second

hole is drilled parallel to the original hole to intersect the upper part of the hydraulically fractured zone. A pump completes the initial cycle in which cold water is forced into the fracture zone through the deeper well. Pumping is discontinued when natural convection in the cycle is achieved. Robinson et al (1971) calculated that a crack of 915 m radius formed in rock at a temperature of 300°C would yield an average power of 89 MW (thermal) for 20 years. However, Smith et al (1973) noted that thermal stressing of the fractured rock would occur on the entry of cold water and that the large tensile voids created by the thermal stressing would create additional fracturing in the formation, thereby greatly extending the life of the reservoir. Calculations are given for a 100 MWe electric power generating plant using two pairs of 5000 m holes in a geothermal deposit at about 300°C temperature.

The feasibility study at the Los Alamos Scientific Laboratory (Rowley, 1972) is based on the theory of stresses in deep rock as illustrated in Figure 6. The compressive stress at depth in rock is proportional to the mass of the overburden, with the vertical component of the stress, given by

$$\sigma_z = -\bar{\gamma}h$$

where $\bar{\gamma}$ is the average density of the overburden and h is the depth. The horizontal components, σ_x and σ_y for an elastic medium are given as

$$\sigma_H = \sigma_x = \sigma_y = \frac{\nu}{1-\nu}\sigma_z$$

where ν is Poisson's ratio for the rock. The elastic stress state in a vertical borehole of radius a filled with fluid to produce pressure P_0 at depth is shown in Figure 6. The radial stress around the hole (Figure 6)

is given by

$$\sigma_r = \sigma_H - (P_0 + \sigma_H) \left(\frac{a}{r}\right)^2$$

and the tangential stress (Figure 6c) is given by

$$\sigma_\theta = \sigma_H + (P_0 + \sigma_H) \left(\frac{a}{r}\right)^2$$

The tangential stress in the wall created by the internal pressure is tensile opposite in sign to the compressive stress represented by σ_H . Thus, if the internal pressure P_0 is increased by high-pressure pumping at the surface, so that $P_0 > 2\sigma_H$, the net tangential stress in the wall will be tensile. For granitic rocks of Poisson's ratio, $\nu = 0.2$, the tangential stress at $r = a$ will be

$$\sigma_\theta = P_0 - \frac{2\nu}{1-\nu}\sigma_H = P_0 - 0.5\sigma_H$$

Thus a sufficient increase in internal pressure by hydraulic pumping would be expected to cause vertical cracks in the formation, as shown in Figure 6d. Since tensile strengths of rocks are generally low, ranging from 40 to 100 bar, the pressure required in a deep hole to form vertical cracks is less than the overburden pressure. The results of hydraulic fracturing in oil fields at depths to 3.6 km in sedimentary rocks indicate a fracture pressure of about 0.44 to 0.75 times the overburden pressure (Harrison et al, 1966).

The important aspects of initiating the crack and inserting porous material to hold it open has been well studied (Howard and Fast, 1970). The important aspects for hydraulic fracturing of geothermal reservoirs are the maximum radius that can be propagated, the crack width, and the crack volume; these determine the extent to which heat transfer can be obtained with convective heat exchange. For a liquid-filled crack, the

volume V , width B , and heat transfer surface area A can be estimated by

$$V = \frac{16}{3} \frac{(1-\nu^2)}{E} \Delta P L_c^3$$

$$B = \frac{8}{\pi E} (1-\nu^2) \Delta P L_c$$

$$A = 2\pi L_c^2$$

where $\Delta P = P_0 - \frac{\nu}{1-\nu} \bar{\sigma}_H$ is the net pressure in excess of the horizontal lithostatic compression, $\bar{\sigma}_H$.

For a granitic material with an elastic modulus $E = 10^6 \text{ kg/cm}^2$ and Poisson's ratio $\nu = 0.2$, a crack radius $L_c = 1000 \text{ m}$, crack width, $B = 2.0 \text{ cm}$, and crack volume, $V = 4.2 \times 10^5 \text{ m}^3$ could be produced with a heat transfer area, $A = 6.3 \times 10^6 \text{ m}^2$, and with a net crack extension pressure, $\Delta P = 80 \text{ kg/cm}^2$. These data indicate that relatively small crack-propagation pressures can potentially form long thin cracks with large heat transfer areas.

Thermal Stress Cracking

An important form of reservoir stimulation may result from the stresses caused by temperature changes. Injection of colder fluids into a geothermal formation that is fractured naturally or by hydraulic or explosive methods will produce a temperature gradient through the fractured rocks, and the tension stresses caused by thermal contraction may cause thermal stress cracking to form in the fractured rock formation. Examination of this possibility is part of the hot dry rock experiment at the Los Alamos Scientific Laboratory (Rowley, 1972). Rowley notes that slope of the thermal gradient and the surface temperature differential is a function of the heat extraction rate.

Upon the introduction of colder water, a thermal stress, σ_{th} , results, estimated as:

$$\sigma_{th} = \frac{\bar{\alpha}E}{1-\nu} (T_0 - T_s)$$

where $\bar{\alpha}$ = mean coefficient of thermal expansion, $^{\circ}\text{C}^{-1}$

E = elastic modulus, kg/cm^2

ν = Poisson's ratio

T_0 = temperature of undisturbed rock mass

T_s = temperature of rock surface, $^{\circ}\text{C}$

Rowley (1972) estimated the stress for granites having the properties $\bar{\alpha} = 8 \times 10^{-6} \text{ }^{\circ}\text{C}^{-1}$, $E = 10^6 \text{ kg/cm}^2$, and $\nu = 0.2$ as

$$\sigma_{th} = 10\Delta T$$

and noted for granite strengths in the range of 40 to 100 kg/cm^2 , a surface cooling of only 4 to 10 $^{\circ}\text{C}$ might be sufficient to initiate thermal stress cracks. Although the stress state in deep dry hot rock is complex, it is expected that for temperature changes in excess of 100 $^{\circ}\text{C}$, thermal stress cracking could become an important process to increase the extractable heat from a fracture-stimulated reservoir.

Another indication of this potential is noted from an estimate of the relative volumetric contraction caused by the temperature change

$$\frac{\Delta V}{V} = \beta \Delta T$$

where β is the volumetric coefficient of thermal expansion. From the heat extraction equation

$$\Delta H = \Delta T \rho C V$$

where ρ is the density and C is the specific heat

$$\Delta V \approx -\frac{\beta \Delta H}{\rho C}$$

Smith et al (1973) calculate for the production of 2400 MWh of heat from a fractured granite with properties $\beta = 2.48 \times 10^{-5} \text{ } ^\circ\text{C}^{-1}$, $\rho = 2.69 \text{ g/cm}^3$, and $C = 0.19 \text{ cal/g } ^\circ\text{C}$, the resulting volumetric contraction would be $\Delta V = 100 \text{ m}^3$. If this new void volume is formed as thin cracks over a large area of fractured rock, the new surface available for heat transfer could significantly increase the rate or duration of energy extraction from the reservoir. A mathematical model for hydraulic fracturing and propagation of cracks by water circulation, heat transport, and rock fracture has been described by Harlow and Pracht (1972).

Explosive Fracturing

Studies have indicated that explosive fracturing of geothermal reservoirs may be commercially feasible for stimulation of hydrothermal and hot dry rock reservoirs. Explosive stimulation with chemical and nuclear explosives covers a wide range of effects, and since the technology and environmental impact of these two types of explosives are very different, they are generally considered as separate methods.

The use of chemical explosives for stimulation of geothermal reservoirs was discussed by Austin and Leonard (1973). They considered stimulation for wells with insufficient production, decrease in production due to loss of porosity or permeability by mechanical alteration of the rock or by mineral deposition, and the potential need to increase the fluid-acceptance rate in a reinjection well. Figure 7 shows the application of chemical explosives to "spring" a drill hole to create a larger-diameter hole at a selected horizon, to fracture a zone of rock adjacent to a natural fracture, to shatter brittle minerals sealing a producing zone, interconnect zones of tight fractures, and to increase permeability around a well by gun perforators using conical-shaped charges.

Major problems in the use of chemical explosives for reservoir stimulation include the availability of explosives that can withstand the temperature and pressure environments at depth without boil-off, decomposition or premature detonation, the limited amounts of explosive that can be emplaced in the working horizon, and the control features required for safe handling in the field.

