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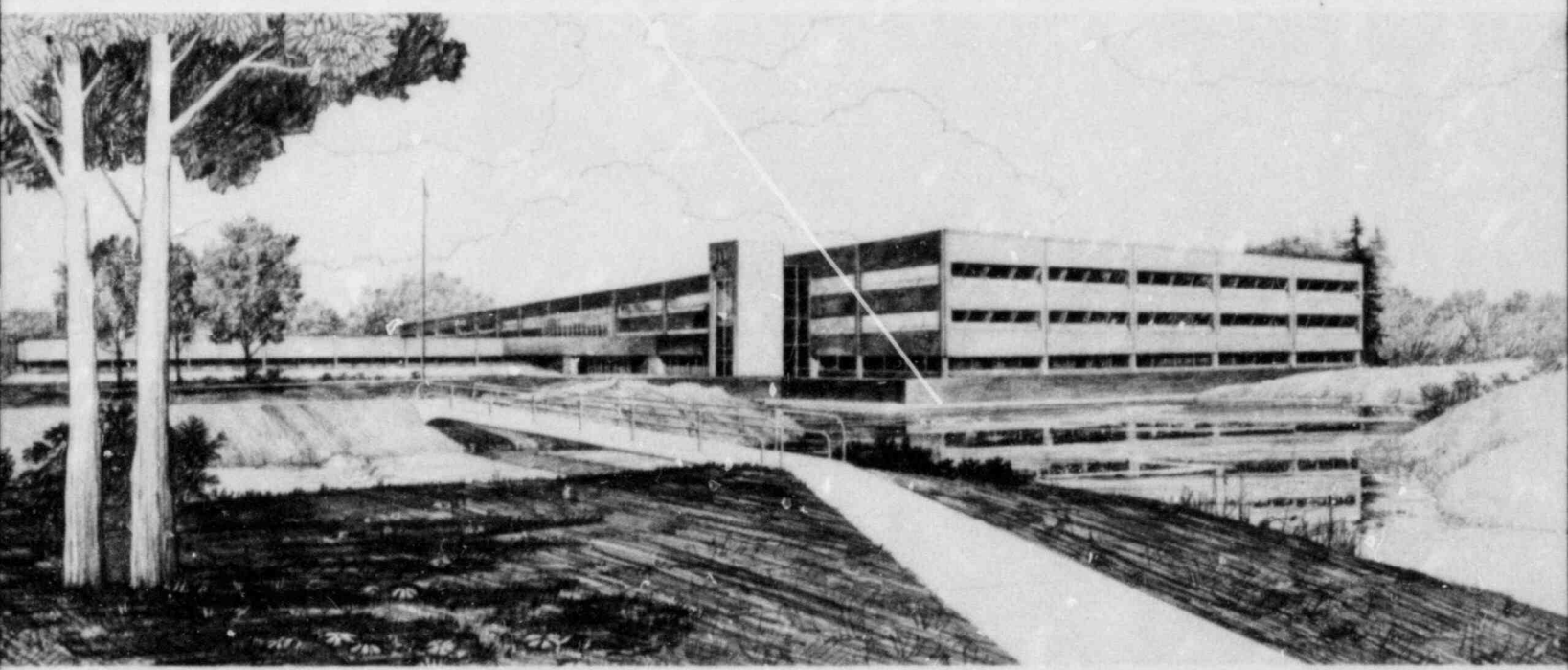
A FIBER OPTIC VOID FRACTION MEASUREMENT SYSTEM FOR THE STEAM GENERATOR IN LOFT

Stuart C. Snyder

Idaho National Engineering Laboratory
Operated by the U.S. Department of Energy



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R. R. Landry, Experimental Program Branch, Division of Accident Evaluation, Office of Nuclear Regulatory Research

EG&G Idaho, Inc.
Idaho Falls, Idaho **83415**

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ABSTRACT

This report presents the tests that were performed to determine the suitability of the optical void fraction probe (designed by EG&G Idaho for the 3D project) for use in a void fraction measurement system, in the secondary side of the steam generator in LOFT. Included were autoclave tests to determine the survivability of the probe in a simulated steam generator hydrothermal environment and radiation tests to study the effects of gamma radiation on the optical components of the probe. Compatability of the output of the probe with LOFT data acquisition and analysis techniques was also investigated. It was found that the sapphire component of the optical probe will not withstand the hydrothermal environment of the secondary side of the steam generator. The effect of gamma radiation on the probe was found to be insignificant. The signal output of the probe is compatable with LOFT data acquisition, and data reduction techniques developed for use with conductivity probes.

FIN No. A6043--LOFT Instrumentation

SUMMARY

This study was performed to assess the feasibility of using the optical void fraction probe developed by EG&G Idaho for the 3D Program as a void fraction measurement system in the secondary side of the steam generator in LOFT.

An optical void fraction probe is simply a 45-degree sapphire cone with the ends of two optical fibers butted against its base. On the opposite end, one fiber is connected to a light source, and the other is connected to a photodetector. If the sapphire tip is in steam, light from the source fiber is reflected to the return fiber and detected. If the tip is in water, light from the source fiber is not reflected to the return fiber. Hence, the probe can measure the local time average local void fraction of a flow.

