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Design of an Insulated Coaxial Pipe Assembly for a Drilled Geothermal Well

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ABSTRACT

The design of an insulated coaxial pipe assembly for a 50,000 ft (15.24 km) drilled geothermal well is given. The design permits the removal of heat from the earth's crust by the circulation of water through a single well. The design problems are compounded by the presence of a hot and cold fluid in counterflow, large differential thermal expansion between the liners of the coaxial pipe assembly, large hydrostatic pressures resulting from the depth of the well, and a feasible means of insulating, supporting and installing the ten-mile long coaxial pipe assembly. The paper gives a conceptual solution with oil being used as the insulating material between the hot and cold water. The support of the coaxial pipe assembly is accommodated by installing it in 2500 ft (762 m) sections, each to be fastened by "spiders" to the outer casing. Differential thermal expansion is accommodated by slip joints. Well drilling to a depth of 50,000 ft (15.24 km) was found to be within today's technological limits although the maximum depth of a drilled well to date is approximately 35,000 ft (10.67 km). An installation technique is also outlined.

NOMENCLATURE

A	cross-sectional area
D	pipe diameter
d_e	equivalent diameter
f	friction factor
g	gravitational constant
h	enthalpy
J	778 Btu/ft lbf
k	thermal conductivity
L	maximum well depth
$\dot{m}$	mass flow rate
p	pressure
q	heat flux
r	radial coordinate
S	2,500 ft (762 m)
T	temperature
U	overall heat transfer coefficient
V	water velocity
z	axial location
α	gradient of water, also thermal expansion coefficient
ρ	density
σ	stress

General Subscripts

d	downer
f	friction
g	ground
i	inner
ins	insulation
o	outer
r	riser
ω	water

Temperature Subscripts

1	well inlet (downer)
2	well bottom
3	well outlet (riser)

INTRODUCTION

With the increasing demand for more electrical energy, there is renewed interest in the thermal energy stored deep in the earth's crust. The region of interest is the rigid crust which extends an average of 16,500 ft (5029 m) below the ocean, and 125,000 ft (38,100 m) under the continents and reaches temperatures up to 2000 F (1093 C). Below the crust, the upper mantle extends another 500 miles (805 km) before molten rock above 3300 F (1816 C) is reached. The recoverable reserve of thermal energy in the western U. S. has been optimistically estimated to be 10^8 MW-centuries(1)[1].

Geothermal energy for electrical power generation has been classified according to its source as either "wet" or "dry". The "wet" source is based on using natural emissions of hot water and steam. Fumaroles, geysers and quiescent subterranean reservoirs are tapped and used to produce pressurized steam, or used directly to drive conventional turbine-generators. Unfortunately, natural, or "wet" geothermal resources are generally limited to volcanic regions which are sparse and rarely coincide with regions of high power demand.

The "dry" source is the vast quantity of energy associated with dry hot rock, primarily granite, in the earth's crust. Power generation from "dry" sources is as yet a proposed concept to tap an enormous thermal reservoir. This widespread reservoir is estimated to be above 700 F (371 C) at a depth of 10 miles (16.1 km), or less, beneath the earth's surface. Two proposed approaches which have been reported for gaining access to this energy source are:

1) A pair of drilled wells, intersecting a network of cracks hydrofractured in the earth's crust. Water would then circulate down one well, through the cracks in the hot rock and up the other well transporting energy that could be used to generate power at the surface. (2)

2) A single deep drilled well (e.g. 50,000 ft (15.24 km)) in which is suspended an insulated coaxial pipe as shown in Fig. 1. In this concept, cold water passing down the outer annulus is heated by the earth, and then returns from the bottom through an insulated inner pipe. This brings the hottest water to the surface where it is then used to generate electrical energy. (3)

Although the analysis considered in this paper specifically involves the latter concept, the principles and design considerations also apply to the former concept or any other situation involving the transport of two adjacent fluids and/or the insulation of a geothermal well. The literature regarding the single drilled well approach is limited; References 4-9, however, cover the general field of geothermal power and the related deep well drilling. This paper gives the design considerations and the related solutions of the problems described above. The problem is characterized by a hot and cold fluid in counterflow where the design must accommodate thermal expansion, large hydrostatic pressures and a feasible means of insulating, supporting, and installing a coaxial pipe assembly approximately ten miles long.