Commercial firms are developing explosives for use in high-temperature geothermal wells. One specific candidate has been described by LaRocca et al (1974) as a highly energetic, hydrazine-based family of liquid explosives known as Astrolite. A safety feature of these explosives is that they are produced as two non-explosive pumpable components which can be emplaced independently and simultaneously and blended to form the explosive mixture down hole. Surface explosive hazards are thereby eliminated. A possible use for such a liquid explosive would be as the medium for hydraulic fracturing of a hot dry massive followed by detonation of the explosive to create additional fracturing.

The volume of chemical explosives that can be emplaced in the working horizon of a geothermal reservoir determines the total explosive energy for stimulation. For an explosive of density 1.35 g/cm^3 and heat of detonation of 1000 cal/g , in 30 m of a 20-cm diameter well, the explosive mass of 1.27 metric tons would provide an energy of $1.27 \times 10^9 \text{ cal}$. The explosion effects of this energy would depend greatly on the mechanical properties of the reservoir materials and the amount of natural fracturing. With a liquid explosive it would be possible to recharge the fractured volume of a prior detonation and increase the fracture volume by a second detonation. Chemical explosive stimulation appears to be a worthy subject for extensive research.

Nuclear explosives become more efficient in size and cost for explosive yields above 3×10^{12} cal (3 kt) and are being studied for applications to create large volumes of fractures in underground formations. Nuclear explosives are being designed for commercial use in deep-emplacement wells of the diameters usually employed by the oil and gas industry (Kruger, 1972). In the United States, three experiments have been conducted for the stimulation of natural gas production in deep, low-permeability gas fields with nuclear explosives ranging in size from 29 to 90 kt. In the Soviet Union, nuclear fracturing has been successfully demonstrated for the stimulation of oil production with nuclear explosives of 2.3 and 8 kt yield. The use of large-yield (200-1000 kt) nuclear explosions has been suggested for the stimulation of hot dry rock formations by several investigators (e.g. Burnham and Stewart, 1973) and of hydrothermal systems by low-yield (5-100 kt) nuclear explosions by Raghaven et al (1971).

Early concepts of nuclear stimulation of geothermal reservoirs were first proposed by Carlson (1959) and Kennedy (1964). The production of steam in hot dry geothermal deposits fractured with a suitable array of multiple large-yield nuclear explosives was evaluated by Burnham and Stewart (1970) and by a joint government/industry study (American Oil Shale Corporation et al, 1971). An analysis was made of detonation configurations to produce an optimum volume of fractured rock from which heat could be extracted with a closed-loop cycle of surface water to operate a 200 MWe power plant for 30 years at an 80 percent plant factor. In a recent review Burnham and Stewart (1973) noted that the explosive array required for explosives of 200 to 1000 kt each was a function of the fracturing

efficiency of the array. The cost of the recovered energy was also a function of the thermal efficiency, the explosive yield, and the drilling cost (which is dependent on the depth of the geothermal deposit and the explosive diameter).

Explosive stimulation of hydrothermal reservoirs, proposed by Raghaven et al (1971), considers the use of a low-yield (5-100 kt) nuclear explosive to create a rubble-chimney wellbore in a geothermal reservoir. By appropriate control of the production rate and steam and quality in the explosion-produced wellbore, it may be possible to extract geothermal energy from the reservoir in excess of that contained in the hydrothermal fluids alone as noted in Tables 7 and 8. Flashing of the hydrothermal fluids may result in the extraction of a significant fraction of this energy.

ARTIFICIAL CIRCULATION SYSTEMS

The commercial feasibility of most geothermal reservoirs will depend on the extractability of sufficient energy to justify the required size of power plant or hot-water heating system. Many ways to extract heat from underground deposits have been enumerated; they include heat pipes, downhole heat exchangers, materials for direct thermoelectric conversion, and circulation of heat extraction fluids. Heat pipes have been used in many places for local heating; they are not efficient for electric power production. Thermoelectric converters appear promising for future development, but currently the most feasible technique appears to be the installation of an artificial circulation system, in which water (or some other low-cost fluid with better heat-capacity properties) is used as the heat carrier.

The major components of a heat extraction system consist of inlet and outlet boreholes transecting a zone of natural or artificially created fracture permeability, and a surface complex of processing equipment, heat exchangers, and reinjection pumps for the circulating heat carrier.

Several projects are under study to establish an artificial circulation system for heat extraction from deposits of hot rock. Other projects are aimed at developing useful numerical models to determine the fluid mechanics and heat transfer properties in artificial circulation systems; for example the LASL project in New Mexico, the Leningrad project for the Northeast part of the USSR, and the laboratory project on stimulation at Stanford University.

The project at the Los Alamos Scientific Laboratory (Smith et al, 1973), seeks to create a pressurized-water circulation loop by drilling two holes in a hot rock massive and connecting them by a large crack created by hydraulic fracturing. A schematic diagram of this concept was shown in Figure 5. The heat carrier for this project is water in an area where surface waters are generally in short supply. A two-dimensional, quasi-steady state, finite-difference numerical model is being developed (Smith and McFarland, 1974) to estimate the fluid mechanics and heat exchange properties of the system. Preliminary results of this model suggest that adequate heat extraction will be possible even at relatively high flow rate solely through buoyant circulation of pressurized water and that short circuiting across the hydraulic fracture system will probably not be a major problem. The parameters that are being examined include the formation

temperature and fracture permeability, the cost of drilling, the availability of makeup water, and the requirements for the utilization of the extracted heat.

The LASL project envisions that the reservoir can be developed with conventional drilling and large-radius hydraulic fracturing with secondary surface area produced by thermal stress during production. Some of the problems to be evaluated during the project include the need for downhole pumps to maintain water pressure, the mechanical history of the fractures and stress fields, the need for mechanical pumping of the fluid, and the chemical properties of the produced fluid.

Results to date (Tester, 1974) have been given for the experimental holes GT1 and GT2. Hydraulic fractures were created in GT1 at surface pressures of 10.3 MPa (1500 psi), and the cracks were essentially vertical in the circulation of the regional tectonic stress field. Current efforts are focused on drilling of hole GT2 which has reached a depth of 2042 m, where the temperature was 146°C. Attempts to induce vertical fractures in GT2 are underway.

The LASL model is derived by two-dimensional equations for the conservation of fluid mass, momentum, and energy solved numerically by finite differences. The model is quasi-steady with neglect of transient terms in momentum and continuity. Heat transfer is determined by temperature, space, and time, with evaluation of viscosity and buoyancy.

Fractured rock contains two types of void space: macropores, the void space between rock fragments, and micropores, the pore space inside individual fragments. Micropores may be either natural porosity or microfractures caused by hydraulic, thermal, or explosive stressing. The mass

flow and heat transfer area due to micropores may be an important factor in the success of artificial circulation systems.

In the LASL model, the heat transfer calculation is based on assumptions of secondary crack structure by thermal stresses. Harlow and Pracht (1972) considered the case of a large vertical volume of fractured rock with negligible thermal resistance. The opposite case is with no secondary fractures, for which a cooled layer of rock surface will form rapidly. The LASL model uses a one-dimensional, transient solution for the case of no secondary cracks and an effective rock thermal conductivity to reflect some secondary cracking.

Extraction systems for producing thermal waters in areas of permafrost in the northeast part of the USSR have been described by Dyadkin et al (1973). Figure 8 shows some of the variants considered for the shapes of reservoirs created by connecting zones of naturally and explosively created fractured hot rock. Part a shows a single-multichannel well and part б dual-multichannel wells with connected fracture zones; part в and part г show these wells with linear fracture zones; and part д and part е show such wells with a volumetric zone of artificial fractures. Figure 9 shows a planned project for a circulation system with elongated zones of fractures; the section through А - А shows three channels of hydraulic connection between wells 1 and 4 obtained by oblique directional drilling and subsequent connection by explosive charges to produce the large fracture volumes in zone 3. The linear zones of fracture, 2, are produced by torpedo (oil-well) drilling in the water-impermeable rock in the geothermal formation. Vertical portions of the wells will be cased and cemented. The circulation pump, 5, injects cold water, and hot water is produced through well 4 to the heat exchanger, 6.

The model for the heat balance of this system was given by Dyadkin et al (1973) as

$$t_2 = t_1 e^{-Al} + (T_1 - \frac{K}{A})(1 - e^{-Al}) + Kl$$

where t_1, t_2 = water temperature at the start and end of the calculated section, l , °C

T_1, T_2 = initial temperature of the rock massive at the start and end of l , °C

K = temperature gradient across l , °C/m.

