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FORMATION TEMPERATURE GAUGE
FEASIBILITY STUDY. VOLUME 2

Interim Report

March 9, 1977

Work Performed Under Contract No. EY-76-C-03-0936-048

IRT Corporation
San Diego, California

U. S. DEPARTMENT OF ENERGY
Geothermal Energy

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1. FEASIBILITY STUDY OF THE FORMATION TEMPERATURE GAUGE

1.1 PRINCIPLES OF OPERATION

As noted in the introduction, the present interim report presents in detail the status of the formation temperature gauge feasibility study. It also demonstrates the feasibility of the technique in the simplified situations examined to date both analytically and experimentally. This section deals with the theory underlying the technique. The next three sections will describe in turn the temperature gauge, the simplified model calculations of the gauge response, and the preliminary experimental measurements performed to verify the results of the computational study. The final section will also describe the formation temperature test stand designed to demonstrate the feasibility of the technique in the geothermal well geometry. This test stand has been assembled and measurements of the gauge response will begin shortly. These are outlined at the end of this report.

1.1.1 General Theory

Neutrons injected into a medium undergo collisions with the surrounding matter. If an injected neutron has kinetic energy higher than a few electron volts (eV) (slow neutron), or a few thousand eV (fast neutron) it will propagate through the medium losing its energy both elastically and inelastically to surrounding atoms. The process is called neutron slowing down, and the medium in which it occurs is called a moderator. Slowing down will continue until the neutron kinetic energy has been reduced to the sub-electron-volt range. Since the moderator atoms are in thermal (periodic) motion with energies generally below one eV, on the average, a neutron with energy in this range can no longer be slowed down. Instead, it will diffuse through the medium undergoing collisions with the surrounding atoms. Each collision

will result in either energy loss by the neutron or in energy gain. In this state, the neutron is in thermal equilibrium with the moderating medium. Such a neutron is said to have been thermalized and is called a thermal neutron; sub-electron volt energies are called thermal energies. If a neutron injected into the medium already has kinetic energy in the thermal range, it will diffuse through the medium, rapidly achieving thermal equilibrium by adjustment of its average kinetic energy in its first few collisions. The degree of such a change will depend on the magnitude of the thermal motions of the moderating atoms. Diffusion will continue until the neutron is absorbed or it decays (a neutron has a finite lifetime). Since thermal neutrons diffusing through a medium are in thermal equilibrium with their surroundings, their energy distribution reflects the thermal state of the medium, i.e., its temperature, and its neutron properties, i.e., absorption and scattering.

As a result of the thermal motion of the interacting atoms, and the statistical (random) nature of the thermal neutron diffusion, the thermal neutrons energies are not all equal, even if their initial energies were the same, but are distributed over the entire thermal energy range. The energy distribution of thermal neutrons in a moderating medium generally consists of a low energy region which is nearly a Maxwellian function, and a higher energy region varying inversely with neutron energy, i.e., the $1/E$ region. The neutron energy distribution is exhibited by the energy dependence of the thermal neutron flux. Flux is the product of the density of neutrons, $n(E)$, having certain kinetic energy E , and their velocity, $v(E)$, and it is the neutron field parameter which, in conjunction with the moderator properties, determines the neutron interaction rates, e.g., scattering interactions, absorption, etc. The thermal neutron flux, $\phi(E)$, is generally represented by

$$\phi(E) = 2\pi n \left(\frac{2}{m_n} \right)^{1/2} (\pi k T_n)^{-3/2} E \exp(-E/kT_n) + CE^{-1} \quad (1)$$

where n is the density of all neutrons at a point regardless of energy, m_n is the neutron mass, k is the Boltzman constant. T_n in the above expression is the neutron temperature or the characteristic temperature of the Maxwellian function [the first term in Eq. (1)], and it is simply related to the temperature of the moderator. This functional relationship is

$$T_n = T \left(1 + \alpha \frac{\Sigma_a}{\Sigma_s} \right). \quad (2)$$

where T is the temperature of the medium, α is an empirical constant, and Σ_a and Σ_s are the absorption and scattering properties, respectively, of the medium. C in equation (1) is a constant equal to zero below approximately 0.15 electron volts, but non-zero for neutron energies higher than 0.15 eV.

It is obvious from Eq. (1) that the information regarding the temperature of the slowing down medium is implicit in the energy distribution of the thermal neutrons propagating through it. $\phi(E)$ given by Eq. (1) is plotted in Figure 1 for several values of T_n . It is apparent from these plots and the above equations, that it is possible to determine the temperature of a moderating medium by appropriate sampling of the energy spectrum of thermal neutrons propagating (diffusing) through it. Such a medium could be the formation surrounding a geothermal well. In this case one must introduce fast neutrons into the formation and provide for the appropriate sampling of those which have been thermalized through collisions with atoms in the formation.

1.1.2 Methodology

Fast neutrons can be injected into the formation in the vicinity of a well by introducing an isotopic source of neutrons in the well at the region of interest. Energetic source neutrons will propagate through the formation around the source. They will interact with the surrounding atoms and they will be slowed down. The neutron penetration distance into the formation, depends on the initial neutron energy and the formation absorption and scattering characteristics. For fission neutrons [average energy ~ 2 MeV (million electron volts)] this penetration varies from as little as six cm in pure light water (H_2O) to nineteen cm for graphite and to even greater distances for moderators consisting of heavier, not strongly absorbing elements. Unless the source neutrons are absorbed in the process of slowing down, they will eventually be thermalized, and they will reach thermal equilibrium with the formation at some average distance from the borehole wall.

Figure 1. Thermal neutron energy distributions for several neutron temperatures, T_n , calculated on the basis of Eq. (1). These clearly display the spectral dependence on the moderator temperature, T , since $T_n = T(1 + \alpha \Sigma_a/\Sigma_s)$ (Eq. 2).

Since the slowing down process is statistical, some neutrons will be slowed down faster than others even if their initial energies were the same. Some of these neutrons will diffuse back toward the wall and will eventually leak through the borehole wall. Again some of the returning neutrons will be absorbed in the formation. The thermalized neutrons which do diffuse back to the borehole wall, however, carry back with them, implicit in their energy distribution, information regarding the formation temperature. This information can be extracted by appropriate sampling of the thermal neutron energy spectrum at the borehole wall.

Obviously, the ideal sampling method would be to measure the neutron energy distribution itself. Such an elaborate measurement, however, is not necessary and a much simpler and much more practical ratio technique will suffice. Such sampling can be obtained by a thermal neutron detector. It would involve counting with the detector surrounded by a neutron filter, i.e., a material with selective, energy dependent, thermal neutron absorption characteristics (filtered detector count), and comparing this with the response of the same or an identical detector without a filter (bare detector count). The filtered-to-bare detector count ratio would determine the temperature of the formation.

