UCRL-84109
PREPRINT

CONF-800719--1

MASTER

DESIGN AND IMPLEMENTATION OF A
FIBER-OPTIC GAMMA-MEASUREMENT SYSTEM

R. P. Reedy
D. W. Crawford
F. Roeske, Jr.

Proceedings of the Society of Photo-Optical Instrumentation Engineers,
International Symposium,
San Diego, California, July 28 to August 1, 1980.

May 19, 1980

The logo for Lawrence Livermore Laboratory, featuring a stylized 'L' and 'L' intertwined, with the text 'Lawrence Livermore Laboratory' written diagonally to the right.

Lawrence
Livermore
Laboratory

This is a preprint of a paper intended for publication in a journal or proceedings. Since changes may be made before publication, this preprint is made available with the understanding that it will not be cited or reproduced without the permission of the author.

Design and Implementation of a fiber-optic gamma-measurement system

R. P. Reedy, D. W. Crawford, and F. Roeske, Jr.

University of California, Lawrence Livermore National Laboratory
P. O. Box 808, Livermore, California 94550

Abstract

The planning of scientific field experiments that use delicate optical instrumentation poses a challenge to the designer. At the U.S. atomic test site in Nevada, many experiments are conducted under the most adverse conditions for instrumentation, including extremes of temperature and dust, while the instruments are being installed, aligned, and tested above ground. They are subjected to mechanical shock while being lowered into place deep underground and during the back-filling process. Before being destroyed by the blast, they then must operate in intense radiation fields long enough to transmit their data to a recording station.

In this paper we present the design and implementation of the "downhole" portion of a measuring system for gamma rays. Included are three alternative designs for radiation-resistant collimating and condensing lenses, sample cells, turning mirrors, and fiber-optic termination techniques. Also discussed are mechanical mounts and positioners, shielding, alignment, test methods, and field installation. Some general design suggestions for optical systems in adverse environments are also presented.

Introduction

Experimental devices are tested deep underground at the U.S. atomic test site in Nevada. Specially designed diagnostic systems have been developed to measure their performance. One such system is based on the solvated-electron absorption of light by an aqueous solution when struck by intense radiation. The optical transmission decreases logarithmically as the radiation intensity increases and is measured by passing a beam of light through a cell containing the solution and recording the change. The response time is very fast, as indeed it must be to measure this fast gamma-ray signal. Light is furnished by a laser and is transmitted "downhole" through an optical fiber to the cell. The attenuated light is collected and fed into another fiber, which travels to a recording station located above ground. Timing and radiation-decay information can also be obtained by using several cells spaced a few feet apart along the line-of-sight (LOS) pipe.

A diagram of one unit of the overall system is shown in Figure 1. The "downhole" portion of the system is the subject of this paper. Environmental considerations, optical and mechanical component design, alignment, testing, and some suggestions about fielding optical systems in general are discussed.

DISCLAIMER

This document contains information that is classified as "Secret" under Executive Order 11652, Section 1.5, and is exempt from automatic downgrading and declassification under Executive Order 11652, Section 1.5. It is the property of the U.S. Atomic Energy Commission and is loaned to you. It and its contents are not to be distributed outside your organization. If you are not an authorized recipient, please return this document to the U.S. Atomic Energy Commission, Office of Technical Information, P.O. Box 217, Springfield, MA 01104.

Figure 1. One unit of the overall gamma-measurement system.

General design considerations

Radiation of 1- to 10-MeV gamma rays and Cerenkov light influence the general layout of components, the shielding, and the selection of optical materials.

Space is restricted by the clearance between the LOS and the side of the canister to 180 x 180 mm and 64 mm in height because of the location of a neighboring experiment.

Alignment accuracy and shock resistance are key elements in the design of mechanical components. A 62- μm (0.0025-inch) spot is focused on a 62- μm fiber. Any misalignment reduces the system efficiency. This could not be tolerated because of the anticipated low-level signal at the receiver. The system is subjected to shock during the shielding process when the lead fitters place the solid lead and lead shot around the instruments. Further shock is expected during final emplacement of the canister below ground.

Optical accuracy will affect system efficiency. One-half of a wave was established as a wavefront accuracy limit for most components because of compromises between accuracy and low mass.

A laser operating at a 632.8-nm wavelength was selected as the best available compromise between power output, fiber transmission characteristics, and detector response.

The housing is designed to withstand the stresses caused by the shielding material and is sealed against desert dust.

The cell contains perchloric acid (HClO_4) in varying concentrations up to full strength. Should any of this highly corrosive acid escape it would not only damage this experiment but also those located farther down the LOS.

Optical components

Lenses

Three computer-optimized lens designs were considered for use as collimating and condensing lenses. Figure 2 illustrates the "downhole" portion of the experiment including the lens functions.

