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IMAGING OPTICAL PROBE FOR PRESSURIZED STEAM-WATER ENVIRONMENT

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ABSTRACT

An air-cooled imaging optical probe, with an outside diameter of 25.4 mm, has been developed by EG&G Idaho, Inc., at the Idaho National Engineering Laboratory (INEL) to provide high resolution viewing of flow regimes in a steam-water environment at 343°C and 15.2 MPa. The design study considered a 3-m length probe. A 0.3-m length probe prototype was fabricated and tested.

The optical probe consists of a 3.5-mm diameter optics train surrounded by two coaxial coolant flow channels and two coaxial insulating dead air spaces. With air flowing through the probe at 5.7 g/s, thermal analysis shows that no part of the optics train will exceed 93°C when a 3-m length probe is immersed in a 343°C environment. Computer stress analysis plus actual tests show that the probe can operate successfully with conservative safety factors.

The objective lens is protected by a sapphire window which tests have shown can survive over 250 hours in 343°C water or steam with negligible loss of resolution and contrast. Moisture accumulation, which can occur on the protective window in some flow regimes, is boiled off by electrically heating the window.

The imaging optical probe was tested five times in the design environment at the Semiscale facility at the INEL. Two-phase flow regimes in the high temperature, high pressure, steam-water blowdown and reflood experiments were recorded on video tape for the first time with the imaging optical probe.

1. INTRODUCTION

A 3-m-long, 25.4-mm-outside diameter air-cooled imaging optical probe for a 343^{o}C, 15.2-MPa steam-water environment has been designed and analyzed by EG&G Idaho, Inc., at the INEL. Using this design, a 0.3-m-long, 25.4-mm-outside diameter optical probe prototype was fabricated and tested. Coupled with a video camera, the optical probe was used to observe and record, for the first time, a high-temperature, high-pressure steam-water blowdown and reflood experiment at the Semiscale facility at the INEL.

In two-phase steam-water flow, the amount of information which is needed to perform a detailed analysis is often surprisingly large. A direct macroscopic view of the steady state and transient flow regime and boundary conditions would be a valuable aid to the analyst. The use of a high-speed video system, an imaging optical probe, and image enhancement and analysis has the potential to provide two-phase flow measurements of outstanding accuracy and reliability.

This paper describes the design, thermal and mechanical analysis, optical window selection, illumination selection, and test results for the Semiscale/3-D Phase-1 application as summarized in Table I. Phase 2 is in progress and Phase 3 is planned as part of the continuing development program.

TABLE I

OPTICAL PROBE DEVELOPMENT REQUIREMENTS

Phase	Program	Pressure (MPa)	Temperature (^{o}C)	Length (m)	Diameter (mm)
1	Semiscale/3-D	15.2	343	0.3 and 3	25.4
2	Semiscale/3-D	15.2	600	0.3 and 3	25.4
3	LOFT (radiation hardened)	15.2	600	0.3 and 3	25.4

The imaging optical probe consists of a 3.5-mm-diameter optics train surrounded by two coaxial coolant flow channels carrying dry laboratory air at 5.7 g/s and two coaxial insulating dead air spaces, as shown in Figure 1.

Figure 2 shows the completed 0.3-m-long optical probe with inlet and outlet cooling gas ports, mounting arrangement, connections for the window clearing heater, and a spring assembly to accommodate axial thermal expansion of an outer 25.4-mm-diameter tube relative to the optics train. The optics train can be removed from the optical probe as shown in Figure 3.

Thermal analysis showed that no part of the cooled optical borescope would exceed 93°C when immersed in 343°C environment, and the mechanical analysis showed that the probe would withstand the 15.2-MPa operating pressure. The 0.3-m-long imaging optical probe prototype was successfully tested in the design environment.

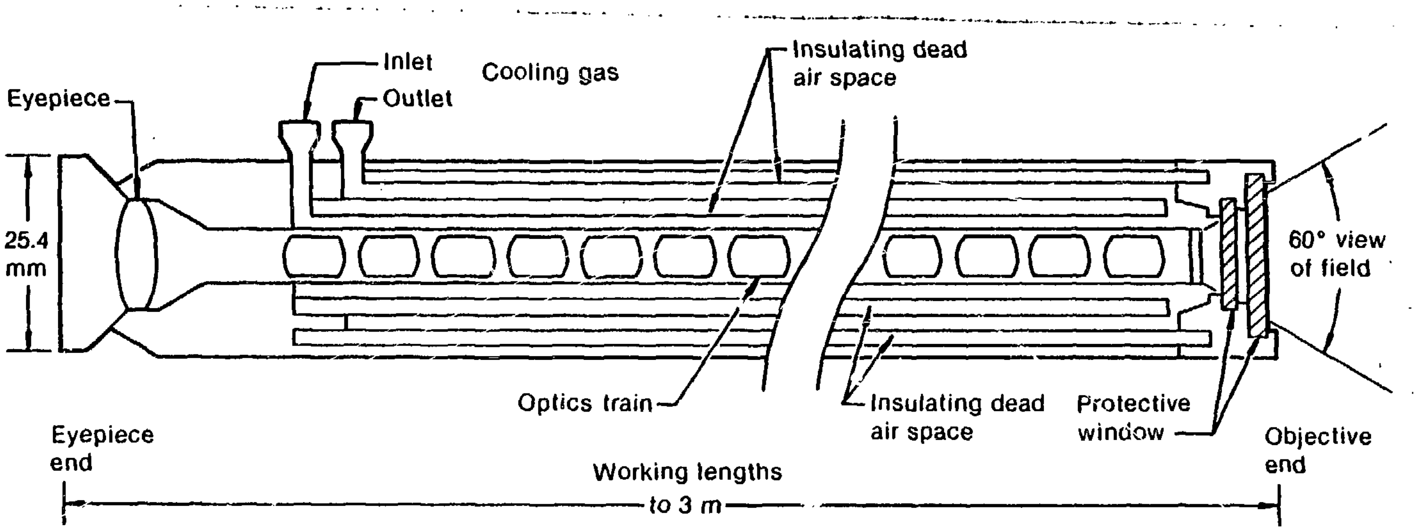

Fig. 1 Cross-sectional view of the imaging optical probe.

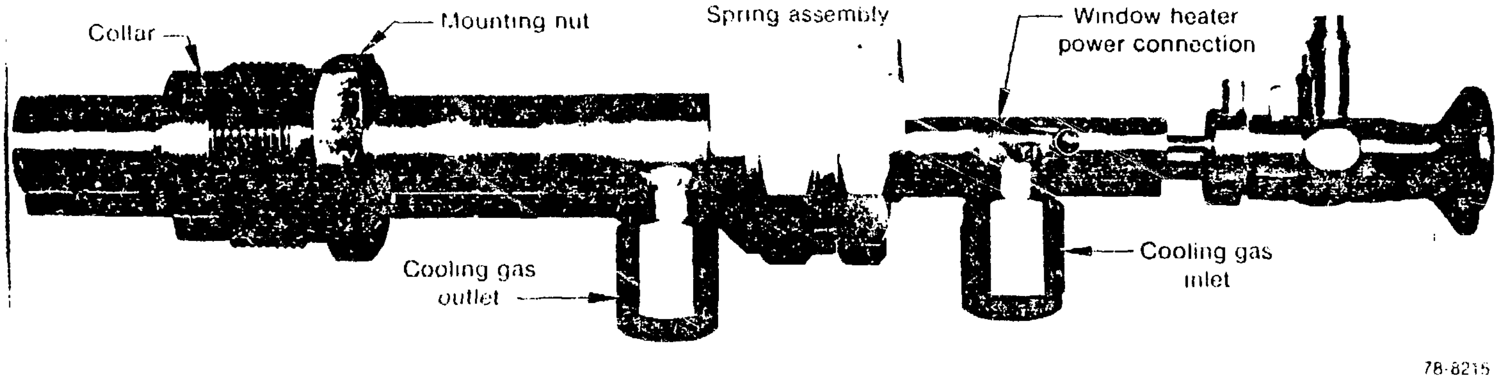

Fig. 2 Imaging optical probe.

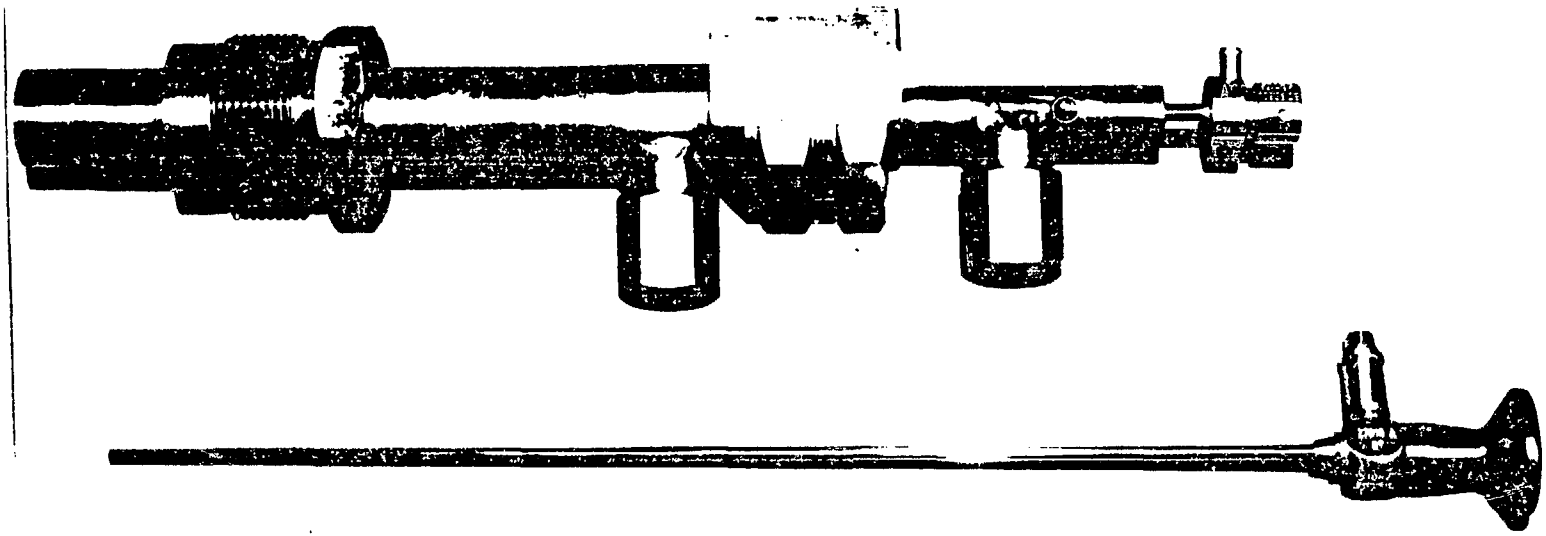

Fig. 3 Imaging optical probe with optics train removed.

2. DESIGN

The imaging optical probe consists of an optics train and a protective housing. The first task in the development of the imaging optical probe was the selection of a suitable optics train, which would satisfy the developmental program requirements of: (a) providing a bright contrasty image over lengths up to 3 m, (b) having a relatively small diameter, (c) withstanding high temperature operation, and (d) possessing high mechanical strength. Once the optics train was selected, basic design criteria were identified to satisfy housing, cooling, window, and sealing requirements. The optics train chosen for the imaging optical probe was a Hopkins[a] rod lens borescope, Model 27015A, manufactured in Germany by Storz[b]. This selection was on the basis of small size, image quality, brightness, ease of adaptation to a video camera, commercial availability to 0.5-m lengths, and the availability of custom optical trains with 3-m lengths.

Table II lists the types of optical trains considered and the relative ratings. For this application, the Hopkins-Storz lens was superior. However, because the objective end of the Storz lens is sealed with a medium temperature (180°C) epoxy, a protective housing had to be designed to protect the optics from the corrosive steam-water environment at 343°C.

The protective housing consists of: (a) a viewing window which can survive the corrosive environment without impairing viewing, (b) cooling to keep the optics train below 180°C when the probe is immersed in a 343°C environment, (c) a main pressure seal to survive a hydrostatic pressure of 15.2 MPa, and (d) an instrument mounting method to keep the probe from being ejected from the test facility.

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[a] U.S. Patent 3,257,902.

[b] Karl Storz Endoscopy - America, Inc.; 658 San Vincente Blvd., Los Angeles, California 90048.

