STIMULATION OF GEOTHERMAL AQUIFERS

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Progress Report No. 1
March, 1973

Grant No. GI-34925

to

Advanced Technology Department
Research Applied to National Needs
National Science Foundation
Washington, D.C.

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INTRODUCTION

Efforts on the research project "Stimulation of Geothermal Aquifers" commenced as an interdisciplinary program at Stanford University during the 1972-1973 academic year at the end of September, 1972. The project has as its goal the research program described in the proposal for the National Science Foundation grant No. GI-34925.

The three major objectives of this program are:

1) Development of experimental and numerical data to evaluate the optimum performance of explosion-stimulated geothermal aquifers.

2) Uevelopment of a geothermal steam reservoir model to evaluate the many thermophysical, hydrodynamic, and chemical parameters involved. The basis of the model will be fluid-energy-volume balances developed by basic reservoir engineering practices. The model will be tested for three potential steam production modes following performance matching of natural geothermal reservoirs. Data from two Plowshare experiments of natural-gas stimulation will be considered.

3) Development of a laboratory model of an explosion-produced chimney to obtain experimental data on the processes of in-place boiling moving flash fronts, and two-phase flow in hot porous media, as well as chemical and radiochemical data for the fluids production.

The project commenced as a joint program between the Civil Engineering

Department of the School of Engineering and the Petroleum Engineering Department of the School of Earth Sciences. In the early period of project design, assistance was solicited from members of other departments in both schools. Personnel now associated with the project include:

Prof. Paul Kruger, Civil Engineering Department, Co-Principal Investigator

Prof. Henry J. Ramey, Jr., Petroleum Engineering Department, Co-Principal Investigator

Prof. William E. Brigham, Petroleum Engineering Department, Faculty Associate

Prof. A. Louis London, Mechanical Engineering Department, Faculty Associate

Mr. Norio Arihara, Petroleum Engineering Department, Graduate Student

Mr. Paul G. Atkinson, Petroleum Engineering Department, Graduate Student

Mr. Alan K. Stoker, Civil Engineering Department, Graduate Student

Mr. Michael B. Tessieri, Civiil Engineering Department, Graduate Student

Because of the long time necessary to construct the experimental facilities associated with the third objective of the program, initial attention was devoted largely to the design of the simulated rubble chimney. In keeping with the commitment to interface this research project with potential users of the results as part of the RANN mission, initial contacts were made with industrial concerns, such as Bechtel

Engineers and Union Oil Company of California, with regard to the design of the rubble chimney model. The design of this facility is included in this Progress Report.

Effort in the first two objectives of the program also commenced with the beginning of the Stanford University 1972-73 academic year. Design of a bench-scale apparatus for measurement of geothermal steam flow characteristics was started. Initial considerations for the development of the project computational models were also undertaken. A study of the general environmental aspects of geothermal well stimulation was initiated. From this has come a general program to study the emanation of natural radon radioactivity from existing geothermal fields, and the water quality aspects of stimulated geothermal fields. The progress achieved during this initial period of the project is reported in this first Progress Report.

THE RUBBLE CHIMNEY MODEL

Design of the Chimney Model

During the current grant period, a considerable effort was expended on the design of an explosion-produced chimney model. The critical items of the model are the simulated-chimney apparatus and the system for heating it to reproduce hydrothermal aquifer conditions.

The model chimney was designed to simulate a large-diameter wellbore in a hydrothermal fluid reservoir resulting from the detonation of a nominal high-energy explosive in the aquifer system. The laboratory model must not only be capable of withstanding the necessary reservoir pressures and temperatures, but it must also have suitable dimensions for scaling to actual situations. The range of desired operating temperatures and pressures to be considered is shown in Figure 1, the data for which are from Cady (1969). Table 1 lists the temperature ranges observed in several geothermal fields around the world. The data suggest a model operating temperature of at least 400°F, with capacity to operate in excess of 500°F. Compressed-liquid reservoirs operate at pressures between 400 to 1200 psia. The model operating pressure should be in this range, with capacity to operate at the higher end of the range.

The shape of the model chimney is obtained from the experience of explosive stimultation of other natural resources, primarily natural gas, as described by Kruger (1966). For low-yield nuclear explosives (*e.g.*, 5 to 50 kt) detonated at containment depths in competent rock media, the

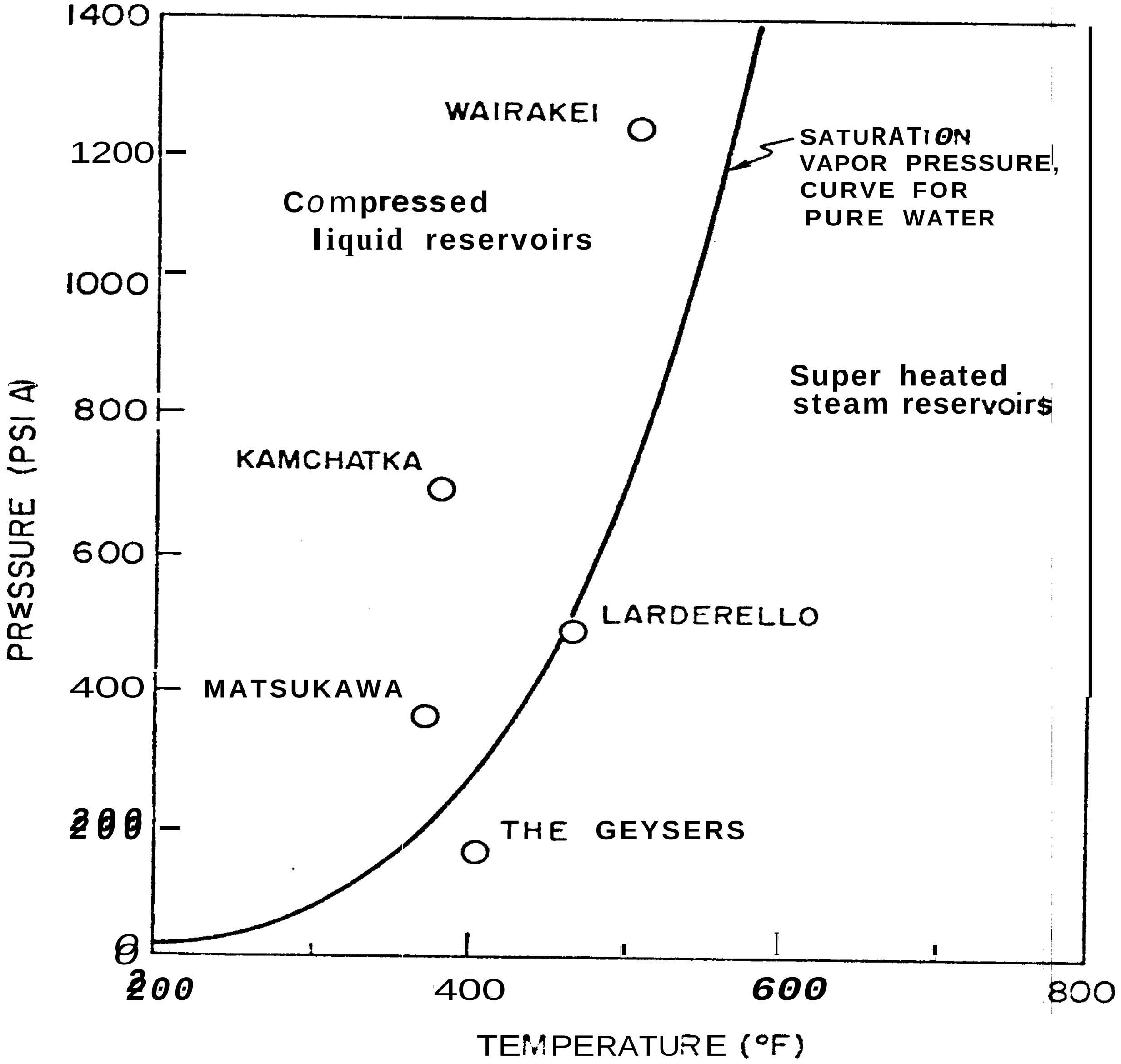


Figure 1. Temperatures and Pressures of Some Major Geothermal Reservoirs (from Cady, 1969)

TABLE 1

TEMPERATURES OF GEOTHERMAL FORMATIONS

Reservoir Location	Approximate Reservoir Temperature (°F)
Matsukawa, Japan	375
Kamchatka, USSR	400
The Geysers, Calif.	410
Larderello, Italy	475
Wairakei, N.Z.	510
Cerro Prieto, Mexico	575+
Salton Sea, Calif.	660

rubble chimney is approximated by a rounded cylinder with relative dimensions given by

$$H = KR \tag{1}$$

where H = height of the chimney

R = radius of the expanded cavity before collapse

K = empirical constant, a function of the formation medium.

Values for K range from 4 to 6, and thus the model chimney is designed as a cylinder with a height to radius ratio of approximately 5 to 1.

An important deviation in the model from an actual rubble chimney is imposed by the need to use an enclosed chamber for the model. In competent rock medium, the rubble chimney is surrounded by the host rock whose fractured extent decreases with the distance away from the axis of the chimney. The fracture radius may be 3 to 4 times the chimney radius, In practice fluid and heat can flow into the chimney from a thickness greater than that of the aquifer alone. In the simulated chimney, heat can flow from the walls of the container, but fluid can enter only from the inlets. The selection of a suitable material was limited in circumventing this deviation.

Several materials were considered, but because of structural problems, steel was chosen as the model material. However, since the volumetric heat capacity (ρc) and the thermal conductivity (k) of steel are greater than the corresponding values for the externally-fractured rock of a rubble chimney, the heat transfer into the rubble rock from the steel walls may present too high a background value for the model. For this case, provision is being made to insert a suitable heat-insulating sleeve inside the model chimney. Consideration was also given to the method of heating the rubble in the chimney to the desired formation temperatures. Calculations were made of the heat transfer by either external heating with conduction into the rubble or a hydrothermal circulation system.

The thickness of steel required for the model chimney depends on the maximum pressure, maximum temperature, and the radius of the cylinder and is given by the Pressure Vessel Codes (1968) of the ASME as

$$p = \frac{S \times t}{R + 0.6T} \tag{2}$$

where p = maximum pressure, psig

S = maximum allowable stress value for a given material and temperature, T, lb/in^2

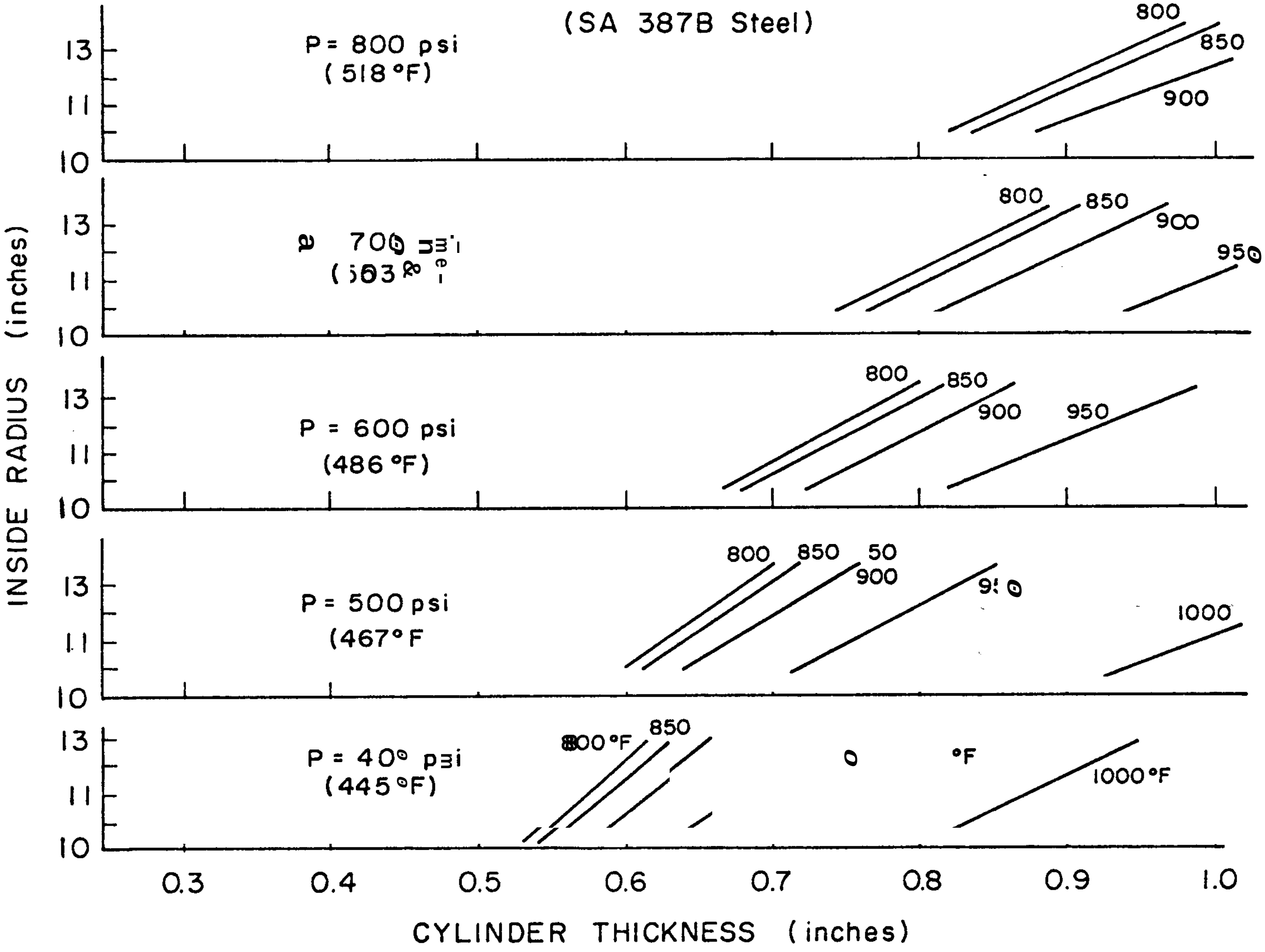
t = cylinder wall thickness, inches

R = inside cylinder radius, inches

T = maximum temperature, °R.

Figure 2 shows the various sets of conditions which fulfill Equation (2). Other factors influence the choice of size in the final design. The total weight of the apparatus should be a minimum to reduce its heat content. The volume should be large enough to reduce wall effects to a negligible level, and outlets for accessibiltty need consideration. For a convenient laboratory model height of 5 ft, equation (1) indicates a model radius of

Figure 2 INSIDE RADIUS VS. CYLINDER THICKNESS AND MAXIMUM TEMPERATURE VESSEL
(SA 387B Steel)



1 ft, and a volume of 15.7 ft^3 which should be sufficient to reduce wall effects to acceptable levels. From the data in Figure 2, a maximum operating temperature of 500°F could be achieved at a maximum pressure of about 800 psia with wall thickness less than 1 inch, making the total weight of the chimney (with flanges), and therefore the total heat content, within acceptable values.

Estimates were made of the power and time of heating requirements to bring chimney rubble to the desired initial reservoir temperature. The use of external resistive heating elements was considered for the case that an insulating sleeve would be required during the production testing period. The heat flow through a cylindrical body is given by Holman (1968) for steady-state conditions as:

$$q = \frac{2\pi L \; AT \; k}{\ln r/r_o} \tag{3}$$

where q = radial heat flow, Btu/hr

L = length, ft

AT = temperature difference, °F

k = thermal conductivity, Btu/hr-ft-°F

r = outside radius, ft

r_o = inside radius, ft.

