SAND80-1522

PRELIMINARY ANALYSIS OF TWO ASPECTS OF MAGMA-
POWERED ELECTRIC-GENERATION PLANTS*

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September 1980

ABSTRACT

Two aspects critical to the development of magma electric generation plants using closed heat exchanger systems are addressed in this study. The heat transfer between the cold fluid in the downcomer and the hot fluid in the upcomer is analyzed using an NTU-effectiveness technique. The results indicate the hot fluid must be thermally insulated from the colder fluid in order to yield a useful temperature difference at the surface. A preliminary system analysis is conducted to determine the well cost requirements of an economically competitive magma electric plant. There is no economic incentive to make the magma tap wellbore larger than conventional deep gas wells. The cost competitiveness of a magma/electric plant is influenced by the depth to the magma, the convective heat flux of the magma, and the expected life of each well.

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* This work was supported by the U.S. Department of Energy under Contract DE-AC04-76DP00789.

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INTRODUCTION

Molten magma bodies in the earth's crust represent large amounts of environmentally clean, high-quality energy. The USGS estimates the energy contained in molten and partially molten magma in the United States at depths less than 10 km to be 5×10^4 to 5×10^5 quads [1]. Because of this tremendous potential, a program was established at Sandia to investigate the scientific feasibility of extracting energy directly from buried magma sources [2].

The objective of this particular study is to provide preliminary analyses of two different aspects critical to the development of magma electric generation plants using a closed heat exchanger system. First, a simple concentric pipe energy transport device is analyzed to determine if the cold downcomer fluid must be thermally insulated from the hot upcomer fluid. The second part of this study is to determine how much one can afford to spend to drill into a liquid magma body, install the well piping and heat extraction device, and still be economical with respect to a conventional coal-fired electric generation facility.

WELL PIPE HEAT TRANSFER ANALYSIS

The portion of the well piping not immersed in the molten magma body was modeled as a concentric pipe counterflow heat exchanger (HX) with the capability to insulate between the inner pipe (downcomer) and the annulus (upcomer). The well pipe configuration is illustrated in Figure 1.

In general, cold water flows down the inner pipe, gets heated or vaporized in the molten magma region, and returns to the surface via the outer annulus as hot water or steam. Some of the key assumptions are given below:

FIGURE 1. Well Pipe Configuration

- (1) The outer pipe is perfectly insulated, i.e., no thermal losses to the formation.
- (2) Only the region above the magma body is modeled.
- (3) The flow rate in the downcomer is equal to the upcomer flow rate.
- (4) The inner pipe flow area is equal to the annulus flow area.
- (5) The fluid parameters are assumed to change very little with depth.

A method based on the effectiveness of the heat exchanger in transferring a given amount of heat was used to analyze this particular problem [3]. Basically, the HX effectiveness is defined as follows:

$$\text{Effectiveness} = \epsilon = \frac{\text{actual heat transfer}}{\text{max. possible heat transfer}} \quad (1)$$

For the counterflow heat exchanger shown in Figure 2, the heat transfer rate, q , is defined as follows:

$$q = (\dot{m}c)_h(T_{h1} - T_{h2}) = (\dot{m}c)_c(T_{c1} - T_{c2}) \quad (2)$$

where the subscript c indicates the cold side, the subscript h indicates the hot side, and $\dot{m}c$ is the heat capacity rate. The subscripts 1 and 2 are used to designate opposite ends of the HX. In this study, the subscript 1 represents the point located just above the magma body while the subscript 2 represents the point located at the earth's surface.

FIGURE 2. Temperature Profile for Counterflow HX

For the maximum possible heat transfer to be attained, one of the fluids must undergo a temperature change equal to the maximum temperature difference present in the exchanger, which is the difference between the inlet temperatures of the hot and cold fluids. The fluid which might undergo this maximum temperature difference is the one having the minimum value of heat capacity rate ($\dot{m}c$) since the energy balance requires that the energy received by one fluid be equal to that given up by the other fluid. Thus, the maximum possible heat transfer is expressed as

$$q_{\max} = (\dot{m}c)_{\min}(T_{h1} - T_{h2}) \quad (3)$$

where $(\dot{m}c)_{\min}$ is the minimum value of $(\dot{m}c)_c$ and combining Equations (1), (2), and (3), we get the following relationship:

$$\epsilon = \frac{(\dot{m}c)_h(T_{h1} - T_{h2})}{(\dot{m}c)_{\min}(T_{h1} - T_{c2})} \quad (4)$$