TABLE II

OPTICS TRAIN SELECTION MATRIX

Configuration	Length (m)	Diameter (mm)	Image Quality	Thermal Mechanical	Brightness	Nuclear	Overall
Custom Storz	3	3	Excellent	Good	Good	Good	Good
Commerical Storz	0.5	3	Excellent	Fair	Excellent	Fair	Fair
Conventional lens system, periscope	20	13	Fair	Poor	Fair	Fair	Fair/Poor
Fiber optics	5	25	Poor	Good	Poor	Poor	Poor
Hybrid system	20	--	Poor	Poor	Poor	Poor	Poor

The imaging optical probe consists of four coaxial channels around the optics train, separated by tubing of 9.53, 12.70 and 15.88-mm outside diameters with 0.5-mm wall thicknesses. To maintain the optics train below its maximum rated temperature of 180°C in a 343°C environment, dry cooling air at 0.4 MPa enters the inlet port and is directed down the innermost channel along the optics train to the tip. The cooling air is then returned along the third-outermost channel to the outlet port and vented to the atmosphere. To reduce radial heat conduction to the optics train, two insulating dead air spaces are provided in the second and fourth coaxial channels as shown in Figure 1.

Extensive computerized thermal analysis on a 3-m length probe model has shown that without at least one insulating dead air space channel, the optics train could not be maintained below 180°C in a 343°C environment by any feasible gas flow rate. In the present design for a 3-m immersed length, with air flowing at 5.7 g/s from a 0.4-MPa source, no part of the optics train was expected to exceed 93°C in the 343°C environment. Also, use of evacuated insulating channels and silvered tubing was expected to maintain the optics train below 120°C in a 1000°C environment with an air coolant flow rate of 11 g/s.

The glass objective lens must be protected by a material which is transparent, possesses high mechanical strength, and can survive the corrosive action of a pressurized steam-water environment. Tests at the INEL have shown that sapphire can perform as an optical window in steam or water at 343°C and 15.2 MPa for over 250 hours. The outer sapphire window on the optical probe is 21.84 mm in diameter and 3.05 mm thick.

The pressure seal between the outer sapphire window and the probe body is made by a Haskel V-seal[a] fabricated of silver-plated Inconel X-750. The V-seal is located in a carefully machined and polished

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[a] Haskel Engineering, 100 E. Graham Place, Burbank, California 91502.

groove behind the outer sapphire window, as shown in Figure 4, and clearance is provided for about a 0.03-mm radial expansion of the sapphire window at 343^{o}C. Prototype window and seal assemblies have successfully survived 343^{o}C blowdown and cold water reflood cycles as fast as 50 s in the autoclave. A thin (1 mm thick) unsealed sapphire window is also placed 1.5 mm inside the outer window to provide an insulating dead air space between the two windows as shown in Figure 4.

During certain flow conditions such as droplet or mist flow, moisture or fog may condense on the outer window surface, obstructing vision. Therefore, an annular heater coil assembly was placed between the two sapphire windows to provide defogging as shown in Figure 4. The heater coil was supported on the back side by a thermally insulating mica washer to direct the heat, up to 10 W, toward the front window.

Since the outer tubing is hotter during operation than the optics train, differential axial expansion makes it necessary to spring-load the optics train to keep the objective lens at a fixed distance from the sapphire window for a constant field-of-view angle. The spring-loading assembly can be seen in Figure 2 between the inlet and outlet cooling air ports.

The eyepiece, a part of the Storz lens, allows direct viewing of the two-phase flow regime. To make videotapes, an enlarging lens was used to magnify the image to cover a standard television vidicon. The Storz lens is removable from the imaging optical probe as shown in Figure 3.

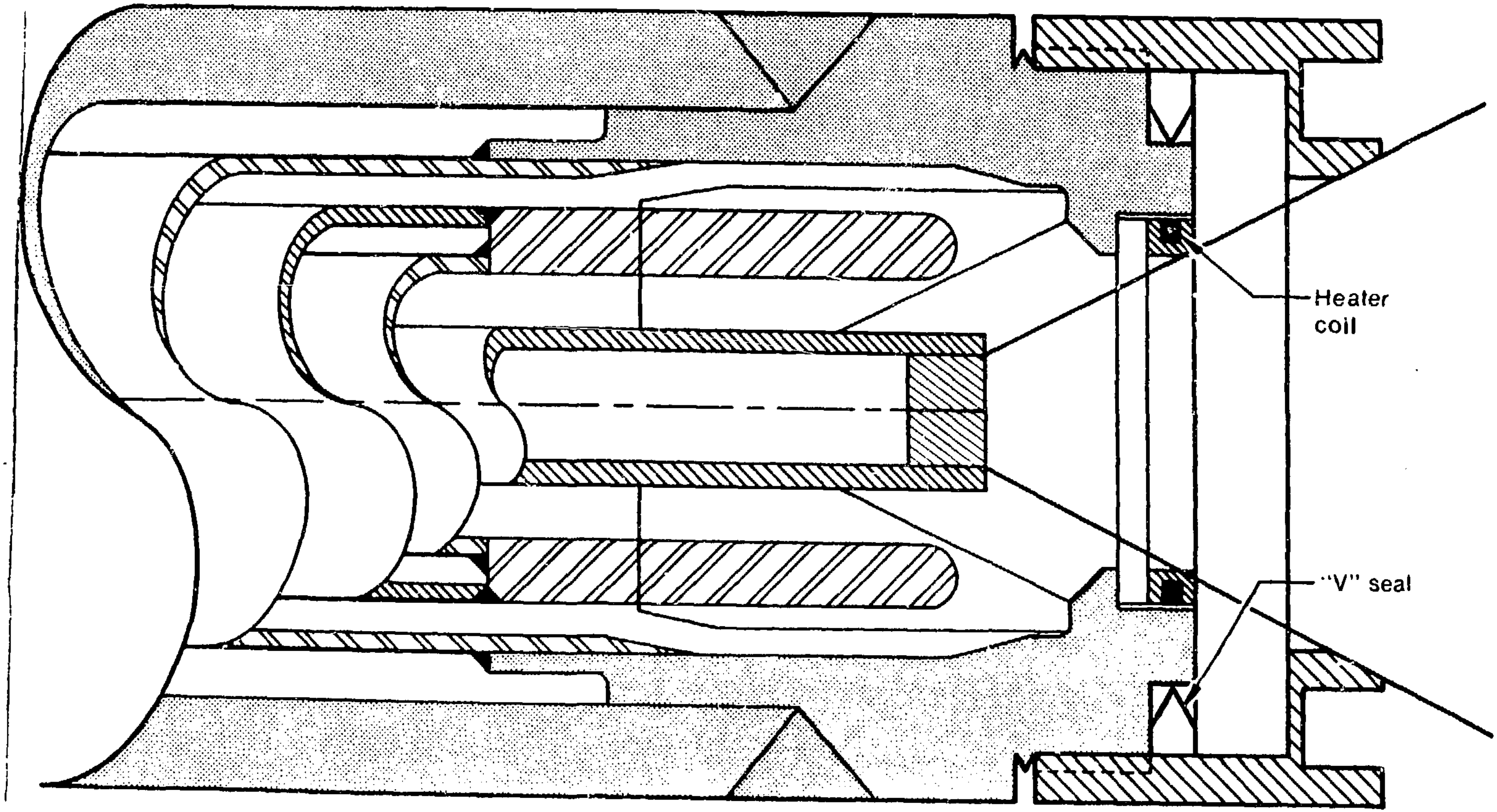

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Fig. 4 Optical probe objective end.

3. THERMAL ANALYSIS

Extensive computerized thermal analysis was performed on a 3-m-long network model of the imaging optical probe design which predicted satisfactory thermal performance in a 343°C environment. This thermal analysis had two purposes: (a) to verify that the temperatures at all points of the optics train would not exceed 180°C and (b) to compute node temperatures for thermal stress evaluation.

A parametric analysis was performed to determine the maximum temperature of the optics train as a function of (a) air mass flow rate, (b) boundary temperature, (c) outer insulating gap conditions, and (d) gap surface emissivities. The block diagram in Figure 5 illustrates the steady state parametric study. A blowdown condition from the Semiscale Mod-1 test series was also analyzed. The blowdown temperature profile is illustrated in Figure 6. For this case, the design condition of T = 343°C, surface emissivity $\varepsilon = 0.4$, and cooling air flow = 0.0057 kg/s with dead air insulating gaps were used. The cooling air mass flow rate of 0.0057 kg/s was chosen after

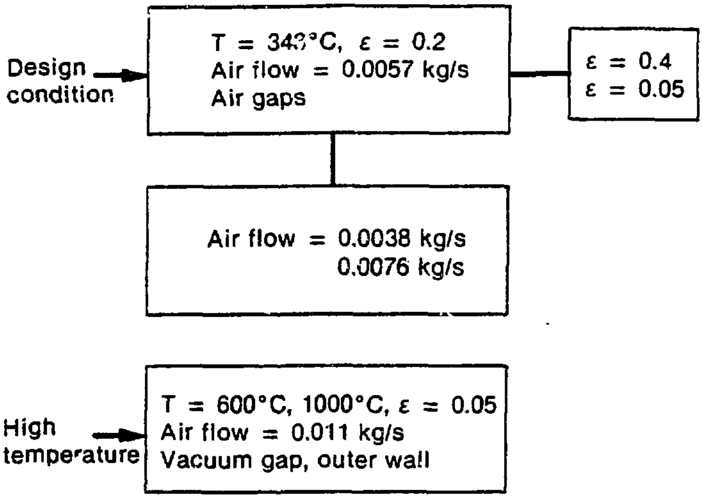

Fig. 5 Parametric analysis of optical probe.

calculations indicated that this flow rate would be easy to obtain with a supply pressure of 0.4 MPa. Flow velocities were computed to be approximately 30 to 46 m/s.

As shown in Figure 6, two special high-temperature cases were also analyzed, in which the test environments were assumed to be 600 and 1000°C and the cooling air mass flow rate was raised to 0.011 kg/s. The outer insulating gap was assumed to be evacuated, effectively eliminating thermal conductivity across the gap; and the surfaces within that gap and the air gap within the flow separator were assumed polished and silvered to obtain a surface emissivity $E = 0.05$.

Two heat transfer computer codes, MITAS II[1] and COUPLE/MOD2[2], were used for the steady state and transient solutions. MITAS II is an n-dimensional, finite-difference code capable of solving any physical problem that can be described by diffusion-type equations and resistor-capacitor networks. COUPLE/MOD2, a two-dimensional code for

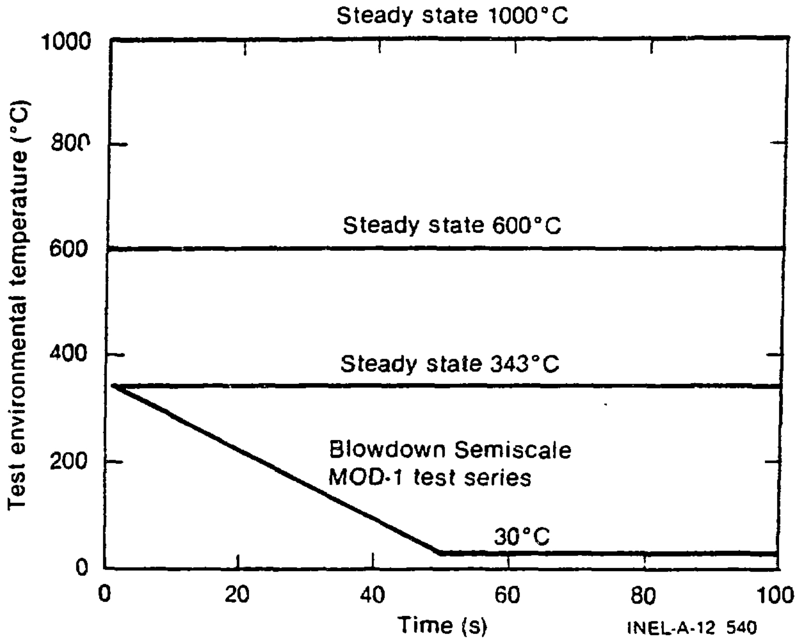

Fig. 6 Environmental temperature profiles for parametric study.

plane or axisymmetric solids, uses finite element techniques to solve steady state and transient heat conduction problems. Material properties may be temperature dependent and anisotropic. The advantage of COUPLE/MOD2 is its convenient grid generation and interface with computer programs used for stress analysis.

MITAS II was used to determine the steady state and transient temperature profile of the cooling gas and optical probe lens. A node diagram of the MITAS II model for the probe tip region is given in Figure 7. This model contains 225 nodes for the 3-m length optical probe. Node spacing is 0.10 m except at the tip where the node spacing is closer as shown in Figure 8.

