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FEASIBILITY INVESTIGATION AND DESIGN STUDY OF OPTICAL WELL LOGGING METHODS FOR HIGH TEMPERATURE GEOTHERMAL WELLS

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ABSTRACT

Measurement of the absorption-edge in the compound semiconductor GaAs shows that changes in temperature over a range from 200°C to 500°C produce a cut-off transmission wavelength approximately coincident with the optimum spectral transmission region of quartz optical fibers. Thin GaAs elements are thus shown to be suitable for use as passive optical temperature transducers in the logging of high temperature geothermal wells in conjunction with fiber-optic cables.

Stress effects on the optical transmission properties of quartz fibers, indicate increased attenuation amounting to approximately 5%, due to tensile stress of 90 ksi, or an elongation of 1%. Temperature effects on optical transmission were found to be negligible at 500°C.

Preliminary results of this study indicate that construction of a borehole geophysical cable based on single-fiber quartz waveguides is entirely feasible. Present upper temperature limits in successfully measuring certain geophysical parameters in boreholes can be extended appreciably by the use of such a cable in conjunction with passive optical transducers which require little or no down-hole electronics.

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I. INTRODUCTION

This document reports the semi-annual progress of a program of investigation of the feasibility of optical methods for performing well-logging operations in high-temperature geothermal wells. The total period of the contract is twelve months. The concept, summarized schematically in Figure 1, is based on the use of single-fiber optical waveguides, protected in a steel armored cable, coupled to down-hole optical transducers capable of passively measuring certain well-bore parameters. Specifically, the project will attempt to develop an instrument for the measurement of high bottom-hole temperatures.

The use of optical signal transmission in well-logging offers the possibility of bypassing many problems normally associated with high-temperature operation. Since optical fibers are highly efficient communication channels, the optical concept also offers the possibility of making measurements which require higher data rates than current well-logging cables permit. The combination of an optical cable and a passive transducer system promises to alleviate problems commonly encountered in applying electronic devices to high temperature applications.

Geothermal energy presents one of the viable energy options currently under serious investigation. A current limitation in the evaluation of this resource is the inability to reliably make adequate geophysical measurements at those temperatures of greatest interest to successful geothermal exploitation. Optical techniques offer one step along the path toward solving these difficulties.

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FIGURE 1. SCHEMATIC OF THE BASIC OPTICAL LOGGING CONCEPT.

II. PROGRESS DURING THE FIRST SIX MONTH PERIOD

In order to accomplish the objectives of the program, a number of specific tasks have been addressed. Good progress has been made on most of these, and others are in preliminary stages. These tasks may be grouped into three principle categories: Cable and Connector Development, Optical Sensor Development and Optical Component Development. Progress in these areas will be summarized in the following paragraphs.

A. Cable and Connector Development

1. General Considerations

In order to be useful, well-logging instruments must be connected to the surface by suitable signal paths. Traditionally, these signal circuits are electrical. Because well-logging is performed in a very severe environment, cables are typically of a steel armored type in which a double layer of steel strands overlays a central core combining several insulated electrical conductors. The cable is terminated at its down-hole end in a pressure connector generally termed a "cable head", the function of which is to connect the cable to suitable instruments, to maintain pressure integrity, and to protect and maintain electrical insulation and continuity. In the concept being explored in this program, it is intended to replace the electrical signal circuits by optical fibers which require no electrical insulation and which are inherently insensitive to temperature effects. There are a number of practical problems associated with combining optical fibers into a well-logging cable, however, and since such a cable has never before been constructed, it is necessary that these problems be thoroughly explored.

2. Optical Fibers

During the reporting period, effort has been devoted to the conceptual design of a cable containing several optical waveguides (optical fibers). Optical fibers are thin, flexible glass wires, each consisting of a central glass core surrounded by an outer concentric glass cladding. Each glass is designed with a different index of refraction. Light which enters one end of the core follows a grazing path down the fiber, continually reflecting internally off the surface between the core and the cladding. The fact that light fails to pass through the wall of the fiber and escape is due to a phenomenon known as "total internal reflection". Quartz fibers of the type considered in this program are approximately 135 μm diameter. The surface of the glass is invariably protected by a buffer coating of plastic or similar material to reduce the effects of abrasion on the tiny, glass filament.

During the initial stages of the reporting period, the voluminous literature associated with fiber optics was thoroughly reviewed. Based on the results of this review and the products available on the commercial market, preliminary selection of fiber types was made. Subjects of concern in the design of the cable included, among others, (a) fiber attenuation over long (>1 km) path lengths, (b) physical properties of the fibers (strength, elongation, bend radius, etc.), (c) effects of heat and pressure on optical transmission of the fibers, and (d) means of mechanically handling the fibers, by coatings or otherwise, to allow the cabling operation. Since no particularly severe optical dispersion requirements were anticipated, step-index fibers were tentatively selected. These fibers are less expensive and more readily available than graded index fibers, in addition to which the latter do not promise any advantages for the final purpose intended.

The two development areas presently receiving greatest attention in the fiber optics industry have to do with fiber strength and fiber attenuation. Improvements in both these parameters are announced with regularity and the availability of fibers with tensile strengths greater than 250,000 psi, and with attenuation in the range of 1 dB/km or less, are assured for the near future. For the purposes of this program, fiber strength was determined to be of the greatest concern for the demonstration phase of the program. Very high strength fibers with attenuation below 15 dB/km are readily available and the substitution of fibers with lower attenuation can easily be accomplished in the cable design at any time. Consequently, the design goal for the prototype cable was set at 15 dB/km or less, the choice for the specific procurement fiber to depend upon the highest strength material available at the time the order is placed.

3. Fiber Buffering

While optical fibers need not be electrically insulated, it is essential that they be protected by a resilient coating to minimize the effects of "microbends". Microbends are localized stresses set up by uneven pressure distribution on microscopic areas of the cladding. These affect the index of refraction slightly, and cause zones of local light loss. Individually, the effect is insignificant; over a long length, the cumulative effect may be serious. A relatively soft, resilient coating over the fiber greatly alleviates this problem.

A second purpose served by the buffer material for the purposes of this program is protection of the fiber from hot well fluids. Super-heated steam or hot water is corrosive to quartz, and it is important that the fibers be isolated from direct contact with such fluids.