[1]Numbers in parentheses denote References at end of paper.

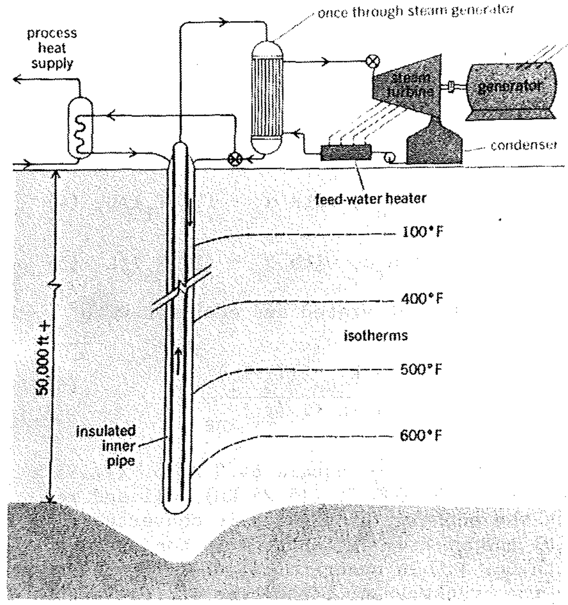

Fig. 1. Drilled Geothermal Power Generating System [3]

ANALYSIS

Design Objectives

The objective is to bring hot water from the bottom of a well of given diameter, back to the top in the central riser, with minimum temperature and pressure drop. Since the water is circulating in a closed loop the wellhead pressure can be maintained to prevent flashing in the riser and the resulting two-phase flow from the well bottom to top. Insulation is necessary to minimize heat transfer along the entire 50,000 ft (15.24 km) length between the ascending hot water and descending cold water. At the same time, the insulation chamber should not severely restrict the flow area. Referring to Fig. 1, the first consideration in the structural design of the well is the amount and type of insulation to be used around the inner pipe. It is worth noting that the maximum depth of an oil well today is about 35,000 ft (10.67 km). With sufficient incentive, however, wells of adequate diameter can be drilled for geothermal energy utilization to 50,000 ft (15.24 km) or more. According to reference 10, it is feasible to drill a well to a depth of 50,000 ft (15.24 km) with an estimated drilling time under ideal conditions of 4-3/4 years and an estimated cost of $20,000,000.

Insulation Considerations

The derivation of the riser temperature loss ΔT_{23} includes the effects of potential energy change. Assume a steady flow of $\dot{m}$ in the riser from a bottom temperature, T_2, to a top temperature, T_3. Applying the First Law to the column and assuming incompressible flow:

$$q_{23} = \Delta h_{23} - \Delta z/J \qquad (1)$$

$$q_{23} = \int_L^0 \pi D_i \; (U_i/\dot{m}) \; (T_r - T_d) dz \qquad (2)$$

Substituting the following approximate relationships

$$U_i = 2k_{ins}/D_i \ln(r_o/r_i)_{ins} \qquad (3)$$

$$T_d = T_1 + \alpha_d z, \text{ with } \alpha_d = (T_2 - T_1)/L \qquad (4)$$

$$T_r = T_3 + \alpha_r z, \text{ with } \alpha_r = (T_2 - T_3)/L \qquad (5)$$

equation 2 can be integrated and combined with equation 1 to give:

$$\Delta h_{23} = \frac{L}{J} + \frac{L \pi k_{ins} (T_3 - T_1)}{\dot{m} \ln (r_o/r_i)_{ins}} \qquad (6)$$

The first term, $\frac{L}{J}$, equals 64.3 B/lb. (1.495 x 10^5 J/Kg) for a 50,000 ft (15.24 km) well and represents the enthalpy drop which is converted to potential energy from well bottom to top, in accordance with Eq. 1. In order to calculate the second term in the bracket, Δh_{23}, the type of insulation must be specified.

The requirements of a good insulation are low thermal conductivity and the ability to withstand high pressures. Many types of insulation are available, as shown in Table 1 with thermal conductivities from 0.00057 to 0.35 Btu/hr-ft-F (9.87 x 10^{-4} to 6.06 x 10^{-1} W/m-C).