Three conservative assumptions were made with this model. First, the outside wall and the inside surface of the outer sapphire window were assumed to be at the temperature of the environment, that is, 343°C. This assumption is conservative since in a real application a heat transfer coefficient would bring the surface temperature of the air-cooled probe down below the hotter environment. Second, the inner surface of the stainless steel housing of the lens element assembly, Figure 8, was assumed to be an adiabatic wall. This assumption was also conservative since higher axial temperature gradients would result. Also, for thermal transients, it was conservative to neglect the heat capacity in the glass lens elements. Third, the air space between the glass lens and the inner sapphire window was considered to be a dead air space; any advantage gained by the turbulence of the flowing air was neglected. This assumption results in higher calculated temperatures at the objective lens.

The maximum allowable limit for the glass lens elements is 180°C. If the steel lens housing temperatures are below the maximum temperature limit for the glass elements, the temperatures of the lenses are certainly below this limit.

Gas temperatures calculated by MITAS II were used to set the boundary conditions for COUPLE/MOD2. This code was used to analyze

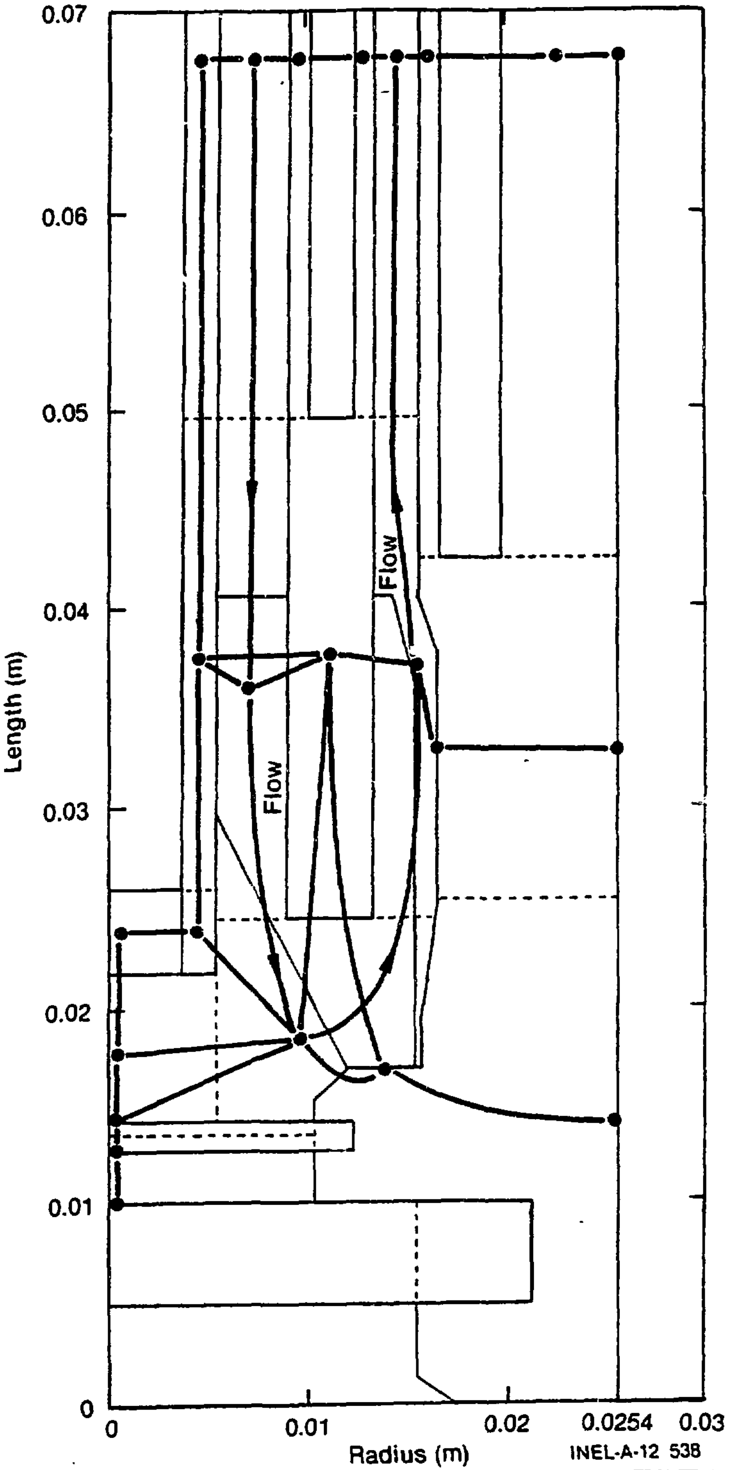

Fig. 7 MITAS II model of optical probe.

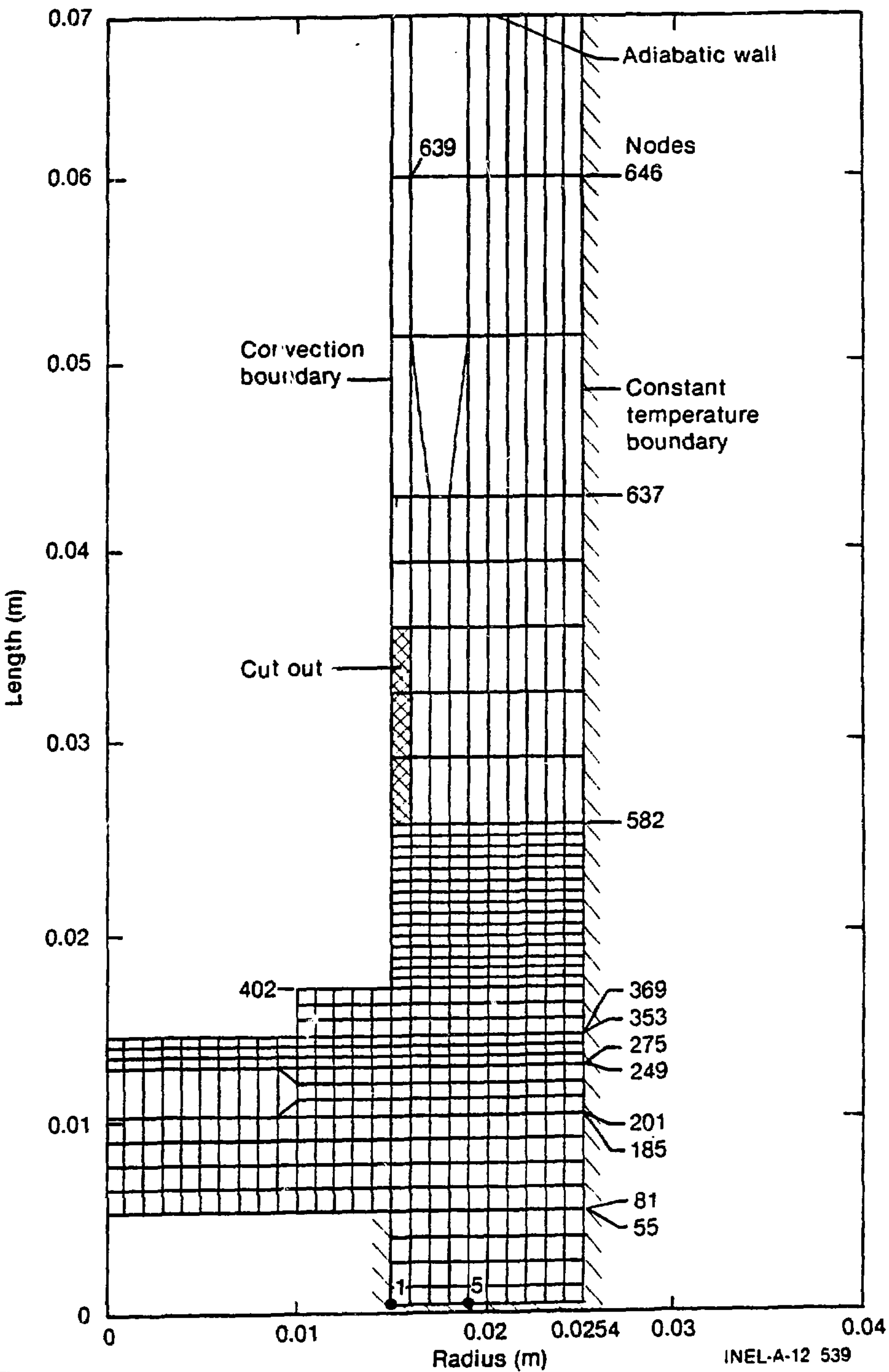

Fig. 8 COUPLE/MOD2 model of optical probe tip.

the probe tip in detail. A finite element mesh was generated of the outer wall and sapphire windows. Although the tip is only 0.076 m long, it contains 727 nodes.

Only the outer wall and sapphire windows were considered in this model. Figure 8 shows the geometric simplifications made for the COUPLE/MOD2 model, such as the chamfered edges and the cut out on the inner surface of the outer wall. These simplifications were made to ease model generation. Neglecting the chamfered edges had an insignificant effect on the thermal results. The model assumed an adiabatic wall 0.0762 m from the tip and that the wall was far enough away to have little influence on the temperature profile through the tip regions of primary interest. The convection boundaries on the inside of the model were based on MITAS II computer temperatures of the cooling air. Boundary temperatures on the outside surface were determined by the particular environment assumed in the parametric study. For steady state design conditions, an air flow of 0.0057 kg/s and a gap surface emissivity $E = 0.4$ were used. For the transient analysis, the blowdown temperature profile illustrated in Figure 6 was applied to the outside surface of the optical probe, maintaining the air flow at 0.0057 kg/s and $E = 0.4$.

Results indicate that coolant mass flow rate is the dominant factor in cooling the optics train as illustrated in Figures 9, 10, 11, and 12. Cooling air temperatures vary as much as $60^{o}C$ near the lens for mass flow rates of 0.0038 and 0.0076 kg/s; whereas, temperatures vary only by $12^{o}C$ at the same location for an emissivity range of 0.05 to 0.4. Lens assembly temperatures vary as much as $64^{o}C$ with the flow rates considered, but only as much as $12^{o}C$ with the emissivity range considered. This is important since surface emissivities are difficult to predict and can vary widely depending upon material, surface characteristics, and temperatures. However, the literature indicates that an emissivity of 0.4 is a conservative estimate for the stainless steel used in the design[3].

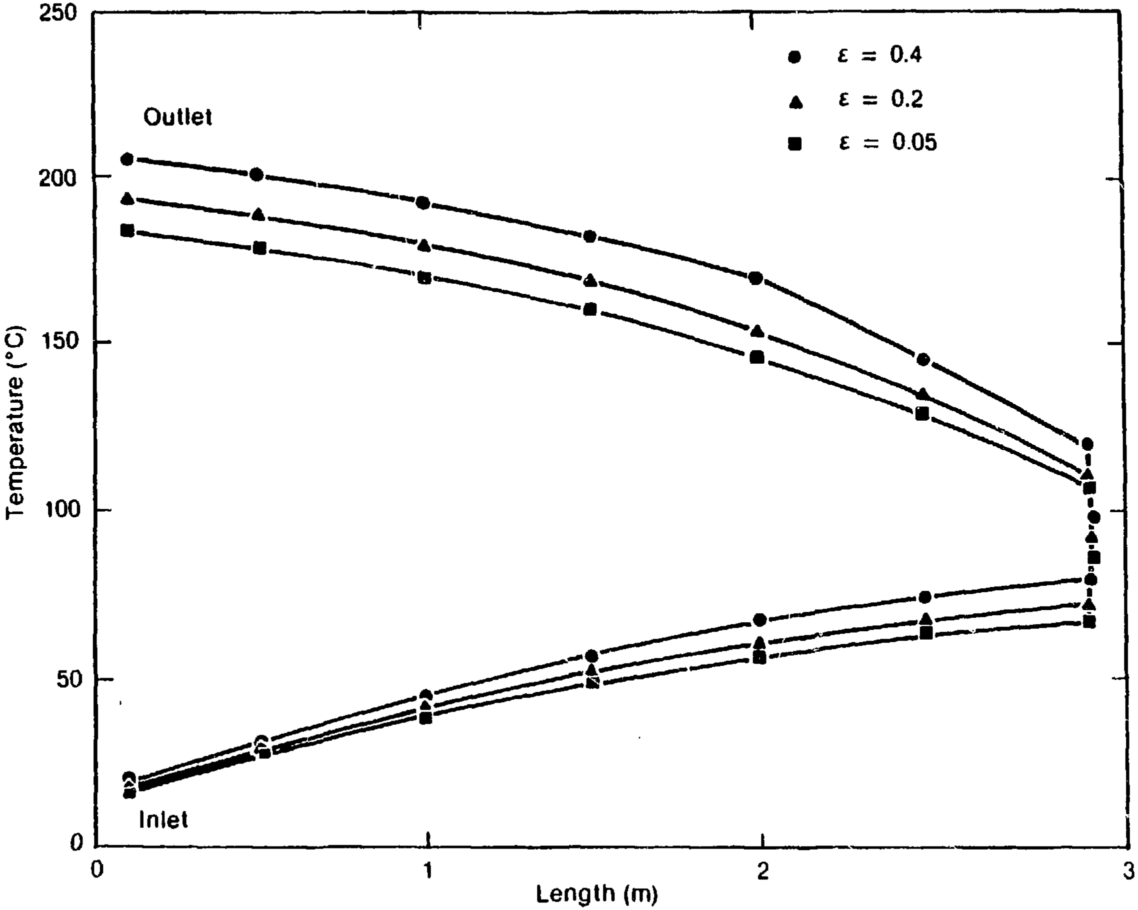

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Fig. 9 Optical probe axial temperature of cooling air with a mass flow of 0.0057 kg/s in a steady state 343°C environment.