Values of k are approximately 40 Btu/hr-ft-°F for steel, 1 Btu/hr-ft-°F for rock, and about 0.3 Btu/hr-ft-°F for an insulating material. The heat conduction into the rock is limited by the heat conduction through the insulator. For an initial temperature difference of AT = 740°F, and for a cylinder of $L = 5$ ft and $r/r_o = 1.16$, the heat flow is approximately $q = 47{,}000$ Btu/hr or 13.75 kW. At the end of the heating period, as the temperature difference decreases to about 300°F, the heat flow would decrease to about 5.5 kW. The time to bring the rubble chimney to initial operating temperature is estimated to be about 16 hours.

By contrast, heat transfer to the rubble by circulation of hot water appears to be more efficient. The heat transfer to the rubble is given by

$$q = hA\,(T_w - T_\infty) \tag{4}$$

where h = convective heat transfer coefficient, Btu/hr-ft^2-°F

A = surface area, ft^2

T_w = wall temperature of the rubble, °F

T = temperature of the water, °F

An estimate for heat transfer into the rubble can be made with the assumption that the rubble consists of solid spheres of radius a. For this case, the boundary condition for equation (4) is:

$$q = kA \left.\frac{dT}{dr}\right|_{r=a} \tag{5}$$

where k = thermal conductivity, Btu/hr-ft-°F

dT/dr = thermal gradient, °F/ft.

The solution to the diffusivity equation for spherical heat flow under condition equation (5) is given by Carslaw and Jaeger (1959) as:

$$T(r,t) = \frac{2HAT}{r}\sum_{1}^{\infty} e^{-S\alpha_n^2 t}\left(\frac{a^2\alpha_n^2+(aH-1)^2}{\alpha_n^2[a^2\alpha_n^2+aH(aH-1)]}\right)\sin a\alpha_n \sin ra_n + AT \qquad (6)$$

where $T(r,t)$ = temperature distribution of sphere

$H = \frac{h}{k}$, ratio of convective heat transfer to thermal conductivity

t = time

AT = initial temperature differential between rock and water

$S = \frac{k}{\rho c}$, ratio of thermal conductivity to heat capacity

a = radius of sphere

a_n = solution to aacotaa + aH-1 = 0

Estimates of the heat transfer rates through fractured rock can be obtained with the data of Rabb (1970) on rock size distribution in an underground rubble chimney. Assuming the rubble is spherical in shape with a mean radius of a = 0.25 ft, the value of dT/dr at r=a is obtained from equation (6) as:

$$\left.\frac{dT}{dr}\right|_{r=a} = 2H\Delta T\sum_{1}^{\infty} e^{-S\alpha_n^2 t}\left[\frac{(\alpha_n a)^2+(aH-1)}{\alpha_n^2[(\alpha_n a)^2+aH(aH-1)]} * \sin a\alpha_n\left(\frac{a\alpha_n \cos a\alpha_n - \sin a\alpha_n}{a'}\right)\right] \qquad (7)$$

and the heat flow into the rubble is given by:

$$q = -8k\pi a^2 H\Delta T*\sum_{1}^{w} [\ 3 \qquad (8)$$

where the **summation** term is the infinite series term in equation (7). A value for h is estimated from the! empirical equation of Vliet-Leppert

(Holman, 1968) for flow of water over spheres:

$$h = \frac{k}{d}(1.2 + 0.53\ Re_d^{0.54}) \left(\frac{\mu}{\mu_w}\right)^{0.25} Pr^{0.3} \tag{9}$$

where h = convection heat transfer coefficient, Btu/hr-ft^2-°F

k = thermal conductivity, Btu/hr-ft-°F

d = diameter

μ = viscosity of water

μ_w = viscosity of water at surface

Pr = Prandtl's number = $\frac{Cp\mu}{k}$

Cp = heat capacity of water

Re_d = Reynold's number

To estimate the heat flow into the rock, a set of values was chosen for the parameters of equation (9). The flow rate through the chimney model determines the flow velocity and thus the Reynold's number. A value of 5 gpm was adopted for the flow rate, which yields a Reynold's number of 6300. Other values for the parameters of equation (9) are:

k = 0.356 Btu/ft-hr-°F

d = 0.5 ft

Cp = 1.13 Btu/lb-°F

μ = 0.26 lbm/ft-hr @ 500°F

μ_w = 2.71 lbm/ft-hr @ 60°F

Pr = 0.83

From these values, the convective heat transfer coefficient, h, is ≈

20 Btu/hr-ft^2-$^{\circ}$F, and the corresponding value of H is ≈ 56 ft. The heat flow into one sphere is estimated by equation (8), and the number of equivalent spheres can be estimated for the 5 ft long by 1 ft radius cylinder loaded with rubble having an assumed packing factor of 0.60 as:

$$\text{No. spheres} = \frac{\text{vol. cylinder} \times 0.60}{\text{vol. sphere}} = 144$$

The total heat transfer is then 144 q. Figure 3 shows the total heat flow as a function of the circulation heating time calculated by equation (8). The data indicate that the rubble would be able to accept heat at a rate of at least 30 kW up to the point where the rubble heat capacity is 80% filled. It is therefore estimated that the system would come to initial operating temperature in about 6 hours.

Figures 4 A and B present the design of the simulated chimney system. The specifications of the model include:

Maximum operating temperature	500°F
Maximum operating pressure	800 psia
Inside radius of cylinder	12 in
Inside height of chimney	∿5 ft
Wall thickness	<1 in
Heater, circulating	∿30 kW
Pump capacity	5 gpm

The pressure vessel has been ordered and the major hardware items are being obtained.

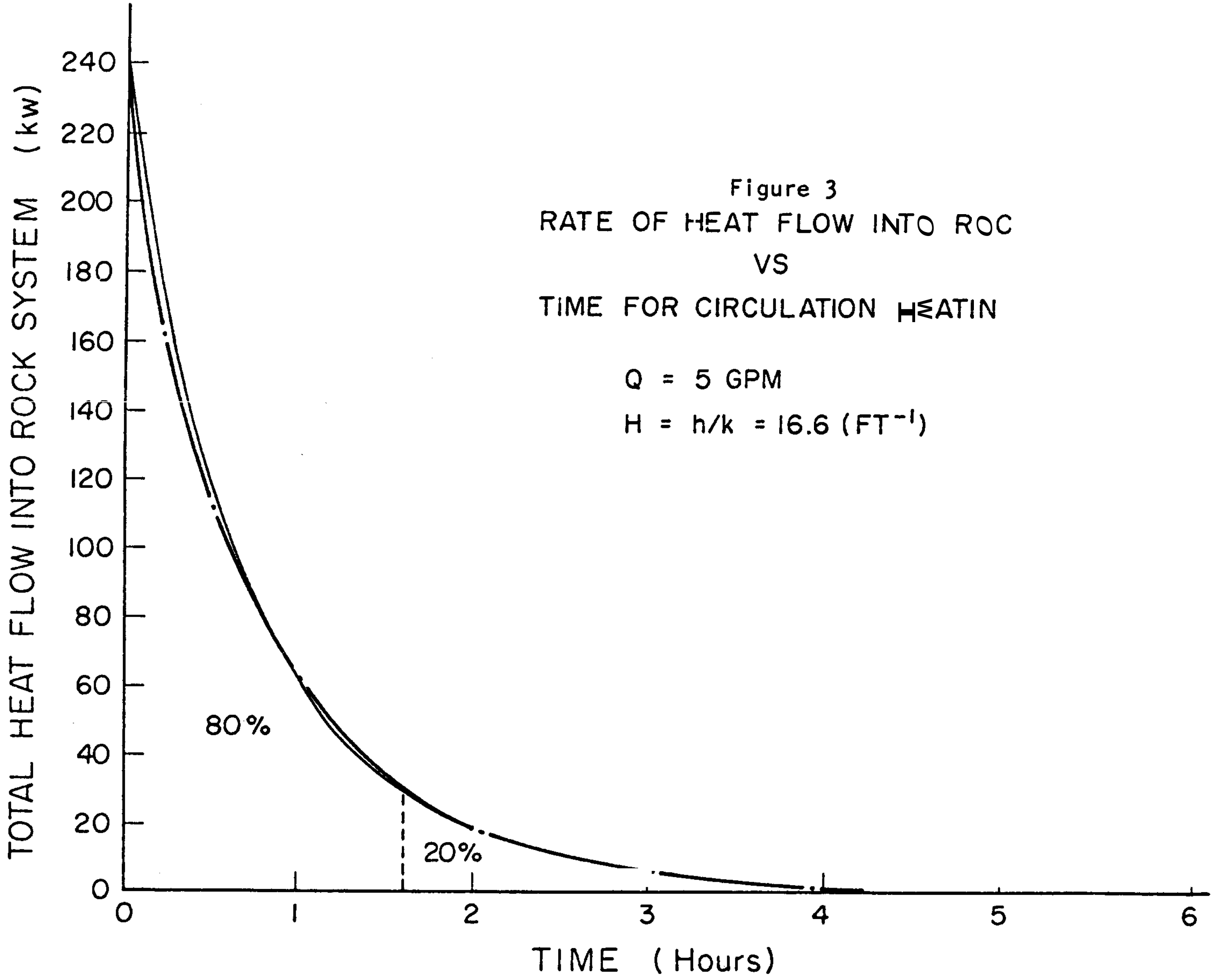


Figure 3
RATE OF HEAT FLOW INTO ROC
VS
TIME FOR CIRCULATION HEATIN

$Q = 5$ GPM
$H = h/k = 16.6\ (FT^{-1})$

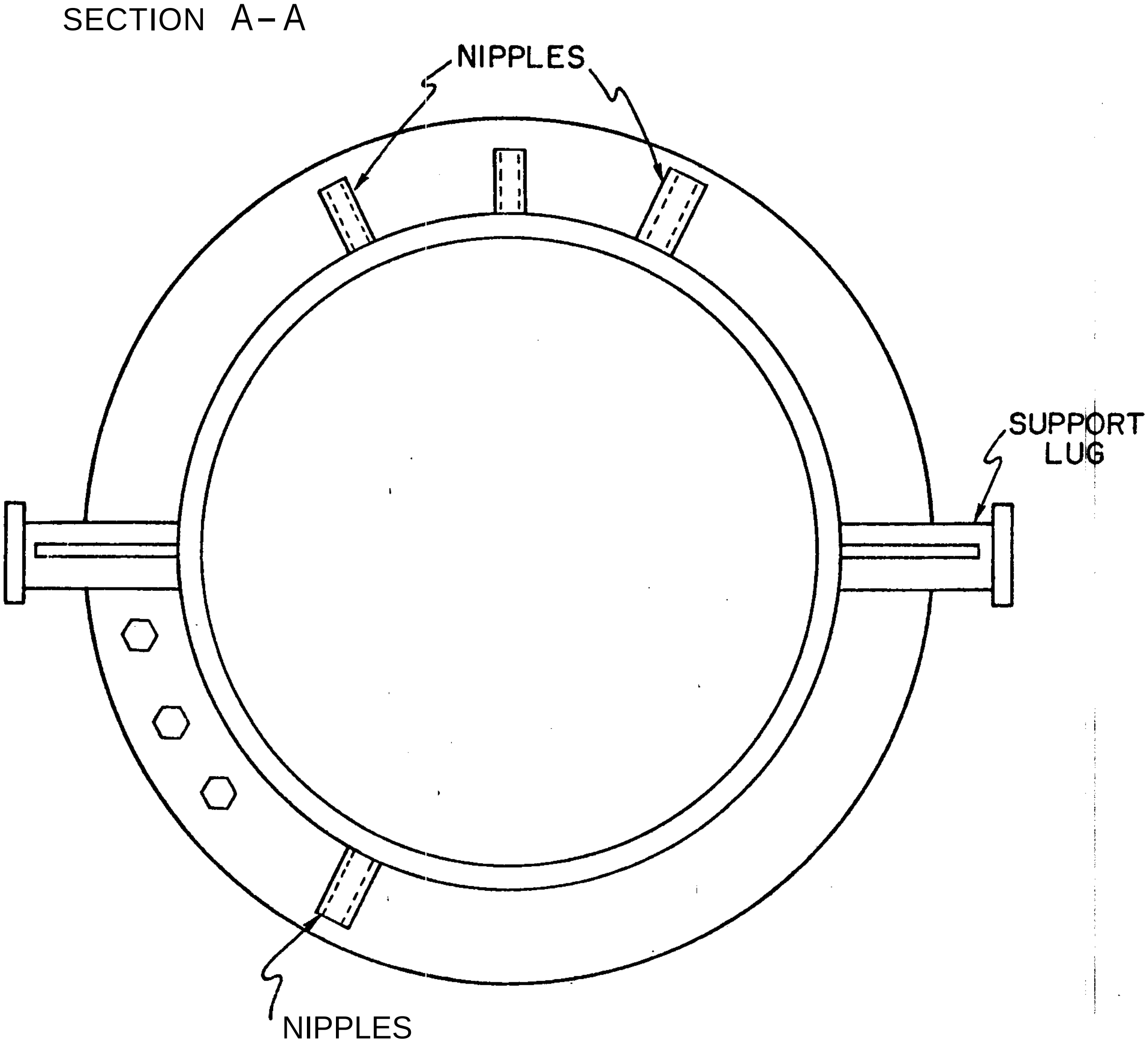


Figure 4A. PRESSURE VESSEL TOP VIEW

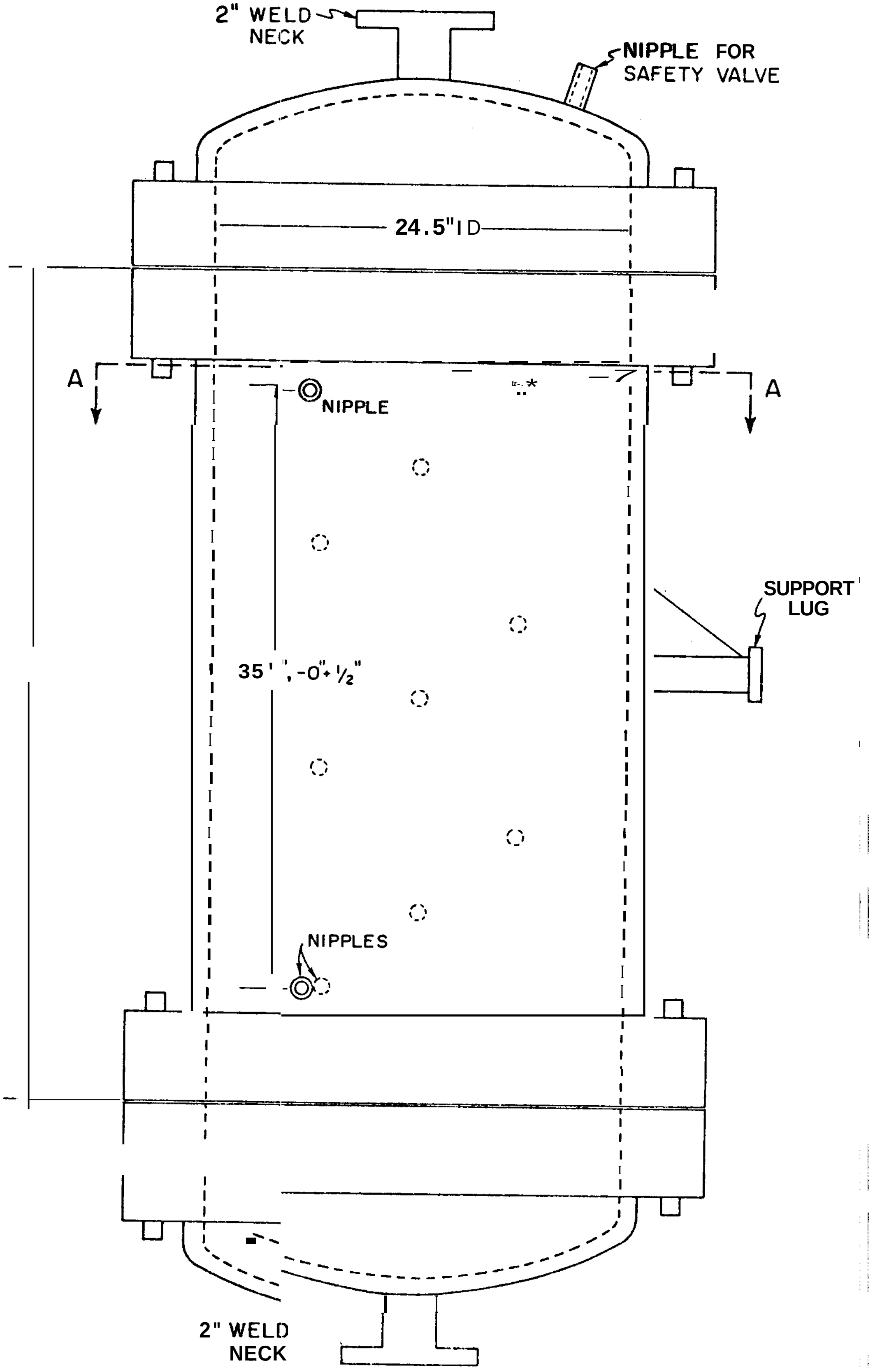


Figure 46. PRESSURE VESSEL SIDE VIEW

Experiments in the Rubble Chimney Model

It has been noted in the section on the design of the rubble chimney model that one of the features of the model that requires calibration is the wall effects of the steel vessel. The effects result from the potentially large heat transfer from the vessel walls to the fluid during periods of production testing.