Tests were performed to determine the survivability of the probes in the steam generator's hydrothermal environment, and to assess the effect on the probes of gamma radiation of the intensity found in the secondary side of the steam generator.

It was found that the probes are not significantly affected by gamma radiation, but will not withstand the hydrothermal environment. It is recommended that a new generation of optical void fraction probes be developed with the sapphire tip replaced by either the more resiliant spinel of titanium dioxide.

CONTENTS

A FIBER OPTIC VOID FRACTION MEASUREMENT SYSTEM FOR THE STEAM GENERATOR IN LOFT

1. INTRODUCTION

Interest has been expressed to characterize the flow in the secondary side of the steam generator in LOFT during a loss-of-coolant experiment. Because of this, a void fraction measurement inside the steam generator is highly desirable.

The physical size of the steam generator precludes the use of standard gamma densitometry techniques to measure a chordal average void fraction. As an alternative, using an array of probes such as conductivity probes or optical void fraction probes to measure the distribution of local void fractions in a flow may be possible.

This report investigates the possibility of adapting optical void fraction probes developed by EG&G Idaho, Inc., for the Japan Atomic Energy Research Institute (JAERI) test program for local time average void fraction distribution measurements in the steam generator. A description of the probe design and operation is presented, along with a void fraction measurement system conceptual design. Tests performed to determine the survivability of the probes in the steam generator environment are discussed, and the test results reported. Conclusions and recommendations are given.

2. SYSTEM DESIGN

2.1 Optical Void Fraction Probe Design and Operation

These probes are optical probes that sense whether the probe tip is surrounded by water or steam, thus determining local void fraction at the probe's location. Basically, the tip is a 3.18-mm-diameter, 45-degree sapphire cone brazed onto the end of a nickel tube 20.64 mm in length, which in turn is welded onto the end of a 1.59-mm stainless steel sheath that is of sufficient length to exit the pressure boundary. The stainless steel sheath houses two 0.30-mm aluminum-clad optical fibers that are butted against the base of the sapphire cone. One fiber lead is connected to an incandescent light source, the other to a silicon photodiode detector. A schematic of the probe is shown in Figure 1.

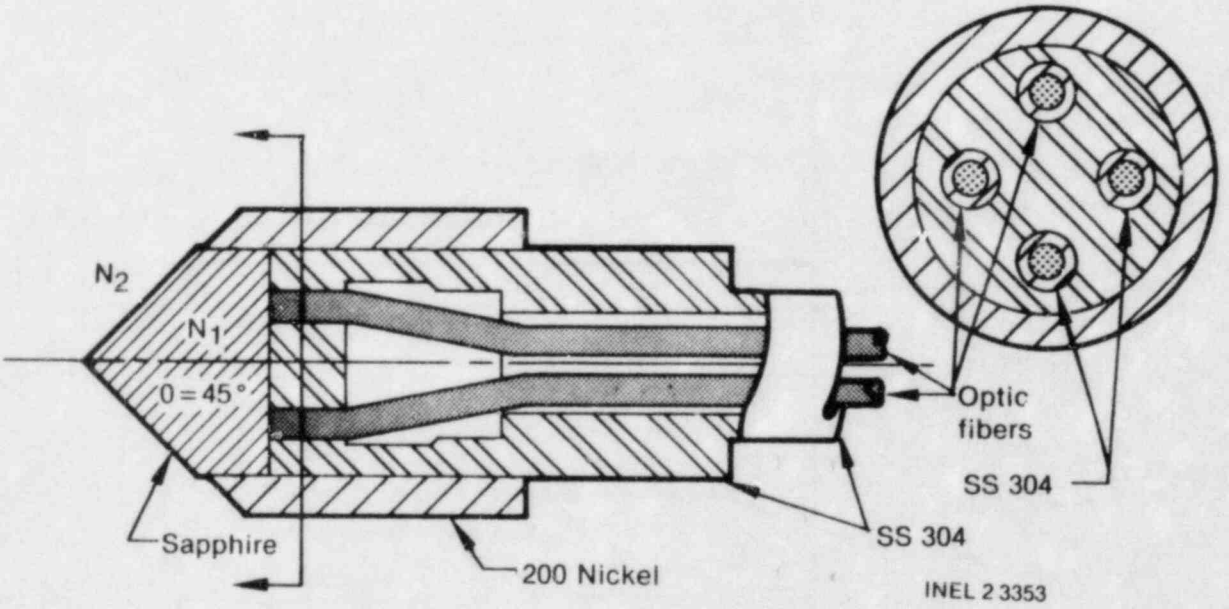


Figure 1. Optical void fraction probe schematic.