TABLE 1. INSULATION PROPERTIES

Descriptive Name	Approx. Density (Kg/m^3)	Thermal Conductivity W/m-C	Interspace Pressure (N/m^2)
Opacified Powder	112.1	.0026-.0069	.133
Evacuated Powder	96.1	.00099-.00199	.133
Gas-Filled Powder	96.1	.002-.007	1.013x10^5
Perlite, Expanded	129.7	.0012	.0133
Mica, Expanded	150.6	.00182	.0133
Powdered MgO		.076	
ZrO_2		.61	
Clear Fused Silica		.585	
J-M Min-K #1301	320.4	.036 (at 600F)	
Motor Oil	800.9	.12	

The powders, opacified, evacuated and gas-filled have the desired quality of low thermal conductivity. However, it would be impractical to design for pressures as low as 10^{-4} mm Hg (.133 N/m^2) in an annular space surrounded by deep well pressures approaching 22,000 psi (152 x 10^6 N/m^2). Johns-Manville, Min-K #1301 insulation, with a thermal conductivity of .0208 Btu/hr-ft-F (3.6 x 10^{-2} W/m-C) therefore appears to be the most attractive at first glance.

Due to the strength requirements, however, it soon becomes clear that an acceptable insulation must either:

(a) have high compressive strength, or
(b) retain its thermal resistance while immersed in high pressure water.

Without these requirements being met, the walls of the coaxial pipe assembly become prohibitively thick. After extensive efforts to accommodate conventional dry insulation, using gas pressurization, bellows, etc., it is found that these requirements can best be met by the use of an annulus of common motor oil which has a thermal conductivity of 0.07 Btu/hr-ft-F (1.21 x 10^{-1} W/m-C). The thermal conductivity is not as low as desired, but the oil is acceptable because of its simplicity. The special merits of oil are its relative incompressibility and retention of thermal resistance while exposed in high pressure water. Also, due to its density being less than that of water, thermal expansion problems are more easily accommodated as shown in the final design, Fig. 2.

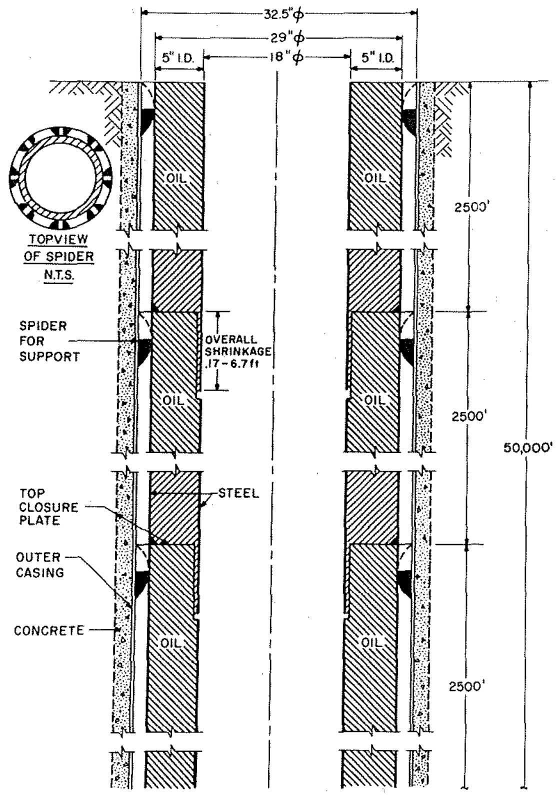

Fig. 2. Proposed Well Design

With a 5 in. (0.127 m) annulus of oil surrounding an 18 in. (0.4572 m) inner pipe, the riser temperature loss will be approximately 71 F (21.1 C), at a mass flow rate of 2.0 x 10^6 lb/hr (3.27 x 10^9 Kg/sec) as shown in Table II.