The number of counts, C_B , recorded by a neutron detector immersed in a neutron field is a convolution of the energy dependent neutron flux at the detector position, and the energy dependent detector counting efficiency. Therefore,

$$C_B = \int_0^{\infty} dE \cdot \phi(E) \cdot \epsilon(E) \quad , \quad (3)$$

where $\phi(E)$ is the flux of neutrons with energy E , and $\epsilon(E)$ is the detector counting efficiency at this energy. Similarly, the count recorded by a filtered detector, C_F , is the integral over the entire neutron energy range of the product of the neutron flux, the filter transmission, and the detector efficiency. Therefore,

$$C_F = \int_0^{\infty} dE \cdot \phi(E) \cdot \tau(E, t) \cdot \epsilon(E), \quad (4)$$

where $\phi(E)$ and $\epsilon(E)$ are the same functions as in Eq. (3), and $\tau(E, t)$ is the filter transmission for neutrons of energy E . This quantity is parametrically dependent on the filter thickness t . The quantity of interest, then, is the ratio of the two integrals, R , where

$$R = \frac{C_F}{C_B} = \frac{\int_0^{\infty} dE \cdot \phi(E) \cdot \tau(E, t) \cdot \epsilon(E)}{\int_0^{\infty} dE \cdot \phi(E) \cdot \epsilon(E)}. \quad (5)$$

Dividing the filtered detector counts by the bare detector response effectively normalizes the system response to the same neutron density, n , Eq. 1.

Substituting the expression for $\phi(E)$, Eq. 1, in the above equation, the count ratio becomes

$$R = \left\{ 2\pi n \left(\frac{2}{m_n} \right)^{1/2} (\pi k T_n)^{-3/2} \cdot \int dE \cdot E \cdot \exp(-E/kT_n) \cdot \tau(E, t) \cdot \epsilon(E) + \right. \\ \left. + C \int dE \cdot E^{-1} \cdot \tau(E, t) \cdot \epsilon(E) \right\} \cdot \\ \cdot \left\{ 2\pi n \left(\frac{2}{m_n} \right)^{1/2} (\pi k T_n)^{-3/2} \cdot \int dE \cdot E \cdot \exp(-E/kT_n) \cdot \epsilon(E) + \right. \\ \left. + C \int dE \cdot E^{-1} \cdot \epsilon(E) \right\}^{-1}.$$

Again it is obvious from this expression that the temperature sensitivity is primarily determined by the Maxwellian term of the neutron flux. The effect of the $1/E$ part of the distribution is second order. Therefore, neglecting for the moment the $1/E$ contribution to the count ratio, R can be written as

$$R \sim \frac{\int dE \cdot E \cdot \exp(-E/kT_n) \cdot \tau(E, t) \cdot \epsilon(E)}{\int dE \cdot E \cdot \exp(-E/kT_n) \cdot \epsilon(E)} .$$

This expression provides a means for an estimate of the temperature gauge response sensitivity. It has been used for a very approximate, preliminary evaluation of the technique sensitivity through numerical estimates of the count ratio. A simple case amenable to manual computation was considered realizing that the validity of the technique is not confined to this very simple example. The detector efficiency, $\epsilon(E)$, was assumed to vary inversely with the square root of the neutron energy which characterizes roughly many neutron detectors in general use. For convenience, the filter was assumed to be 0.0001 inch thick made of boron-10, and its transmission was calculated as will be described in a later section. The calculated count ratio is plotted in Fig. 2 as a function of the neutron moderator temperature which, for simplicity was assumed to be equal to the neutron temperature. The values plotted in this figure have been normalized to the ratio at 250° C. This curve displays a linear dependence of the count ratio on temperature. The sensitivity inferred from the rate of change of the ratio with temperature is, on the average, ~ 0.04 percent change in the ratio per °C change in the temperature in the range between 300°C and 350°C.

The results of the above preliminary estimates have been presented as part of the IRT proposal supplement. It must be emphasized at this point that this example is meant only as a demonstration of the validity of the technique and should by no means be considered as an optimum system. It has been the purpose of this study to optimize the system and demonstrate its ultimate feasibility. The remainder of this report deals with the completed tasks of this study and presents further, more concrete evidence of the temperature gauge feasibility.

The concept under investigation is presented schematically in Figure 3. It makes use of an isotopic ^{252}Cf neutron source whose characteristics will be discussed in the next section. A detector is placed in the sonde at some distance from the fast neutron source to count neutrons thermalized in

Figure 2. Preliminary calculation of the temperature gauge response assuming no $1/E$ contribution to the neutron energy distribution, $1/\sqrt{E}$ detector counting efficiency dependence, and a 0.0001-inch thick boron-10 filter. The technique sensitivity inferred from these computational data is 0.04 percent change in the count ratio per °C change in the temperature.

the formation and diffusing back into the well. A count is obtained first with the detector surrounded by a material of known neutron absorption characteristics (filtered detector count). Another count is then obtained with the same or an identical detector without a filter (bare detector count). The ratio of the filtered to the bare detector counts determines the formation temperature by comparison with the instrument calibration curves. These curves will be generated experimentally by a series of measurements under controlled conditions, i.e., by experimental determination of the filtered to bare detector count ratio at accurately known values of the formation temperature and in well characterized test formations. Figure 3 shows two possible arrangements of the source and detectors. A shield may be necessary to protect the detectors from exposure to source radiation. The off-center arrangement is appropriate for a sidewalled instrument and may be necessary in order to minimize the effect of the borehole fluid.

Figure 3. Schematic representation of two alternate configurations of the formation temperature gauge concept. The configuration on the left is appropriate to a sidewalled instrument. It may be necessary to minimize borehole effects.

2. FORMATION TEMPERATURE GAUGE

2.1 ^{252}Cf SOURCE CHARACTERISTICS

There are currently several types of portable neutron sources in general use. These consist of isotopic neutron sources based on (α, n) reactions (reactions involving the absorption of α -particles and the subsequent emission of neutrons), sealed-beam neutron generators, and isotopic spontaneous fission sources. (α, n) reaction-based sources which include americium-berilium, plutonium-berilium, and radium-berilium among others are not intense enough for general down-hole applications. Similarly, portable neutron generators used primarily in oil well logging to determine formation porosity and neutron absorption properties are intensity limited. More intense, small-sized neutron generators are currently being developed for mineral exploration applications, but these programs are not addressing the high temperature problems. The most immediately applicable neutron source for high temperature use is ^{252}Cf which produces neutrons through spontaneous fission. This source is physically small, and it is available in strengths yielding from less than 10^6 neutrons per second to greater than 10^{10} neutrons per second. Moreover, the standard SR-Cf-100 encapsulation has been tested successfully for integrity to 900°C . The current concept for the determination of formation temperatures makes use of a ^{252}Cf source.