The effectiveness of a counterflow heat exchanger can be expressed as follows [3]:

$$\epsilon = \frac{1 - \exp[(-UA/C_{\min})(1 - C_{\min}/C_{\max})]}{1 - (C_{\min}/C_{\max})\exp[(-UA/C_{\min})(1 - C_{\min}/C_{\max})]}$$

where,

UA = overall heat transfer coefficient

$C_{\min} = (\dot{m}c)_{\min}$

$C_{\max} = (\dot{m}c)_{\max}$

The grouping of terms $UA/C_{\min}$ is called the number of transfer units (NTU) since it is indicative of the size of the heat exchanger.

The overall heat transfer coefficient for the configuration illustrated in Figure 1 can be written as follows [3]:

$$UA = \frac{2\pi L}{\frac{1}{h_i r_{1i}} + \frac{\ln(r_{1o}/r_{1i})}{k_s} + \frac{\ln(r_{2i}/r_{1o})}{k_{in}} + \frac{\ln(r_{2o}/r_{2i})}{k_s} + \frac{1}{h_o r_{2o}}} \quad (6)$$

where,

h_i = inner pipe convective heat transfer coefficient

h_o = annulus convective heat transfer coefficient

k_{in} = thermal conductivity of insulation

k_s = thermal conductivity of steel

r_{1i} = inner pipe I.D.

r_{1o} = inner pipe O.D.

r_{2i} = second pipe I.D.

r_{2o} = second pipe O.D.

L = total length of heat exchanger

Solving Equation (4) for the inlet temperature on the hot side (T_{h1}), we get

$$T_{h1} = \frac{T_{h2} - \epsilon(C_{\min}/C_h)T_{c2}}{[1 - \epsilon(C_{\min}/C_h)]} \quad (7)$$

where $C_h = (\dot{m}c)_h$.

Therefore, if we know the effectiveness, the capacity rate ($\dot{m}c$), the inlet temperature on the cold side (T_{c2}), and the desired hot side outlet temperature (T_{h2}), we can determine the minimum required downhole temperature of the hot fluid entering the annulus.

The flow rate and inner pipe I.D. are assumed to be 10,000 lb/hr and 5 inches, respectively. The flow area is assumed to remain constant in both the downcomer and upcomer. Other important numerical assumptions are given in Table I.

TABLE I
NUMERICAL ASSUMPTIONS

Mass Flow Rate of Fluid	100,000 lb/hr
Specific Heat of Liquid Water	1.0 Btu/lb-°F
Specific Heat of Steam	0.5 Btu/lb-°F
Temperature of Condensate Entering Downcomer	100°F
Temperature of Fluid Leaving Annulus at Surface	700°F
Heat Transfer Coefficient for Liquid Water	200 Btu/hr-ft ² -°F
Heat Transfer Coefficient for Steam	20 Btu/hr-ft ² -°F
Length of HX	20,000 ft
Inner Pipe Diameter	5 inches
Nominal Wall Thickness	1/4 inch
Insulation Thickness	Variable
Thermal Conductivity of Steel	25 Btu/hr-ft-°F
Thermal Conductivity of Insulation	0.03 Btu/hr-ft-°F

In Figure 3, the effectiveness of the HX is plotted versus the NTU parameter ($UA/C_{\min}$) for several different values of $C_{\min}/C_{\max}$. The effectiveness of the HX approaches unity for large values of NTU.

The following two cases were examined:

Case I: Water flowing down the inner pipe and up the annulus.

$$C_h = (\dot{m}c)_h = 100,000 \text{ Btu/hr-}^\circ\text{F}$$

$$C_c = (\dot{m}c)_c = 100,000 \text{ Btu/hr-}^\circ\text{F}$$

$$\therefore C_{\min}/C_{\max} = 1.0$$

FIGURE 3. Effectiveness for Counterflow HX

Case II: Water flowing down the inner pipe and steam flowing up the annulus.

$$C_h = 50,000 \text{ Btu/hr-}^\circ\text{F}$$

$$C_c = 100,000 \text{ Btu/hr-}^\circ\text{F}$$

$$\therefore C_{\min}/C_{\max} = 0.5$$

The first step was to determine the heat exchanger performance assuming no insulation and no second pipe. The results are tabulated in Table II.