TABLE II. HEAT LOSS IN A WELL HAVING A 5-IN. (0.127 m) OIL-FILLED ANNULUS SURROUNDING AN 18-IN. (0.4572 m) INNER PIPE

Flow Rate		Total Temperature Degradation		Temperature Degradation Resulting from Heat Transfer Through Annulus		Temperature Degradation Equivalent to Change in Potential Energy from Well Bottom to Top (C_p = 1.0 Btu/lbm F)	
lbm/hr x 10^{-6}	Kg/sec x 10^{-9}	F	F	F	F	F	C
1.0	1.64	77.4	25.2	13.1	-10.5	64.3	17.9
2.0	3.27	70.9	21.6	6.6	-14.1	64.3	17.9
3.0	4.91	68.7	20.4	4.4	-15.3	64.3	17.9
4.0	6.54	67.6	19.8	3.3	-15.9	64.3	17.9

The table shows that heat transfer through the annulus is small compared to the change in potential energy from the well bottom to top. Therefore, degradation resulting from the large surface area was neglected in the design.

Supporting the Central Pipe

Having determined that the insulated central pipe is to be two coaxial steel liners with a 5 in. (.127 m) oil-filled annulus, the next design problem is how to suspend such a pipe to a depth of 50,000 ft (15.24 km).

If hung from the top of the well, with the oil annulus open at the bottom, the maximum stress at the suspension point of each liner will be $\sigma = L(\rho_{steel} - \rho_{water})$. Therefore, a steel having a yield stress of 80,000 psi (5.52×10^8 N/m^2) can support a pipe no greater than 29,000 ft (8.84 km) long.

This consideration, plus the problems of installation and of differential thermal expansion lead to the concept of a central pipe, made up of twenty 2,500 ft (762 m) lengths. Each 2,500 ft (762 m) length is suspended by a "spider" to a flange in the outer casing wall, and mates with the previous length above it by a sliding joint on the inner lining, and a weld on the outer, for reasons to be described. This detail is shown in Fig. 2.

Compensation for Differential Thermal Expansion Between the Central Pipe Liners

Perhaps the most difficult problem in devising a feasible well structure, is to accommodate the large differential expansion between the inner and outer liner of the central pipe, as soon as the well flow commences. To accommodate this expansion several alternatives were first considered:

(a) supporting the pipe by a number of cables imbedded in the insulation between the inner and outer liners and "locking" the two liners to the same expansion by collars. This idea was dropped since it would produce excessive buckling in one liner;

(b) metal bellows installed on the inner inside pipe which would expand and contract as needed to allow for the thermal expansion of the inner inside pipe. This idea was considered extensively, but dropped due to the tremendous pressure differences that would be imposed on the bellows.

In order to predict the maximum differential thermal expansion between the central pipe liners, a well initially filled with static water at the geothermal gradient is assumed. As each successive 2,500 ft (762 m) section of central pipe is lowered to its assigned depth, its two liners will expand a length

$$\Delta L = \alpha_{th} \Delta T s \qquad (7)$$

As the well flow is initially established, the inner liner will be heated by the rising water to a value corresponding to the bottom temperature, T_2, while the outer liner temperature will fall as the downer reduces the geothermal gradient. The result is a maximum differential expansion of 9.2 ft (2.8 m) in the top 2,500 ft (762 m) length, diminishing to about .24 ft (.073 m) in the lowest 2,500 ft (762 m) length as the well exit temperature varies from 780 F (415.6 C) to 200 F (93.3 C) due to periodic operation.

Selection of Area Ratio, (A_{riser}/A_{downer})

This ratio would normally be chosen to give a minimum overall frictional pressure drop from the riser to the downer, where the frictional pressure drop in each is given by:

$$\Delta p_f = \pm \int_0^L f \frac{dz}{d_e} \left(\frac{\rho_w V^2}{2g}\right) \qquad \begin{matrix} + \text{ for downer} \\ - \text{ for riser} \end{matrix} \qquad (8)$$

The downer, being an annulus and with a lower average temperature will have a smaller value of d_e, a smaller Reynolds Number, and, therefore, will require a lower velocity to keep the two pressure drops equal. However, since the downer is the heat transfer channel, and it is also desirable to maximize the natural circulation "driving head" of the well, it can be shown that equal velocity in downer and riser is close to optimum design. We then have,

$$(A_r/A_d) = (\bar{\rho}V)_d/(\bar{\rho}V)_r = (\bar{\rho}_d/\bar{\rho}_r) \qquad (9)$$

For initial operation in a 50,000 ft (15.24 km) well with T_3 = 700 F (371.1 C), the integrated average density in the downer is about 50 lb/ft^3 (801 Kg/m^3) and in the riser is 33 lb/ft^3 (529 Kg/m^3), giving $(\bar{\rho}_d/\bar{\rho}_r)$ = 1.5. Using the area ratio (A_r/A_d) = 1.5, a chosen inside pipe diameter of 18 in. (.46 m), 5 in. (.127 m) of oil insulation, and 0.25 in. (6.4×10^3 m) thick pipe liners, (as shown in Fig. 2), the outer casing diameter turns out to be 32.5 in. (.83 m).