Selection of an appropriate buffering material is an important part of the cable design. After extensive investigation of manufacturing problems as well as material properties, the two most appropriate candidates for the near-term temperature goal of 275°C were determined to be fluorocarbons of the Teflon family, PFA (perfluoroalkoxy) and TFE (polytetrafluoroethylene). PFA is currently useable for coating quartz fibers. It adapts readily to standard ram extrusion machines, and has a service temperature of at least 275°C. TFE, the properties of which are generally the more desirable of the two, is not directly amenable to extrusion, and a considerable amount of development in its application would be required. At the present time, PFA coated fibers have been tentatively selected for the prototype cable.

In order to extend the temperature capabilities to temperatures above 300°C, other less certain candidates appear. TFE should be useable to 320°C. Polyimides, paralene (a proprietary conformal coating), and various metallic coatings, such as electroless nickel, are possible. Some investigation of all these approaches has been accomplished during the first half of this program. In particular, short lengths of fiber have been successfully coated with polyimide, and will be tested at temperature during the next phase of the program. Continued search for additional new materials is underway.

4. Cable Construction

Early in the program, selected cable manufacturers were solicited for cable development proposals. Vector Cable Co. in Houston, ITT Electrooptics Division in Roanoke, Virginia and Rochester Corporation, Culpepper, Virginia, have all made response. Rochester has attempted to produce a steel-armored cable of the general type used in well-logging, although without high-temperature capabilities. Photographs of two armored cable samples furnished by Rochester are shown in Figure 2. The larger of the two consists of a seven-fiber optical core, produced by Corning under the tradename "Corguide", which has been double-armored with galvanized steel as shown. The smaller cable is also double-steel armored, but the core consists of a single-fiber plastic waveguide. The manufacturer has been solicited for a quotation on a longer sample of the seven-fiber material for our tests, although it will not meet elevated temperature requirements. To date, however, manufacturing difficulties have not permitted delivery.

ITT furnished a development proposal which has been forwarded to the ERDA Technical Monitor with a recommendation for funding. It proposed to develop the methodology for coating fibers with TFE, but the funding requirements were outside the financial scope of this project.

FIGURE 2. SAMPLES OF LOW-TEMPERATURE ARMORED FIBER-OPTIC CABLES. The larger sample contains seven optical waveguides, but manufacture was not entirely successful. (Rochester Cable Co.)

Vector Cable Co., a major supplier of well-logging cable, agreed during the reporting period to assist with the cable design and furnish a prototype cable on a procurement basis. The design will remain the property of Vector, who would eventually become a supplier of the cable for the geothermal industry, if the requirement materializes. A purchase order for this cable was finalized during March. A cross-section of the Vector design is shown in Figure 3. It combines three optical fibers and three electrical conductors, each with an O.D. of .068" over the PFA buffer. These will be combined into a core by spiral-wrapping around a central steel stress wire at a shallow angle. The cable will be filled with PFA, and protected by a single abrasion cover of galvanized steel armor. Effort is now underway on this contract, and samples of the extruded core material are expected early in May. PFA buffered fibers have been furnished by Vector for preliminary approval.

5. Measurement of Fiber Properties

One of the critical aspects of cable design, involves the determination of the effects of various mechanical and environmental parameters on the optical transmission characteristics of fibers. In order to determine these effects, special apparatus was designed and built during the reporting period.

These optical properties as they are affected by stresses which will inevitably be applied to fibers in the manufacture of a long cable, require careful measurement and consideration. At the same time, practicality dictates that the measurements be made on short lengths of fiber. This poses a serious instrumentation problem. A quartz fiber with an optical attenuation of 15dB/km will exhibit attenuation of only .15dB over a 10M length. Sufficient accuracy to determine (in absolute terms) a 1 dB/km change in attenuation, would require absolute measurement accuracy of .001 dB over a 10M length, which is beyond state-of-the-art optical capability. In order to circumvent this problem, a method has been selected and equipment fabricated, in which a differential measurement of two fibers of the same (20M) length are used.

In this procedure, both fibers are illuminated by a common extended light source, and a differential measurement of any change in the matched transmission of the two fibers is made. This permits measurement accuracy approaching 0.1% on a relative basis, which is equivalent to less than 1 dB/km. Stresses of interest (tension, compression, temperature, etc.) can be applied to one of the two fibers while both are coupled to the source and detector and the differential measurement of relative transmission mismatch will yield the relative loss per unit length. A schematic representation of the system is shown in Figure 4.

Specifications:

ELECTRICAL PROPERTIES;

DC RESISTANCE;

11.0 OHMS/1000' @20° C.

23.2 OHMS/1000' @300° C.

VOLTAGE RATING:

500 VRMS

INSULATION RESISTANCE:

2000 MEGOHMS/1000' @20° C.

.1 MEGOHMS/1000' @ 300° C.

OPTICAL PROPERTIES:

OPTICAL PATH:

1.086 23° ANGLE

MECHANICAL PROPERTIES:

BREAK STRENGTH:

1210#

WEIGHT IN AIR

105.4#/1000'

TEMPERATURE RATING:

300° C

FIGURE 3 . TENTATIVE HIGH-TEMPERATURE CABLE DESIGN,
COMBINING THREE OPTICAL AND THREE ELECTRICAL PATHS.
(Vector Cable Co.)

FIGURE 4. SCHEMATIC OF APPARATUS FOR DETERMINATION OF OPTICAL TRANSMISSION PROPERTIES OF SHORT FIBERS BY DIFFERENTIAL MEASUREMENT.

There are four optical parameters in this measurement system which must be carefully controlled: (1) fiber-end preparation, (2) source brightness, (3) input launching (coupling) conditions, and (4) output receiving conditions. These parameters must be uniform and repeatable from measurement to measurement, and also time invariant if meaningful loss data is to be obtained.

The end preparation problem is handled adequately by a "scoring and breaking" technique, equipment for which has been fabricated. Proper end preparation can be assured by microscopic inspection of each fiber end after preparation. An ultrasonic cleaner using acetone solvent has proven effective in cleaning contaminated fiber ends. A scanning-electron micrograph of a properly prepared fiber end is shown in Figure 5.

A 20-watt tungsten microscope illuminator bulb is used as the source for the fiber loss measurements. This bulb is powered by a DC supply with a brightness level feedback-loop to insure constant ripple-free light output.