The parameter A , characterizing the heat exchange, is

$$A = \frac{\pi d_w K_{\tau}}{WC}$$

where d_w = diameter of the well, m

W = production, kg/hr

C = specific heat capacity of the water, kcal/kg°C

K_{τ} = transient heat exchange coefficient, kcal/m²°C hr

In the fractured zone, the equation for the heating of the water over a sufficiently long time is modified as

$$t_3 = t_2 e^{-A_f l_f} + (T_2 - \frac{K}{A_f})(1 - e^{-A_f l_f}) + K l_f$$

where t_2, t_3 = water temperature at entrance and exit from fracture zone °C

T_2 = natural temperature of rock in reservoir, °C

l_f = sum of the linear zones of fracture, m

$A_f = \pi d_f K'_f / WC$

d_f = diameter of the fracture zone, m

K'_f = transient heat exchange coefficient of the fractured zone, kcal/m²°C hr.

The basic factors determining the feasibility of sufficient heat extraction appear to be the extent of heat exchange of the water with the rock massive, the environments of the wells and the fracture zone.

Dyadkin et al (1974) prepared an analytical solution to the problem of transient heat exchange in the filtration zone which includes the sizes of the rock pieces and the conductive heat flow from the surrounding heat mass. They note that an important advantage of artificial circulation systems is the possibility of extracting thermal energy almost anywhere, the cost being a function of the required temperature of the extracted fluid and thus the required depths of the boreholes. Their calculations show that with current methods of drilling and fracturing, artificial circulation systems will be feasible to depths of some 3 to 4 km. A heat carrier at temperatures of 60-90°C can be extracted from such depths almost anywhere with prospective utilization in mining industries, e.g. hot leaching of salts, copper and other ores, subsurface extraction of sulfur, and heat treatment of petroleum deposits.

The concept of using geothermal energy with an artificial circulation system for the production of petroleum from the Orinoco tar-sand deposit in Venezuela has been proposed by Paz-Castillo and Kruger (1971). In this study, the economic feasibility is calculated for using a 1000 kt explosion at a depth of 3340 m where the normal geothermal gradient would be sufficient to produce steam to reduce the viscosity of the oil in the tar sands in the higher formations. The extraction of more than 10^{12} Btu at an estimated cost of less than \$0.50 per barrel of steam produced could result in the economic production of about 18×10^6 bbl oil.

Another study of the heat extraction potential by stimulation and reservoir engineering practices was reported by Kruger and Ramey (1974), in which experimental and computational models have been prepared to evaluate the optimum performance of fracture-stimulated geothermal reservoirs. A laboratory model of an explosion produced chimney, shown in Figure 10, is used to obtain data on the processes of in-place boiling, moving flash fronts, and two-phase flow in fractured hydrothermal reservoirs. Studies are under way to determine the conditions for optimum energy extraction, methods for cyclic and continuous recharge, determination of heat transfer characteristics of fractured rock, water quality aspects of the produced geofluids, and experimental data for the mathematical model to describe the boiling flow of steam and water through hydrothermal reservoirs. Preliminary results of these investigations were reported by Ramey et al, 1974.

Figures 11 and 12 show the operating modes of the chimney model (Hunsbedt et al, 1975): the former is the heating mode which establishes the initial reservoir temperature and pressure conditions; the latter is the production mode which simulates the production from a fractured geothermal reservoir by a desired process. Initial experiments with rock sizes of about 2.5 cm diameter show production by in-place boiling through pressure reduction results in heat extraction about 100% greater compared to external flashing of the pressurized water.

Smaller-scale models are also operated to study the fundamental factors of nonisothermal boiling two-phase flow through porous media.

These experiments complement the chimney model experiments in providing data for an entire reservoir consisting of large volume porosity produced through a fracture-stimulated wellbore.

Several experiments are underway to examine the heat transfer properties in stimulate wellbores with fractured porous rocks containing macropore and micropore types of void space. Although heat transfer is likely to occur primarily between the circulating fluid in the macropores, the extent of mass and heat transfer in the micropores may affect the thermal extraction efficiency of specific artificial fracturing and circulation systems. Three experiments, being conducted simultaneously (Kruger and Ramey, 1974), are providing data on mass transfer in porous media with tritiated water (HTO) as a tracer, heat transfer in microfractured rocks with needleprobe thermal conductivity measurements, and surface emanation porosity with natural radon measurements (Stoker and Kruger, 1975), which may indicate the change in emanating power or porosity resulting from stimulation processes.

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TABLE 1

ELECTRIC POWER GENERATING CAPACITY
FROM GEOTHERMAL HEAT, 1973

<u>NATION</u>	<u>CAPACITY (MW)</u>
ITALY	406
UNITED STATES	396
NEW ZEALAND	170
MEXICO	75
JAPAN	33
SOVIET UNION	5.7
ICELAND	3
TOTAL	<u>1089</u>

Table 2

Forecasts and National Goal for Development of U.S. Geothermal Resources

	<u>Pessimistic Forecasts</u>	<u>National Goal 1985</u>	<u>Optimistic Forecasts</u>
Electric Generating Capacity (MW)	2000 - 4000	20,000 - 30,000	182,000 - 400,000
Equivalent in Nuclear Reactors (No. 1000 MWe Units)	2 - 4	20 - 30	182 - 400
Equivalent Consumption of Oil (10^6 bbl/day)	0.07 - 0.14	0.7 - 1	6 - 14

Table 3

**Problem Areas in the Development
of the Geothermal Energy Cycle**

Variability of Geothermal Reservoirs

Location of Subsurface Deposits

Assessment of Geothermal Reservoirs

Extraction Technology

Conversion Technology

Variability in Utilization

Environmental Impact Control

Table 4

Utilization of Geothermal Energy

Electric Power Production

- Direct use of dry steam
- Flashing of hot water to steam
 - Surface flashing
 - In-situ flashing
- Binary and hybrid cycles
- Innovative single-well converters

Direct Use of Thermal Waters

- Agriculture
- Aquiculture
- Space heating
- Industrial processing
- Medical therapy

Byproducts

- Mineral extraction
- Water resources

ENGINEERING CRITERIA FOR THERMAL WATER UTILIZATION

TYPE OF UTILIZATION	TEMP (°C) NOT LESS THAN	DISCHARGE (M ³ /DAY) NOT LESS THAN	DEPTH OF AQUIFER (M) NOT DEEPER THAN	MINERAL CONTENT (G/L) NOT MORE THAN
GENERATION OF ELECTRIC POWER WITH DIRECT STEAM-WATER CYCLE	100	10000	3000	4
GENERATION OF ELECTRIC POWER WITH SECONDARY FLUID CYCLE	70	2500	2500	50
HEAT SUPPLY OF POPULATION CENTERS	70	1000	2500	2(50) [†]
COOLING SUPPLY	70	500	1500	50
HOT-WATER SUPPLY	40	1000	1500	1(50) [†]
GREENHOUSING-HOTHOUSING	40	500	1500	10(50) [†]
HOT-WATER IRRIGATION	25	250	1000	2
WARMING SOIL	25	500	1500	50
MELTING PERMAFROST	25	250	3000	50
SWIMMING POOLS AND BATH FACILITIES	25	250	1000	50

[†] ALLOWABLE MINERAL CONTENT WITH SECONDARY FLUID HEAT EXCHANGERS.

* FROM F. MAKARENKO AND V. KONONOV, (1970).

Table 5

Table 6

Types of Geothermal Power Plants

<u>Heat Source</u>	<u>Generation Mode</u>
Dry Steam	Steam Turbine
Hot Water ($T > 180^{\circ}\text{C}$)	Steam Turbine
Hot Water ($T < 150^{\circ}\text{C}$)	Binary Cycle
Hot Water (Moderate Salinity)	Hybrid Cycle
Hot Brine (Pressurized)	Binary Cycle
Hot Brine (Flashed)	Impact Turbine Helical Screw Expander Bladeless Turbine

Table 7

ENERGY AVAILABLE FROM A HYDROTHERMAL RESERVOIR^{*}
(From Ramey et al, 1973).