Figure 2. Downhole portion of gamma-measurement system.

The design considerations were as follows:

1. The lenses must be composed of a glass that resists darkening caused by radiation, because any change in transmission would be interpreted as part of the data.
2. The N.A. (0.22) was chosen to be equal to or greater than the fiber in order to prevent light loss.
3. The overall magnification value must be one, because the illumination and signal fibers have the same diameter.
4. The lens focal length must be selected to achieve a 10-mm aperture (1 mm less than the i.d. of the cell) while meeting the N.A. requirements.
5. The design operating wavelength is 632.8 nm for the reasons stated previously.
6. The lenses (and associated optical components) must be very efficient to keep the signal within the sensitivity range of the detector.
7. The same lens design will be used for both the collimating and condensing functions.

An optimized single-element, a doublet, and a three-element lens were each considered. The radial energy distribution is most pertinent to this application because it can be used to determine how much energy will be lost as a result of lens aberrations. Because we are operating at one wavelength, on axis, spherical aberration is the chief concern. The significance of this data is more easily seen by referring to the scale illustrations graphing energy distribution relative to a 65- μ m fiber (see Figure 3). In these illustrations it is assumed that points of light are being imaged at the edge of the fiber, and because of the point spread caused by lens aberrations, energy extends beyond the fiber in varying amounts depending on the design. The data show that less energy is lost with the more complex designs.

The three-element design was selected for the experiment in order to conserve energy. The completed lenses were tested by measuring their Modulation Transfer Function (MTF) and comparing the results with the computer-generated MTF data for the lens. The lens values differed from theoretical predictions by only 3% in the range of zero to 100 cycles/mm. In the final design, the lenses formed an image of a point

Figure 3. Energy distribution plots for three different lens designs. (a) Optimized single-element lens operating at $f/1.8$. (b) Two-element lens, one element being an air-spaced element. (c) Lens with three air-spaced elements operating at $f/1.8$.

source with 100% of its energy contained in a 7- μ m circle. The elements were made from radiation-resistant glass (Schott* Bak1G and SF1G).

Cell

Design considerations for the cell that holds the solvated-electron solution are as follows:

1. The cell must bridge a one-inch circular LOS, have no obstructing supports, and have a minimum mass of material in the LOS to reduce radiation scatter and obstruction to experiments beyond this point.
2. The cell must be able to contain a highly corrosive material (HClO_4) for a period up to several months and must not contaminate the solution or allow it to escape.
3. The end windows must be flat and parallel, be as thin as possible to minimize wavefront distortion and radiation scattering, and be constructed from a material that will resist radiation-induced darkening.

The cell is shown in Figure 2. The body is constructed from available quartz tubing having an outside diameter of 13 mm and a wall thickness of 1 mm. Large flanges are fabricated on both ends where the 0.5-mm-thick Suprasil 1 (fused silica) windows are fusion welded at the outer diameter. This technique minimizes warpage of the windows in the critical transmitting area (we hoped to achieve a deformation of only one-half wavefront through the cell). Seven cells were built, and six of them (the number needed for the experiment) did equal or exceed the specification over a 10 mm diameter. The seventh was used in the spare system. The original design provided for a tapered glass stopper for filling and sealing; however, a last minute decrease in the available height required cutting off the stopper neck and, after filling, cementing a glass cover above the liquid level.

Turning mirrors

Turning-mirror design considerations are as follows:

The mirror mass must be as small as possible to minimize secondary scatter and yet hold a flatness of one-half wave.

The coatings must have a maximum reflection at 632.8 nm and a minimum reflection in the blue (radiation striking the cell generates a copious amount of Cerenkov radiation, which emits predominately in the blue region of the spectrum). This unwanted light could show up as background. Several factors reduce this unwanted light to a negligible level. For example, the emission is strongly forward scattered at right angles to the optical LOS. Also, the only light that could reach the signal fiber would have to be very well collimated down the optical LOS. Additionally, the mirrors are gold-coated, reflecting 94% of the light at 632.8 nm and approximately 40% in the blue.¹ Finally, the fibers transmit poorly in the blue and produce an estimated signal to background ratio of $\geq 10^5$ at the detector.

The mirrors are made 0.75 mm thick, which gives an aspect ratio of 13:1 relative to the beam diameter at the surface. The thickness is a compromise between minimum mass (because of secondary scatter) and the necessary resistance to bending needed to maintain one-half wave flatness. The mirrors are made of fused silica. Fourteen mirrors were mounted and tested for flatness. Eleven were within one-half wave. The maximum deviation from flatness was one wave, and this mirror was placed with the spare units.