^{252}Cf decays by α -particle emission 97 percent of the time. The remaining 3 percent of the time it undergoes spontaneous fission. This fission rate results in the emission of 2.4×10^{12} neutrons per second per gram of this isotope. Spontaneous fission of ^{252}Cf results in the emission of neutrons with the energy distribution shown in Figure 4 which is nearly identical to the fission neutron spectrum in a nuclear reactor. A relatively small number of neutrons are emitted in (α, n) reactions involving α -particles

Figure 4. Californium-252 fission neutron spectrum.

produced by the decay of ^{252}Cf and light nuclei produced by fission. In addition to the neutrons, gamma radiation is also emitted by a ^{252}Cf source. As shown in Figure 5, this consists of contributions from the α -decay of californium, fission, and the decay of the fission products. Although no β -radiation results from the decay of ^{252}Cf itself, β -particles are emitted as a result of fission product decay. Like the α -particles, however, this radiation does not penetrate the capsule surrounding the source material. Consequently, only gamma and neutron radiation is emitted by encapsulated ^{252}Cf sources.

2.2 NEUTRON DETECTORS

There are several factors which must be considered in selecting a neutron detector for the present feasibility study. The most important of these is the detector characteristics. These include primarily its thermal neutron counting efficiency, its operating temperature range, and its sensitivity to background gamma radiation. Another factor is the availability of the various neutron detectors. The final consideration is the applicability of the detector selected for the feasibility study beyond this phase of concept development to the development of a prototype instrument.

The most widely used and apparently most highly developed neutron detectors are gas-filled proportional counters. These are tubes filled with gases containing neutron absorbing elements. Another type of neutron detector currently in use is the scintillation detector. In this case, the neutron absorbing element is contained in a scintillating material (crystal or liquid phosphor). Such devices, however, are not appropriate for applications at temperatures above 25°C because they make use of photomultiplier tubes which operate reliably at or below room temperature. Therefore, scintillation neutron detectors would require cooling even at very low temperatures encountered in geothermal environments. Another important disadvantage of these detectors is their high sensitivity to gamma radiation rendering their operation inappropriate in the presence of even moderate gamma fields. Certain kinds of gas-filled counters, on the other hand, are currently used to monitor fluxes in high temperature regions inside nuclear

Figure 5. Californium-252 gamma spectrum. The various components of the spectrum are shown as described in the text.

reactors. Such detectors are operable at temperatures up to 760°C without cooling. Furthermore, gas-filled counters are generally very insensitive to gamma rays even in very intense fields.

The major components of a thermal-neutron gas-filled proportional detector are the neutron sensitive element and the fill gas. The neutron sensitive element is an isotope with high affinity for thermal neutron absorption; i.e., high thermal neutron absorption cross section. It can be part of the fill gas as boron-10 in BF_3 filled counters and helium-3 in ^3He filled detectors, or it may be plated to the counter walls as boron-10 in boron-lined detectors and uranium-235 in fission detectors. Neutron absorption by the neutron sensitive elements results in the release of various charged particles in the detector chamber occupied by the fill gas. These charged particles traverse the chamber volume in directions defined by an applied electric field causing ionization of the fill gas. Collection of the induced ions and electrons by the field electrodes results in the detector output of a charge pulse for each neutron absorbed in the sensitive volume of the detector.

The various types of gas filled thermal neutron detectors are distinguished by the kind of filling gas and the kind and form (gaseous or plated) of the active element used. The general design characteristics obviously determine the general operational detector characteristics. The type and abundance (fill gas pressure or plate thickness) of the neutron sensitive isotope used, together with the detector chamber geometry, structural design, and fill gas pressure determine the counting efficiency. The fill gas ionization characteristics determine the pulse shape, and, hence, the detector resolution. The general insensitivity of these devices to gamma radiation is a result of the low density of the fill gas even at high fill gas pressures. The low density results in relatively low ionization of the fill gas by gamma rays.

Of the various gas filled neutron detectors available, the ^3He counters are the most efficient followed in order of decreasing counting efficiency by BF_3 filled, ^{10}B lined, and ^{235}U lined detectors. The rating in terms of sensitivity to gamma radiation is exactly the same with ^3He filled detectors being the most sensitive and the ^{235}U fission chambers being the least sensitive. Even the most sensitive ^3He detectors, however, are relatively

insensitive to gamma radiation and they have been operated satisfactorily in the presence of moderately high gamma fluxes. Standard ^3He filled detectors used in oil well logging can be used at temperatures up to 200°C . The operating temperature limit of standard BF_3 filled counters is 100°C although special design has extended this limit to 150°C . Standard ^{10}B lined detectors are limited to operation at temperatures at or below 150°C , while specially designed devices are operable up to 300°C . ^{235}U fission chambers are operable at temperatures above the operating range of other gas filled neutron detectors. Standard devices are operable up to 300°C , while specially designed detectors have been operated at 760°C .

A ^3He filled neutron detector was selected for use in the present feasibility study of the formation temperature gauge for various reasons. ^3He filled detectors are the most efficient of the gas filled proportional neutron detectors. The specific detector selected for use in this study is a Reuter-Stokes P4-0410-204 counter. This is a one-half-inch diameter by 10-inch long cylinder filled with ^3He gas at 20 atmospheres pressure. The counting efficiencies of this detector and a similar ^3He counter filled at 5 atmospheres pressure have been calculated and are shown in Figure 6. It is readily seen that the counting efficiency of these detectors is high for thermal neutrons but it decreases rather rapidly as the neutron energy increases beyond the thermal range. These calculated counting efficiency curves have been used in the computational study of the formation temperature gauge response (Equation 5) which will be discussed in a later section. In addition to high neutron counting efficiency, the above detectors are sufficiently insensitive to gamma rays. The anticipated background gamma radiation due to gamma emission by the ^{252}Cf source and by formation elements subsequent to neutron absorption will not significantly affect the operation of these detectors. Furthermore, the operating temperature range of the detector chosen is sufficiently high for the purposes of the present experimental feasibility study. Moreover, this counter was readily available.

The above consideration led to the selection of the ^3He detector for use in the present study. Regarding the applicability of this detector beyond the technique feasibility phase, it should be noted that the RS-P4-0410-204 detectors have been used in oil well logging tools and, therefore, their operating characteristics in logging operations have been established within

Figure 6. Calculated detector efficiency of ^3He filled proportional counters. The solid curves represent the efficiencies at the lower energies, 0.001 to 1.0 eV, while the dashed curves are their corresponding extensions in the energy range from 1.0 to 1000 eV.

its present operating temperature range. Since the operating temperature range is limited by structural design considerations, it is possible that the 200°C upper limit can be extended, perhaps to or beyond the 275°C ERDA short-range goal, by special design. If the high operating temperature limit cannot be extended by advanced design, ^3He detectors may still be used in a geothermal well logging tool provided that they are cooled to temperatures somewhat below 200°C. This may prove to be not a very difficult task. Assuming that cooling the detector proves to be inconvenient or inappropriate, then a ^{10}B lined detector operable at temperatures up to 300°C may be used instead of the ^3He filled counter. It is expected that in that case, the qualitative conclusions of this study will still be valid.