The principle operation of the probes is quite simple. If the probe tip is in steam, light transmitted down the fiber from the source is incident on the sapphire tip at an angle θ_i which is greater than the critical angle θ_c for total internal reflection. The critical angle is given by

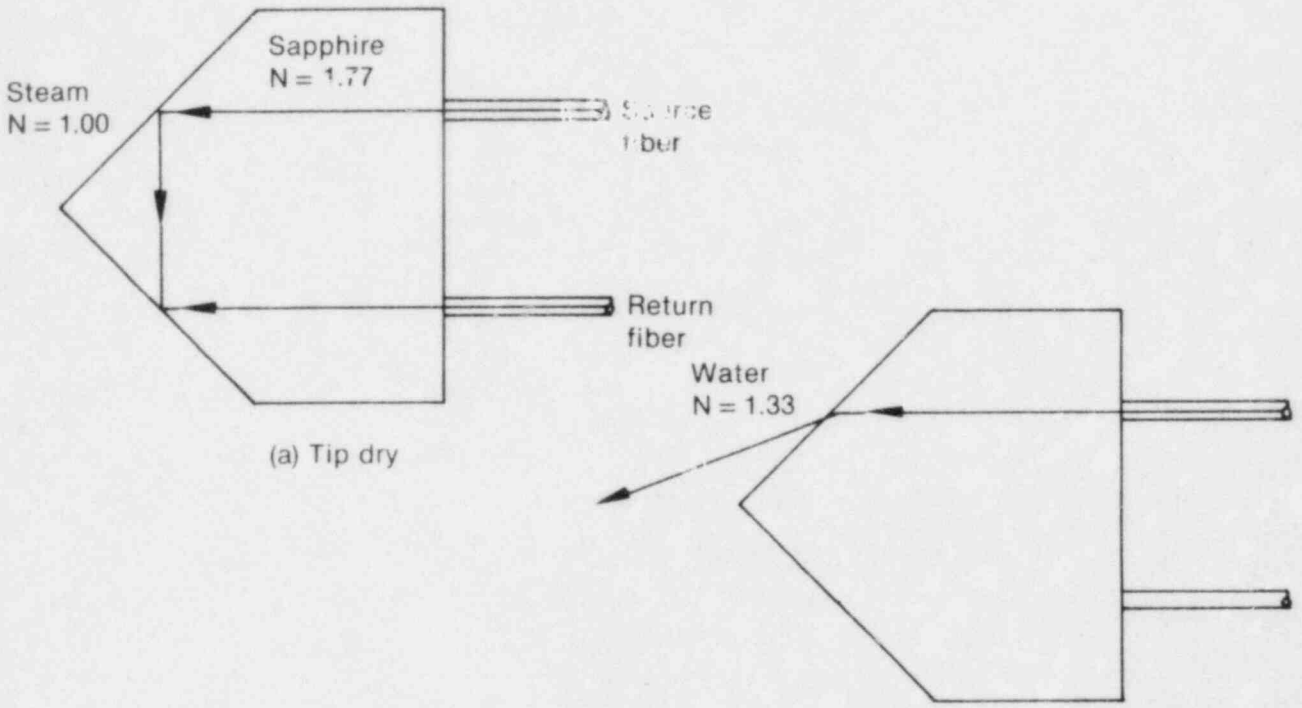
$$\theta_c = \sin^{-1} \frac{n}{n_i} \tag{1}$$

where n is the index of refraction of medium surrounding the tip, and n_i is the index of refraction of sapphire. The light is then reflected to the return filter and transmitted to the detector. If the tip is immersed in liquid water, the condition for total internal reflection is not met, and the light passes from the filter and through the tip, with very little light being reflected to the return fiber. The void fraction probe is ideally a binary device; a maximum signal output when the tip is in steam, and a minimum signal output when the tip is in liquid water. Figure 2(a) and (b) illustrate the operation of the probe.

Intermediate signal levels occur if the tip is in steam, but wet with a thin film of water. It can be seen from Figure 2(c) that a ray of light from the source fiber parallel to the axis of the probe is not returned to the detector because of refractions and reflections by the water film.[1] On the other hand, light diverges as it exits the source fiber and some nonaxial rays will be returned to the detector. The net result is a reduction of the light signal compared to the dry tip case; the thicker the water film, the greater the signal reduction. An example of raw void fraction probe data is shown in Figure 3.

Since the probe output is binary in nature they measure the individual phase residence time fraction at the probe's location. The time average local void fraction, α is defined as[2]