Uniform coupling to the fiber is obtained by means of a relatively simple optical collimator and a rigid mechanical mount. Referring to Figure 4, light from the small tungsten bulb is collected and collimated by the field lens. The focal length of this lens is greater than 100 filament diameters, and the resulting light field at the lens position is highly uniform across the lens surface. A fiber placed near the lens opposite the source captures a portion of the collimated light coming from the lens. Because the light is collimated and because the light field is very uniform at this point, small displacements and repositioning the fiber from its initial position in any axis will produce negligible changes in the amount of light launched into the fiber. Angular misalignments are minimized by precision fiber mounting fixtures.

Detection uniformity is achieved through the use of large area detectors and rigid mechanical fiber mounts. The large area of the detector ensures that all of the light emerging from the end of the fiber will fall on the active surface of the detector, minimizing measurement errors caused by slight position errors in mounting the fiber.

6. Results of Physical Tests on Fibers

There are three areas of known concern in the use of optical fibers under severe environmental conditions. These are the effects of tensile stress, temperature effects, and the effect of "micro bends", all three as they may affect optical transmission properties. The experimental apparatus described in the previous section was used in assessing two

a

b

FIGURE 5. SCANNING-ELECTRON MICROGRAPH OF QUARTZ OPTICAL FIBER END. (a) Broken by hand and (b) prepared by the "Tension, Scribe and Break" technique. Fiber diameter is $135\text{ }\mu\text{m}$.

of these variables, namely tension and temperature. The effect of micro-bends is more subtle, and can be assessed much more realistically when the prototype cable core material becomes available.

An experiment was designed to permit measurement of the increase in transmission loss due to the physical tests. Thus, while measurement of the absolute attenuation of a short length of low-loss fiber is impractical, two identical fibers supplied with constant light flux and terminated by identical optical detectors, can be employed with a difference amplifier, the output of which is normalized for common, initial conditions. Then, as one of the fibers is subjected to a test condition, the change in attenuation, as a percentage of the initial attenuation, can be measured with high accuracy (of the order of 0.1% or less). For example, if one 10m fiber is stressed in tension to 10,000 psi, the increase in attenuation may be of the order of 1%, which can easily be determined. On this basis, if a 1 km length of the same material were stressed to the same 10,000 psi, its attenuation could be expected to increase 1% as well. Effects of tensile tests on a typical 135 μ m, 15 dB fiber (Corning) are summarized by the curve shown in Figure 6. This particular fiber exhibits a reasonable attenuation increase at stress levels as high as 90 ksi, the equivalent of 1% elongation. The latter is the design limit to which we intend to design the optical cable. From this data, it can be seen that a 1 km fiber of this material, which exhibits a transmission loss of 15 dB at no-load, would exhibit a loss of 15.75 dB at $\approx$ 1% elongation, or 90 ksi stress level. This is not a highly significant factor.

Preliminary experiments with unbuffered fibers were performed in the same way, in a high-temperature environment with one fiber inside the temperature chamber, and one outside. At 500°C, no measurable effect on the transmission properties of the heated fiber were noted. When measurements were extended to 1,000°C, some transmission loss was incurred, but it amounted to less than a 5% increase, which is nominal. The results indicate that temperature will not be a significant factor in the performance of the optical fiber. Further tests of this nature will be performed on the buffered fibers, and on lengths of the prototype core material, when these become available.

7. Connector Development

An important aspect of the optical well-logging system is the method of cable termination, including the connection to various instruments. This connector, normally called a "cable head", must align and connect optical waveguides, terminate the stress members of the cable and transfer the load of the instrument housing to them, and maintain pressure integrity at the instrument-cable interface.

FIGURE 6 : EFFECT OF TENSILE STRESS ON ATTENUATION

a. Angular and Position Alignment

Angular and position alignment of one fiber to a connecting fiber is critical for the performance of the system and represents a significant area of concern. While it is possible under some conditions to have slight angular misalignment between two fiber ends without serious loss of signal, it is necessary that connected fibers be aligned axially with high accuracy. Axial misalignment of as little as 10% (0.5 mils with two 5 mil fibers) can cause signal attenuation as great as 3 dB. The problem then in alignment is to provide a flat surface, perpendicular to the axis of the fiber, and accurately position fibers with respect to each other.

Even precision machining operations are not adequate to accomplish the alignment accuracy required and consequently, a special fabrication method must be developed. A method that has received preliminary investigation during the first half of this project involves the alignment of the fibers by means of a series of thin, photo-etched plates. This process permits components to be manufactured with extremely close dimensional tolerances. A second key element in this system is a tiny, slotted precision tube, or alignment sleeve, into which the prepared fiber end will be inserted. These sleeves, each containing a fiber, will be held in proper alignment by the small chemically etched plates. Each alignment sleeve will be slotted at one end to form a small collet which will grip the fiber when the discs are in place.

The concept is illustrated in Figure 7. A prepared glass fiber is shown at "A", inserted into a flanged tube "B"; pressure from the chemically etched plate "C", when pressed over the type, closes the slotted end of the tube around the fiber. In the drawing, the assembly is shown composed of a stack of these plates "D"; in practice, it may be more desirable to use a combination of a cylindrical body to position the tubes approximately, stacked with several photo-etched plates to complete the assembly. The entire structure will then be held together with high-temperature epoxy, ceramic adhesive, or a combination of adhesive and spot-welding as at "E". The interface between the two finished connector halves shown at "F" will consist of two optically polished faces in which the epoxy or ceramic adhesive and the fiber ends are polished together by a special fixture fitted over the subassembly as the final step. A mating alignment pin (not shown) is secured in position at the same time the tubes are being oriented. The alignment pin will key the finished assembly to its mating assembly in the other connector half.

In Figure 8, the small subassembly just described, is shown in end view in the cable head, the fibers being on the smaller circle at "A". The tab at "C" in the figure is for approximately aligning the fiber

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FIGURE 7. OPTICAL FIBER ALIGNMENT

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FIGURE 8. FACE OF CONNECTOR

subassembly within the cable-head housing, where it will have some freedom to "float" before joining the mating connector half by means of the small alignment pins at "B".

Figure 9 shows a complete conceptual cable-head assembly, with the small fiber subassembly at "A", backed by an elastomeric O-ring held in place by a washer and retaining ring. The purpose of the O-ring is to provide a resilient base on which the plate assembly is allowed to float. This ring, which will not be a pressure interface, will be made of neoprene. Neoprene is an excellent high-temperature material, except when exposed to petroleum derivatives. In this position, the latter will not be a problem since the ring will not be exposed to well fluid.

b. Pressure Integrity

The pressure sealing philosophy now being conceptually followed, also illustrated schematically in Figure 9, consists of a rope socket, or stress link "B", the exposed cable core at "C", and optical fibers individually sealed through a separate pressure plate at "D". The three seal points are at "E", around each individual buffered fiber; at "F", around the pressure barrier disk; and at "G", where the cable-head mates with the instrument housing. For the 275°C intermediate temperature goal, O-ring seals are still the most practical means of performing the sealing function. Three types of O-ring material are being investigated for this purpose; Viton, a fluorocarbon rubber rated at 260°C, neoprene coated with TFE, and solid TFE. Seals designed with these three materials will be individually studied during the coming months of the program.