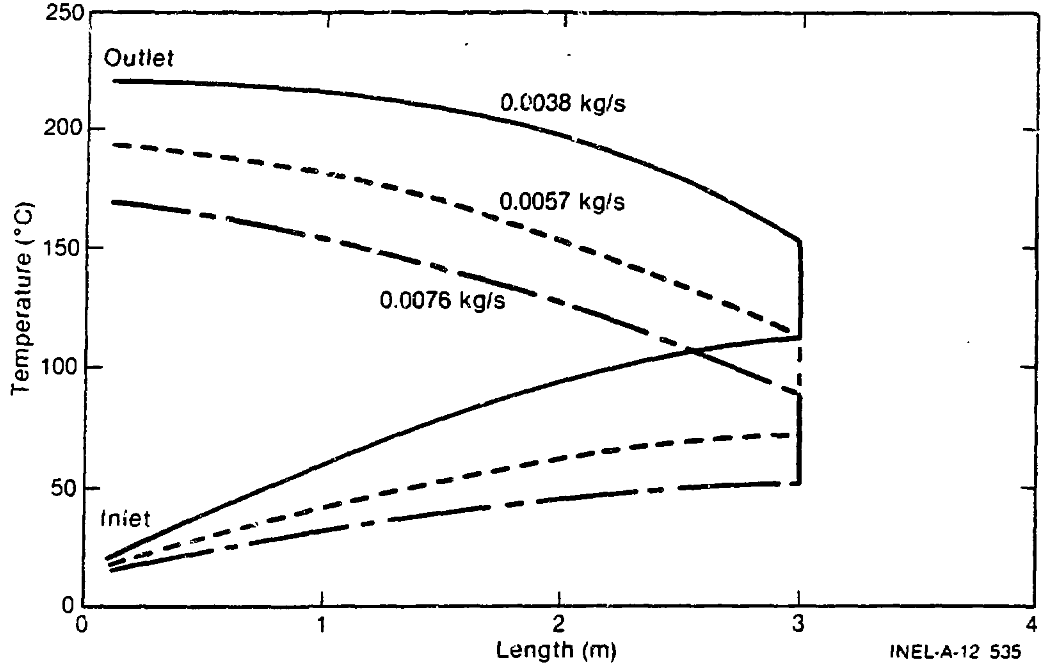

Fig. 10 Optical probe axial temperature of cooling air with emissivity = 0.20 in a steady state 343^{0}C environment.

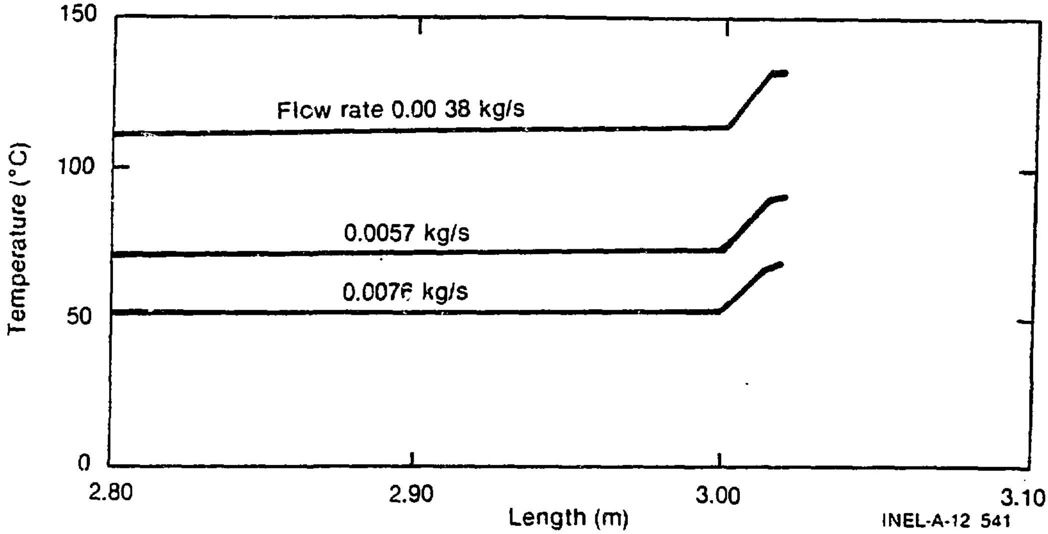

Fig. 11 Lens segment assembly tip temperatures with emissivity = 0.2 in a steady state 343^{0}C environment.

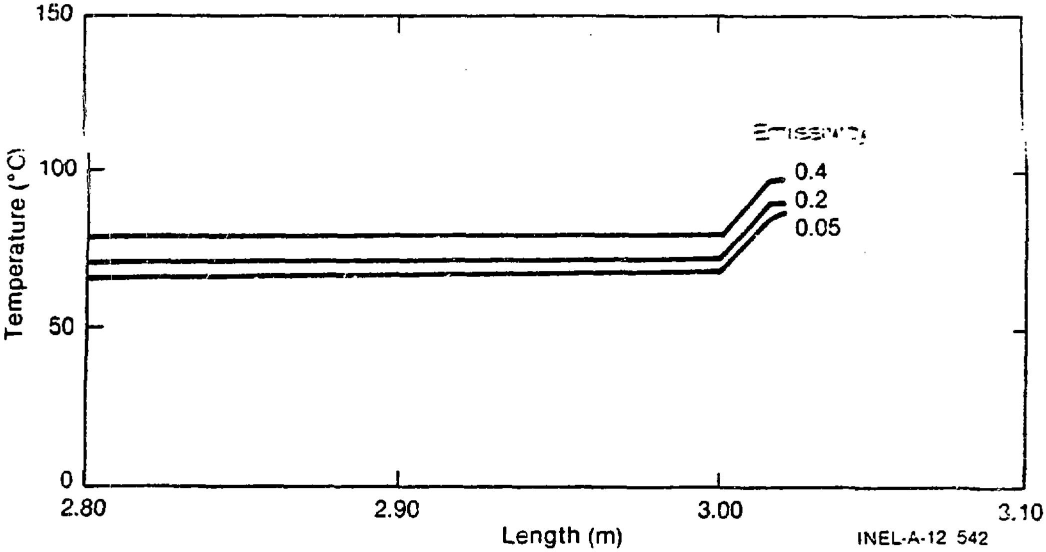

Fig. 12 Lens segment assembly tip temperature with a mass flow of 0.0057 kg/s in a steady state 343°C environment.

For the special high temperature cases (600 and 1000°C), the mass flow rate was raised to 0.011 kg/s. The outer insulating air gap was assumed evacuated to effectively eliminate thermal conductivity across this gap. Surfaces within this gap and the air gap within the flow separator were also assumed polished and silvered to obtain an emissivity of $E = 0.05$. Resulting objective lens temperatures were 60°C for the 600°C environment and 106°C for the 1000°C environment. Figure 13 shows the temperatures predicted by the computer model for the optics train when the optical probe is operated under various conditions[a].

The transient calculation was done primarily for thermal stress analysis. The thermal gradients were reduced during blowdown, which reduced thermal stresses below steady state values. With a maximum temperature specification of 180°C for the optics train, this optical probe will be sufficiently well protected with the coolant air mass flow rates assumed and thermal environments considered.

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[a] The thermal analysis was performed by G. Kyllingstad at EG&G Idaho, Inc.

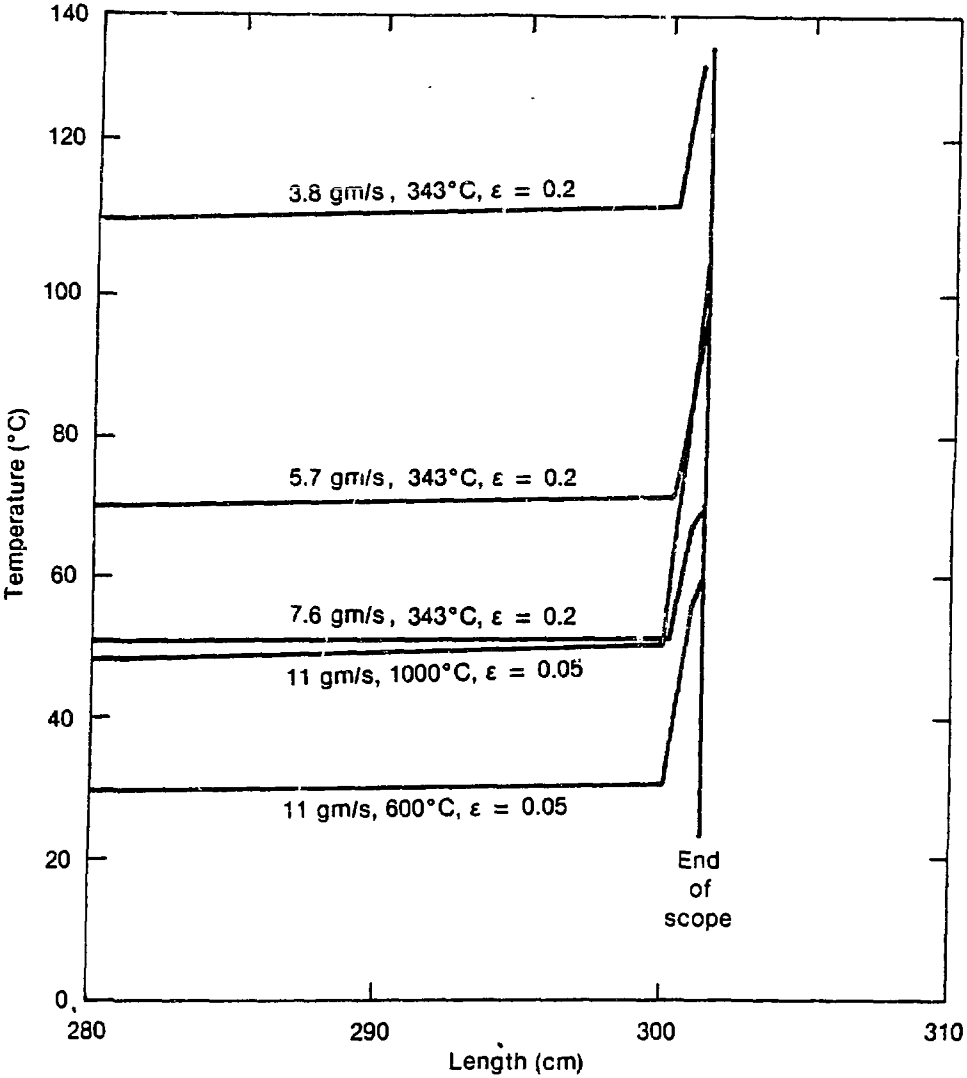

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Fig. 13 Cooled endoscope temperatures in various environments.

4. MECHANICAL ANALYSIS

A computerized investigation was performed which verified the structural adequacy of the pressure boundary for the 3-m length imaging optical probe design. The probe will be installed in various test facilities during its service life and will be inserted in an outer tube, or shroud, for protection. The shroud will provide lateral support and thus eliminate the possibility of column-buckling of the probe. The shroud also will isolate the probe with regard to loads associated with coolant flow (bending loads). The pressure boundary, as defined for this analysis, includes the outer tube of the optical probe assembly (25.4-mm-outside-diameter) and the probe tip.

The optical probe will be used in test facilities designed to ASME Boiler and Pressure Vessel Code standards. These code standards present rules for determining the minimum wall thickness (t) for cylinders subjected to an external pressure. The optical probe design does not conform to these minimum requirements (t = 3.05 mm actual versus t = 3.56 mm required by the standards for a 25.4-mm-outside-diameter cylinder subjected to a 15.2-MPa external pressure). Therefore, the pressure stresses were investigated in a detailed analysis using finite element methods. Additionally, such an analysis was required to investigate the probe tip region and to determine stresses associated with steady state and transient thermal gradients.