$$\alpha = \frac{\sum_n B_n}{N} \tag{2}$$



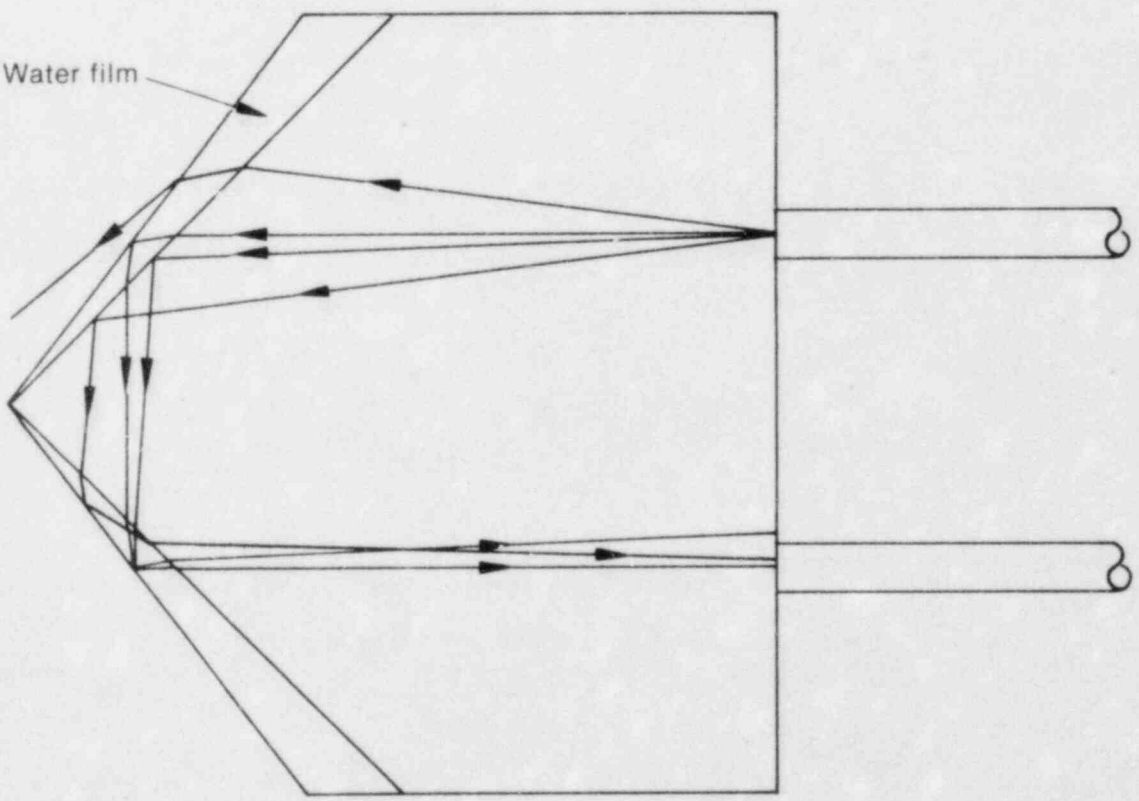


Figure 2. Principle of probe operation.