TABLE II
HX PERFORMANCE WITHOUT INSULATION

	$UA \left(\frac{\text{Btu}}{\text{hr-}^\circ\text{F}} \right)$	NTU	ϵ	Required Hot Side Inlet Temp. ($^\circ\text{F}$)
Case I: Water-Water	2,532,000	25.32	0.962	15,890
Case II: Water-Steam	510,840	10.22	0.997	200,100

In order to get a useful outlet temperature like 700°F, the hot side inlet temperature must be ridiculously high due to the heat loss to the downcomer fluid. Obviously, the downcomer must be insulated from the annulus or upcomer in order to provide a reasonable ΔT at the surface.

Given the assumptions listed in Table I and the relationships described previously, the minimum required inlet annulus temperature was calculated for different values of the insulation thickness. The results are presented in Figure 4. An insulation thickness of less than half-an-inch is very effective in reducing the heat loss to an acceptable level.

FIGURE 4. Minimum Required Hot Side Inlet Temperature

MAGMA TAP COST REQUIREMENTS

In order to extract energy from a magma source at depth in the earth's crust, one must first drill a wellbore into the molten rock. Next, a heat exchanger is placed in the magma and a solidifying crust forms on its surface. The crust thickness will continue to increase until the heat being conducted through the crust and into the heat exchanger is equal to the convective heat coming from the molten magma. A closed HX/Magma configuration is illustrated in Figure 5.

FIGURE 5. Heat Exchanger/Magma Crust Configuration

From Hardee [4], we get the following governing equations for heat extraction for such an arrangement.

$$\left(\frac{R_o}{R_e}\right) \ln\left(\frac{R_o}{R_e}\right) - \frac{k(T_o - T_e)}{R_e q_o} = 0 \quad (8)$$

$$q_e = q_o (R_e/R_o) \quad (9)$$

$$Q_T = 2\pi R_e L q_e \quad (10)$$

where,

R_e = heat exchanger radius (m)

R_o = crust radius (m)

T_e = temperature at HX surface ($^{\circ}\text{C}$)

T_o = temperature at outer crust surface ($^{\circ}\text{C}$)

q_e = heat flux at HX surface (kW/m^2)

q_o = convective heat flux at crust/magma interface (kW/m^2)

k = conductivity of magma crust ($\text{kW/m-}^{\circ}\text{C}$)

L = total length of HX in contact with magma (m)

Q_T = total heat extraction rate (kW)

Solving Equations (9) and (10) for R_o/R_e , then substituting for (R_o/R_e) in Equation (8), we get:

$$R_o/R_e = \frac{Q_T/L}{2\pi R_e q_o}$$

$$\left(\frac{Q_T/L}{2\pi R_e q_o} \right) \ln \left(\frac{Q_T/L}{2\pi R_e q_o} \right) = \frac{k(T_o - T_e)}{R_e q_o} \quad (11)$$

If we know R_e , q_o , k , T_e , and T_o , we can solve Equation (11) for the linear heat rate (Q_T/L). The ratio (R_o/R_e) is plotted in Figure 6 as a function of the product $(R_e q_o)$. As one would expect, the crust thickness decreases as $R_e q_o$ increases.

FIGURE 6. Variation of Crust Size

Assuming the magma to be a Newtonian fluid, Hardee calculated the convective heat fluxes for several different types of magmas. These are tabulated in Table III.

TABLE III
TYPICAL CONVECTIVE HEAT FLUXES

Magma Description	q_o (kW/m ²)
Dry Andesitic, Laminar Flow	1.06
Dry Andesitic, Turbulent Flow	6.19
Wet Andesitic (4% H ₂ O), Laminar	3.24
Wet Andesitic (4% H ₂ O), Turbulent	19.40
Basaltic, Laminar	7.55
Basaltic, Turbulent	43.30

Also from Hardee's work, we get the following "typical" values for k , T_e , and T_o .

$$k = 0.00293 \text{ (kW/m} \cdot \text{°C)}$$

$$T_e = 350^\circ\text{C}$$

$$T_o = 1050^\circ\text{C}$$

Thus, a "typical" value for $k(T_o - T_e)$ is simply:

$$k(T_o - T_e) = 0.00293 (1050 - 350) = \underline{2.051} \text{ kW/m}$$

Based on this calculation the linear heat rate (Q_T/L) is plotted in Figure 7 as a function of ($R_e q_o$) for values of $k(T_o - T_e)$ of 1.0, 1.5, 2.0, and 2.5 (kW/m). It is important to realize that these results are dependent on the assumption that the cold dowcomer fluid is perfectly insulated from the hot upcomer fluid.