2.3 FILTER MATERIALS

The neutron filter, i.e., a material with selective (energy dependent) neutron absorption (or transmission) properties, is one of the critical, if not the most important component of the formation temperature gauge. Therefore, care has been taken to select the most suitable element. An ideal filter material would be one which absorbs practically all neutrons with energies lower than ~ 0.03 eV (see Figure 1), but none of the neutrons with energies higher than this cutoff. Such a material would have to have a very high-neutron absorption cross section below the cutoff energy, and very low or zero cross section above it. The neutron transmission for this ideal filter then would be essentially zero below and 100 percent above the cutoff. Unfortunately, such an ideal material does not exist. Therefore, the first criterion in selecting a suitable neutron filter for the temperature gauge is that its neutron absorption (transmission) characteristics approximate as closely as possible those of the ideal.

A search revealed several promising materials. These can be categorized as $1/v$ absorbers and low-energy resonance absorbers. The first category includes elements whose thermal neutron absorption cross section varies inversely with the neutron velocity (or inversely with the square root of the neutron kinetic energy) and is exemplified by boron-10 (^{10}B) and lithium-6 (^6Li). The second category includes elements with resonances (peaks) in their thermal absorption cross section. Such elements include

cadmium (Cd), lutetium (Lu), samarium (Sm), xenon-135 (^{135}Xe), and gadolinium (Gd) with resonances at 0.173, 0.142, 0.095, 0.082, and 0.03 eV, respectively.

Further considerations in the filter selection process include nuclear stability of the above elements, availability, and radiation emission subsequent to neutron absorption. On the basis of these and the above criterion, the filter choice was narrowed down to B, Sm, and Gd. Neutron transmission curves were computed for these materials using the expression

$$\tau(E,t) = \exp[-\Sigma_a(E) \cdot t] \quad , \quad (6)$$

where $\Sigma_a(E)$ is the neutron absorption cross section for neutrons with kinetic energy E , and the remaining variables are the same as in Equation 4. The computed transmission curves are shown in Figure 7. The ultimate criterion for the selection of the most suitable filter is the temperature gauge sensitivity or rate of variation of the filtered-to-bare detector count ratio with temperature, Equation 5, obtained when each of the three filters is used. This selection has been made on the basis of calculations described in the next section.

Figure 7. Calculated transmission functions for boron, samarium, and gadolinium filters. The corresponding filter thicknesses are given. In each case, the isotopic abundance of the filter material is that which is found in the natural composition of the element.

3. COMPUTATIONAL STUDY OF THE TEMPERATURE GAUGE RESPONSE

As is generally the case with the study of a new concept, the purpose of the present computational analysis is two-fold. First, it is the purpose of the calculations to be described in this section to establish the soundness of the formation temperature gauge concept and in so doing, to determine whether or not an experimental study of the technique is warranted. Having established the applicability of the method, the results of the calculations determine suitable detector and filter combinations and serve as a starting point for optimization experiments.

It is extremely difficult and very costly to perform the necessary calculations for situations corresponding exactly to the experimental arrangement in terms of geometric and compositional details. Since the above stated aims of the computational study can be fulfilled by performing approximate (simplified model) calculations, elaborate calculations are not warranted at this time. The computations which will be described in the following paragraphs were carried out on the basis of a simplified model, and, although they serve the purposes stated above, their results are rather approximate. For this reason, it is not, nor has it ever been, our intention to use the results of the present computational study as a calibration of the temperature gauge response. As previously stated, the instrument calibration curves will be generated experimentally.

3.1 COMPUTATIONAL ARRANGEMENT

As noted in preceding paragraphs, the neutron temperature (the characteristic temperature of the Maxwellian portion of the thermal neutron spectrum) is directly proportional to the moderator temperature, the proportionality constant depending simply on the formation neutron properties in Equation 2. In order to determine the proportionality between the neutron

and moderator temperatures for materials to be used in this study, and to check the validity of assumptions made regarding the nature of the thermal neutron energy distributions, fluxes were computed at various temperatures of the moderator using essentially a very simple transport code. The particular computer code used is called GGC, and it was developed at General Atomic. It considers a monoenergetic, fast-neutron source uniformly distributed in the moderating medium. To avoid the complexity inherent in finite geometry computations of this kind, the code also assumes an infinite medium. The thermal neutron flux resulting from the slowing down of source neutrons is computed using well established, standard nuclear reactor physics techniques, and the most recent nuclear cross-section data.

To test the validity of our assumptions regarding the shape of the thermal neutron energy distributions, Equation 1, thermal neutron fluxes were calculated in an infinite water moderator at various temperatures in the range of interest (300°K to 600°K , or from about room temperature to 327°C). The results of this set of calculations verified our assumptions. The calculations indicate that Equation 1 is completely valid for a water moderator. Furthermore, they show that in water the neutron temperature, T_n , is equal to the moderator temperature, T , i.e., the proportionality between the two quantities, Equation 2, is one. This is shown in Figure 8 which is a comparison between the GGC-calculated flux in water at 300°K (27°C) and a Maxwellian functions with $T_n = 300$. The agreement is just as good at the various other temperatures at which similar comparisons were made. The constant C to be used in Equation 1 can be determined from the high-energy region of the GGC-calculated flux. For water $C \sim 4125 \cdot n$.

Similar computer calculations of the thermal neutron flux were performed for moderators consisting of various mixtures of silica sand (SiO_2) and water at 300°K . As in the case of the pure water moderator, this set of calculations verifies the assumed functional dependence of the thermal neutron flux on the neutron energy, Equation 1. In this case, however, the neutron temperature, T_n , is not the same as the temperature of the moderator, T . The proportionality constant is shown graphically in Figure 9 as a function of the water content of the $\text{SiO}_2 \cdot \text{H}_2\text{O}$ mixture. The points represent the neutron temperatures inferred from the CGC-calculated thermal neutron fluxes and the error bars represent the corresponding uncertainties. The

Figure 8. Comparison between the transport-calculated (GGC) thermal neutron flux in water at $300^\circ K$ and the corresponding Maxwellian function, i.e., the first term of Eq. (1), with $T_n = 300^\circ K$.