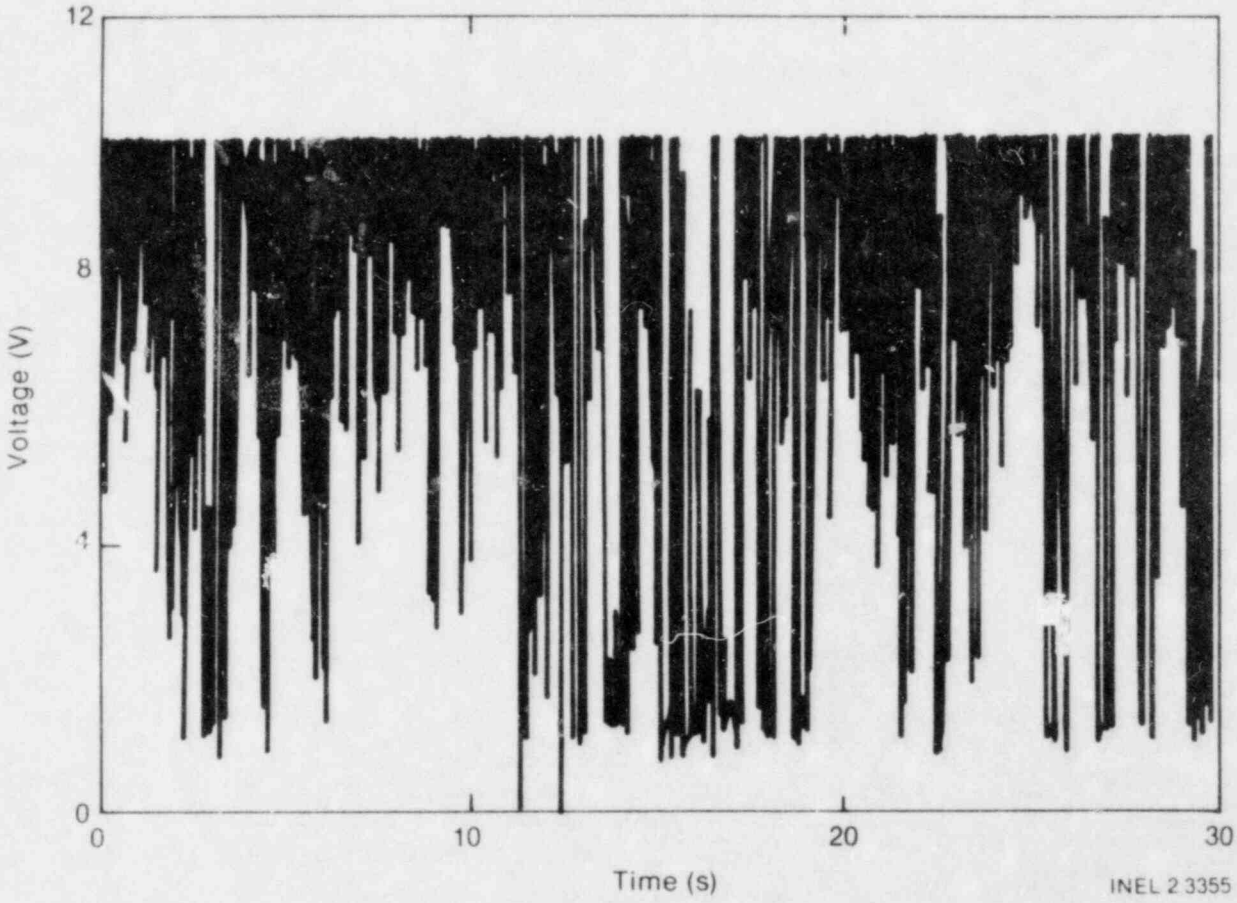


Figure 3. Raw optical void fraction probe data.

where

B_n = 1 if the tip is in steam

= 0 if the tip is in water

N = total number of data points taken and depends on the sampling rate of the device.

Because of the intermediate voltage levels, the values of B_n appearing in Equation (2) should be redefined as

b_n = 1 if the voltage output is greater than some threshold value

= 0 if the voltage output is less than some threshold value.

The level of the threshold value for an array of probes may be determined by calibration with reference instrumentation such as a gamma densitometer, providing this is possible.

Another approach is to analyze the data with a computer algorithm called the automated discriminator process.[3] This method assumes the intermediate signal levels occur as uniform random noise. The signal is differentiated and a threshold value calculated. The algorithm then calculates the time average local void fraction with an estimated uncertainty of <10% of range. This method is quite useful when calibration of the probes against reference instrumentation is not possible. Although developed for use with conductivity probe data, the method was tested successfully by T. Meachum[4] with probe data taken in May 1981, during 2D/3D OLLD tests at INELs Water Reactor Research Test Facility (WRRTF).[5]

2.2 Void Fraction Measurement System

Being an intrusive device of a finite size, an optical void fraction probe can give only an approximate value of the local void fraction at the probe's location. It is unreasonable to expect the probes to detect steam bubbles of diameters of less than the tip diameter. To get an idea of the local void fraction distribution in a two-phase flow, it is necessary to use a grid of probes spanning the flow. The number of probes used in such a grid of course, depends on the resolution desired.

Because of mechanical and geometrical considerations, it appears that the best void fraction measurement system for the steam generator would be a vertical string about 1.52 m in length of probes suspended under the shroud. The probe tips should be pointed up to allow water droplets to readily drain off. Depending on stress analysis and available space, it might be possible to install more than one string of probes.

Such a configuration of probes would provide information on local void fraction versus height in the steam generator in the immediate vicinity of the string. Again, the resolution of the void fraction distribution depends on the number of probes installed.

3. TEST PROGRAM

The environment within the steam generator is quite severe, with operating temperatures and pressures of about 280°C at 6.9 MPa. The water's pH is adjusted to a value of 9-1/2 by adding ammonium hydroxide. A small amount of hydrazine is added to remove oxygen. Radiation levels inside the steam generator with the reactor at full power are estimated to be 5 R/h maximum. During a typical test at LOFT, the probes would be subjected to this environment for about 100 h.

Two phases of testing were planned and carried out to determine if the probes could survive in the LOFT steam generator environment. The first phase involved autoclave tests performed at ARA III. The second phase of testing studied the effects of gamma radiation on the probes using the gamma facility at ATR.

3.1 Autoclave Tests

Six probes, approximately 4.6 m in length, were constructed according to procedures established by the 3D program to produce quality assurance level 2 probes. These probes were used for the autoclave tests at ARA III.

The test program involved cycling the probes from a 24 h period in an all-water environment at 280°C and a pressure of 6.9 MPa to a 24 h period in an all steam environment at 278°C and 6.2 MPa of pressure. The temperature of the autoclave was allowed to cool to about 38°C in between the liquid water and steam phases to test the effect of temperature cycling on the probes. The water in the autoclave was demineralized with the pH adjusted to 9-1/2 with ammonium hydroxide. Prior to commencing the test, the water was boiled to remove oxygen in lieu of adding hydrazine. The probes were connected to a light source and detector, and the voltage output was constantly recorded on a Brush Model 260 oscillograph. Two separate tests were conducted with three probes tested during each run.

3.2 Gamma Irradiation Tests

The effect of gamma radiation on the probes was investigated at the ATR dry tube gamma facility. The attenuation of a light signal propagating through an optical medium results from intrinsic absorption of the light by the medium, scattering of the light by cracks, bubbles, and other such imperfections, and the preferential absorption of certain wavelengths of light by defects known as color centers. Exposing optical materials to ionizing radiation increases the number of color centers making the material less transparent to certain wavelengths of light.[6]

Two probes were connected to a common light source and separate detectors. One probe was exposed to gamma radiation, while the other was not, and was used as a reference. Both probes were continually operated and their outputs recorded on a two channel Gould Model 110 strip chart recorder. The probes were in air at room temperature and pressure at all times.