The pull-out link, or rope socket, is designed to grip the central stress member by means of wedges driven into a tapered hole around the stress-strand shown at "H". Elements of this system will be dimensioned to provide pull-out at a stress somewhat below cable break-strength.

c. Pressure and Temperature Testing

A small high-pressure test facility has been designed, and pressure tests of small, individual seals and components will begin during the next reporting period. The pressure chamber consists of a small hydraulic cylinder with removable piston, approximately 1 in. in diameter. The piston is readily replaceable, and several will be constructed for components. The piston will be sealed with TFE O-rings, and pressure will be supplied by a hydraulic hand pump, connected by tubing to the cylinder. The entire cylinder assembly, external to the pump, will be placed in a high-temperature oven facility, so that temperature and pressure can be controlled separately and remotely. The seals of individual buffered optical fibers will be tested first.

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FIGURE 9. CONNECTOR HALF

d. Ceramic Seals

Another concept expected to be useful in the sealing applications, particularly for extended temperature service, makes use of materials called "castable ceramics". These are alumina compounds in liquid or paste form, which adhere well to metal, glass and other ceramics, and cure at low temperature (approximately 100°C) into hard, ceramic-like material. Ceramic-to-metal seals have been constructed experimentally in this way during the program, and other testing is underway. When properly cured, the substances can tolerate temperatures above 2,000°C, and in virtually every respect, exhibit the properties of kiln-fired ceramics. Glass-to-metal seals are a common solution to very high-temperature, high-pressure applications, but suffer the disadvantage of being difficult to install. The castable ceramics are expected to alleviate the problem considerably. Testing continues on a series of these materials.

B. Optical Sensor Development

1. General Considerations

A principal effort in this program involves the incorporation of passive optical transducers with optical waveguides, thus eliminating the need for down-hole electronic packages. This would greatly simplify the temperature problems in logging geothermal wells. Of first priority in this effort is the development of an optical transducer for continuous temperature measurement. Two approaches proposed for this development, include the use of color center annealing in certain optical materials, and the shift in the absorption edge of semiconductors with temperature. Both approaches are promising.

In evaluating these two concepts, two serious constraints were found to exist on the system, both dictated by the optical characteristics of fiber optics. The first is the spectral transmission bandwidth of quartz fibers which is limited to the visible spectrum and the near infrared. The second limitation is created by the effect of a number of parameters on the optical transmission of fibers which, consequently, interfere with measurement of direct amplitude variation. Because of the latter, measurements involving wavelength or frequency modulation are greatly to be preferred over amplitude measurements. Based on these and other considerations, preliminary assessment of the two basic approaches to temperature measurement, produced an early decision to proceed first with the investigation of the absorption edge phenomenon. The "absorption edge" is the wavelength range over which most semiconductor materials become opaque.

The two III-V semiconductors found to be of greatest interest were GaAs and InP. Both materials exhibit an absorption edge in the near infrared and this absorption edge in both materials is known to be highly temperature dependent. Since the variable is the wavelength, both materials satisfy the general constraints imposed by the properties of optical fibers. Both GaAs and InP are transparent over a wavelength region at which quartz transmits with lowest attenuation.

While the initial promise of the semiconductor approach is high, some serious questions about the use of the absorption edge phenomenon were evident. Consequently, evaluation of color center annealing in materials was also continued as an alternate approach.

2. Color Center Investigation

A complete survey of the literature dealing with color centers in materials was conducted, and the pertinent material carefully assessed. Colloidal color centers were selected as best suited for the purposes of this program. Color centers are defects which occur in materials for a variety of reasons, common among which is exposure to ionizing radiation. Once formed, they inhibit the transmission of light through the material. These color centers are subject to annealing, and are removed by exposure to high temperature. Thus, if an appropriate crystal containing color centers at room temperature were placed in a high-temperature well, the defects would gradually disappear at an annealing rate dependent upon the material and the temperature. With proper selection of materials, exposure temperature could be calculated from the annealing rate.

Colloidal particle formation in crystals is apparently diffusion limited, the excess F centers diffusing into aggregates. When some "magic number" is accumulated, the trapped electrons become associated with a specific metal ion and a colloid of metal atoms is formed. Ionized "F" centers inhibit this colloidal formation since they repel one another and do not form large aggregates. This explains why higher temperatures, or light of sufficient frequency to ionize the "F" centers, inhibit colloidal formation. Two means of temperature sensing by utilizing this phenomenon are promising: (1) colloidal band position and (2) colloidal band strength. The mean size of the colloidal particles can be inferred from the band position. The colloidal band strength is less desirable as a temperature measurement parameter because it relies on amplitude rather than frequency or wavelength measurement.

3. Semiconductor Absorption Edge Measurement

One of the promising sensor candidates for absorption edge measurement is gallium arsenide (GaAs). Gallium arsenide exhibits a temperature dependent absorption edge at wavelengths that approximately coincide with the optimum transmission range of quartz fibers at the temperatures of interest (200°C - 500°C). This raises the possibility of continuous measurement of borehole temperature by (1) transmitting light down a fiber to a small gallium arsenide element, (2) returning the transmitted light to the surface, and (3) determining the optical wavelength at which the material becomes transparent. From this measurement, the temperature of the GaAs crystal can be easily inferred. Thus only passive elements (the crystal and its fiber-optic transmission line) would be exposed in the geothermal well.

In order to evaluate the absorption edge of GaAs experimentally, apparatus was designed and an experiment conducted in which the transmission of a wafer of GaAs was measured at temperatures from 100°C to 500°C. Experimental apparatus is shown schematically in Figure 10. It consists of a GaAs disc, 15mm diameter by 2mm thick, with optically polished faces, placed in a specially designed metal holder. The mounted disc was accurately located in the high temperature zone of a commercial diffusion furnace. This furnace is in the form of a cylinder approximately 1m long with a continuous through-passage through its length. A collimated airpath optical beam from a broad spectrum source (tungsten-halogen lamp) was focussed on the crystal from outside one end of the furnace, with detection apparatus at the other end. This permits thermal isolation of the gallium arsenide, allowing its temperature properties to be measured. The furnace serves as an accurately controlled temperature chamber. Temperature can be directly incremented and held to close tolerances by control circuitry integral with the furnace. Temperatures from 200°C to more than 1000°C are easily obtained and can be held to extremely close tolerances. For the purposes of this experiment, a temperature range from 200°C to 500°C was used.