COMPONENT	STEAM RESERVOIR			HOT-WATER RESERVOIR		
	MASS (10 ⁶ LB)	AVAILABLE ENERGY (10 ⁶ BTU) (%)		MASS (10 ⁶ LB)	AVAILABLE ENERGY (10 ⁶ BTU) (%)	
AQUIFER ROCK	5.410	233	94.0	5.410	233	69.8
FLUID	0.016	15	6.0	0.534	101	30.2
TOTAL	5.426	248	100	5.944	334	100

^{*} BASED ON A 1 AC-FT RESERVOIR, 25% POROSITY, 500°F AQUIFER TEMPERATURE,
DELIVERY AT 100 PSIA PRESSURE (327.8°F).

Table 8

PRODUCTION FROM A HYDROTHERMAL RESERVOIR*

(From Ramey et al, 1973)

	STEAM RESERVOIR	HOT WATER RESERVOIR
INITIAL FLUID CONTENT (LB)	16,160	533,800
CONTENT AT ABANDONMENT (LB)	1,950	62,300
PRODUCTION		
AS STEAM (LB)	14,210	372,000
AS WATER (LB)	0	99,500
TOTAL (LB)	14,210	471,500
RECOVERY		
AS % INITIAL FLUID MASS	87.9%	88.3%
AS % TOTAL AVAILABLE ENERGY	5.6	99.1

* BASED ON A 1 AC-FT RESERVOIR, 25% POROSITY, 500°F
AQUIFER TEMPERATURE, DELIVERY AT 100 PSIA PRESSURE
(327.8°F), 1000 BTU/LB ENTHALPY.

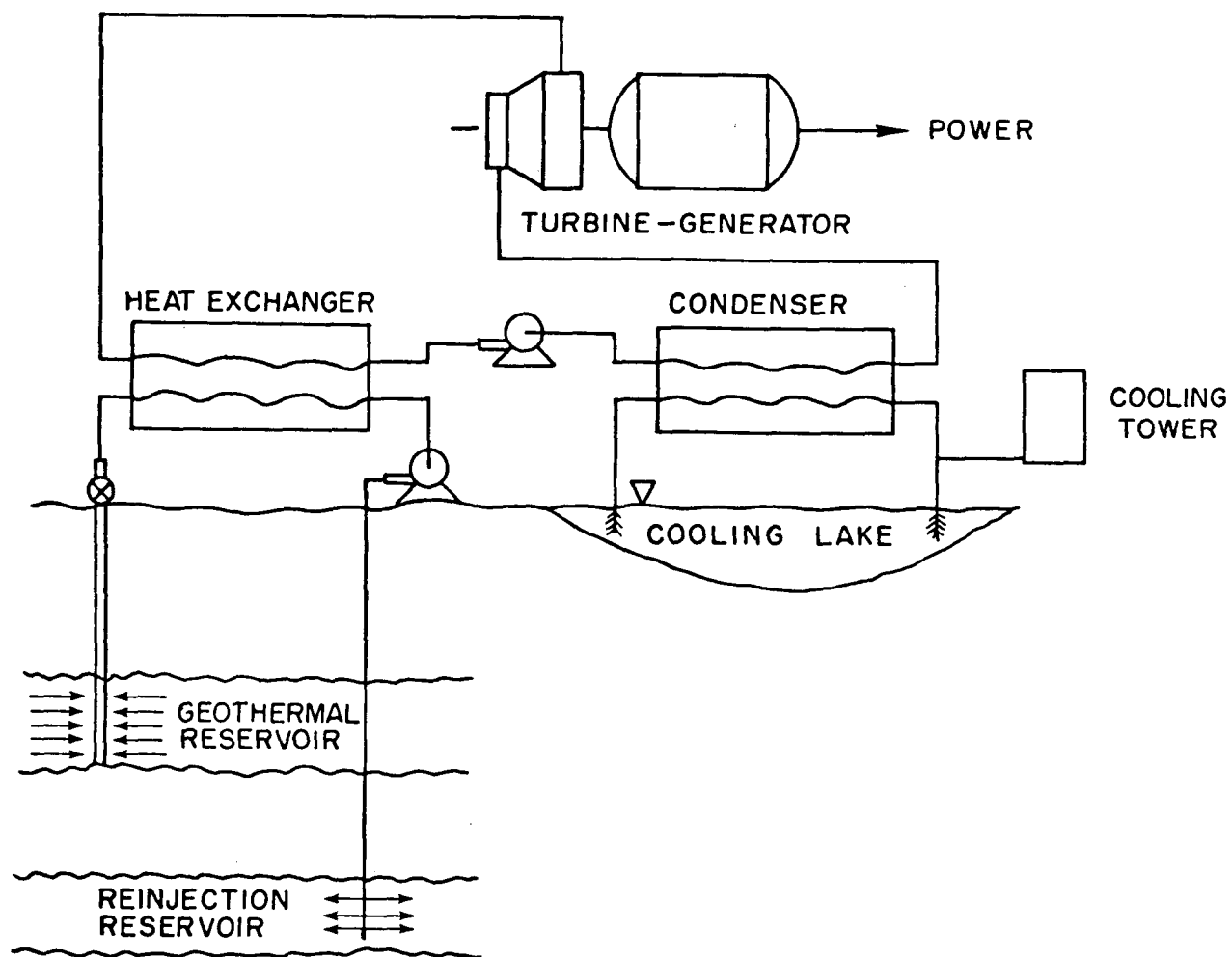


Figure 1. Schematic of a binary-fluid cycle for electric power generation from geothermal fluids.

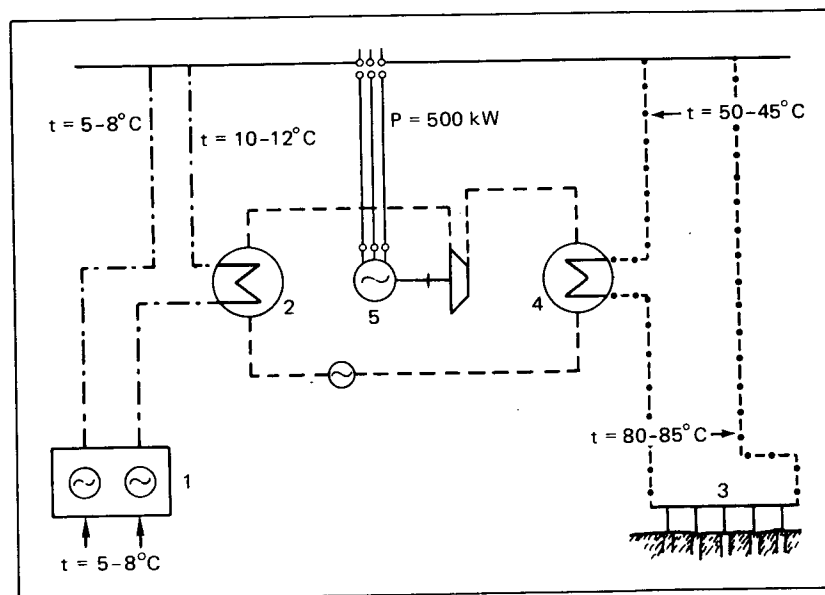


Figure 2. Technological scheme of the geothermal power plant and hot-green-house station. 1. Pumping station for cold water. 2. Condenser. 3. Hot water source. 4. Heat exchanger. 5. Turbo generator. (from Moskvicheva and Popov, 1970)