The probe to be irradiated was placed in the facility at a position where the radiation level was about 5.5 R/h. The probe was coiled to assure that all parts of the probe received the same exposure. Five Type TLD-700 thermoluminescent radiation chips furnished by the Department of Energy's Radiological and Environmental Sciences Laboratory were equally spaced on the coil to measure the total exposure of radiation the probe received.

4. TEST RESULTS

4.1 Autoclave Test Results

All six of the optical void fraction probes tested during the two separate autoclave tests failed at some point during the test.

The cause of failure of the first three probes tested provided no conclusive information on the probe's survivability in the steam generator environment. During construction of the probes, a small hole is drilled into the stainless steel tube housing the two optical fibers. Through this hole, the probe is evacuated and filled with dry argon. The hole is then sealed with a potting compound. It is important to fill the probes with dry argon because moisture and oxygen attack the optical fibers at higher temperatures and destroys them. The purge holes, located near the end of the probes where the two optical fibers exit, were inadvertantly located on the high pressure side of the pressure boundary when loaded into the autoclave. The potted purge holes leaked when exposed to high pressure and temperature, and the optical fibers were destroyed about 2 h into the test.

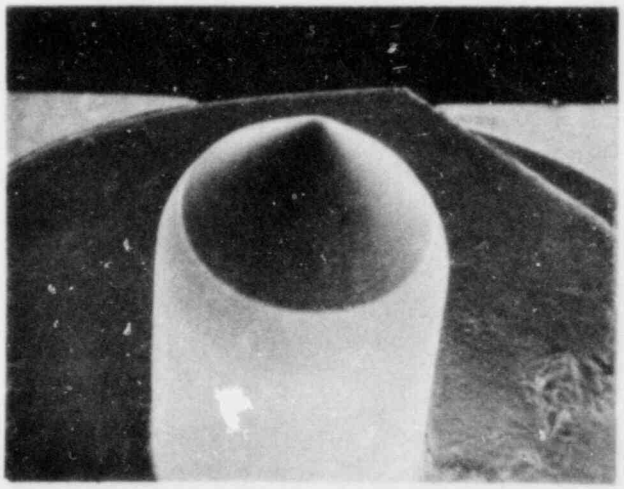
For the second test, precautions were taken to ensure the purge holes were located on the atmospheric side of the pressure boundary. It was observed during the first steam phase of the test that the three probes were no longer functional. The signal level of the probes with the light source turned off was the same as when the light source was turned on. Had the probes been functional, a maximum light signal would have been observed while the probes were in steam. The test was terminated after 27 h.

After removing the probes from the autoclave, visual inspection of the tips revealed that their surfaces had become frosted, apparently due to chemical action of the high temperature and pressure water. If the tips do become frosted, light incident on its surface is scattered in all directions, regardless of the tip's environment, with very little light reaching the return fiber. This was verified by analysis of the probe tips by the Material Science Laboratory at ARA 1, which compared scanning electron micrographs of an untested probe tip with the three tested probe tips. The results of this analysis are:

1. "Scanning electron micrographs of the untested probe shown in Figure 4(a), (b), and (c), show virtually an unaffected interface and optical-tip surface. However, the same areas of the three autoclaved probes shown in Figure 5(a), (b), and (c), exhibit an alteration of the probe-tip surfaces and the formation of a crack at the interface resulting in an apparent separation of the probe tip from the metal sheath. A longitudinal section of an autoclaved probe shown in Figure 6 indicates that the separation is enhanced at the sheathed-probe-tip junction and penetrates along the sheath-probe-tip interface. It should also be noted that the braze region is only intermittent, and does not appear to provide a completely closed path along the interface."

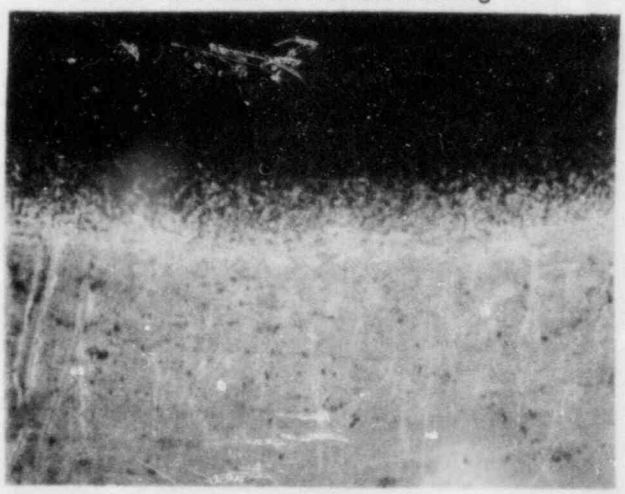
2. "There is little doubt that the Al_2O_3 was attacked (etched) by the hydrothermal environment. This is not surprising in that it is well known that silicates and aluminates hydrate easily in hydrothermal environments. This chemical attack combined with the thermal and mechanical stresses introduced by the brazing process result in crack initiation at the probe-tip-sheath junction which when fed by stress and corrosion propagates easily along the interface.[7]

Similar autoclave tests were performed by Delhaye et al.,[8] on sapphire tipped optical probes of essentially the same design as the 3D probes. These probes functioned normally after 100 h of exposure to demineralized water at 360°C and 18 MPa. However, tests performed for EG&G Idaho by the Oesterreichisches Forschungzentrum Siebersdorf[9] on the behavior of various optical materials under PWR primary coolant conditions also demonstrated that sapphire frosted after 32 h exposure to distilled water at 344°C and 15.2 MPa with 300 ppm boron added along with lithium hydroxide to adjust the pH to 8.0. Evidently, alkaline water accelerates corrosion of the sapphire tip material.