The detection system at the exit beam consisted of a standard laboratory monochromator (for determining wavelength) and a silicon avalanche detector, with associated electronics. A second detector monitored the entrance beam directly from the light source, so that small variations in lamp intensity due to voltage fluctuations and lamp aging could be accommodated. The monochromator is adjustable in one nanometer steps, and the photodetector output at each wavelength was recorded. The plot of detector output vs. wavelength, corrected for the silicon detector response, yielded the transmission curve for the gallium arsenide crystal. The results of these measurements are shown by the plots of normalized absorption coefficient vs. wavelength and temperature in Figure 11.

FIGURE 10. SCHEMATIC REPRESENTATION OF APPARATUS FOR MEASUREMENT OF TEMPERATURE CHARACTERISTICS OF GaAs AS AN OPTICAL ELEMENT.

FIGURE 11. EXPERIMENTALLY MEASURED ABSORPTION COEFFICIENT FOR GaAs vs. WAVELENGTH AND TEMPERATURE.

From this data it is apparent that gallium arsenide performs well in fulfilling the temperature sensing requirements. The spectral range of the absorption edge over the temperatures of interest generally conforms to the transmission characteristics of quartz fibers, and the absorption edge itself is sharp and well defined. The small physical mass of a suitable gallium arsenide element further recommends it for this purpose, because of its low thermal inertia.

4. Analysis of Experimental Results on GaAs

To compare and understand the results of the experiments in the context of information in the literature, the various constants were calculated. Assuming a parallel optical interface, the following equation for transmission of light⁽¹⁾ applies

$$T = \frac{I}{I_0} = \frac{(1 - R)^2}{e^{\alpha D} - R^2} e^{-\alpha D} \quad (1)$$

where R is the reflectivity, D is the thickness, and α is the absorption coefficient. In a wide band-gap semiconductor such as gallium arsenide, the absorption is cut off above some definite wavelength since photons of higher wavelength do not have enough energy to excite the carriers from the valence to the conduction band. The equation for the absorption coefficient around this absorption edge⁽²⁾ is

$$\alpha = \frac{\alpha_0}{1 + \exp [\delta (1/\lambda_g - 1/\lambda)]} \quad (2)$$

where α_0 is the low wavelength limit, λ_g is the cutoff wavelength, and δ is the "steepness" of the cutoff. Thus, the problem was to analyze the experimental data to determine the four unknowns: R , λ_g , δ , and α_0 .

a. Reflectivity

The reflectivity was determined by analyzing the transmission data in the region where there was no absorption, thus

$$T = \frac{I}{I_0} = \frac{(1 - R)}{1 + R} \quad (3)$$

Figure 12 shows the result of this analysis for temperatures of 23°C to 500°C. Note that the inadvertent deposition of material (tin) on the surface of the sample during the experiment at high temperatures is very evident in this plot. A fit to the data for temperatures in the 200-400°C range was made and is also plotted in Figure 12. This equation is

FIGURE 12: REFLECTIVITY FOR VARIOUS TEMPERATURES

$$R = 0.777 - 0.000297 \lambda \quad (4)$$

where λ is wavelength in nanometers (approximate values of 0.530 and 0.565 were adopted for the 450°C and 500°C curves). The curve fit compares favorably with reported values of about 0.3 for electropolished crystals⁽³⁾. The absorption coefficients and slopes corrected for reflection are plotted in Figures 13 and 14.

b. Cut-Off Wavelength

The cut-off wavelength was found by analyzing the slope of the absorption coefficient. Differentiating Equation (2) produces

$$\frac{d\alpha}{d\lambda} = \frac{-\alpha_0 \gamma \exp[\gamma(\frac{1}{\lambda_g} - \frac{1}{\lambda})]}{\lambda^2 (1 + \exp[\gamma(\frac{1}{\lambda_g} - \frac{1}{\lambda})])^2} \quad (5)$$

This slope is a maximum at the cut-off wavelength. The values of the cut-off wavelengths for the various temperatures are given in Table 1. A fit was made to this data using the band gap as an adjustable parameter. For a band gap of 1.4ev the resulting fit is plotted in Figure 15.

TABLE 1

<u>Temperature</u>	<u>λ_g(nm)</u>	<u>α_0(cm⁻¹)</u>	<u>γ(nm)</u>
23°C	888	31	265000
200°C	946	44	190000
250°C	969	47	181000
300°C	987	48	179000
350°C	1013	50	179000
400°C	1036	50	180000
450°C	1049	55	179000
500°C	1081	51	177000

c. Low Wavelength Limit of Absorption Coefficient

The low wavelength limit was calculated using the fact that at the cut-off wavelength the absorption coefficient is one-half of the low wavelength limit (see Equation (2)). The results of this calculation are given in Table 1. A discrepancy with reported values is seen here. The reported values of the low wavelength absorption coefficient are of the order of 10^4 cm⁻¹, a factor of 200 higher than our measured values. This discrepancy is one that requires resolution and effort has been directed at that question.

FIGURE 13: ABSORPTION COEFFICIENT CORRECTED FOR REFLECTION

FIGURE 14: ABSORPTION COEFFICIENT SLOPE

FIGURE 15 : CUT-OFF WAVELENGTH

d. Steepness of Cutoff

The steepness of the cutoff was also found by analyzing the slope of the absorption coefficient. Evaluating Equation (4) at the cutoff wavelength and solving for the steepness,

$$\gamma = \frac{4\lambda_g^2}{\alpha_0} \left. \frac{d\alpha}{d\lambda} \right|_{\lambda_g} \quad (6)$$

Thus, one has to use the low wavelength limit of the absorption coefficient from 3 (above) and cutoff wavelength from 2 (above) in order to calculate the steepness. The results of this calculation are given in Table 1 and plotted in Figure 16. These values are of the same order of magnitude as reported values, but do not exhibit the usual dependence on temperature^(5, 6). The Urbach rule given by the following equation is the normal means of explaining the exponential tail steepness⁽⁷⁾.