Calibration experiments are being designed for early operation of the rubble chimney model to determine the extent to which the heat transfer from the steel vessel can be eliminated or determined for background subtraction. Several approaches are being evaluated. One possible method is to bring the chimney to initial pressure-temperature conditions in the absence of porous media, and produce the heat from the system by pressure reduction. The fraction of heat content of the vessel which can be transferred to the fluid is time dependent and can be compared to the total heat content of the water. The experiment can be run over a range of useful production rates to determine the time properties of the heat transfer from the steel. The value of heat transfer from the vessel as a function of production rate and time can be used in two ways: 1) to be subtracted as a background value for succeeding production tests with rubble media, and 2) to simulate heat flow from the surrounding rock media in an actual well bore.

Upon completion of the vessel heat transfer calibration tests, the heat transfer from the test rock media can be measured with a set of similar experiments. In these tests, the production rate can be determined as a function of pressure reduction and time. The range of production rates can be determined to optimize: the heat transfer from the rock. Over the useful range of production testing, the pressure-time history will be examined in terms of the mass, and enthalpy production rates. These calibration tests will be performed for each of the aquifer rocks to be examined in this program. Likely candidates are unconsolidated sands, sandstones, and explosion fractured hard rocks, e.g., Piledriver chimney rock from the Nevada Test Site.

Upon completion of calibration testing of each rubble material, production testing will be carried out for at least three potential production modes. The water level gauge of the rubble chimney vessel can be calibrated to measure the velocity of a receding flash front. Control of the production rate can be maintained by aquifer fluid replenishment and by heating/cooling of the vessel to maintain the desired pressure-temperature conditions. Under a range of these conditions, the receding flash front velocity can be determined and examined in relation to the mass-energy production rate and the fraction of heat removable from the chimney rock. A second set of such experiments can be used to fix the production-time history and determine the recharge conditions required to maintain a given velocity of the receding flash front. Conversely, the ability to maintain a stationary flash front by either regulation of the recharge or depletion of the production with time can be evaluated. Finally the concept of cyclic production and recharge can be investigated with measurements of the production-time history with no recharge over a half-cycle followed by half-cycle of mass-heat restoration by recharge.

A second set of experiments can be run to determine the heat effects on the hydrothermal aquifer as a result of recharge. In these experiments the produced fluid can be condensed under various field operation conditions and recycled through a model porous media heat source prior to re-entry to the rubble chimney. The results of this one-dimensional experiment can be related analytically to behavior of a real hydrothermal system with one or more recharge wells.

All of these empirical studies can be examined in relation to principles of heat transfer by comparison with a numerical model being developed under the program. After calibration of the chimney model is well established, parameter studies for the basin model constants can be undertaken. These data can be used to verify the pressure-temperature conditions and the fluid and energy production-time history generated by the numerical model.

COMPUTER MODELING

A major objective of the project is the development of a computational means for modeling the behavior of actual systems. The model will be based upon a mathematical description of the system using basic principles and valid physical laws. One possible system configuration discussed in the project proposal is that of an explosion-fractured chimney intersecting a hydrothermal aquifer.

There are three main energy transfer processes which must be considered to simulate the extraction of geothermal energy from such a system. Briefly, they are:

1) The retreat of a flashing front into the chimney. As the fluid boils, it could be expected to obtain much of its latent heat of vaporization from the rock matrix, and clearly the manner in which the front recedes will affect energy extraction.

2) The rate at which the rock matrix gives up its thermal energy in response to temperature changes of the fluid. These changes may be associated either with the flashing of water to steam, or with the injection of a cooler fluid into the aquifer. Since much of the thermal energy contained in a hydrothermal system is in the rock matrix as sensible heat, the rate at which this energy can be extracted from the rock is of concern.

3) Heat losses to the surrounding environment from geothermal fluids

in transit. Wellbore and surface equipment heat losses may reduce the available energy.

These energy transfer processes are not unique to the system configuration just indicated. Their effectiveness as energy transfer mechanisms must be important to the success or failure of energy exploitation of most hydrothermal system configurations. As a result of this observation, initial efforts will be directed towards modeling and studying the thermal and fluid dynamics behavior of simple hydrothermal systems which include the first two effects indicated. Modeling of the third effect, wellbore heat losses, will not be a problem because methods to account for these are available (Ramey, 1962, 1964).

Modeling of the first two types of behavior does not seem to have been done before.* Therefore, even though the computational model to be developed will be based upon valid physical laws and principles, it will be expedient to confirm this approach by physical modeling. Another main objective of physical experimentation will be to determine the effects of the presence of dissolved solids on geothermal fluid production. Examples of such effects are the plugging of the formation due to precipitation (not included in the initial modeling efforts), and potential health aod environmental hazards. These aspects are discussed in a later section.

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* An exception is the existence of a hydrothermal model developed by the staff at Los Alamos Scientific Laboratories. A report of the efforts by F. Harlow and W. Pracht (1972) predicts the coupled effects of liquid-phase fluid flow, heat transport, and rock fracture in a hot, impermeable zone tapped by a dry well.

Interaction of numerical modeling efforts with the physical modeling efforts will be necessary.

Program for the Numerical Modeling

Within the three year program oulined in the main proposal, it seems that during the first year the basic modeling and verification should be mostly completed. During the second year, further development of the mathematical model and computational techniques should continue, modeling more complicated situations. Experimental verification of the more sophisticated arid complicated systems should continue. By the end of the second year, evaluation of the physical performance of the different production modes should be well under way. Attempts to develop the scheme of technical and economical evaluation should begin early, such that they can be! applied to the first physically realistic results generated. In this manner alternate methods of energy exploitation may be suggested from physical, numerical, technical and economic data. The economic evaluation scheme could also be developed more thoroughly by using it as soon as possible.

Basic Modeling Concepts---In addition to the three energy transfer processes mentioned, it will be necessary to model the fluid flow in the system. Such phenomena as fluid expansion, interphase mass transfer, gravity drainage or segregation, and fluids influx must be incorporated into the model. Under some system configurations and production modes, some of these effects may become negligible. But we should at least be able to evaluate the potential influence on system behavior.

A general model which incorporates all of these fluid effects becomes quite complicated. In order to make the initial approach to the problem manageable, it will be convenient to consider first a simple model, such as the behavior of a linear horizontal system which is closed at one end. Thus, the initial effort will incorporate the two main energy transfer processes in a porous or fractured system, as well as the effects of fluid expansion and interphase mass transfer. Actual physical verification of such a linear model could be conveniently carried out using bench experimental apparatus.

One linear physical system that we might want to simulate would be vertical fluid flow out the top of an explosion chimney. In this case gravity may have a significant effect on system behavior. This could be included in the flow potential model of Hubbert (1956).

Other geometries, such as a radial system for a single well in a large hydrothermal aquifer, or a Cartesian system for a multiple-well field, could also be developed. We may want to include the effects of fluid influx at outer boundaries, because this will be a major cause of energy transfer for same configurations and modes of production. Mass influx at outer boundaries can be simulated by using aquifer response functions, as is discussed in the project proposal. The effect of cold water influx on heat extraction from the hot fractured rock can be considered by using an appropriate temperature response function for the rocks.

The general approach to modeling that will be taken will be to write a series of equations describing mass and energy balances, and including statements of transport laws, equations of state, thermodynamic phase equilibrium, and other effects. This series of equations will then be solved numerically for temperature, pressure, and fluid content distributions as functions of time. Although finite difference numerical schemes for solving systems of partial differential equations have been used extensively, it may prove advantageous to use the finite element approach.

In addition to developing a numerical scheme for predicting the two-phase single-component flow of a fluid (water) in a fractured rock or porous medium system, we will also attempt to develop alternative methods of solution. Through the use of simplifying assumptions, and techniques used in other fields, it is hoped that a convenient scheme can be found. Even though such a scheme may only remain valid under restrictive conditions, it still may prove to be useful.

Initial Modeling Efforts--Initial efforts will be directed towards solving the transient linear horizontal behavior of an initially compressed hot liquid in fractured rock or porous media. One end of the system will be considered closed, the other will be specified at constant producing pressure or possible constant mass flowrate. The most reasonable boundary condition along the physical system (defined as fluid plus local rock) is that of an adiabatic surface. Thus, conceptually, heat from local rocks will be included, whereas the effect of sensible heat from rocks near the flow regime will not be included. In practice, this may be unnecessary because both effects could be included in a rock source term $\dot{Q}_{rock}(x,t)$.

Fundamental considerations lead to the mass balance:

$$\frac{\partial}{\partial x}\left[\left(\frac{\rho_o e^{c(p-p_o)} K_L(S_L)}{\mu_L(T)} + \frac{pM\ K_g(S_L)}{z(p,T)RT\ \mu_g(p,T)}\right)\frac{\partial p}{\partial x}\right] - \phi\frac{\partial}{\partial t}\left[\frac{pM}{z(p,T)RT}\right.$$

$$\left. + S_L\left(\rho_o e^{c(p-p_o)} - \frac{pM}{z(p,T)RT}\right)\right] = 0 \qquad (10)$$

and the appropriate heat balance:

$$\frac{\partial}{\partial x}\left[\left(\frac{\rho_o e^{c(p-p_o)} K_L(S_L)h_L(p,T)}{\mu_L(T)} + \frac{pM\ K_g(S_L)h_g(p,T)}{z(p,T)RT\mu_g(p,T)}\right)\frac{\partial p}{\partial x} + k\frac{\partial T}{\partial x}\right] - \dot{Q}_{rock}(x,t)$$

$$- \phi\frac{\partial}{\partial t}\left[\frac{pMh_g(p,T)}{z(p,T)RT} + S_L\left(\rho_o e^{c(p-p_o)} H_L(p,T) - \frac{pMh_g(p,T)}{z(p,T)RT}\right)\right] = 0 \qquad (11)$$

Symbols are defined in the Nomenclature section.

More simply:

$$\frac{\partial}{\partial x}\ [K_1(p,T,S_L)\frac{\partial p}{\partial x}] = \phi\frac{\partial}{\partial t}[K_2(p,T,S_L)] \qquad (12)$$

and:

$$\frac{\partial}{\partial x}\ [K_3(p,T,S_L)\frac{\partial p}{\partial x} + k\frac{\partial T}{\partial x}] - \dot{Q}_{rock}(x,t) = \phi\frac{\partial}{\partial t}[K_4(p,T,S_L)] \qquad (13)$$

where K_1, K_2, K_3, and K_4 are known functions of P, T, and S_L.

Although there appear to be three unknowns $p(x,t)$, $T(x,t)$, and $S_L(x,t)$, when two phases are present pressure and temperature are dependent as defined by a vapor pressure curve for the system (which may depend on S_L). Thus we have a system of two equations in two unknowns, and from a mathematical point of view a solution should be determinable. From a practical point of view, in order to obtain a solution we will have to select the correct S_L for a given time by trial and error, such that the two equations give the same pressure distribution as a solution. Alternatively we might assume some initial $p(x)$ (or $S_L(x)$), and then substitute the resulting $S_L(x)$ solution into the second equation. The resulting $p(x)$ solution could be placed back into the first equation, and the process continued until the two $p(x)$ and $S_L(x)$ solutions do not change.

For isothermal liquid flow only, (‘rock = 0) the two equations become identical and reduce to the flow equation for a slightly compressible liquid in porous media:

$$\frac{\partial^2 p}{\partial x^2} = \frac{\phi \mu c}{k} \frac{\partial p}{\partial t} \qquad (14)$$

Because of the mathematical similarity of the flow equations for isothermal single-phase liquid flow, and two-phase flow, the development of a flashing front from compressed liquid can be simulated. Initial efforts will be in this direction.

Nonisothermal liquid flow may be described by the mass equation:

$$\frac{\partial}{\partial x}\left[\frac{\rho_o e^{c(p-p_o)} K_L}{\mu_L}\frac{\partial p}{\partial x}\right] - \phi\frac{\partial}{\partial t}\left[\rho_o e^{c(p-p_o)}\right] = 0 \tag{15}$$

and the heat balance:

$$\frac{\partial}{\partial x}\left[\frac{\rho_o e^{c(p-p_o)} h_L(p,T)}{\mu_L(T)} K_L \frac{\partial p}{\partial x} + k\frac{\partial T}{\partial x}\right] - \dot{Q}_{rock}(x,t)$$

$$- \phi\frac{\partial}{\partial t}\left[\rho_o e^{c(p-p_o)} h_L(p,t)\right] = 0 \tag{16}$$

These equations do not include the effect of temperature on liquid density, although it will be necessary to do so later. Whatever mathematical form more accurate representation of compressed nonisothermal liquid flow takes, it should be noted that pressure and temperature will be independent variables. The numerical approach for solving these equations will be similar to that used for equations 10 and 11. Because of different sets of independent variables for the two systems equations 10 and 11, and 15 and 16, it will not be convenient to simulate flashing from nonisothermal liquid flow. For this reason, initially it will not be attempted. Because one of the major energy extraction processes is caused by the injection of cooler water causing nonisothermal flow, it will be necessary to study equations 15 and 16.

For isothermal ideal gas flow only, equations 10 and 11 reduce to an equation commonly encountered in natural gas engineering:

$$\frac{\partial^2 p^2}{\partial x^2} = \frac{\phi\mu}{kp}\frac{\partial p^2}{\partial t} \quad (\dot{Q}_{rock}=0,\ z=1) \tag{17}$$

For nonisothermal real gas flow, two equations in two unknowns, p(x,t), and T(x,t) result:

$$\frac{\partial}{\partial x}\left(\frac{K_{st}}{\mu_{st}}\frac{p}{ZT}\right)\frac{\partial p}{\partial x} - \phi\frac{\partial}{\partial t}\left\{\frac{p}{ZT}\right\} = 0 \tag{18}$$

and

$$\frac{\partial}{\partial x}\left(\frac{MK_{st}h_{st}(p,T)}{zRT\mu_{st}}\, p\frac{\partial p}{\partial x} + k\frac{\partial T}{\partial x}\right) - \dot{Q}_{rock} - \frac{\partial}{\partial t}\left(\frac{pM}{zRT}\, h_{st}(p,T)\right) = 0 \tag{19}$$

If a dry steam zone developed adjacent to a flashing zone, then cooler dry steam from the cooling boiling zone would be entering the gas flow regime. As a result of this cooler gas influx, the assumption of isothermal gas flow would not be correct, and equations 18 and 19 should be used to describe behavior in a developing dry steam zone.