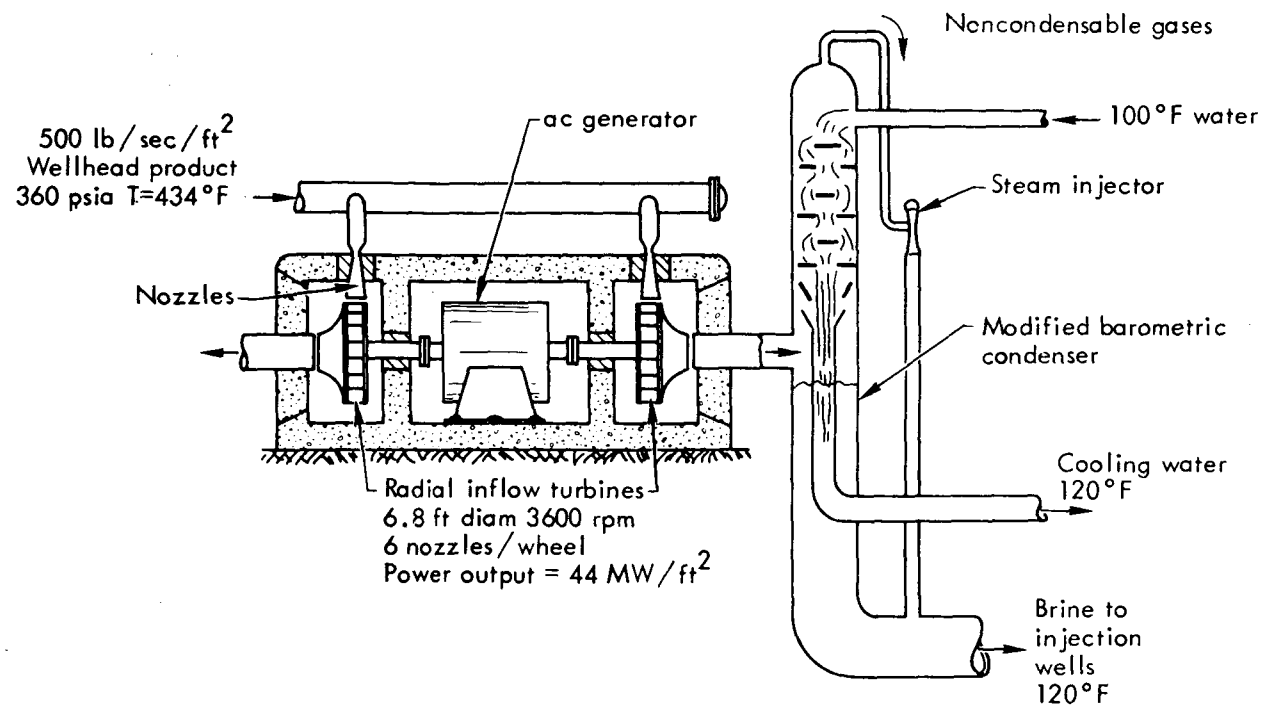
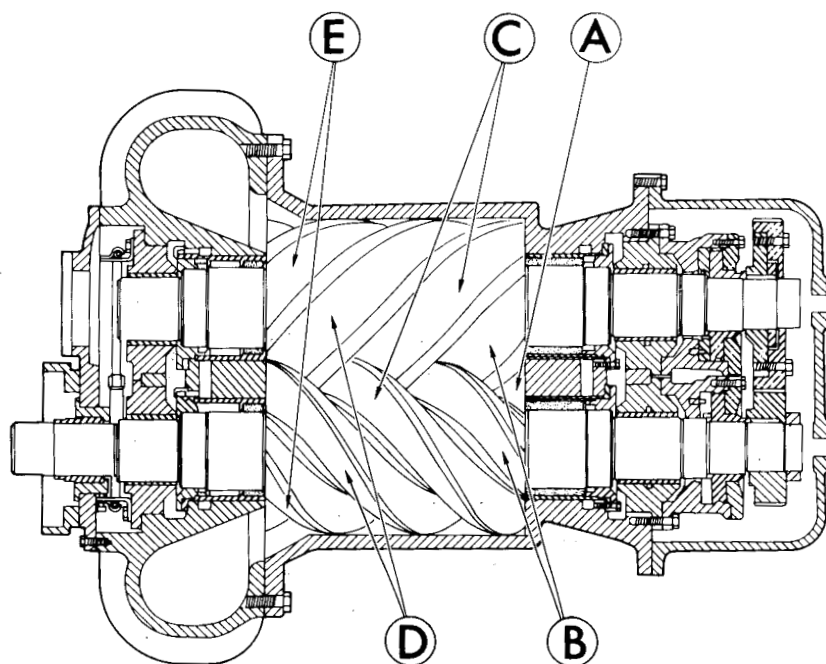
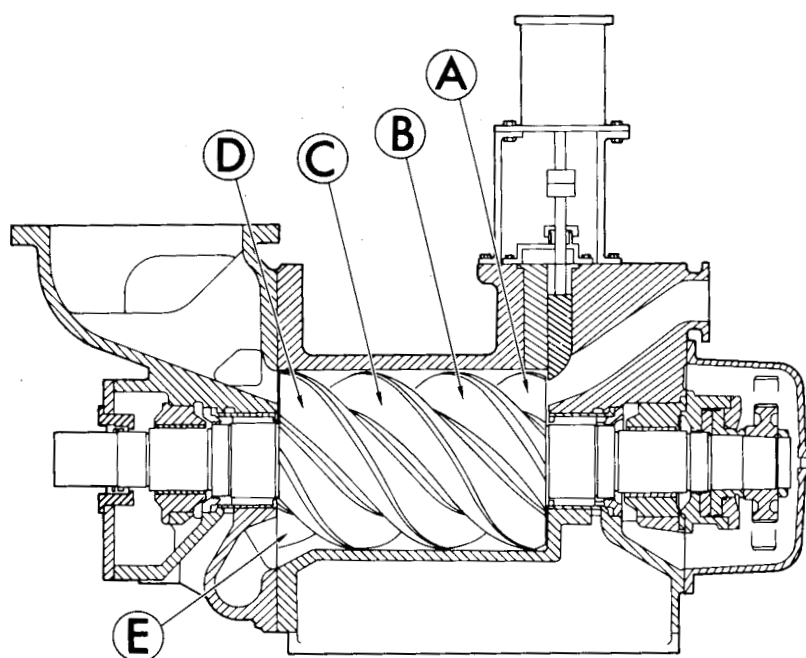


Figure 3. The radial impact turbine concept for conversion of hot brines.
(from Austin, Higgins, and Howard, 1973)

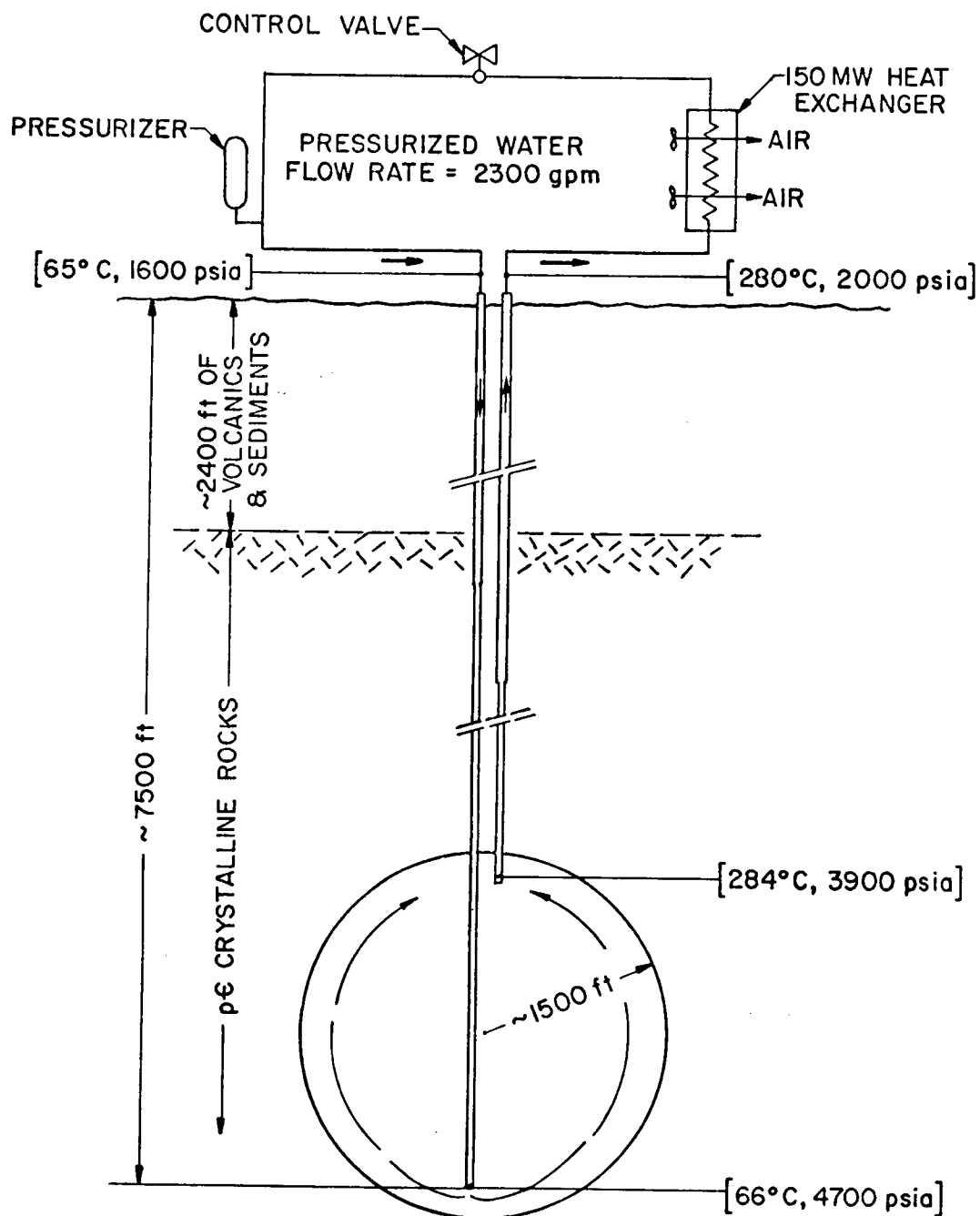


PLAN SECTION VIEW



SIDE SECTION VIEW

Figure 4. Helical rotary screw expander. (from McKay and Sprankle, 1975)