The ASME Code standard rules for cylinders subjected to external pressure loading take both column and ring-type buckling into consideration. Since ASME requirements for minimum wall thickness were not adhered to, an analysis was performed to confirm that buckling would not be a problem before a detailed stress analysis of the probe data was performed. The following points are pertinent to this investigation:

(1) Column buckling is prevented by a shroud which surrounds the probe and provides lateral support.

(2) Axial compressive loading for this case does not have an appreciable effect on the pressure required to cause ring buckling.

(3) Critical pressure associated with ring buckling can be determined by applying "text-book" equations. Calculations were performed which indicate that a very high pressure (p = 656.6 MPa) would be required to initiate

ring buckling. Since the calculated pressure is much higher than the design or test pressure, ring buckling will not occur so long as the yield strength of the tube is not exceeded.

Stresses were determined using the SAAS III[4] finite element program. Special slip elements were used at those locations where the sapphire windows contact the metal shell and retaining cap. These elements were given material properties such that they could carry compressive loads but would provide no resistance to shear loads. Thus, the windows could move freely in the radial direction relative to the shell and cap, as required to accommodate differential thermal expansion (note that the pressure seal offers little resistance to radial expansion). The SAAS III program provides a mesh generation option used to develop the rectangular mesh. The actual geometry of the tip region was changed slightly to simplify the modeling task; however, such changes had only a minor effect on computer stress values. Elements located where metal does not actually exist were given zero strength properties. Several triangular elements were added to the generated mesh in the annulus region.

The sapphire windows are held in place by means of a retaining cap which screws onto the shell. The cap does not stiffen the shell significantly when the specified loading is applied. Therefore, elements forming the boundary between the cap and shell were assigned properties such that they would have zero strength in the hoop and radial directions. The model thus responded properly to the applied loading. As a result, stress values computed for the cap are conservative, whereas those for the shell may be regarded as representative of the actual case.

Properties for the sapphire windows were obtained from vendor literature. A value for Poisson's ratio (w) was not given, so w = 0.3 was used for the analysis. Several runs were submitted using various other values for this ratio to determine the effect on computed stress values. It was found that this effect was not significant.

The following loads were considered: (a) external design pressure of $p = 15.5$ MPa at $T = 620$ K design temperature, (b) preload applied to the outer sapphire window, (c) steady state thermal gradients, and (d) transient thermal gradients due to heatup - cooldown or due to blowdown with quench (reflood). Node-point temperatures determined in the thermal analysis were stored on magnetic tape. This temperature information was then read directly for the SAAS III thermal stress runs. Thermal stresses were computed for the following time steps: t = zero (steady state conditions) and for $t = 2$, $t = 6$, $t = 10$, $t = 14$, $t = 20$, and $t = 60$ s after initiation of blowdown. This number of steps is adequate to determine the maximum thermal stresses associated with the transient and to establish the fact that there would be no reversal of signs of the stresses.

The design specification did not define structural adequacy criteria for the probe and a definite requirement was not established for qualifying it as an ASME Code component. However, the probe will be placed in ASME Code vessels at times and it seemed advisable to adhere to ASME Code rules and procedures as closely as possible in performing the analysis.

As indicated previously, the probe could not be qualified as an ASME Code component since minimum wall thickness requirements were not satisfied for the shell. Other departures from ASME Code rules were:

(1) The windows (sapphire) are fabricated from a non-ASME Code material

(2) Conformance with ASME Code requirements for quality assurance were not established.

The stated deviations do not necessarily mean that the probe cannot be used in ASME Code vessels. Such use can be justified if the analysis shows that stresses are maintained at a reasonable level.

The analysis followed ASME Code procedures for Class 1 components. Allowable stresses are the same for Class 1 and Class 2 components in this case, since a detailed stress analysis was performed.

Stress results indicate that both primary and secondary stresses are satisfactory, based on the established criteria. The stainless steel retaining cap and outer shell (25.4-mm-outside diameter tube) will have a long service life. Fatigue data were not available for the sapphire windows, but judgment indicates that they would also have a long service life since stress levels are low and polished surfaces are provided for the window surfaces.

The conclusion reached was that the optical probe design will be suitable for the intended use, so far as structural adequacy is concerned[a]. However, installation of the probe in an ASME Code facility will involve a management decision based on analysis results and consequences of a possible failure. The imaging optical probe assembly will be suitable for an external cold hydrostatic test pressure of 21.5 MPa.

5. WINDOW TESTS

The glass objective lens of the optics train must be protected by a window which is transparent, possesses high mechanical strength, and can survive the corrosive action of a pressurized steam-water environment. An extensive autoclave test program, outlined in Figure 14, was performed on 25.4 mm diameter quartz and sapphire windows in distilled water. Each test phase consisted of 1, 1, 1, 4, 8, 16, and 32-hour steps. After each step, an evaluation was performed as outlined in Figure 15 in which the light transmission was measured from 300 to 2500 nm and a resolution chart was photographed through the test window. Also, the samples were weighed. Sapphire was found to be a satisfactory protective window for Semiscale optical probe applications.

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[a] The stress analysis was performed by R. A. Goodell at EG&G Idaho, Inc.

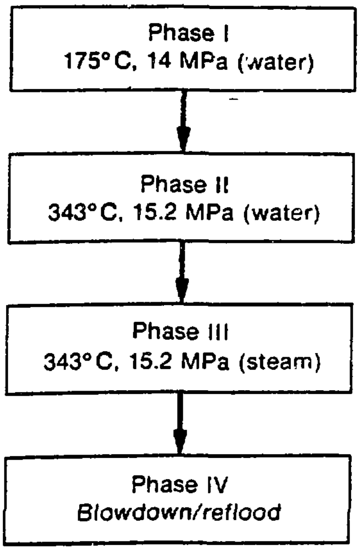

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Fig. 14 Test program for protective window.

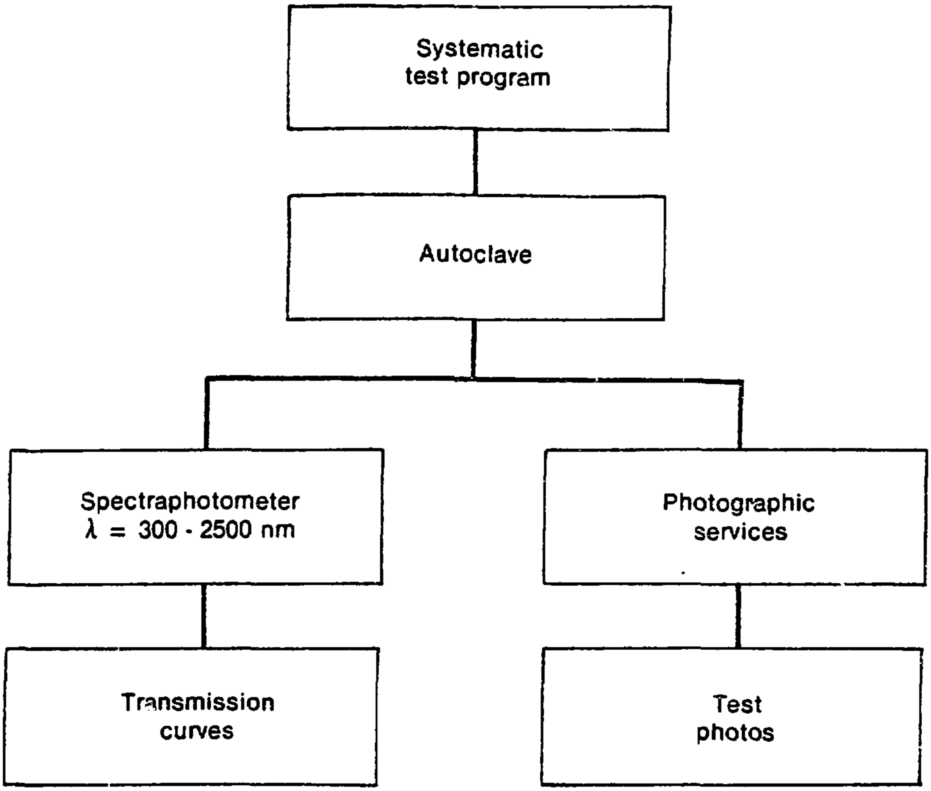

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Fig. 15 Required output from window autoclave testing.

In Test Phase I at 175^{0}C and 14 MPa, neither the quartz nor the sapphire was significantly affected.

Figure 16 and Table III show that the weight loss of the quartz in Phase II at 343^{0}C was relatively rapid, while the sapphire suffered insignificant weight loss over 127 hour with exposure to both sides of the window. The transmission of the quartz was essentially zero after 2-hours of test time (see Figure 17); however, the quartz dissolved to such an extent in 31 hours, that the quartz testing was terminated. The light transmission of the sapphire, Figure 17, remained excellent. The uncertainty of the light transmission measurements is several percent due to varying abrasion rates at different locations on the window surface, where the measurements were made.

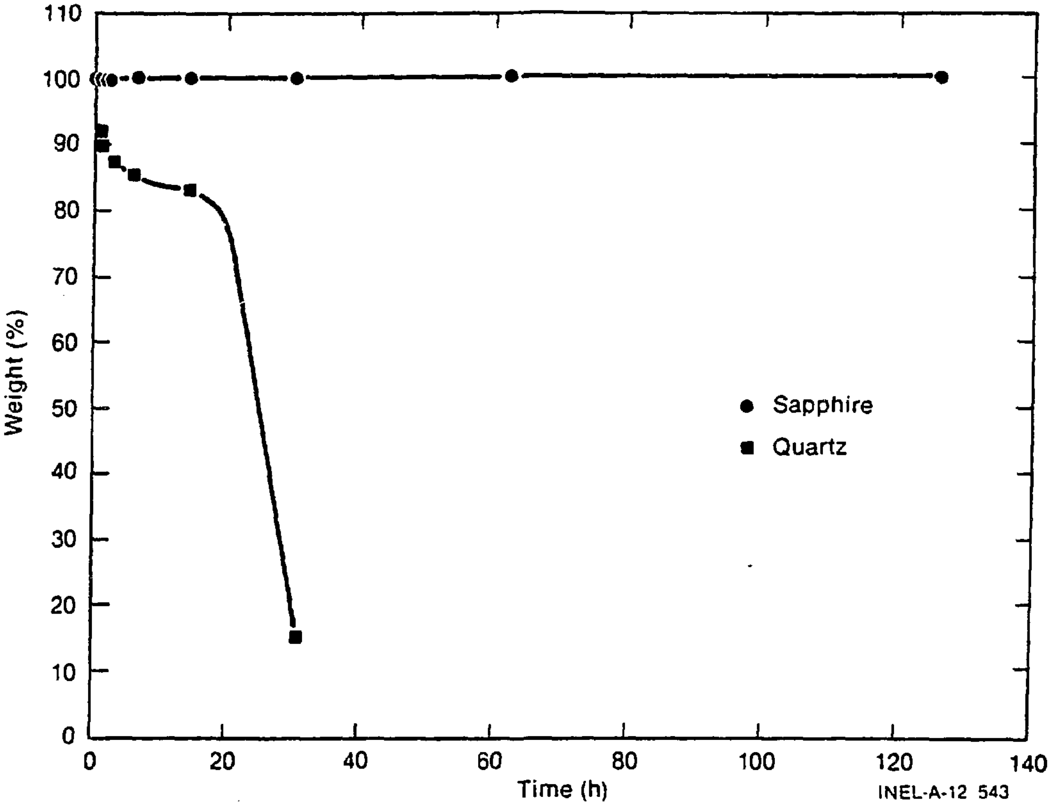

Fig. 16 Weight of protective windows after autoclave tests in a 343^{0}C and 15.3-MPa environment.

TABLE III

AUTOCLAVE TESTING OF OPTICAL WINDOWS AT 343°C AND 15.5 MPa

Test	Quartz Weight (g)	Sapphire Weight (g)
Test 1		
Before	2.3719	6.4252
After 1 h	2.1742	6.4231
Test 2		
Before	2.1742	6.4231
After 1 h	2.1370	6.4229
Test 3		
Before	2.1370	6.4229
After 1 h	2.0861	6.4222
Test 4		
Before	2.0861	6.4222
After 4 h	2.0197	6.4215
Test 5		
Before	2.0197	6.4215
After 8 h	1.9746	6.4215
Test 6		
Before	1.9746	6.4215
After 16 h	0.3699	6.4155
Test 7		
Before		6.4155
After 32 h		6.4065
Test 8		
Before		6.4065
After 64 h		6.3864

Figure 18 shows the sapphire window after exposure of the center portion, on both sides, to water at 343°C and 15.3 MPa for 127 hours. Test photographs of a high contrast resolution chart taken through this window showed negligible loss of resolution and moderate loss of contrast. Since the protective window is exposed to the steam-water environment on one side only in the optical probe, the useful life is estimated to be in excess of 250 hours.