$$\gamma = \frac{2\sigma}{\hbar\Omega_0} \tanh\left(\frac{\hbar\Omega_0}{2k_B T}\right) \quad (7)$$

where σ is a constant, Ω_0 is the optical phonon frequency and T is the temperature. The curve in Figure 16 is a plot of the Urbach rule, showing that at room temperature the steepness may obey Urbach's rule but is apparently a constant at higher temperatures.

e. Conclusions

We were not observing the interband absorption edge, shown by the discrepancy in our value for the absorption coefficient. In an attempt to explain these results, it was proposed that we were observing some other weaker absorption edge, e.g., excitons, vacancies, impurities, etc. The proposed model is that the actual absorption coefficient is a sum of the absorption from the two sources,

$$\alpha = \frac{\alpha_1}{1 + \exp[\gamma_1(\frac{1}{\lambda_1} - \frac{1}{\lambda})]} + \frac{\alpha_0}{1 + \exp[\gamma_0(\frac{1}{\lambda_0} - \frac{1}{\lambda})]} \quad (8)$$

where α_0 , γ_0 , λ_0 are the constants for this weaker absorption and α_1 , γ_1 , λ_1 are constants for interband absorption. The reported Urbach rule value for γ_1 is adopted.

FIGURE 16 : STEEPNESS

$$\gamma_1 = \frac{1.02 \times 10^8}{T + 273} \quad (9)$$

and λ_1 is assumed to be shifted to a slightly shorter wavelength,

$$\lambda_1 = \lambda_0 - \Delta\lambda \quad (10)$$

using this approach the curve-fit in Figures 17, 18 and 19 were obtained with values of α_0 , α_1 , T and $\Delta\lambda$ as given in Table 2.

TABLE 2

<u>T</u>	<u>α_0</u>	<u>α_1</u>	<u>$\Delta\lambda$</u>
200°C	33	100000	.lev
300°C	36	200000	.lev
400°C	42	200000	.lev

We apparently observed effects of a secondary absorber which is shifted about 0. lev from the direct band-gap absorber. A literature survey was conducted for candidates for this absorber and the most logical appeared to be impurities in the GaAs. In order to verify this, several samples of undoped, and of highly Zn-doped GaAs were ordered, and verification experiments planned. The use of the "impurity edge" in GaAs may be very desirable, since it would permit the use of a much thicker element than would the primary absorption edge. The possibility of using a thin ($\approx 100 \mu\text{m}$) GaAs film deposited on a quartz substrate has also been investigated, but the thermal expansion coefficients of GaAs and fused quartz are so different that this approach is considered impractical. This approach would require deposition of the GaAs film on a spinel or sapphire substrate, with thermal expansion coefficients closely approximating that of GaAs. However, if the impurity absorption edge is easily reproducible, it can be measured on much thicker crystals, and the instrument design will be greatly simplified.

A parameter study was performed to determine the optimum thickness for measuring this secondary absorption edge. Figure 20 is a plot of the slope of the intensity ratio at the cutoff wavelength. A critical point is noted at about 0.5 mm. Figure 21 gives the corresponding plots of the intensity ratio for thicknesses from 0.1mm to 1.7 mm, showing the effect of varying thickness. It was concluded that a thickness of about 0.5mm would represent an optimum value.

5. Follow-Up Experiments on GaAs

In order to resolve the uncertainties in the results of the temperature experiments on GaAs, both undoped and highly Zn-doped samples

FIGURE 17: THEORETICAL FIT TO DATA, TEMP=200

FIGURE 18 : THEORETICAL FIT TO DATA, TEMP=300

FIGURE 19: THEORETICAL FIT TO DATA, TEMP=400

FIGURE 20: CHANGE IN SIGNAL FOR OPTIMUM THICKNESS

FIGURE 21 : CHANGE INSIGNAL FOR THICKNESS OF .1 , .5 , & 2.5 MM
TEMP=300

of GaAs were procured. Preliminary experiments have been performed to verify that the discrepancy observed in the previously measured absorption edge experiments was due to impurities. These experiments were performed at room temperature (23°C), with oven experiments to follow. Considerable effort went into the polishing of these GaAs specimens, since they were made considerably thinner than the original. One of the finished elements, 0.3mm (0.012") thick is shown in Figure 22. A method of electropolishing after initial mechanical polishing, has been developed for reproducing these elements.

Figures 23, 24 and 25 summarize the results of the room temperature experiments. Figure 23 shows the absorption properties of the undoped and Zn-doped GaAs single crystals. As expected, the doped crystal exhibits an absorption edge that is shifted at lower values of the absorption coefficient due to impurity absorption. Figures 24 and 25 also show this shift in the slope of the absorption coefficient. Thus, this experiment seems to confirm that the shift previously noted was an impurity effect. However, the "shoulder" is still at such a high value of the absorption coefficient as to make measurements difficult with crystals of this thickness. Because this impurity absorption level should be dependent on the impurity concentration, it is planned tentatively to design an instrument around a specific impurity level. Additional crystals with intermediate zinc concentrations will now be obtained. This should also further verify the impurity absorption theory.

To speed-up the process of experimentally measuring the absorption spectra, a direct interface from the experimental apparatus to the computer via an analog-to-digital converter has been completed. This eliminates the slow, tedious task of entering the data by hand. A 0.1% linear potentiometer is attached to the monochromator via gears and serves as a voltage divider. The voltage from the potentiometer is thus a linear function of the wavelength. Two channels of an eight-channel analog-to-digital converter are then fed the wavelength and optical intensity signals via coaxial cable, and the A to D output is accepted by an HP2100 computer system. The results are stored on magnetic tape via the Tektronix 4051 graphic terminal system. This procedure enables us to obtain an individual absorption curve in a matter of a few minutes, including the calculations involved.

6. Advanced Sensor Development

Advanced sensor investigations have been concerned primarily with the investigation of a passive, optical detector for neutron well-logging. This effort, which is reviewed below, has identified a promising mixture of materials that should prove to be a highly efficient thermal neutron scintillator. Plans for experimental tests of such a sensor are now being formulated.

FIGURE 22. UNDOPED GaAs TEST WAFER USED IN SENSOR EXPERIMENTS TO RESOLVE ABSORPTION-EDGE UNCERTAINTIES. Surface of 200 μm thick specimen appears specular in white light.

FIGURE 23: UNDOPED (1) AND ZN-DOPED (2) GAAS ABSORPTION EDGES, TEMP=23C.