With motor oil as the insulation, thermal expansion is easily accommodated by letting the bottom of the inner pipe of one 2,500 ft (762 m) section slip over the top of the next 2,500 ft (762 m) section. Since the oil is lighter than the water, no seals are necessary as the oil will always rise to the top of the annular interspace and will always be in pressure equilibrium with the inner water. Also, due to the fact that the lower temperature water in the outside downer will always be at a lower pressure than the rising hot water, the outer liner will always be in tension eliminating any buckling problems.

Coaxial Pipe Installation

During the drilling of the well the outer well casing with the female spider support welded every 2,500 ft (762 m) is installed and cemented in place. The final problem then, is to assemble and install the inner and outer liner in the water filled well and fill the annular interspace with the oil insulation.

The proposed installation technique begins with 100 ft (30.48 m) pipe lengths delivered to the site by rail or truck. On removal from the car each 100 ft (30.48 m) length is lowered to the top of the well by a standard oil-derrick and welded to the preceding pipe section until a 2,500 ft (762 m) outer pipe assembly has been produced. In this procedure a specially designed clamp may be used to hold the partially assembled pipe section that is already in the well, so that the next 100 ft (30.48 m) length of pipe can be welded to it. This part of the installation is shown in Fig. 3. As shown in Fig. 4 the male spider support is welded to the top of the assembled 2,500 ft 762 m) section and lowered into the well by letting the male spider go between the female spider. Then when the section is at the proper position in the well, it is turned so that the male and female spiders are aligned and then dropped into place.