Nonlinear Coefficients in the Basic Equations--Most of the nonlinear coefficients are reasonably well-known thermodynamic and physical property functions of pressure and temperature. Two of these terms deserve further discussion.

The first is the permeability of the medium to both liquid and gas (k_l, K_g). In the case of simulating flow behavior in fractured rock, it is assumed that Darcy's Law is applicable, and that suitable permeability relationships for such systems are available. It may be desirable in some cases to use a rate equation appropriate for non-Darcy flow. This would happen if scaled realistic model conditions result in flowrates high enough to cause "turbulent" flow.

K_l and K_g are listed in the first equation as functions of S_L only. It may be desirable to include recent experimental results which include an important effect of temperature on permeability (Poston, 1970; Weinbrandt, 1972).

One of the most significant terms in the main equations is the term $\dot{Q}_{rock}(x,t)$. This term is included to describe heat added to the fluid from the rock matrix as the fluid and rock surface cool. For a porous formation, it can be assumed that the average temperature of the rock falls with fluid temperature, and $\dot{Q}_{rock}$ is equal to the sensible heat released. For a rubble chimney containing a large range of fractured rock sizes, this assumption is not suitable. It will be necessary to consider the temperature difference between the fluids and rock. Physical experiments with the chimney model will provide data for computer matching, and quite likely very important correlations for boiling, two phase, and single phase flow in such geothermal systems.

It should also be noted that the effective thermal conductivity of the rock/fluid system is a function of temperature, liquid saturation, and flow direction (Kunii, ~~et al.~~, 1961; Adivarahan, et al., 1962; Willhite, et al., 1963).

Finally, results of computer modeling will also be used in analysis of bench scale flow experiments. Although much is known concerning multiphase flow through porous media, recent studies (see Poston, 1970; Weinbrandt, 1972) indicate the possibility of temperature sensitivity.

BENCH-SCALE FLOW EXPERIMENTS

In order to investigate basic phenomena in the flow of hot water through porous media, a linear flow system can be considered. When hot water flows through a column of porous rock, the decline in fluid pressure causes vaporization of water to begin at a section. Upstream from this section the fluid moves entirely as a liquid and downstream from it, a mixture of steam and liquid flows. This two-phase flow should be characterized by temperatures and pressures which follow some sort of a vapor pressure curve. As the pressure decreases, the volumetric steam-water ratio would increase. Correspondingly, the permeability to steam would increase and the permeability to liquid decrease. On the other hand, the pressure-enthalpy diagram for water indicates that the enthalpy of steam is much larger than the enthalpy of liquid at the same temperature. Therefore, the relative amount of steam and water affects heat loss, and total available energy of the flow. In these senses, the relative permeabilities of porous media to steam and water must be important factors ffor study of two-phase flow of water. Another important factor in two-phase flow is the appropriate vapor pressure. Vapor pressure is the pressure at which a single component gas and liquid can co-exist in thermodynamic equilibrium. Vapor pressure may vary with the shape of the gas-liquid interface due to surface tension. This surface tension effect (capillary pressure), may result in a lowering of the flat surface vapor pressure at a given temperature. This could tend to prevent boiling of liquid at low pore-space liquid contents (saturation).*

Preliminary literature study indicates that three kinds of experiments might be performed to obtain the necessary data for study of the factors stated above. They are:

1) dynamic displacement experiment
2) steady flow experiment
3) pressure depletion experiment.

Dynamic Displacement Experiment

Figure 5 is a schematic diagram of an apparatus for the experiment. First, a core is saturated with the displacing fluid (wetting phase). The entire system is allowed to reach run temperature in an air bath. Then, the core is flooded with the displaced fluid (non-wetting phase), to obtain an irreducible saturation of displacing phase, which becomes the initial liquid saturation, S_i. This procedure yields drainage relative permeability data. Next, the injection of displacing fluid provides imbibition relative permeability data. During each run, cumulative injection and production volume, injection rate, pressure difference between inlet and outlet faces of the core, and volumetric fraction of each phase in the produced fluid are measured.

By this method, the permeability ratio and individual relative permeability curves of displacing and displaced phases may be calculated. The method was described by Johnson, Bossler, and Nauman (1959).

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* The term "saturation" can be confusing. In thermodynamics the term is used to mean a liquid or gas at temperatures and pressures along the vapor pressure curve. In petroleum engineering, the term means the volume fraction of pore space filled by a given phase. A liquid "saturation" of 25% means one quarter by volume of the pore volume is filled with liquid.

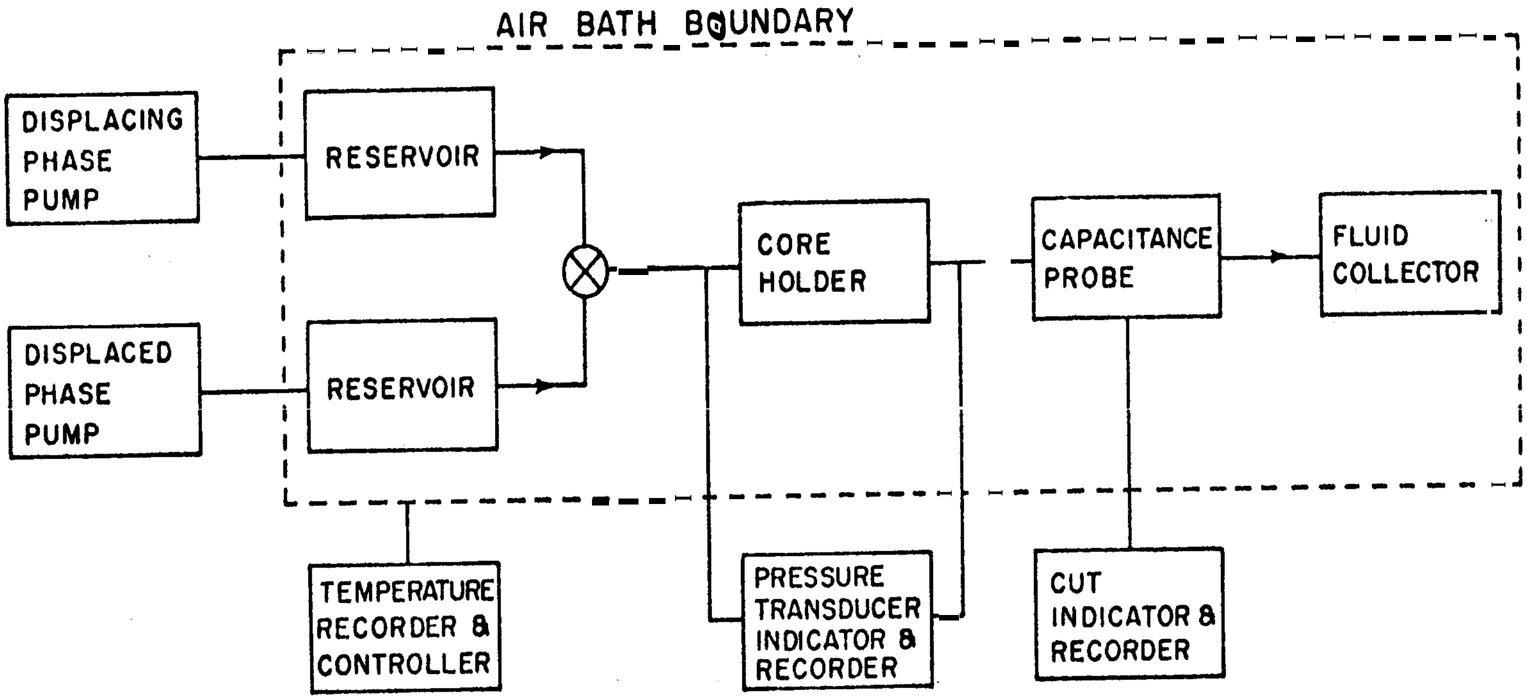

FIG. 5. DYNAMIC DISPLACEMENT EXPERIMENT

Production of the displaced phase in pore volumes, N_p, is converted to the average displacing saturation as follows:

$$S_{av} = S_i + N_p \tag{20}$$

where S_i is the initial saturation.

S_{av} is plotted vs. cumulative displacing-phase injection in pore volume, W_i. Then, the flowing fraction of displaced phase is equal to the derivative of the displaced-phase production with respect to the injection, i.e.

$$f_o = dN_p/dW_i = dS_{av}/dW_i \tag{21}$$

The outflow face saturation, S_2, is given by:

$$S_2 = S_i + N_p - W_i f_o, \quad \text{or:} \quad S_{av} = S_2 + W_i f_o \tag{22}$$

From the fractional flow equation for the displaced phase:

$$f_o = 1/[1 + (k_w \mu_o)/k_o \mu_w)], \tag{23}$$

and the permeability ratio is obtained as:

$$k_w/k_o = (f_w \mu_w)/(f_o \mu_o) \tag{24}$$

where k, f, and μ are permeability, fractional flow, and viscosity respectively, and subscripts w and o mean the displacing and displaced phase respectively in the context of this discussion. For the calculation of the individual relative permeabilities, the Johnson, Bossler, Naumann equation might be used:

$$f_o/k_{ro} = W_i d(1/I_r)/d(W_i) + 1/I_r \tag{25}$$

The injectivity ratio, I_r, is given by:

$$I_r = (u/\Delta p)/(u/\Delta p \text{ at start of injection}) \tag{26}$$

where u is the injection velocity at the inlet and Δp is the pressure difference between the inlet and outlet faces of the core. The permeability to the displaced phase is given by:

$$k_{ro} = f_o/(f_o/k_{ro}). \tag{27}$$

If steam and water are used as the displacing and displaced phases respectively, or vice-versa, then vaporization or condensation occurs at the interface, and heat and mass transfer occur continuously between the two phases. Immiscibility cannot be guaranteed, and it is impossible to have exact isothermal conditions. For these reasons, the experiment described previously cannot be applied directly. However, it may well be possible to develop an analogous non-isothermal theory. This matter is worth consideration as it would have broad application to flow in porous media.

Steady Flow Experiment

A schematic diagram of an apparatus to perform a steady flow experiment is illustrated in Figure 6[*]. Because the steady flow of hot water which leads to a two-phase flow of steam and liquid is non-isothermal flow, an adiabatic condition will be assumed.

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[*] This experiment is related to that of F. G. Miller (1951) who studied boiling propane flow.

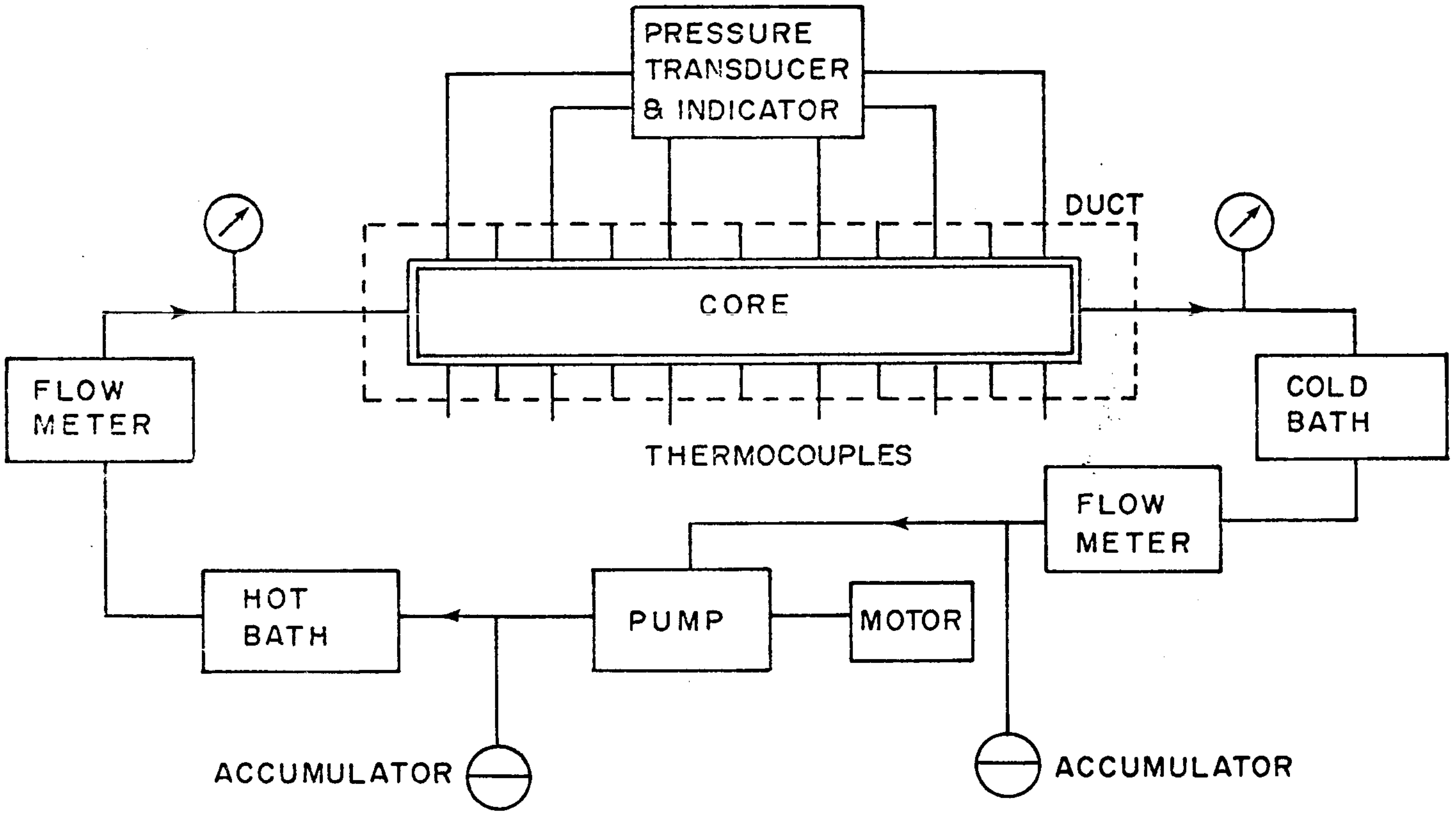

FIG. 6. STEADY FLOW EXPERIMENT

The system may be operated first: by circulating water and establishing a predetermined air-temperature distribution in the ducts enveloping the core holder. Then, the temperatures of the hot and cold baths could be adjusted, water withdrawn as necessary from the circuit to the accumulators, and the pump speed regulated. Steady flow can be attained by adjusting the air-temperature distribution in the ducts to the flow temperatures. The inlet and outlet total weight rates of flow, and temperature and pressure distributions along the core would be measured. The outlet enthalpy and water saturation distribution along the core could be measured with a calorimeter, and a capacitance probe respectively.