4195

FIGURE 24: UNDOPED GAAS

TEMP=23C

4196

FIGURE 25: ZN-DOPED GAAS

TEMP=23C

A significant effort has also been devoted to the search for a suitable passive pressure sensor. Although we have identified a promising concept, a detailed investigation is just now getting underway, and performance predictions are not yet available. The basic concept is described in the second part of this section.

Our original approach to the development of an optical neutron detector was to measure the increase in optical absorption caused by neutron-induced color centers in a suitable crystal. The principle involved here is that the change in absorption is proportional to the neutron dose absorbed by the crystal. Thus, by measuring the rate of change in the intensity of an optical signal transmitted through the crystal by means of optical fibers, one obtains a remote, optical measurement of the dose rate at the crystal.

Although this approach is valid in principle, a review of pertinent literature soon showed that typical color center production rates are much too low for the optical absorption approach to be feasible with neutron sources of practical size. The idea was therefore abandoned in favor of neutron detection methods that involve the emission of optical signals.

Early work along this line involved a search of the literature on luminescent materials, particularly those under investigation for use as thermoluminescent dosimeters. Several possibilities were identified, the most promising of which was $\text{Li}_2\text{B}_4\text{O}_7\text{:Mn}$. This material emits radiation in the red and near infrared at temperatures near 200°C after being subjected to neutron radiation.

Although quantitative data on neutron sensitivity and possible scintillation effects are not available, it is expected that the thermal neutron sensitivity is good because both Li and B have large thermal neutron cross sections for the production of energetic alpha particles. Thus, when $\text{Li}_2\text{B}_4\text{O}_7\text{:Mn}$ is subjected to thermal neutron irradiation at high temperatures, one might expect the crystal to scintillate, i. e., to emit pulses of radiation in the red and near-infrared, through the recombination of electron-hole pairs created by alpha particles. If this does indeed happen with adequate efficiency, $\text{Li}_2\text{B}_4\text{O}_7\text{:Mn}$ might be useful as a remote thermal neutron counter. This could be accomplished by coupling the crystal to an optical fiber and transmitting the neutron-induced pulses to an optical receiver.

Another possibility, which now appears more attractive, is to use a mixture of materials, one of which is a boron compound and the other an infrared phosphor. The idea is basically the same as with $\text{Li}_2\text{B}_4\text{O}_7:\text{Mn}$, namely, the alpha particles produced by the $^{10}\text{B}(n, \alpha)$ reaction lead to ionization and the subsequent emission of radiation in the phosphor.

Room-temperature, visible-light sensors of this type have been thoroughly studied, and were found to be highly efficient. In fact, it was demonstrated some time ago that the counting efficiency of such a scintillator compares favorably with that of a BF_3 (boron trifluoride) counter, which has been the standard thermal neutron detector for many years⁽⁸⁾. Our objective, therefore, is to adapt this proven concept to thermal neutron counting at high temperatures with scintillation spectra suitable for fiber optic data transmission.

A review of the literature on scintillator materials reveals that cadmium sulphide (CdS), doped with copper and chlorine, emits radiation in two broad bands centered at 820 nm and 1020 nm when subjected to ionizing radiation at room temperature⁽⁹⁾. Although either band would be suitable from a fiber optic transmission standpoint, it is expected that only the longer wavelength band will be useful at high temperatures. This is because experiments with a similar material (ZnS) show that the luminescent efficiency of the shorter wavelength emission drops off rapidly as the temperature is increased above about 100°C , while the longer wavelength emission persists at temperatures up to about 300°C ⁽¹⁰⁾.

However, from data on the temperature dependence of the energy bandgap in CdS ⁽¹¹⁾ it is expected that at temperatures in the 200°C to 300°C range, the band centered at 1020 nm at room temperature will shift to 1200 nm to 1300 nm, which is slightly too long for efficient transmission in presently available optical fibers. On the other hand, experiments with alloys of CdS with ZnS ⁽¹²⁾ show that the addition of Zn shifts the emission to shorter wavelengths, thus suggesting that alloying with ZnS would be helpful. From such experimental data we estimate that an alloy containing about 85% CdS by weight and 15% ZnS by weight should emit radiation in the 1000 nm to 1100 nm optical fiber transmission window at 200°C to 300°C . Thus, the phosphor we plan to use in forthcoming experiments is a CdS-ZnS alloy doped with copper and chlorine.

In choosing a boron compound to mix with the phosphor, one needs a material with high melting point, high boron content and minimum optical absorption in the 1000 nm to 1100 nm band. Although boron nitride is not ideally transparent at these wavelengths⁽¹³⁾, it satisfies the other requirements quite well, and is readily available in the form of a fine powder. We therefore plan to use a mixture of boron nitride and phosphor powders in experimental studies of the scintillator design.

Our plan calls for experiments with an alpha particle source in which we will vary the ratio of boron nitride to phosphor material and the specimen thickness to determine the optimum configuration. From a knowledge of the source strength and observation of the scintillation counting rate we can then determine the counting efficiency for alpha particles. This result, along with cross section data for the $^{10}\text{B}(\alpha, n)$ reaction, will enable us to estimate the thermal neutron counting efficiency.

C. Optical Components

A very important consideration in the optical well-logging system, is a suitable emitter, or light source, for the optical carrier. In order to match the most favorable spectral transmission region of quartz fibers, the emitter should operate in the near infrared, in the vicinity of 1,000 nanometers. Optical fibers have acceptable losses (1 to 15 dB/km), once the radiation has been coupled into the core. However, launching a wave into the core presents severe problems with sources of almost every type, due to the low effective aperture, or acceptance angle, of a practical fiber. Both incandescent lamps and semiconductor LEDs are spherical emitters, and only a small fraction of the total light emitted can be collected and transferred to the fiber. Laser sources are much more efficient from this standpoint, and would represent the preferred choice, except for another severe restraint imposed by the optical sensors under investigation.

It has already been explained that the most desirable method for efficiently utilizing fiber optics for communication purposes is frequency or wavelength modulation, since amplitude effects caused by stress and other physical environmental parameters affect optical transmission of fibers. Moreover, the temperature sensor concept that appears most promising in this program, i. e., the absorption edge effect in semiconductor materials, is a wavelength-sensitive phenomenon. This implies that the optical source be capable of emitting light over a relatively wide range of the infrared spectrum. Neither LEDs nor lasers are capable of emission over a wide wavelength range, with the exception of tunable dye lasers. During the first half of this program, a detailed study of the source problem has been undertaken. The results indicate that, for the absorption edge measurement, only two sources are suitable; the most desirable from a power and efficiency standpoint is the dye laser; the other is the common incandescent lamp. None of the other sources investigated have either the spectral range or the power capabilities required. In the 1,000 nanometer range, even dye lasers are not immediately available, although it is likely one of suitable characteristics might be developed. Based on these facts, the incandescent sources were determined to offer the only immediate solution to the emitter problem. Study was made of the potential capabilities of such sources, and experimental verification of several concepts was obtained.