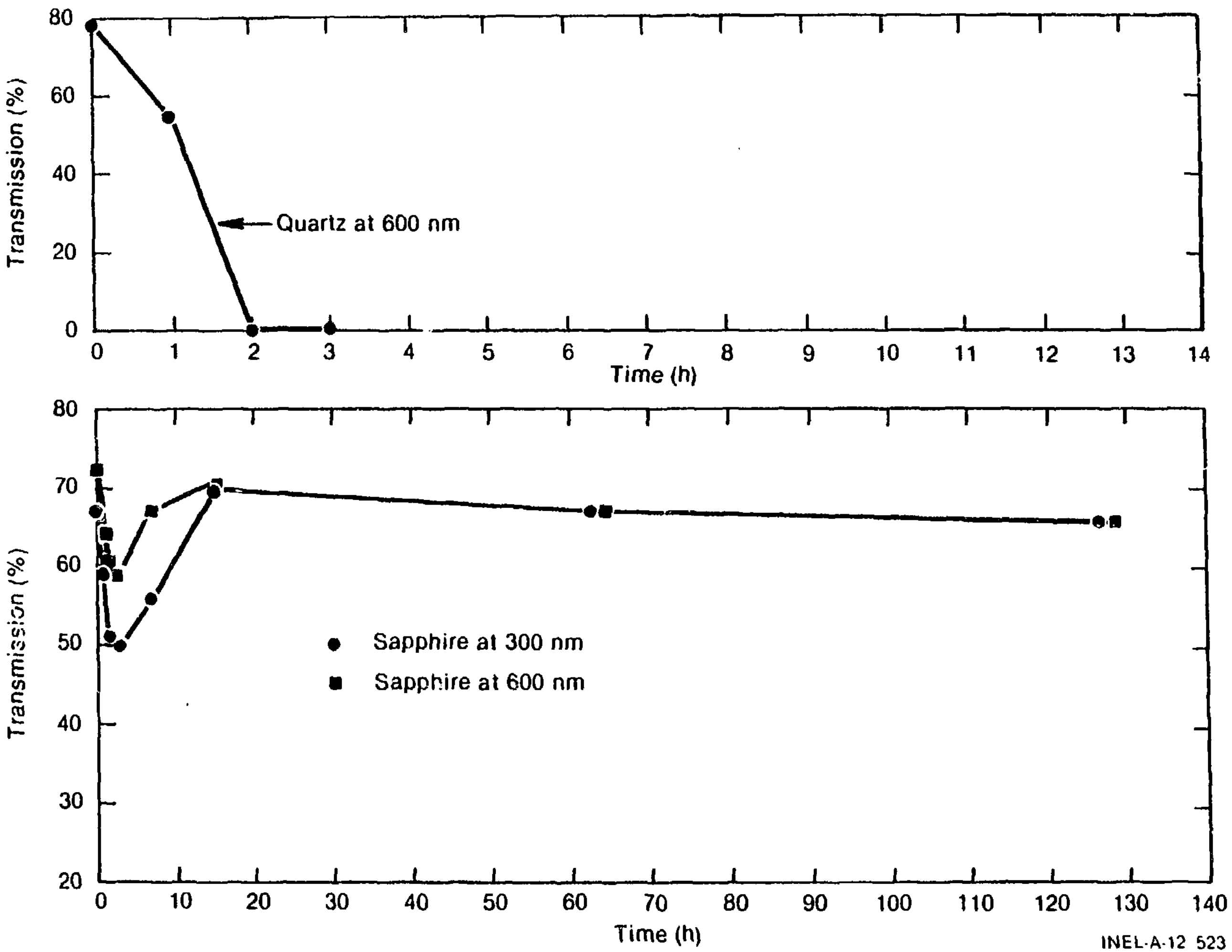

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Fig. 17 Protective window light transmission tests after autoclaving in water in a 343°C and 15.3-MPa environment.

Fig. 18 Sapphire window after exposure of the center portion, on both sides, to water in a 343°C and 15.3-MPa environment for 127 h.

The Phase III test in steam at 343°C showed results very similar to those from the Phase II test in water. However, steam did not abrade the sapphire quite as much as water at the same temperature. Table IV gives a summary of the conclusions about quartz and sapphire windows for 127 hours in a 343°C water or steam environment.

TABLE IV

CONCLUSIONS ABOUT QUARTZ AND SAPPHIRE WINDOWS AFTER TESTING FOR 127 HOURS IN A 343°C WATER OR STEAM ENVIRONMENT

Optical Characteristics	Quartz	Sapphire
Light Transmission		
Before test	∿80%	∿70%
After test	None	Unchanged
Resolution		
Before test	Excellent	Excellent
After test	None	Unchanged
Contrast		
Before test	High	High
After test	None	Moderate

To test the resistance of windows to thermal shock and also to evaluate the Haskel V-seals, a series of autoclave blowdown tests was performed with the sapphire window sealed by V-seals into a small test fixture inside the autoclave, which was connected to an external pressure transducer to measure any leakage.

The pressure and temperature-versus-time curves for the most severe of these tests is shown in Figure 19. In this test, a cold water reflood was initiated 40 s after blowdown at the point marked 267°C. Within 70 s after blowdown from 343°C, the temperature, which was measured by a thermocouple in the autoclave at the same height as the sapphire window, was below 40°C. This autoclave blowdown and reflood experiment was much more severe than can be performed in a larger facility, such as Semiscale. The sapphire window survived successfully, and there was no seal leakage.

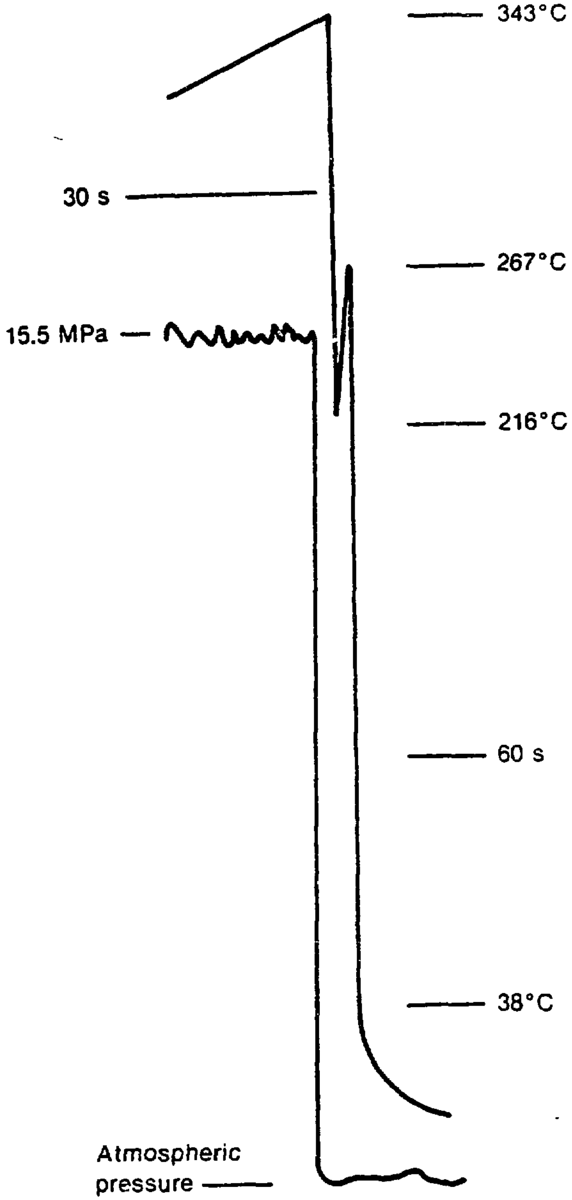

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Fig. 19 Temperature and pressure for autoclave blowdown and reflood test.

6. LIGHTING AND VIEWING

Two-phase steam-water mixtures are very low contrast subjects for photography. Therefore, optimum lighting is essential for defining the flow regime.

A hexagonal glass test tank was used for lighting studies which allowed viewing through one face while directing illumination through any combination of the other faces. With the tank filled with water, a trail of gas bubbles was directed vertically upward through the field of view of the Storz lens. Many combinations of light sources and intensities were systematically tested, and the results were recorded on video tape and are summarized in Table V.

Under test tank conditions, two 1000-W flood lamps, placed 120^0 behind the viewing face on opposite sides, produced the best bubble definition. With this lighting configuration, several background colors were evaluated. For optimum viewing of flow regimes in a vertical pipe, two collimated light sources placed 120^0 behind the viewing port with all other faces painted black is preferred.

On the basis of this information, a cylindrical test tank was fabricated which allowed the generation of various air-water flow regimes. An instrument washer was fabricated to incorporate the viewing and lighting ports with the inside surface black chrome plated as shown in Figure 20.

Under certain flow conditions, water droplets or fog may collect on the protective window and obstruct the view; therefore, a method of window clearing was needed.

Three methods of window clearing were evaluated:

(1) Windshield wiper - This method was not practical due to the mechanical problems involved.

TABLE V

LIGHT SOURCE RESULTS

Light Source (W)	Illumination Position			
	0°	60°	120°	180°
1 to 15[a]	Poor	Poor	Poor	Poor
1 to 150[b]	Poor	Good	Good	Bad
1 to 1000[c]	Bad	Better	Better	Bad
2 to 1000[c]		Better[d]	Best[d]	
2 to 750[e]		Better[d]	Best[d]	

a. Strobe lamp.

b. Incandescent flood.

c. Quartz-iodine flood.

d. One either side of viewing face.

e. Collimated source.

(2) Clearing gas - This method used a burst of gas directed across the window surface from the pipe shown in Figure 20. This technique worked very well during the droplet flow condition but completely obscured viewing during any other flow condition, which contained a large quantity of water.

(3) Heated window - To evaluate this method, it was necessary to divide the work into two phases: Phase A - prove the principle, and Phase B - adapt it to the optical probe design.

To prove the principle of using a heated window and satisfy Phase A, a heated window was fabricated by sandwiching a 0.013-mm-diameter nichrome wire (formed in a sinusoidal pattern) between two

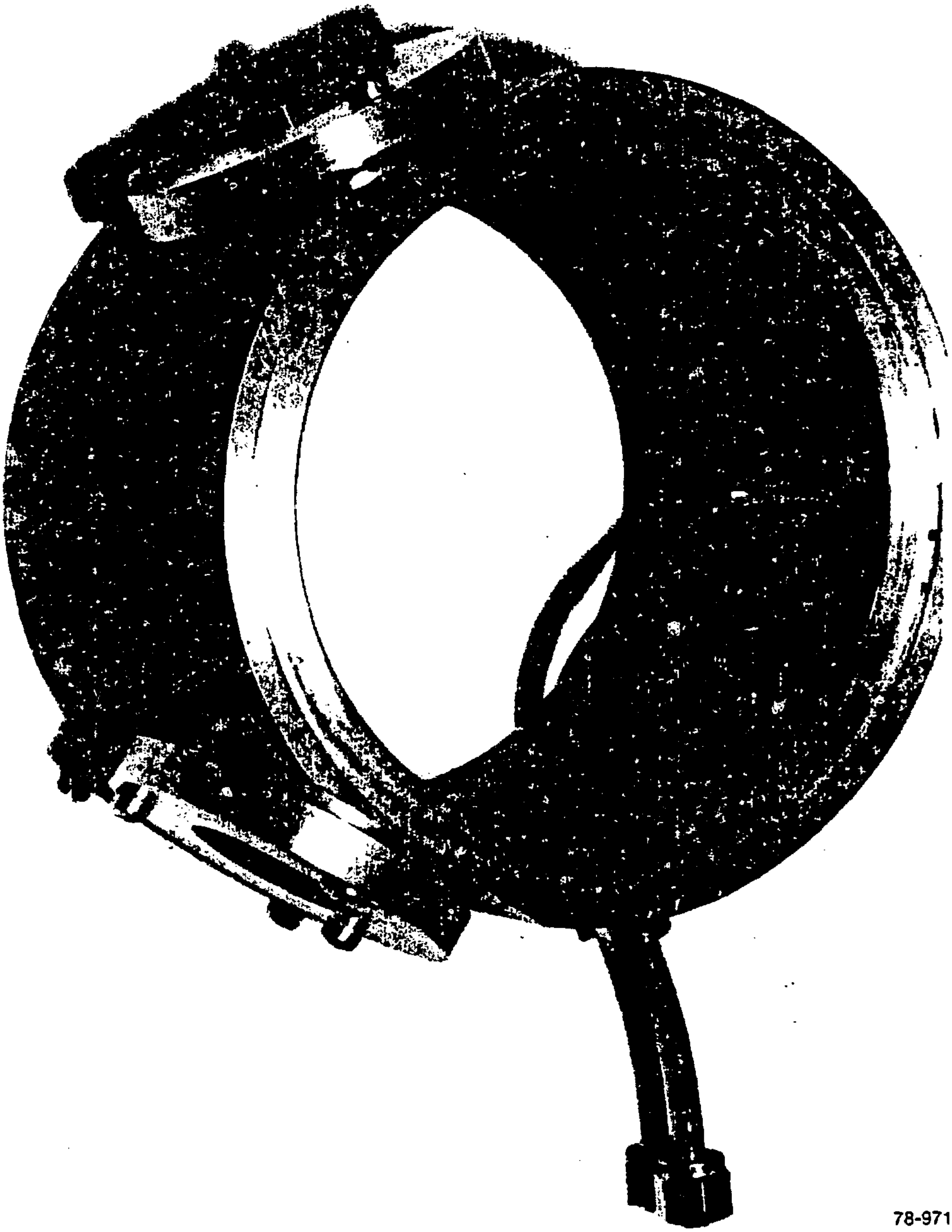

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Fig. 20 Instrument washer with lighting and viewing ports and tube for gas window clearing.