FIGURE 7. Linear Heat Rate of the Heat Exchanger

The sensitivity of the linear heat rate (Q_T/L) to changes in the heat exchanger radius (R_e) is easily obtained using the information in Figure 7. For example, if we make the following assumptions,

$$R_e = 0.10 \text{ m}$$

$$q_o = 10.0 \text{ kW/m}^2$$

$$k(T_o - T_e) = 2.0 \text{ kW/m}$$

the linear heat rate is found to be 15 (kW/m). Now, if we double the HX radius leaving everything else the same, the linear heat rate (Q_T/L) increases to 22.5 (kW/m). The net gain in output is only about 50% while the well cost will almost certainly more than double. In fact, the well cost may increase as the square or even the cube of the hole radius. Therefore, there does not appear to be any incentive to make the wellbore larger than, say, conventional deep gas wells. The lower bound on the wellbore radius will probably be determined by structural considerations such as twist-off of the drill string, etc. In addition, since the cross-sectional flow area of the HX decreases as the square of the radius, the pumping power requirements will increase drastically as the HX radius decreases. Therefore, in my opinion, a HX radius of 0.10 metres is probably close to optimum.

In order to perform an economic analysis comparing a magma electrical generation plant to a conventional coal-fired plant, one must make several assumptions about costs, performance, and economic conditions. The assumptions used in this particular study are given in Tables IV and V. The results of the analysis are illustrated in Figures 8 and 9.

TABLE IV
COST AND PERFORMANCE ASSUMPTIONS

	Coal	Magma
Nominal Plant Size (MWe)	1000	1000
Installed Plant Cost (\$/kWe)	1000	400
Installed Well Cost (\$/kWt)	----	Variable
Excess Well Capacity	----	10%
Fuel Cost (\$/MMBtu)	1.00, 2.00	----
Net Plant Efficiency	37%	30%
Capacity Factor	70%	80%
Immersed HX Length (m)	----	1000
Nominal HX Radius (m)	----	0.10
$k(T_o - T_e)$ (kW/m)	----	2.0

TABLE V
ECONOMIC PARAMETERS

System Operating Lifetime	30 yr
Magma Tap Well Lifetime	15, 30 yr
Effective Income Tax Rate	0.50
Ratio of Debt to Total Capitalization	0.50
Ratio of Common Stock to Total Capitalization	0.40
Ratio of Preferred Stock to Total Capitalization	0.10
Annual Rate of Return on Debt	0.10
Annual Rate of Return on Common Stock	0.14
Annual Rate of Return on Preferred Stock	0.12
Annual "Other Taxes" as Fraction of Total Capital Investment	0.02
Annual Insurance Premiums as Fraction of Total Capital Investment	0.0025
Annual O&M Costs as Fraction of Total Capital Investment	0.02
General Inflation Rate	0.08
Fuel Escalation Rate	0.10
Base Year	1980
Price Year	1980
Expenditure Year	1980
Startup Year	1981

The economic analysis of both types of generating facilities is performed using the assumptions in Tables IV and V in conjunction with the DOE/JPL required revenue methodology [5]. The levelized energy cost ($\overline{LEC}$) of the magma electric generation plant is presented in Figure 8 as a function of the incremental well cost ($\$/kW_T$) for average well lives of 15 and 30 years. For an initial fuel cost of $\$1.00/\text{MMBtu}$ and $\$2.00/\text{MMBtu}$, the $\overline{LEC}$ of the conventional coal-fired plant is $7\text{¢}/\text{kWh}$ and $10\text{¢}/\text{kWh}$, respectively.

From the results in Figure 8 we can determine the incremental well cost that allows the magma plant to produce electricity at the same cost as the coal-fired plant. This is called the breakeven incremental well cost. For example, if the average well life is 15 years and the initial coal cost is $\$1.00/\text{MMBtu}$, the breakeven incremental well cost is approximately $\$250/\text{kW}_T$.