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Figure 9. Variation of the apparent formation temperature (Maxwellian temperature) of 17 percent porous quartz formation with various degrees of water saturation. The neutron temperatures inferred from the GGC-calculated spectra (data points) are compared with the expression of Czubek (1969) (solid curve). The dashed curve represents a least squares fit to the data by a similar expression by varying the empirical constant (implicit in 0.02687).

solid line is a plot of the expression reported by J. A. Czubek in a paper published in the Proceedings of the Symposium on the Use of Nuclear Techniques in the Prospecting and Development of Mineral Resources held by the IAEA in Buenos Aires, on November 5 - 9, 1968. This expression is equivalent to Equation 2. The dashed curve represents the same equation with a rather small adjustment of the empirical constant in Czubek's expression, contained in 0.02687, whose value is "questionable". The adjusted expression fits the neutron temperatures inferred from the GGC-flux calculation very well, thus establishing the validity of Equation 2, and the relation between T_n and T for various $\text{SiO}_2 \cdot \text{H}_2\text{O}$ mixtures.

3.2 CALCULATION OF THE FILTERED-TO-BARE DETECTOR COUNT RATIO

In order to minimize the complexity of the problem and to make comparison between calculation and experiment as direct as possible, the filtered to bare detector count ratios, Eq. (5), were computed for an infinite water medium. This approach avoids finite geometry problems, thus keeping the calculations as simple as possible, and takes advantage of the equality between the neutron and moderator temperatures. The results of these calculations will be compared with measurements of the corresponding ratios in water, the geometry of the experiment being such as to approximate as closely as practicable the computational situation. Such a comparison will result in a basic understanding of the gauge response which is essential prior to its application in the complex geometry approximating closely the geothermal well environment.

The temperature gauge response, i.e., the filtered to bare detector count ratio as a function of temperature, has been calculated according to Eq. (5). The necessary integrals, Eqs. (3) and (4), were evaluated on a computer by numerical integration. Count ratios, R , were computed at moderator (water) temperatures from 300°K (27°C) to 600°K (327°C). The thermal neutron fluxes, $\phi(E)$, used in the calculations were computed according to Eq. (1) with the value of the constant C extracted from the GGC-calculated fluxes. Most of the calculations were performed using the calculated counting efficiency of the RS-P4-0410-204 ^3He detector shown in Fig. 6, although a

limited number of calculations were also performed for comparison using the efficiency curve of the 5 atmosphere fill gas pressure detector. The transmission functions of boron, samarium, and gadolinium filters computed according to Eq. (6) were used to determine the most suitable filter.

The computed count ratios appropriate to the RS-P4-0410-204 ^3He filled detector and to boron, samarium, and gadolinium filters of various thicknesses are shown in Figs. 10, 11 and 12, respectively. The technique sensitivities corresponding to the various filters and filter thicknesses are more readily compared when the corresponding gauge responses are normalized to the count ratio values at one temperature. Therefore, the same sets of curves normalized to the corresponding count ratio values at 27°C (300°K) are shown in Figs. 13, 14, and 15, respectively. The normalized curves for each of the three filters show that use of the thicker filters results in higher gauge sensitivity. The higher sensitivity, however, is achieved at the expense of lower transmission as shown by the corresponding absolute values of the count ratios. Therefore, the system sensitivity is limited by the filter transmission, and a filter thickness should be used which renders the gauge sufficiently sensitive at reasonable filter transmission values. Put another way, the filter transmission must be sufficiently high to yield detector count rates yielding high statistical accuracy at reasonable counting intervals. Comparing the computed temperature gauge response corresponding to the various filters it is apparent that the highest sensitivity is obtained with the "thick" gadolinium filters. On this basis a ~ 0.006 cm thick gadolinium filter appears to be the most suitable.

The accuracy of the computed values of the count ratio, R , can be estimated in terms of the relative uncertainties in the thermal neutron flux, the detector counting efficiency, and the filter transmission. This is readily accomplished by the standard error propagation method once the integrals in Eq. (5) are approximated by sums in the process of numerical integration. In other words, since

Figure 10. Calculated formation temperature gauge response, Eq. (5), in water using a RS-P4-0410-204 ^{31}Li filled detector, and natural isotope abundance boron filters of various thicknesses.

Figure 11. Calculated formation temperature gauge response, Eq. (5), in water using a RS-P4-0410-204 ^3He filled detector, and natural isotope abundance samarium filters of various thicknesses.

Figure 12. Calculated formation temperature gauge response, Eq. (5), in water using a RS-P4-0410-204 ^3He filled detectors, and natural isotope abundance gadolinium filters of various thicknesses.

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Figure 13. Calculated formation temperature gauge response, Eq. (5), in water using a RS-P4-0410-204 ^3He filled detector, and natural isotope abundance boron filters of various thicknesses. These curves have been normalized to the corresponding count ratio values at 27°C.

Figure 14. Calculated formation temperature gauge response, Eq. (5), in water using a RS-P4-0410-204 ^3He filled detector, and natural isotope abundance samarium filters of various thicknesses. These curves have been normalized to the corresponding count ratio values at 27°C.

Figure 15. Calculated formation temperature gauge response Eq. (5), in water using a RS-P4-0410-204 ^3He filled detector, and natural isotope abundance gadolinium filters of various thicknesses. These curves have been normalized to the corresponding count ratio values at 27°C .

$$R = \frac{C_F}{C_B} \sim \frac{\sum_i \Delta E_i \cdot \phi(E_i) \cdot \tau(E_i, t) \cdot \epsilon(E_i)}{\sum_j \Delta E_j \cdot \phi(E_j) \cdot \epsilon(E_j)} \quad (7)$$

$$\begin{aligned} \sigma_R^2 \sim & \left\{ \Delta E_i \cdot \epsilon(E_i) \cdot \sum_j \Delta E_j \cdot \phi(E_j) \cdot \epsilon(E_j) + \right. \\ & \left. - (\Delta E_i)^2 \cdot \phi(E_i) \cdot \epsilon^2(E_i) \right\}^2 \frac{e^{-2 \cdot \sum_a(E_i) \cdot t} \cdot \sigma_{\phi(E_i)}^2}{[\sum_j \Delta E_j \cdot \phi(E_j) \cdot \epsilon(E_j)]^2} + \\ & + \left\{ \Delta E_i \cdot \phi(E_i) \cdot \sum_j \Delta E_j \cdot \phi(E_j) \cdot \epsilon(E_j) + \right. \\ & \left. - (\Delta E_i)^2 \cdot \phi^2(E_i) \cdot \epsilon(E_i) \right\}^2 \frac{e^{-2 \cdot \sum_a(E_i) \cdot t} \cdot \sigma_{\epsilon(E_i)}^2}{[\sum_j \Delta E_j \cdot \phi(E_j) \cdot \epsilon(E_j)]^2} + \\ & + \left\{ \frac{\Delta E_i \cdot \phi(E_i) \cdot \epsilon(E_i)}{\sum_j \Delta E_j \cdot \phi(E_j) \cdot \epsilon(E_j)} \right\}^2 \cdot t^2 \cdot e^{-2 \cdot \sum_a(E_i) \cdot t} \cdot \sigma_{\sum_a(E_i)}^2 \quad (8) \end{aligned}$$

where σ_R , $\sigma_{\phi(E_i)}$, $\sigma_{\epsilon(E_i)}$, $\sigma_{\sum_a(E_i)}$ are the uncertainties in the count ratio, and the flux, detector efficiency, and filter absorption cross section at neutron energy E_i . Assuming that the relative uncertainty in the flux is ± 5 percent throughout the thermal energy range, the relative uncertainty in the computed counting efficiency is ± 0.5 percent, and the relative uncertainty in the neutron absorption cross section is ± 2 percent, the uncertainty in the calculated count ratios, R , is ± 1 percent in the temperature range considered. The corresponding uncertainty in the temperature for the system using a 0.006 cm thick gadolinium filter is $\sim \pm 2^\circ \text{C}$. Since the sensitivity is lower for the various other filters considered the corresponding temperature uncertainty will be greater than $\pm 2^\circ \text{C}$.