25.4-mm-diameter quartz windows, see Figure 21. With water droplets forming on the window, power was applied in increasing steps (see Table VI) until the droplets began to boil away. It was found that a power greater than 10 W was required to boil away the droplets. This method of window clearing was superior to the clearing gas method because it was effective in all types of flow conditions without interfering with viewing.

After the heated window principle was proved, the heater was adapted to the actual probe tip design shown in Figure 4 (Phase B). Because of the smaller window area in the actual probe, the wire pattern density would have had to be increased by a factor of 6, which would severely obstruct viewing, in order to maintain the same total heater wire resistance. Therefore, an annular heater was designed which would not obstruct viewing.

The annular window heating coil shown in Figure 22 serves two purposes: (a) to separate the two windows, creating a dead air space and (b) to defog and remove water droplets from the outer sapphire window. The heater was wound on a stainless steel coil form with 30 turns of 0.0762-mm-diameter Secon-406 wire, resulting in a coil resistance of 37 ohms.

For test purposes, the heater coil was sandwiched between two 25.4-mm-diameter quartz windows. A thermocouple was attached to measure the outside window surface temperature. Table VII shows the power required to achieve a certain window temperature. It was determined that the window temperature had to be maintained well above ambient temperature to have enough heat capacity to boil away water droplets rapidly.

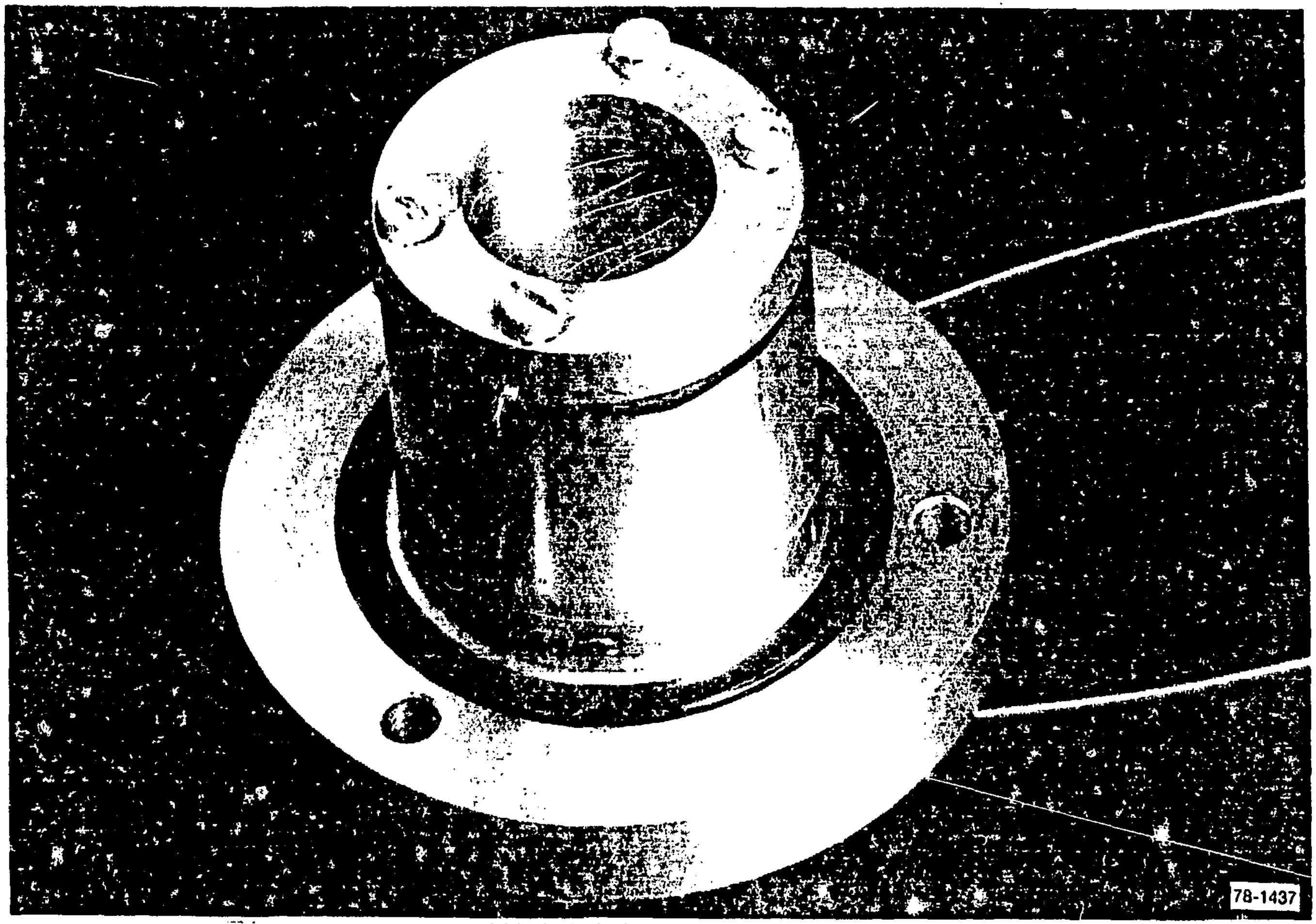

Fig. 21 Window clearing using a heated wire between two windows.

TABLE VI

POWER STEPS USED TO TEST HEATED WINDOW PROTOTYPE

Coil Voltage (V rms)	Coil Current (amp)	Power (W)
4.723	0.445	2.1
5.25	0.492	2.6
6.74	0.632	4.3
8.12	0.755	6.1
9.17	0.855	7.8
10.33	0.954	9.9
12.76	1.172	15.0

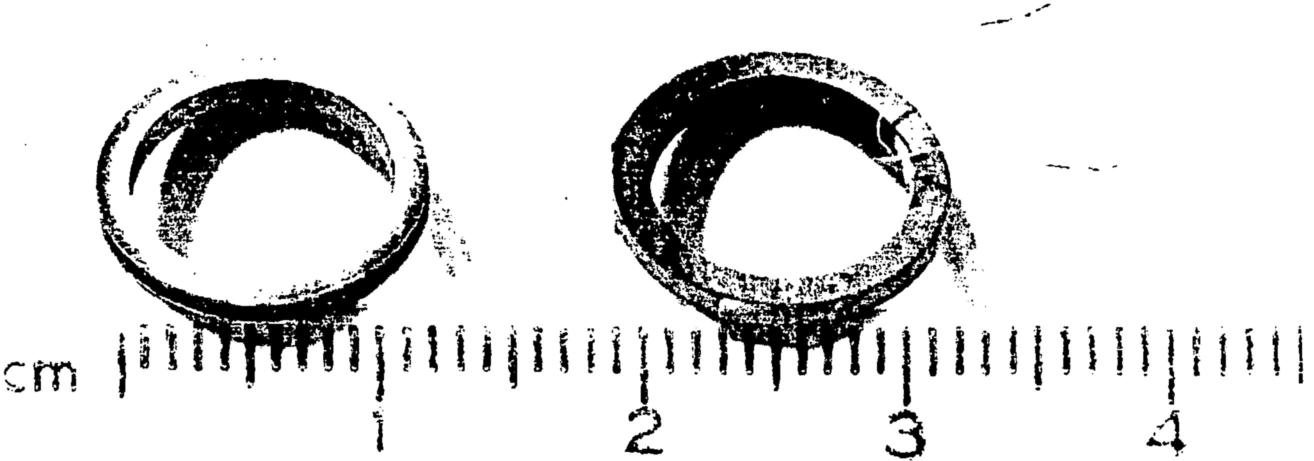

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Fig. 22 Annular window heating coil.

TABLE VII

HEATER COIL POWER AND CORRESPONDING WINDOW SURFACE TEMPERATURE

Coil Voltage (V dc)	Coil Current (amp)	Power (W)	Temperature (C^o)
0	0	0	24
2	0.05	0.1	28
3	0.09	0.27	33
4	0.11	0.44	41
5	0.14	0.70	52
6	0.16	0.96	63
7	0.18	1.26	77
8	0.21	1.68	86
10	0.25	2.50	110
12	0.30	3.6	138
14	0.34	4.7	174
21	0.50	10.5	274

7. TEST RESULTS

The first use of the imaging optical probe was in a high-temperature (343°C), high-pressure (15.2 MPa) blowdown test in the Semiscale facility at the INEL. The optical probe was installed in a simulated nuclear reactor downcomer pipe, as shown in Figure 23, by means of an instrument washer, whose inside diameter was the same as the pipe to which it was attached.

The instrument washer, as shown in Figure 24 had three ports spaced 120° apart. One port was for the optical probe and the other two ports were for mounting fiberoptic light pipes. The inside surface was black chrome plated for the optimum background color. Figure 25 shows the instrument washer with the probe and light pipes installed.

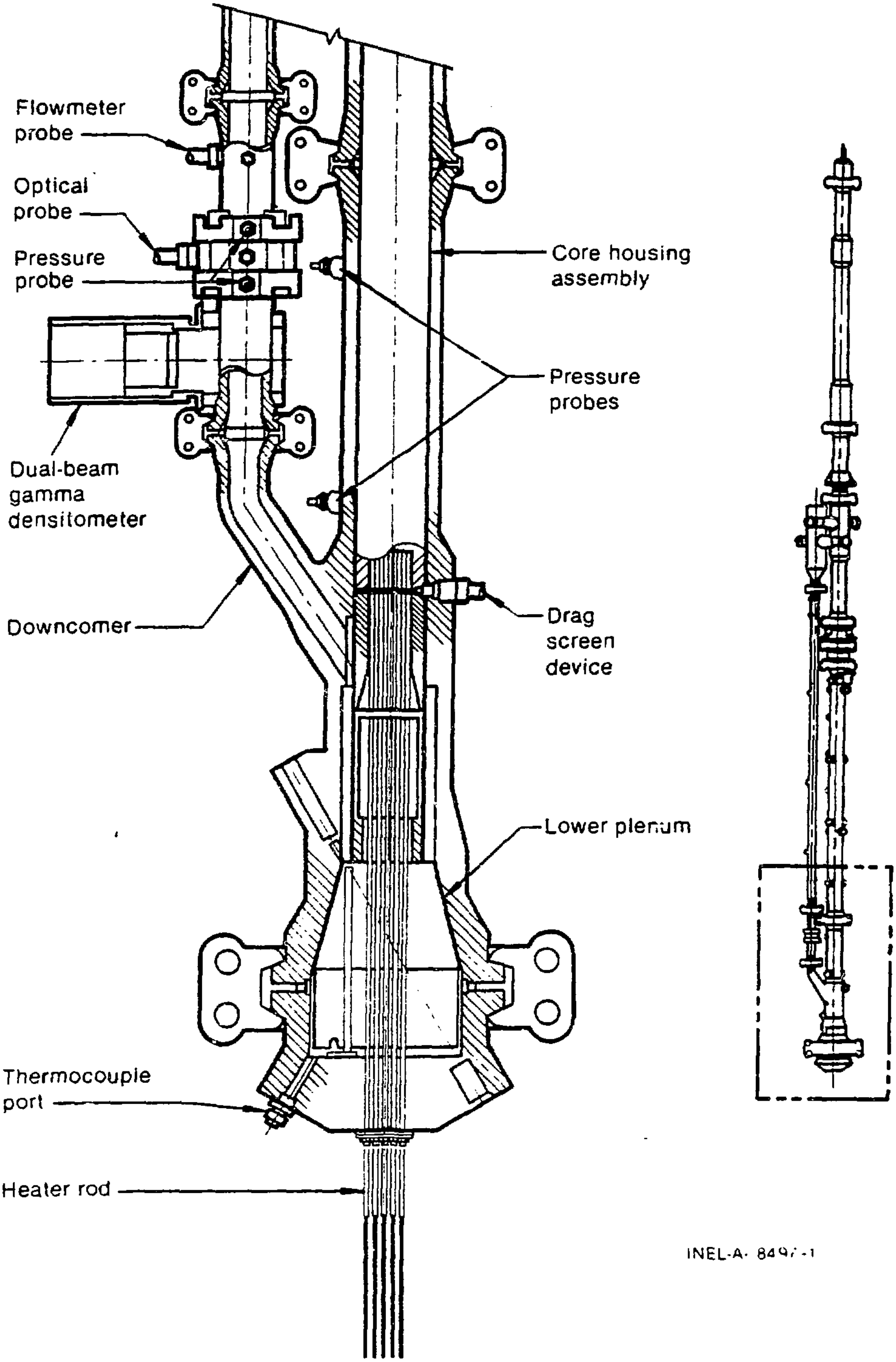

Fig. 23 Semiscale Mod-3 vessel system showing location of optical probe installation.