Optical fibers

Because the experiment was designed to measure a very fast gamma-ray signal, it was necessary to use high-bandwidth, graded-index optical fiber. Unfortunately, these fibers are the most susceptible to radiation-induced absorption. Corning, 62- μ m, IVPO graded-index fiber was chosen to be used in the field of highest radiation, because it appears to have approximately five times less sensitivity to radiation-induced absorption than the "standard" OVPO fiber available. Nevertheless, this fiber has a radiation sensitivity of approximately 0.05 db/cm/krad.

Mechanical components

General design

The physical layout of the system (see Figure 2) was mainly influenced by the desire to minimize the radiation reaching the lens and fiber and to minimize the length of fiber in the high-radiation environment.

The area surrounding the housing that contains the optical components was heavily shielded and did not permit a significant amount of radiation to reach the fiber from any source other than the LOS pipe. The gamma radiation coming up the LOS pipe scatters when it impinges on the hydrated-electron cell, thereby creating a secondary source. This must be kept in mind when shielding the fibers and lenses.

*Reference to a company or product name does not imply approval or recommendation of the product by the University of California or the U.S. Department of Energy to the exclusion of others that may be suitable.

Key design features incorporated the following physical ideas to reduce the radiation on the fiber:

1. By moving the fiber as far away as practical from the cell, we take advantage of the solid-angle reduction in radiation.
2. By arranging the fibers so they lie in a plane perpendicular to the LOS pipe, we only have to deal with 90° -scattered radiation. This has two advantages: the differential cross section for high-energy photons is strongly peaked in the forward direction, that is, fewer of the gammas are scattered in the 90° plane; for incident photons in the range of 1 to 10 MeV, the 90° -scattered photons have energies from 400 to 500 keV, thus, making shielding in this direction more effective for the low-energy photons.
3. To take further advantage of 90° scattering, we incorporated turning mirrors in the unshielded optical path so that radiation would have to be doubly scattered at 90° to reach the fibers. The mirrors were made as thin as optical stability would permit in order to reduce scattering from them.
4. Finally, as much lead as possible was introduced between the cell and the fibers to reduce the singly scattered flux. A minimum of one inch of lead was used.

This particular design reduced the flux on the nearest segment of the optical fiber of lens by a factor of 8×10^{-7} from that of the main beam in the case of single scatter and by a factor of 1×10^{-8} for double scatter.

Adjustments for alignment

Six fine adjustments (lens of micrometers) and two very fine adjustments (micrometers) are used for alignment. The first three fine adjustments are used to place the fiber at the focal point of the collimating lens in the Z plane (x and y were fixed) and to rotate and pivot the first turning mirror in order to steer the beam into the correct location at the second turning mirror. The next three fine adjustments are used to rotate and pivot the second turning mirror to place the beam in the center of the condensing lens aperture and focus the condensing lens on the output fiber. The two very fine adjustments are used to translate the output fiber in x and y relative to the condenser-lens focal point. A combination of fixed and removable translators accomplish these adjustments. In all cases, the translators had to be designed and built to satisfy the following requirements:

1. Once alignment is achieved, the locking techniques must be absolutely positive, because a few micrometers of movement could cause enough misalignment to reduce the output signal to below a usable level. After the unit is installed and shielding begins, it is no longer accessible for adjustment;

2. The components must be miniaturized to leave room for the shielding.

Space was saved by using removable translators wherever possible. A close-fitting split sleeve and compression bolt are used to lock the mirror support tubes, which are rotated for one of the adjustments, and the lenses which slide in their sleeves to accomplish focusing. A second locking technique clamps the mirror-support block to the base plate after it is pivoted about a pin, thereby rotating the mirror for adjustment.

The translator used for locating the signal fiber relative to the condensing lens is self locking. The fiber is located at the center of a hardened steel disk with a tapered (10°) edge. Three screws with a matching taper are equally spaced around the periphery of the disk. Very fine translation of the disk (and fiber) is accomplished by advancing one of the screws, which produces a small displacement and loads the opposing screws, thereby locking the disk in position. The shallow taper gives a large mechanical advantage. A screw with 32 threads per inch is used with the same control that 100 threads per inch allows when translating directly.

A removable translator was used to adjust both lenses in their sleeves. It consists of the micrometer movement of a spring-loaded cylinder with a link clamped to the lens (Figure 4). The turning mirrors are rotated into their correct positions by clamping an adjustment arm on the support tube. The other end of the arm is placed between opposing screws, which provide the adjustment (see Figure 4).

The turning mirror faces are located on a plane that extends through the centers of the pivot pins located in the support blocks. Mirror adjustments are made by moving the opposing screws located in the back of the support block, thereby causing the block and mirrors to rotate about the center of the pin.

Mechanical supports

All the components are fixed to a rigid base plate constructed from Meehanite, which was chosen for its stability. The base plate is fastened at three points to the housing. To minimize stress on the plate, part of the lead shielding is suspended from the top of the housing.