(a) Tip magnified 20X

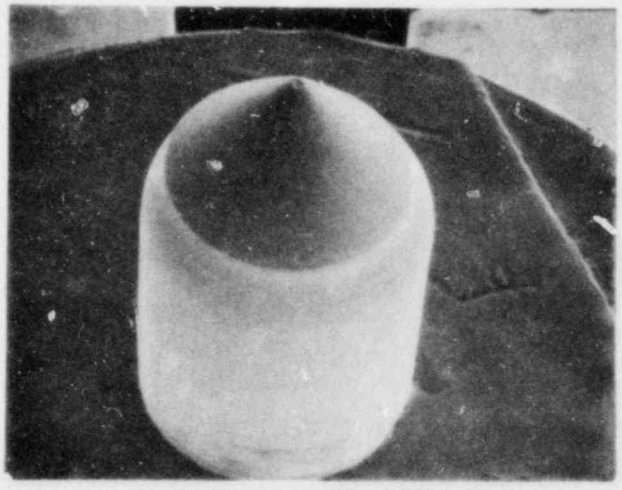
(b) Tip surface magnified 200X showing surface defects because of manufacturing



(c) Sapphire-nickel braze interface magnified 200X

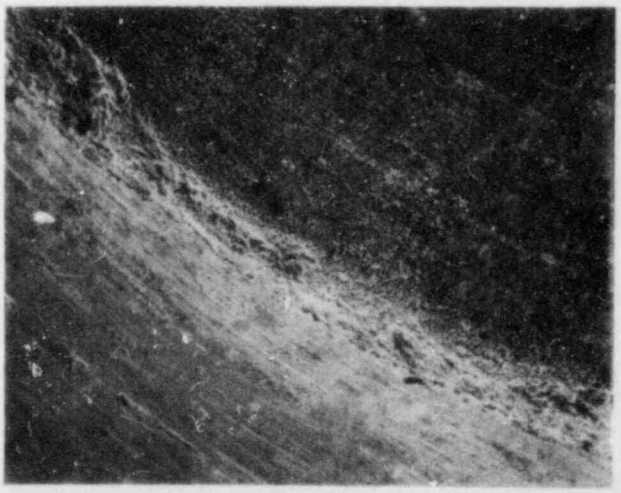
INEL 2 2436

Figure 4. Microphotographs of untested sapphire tip.



(a) Tip magnified 20X

(b) Tip surface magnified 200X



(c) Sapphire-nickel braze interface magnified 200X

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Figure 5. Microphotographs of tested sapphire tip.

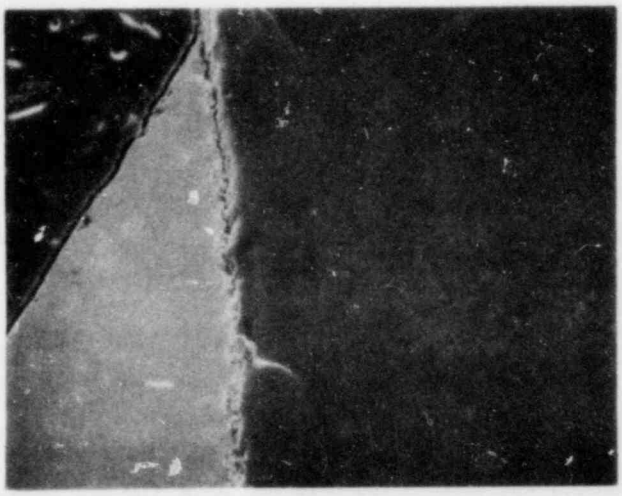

Figure 6. Longitudinal section of tested tip magnified 500x, showing separation at the sapphire-nickel junction.

4.2 Gamma Irradiation Test Results

It was originally intended to give the test probe about 500 R total exposure. This would approximate the total exposure the probes would receive during an actual test at LOFT. For some reason, the exposure rate as determined from the radiation chips was not 5.6 R/hr but 50.6 R/hr. For a test of 100 hr duration, the total exposure the probe received was about 5060 R.

Some deterioration of the signal from the test probe was observed. Some of this deterioration can be attributed to drift since the reference probe also showed a decrease in its signal level of about 5% during the duration of the test. Assuming the amount of drift in the outputs of the test and reference probe is the same, measurement of the change in signal level of the reference probe can be used to compensate for drift in the test probe. Correcting for drift the test probe showed about a 4% decrease in signal level, presumably due to radiation darkening. Results of this test are shown graphically in Figure 7.