EXPERIMENTAL CONFIGURATION AND OPERATING CONDITIONS

Figure 5. Schematic diagram of the proposed Los Alamos experimental system. (from Brown, Smith, and Potter, LA-DC-72-1157, 1972)

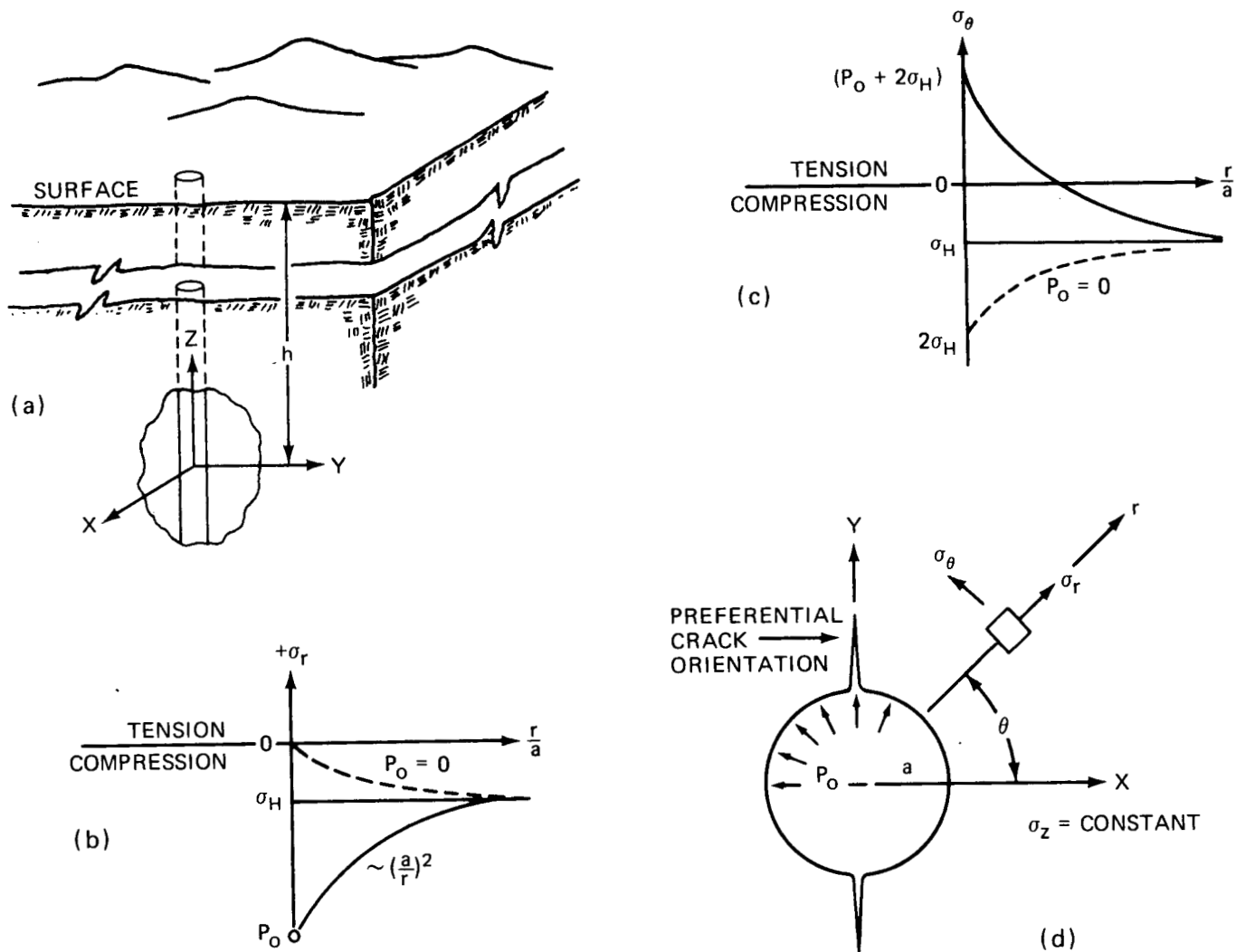
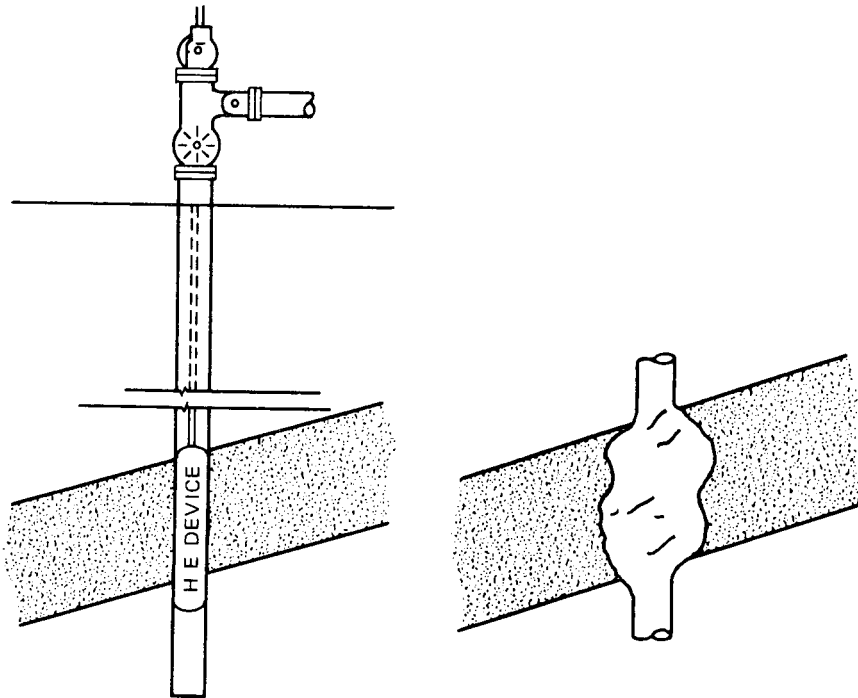


Figure 6. (a) The stress situation around a pressurized deep hole in the earth's crust; (b) the radial stress state in rock around the hole; (c) the tangential stress state; (d) vertical cracks formed by the internal pressure. (from Rowley, 1972)

BORE HOLE ENLARGEMENT (Increased Permeability)

STRESS WAVE



PERFORATION (Shape Charge and Projectiles)

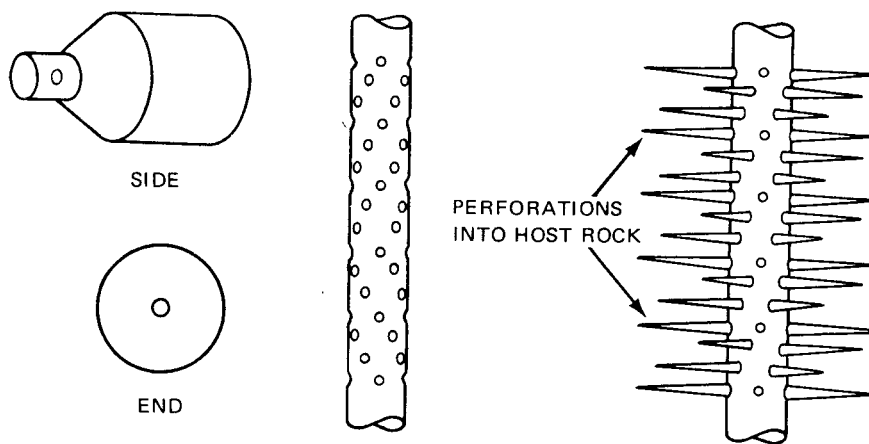


Figure 7. Methods of chemical explosive stimulation.
(from Austin and Leonard, 1973)