The sensitivity of the temperature gauge utilizing a 0.006 cm thick gadolinium filter is plotted in Fig. 16. The quantity plotted here is the percent change in the computed count ratio per $^{\circ}\text{C}$ change in the water temperature. It should be pointed out that this sensitivity represents an order of magnitude improvement over our preliminary estimates (Fig. 2).

The effect of the detector efficiency on the gauge response has been examined by comparing the calculated count ratios corresponding to two detectors with different counting efficiencies, i.e., different fill gas pressures. The two detectors considered are the RS-P4-0410-204 (20 atm fill gas pressure) and the 5 atmosphere fill gas pressure detector whose counting efficiencies are shown in Fig. 6. The computed count ratios are plotted in Fig. 17. The more efficient (higher fill gas pressure) detector yields higher count ratios and a slightly higher slope of the count ratio vs temperature curve. Therefore, the temperature gauge utilizing the more efficient detector is more sensitive.

In an infinite moderating medium with a uniformly distributed neutron source, the flux given by Eq. (1) is independent of position. In a finite moderator, localized source situation, however, the $1/E$ portion of the neutron energy distribution is position dependent in the immediate vicinity of the source. In other words, C in Eq. (1) decreases with increasing distance from the source approaching its infinite moderator-uniformly distributed source value at points sufficiently removed from the neutron source. Thus at sufficient distance from the neutron source, a state of equilibrium is established between thermal neutron diffusion and fast neutron thermalization. Beyond the distance necessary for the onset of this equilibrium C stays fixed, and the neutron flux, Eq. (1), in the finite geometry differs only slightly from that in the infinite medium-uniformly distributed source situation.

The effect of position dependence of $\phi(E)$ on the temperature gauge response has been examined by comparing the computed count ratios corresponding to neutron fluxes with various numbers of neutrons in the $1/E$ portion of the energy distributions, i.e., for various values of C . These ratios are plotted in Fig. 18. It is apparent that a higher $1/E$ contribution

Figure 16. Formation temperature gauge sensitivity derived from the calculated temperature gauge response in water using Eq. (5), an RS-P4-0410-204 ^3He filled detector, and a 0.006 cm thick natural isotope abundance gadolinium filter.

Figure 17. Calculated formation temperature gauge response using Eq. (5) with a RS-P4-0410-204 ^3He filled detector and a similar detector with 5 atmospheres fill gas pressure and with a 0.006 cm thick natural abundance gadolinium filter. Higher sensitivity is obtained with higher detector efficiency, i.e., higher fill gas pressure.

Figure 18. Calculated formation temperature gauge response using Fq. (5) at various 1/E spectrum amplitudes (various values of C) with a RS-P4-0410-204 ^3He filled detector and a 0.006 cm thick natural abundance gadolinium foil. Higher sensitivity results with more complete thermalization, i.e., lower 1/E contribution.

(small source to detector distance) results in higher count ratios but lower sensitivity (lower slope of the count ratio vs temperature curve). Since the contribution to the count ratio by neutrons in the $1/E$ region cannot be eliminated, it should be minimized by locating the detector sufficiently far from the neutron source where the equilibrium state discussed in the previous paragraph exists.

4. EXPERIMENTAL STUDY OF THE TEMPERATURE GAUGE RESPONSE

4.1 PRELIMINARY MEASUREMENTS

Having computed the response of the formation temperature gauge on the basis of a simplified model as described in previous sections, simple, preliminary measurements were performed. Their purpose was to verify the results of the calculation and determine their reliability before proceeding to more elaborate, costly, realistic experiments. The preliminary measurements were performed with an experimental arrangement using the simplest possible geometry reproducing fairly closely the computational situation.

4.1.1 Experimental Arrangement

The water in which the preliminary measurements were performed was contained in a 1/8 inch thick wall cylindrical stainless steel container. Its diameter was 10.5 inches and its length 27 inches. Two immersion heaters capable of supplying 1000 watts each at 240 volts were fitted to the bottom of the container. A Variac was used to control the voltage applied to the heaters and hence their power output and water temperature. Provisions were made to circulate the water from the bottom of the tank to the top in a closed loop using a pump with maximum circulation rates of ~ 7 gallons/min. This was done to insure that the water was evenly heated. Alternatively the water could be circulated through a heat exchanger to enhance cooling. This was necessary to reduce the times required to lower the water temperature, and also to provide additional temperature control. Such control was accomplished manually. The water temperature was determined sufficiently accurately (to within a few tenths of a degree) using a laboratory mercury thermometer.

Figure 19 a schematic top view of the experimental arrangement showing the positions of the ^{252}Cf source and the ^3He filled detector. Very thin wall stainless steel tubes with the bottom ends closed were immersed in the water. They were located on a diameter each approximately 2 inches away from the tank wall and with a separation distance of 6 inches between their centers. The californium source ($0.3\ \mu\text{g}$ ^{252}Cf equivalent to $\sim 150\ \mu\text{Ci}$) was lowered into one of the tubes ~ 7 inches below the surface of the water, and the detector was inserted into the other. Although most of the measurements described below were performed in this configuration data were taken at various other source to detector and source to water surface distances to insure that the above configuration was optimum.

The detector used was an RS-PA-0410-204 ^3He filled proportional counter designed for oil well logging application. The detector and associated standard counting electronics used were available at our laboratory. The filter used was a cylinder with diameter slightly larger than that of the detector ($\sim 1/2$ inch), and 0.005 cm thick wall. It was made of two layers of 1 mil thick gadolinium foil.

4.1.2 Measurements

The measurements described in this section consist of counts taken at various temperatures between 20°C and 95°C . At each temperature counts were recorded with the detector alternately bare (without a filter) and shielded by the 2 mil thick gadolinium sleeve. The measurements were made after the water temperature had been stabilized at preselected values by adjusting the voltage to the immersion heaters and/or the circulation rate through the heat exchanger. Sufficient counts were accumulated at each temperature for the statistical uncertainty to be acceptably low. The count ratio was computed at each temperature by dividing the filtered detector count by the bare detector count at the same temperature.