For steady, two-phase, adiabatic flow of water through a horizontal column of core:

$$dW/dx = dW_g/dx + dW_l/dx = 0 \tag{28}$$

where W, W_g, W_l are total weight rate of flow, weight rates of steam and water respectively. Assuming small changes of kinetic energy, an isenthalpic process is considered, i.e.,

$$W_lH_l + W_gH_g = WH = \text{constant} \tag{29}$$

where H_l, H_g, and H are enthalpy per unit weight of water, of steam, and of two-phase respectively. Introducing the weight fraction of steam as:

$$f = W_g/W \tag{30}$$

the previous equation becomes:

$$(1 - f)H_l + fH_g = H \tag{31}$$

Hence:

$$f = (H - H_l)/H_g - H_l) \tag{32}$$

Darcy's law is:

$$W_l = -\frac{A\,k_l}{\mu_l \bar{v}_l}\frac{dp}{dx}, \quad \text{and } W_g = -\frac{A\,k_g}{\mu_g \bar{v}_g}\frac{dp}{dx} \tag{33}$$

from which:

$$\frac{W_l}{W_g} = \frac{k_l}{k_g}\frac{\mu_g}{\mu_l}\frac{\bar{v}_g}{\bar{v}_l} \tag{34}$$

where k, μ, and $\bar{v}$ are permeability, viscosity and specific volume resepctively and the subscripts g and 1 pertain to steam and liquid phase respectevely. Finally:

$$\frac{k_l}{k_g} = \frac{\mu_l}{\mu_g}\frac{\bar{v}_l}{\bar{v}_g}\frac{1 - f}{f} \tag{35}$$

Therefore, using the data of temperature and pressure distributions along the core, the permeability ratio, k_l/k_g, can be determined as a function bf water saturation. Further,

$$W = -A\,k\left[\frac{k_l/k}{\mu_l \bar{v}} + \frac{k_g/k}{\mu_l \bar{v}_g}\right]\frac{dp}{dx} \tag{36}$$

or integrating with respect to x:

$$W x = A k \int_{p}^{p_1} \left| \frac{k_l/k}{\mu_l \bar{v}} + \frac{k_g/k}{\mu_g \bar{v}_g} \right| dp \qquad (37)$$

where p_1 and p are fluid pressures at the upstream end of core and at a distance x from the inlet face respectively. Because the pressure distribution or pressure gradient, and k_l/k_g values along the core are known in the two-phase region, the relative permeabilities, k_1/k, and k_g/k can be determined.

The preceding discussion has been made without consideration of capillary pressure effects. To investigate capillary pressure effects, the temperature and pressure data collected in the two-phase fluid portion may be plotted on the vapor-pressure curve for a flat surface liquid. Then, a correlation between vapor pressures and liquid saturations, or between vapor pressures and relative permeability curves may be obtained.

Pressure Depletion Experiment

In this experiment, depletion types of geothermal reservoirs and pertinent recovery mechanisms may be simulated. Depending upon reservoir pressures and temperatures, several types of geothermal reservoirs may exist, *e.g.* compressed liquid reservoirs, steam reservoirs, and two-phase reservoirs.

Compressed liquid reservoirs have initial temperatures and pressures above the saturation curve on a pressure-temperature diagram for water. At early production stages, pressure decreases at essentially constant temperature. When the reservoir pressure reaches the saturation pressure at reservoir temperature, liquid begins to boil and liquid and steam phases exist in equilibrium. A two-phase reservoir may be characterized by a decrease in temperature with pressure decline in order to maintain phase equilibrium. This means that temperatures and pressures follow some sort of vapor pressure curve.

A steam reservoir initially contains superheated steam as the only fluid. A steam reservoir may be characterized by constant system temperature and by a significant: increase of the reservoir fluid enthalpy during pressure depletion.

In regard to physical experimentation, a model geothermal reservoir might be constructed to study the energy production. Figure 7 is a schematic diagram of an experimental apparatus (see Cady, 1969). Water is pumped into the core, and the core holder is heated to the desired initial temperature. The initial pressure should be well above the saturation pressure. Turning off the heater, fluids are produced until some pressure drop is attained. The temperature and pressures along the core as well as mass and steam quality of the produced fluids are measured during the production. If this procedure is repeated by reheating the core at the end of each run without liquid recharging, the liquid saturation decreases until no more fluid can be produced from the core. The temperatures and pressures during the reheating period are also measured.

For three kinds of experiments, both natural reservoir rock and artificially-cemented core might be used. Distilled water might be used as the fluid at first, then brine could be used. Because chemical composition of reservoir fluid is an important factor to both thermodynamics and relative permeability flow studies, the effects of chemical solution and precipitation on the available energy, and vapor-pressure lowering should be studied.

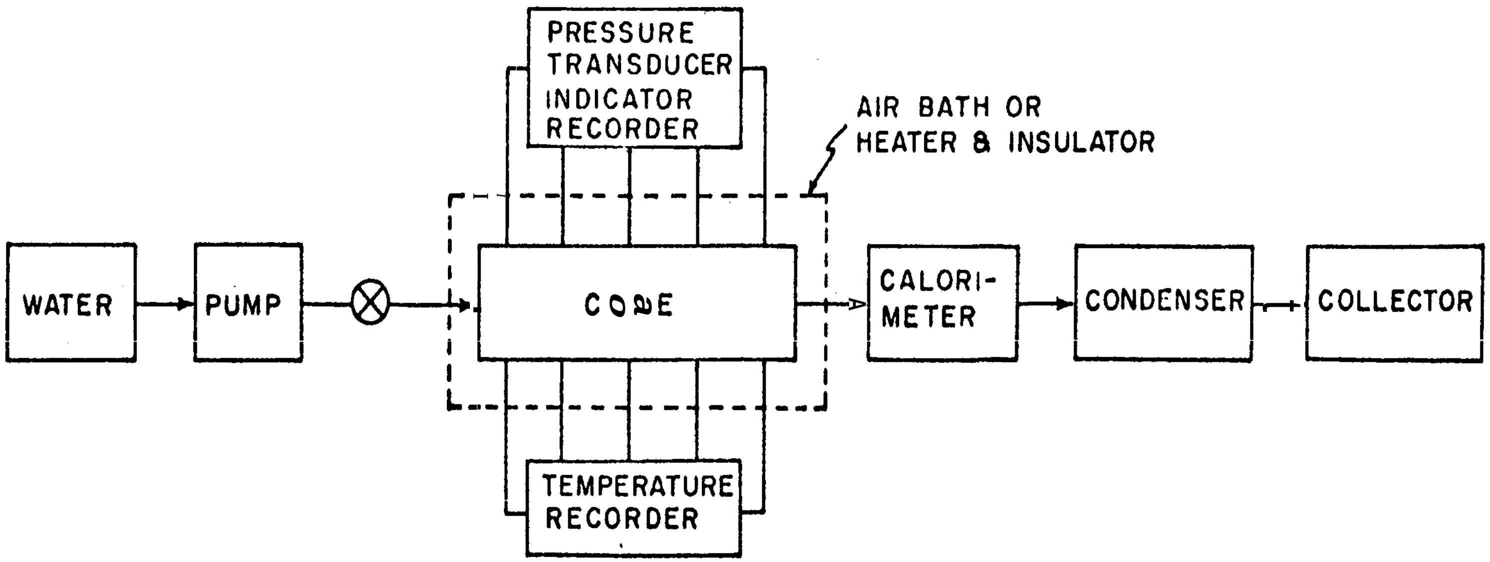

FIG. 7. PRESSURE DEPLETION EXPERIMENT

A review of the benefits and problems associated with all three experimental methods indicated significant promise in each. In view of the time limit (three years) for the project, the steady-flow method appears best suited for initial experiments. Appropriate equipment is currently being selected and ordered.

The final phase of the project currently under study involves water quality aspects of geothermal well stimulation.

ENVIRONMENTAL QUALITY ASPECTS

Geothermal energy is considered to be one of the least polluting of the several forms of energy available to man. Nonetheless, the public is expected to insist that pollution from all energy sources be investigated, and the environmental impacts be assessed in accordance with societal goals. It is required by law that the development of geothermal resources will also be preceded by the environmental impact statements required under the National Environmental Policy Act. It is also evident that investigation of operational aspects of geothermal energy production will be required to assess safety of personnel and maintenance of plant facilities. Thus an important part of the research and development needed to foster the utilization of geothermal energy is the examination of the environmental impacts and operational hazards both for natural and stimulated geothermal resources. The types of environmental aspects that have been enumerated (e.g., Bowen, 1973) include: contamination of the atmosphere, contamination of surface waters and ground waters, explosive seismic effects, induct on of earthquakes, land subsidence, thermal releases, modification of local climatology, land and energy utilization, and visual and noise pollution.

It is apparent that these effects will be examined in detail for specific resource developments by a variety of experts in various disciplines. Many of the effects are social in nature, and decisions regarding acceptability may require lengthy consideration. Common to all geothermal resources are consideration of water quality. Water quality has long been considered a vital factor of man's environment, and concern about water quality has resulted in significant research and quality control study. Water quality concerns have been singled out as deserving special investigation under this project. This is not meant to imply that other environmental effects (contamination of the atmosphere, seismic effects, etc.) are not important. But within the constraints of the project, water quality was deemed most important for initial study. Water quality aspects are of importance not only for the natural material effluents from a geothermal resource, but also for the additional materials that may be introduced by stimulation techniques. Water quality aspects are also of importance for assessing aspects of safe and efficient operation of the resource and the accompanying power plants.

A matrix of natural and introduced materials in the environmental and operational aspects is outlined in Figure 8. The release of non-condensible gases is already a well-studied problem in existing geothermal reservoirs (*e.g.*, Budd, 1973). The release of heavy and toxic elements as particles in the water or steam phase requires attention. Also requiring attention is the effluent of natural radioactive nuclides with the reservoir fluids. These effluents must be considered individually in both surface and ground waters. Releases to the atmosphere must be considered.

Releases ~~to the~~ Hydrosphere

In considering the hydrosphere by the matrix of Figure 8, the releases of both naturally-occurring and stimulation-produced contaminants

	ENVIRONMENTAL EFFECTS	OPERATIONAL ASPECTS
NATURAL RESERVOIRS	Solid Effluents: B, Hg, As, NaCl, Se, Pb, Ba Gaseous Effluents: H_2S, SO_2, NH_3 Radioactive Effluents: ^{226}Ra, ^{222}Rn	Solid Effluents: SiO_2, $CaCO_3$, $CaSO_4$ Reservoir Precipitation: SiO_2, $CaCO_3$ Corrosive Effluents: H_2SO_4, NaCl, H_2, CO_2, H_2S, NH_3
STIMULATED RESERVOIRS **Additional** Effects:		
Thermal Fracturing		Land Subsidence
Chemical Explosives	Combustion Products, Heavy Metals	Ground Shock
Nuclear Explosives	Radioactive Effluents: Volatile fission products Soluble activation products HTO	Radiation Safety Ground Shock

Figure 8. A materials matrix for natural and stimulated geothermal reservoirs and their environmental and operational impacts.

may be examined for both surface and ground water effects.

Naturally-occurring contaminants--

1) Surface water effects:

Surface waters may be affected in several ways. The most important effect associated with vapor-dominated fields results from the use of surface waters to receive the condensate. For example, boron, ammonia, bicarbonate, and sulfates and elemental particulate sulfur (resulting from the oxidation of H_2S) are found in the condensate at The Geysers. Treating the condensate was impractical as a means to meet water quality standards, and reinjection of the fluid is now used as a successful disposal method (Finney, 1973).

Contaminant concentration ranges depend on many factors including the parent compound's steam solubility; pH, temperature, and oxidizing-potential effects on equilibria and rate processes; and the turbine-condenser-cooling system characteristics. Though the general features will be similar, the specific values of these factors are all site dependent, and must be evaluated individually.

Possible effects on surface waters from production of hot water differ mainly in extent. Compared to dry-steam reservoirs, a larger mass of fluid must be extracted from hot-water reservoirs per unit of electricity produced, but also, the hot water will normally contain higher concentrations of contaminants. On flashing and separation, these concentrations will be further increased. When the water loses heat and its temperature is lowered, many substances will become less soluble and

and precipitation may occur. An important exception is calcium carbonate, whose solubility increases with decreasing temperature.

Table 2 summarizes a range of materials and their observed concentrations in a variety of geothermal fluids. Criteria concentrations applicable to specific beneficial water uses are also given for comparison. Various disposal techniques include dilution with low concentration natural waters, chemical recovery and treatment, reinjection, ponding for cooling and evaporation, seepage infiltration, and controlled precipitation of solids before reinjection. These methods need to be evaluated for compatibility with individual situations.

The occurrence of heavy metals such as mercury, arsenic, and lead in thermal waters is of concern with respect to biological uptake and ecological magnification in aquatic systems. They may have to be monitored and controlled (White, 1973).

One contemplated means of utilizing energy from a hot-water reservoir is in a closed cycle, in which energy is transferred in a heat exchanger to a secondary fluid, such as freon or isobutane, in the turbine cycle. The partly cooled and still pressurized water would be reinjected to the ground, avoiding surface water contamination problems. However, additional cooling water would be necessary to remove heat from the secondary fluid condenser.

Naturally occurring radioactivities are present in geothermal) fluids. Most important are those of the natural uranium and thorium decay chains. These nuclides are commonly observed at above average concentrations in geologic formations associated with volcanic

TABLE 2

WATER QUALITY CONSTITUENTS
(all values in mg/l)

Element	Criteria Concentrations 1/	Vapor Dominated Systems 2/	Water Dominated Systems 2/
B	0.5-1.0	3-15	1-4000
Li	5	--	12-320
$N(NH_4^+)$	--	111-1900	0.9
F	0.7-1.7	--	0.7-8
Na	various	12-18	75-55000
Si	50	66-225	0.7
$S(SO_4^=)$	250	766-5710	35-750
Cl	various	0.5-1.5	30-185000
Ca	100	~50	0.5-40000
Mh	0.01-2	1.4	0.02-2.11
HCO_3^-	--	0-176	19-165
Fe	0.05-0.3	63	0.1-2500
Ni	0.5	--	0.001-2.0
cu	0.2-1.0	--	0.003-6.0
As	0.01-1	--	0-4.8
Br	--	--	0.4-700
Mb	0.005	--	0.001-0.07
cs	--	--	0.02-20
Hg	--	detected	--
Pb	0.05-50	--	0.001-85

1/ Criteria Concentrations refer to water that may be used for various municipal and public water supplies. Industrial uses may be even more stringent in specific cases. The given values reflect USPHS Drinking Water Standards, W.H.O. standards and Water Quality Criteria recommendations.

2/ Observed Values are compiled from various sources including: Finney, 1973; White, et al., 1971; Barnes, 1967; Summers, 1972; Livingston, 1972; Hewitt, et al., 1972; Consortium, 1971.

or orogenic activity. In terms of potential radiation exposure, ^{226}Ra ($T_{\frac{1}{2}}$ = 1620 years) and its daughter products, ^{222}Rn ($T_{\frac{1}{2}}$ = 3.8 days) and ^{210}Pb ($T_{\frac{1}{2}}$ = 20 years), are of particular significance. Radon is unique because it is an easily-transported noble gas, and lead is of biological importance. Radium is sufficiently soluble in water that it can exceed the recommended maximum permissible concentration in water, $(MPC)_w$ = 0.01 pCi/ml (Eisenbud, 1963; Holtzman, 1964).

Thermal waters from hot mineral springs frequently contain large concentrations of radium. Lead concentration is limited by its tendency towards adsorption and by chemical reactions with H_2S and sulfates. Tritium (T_3 = 12.3 years) produced by cosmic ray interactions in the atmosphere and resulting from nuclear weapons testing is present in natural water. Geothermal water contains varying concentrations of ^3H depending on rates of recharge of meteoric water. Although Concentration of natural tritium is not of concern as a contaminant, it can be useful as a means of studying circulation processes.

2) Groundwater effects:

Geothermal reservoir development is closely related to groundwater recharge. Only a small fraction of thermal water is thought to be juvenile. Questions of effective economic lifetime of geothermal reservoirs depend on the rates and nature of meteoric water recharge through ground water aquifers and interactions with convection currents that are probably responsible for heat transfer from deep magma.

Reinjection is currently considered to be a probable means of extending the usefulness of a geothermal field by replenishing fluid as well as a convenient means of disposal of the mineralized water effluent from a power plant. Fluids may be reinjected into the producing reservoir, or into other groundwater reservoirs. Well casing leaks and induced fractures may provide communication paths for unwanted contamination. More probable difficulties relate to effects on the geothermal reservoir itself.

Reinjected water will be modified according to the plant cycle. Energy and mass exchanges may increase the probability of precipitation of solids. Increasing salt concentrations in a reservoir may alter the, thermodynamics of heat transfer and steamproduction. Salinity reduces the vapor pressure and increases the boiling point of a solvent in direct proportion to the mole fraction of solute.