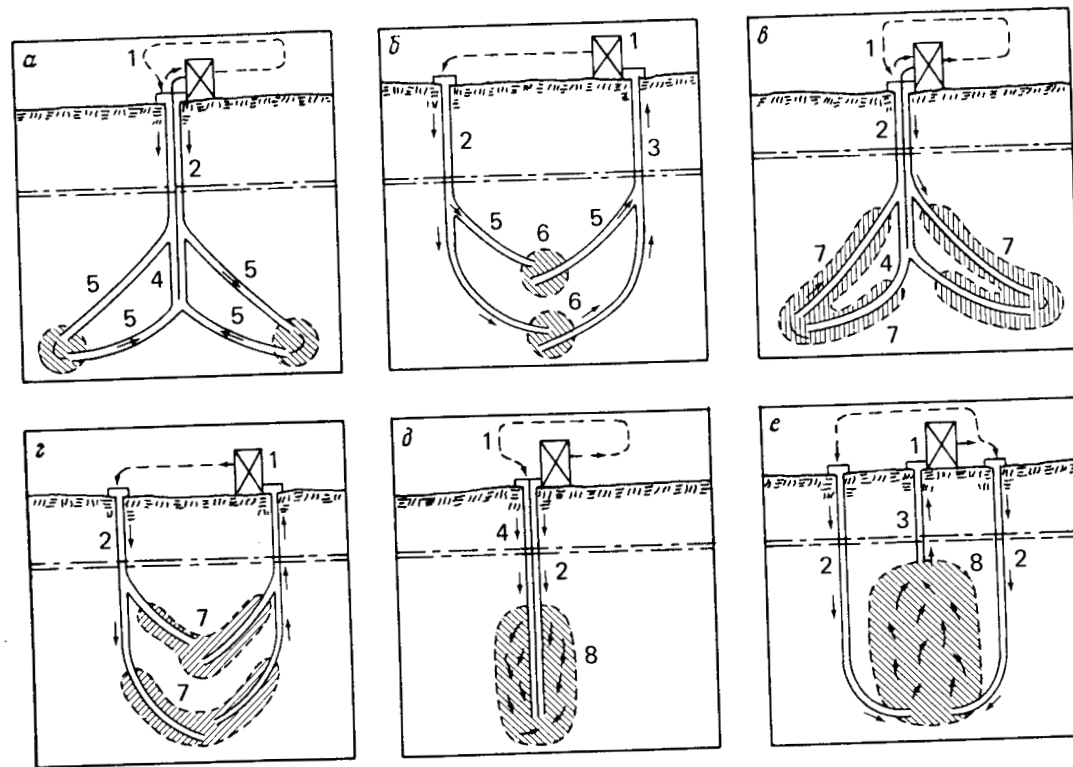


Figure 8. Extraction systems. (from Dyadkin et al., 1973)

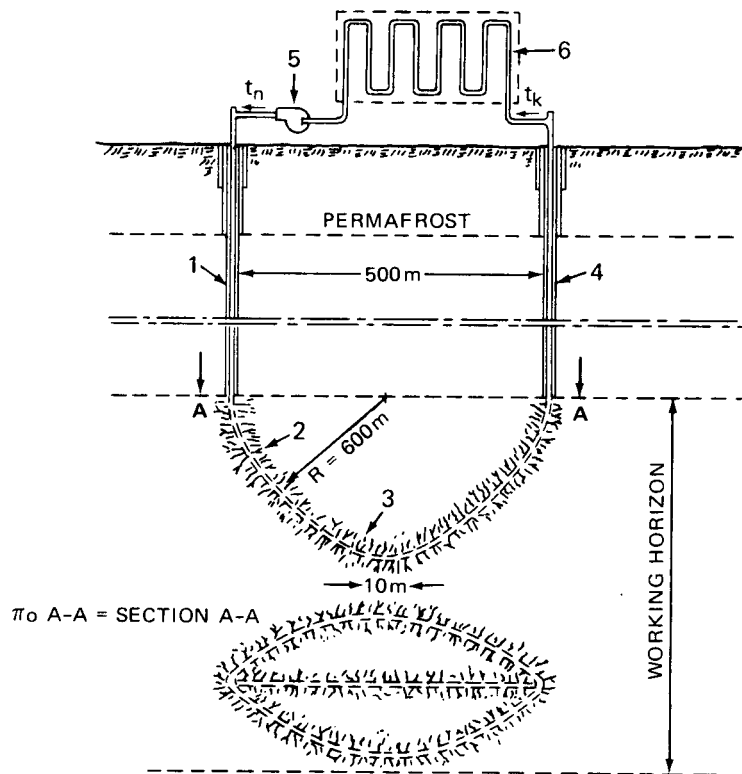


Figure 9. Circulation system with elongated fractures.
(from Dyadkin et al., 1973)

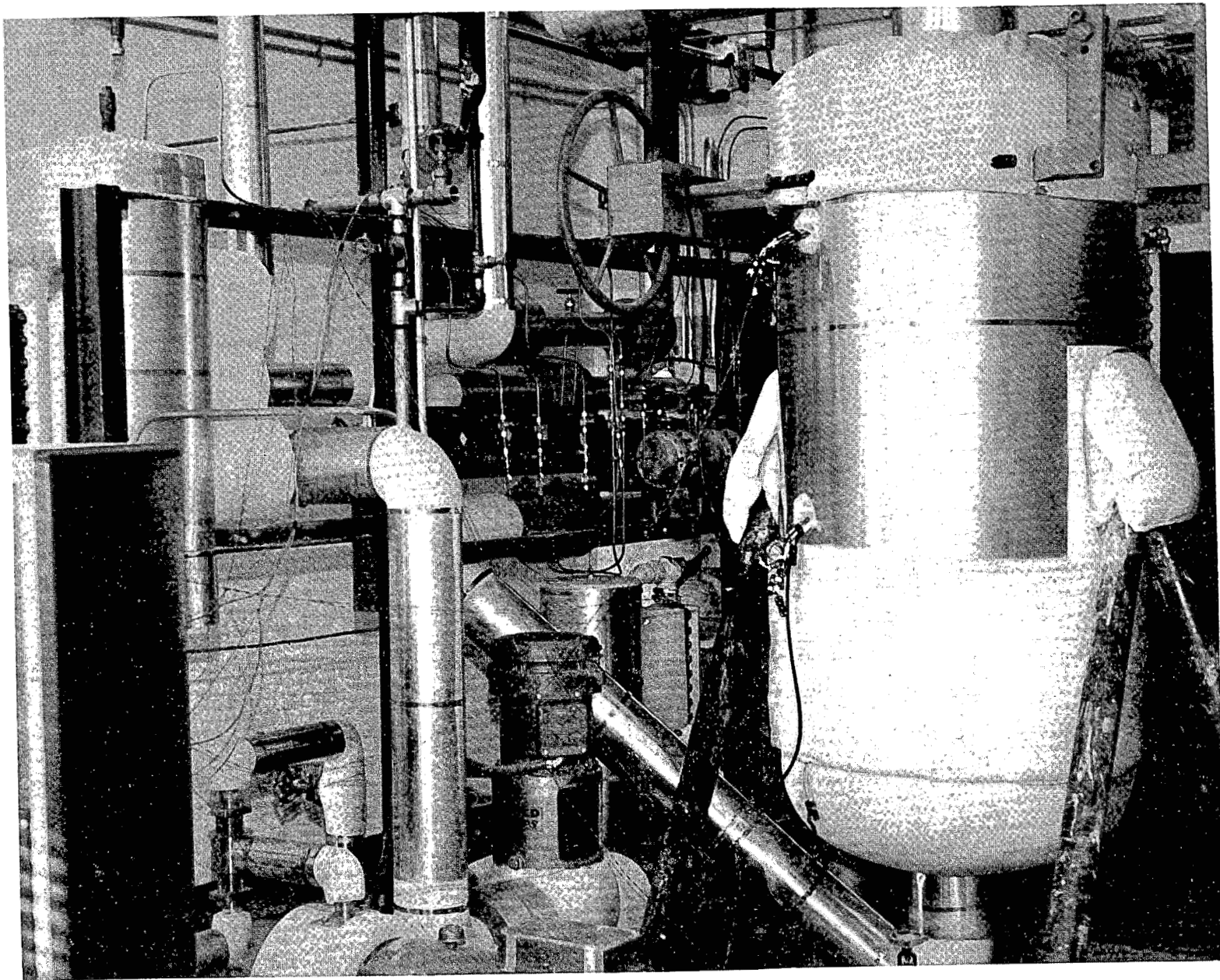


Figure 10. Photograph of chimney model. (from Kruger and Ramey, 1974)