One of the conclusions of our computational study was that the temperature gauge sensitivity is higher the smaller the relative number of neutrons with energies in the $1/E$ region of the flux, i.e., the lower value of C in Eq. (1).

Figure 19. Schematic of top view of the experimental arrangement for preliminary temperature gauge response measurements. The diagram shows relative positions of the neutron source and detector.

In fact, in a finite moderator with a localized neutron source the sensitivity is maximum when the detector is located at points sufficiently far from the source where equilibrium exists between fast neutron thermalization and thermal neutron diffusion. Therefore, it was important at the outset to determine the optimum source to detector distance. This distance is determined by two competing factors. The thermal neutron flux decreases very rapidly with distance away from the source, but the sensitivity increases up to a certain point with increasing distance from the source. Therefore, the optimum distance is that at which the above equilibrium state is reached if it is not so large that the thermal neutron flux is unacceptably low. In the present arrangement it was found to be ~ 6 inches. This value was determined by measuring the count ratio, R , for various source to detector distances. The count ratio reached its minimum value at or slightly below the 6-inch source to detector separation.

Having optimized the experimental arrangement, the temperature gauge response was obtained for water and for water containing various amounts of a neutron absorber, i.e., boric acid (H_3BO_3). The gauge response for each of the various water-absorber solutions consists of a plot of the observed filtered to bare detector count ratio as a function of temperature. The most extensive measurements were made in water with no absorber added. The observed ratios are shown in Figure 20. The error flags in this case represent the corresponding statistical counting uncertainties. At several temperatures, the corresponding count ratios were determined more than once to demonstrate repeatability. On the same figure is shown the calculated response for the infinite moderator. It can readily be seen that although the agreement between the measured and calculated gauge response is not exact, the maximum disagreement is about 15 percent at the lower temperatures. (Note that the vertical axis of this figure starts at a count ratio value of 0.05 not 0). The discrepancy is most likely due to the finite geometry of the experimental arrangement. The effect of finite geometry is to allow thermal neutrons to diffuse out of the moderating medium, thus, shifting the energy distribution to higher energies. As a result, the gauge response indicates a temperature higher than that of the water moderator. Since the calculations were made for an infinite moderator, they do not take into account effects of the finite geometry. Therefore, the above discrepancy is attributable to the inadequacy of the simplified model calculations.

Figure 20. Calculated and observed count ratios of Gd filtered to bare detector counts in water. The calculated response (line curve) was obtained for an infinite medium using Eq. (5). The measured response corresponds to the finite geometry arrangement in Figure 19. In both cases the filter is 0.005 cm thick natural abundance gadolinium. Both calculation and experiment imply a gauge sensitivity of ~ 0.3 percent count ratio change per $^{\circ}\text{C}$ temperature change.

For the reason cited above, the discrepancy between the observed and calculated temperature gauge response shown in Figure 20 is not important. The important fact is that both the calculated and the measured count ratios vary with temperature. Furthermore, the relative variations are approximately equal and, more importantly, they are very reasonable as far as the technique feasibility is concerned. The average sensitivity implied by both the calculated and the measured response shown in Figure 20 is approximately 0.3 percent change in the count ratio per °C change in the temperature.

Comparison of the measured and calculated response shown in Figure 20 cannot be used to assess the temperature sensitivity of the concept. Such an assessment cannot be made on the basis of the data presented here because both in the measurement and in the calculation temperature is the independent variable, i.e., the temperature is accurately known in each case. The temperature sensitivity of the gauge can only be determined by comparing the observed count ratio at an arbitrary temperature with the gauge calibration curves. Therefore, the above discrepancy between measured and calculated ratios should be of no concern, since as was pointed out previously, it is not our intention to use these computational results as a calibration of the gauge response. The discrepancy merely shows the inadequacy of the present computational technique.

Measurements have also been performed in various water-boric acid solutions to study the effect of moderator absorption on the temperature gauge response. The neutron absorbing element in boric acid is boron. The solutions studied contained 42.5, 85.0, and 127.5 g boric acid which in terms of absorption are equivalent to salt (NaCl) solutions of 2.4, 4.8, and 7.2 weight percent, respectively. The results of this set of measurements are plotted in Figure 21, together with data in water with no added absorber. The error bars in this case are not larger than the size of the data points. Repeatability is again demonstrated at several temperature. The curves in Figure 21 indicate that the temperature gauge concept is applicable even in the presence of rather high thermal neutron absorber concentration. The increase in the count ratio with increased amounts of the dissolved absorber is caused by the thermal neutron absorption cross section of boron which varies as $1/\sqrt{E}$. Therefore, since the lower energy thermal neutrons are more readily absorbed, the neutron energy distribution, Eq. (1), is shifted to higher energies increasing the neutron temperature, T_n , relative to the temperature

Figure 21. Ratios of observed Gd filtered to bare detector counts in water and various water-boric acid solutions. These measurements were made using the preliminary arrangement (Figure 19) described in the text.

of the moderator, T , Eq. (2). The energy dependence of the thermal neutron absorption cross sections of most absorbing elements is similar to that of boron. Therefore, in general, absorbers present in the formation will affect the temperature gauge response in a similar manner.

4.1.3 Experimental Technique Accuracy and Sensitivity

As noted earlier, the formation temperature, in actual practice, is to be determined by comparing the gauge response with the instrument calibration curves. These calibration curves must be generated by a series of measurements under controlled conditions. In the specific case of the temperature gauge, calibration curves are obtained by experimental determination of the filtered to bare detector count ratio at accurately known values of the formation temperature. This establishes the rate of variation of gauge response with temperature and determines the sensitivity of the technique. The greater the rate of the gauge response variation the higher its sensitivity.

The experimentally determined uncertainty in a single determination of the filtered to bare detector count ratio in the above measurements, Figure 21, is ± 0.0004 for values of the ratios in the range from 0.0750 to 0.1350. This results in a temperature uncertainty of less than $\pm 3.5^\circ\text{C}$ near room temperature, for the highest concentration boric acid solution, to less than $\pm 2^\circ\text{C}$ near 100°C . These values of the temperature uncertainty are conservative estimates of the proposed technique sensitivity because no attempt has been made to optimize the system response. That is, we have used only a very small neutron source ($0.3\ \mu\text{g}\ ^{252}\text{Cf}$), reasonably short counting intervals (15 minutes), and standard detection and counting equipment available in our laboratory. Therefore, a precision of $\pm 2^\circ\text{C}$ at a temperature of 300°C is a reasonable projection of the above low temperature data.