Changes in concentration of carbon dioxide can change the pH of the fluids. If sufficient CO_2 is lost, the pH will rise, resulting in supersaturation of carbonate solids such as $CaCO_3$. This effect has been observed in wells at Wairakei (White, 1972).

Contact with the atmosphere or less of H_2 from solution could result in changed oxidation potential, resulting in increased capacity to dissolve some compounds, or affect solids precipitation.

Deposition or solution processes can affect porosity, permeability, and surface heat conduction characteristics of geothermal reservoir rock, thereby altering production rates or useful lifetimes.

Other closely-associated water quality problems relate to the operation of a geothermal power plant. Most studied thus far is the group df volatile materials that may be present in the steam. The concentrations of silica, chlorides, carbonates and sulfur compounds are considerably higher in geothermal steam than those produced in a conventional thermoelectric boiler. These materials can result in serious problems of scaling and corrosion in the steam handling equipment and turbines.

Chlorides, ammonia, carbon dioxide and hydrogen sulfide may be corrosive. Deposits may be formed on turbine blades by NaCl, NaOH, Na-silicates, Na_2CO_3 and Na_2SO_4. Silicic acid, amorphous silica, iron oxides and calcium carbonate may form scale insoluble in wash water. Scale formation within the porous rock media of the reservoir may be a limiting factor for production by in-place boiling. Flashing of hot water into steam within the well bore is known to deposit SiO_2 and $CaCO_3$ (White, 1973). The permeability and hence productivity could be severely restricted in the formation adjacent to the well bore or in a rubble chimney, although there is no positive evidence of this phenomena. Refractory scale has been formed on the sides of a laboratory vessel simulating geothermal steam production from water boiling on rock media. The scale was 90 percent silica and could be dissolved only by 3 to 5 hour exposure to 48 percent hydrofluoric acid (Charlot, _et al._, 1971).

Stimulation-produced contaminants--The effects on the hydrosphere resulting from geothermal reservoir stimulation must be considered by relating specific techniques to specific situations.

Hydraulic and thermal fracturing, applicable to hot water and dry rock systems, could be expected to result mainly in effects such as increased dissolution and transport of natural materials.

1) Chemical explosion stimulation:

Effects of chemical explosive fracturing may be evaluated by considering the production and initial distribution of residues by the detonation. The residues may include relatively small amounts of products from the primary explosives constituents such as lead azide, mercury fulminate and lead styphnate, commonly used in initiating devices. The major residues will come from oxidation products of the high explosives. Common high explosives are mainly carbon-hydrogen-oxygen-nitrogen compounds; slurrys that may contain fuel oil, aluminum; and nitrocarbonitrateoxiditingagents (Johnson, 1971). Primary data on the nature and distribution of explosion products may be obtainable from experimental programs being conducted by the U.S. Bureau of Mines, and the Naval Weapons Center. From such data or theoretical estimates, predictions can be made regarding the transport of various chemicals using such factors as the distribution coefficients for ionic species and solubility products for solids to estimate the concentration of the products in the thermal fluids. Evaluations of potential for corrosion, contamination and toxicity can then be made.

2) Nuclear explosion stimulation:

A principal public concern over the use of nuclear explosives is contamination by radioactive explosion products. As with chemical explosives, it is necessary to consider the production of the contaminants, their initial distribution in the explosion environment, and their behavior in a geothermal fluid reservoir. Estimates of the first two factors may be made from existing data from several underground nuclear explosion experiments. The presence of geothermal fluids must be evaluated separately. Radioactive materials are produced by three processes in a nuclear explosion: nuclear fission, thermonuclear fusion, and radioactivation reactions. Fission products include several isotopes of each of about 30 chemical elements, primarily neutron-rich nuclides that decay by sequential beta-particle emissions, giving rise to chains of daughter products with constant mass number but different chemical identity.

Radioactive nuclides are also produced by radioactivation by the excess neutrons with the stable nuclides in the material surrounding a nuclear explosion. Activation depends on the type and size of the explosive, the composition of the surrounding soil media, and the degree of shielding (Green and Lessler, 1971).

Table 3 presents a compilation of examples of predicted production of major radioactivities remainihg 6 months after detonation. There will also be other activation products from the container for the explosive. For example, one estimate includes 17 Ci/kt of ^{185}W ($T_{\frac{1}{2}}$ = 75d) and 0.53 Ci/kt of ^{55}Fe ($T_{\frac{1}{2}}$ = 2.60 y) 6 months after detonation of a 100 kt device (Kruger, 1970).

The single most important radionuclide from thermonuclear fusion is

TABLE 3

RADIOACTIVE PRODUCTS FROM NUCLEAR EXPLOSIVES

Nuclide*	$T_{\frac{1}{2}}$	Teller et al., 1968	Kruger 1970	Tewes & Taylor, 1971	N.V.O., 1969	Charlot, et al., 1971	
			Fission Products				
^{137}Cs	33Y	190	190	182	188	180	
^{90}Sr	28y	67	64.1	150	147		
^{85}Kr	11y	13		22	24-25.8	19	
^{125}Sb	2.7y		35.7	60		60	
^{147}Pm	2.6y		594	680	700		
^{155}Eu	1.7y		102	*30*			
^{106}Ru	1.oy		2800	380	3750	1000	
^{144}Ce	290d		2253	3600	3680		
^{123m}Sn	131d		7.5	6.2			
^{127m}Te	90d		61.9	70		90	
^{95}Zr	63d		3017	4400	4800		
^{91}Y	58d						
^{89}Sr	54d		925	2200	2280		
^{115m}Cd	43d	1.65	2.1	1.08			
^{103}Ru	41d		2130	1020	1020	1150	
^{129m}Te	33d		57.4	16.6			
^{141}Ce	32d		971	1280	1300		
				Tritium			
						fission	fusion
^{3}H	12.3y					220	20290
			Activation Products from Soil Media				
^{14}C	1620y				0.0025- 0.025		
^{39}Ar	260y				0.05-0.5		
^{22}Na	2.6y						0.6
^{134}Cs	2y					14	18.3
^{35}S	88d					29	40
^{3}'Ar	35d				0.25-2.5		

*All values in curies/kiloton at 180 days after detonation; variations are based on assumed conditions of the fission neutron environment.

12.3 year tritium, an isotope of hydrogen. Estimates of tritium production from thermonuclear explosives range from about 5,000 to 20,000 Ci/kt (Green and Lessler, 1971). In addition to the amount from fusion already mentioned, about 1 Ci/kt results from ternary fission (Lessler, et al., 1971) and some is produced by activation reactions with lithium and boron in the geologic media. Development of special explosives for commercial applications is expected to reduce the production of tritium substantially. The prediction of a total of about 12 Ci/kt for the 80 kt Plowshare Miniata Event (Lessler, et al., 1971), one of the Diamond family of explosives being specifically designed for peaceful underground engineering applications, will serve as an estimate of tritium to be expected in a geothermal stimulation situation. Tritium is especially important for proposed geothermal applications because it readily forms tritiated water (HTO) which will be incorporated in any produced fluids.

The radionuclides from a stimulation explosion will be distributed throughout the explosion environment in a complex manner depending on the chemical nature of a given nuclide and its precursors, and the physicochemical nature of the explosion environment, both being functions of time. As chimney collapse occurs, quenching the melt, the more volatile nuclides and the gases will be distributed throughout the void space. Table 4 lists some of the radionuclides that are potentially volatile and the conditions that influence their volatility (Krikorian, 1973).

When the pressure in the chimney is less than that in the surrounding formation, water will begin to fill. Conceptual models have been developed

TABLE 4

RELATIVE VOLATILITIES IN STEAM FOR GAMMA EMITTING PRODUCTS

Nuclide	Volatility in Steam 80 atm., @ 623°K
^{85}Kr	Permanent Gas
^{103}Ru, ^{106}Ru	High under oxidizing conditions Low under reducing conditions
^{125}Sb	Probably high
^{127m}Te	High
^{137}Cs, ^{134}Cs	High initially, decline with time CO_2 will decrease, Cl^- will increase

to predict this process (Fenske and Charnell, 1971). Gases may dissolve or be displaced vertically and laterally. Condensed nuclides may dissolve or be transported as particulates. Some of the more volatile nuclides may plate out on surfaces or be dissolved. The highest concentrations of mobile materials are expected to be at the rising water front (Castagnola, 1969). An estimate of the concentrations can be made by assuming uniform initial distribution; data of the solubility of various nuclides for the Piledriver event are summarized in Table 5 (Rabb, 1970).

Many potentially troublesome radionuclides are adsorbed to some extent as ionic species, with two principal effects: 1) the concentration in pore water in the region of deposition may be limited by the distribution coefficient, and 2) the apparent velocity of the ions may be retarded in relation to the velocity of the water itself. These factors can limit the transport of radioactive materials in produced geothermal fluids or away from the stimulation site by water flow in the thermal aquifer.

The concentration in pore water can be estimated for a given radionuclide from empirical formulae (Charnell, *et al.*, 1967 as cited in Kruger, 1970). As an example, the predicted concentration for ^{137}Cs from a 100 kt fission explosive detonated at 1000 m is 10.3 pCi/ml. This value *is* comparable to its $(MPC)_w$, *i.e.*, 20 pCi/ml.

After the rubble chimney is filled and before production of geothermal fluids is initiated, transport of contaminants away from the site in moving groundwater can be estimated using a model that includes dispersion, radioactive decay and ionic retardation effects (*e.g.*, Holly and Fenske,

TABLE 5

SUMMARY OF DATA FROM PILEDRIVER ANALYSES

Activity	Amount Trapped in Melt	Amount Deposited Elsewhere	Percolation Leach Tests	
			Amount Leached by acid	Amount Leached by water
Gross gama			40%	25%
^{106}Ru, ^{103}Ru	25%	75%		
^{137}Cs	12%	88%	20%	
Sr	?	?	60%	
Ce	?	?	15%	
^{125}Sb, ^{95}Zr, ^{147}Pm, ^{185}W		some		
All nuclides not specified	95%			

1968 as cited in Nork, 1970).

The distribution of tritium must be considered separately. Although it may initially be present predominantly as a gas (HT), its exchange with water will quickly convert the tritium to the form of water (HTO). Other exchanges may occur with H_2S, CH_4, HCO_3, and NH_3, but tritium is expected to be present mainly as tritiated water in stimulated geothermal reservoirs (Smith, 1970; Jacobs, 1968).

Tritium disposition is uncertain because of sampling difficulty (Smith, 1971) and the possibility that much tritium may be trapped in the melt or bound to rock surfaces by hydration or exchange (Power and Bowman, 1970).

The significance of tritium can be estimated in two ways: the total amount involved and the possible concentrations in produced fluids. An estimate of expected concentrations can be made using the assumption that tritium is uniformly distributed throughout the water which completely fills the void space produced by the explosion.

Using appropriate chimney scaling laws and selecting reasonable physical constants, the tritium concentration resulting from a fission device producing 12 Ci/kt would be on the order of 0.002 uCi/ml. This value compared with the (MPC)w for uncontrolled releases of 0.001 uCi/ml suggests that tritium will require careful attention.

As steam is vaporized from tritiated water, fractionation occurs, the partial pressure of the heavier HTO form of water is somewhat lower than H_2O. However, this effect is small and decreases with temperature.

Experimental data concerning the behavior of some radionuclides in a simulated geothermal environment are given in Table 6 (from Charlot, et al., 1971). The study concluded that the chemistry of the hot rock-water system is complex and cannot be predicted adequately from knowledge

TABLE 6

LIQUID PHASE CONCENTRATION AND APPARENT STEAM-WATER DISTRIBUTION COEFFICIENTS*

	650°F (343°C)		550°F (288°C)		450°F (232°C)	
	Concentration (ppm)	Distrib. Coeff.	Concentration (ppm)	Distrib Coeff.	Concentration (ppm)	Distrib Coeff.
Silicon (SiO_2)	1000	10^{-2}	800	5×10^{-4}	600	5×10^{-4}
Sodium	20	3×10^{-3}	50	8×10^{-4}	60	9×10^{-4}
Potassium	10	4×10^{-3}	20	2×10^{-4}	30	2×10^{-4}
Chlorine	12	6×10^{-2}	14	8×10^{-2}	20	4×10^{-2}
Aluminum	5	4×10^{-2}	6	4×10^{-2}	8	8×10^{-2}
Antimony**	2	6×10^{-3}	1	4×10^{-3}	1	10^{-3}
Boron	1	6×10^{-1}	0.7	3×10^{-1}	0.8	2×10^{-1}
Cesium**	0.08	10^{-3}	0.1	3×10^{-4}	0.1	4×10^{-4}
Iron	0.1	--		--		--
Cobalt**	0.05	--	0.03	--	0.03	--
Manganese	0.02	--	0.01	--	0.01	--
Calcium	<0.01	--	<0.01	--	<0.01	--
Copper	<0.005	--	<0.005	--	<0.005	--
Strontium	<0.005	--	<0.005	--	<0.005	--
Magnesium	<0.002	--	<0.002	--	<0.002	--
Cerium**	<0.02	--	<0.02	--	<0.02	--
Ruthenium**	<0.02	--	<0.02	--	<0.02	--
Europium**	<0.02	--	<0.02	--	<0.02	--

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* data from Charlot, et al., (1971)

**Experiment "spiked" with 50 ppm of specified element as oxide or nitrate significant fractions of Cs and Sb radionuclides are leached by acid solution but adsorption strongly limits their transport (Crouse, et al., 1970).

Other indications of the transport of nuclides in water vapor are given by Gasbuggy data (Smith, 1971). Even though the conditions in the Gasbuggy chimney are different from those expected in a geothermal reservoir chimney, the total amount of non-tritium radioactivity carried by water vapor may be anticipated to be of the same order as the $(MPCU)_w$ of 0.1 pCi/ml applicable to unidentified radionuclides.

One potential difficulty is the possibility that radioactivity carried by the steam may coprecipitate on the generating equipment. Concentrations of radioactivity may thus build up under normal operating conditions (Krikorian, 1973).

At least some radioactivities can be expected to be present in produced fluids in significant concentrations. Therefore it can be anticipated that control technologies will have to be provided for any geothermal power plant based on nuclear explosion stimulation. Experiments may be able to identify critical nuclides and conditions.

Releases ~~to the~~ Atmosphere

Effluents from geothermal power production may ultimately be released to the atmosphere depending on the operating cycle. Commonly cited materials include the various gases that occur in geothermal fluids. Table 7 presents a compilation of some of the more important gases. As an atmosphereic pollutant, the amount of CO_2 would be insignificant in

TABLE 7

GASEOUS CONSTITUENTS IN GEOTHERMAL FLUIDS

	Finney, 1973	White, et al., 1971		Barnes, 1967		
	Geysers wt%	Geysers vol%	Larderello vol%	Wairakei (mole%. excludes H_2O)	Geysers	Larderello
CO_2	0.79	1.24	1.79	92.2	69.3	92.8
H_2S	0.05	0.033	0.049	4.2	3.0	2.5
CH_4	0.05	0.299		0.9	11.8	2 (CH_4 + H_2)
NH_3	0.07	0.025	0.033	0.6	1.6	1.7
N_2	0.03	0.069 (N_2 + A)	0.011	0.3 (N_2 + A)	1.6 (N_2 + A)	0.55 (N_2 + A)
H_2	0.01	0.29	0.037	0.18	12.7	
C_2H_6	<0.002					
H_3BO_3				0.05	0.1	0.45
Total gases in steam at 1 atm. pressure separation				0.066 in steam which is 30% of total discharge	0.40 in steam which Is 100% of total discharge	2.0 in steam which is 100% of total discharge

comparison to that released by burning fossil fuel in a conventional power plant.