The quartz cell containing the acid is supported by a split yoke lined with a thin rubber cushion. The turning mirrors are attached to the end of a glass tube with a resilient adhesive to minimize stress,

Figure 4. Optical unit with translators attached. Removable translator (used to focus lenses) is shown at far left-hand side of base plate. At top left is the removable device used to rotate the mirrors to their correct positions.

which tends to warp the glass, and to absorb shocks. The glass support tube is long enough so the metal support can be located out of the optical LOS to the lenses. This reduces the secondary scatter from the metal. The support is a glass tube to minimize the material cross section facing the primary source of scattering and to allow radiation penetrating the mirror to continue unobstructed ("get lost"). The glass tube is surrounded by a thin layer of Teflon and is placed in a housing of the split-clamp design, allowing smooth rotation for adjustment and some resiliency when the metal housing is closed tightly.

The fibers are cleaned, inspected, and mounted in metal ferrules with epoxy, allowing the fiber to protrude approximately 0.5 mm beyond the face of the ferrule; this assures the tip will be free of the adhesive. The metal ferrules containing the fibers are then clamped in supports.

Rubber seals are placed between the fiber support and the lens support to prevent any dust particles from entering this critical region. One dust particle could cut off the signal.

Alignment testing and fielding

The optical alignment of this experiment is relatively simple. The illumination fiber is located mechanically in x and y. The z dimension locates the focal point of the collimating lens relative to the illumination fiber to produce parallel light. This is accomplished by moving the lens in its housing with the aid of the special translator. The illumination fiber attached to this optical plate is a 10-m long pigtail and is fed by a He-Ne laser for alignment and test purposes. By observing and adjusting the size of the exit beam from the collimating lens over a distance of a couple of meters, a collimated beam can be obtained. Next, the turning mirrors are adjusted to center the beam on the cell and then on the aperture of the condensing lens. The signal fiber has previously been located to within a few tenths of a millimeter from the correct location. A few trial movements of the fiber then locates the beam, and precise alignment can be achieved by adjusting the lens focus and fiber position.

A final lab test measures the output from the signal fiber relative to the output from the illumination fiber, thereby testing the complete system exclusive of the illuminating fiber. These tests revealed that six of the seven units built had losses ranging from 3 to 4 db. A complete unit with the alignment translators removed is shown in Figure 5.

Figure 5. Optical unit with the translators detached. The unit is ready for the installation of lead shielding.

Figure 6. Blackbox (center of picture) used to house one of the downhole optical systems. The LOS pipe extends down through the box. The illumination and signal fiber enter the front of the box through the tubing and elbows. At this stage, the equipment is ready for the lead shielding, which will fill the remaining volume inside the canister.

These units were designed to be completely aligned in the laboratory and any field alignment would be on an emergency basis only. They were shipped bolted into their housings and individually packaged in special carrying cases. The picture of the field installation seen in Figure 6 was taken before the shielding operation began.

Conclusions

The various environmental elements considered in designing this experiment are typical of "underground" atomic testing. When an experiment is being designed, fabricated, tested, and fielded with only one chance to work perfectly the first time, every step must be given careful consideration. If something does fail, it is difficult to diagnose the problem because nothing is left. Based on our experience, we can offer some suggestions:

- Find out as much as possible about the conditions under which the system must operate.
- Where possible, include contingency plans, including spare units and various plans of action.
- Design the system to be as modular as possible with easily replaceable units, because a unit may fail or there may be last-minute modifications that must be accommodated.
- Design in a safety margin commensurate with the known conditions. Previous designs may not be adequate.
- Use proven materials where possible. Personally test the materials if necessary.
- "Dry run" the system but do not dry run it to death. The point of a dry run is to establish reliability; certainly we do not want to exceed the life expectancy of the components.
- Work to a schedule, and leave room for error. Most schedules include a place where one must depend on others to finish their part on time.
- If the system must interface with another person's unit, plan together and stay in frequent contact because there will be communication breakdowns and these can be disastrous.
- Plan the field installation carefully. Include checkoff lists and provide a satisfactory working environment. Locate facilities for making emergency repairs and sources for emergency supplies. Work within the schedule.

These are a few thoughts on fielding complex systems. We are certain the reader can add some of his own. Be sure to remember Murphy's law, "If anything can go wrong, it will".

Acknowledgments

The authors gratefully acknowledge the work of David Jones and Thomas Schaffer, in particular, for designing and constructing the housing and shielding and for their participation in fielding the experiment. We would also like to thank George Michael for his helpful editing. This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under contract No. W-7405-Eng-48.

Reference

1. Chopra, Kasturi L., Thin Film Phenomena (McGraw-Hill, New York, 1969) p. 777.