Since the observed uncertainty due to counting statistics is ± 0.0002 to ± 0.0003 in the above ratio range, it is obvious that the uncertainty in the system response is mainly due to counting statistics which depend entirely on the number of counts recorded by the neutron detection system. Therefore, it can be minimized by increasing the total number of recorded counts, i.e., by increasing the detection efficiency, the neutron source strength, and/or the length of the counting interval. Systematic errors can result from system

instabilities and these have to be determined by a large number of independent measurements. Having experimentally determined the temperature dependence of the gauge response and the uncertainty in any single determination of this response, it was possible to estimate the total uncertainty in the temperature measurement. The above precision estimates take into account both the counting and systematic uncertainties. In the final analysis, however, it is expected that the perturbations caused by the borehole will be the limiting factor in achieving the best possible precision. The experiments described below will help define these limitations.

4.2 FORMATION TEMPERATURE GAUGE TEST STAND

Geometry effects notwithstanding, the preliminary measurements described in the preceding section do substantiate the results of our computations. Furthermore, they demonstrate the feasibility of the concept in the "simple" geometry and indeed justify proceeding with the second phase of the experimental study involving measurements in an arrangement simulating a geothermal well. A test stand to perform these measurements has been designed, its components have been fabricated, and it has been assembled. The system is presently being checked out in preparation for the final phase of the present experimental study.

A schematic drawing of the system is shown in Figure 22. The test formation is placed on a platform so that the "borehole" and sonde mockup are accessible from the bottom as well as from the top. The test formation consisting of pure silica sand or various silica sand and water mixtures as well as just plain water is contained in a large cylindrical tank made of 1/4-inch mild steel. It has a 54-inch diameter and it is 54 inches high. The central hole, the borehole, is formed by a 10-inch diameter, 0.094-inch thick wall aluminum tube extending about 4 inches above the top of the formation container. The above borehole diameter was chosen to correspond closely to the minimum diameter of an uncased geothermal well. Through a literature search and discussions mainly with Sandia Geothermal Division personnel, this diameter was found to be 9-5/8 inches. The inside diameter of the central tube in Figure 22 is 9.81 inches. As a result, the test formation thickness is 21.75 inches. This dimension is several times greater than the effective infinite volume

Figure 22. Schematic diagram of the formation temperature gauge test stand. Its various components and their dimensions are discussed in the text. (*) designate thermocouple positions.

dimension for water but only about $2/3$ the effective infinite volume dimension for pure, dry silica. Effective infinite volume is defined as the finite volume of a sample whose dimensions are sufficiently large so that the effect of the finite geometry on the quantity being measured is negligible. As a consequence of the above choice of the test formation thickness, practically all of the source neutrons entering the test volume will be thermalized within a few inches (~ 6 inches) from the borehole wall when the tank is filled with water. On the other hand, when the test formation is dry silica sand all but a small fraction (< 5 percent) of the neutrons traversing the 21.75 inches of silica will have been thermalized. It is not expected that this will have a significant effect on the results of this study. A larger sample volume for the present study would not be practical because of heating requirements.

In the present experimental arrangement, the power necessary to heat the test formation is provided by 12 strip heaters oriented parallel to the cylinder axis, and spaced equally around the periphery. Each heater generates 1250 watts of heat at 240 volts and can withstand temperatures as high as $250-300^{\circ}\text{C}$. Variable voltage is provided by three coupled variacs each controlling four heaters connected in parallel. The variac output is switched on and off by a contactor switch which is operated by a thermocouple controller so that it is engaged, and the variac output is applied to the heaters, when the controlling thermocouple indicates a temperature below the preset value. When the temperature has reached (or just passed) the value preset on the controller, the contactor is disengaged and the voltage to the heaters is cut off. Power to the strip heaters is then cycled on and off controlling the formation temperature automatically with small, periodic deviations from the preset value.

The controlling thermocouple is one of about 18 thermocouples, 15 of which are located in the test formation and the remaining three in the borehole. Their locations are designated by asteriks (*) in Figure 22. The rather large number of thermocouples is necessary to determine very carefully the temperature variations within the test formation. This will be important in interpreting the data. The thermocouples inside the central tube (borehole) are needed to monitor the temperature of the water which will be circulated through it as will be discussed below.

The test formation container and attached heater are covered on all sides by thermal insulation (ETR board). This essentially eliminates large heat losses to the room air and facilitates heating of the test formation, thus drastically reducing the wait times for temperature changes.

The sonde mockup consists on the outside of a 3-inch diameter x 0.083-inch thick wall stainless steel (type 304) tube. The 3-inch outside diameter was selected to be near the diameter of standard downhole tools used in logging uncased oil wells. The diameter of such instruments is 3-5/8 inches. Inside the 3-inch diameter tube are spotwelded two thin wall stainless tubes. The two tubes are lined up on one side of the "sonde" as shown in Figure 22. The tube located on the top has a 3/16-inch outside diameter, 0.012-inch-thick wall, and is open at both ends. The tube located at the bottom has a 5/8-inch outside diameter, 0.010-inch thick wall, and its top end is sealed. The function of the two tubes is seen in Figure 22 which shows the ^{252}Cf source inserted in the top tube while the neutron detector is located inside the one at the bottom. The bottom end of the sonde mockup is sealed, except for the opening of the thin wall tube, and is filled with a solution of boric acid (H_3BO_3) in glycerin ($\text{C}_3\text{H}_8\text{O}_3$). This shields the detector from neutron radiation from the source as well as from source neutrons thermalized by the borehole fluid (water in the central, aluminum tube). Glycerin was chosen as the solvent because of its high hydrogen content and relatively high boiling point (290°C). The high hydrogen concentration in the shield is needed to slow down the fast source neutrons (hydrogen in the most efficient neutron moderator) so that they can be absorbed by the boron atoms in the boric acid.

In order to simulate the effects of the fluid flow through a borehole, provisions have been made to circulate water through the center tube. As shown schematically in Figure 22, water is pumped into the center tube at the bottom. The water can also be circulated through a heat exchanger before entering the central tube to remove heat as necessary to keep the water temperature constant throughout the counting interval. The water temperature will be lower than that of the test formation as is generally the case in geothermal wells. The maximum flow rates obtainable with the present system will be 6-9 gallons of water per minute.

4.3 MEASUREMENTS PLANNED

The next month will be devoted to measurements of the formation temperature gauge response in the borehole geometry using the test stand and sonde mockup just described. The experiments planned include measurements of the gauge response under the following conditions:

1. Water test formation with air in the borehole.
2. Water test formation with water flowing through the borehole (borehole fluid temperature is different than that of the test formation).
3. Water with dissolved absorber formation with water flowing through the borehole.
4. Dry silica sand test formation with air in the borehole.
5. Dry silica sand test formation with water flowing through the borehole at lower temperatures.
6. Wet silica sand test formation with water circulated through the borehole at lower temperatures.