Hydrogen sulfide is probably the most important gas as a pollutant and corrosive agent. A large amount can dissolve in water and be oxidized to elemental sulfur, or sulfate. The fraction released to the air is probably of greatest concern to humans because of its odor. The San Francisco Bay Area Air Pollution Control District set H_2S standards at 0.03 ppm based on odor. Although H_2S is toxic at concentrations of 20 ppm, attaining a toxic level would probably be limited solely to confined spaces or buildings. H_2S can induce corrosion and embrittlemen of metal resulting in equipment failure at all operational stages from drilling through power production. Thus the problem would be one of industrial safety and efficiency rather than one of public health.

Some geothermal fluids contain large amounts of ammonia which could result in nuisance odors. Because ammonia readily dissolves in water, an environmental quality problem may occur in surface waters.

The nitrogen and argon contents are negligible except as they affect turbine efficiency. Methane and ethane are colorless and odorless and are not considered as pollutants in the expected low concentrations. Hydrogen content shows considerable variability but probably cannot be considered a pollution problem. Boric acid tends to dissolve in water and probably would not be an atmospheric problem.

Some materials are soluble to varying extents in steam. If released to the atmosphere via a cooling tower or venting, they might ultimately result in particulates after further evaporation takes place. One preliminary study done at The Geysers showed small but measurable increases in particulate matter concentrations of S, Cl, K, Ca, and Fe at sampling sites. No significant amounts of heavy metals were detectable in the aerosols (Cahill, 1972).

Gaseous emissions may contain some radioactivity resulting from naturally occurring radionuclides or, in the case of a stimulated reservoir, from the debris of a nuclear explosion.

Radon-222 is the most important of the natural activities. Radon has been observed in natural waters at widely varying concentrations. It is generally present in much larger concentrations than would be indicated for secular equilibrium with ^{226}Ra dissolved in the water. This results from the relative solubility of radon and the direct migration of radon into water from the host rock. The presence of water in a porous rock increases the effective emanation of radon because during the formation process the radon ions lose their recoil energy over small distances in water. The emanation of radon may be of particular consequence in stimulation of geothermal reservoirs. Fracturing and cracking rock reduces the average grain size. If the proportion of particles in the size of about 10^{-5} cm is increased and water is allowed to penetrate interstices, radon emanation would be increased.

As geothermal fluids are produced, advective transport could bring a significant amount of radon to the surface. An important parameter would be the mean transport time through the reservoir as compared to the 3.8 day half-life of radon.

The release of radon to the environment will be predominantly in the gas phase. Some estimates of the possible significance of radon from geothermal resources can be made from limited available data. Measurements made on natural fumaroles in New Zealand show a range of radon concentrations in the non-condensable gases (>85 percent CO_2) from 320 to 340,000 pCi/l (Belin, 1959). One reported value for the total alpha activity of steam at The Geysers is 150 pCi/l of condensate (Bowen, 1973). An estimate of radon concentration in non-condensable gas at The Geysers can be assumed on the order of 5 to 50 pCi/l.

Using typical operational data from The Geysers a value can be estimated of total radon release for various assumed concentrations:

^{222}Rn activity in non-condensables (pCi/l)	Daily release for 1000 MW_e plant (Ci)
50	0.055
1,000	1.1
300,000	331

Though not directly comparable, the daily radioactivity releases from fossil fuel and nuclear plants have been estimated by Hull (1971) as:

	Daily Releases for 1000 MW_e (Ci)		
Activity	Coal Fired	Oil Fired	Nuclear
^{226}Ra	0.000047	0.0000004 1	--
^{228}Ra	0.000029	o.00000096	--
^{85}Kr, ^{133}Xe	--	--	1.6 - 3000
^{131}I	--	--	0 - 0.85

These values may be contrasted with natural world-wide production rates of radon estimated by Junge (1963) to be 5 x 10^6 Ci/day.

One means of determining the significance of any release is to estimate the effect on steady state concentration of radon in the atmosphere.

The background ambient levels of radon in the ground level atmosphere over continental areas is on the order of 0.5 pCi/l (Gold, et al., 1964). Based on an assumed concentration of 1000 pCi/l in released gases, it would take something on the order of 10^5 plants to double the radon concentration in the atmosphere, which would result in levels just about equal to the (MPC)a. On a world-wide scale the preliminary conclusion is that radon release from a reasonable number of plants would not be significant.

However, on a local basis, concentrations of radon could fall in a range from one percent to several times (MPC)a as estimated by a simple box model and Sutton's plume dispersion equation. More detailed information on actual release rates to be expected from geothermal reservoirs will be required. From field and laboratory data, estimates of radon dispersion can be made for a variety of meteorological situations (Slade, 1968).

Evaluation of the importance of radon release to the atmosphere must also include consideration of the ultimate deposition of the various daughter products. The overall explosure to the lungs, for example, resulting from the daughter decays is about 500 times, that of radon itself (Eisenbud, 1963).

The transport and fate of the daughter ions depend on many factors including the concentration of particulates in the air, the electric field, eddy diffusion and convection effects (Roffman, 1972). The deposition of ^{210}Pb, the longest lived daughter ($T_{\frac{1}{2}}$ = 22 years), is determined mainly by the atmospheric circulation processes for particulates. Because of the 3.8 day half-life of ^{222}Rn it is virtually impossible to correlate the location of production of ^{210}Pb with a partitular source of radon. One would expect a very small effect on ^{210}Pb concentrations or deposition in the vicinity of a geothermal plant. This conclusion can and should be checked by actual measurements around sources of known strength. Such data would provide grounds to estimate any increased ^{210}Pb deposition over a large area which could then be related to transport into and through natural water systems (Huff and Kruger, 1970).

With particular reference to stimulation, estimates can be made of the release of explosion-produced contaminants in the atmosphere. For chemical explosions the priimary information would be amounts and nature of residues produced for a given type and yield of explosive. Then the solubilities and volatilities can be determined by chemical thermodynamics to estimate possible concentrations in effluenh vapor or non-condensable gases. Atmospheric dispersion models can be used to estimate environmdntal impact.

Nuclear stimulation will result in the production of radioactive gases, notably ^{85}Kr, ^{35}Ar,, and ^{37}Ar, and tritium, which will be associated mainly with water vapor releases. Some tritium might also be released in the form of CH_3T, NH_2T, HT,, and HTS, depending on exchange equilibria.

Other radioactive products may be present to extents determined by their volatilities in steam. Depending on their initial distribution within the nuclear cavity, the noble gases will probably present the most severe problem during early operations. The short-lived ones will decay in-place during the shut-in period. The others might be condensed and contained during initial operations from the chimney.

Limits on other radioactivities present in gases can be estimated from Gasbuggy data. The most volatile expected nuclide, ^{131}I ($T_{\frac{1}{2}}$ = 8.05 days), was present in concentrations (extrapolated to time of detonation) of 0.04 pCi/cm^3 of gas (Smith, 1971). From these data the atom volumetric concentration can be estimated. By comparison with the expected ^{131}I production, upper limits for volatility could be established. The biologically important fission products ^{137}Cs or ^{90}Sr were not detectable in the gas.

Tritium can be expected to be produced along with the steam or hot water; there is virtually no way to separate HTO from H_2O on a large scale. Thus it will be necessary to predict accurately the rate of tritiated water production from a stimulated reservoir and make provisions for control of fluids with tritium concentration greater than that allowed.

Development ~~of the~~ Experimental Program

In following the survey of effects on water quality (and atmospheric releases) from natural and stimulated geothermal reservoir production, several potentially worthy areas of research become evident. An important category of the naturally-present materials include those that can affect environmental quality as effluents into surface waters, ground waters, or the atmosphere. These materials are of concern in all types of reservoir development. Experiments are being planned to study these materials during in-place boiling in the simulated rubble chimney. Laboratory-scale experiments can be readily achieved for such potential contaminants as B, Se, Pb, As, Hg, and Ba with appropriate radioactive tracers. The dissolution, transport, deposition, and effluent behavior can be examined under various pressure, temperature, flowrate, and boiling conditions. The production history can be determined.

Radon release should be studied extensively. A radon measurement system is under construction. In this system, a carbon adsorption trap concentrates the radon from gas samples obtained directly or bubbled from solution. The concentrated radon is transferred to scintillation flasks for measurement with a photomultiplier tube-scaler system (Lucas, 1957). This system will also be used to measure low-level radium concentrations in water solution. Arrangements are being made to obtain effluent samples at several existing geothermal installations, such as the Geysers, the Jemez Mountains area of the Los Alamos Scientific Laboratory project, the Imperial Valley, Cerro Prieto, Mexico, geothermal fields, and possibly from the Wairakei and Lardarello fields. A range of laboratory scale studies are being planned to determine if any significant change in the radon emanation occurs as a function of the extent of fracturing, a pressure-temperature-flowrate conditions for various radium bearing rocks. Such results should permit evaluations regarding the importance of radon in geothermal resource development. The behavior of ^{210}Pb and radium might also require some experiments in the rubble chimney model to establish typical concentrations and distribution under production conditions.

Other radiologic field data will be obtained to provide base-line measurements for natural radioactivities including ^{210}Pb, ^{226}Ra, ^{3}H and gross gama radiation. Such measurements will be necessary for comparison with projected activities from nuclear stimulation, evaluation of normal releases to satisfy questions of possible hazards, and Planning any in-situ tracer experiments.

Precipitation, scaling, and dissolved salt concentration problems seem among the most critical in relation to geothermal plant operation and reservoir life. Furthermore, data for these effects are required for implementing and verifying the computer modeling effort, as they may influence energy transfer and fluid flow. The in-place boiling and reinjection processes are expected to be most critical in solids buildup. Experiments will be performed to estimate the rate of buildup of particular materials under varying conditions. Calcium sulfates, calcium carbonate and silicates are probably the most important. Measurement of rates of deposition and buildup could utilize radioactive isotopes of materials such as carbon, calcium and sulfur. Activation analysis might also be appropriate. Beta emitting isotopes (^{14}C, ^{145}Ca and ^{35}S) can be measured in the liquid phase in the liquid scintillation counter and in the solid phase (except ^{14}C) in our proportional beta detectors. Depletion of specific activity in outlet fluids could be monitored to determine loss by deposition. Measurements of rock material after the flow experiment could identify sites of deposition. Some aspects of dissolution may be studied by tracing activities leached from Piledriver rock which will be procured from the Nevada Test Site. Problems due td reinjection can also be investigated. If deposttion in cracked rock under reinjection into the! reservoir is found to be significant it might suggest a modified approach to stimulation whereby a second, smaller cracked rock chimney is created specifically with the idea of permitting the formation and entrapment of precipitates before they can reduce permeability in the more vulnerable porous media. Also silicate deposition, dissolution, and transport in cracked rock media could be traced with the short half-life ^{31}Si ($T_{\frac{1}{2}}$ = 2.62 hours) produced in our activation facilities on campus.

A second major class of chemical constituents, those introduced by an explosive, can be divided into the obvious categories of chemical explosives and nuclear explosives.

The potential for dissolution and transport will depend on the chemical form of each material. The first step regarding chemical explosives should be an attempt to determine if any actual field data are available for the residues of chemical explosives in systems similar to geothermal aquifers.

The radioactive residues from a nuclear explosive can be treated in several ways. Available data regarding the amounts and distribution of radioactive materials in a chimney (such as the Piledriver data) could be used along with accepted mathematical models for transport of dissolved and ionic substances in water to make predictions of important radionuclides. Another approach would be to use analogous data for the behavior of their chemical homologs. For example, strontium and cesium behavior can be expected to parallel that of calcium and potassium respectively. Simple tracer experiments to verify the expected behavior in terms of adsorption through the aquifer and cracked rock system, and the distribution coefficients in steam can be implemented. A study of the behavior of fission products and activation induced radioactivity would appear to be justified as a further objective of this project. Significant information and predictive models are available, but the behavior in a hydrothermal aquifer system would require investigation.

Tritium is being considered separately because of its probable occurrence in the chemical for HTO. Fractionation effects as the steam is produced and exchange effects that might retard the flow of tritiated water with respect to bulk water are expected to be small but should be measured. Such experiments can be performed in the chimney model or non-flow experiments which attempt to establish maximum values for exchange equilibria with various types of fractured rocks under geothermal pressure-temperature conditions.

The tritium experiments will be conducted with the principal goal of establishing the occurrence or non-occurrence of a y unique behaviors influencing its behavior in geothermal systems. This knowledge could be used to predict transport of explosion produced tr tium or natural or injected tritium as a tracer.

Consideration will be given to the possibility of making field tracer studies using tritium in an actual geothermal system, perhaps even an operating system such as The Geysers. This could be particularly useful in determining the paths and fate of reinjected fluids.

NOMENCLATURE

~~For the~~ Mathematical Model, Computer Modeling

A = cross-sectional area of flow, unless otherwise indicated

c = isothermal compressibility of the liquid

h = unit enthalpy of fluid, unless otherwise indicated

k = effective thermal conductivity of the rock/fluid medium

K = effective permeability of the medium to the indicated phase

M = molecular weight of the gas

p = pressure

‘rock = rate of heat flow from rock to fluids

Q_{rock} = thermal energy stored in rock

$\dot{q}$ = overall energy transfer along system as heat conduction

R = universal gas constant

t = time

T = temperature

x = linear distance

z = real gas compressibility factor

S_L = liquid saturation, fractional pore volume

$1-S_L$ = gas saturation

$\dot{W}$ = mass flow rate

ϕ = porosity, fractional bulk volume

μ = fluid viscosity

ρ = fluid density

Subscripts-- g = gas

L or 1 = liquid

st = steam (synonymous with gas)

o = datum condition for liquid

For Two-Phase Boiling, Bench-Scale Flow Experiments

f_o = fraction of displaced phase in produced fluid

f_w = fraction of displacing phase In produced fluid

I_r = injectivity ratio, see Eq. 26

k_w, k_l = effective permeability to wetting phase, md.

k_o, k_g = effective permeability to non-wetting phase, md.

N_p = cumulative production of displaced phase, pore volumes.

p_1 = pressure at core inlet, psi

S = pore volume saturation, fraction

S_{av} = average displacing phase saturation, fraction of pore volume

S_i = initial displacing phase saturation, fraction of pore volume

S_2 = outflow face saturation, volume fraction of pore volume

u = velocity, ft/day

$\bar{v}$ = specific volume, ft^3/lb

W = total weight flow rate, lb/day

W_g = weight gas flow rate, lb/day

W_l = weight liquid flow rate, lb/day

W_i = cumulative displacing phase injected, fraction of pore volume

μ_w = viscosity of wetting phase, cp.

= viscosity of non-wetting phase, cp.

Ap = pressure difference, psi.