FIGURE 8. SENSITIVITY OF $\overline{LEC}$ TO AVERAGE WELL LIFE

Using the performance data in Figure 7 and the assumptions itemized in Table IV, we can determine the steady-state thermal output of a magma tap well. For example, if we drill into a molten magma body that has a convective heat flux (q_0) of 20 kW/m^2 and immerse a 1000 metre closed-loop HX in the magma, the thermal output of such a well is approximately $22,500 \text{ kW}_T$. If the breakeven incremental well cost for a particular magma plant is $\$250/\text{kW}_T$, the maximum allowable cost to drill and complete such a well is $\$5,625,000$. This is called the breakeven well cost and must include such things as road and pad construction, all drilling costs, casing and cementing costs, fluid transport piping, thermal insulation between the hot and cold fluids, and the 1000 metre long magma tap heat exchanger. The breakeven well cost is plotted in Figure 9 as a function of the convective heat rate (q_0) for four different cases.

FIGURE 9. BREAKEVEN WELL COST FOR DIFFERENT VALUES OF THE CONVECTIVE HEAT FLUX

For purposes of comparison, I have tabulated, in Table VI, the cost of drilling and completing several gas and geothermal wells in recent years in 1980 dollars.

TABLE VI
TYPICAL WELL COSTS FOR 8-INCH BOTTOMHOLE DIAMETER

<u>Type of Well</u>	<u>Location</u>	<u>Depth (ft)</u>	<u>\$/ft</u>	<u>Cost(\$)</u>
Geothermal Well	Geysers, CA	6000	200	1,200,000
Gas Well	Jackson, WY	20,000	400	8,000,000
Gas Well	Oklahoma	25,000	280	7,000,000
Gas Well	New Mexico	22,000	150	3,300,000

Suppose the average well life of the magma plant is 15 years and the initial cost of fuel for the coal-fired plant is \$1.00/MMBtu. Using Figure 9 the breakeven well cost for a convective heat flux of 10 kW/m^2 is approximately \$3,500,000. If the convective heat flux of the magma is 40 kW/m^2 instead of 10 kW/m^2 , the breakeven well cost is \$9,000,000. Therefore, in order to compete with the conventional coal plant using \$1.00/MMBtu fuel, we will have to drill and complete each magma tap for about what deep conventional oil and gas wells currently cost.

Now, if we double the cost of coal to \$2.00/MMBtu and keep everything else constant, the breakeven well cost will increase by 60%. On the other hand, if we double the expected life of each well to 30 years, the breakeven well cost will almost double. Thus, the breakeven well cost is much more sensitive to the average well life than the initial cost of coal.

CONCLUSIONS AND RECOMMENDATIONS

The conclusions of this study are summarized below:

- The hot fluid in the annulus/upcomer must be thermally insulated from the colder fluid in the inner pipe/downcomer.
- The insulation need not be very thick and, therefore, should not increase the wellbore size significantly. However, the cost of the heat exchanger itself will increase significantly due to the additional concentric pipe, insulating material, and fabrication time required.
- The problem is less severe for Case I (water-water) than for Case II (water-steam). This is because the heat exchanger effectiveness is lowest for $C_{\min}/C_{\max} = 1$.
- There are no reasons (economic or otherwise) to make the wellbore of the magma tap any larger than conventional deep wells because the well cost increases much faster with the magma heat exchanger radius than does the rate of heat extraction.
- In the final analysis the cost competitiveness of the magma electric generation facility will be strongly influenced by the depth of the magmatic body (i.e., the well cost), the convective heat flux of the magma, and the expected life of each well.

A number of areas need additional work. For example, the well piping should be modeled in a more complete manner to determine if insulation is needed between the outer pipe and the formation. Such an analysis should consider both heat loss to the upper formations and heat extraction from the margin zone directly above the magma source as well as the heat transferred from the hot upcomer fluid to the cold downcomer fluid. The GEOTEMP computer

code, which was developed to compute downhole temperatures in and around a geothermal well [6], could be easily adapted for such an analysis. If sizable aquifers are present in the upper formations, the additional heat loss may be much larger than the heat extracted from the margin zone above the magma body. Under these conditions, the upper portion of the wellbore may have to be insulated which will increase the cost of energy extraction.

Other heat extraction concepts such as the "open" system should be compared with the simple closed counterflow heat exchanger. One should also investigate techniques for enhancing the heat transfer rates in the magma by water injection, etc.

Better information on the cost of drilling and completing a magma tap is needed before one can perform a more exhaustive system optimization analysis. However, the effects of well cost reduction efforts in the geothermal drilling program could be incorporated into any future magma drilling cost study.

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