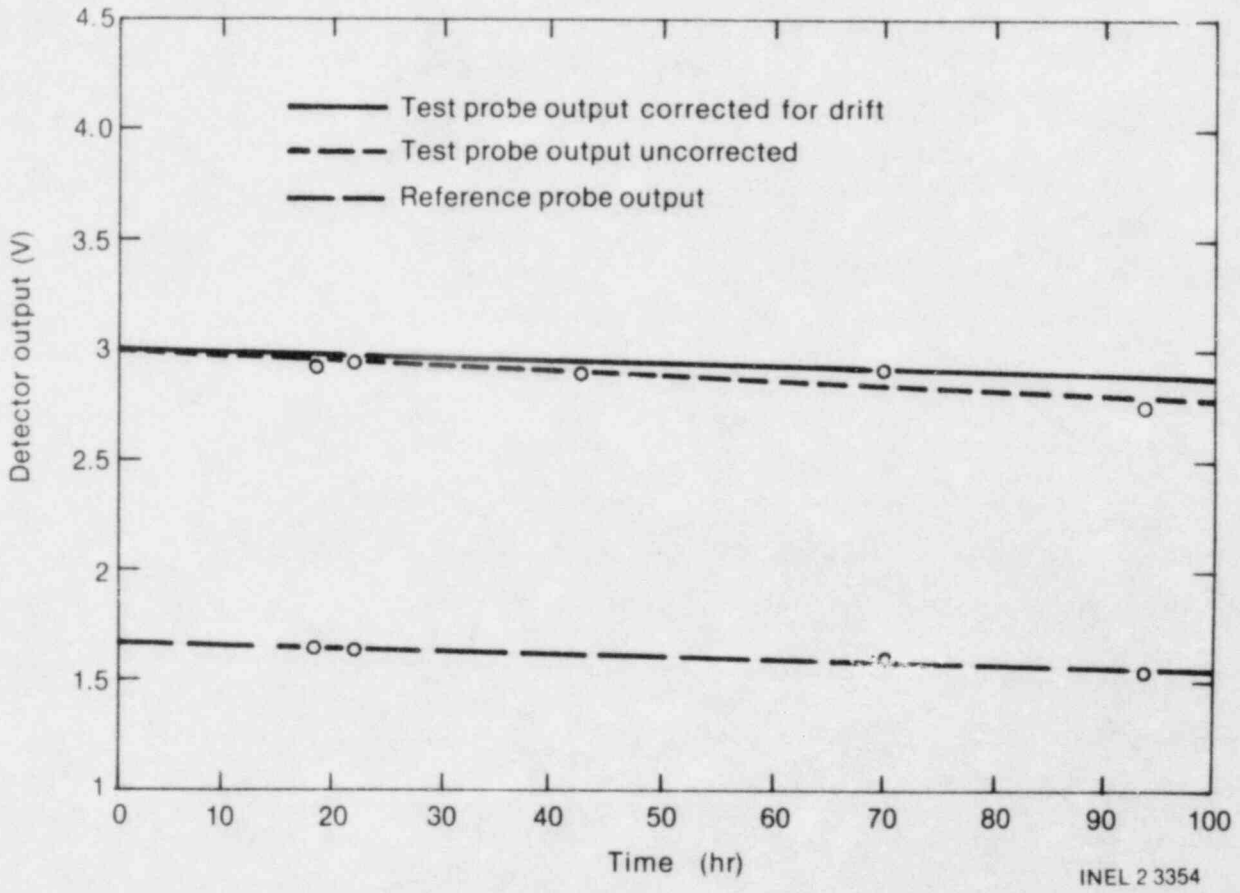

Figure 7. Radiation test results.

5. CONCLUSIONS

The JAERI optical void fraction probes, as presently designed, will not survive the hydrothermal environment of the LOFT steam generator and are therefore unsuitable for use in an optical void fraction measurement system.

The gamma radiation intensity level inside the steam generator during the test does not significantly darken the optical probes. The amount of darkening that did occur may be reduced when the probes are heated, since heating tends to reduce the number of color centers present in the optical components.

The problem of tip erosion must be solved before an optical void fraction probe can be used in the steam generator hydrothermal environment. A possible solution is to replace the sapphire tip with a material that does not hydrate such as spinel, or titanium dioxide. In doing so, a technique for brazing the tip material to the nickel sheath, must be demonstrated. It may also prove desirable to replace the nickel sheath by one of another material such as Kovar, Invar, or Inconel.

Another possible alternative to the present design is a single fiber probe with a small diamond tip. Such a probe would be considerably smaller (0.51 to 1.02 mm diameter) than the present probes. In any event, redesigned probes should be smaller if possible to improve their resolution.

Data analysis techniques developed for conductivity probes are apparently adaptable to optical void fraction probes although further testing is indicated where void fraction measurements made by the optical probes can be compared against gamma densitometer results.

It must be emphasized that the probes were not successful because of material failure, not conceptual failure. If probes could be made to withstand the environment, a vertical string of probes in the steam generator, or several strings if space and mechanical considerations permit it, would provide information on the void fraction distribution as a function of height in the immediate vicinity of the string.

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