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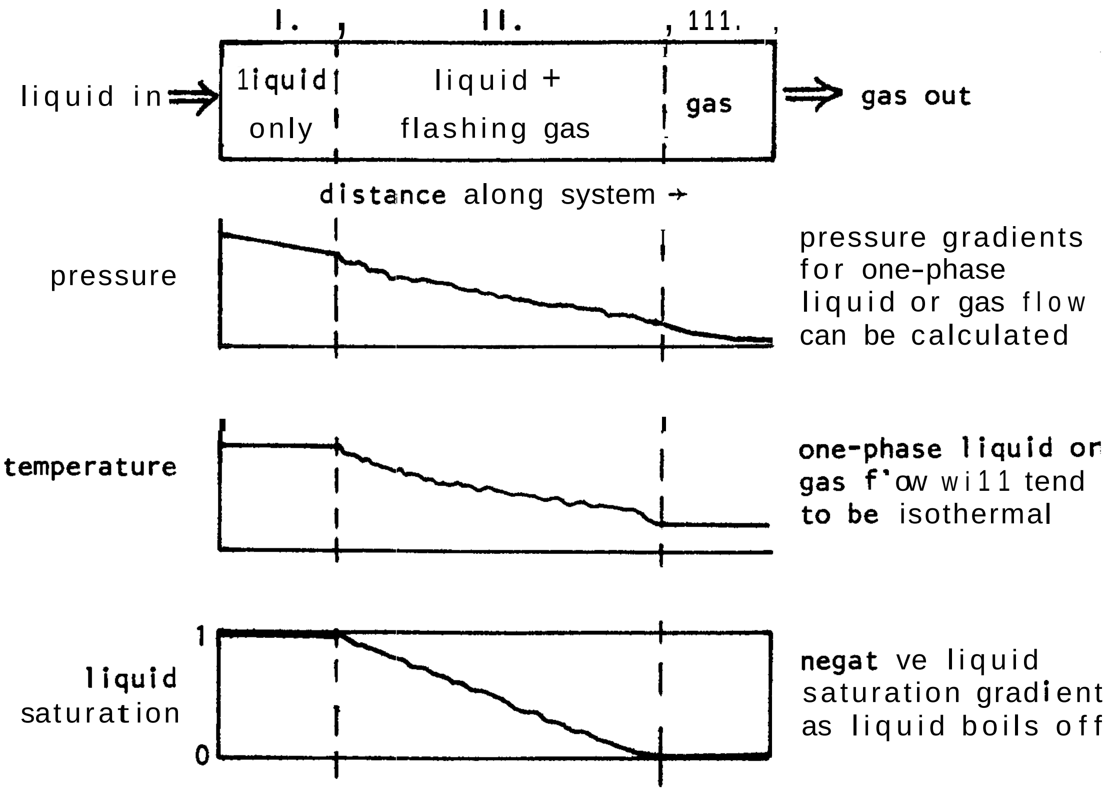
APPENDIX A

MATHEMATICAL DESCRIPTION OF LINEAR HORIZONTAL TWO-PHASE SINGLE-COMPONENT FLOW IN POROUS MEDIA

Physical Considerations

Flow Regimes



pressure gradients for one-phase liquid or gas flow can be calculated

one-phase liquid or gas flow will tend to be isothermal

negative liquid saturation gradient as liquid boils off

wavy lines on graphs are supposed to suggest unknown shape

In order for all three flow regimes to exist, a very long system of special surface and boundary conditions might be necessary.

Initially we will be concerned only with the behavior of a liquid flashing front. Development of a dry gas zone will not be studied at this time.

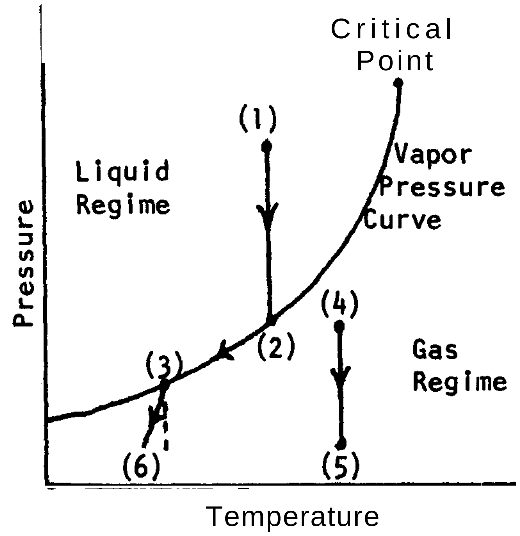
Thermodynamic Considerations

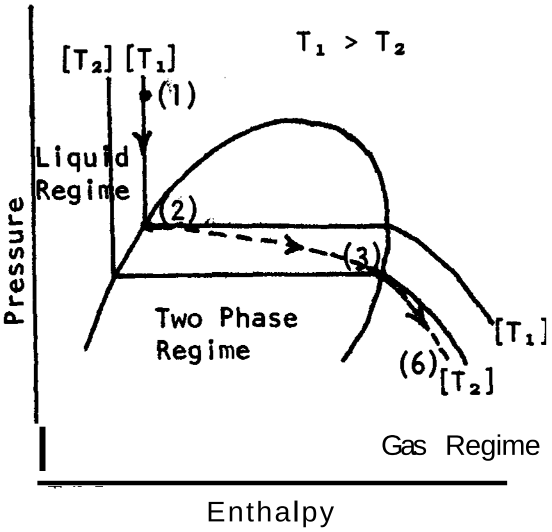
Liquid Flow Only (1) → (2)--Will be essentially isothermal.

Two-Phase Single-Component Flow (Flashing Front) (2) → (3)--If thermodynamic equilibrium exists at every cross-section, then this flow regime has only one degree of freedom (after Gibb's phase rule) and must follow the vapor pressure curve for the fluid in the system.

Steam Only (4) → (5)--Flow will tend to be essentially isothermal.

Transition from Flashing Front to Dry ~~Gas~~ (3) → (6)--The dry gas will tend to flow isothermally, but influx of cooler gas as the flashing front pressure and temperature drop will tend to lower flowing gas temperature. If severe vapor pressure lowering effects are encountered, then this stage may never be reached.





When only one phase is present, pressure and temperature are independent.

When two phases coexist and are in equilibrium, pressure and temperature are dependent.

Although consideration of isenthalpic flow leads to a pseudo-analytic solution for steady state flow (Miller, 1951), adiabatic flow for the core system is a more realistic idealization.

Mathematical Development of Flow Equations

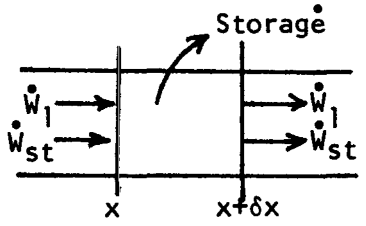
Apply basic principles on a rate basis to the system defined as fluid plus rock matrix.

1. Mass Balance--

$\text{Mass Out} - \text{Mass In} + \dot{\text{Storage}} = 0$

$$(\dot{W}_1+\dot{W}_{st})_{x+\delta x} - (\dot{W}_1+\dot{W}_{st})_x + \frac{\partial}{\partial t}(\text{Total Mass}) = 0$$

$$\frac{\partial}{\partial x}(\dot{W}_1+\dot{W}_{st}) + A\phi\frac{\partial}{\partial t}\left[\rho_{st} + S_L(\rho_1-\rho_{st})\right] = 0 \tag{1}$$



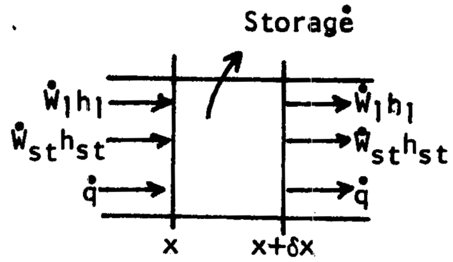
Elemental fluid volume = $A\phi\delta x$

$$\text{Total Mass} = A\phi\Delta x\left[\rho_1 S_L + \rho_{st}(1-S_L)\right]$$

2. Energy Balance--

Energy Out − Energy In + Energy Storage = 0

Energy Transfer = Mass Associated + Heat Conduction



Considering thermal energy storage in an element:

Energy Stored = Energy in Fluids + Energy in Rock Matrix

$$= A\delta x\phi\left[S_L\rho_1h_1 + (1-S_L)\rho_{st}h_{st}\right] + Q_{rock}$$

Thus :

$$0 = \left[\dot{W}_1h_1+\dot{W}_{st}h_{st}+\dot{q}\right]_{x+\delta x} - \left[\dot{W}_1h_1+\dot{W}_{st}h_{st}+\dot{q}\right]_x + \frac{\partial}{\partial t}\left[A\phi\delta x\left(\rho_{st}h_{st} + S_L(\rho_1h_L-\rho_{st}h_{st})\right) + Q_{rock}\right]$$

$$0 = \frac{\partial}{\partial x}(\dot{W}_1h_1+\dot{W}_{st}h_{st}+\dot{q}) + A\phi\frac{\partial}{\partial t}\left[\rho_{st}h_{st}+S_L(\rho_1h_1-\rho_{st}h_{st})\right] + \dot{Q}_{rock} \qquad (2)$$

3. Equations of State--

Real Gas: $\rho = \frac{pM}{zRT}$, where $z(p,T)$ is tabulated (3)

$h = h(p,T)$ is tabulated

Slightly Compressible Liquid: $\rho = \rho_o e^{c(p-p_o)}$ (4)

$h = h(p,T)$ is tabulated (4)

This form for the liquid is fairly accurate only for isothermal expansion. A different form of $\rho(p)$ will ultimately be used in two-phase flow.

4. ~~Rate~~ Equations---

Fluid Flow in Porous Media or Fractured Rock: Darcy's Law is assumed to be valid. At a later time modifications can be made to account for non-laminar flow if necessary.

For horizontal flow, assuming liquid pressure equals gas pressure:

$$\vec{v} = \frac{K}{\mu}\frac{\partial p}{\partial x} ; \; q_1 = \vec{v} \times A = \frac{KA}{\mu}\frac{\partial p}{\partial x} ; \; \dot{w}_1 = q_1 \rho_1$$

so:

$$\dot{w}_1 = -\rho_1 \frac{K_1 A}{\mu_1}\frac{\partial p}{\partial x} \qquad (5)$$

and

$$\dot{W}_{st} = -\rho_{st}\frac{K_{st} A}{\mu_{st}}\frac{\partial p}{\partial x} \qquad (6)$$

5. Statement of Thermodynamic Equilibrium--At any point along the system phase equilibrium has been reached. This means that if two phases are present, they are at the same pressure and temperature. It is not being assumed that the rock matrix is at uniform temperature; only that its surface temperature is that of the surrounding fluids.

6. Algebra--

Mass Balance: 3, 4, 5, 6 into 1

$$\frac{\partial}{\partial x}\left[\left(\rho_{ol}e^{c(p-p_o)}\frac{K_L}{\mu_L} + \frac{pM}{zRT}\frac{K_{st}}{\mu_{st}}\right)\frac{\partial p}{\partial x}\right] - \phi\frac{\partial}{\partial t}\left[\frac{pM}{zRT} + S_L\left(\rho_o e^{c\Delta p} - \frac{pM}{zRT}\right)\right] = 0$$

where Ap $= p-p_o$.

Energy Balance: 3, 4, 5, 6, 7 into 2

$$\frac{\partial}{\partial x}\left[\left(\rho_{ox}e^{c\Delta p}\frac{K_L}{\mu_L}h_L + \frac{pM}{zRT}h_{st}\frac{K_{st}}{\mu_{st}}\right)\frac{\partial p}{\partial x} + k\frac{\partial T}{\partial x}\right] - \phi\frac{\partial}{\partial t}\left[\frac{pM}{zRT}h_{st}\right.$$

$$\left. + S_L\left(\rho_{ol}e^{c\Delta p}h_L - \frac{pM}{zRT}h_{st}\right)\right] - \dot{Q}_{rock} = 0$$

These equations are expressed in greater detail in the next page.

$$\frac{\partial}{\partial x}\left\{\left[\frac{\rho_{ol}\, e^{c(p-p_o)}\, K_L(S_L,p,T)}{\mu_L(T)} + \frac{pM\, K_{st}(S_L,p,T)}{z(p,T)RT\mu_{st}(p,T)}\right]\frac{\partial p}{\partial x}\right\} - \phi\,\frac{\partial}{\partial t}\left\{\frac{pM}{z(p,T)RT}\right.$$

$$\left. + \; S_L\left[\rho_{ol}\, e^{c\Delta p} - \frac{pM}{z(p,T)RT}\right]\right\} = 0$$

$$\frac{\partial}{\partial x}\left\{\left[\frac{\rho_{ol}\, e^{c\Delta p}\, K_L(S_L,p,T)h_L(p,T)}{\mu_L(T)} + \frac{pM\, K_{st}(S_L,p,T)h_{st}(p,T)}{z(p,T)RT\,\mu_{st}(p,T)}\right]\frac{\partial p}{\partial x} + k\,\frac{\partial T}{\partial x}\right\}$$

$$- \dot{Q}_{rock}(x,t) - \phi\,\frac{\partial}{\partial t}\left\{\frac{pM\, h_{st}(p,T)}{z(p,T)RT} + S_L\left[\rho_{ol}\, e^{c\Delta p}\, h_L(p,T) - \frac{pM\, h_{st}(p,T)}{z(p,T)RT}\right]\right\} = 0$$

Two simultaneous nonlinear partial differential equations in $p(x,t)$, $S_L(x,t)$, and $T(x,t)$:

$$\frac{\partial}{\partial x}\left[K_1(p,S_L)\,\frac{\partial p}{\partial x}\right] = \phi\,\frac{\partial T}{\partial t}\left[K_2(p,S_L)\right]$$

$$+ \; \frac{\partial}{\partial x}\left[K_3(p,S_L)\,\frac{\partial p}{\partial x} + k\,\frac{\partial}{\partial x}\right] = \phi\,\frac{\partial T}{\partial t}\left[K_4(p,S_L)\right] + \dot{Q}_{rock}(x,t)$$

Note that for $0 < S_L < 1$, $p = f(T)$.

Limiting Conditions

A. $S_L = 1$, isothermal flow: both equations can be reduced to

$$\frac{\partial^2 p}{\partial x^2} = \frac{\phi\mu c}{k}\,\frac{\partial p}{\partial t} \qquad \left[\dot{Q}_{rock} = 0\right]$$

B. $S_L = 0$, isothermal flow: both equations can be reduced, for a perfect gas, to:

$$\frac{\partial^2 p^2}{\partial x^2} = \frac{\phi\mu}{kp}\frac{\partial p^2}{\partial t} , \quad \left[\dot{Q}_{rock} - 0\right]$$

C. $S_L = 0$, non-isothermal flow:

mass balance:

$$\frac{\partial}{\partial x}\left\{\frac{K_{st}}{zT\mu_{st}} p \frac{\partial p}{\partial x}\right\} - \phi \frac{\partial}{\partial t}\left\{\frac{p}{zT}\right\} = 0$$

energy balance:

$$0 = \frac{\partial}{\partial x}\left\{\frac{MK_{st}\, h_{st}(p,T)}{zRT\mu_{st}} p \frac{\partial p}{\partial x} + k \frac{\partial T}{\partial x}\right\} - \dot{Q}_{rock} - \phi \frac{\partial}{\partial t}\left\{\frac{pM\, h(p,T)}{zRT}\right\}$$

This yields:

$$\frac{\partial}{\partial x}\left\{\frac{K_{st}}{\mu_{st}} \cdot \frac{1}{zT} p \frac{\partial p}{\partial x}\right\} - \phi \frac{\partial}{\partial t}\left\{\frac{p}{zT}\right\} = 0$$

and

$$\frac{\partial}{\partial x}\left\{\frac{MK_{st}\, h_{st}(p,T)}{zRT\mu_{st}} p \frac{\partial p}{\partial x} + k \frac{\partial T}{\partial x}\right\} - \dot{Q}_{rock} - \phi \frac{\partial}{\partial t}\left\{\frac{pM\, h_{st}(p,T)}{zRT}\right\} = 0$$

There are two equations in two unknowns; $p(x,t)$, $T(x,t)$ are independent variables now.

D. $S_L = 1$, $K_g = 0$, non-isothermal liquid flow, for $\rho = \rho(p)$ only:

mass balance:

$$\frac{\partial}{\partial x}\left\{\frac{\rho_o^{\;c(p-p_o)}\; kK_L}{\mu_L (T,} \frac{\partial p}{\partial x}\right\} - \phi \frac{\partial}{\partial t}\left\{\rho_o\, e^{c'(p-p_o')}\right\} = 0$$

energy balance :

$$\frac{\partial}{\partial x}\left\{ \frac{\rho_o \, e^{c(p-p_o)} \, h_L(p,T) K_L}{\mu_L(T)} \frac{\partial p}{\partial x} + k \frac{\partial T}{\partial x} \right\} - \dot{Q}_{rock}(x,t)$$

$$- \phi \frac{\partial}{\partial t} \left\{ \rho_o \, e^{c(p-p_o)} \, h_L(p,T) \right\} = 0$$