CHIMNEY MODEL Heating Mode

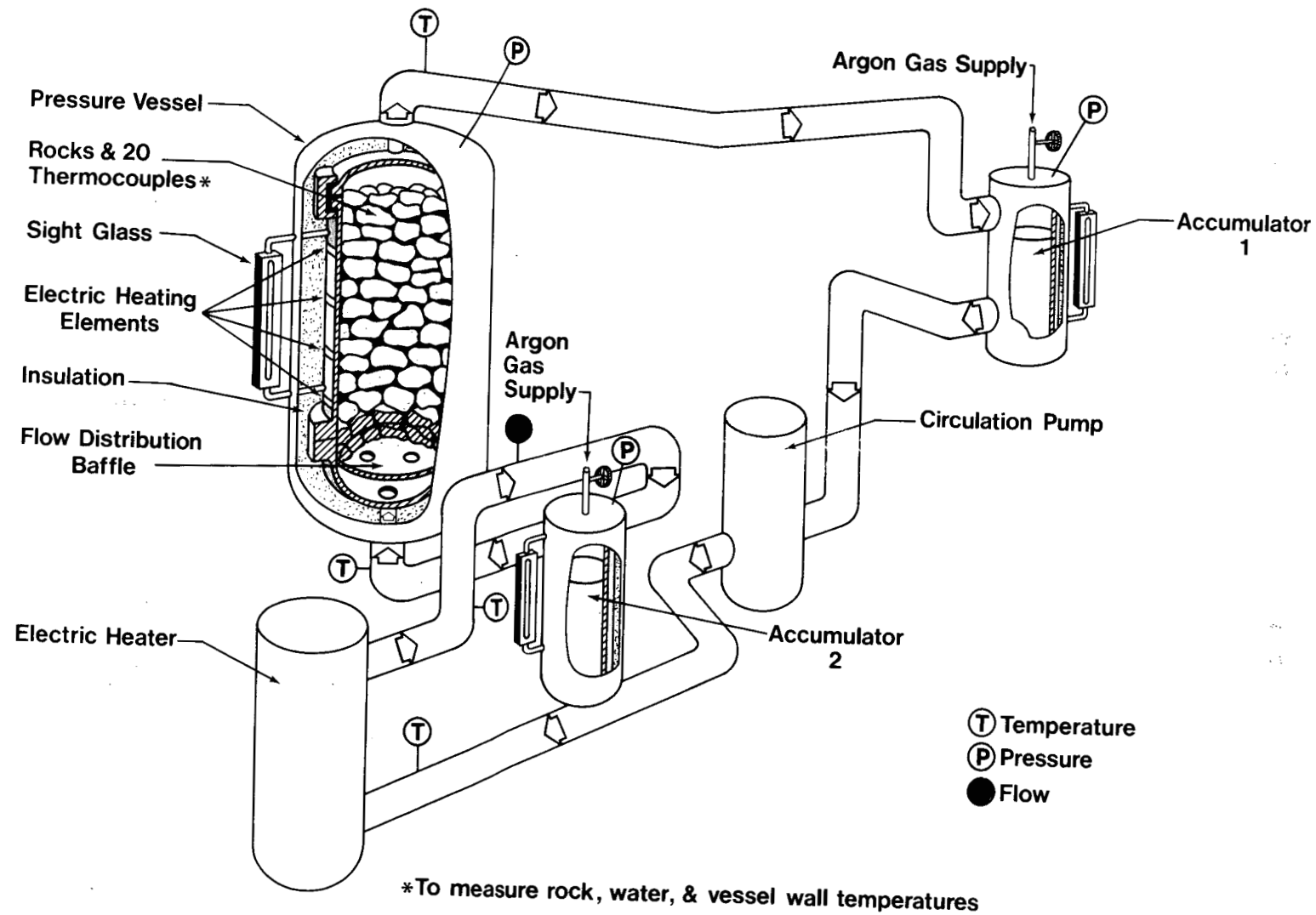


Figure 11. Heating mode operation of the chimney model system. (from Kruger and Ramey, 1974)

CHIMNEY MODEL

Fluid Production Mode

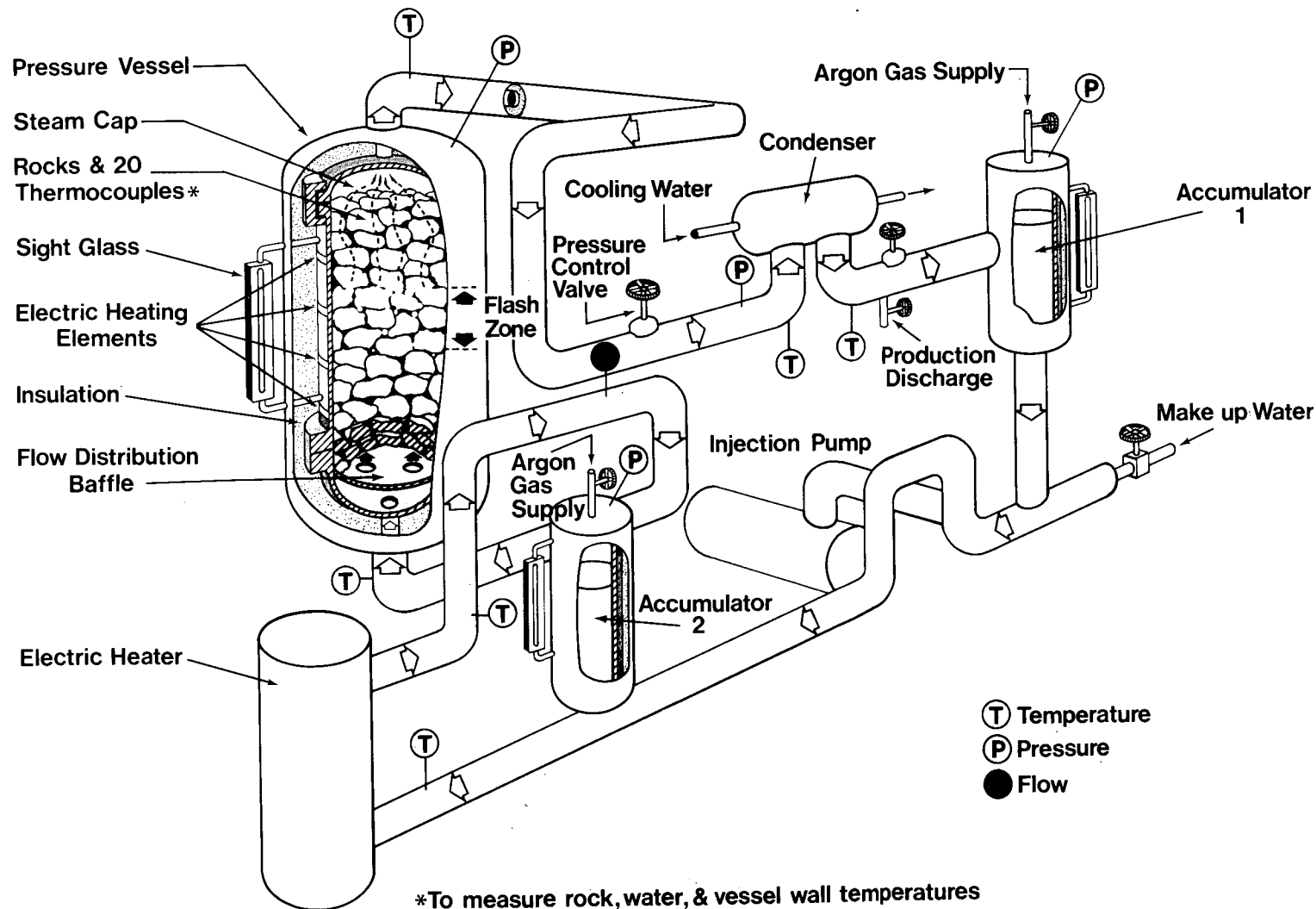


Figure 12. Fluid production mode operation of the chimney model system. (from Kruger and Ramey, 1974)