As an emitter for optical waveguides, the basic problem with an incandescent source is the fact that it represents an extended source; it has finite and relatively large dimensions. The filament is brought to a high temperature, and radiates in all directions. To collect a large part of this radiation (only a small fraction of which is in the correct spectral region) and transfer it to the fiber aperture is impossible. The best that can be accomplished is to image a single spot on the filament, at the fiber end. This means that by far the majority of the emitted energy will inevitably be lost. Even reflectors and other collection devices can only improve the extremely poor collection efficiency by factors of 2 or 3, or at the most 5; thus, most of the light will not enter the fiber and the parameter of greatest interest is the radiation power-density of the filament, not the overall power of the lamp.

This collection problem from an extended source such as a tungsten lamp was studied theoretically and experimentally. To satisfy the immediate requirements of the experimental part of the program now under way, a practical source was constructed. It consists of a 600W tungsten-halogen lamp, two-stage collection optics, and an objective lens for focusing on as small an area as possible. This particular source will be used throughout the part of the experimental program which involves the semiconductor temperature sensors. From the measurements made on the efficiency of collection from this source, it is calculated that it will be capable of transmitting over more than 1 km of 15 dB/km fiber, which will be adequate for all the testing anticipated. For extending the capability to a cable of several kilometers, the source will still be suitable if fibers of attenuation near 1 dB/km can be obtained (almost a certainty at this time).

A second incandescent source of considerable interest was obtained from the Oriel Company. In this concept, the end of a tungsten wire is heated to incandescence by a very small electric arc, which is initiated on the periphery of the wire. The glowing spot produced is very small, with a diameter equivalent to that of the tungsten wire. Further investigation of this source is worthwhile, but at the present time it has not been pursued; it exhibits rather severe fluctuations in output, apparently due to variation in the arc intensity within the lamp. Its advantage would be to transmit essentially the same power into the fiber as a much larger lamp, but with lower power input. Since this is not a primary limitation in the demonstration of the feasibility of the optical logging concept, it is of secondary importance at this time.

For other communication purposes, such as transmission of a modulated optical signal directly from a down-hole instrument to the surface, the two concepts that appear most practical at this time consist of

temperature-hardened LEDs and small tungsten lamps such as those commonly called "grain of wheat" bulbs. Although the latter operate at very low power, the power density from the filament is not greatly less than that of much higher powered lamps, and the collection efficiency can be made higher because of the small size of the envelope.

Special semiconductor LEDs capable of high-temperature operation appear feasible, although no such device is presently available. Experiments are planned for early in the next period for determining the radiation characteristics with temperature for various commercial infrared LEDs. Preliminary literature investigation of this subject is currently underway.

Other optical problems of importance include coupling fibers to transducers, in particular to GaAs or InP temperature sensors. In study of this problem, two optical ray-trace computer programs have been obtained, and one has been modified for analysis of various coupling concepts. These can be easily modeled on the computer, and valid approaches attempted experimentally. The analysis will begin immediately.

III. SUMMARY

The construction of a practical well-logging cable based on optical fibers appears to be feasible. Design of such a cable has been completed, and construction is under way for a cable capable of meeting the intermediate temperature goal of 275°C. The problems of extending the temperature range beyond 300°C are understood, and approaches are in preliminary stages of investigation. Samples of the completed optical cable core for laboratory tests are promised for the month of May.

The design of a cable connector is well underway. The connector concept being pursued is based on small high-precision components, produced by a photo-etch process to maintain the necessary accuracy of fiber alignment. Pressure integrity will be maintained by relatively conventional O-ring seals held to minimum size and complexity. At the intermediate goal of 275°C, properly engineered O-ring seals are feasible. Three sealing materials are under direct investigation. These include Viton, a fluorocarbon rubber, polytetrafluoroethylene coated neoprene, and solid polytetrafluoroethylene. Other advanced materials are also under study, including ceramic-to-metal seals made with a liquid castable ceramic which cures at low temperature. Other materials of interest include a high temperature epoxy adhesive, and a very high-temperature ceramic adhesive.

Program effort is also concentrated on development of passive optical transducers. A sensor suitable for temperature logging based on the absorption edge phenomenon in Type III-V semiconductors has been investigated in considerable depth. The feasibility of measuring temperature in the range of 100°C to 500°C by this method has been demonstrated. An instrument will be designed using a thin wafer of polished gallium arsenide (GaAs) or indium phosphide (InP) in which the variation in temperature in a geothermal well will be detected by measurement of the change in wavelength at which the material becomes opaque. The effect of simple dopants on the GaAs absorption edge has been demonstrated, and the usefulness of controlled amounts of impurities have been shown to give some degree of control to the absorption measurement.

A promising approach to slow neutron logging by optical means is under study. In this concept, a phosphor which scintillates at infrared wavelengths in response to alpha bombardment (CdS), will be mixed with a transparent boron compound with a high cross-section for the (n, α) reaction. The emitted light will be collected and transmitted directly to the surface over the optical cable, where individual pulses will be counted in the usual manner. The efficiency of such a detector, based on calculations from scattered data in the literature, indicates that the system should be sufficiently sensitive to permit neutron logging with a practical neutron source.

Emitters, which are sources of infrared with suitable characteristics for use with optical fibers, have been investigated. Because of the wavelength dependent nature of the temperature sensing concept, a tungsten-halogen incandescent lamp has been selected for the design of a source capable of transmitting energy over 1 km or more of 15 dB per kilometer cable. Coupling fibers to transducers in down-hole instruments has also received study, and a computer model for this analysis has been adapted from an available ray trace program.

The effects of stress and temperature on the transmission properties of quartz fibers have been studied. Laboratory measurements indicate that direct tensile stress of 90,000 psi, equivalent to approximately 1% elongation, produces an increase in attenuation of about 5%. Temperature measurements indicate no discernible effect on transmission at 500°C, with an increase in attenuation of 5% or less at 1000°C.

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