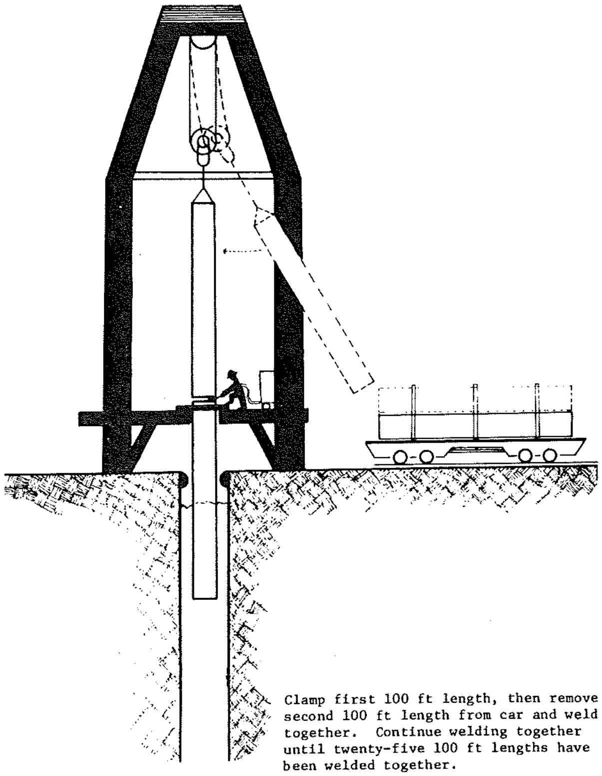

Fig. 3. Coaxial Pipe Installation

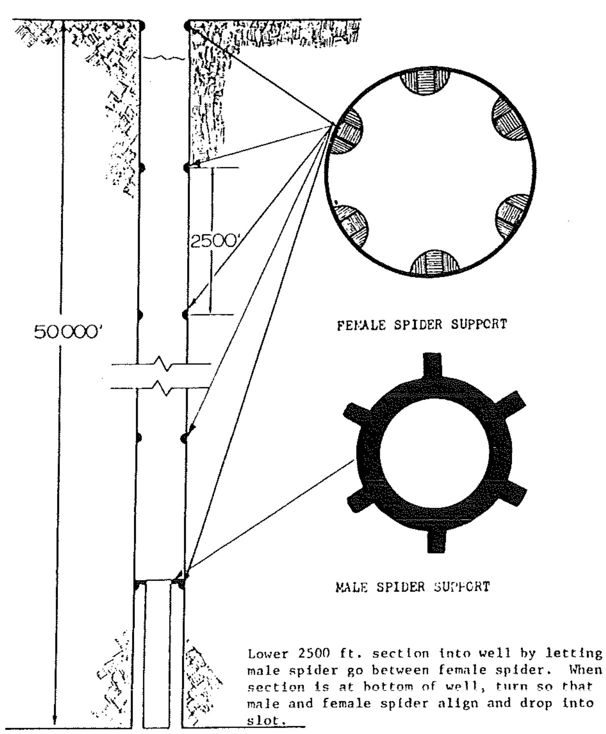

Fig. 4. Coaxial Pipe Installation

The inner liner of the insulated pipe is assembled and lowered into the well in 100 ft (30.98 m) lengths similar to that for the outer casing. When a 2,500 ft (762 m) length is constructed the top closure plate shown in Fig. 2 is welded in place, and the section is lowered to the bottom of the well. A remote welding device is then used, as shown in Fig. 5, to join the two sections together.

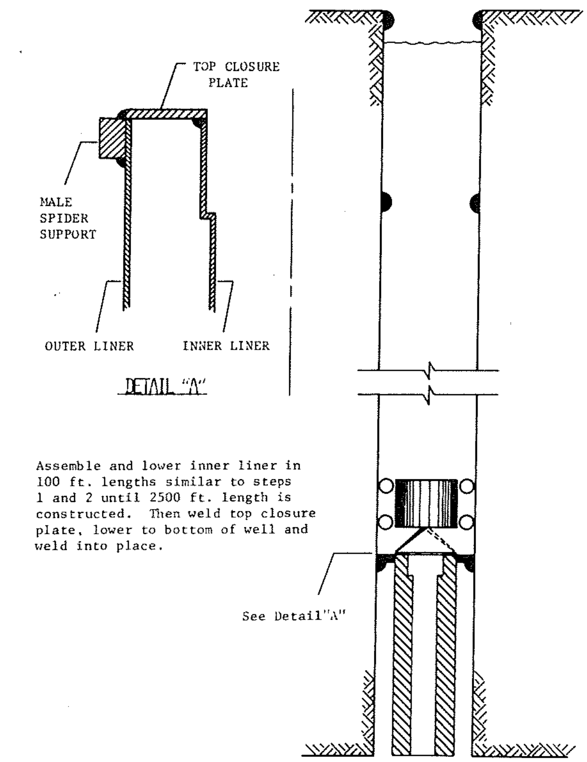

Fig. 5. Coaxial Pipe Installation

This device will have to be specially designed to stand the high pressures and temperatures. It could be supported from the top by cables and with wheels that would run against the outer or inner casing to help in the aligning process. Using a hooked-end hose, oil will be pumped into the 2,500 ft (762 m) long water-filled annulus at the bottom. Since the oil is lighter, it rises, displacing the water, and fills the annulus. Due to the buoyant force of the oil, the size of the top closure plate which supports the inner liner is considerably reduced. After filling the annulus with oil, the above process is repeated until the entire coaxial pipe assembly is installed.

Summary

The design and installation of an insulated coaxial pipe assembly in a 50,000 ft (15.24 km) drilled geothermal well thus appears to be feasible. Using an oil insulation, the design accommodates thermal expansion, suspension of the pipe and extremely high pressures. A possible installation procedure has also been described. It depends, however, on the feasibility of a specially designed remote controlled underwater welding device which can withstand pressures up to 20,000 psi (138×10^6 N/m^2) and temperatures up to 800 F (427 C). It is also now known that wells can be drilled to an acceptable size depth for geothermal utilization, with an approximate cost using present technology of $20,000,000 for a 50,000 ft (15.24 km) hole. Although a feasible design of the insulated coaxial pipe has been shown, design details must be worked out before the additional costs of fabricating and installing the inner pipe can be determined.

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