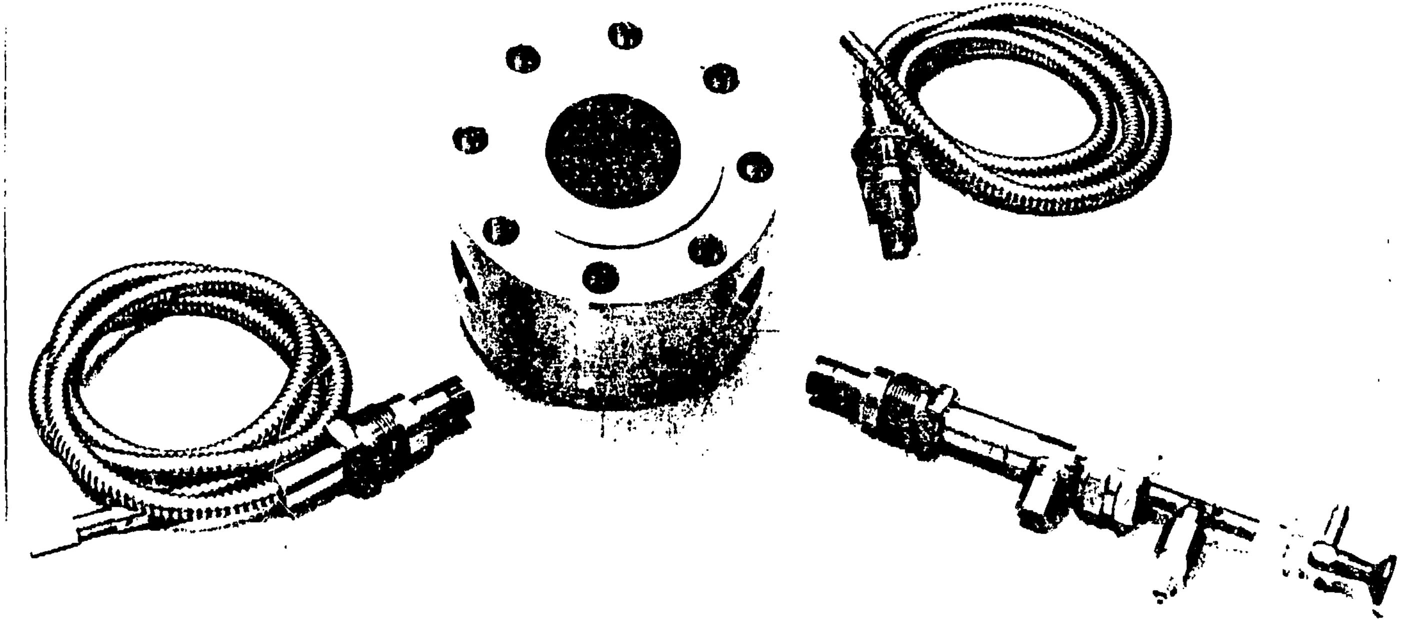

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Fig. 24 Instrument washer showing three ports for lighting and viewing fiberoptic light pipes and optical probe.

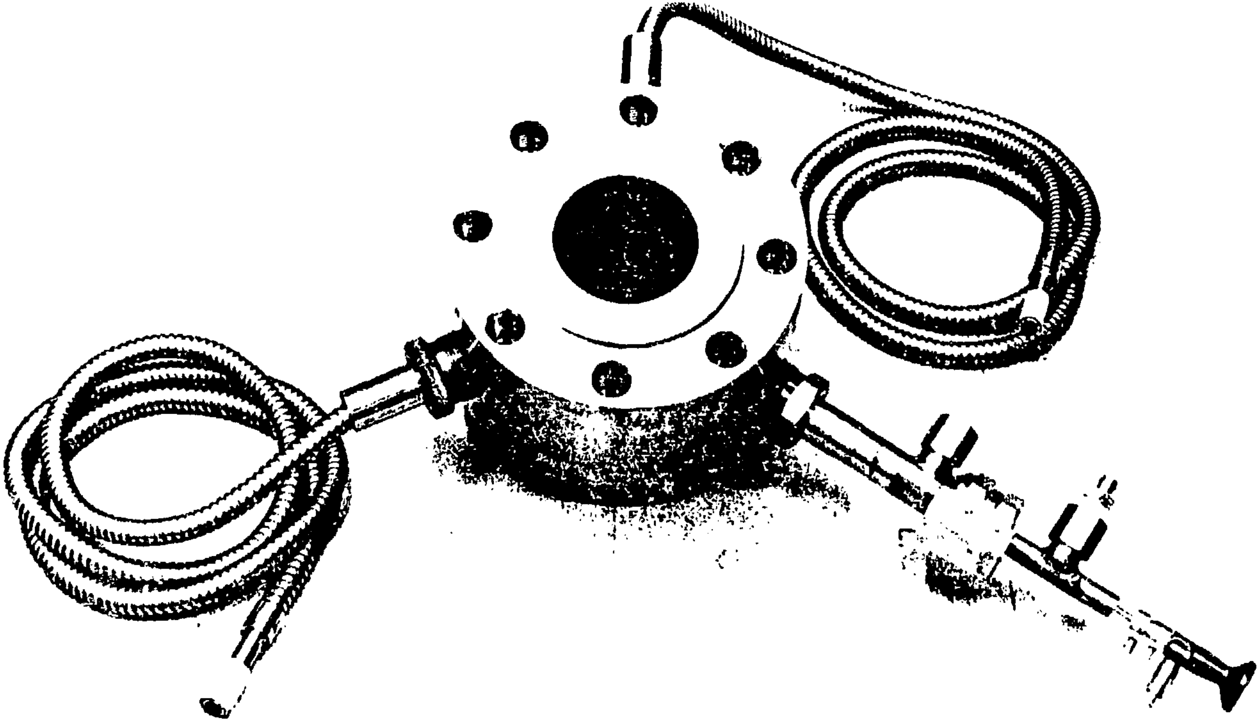

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Fig. 25 Optical probe and two fiberoptic light pipes installed in instrument washer.

The fiberoptic light pipes were connected to a dual quartz-iodine incandescent light source. This combination produced a collimated light source which illuminated all flow regimes passing in front of the optical probe.

Figure 26 shows the optical probe equipment layout for Semiscale Test S-07-10B. The optical probe was attached, by means of a lens adapter, to a Model 4415 COHU video camera. Figure 27 is a single frame photographed from the video monitor during an all water flow condition (620 K and 15.2 MPa) just before blowdown. The two images are the result of the camera operating at twice the normal rate or 120 fields per second. The two bright objects on the sides of each image are the fiberoptic light pipe ports. They are visible because of the 60° field of view of the probe.

At blowdown, the pressure dropped, causing the water to flash to steam as seen in Figure 28. This process continued until all the water was boiled away and the downcomer and core pipes were dryed out, as shown in Figure 29. The tips of the fiberoptic light pipes are more visible than in the all water condition in Figure 27. Figure 30 shows the reflood cooling water boiling off from the wall as it entered the hot downcomer pipe. After a few minutes, the downcomer wall was cooled down so that more reflood water was available to cool the core. Figures 31 and 32 indicate that core temperature was lowered to below boiling temperature because rapid steam bubble generation had ceased.

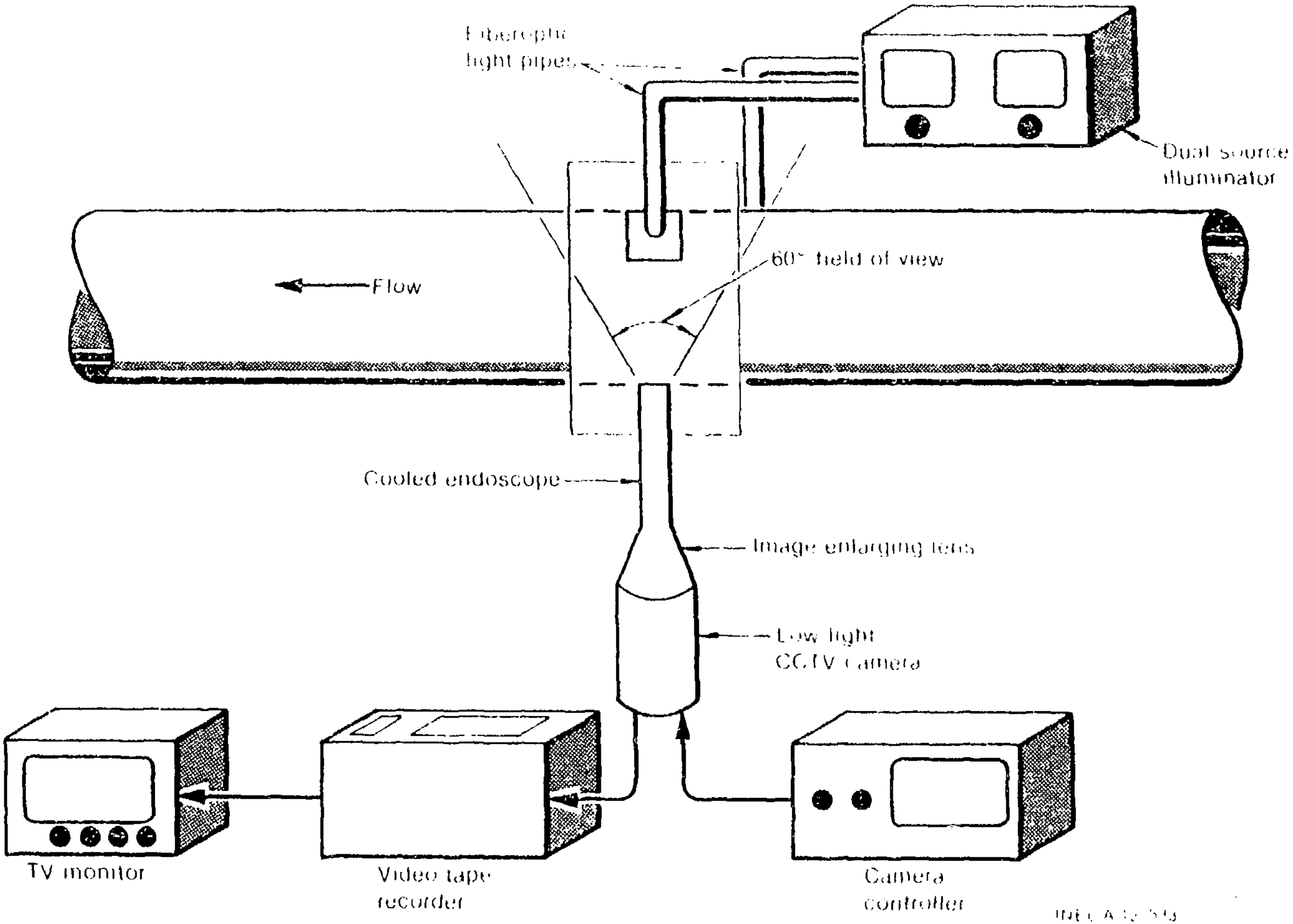

Fig. 26 Flow regime viewing using optical probe and closed-circuit television.

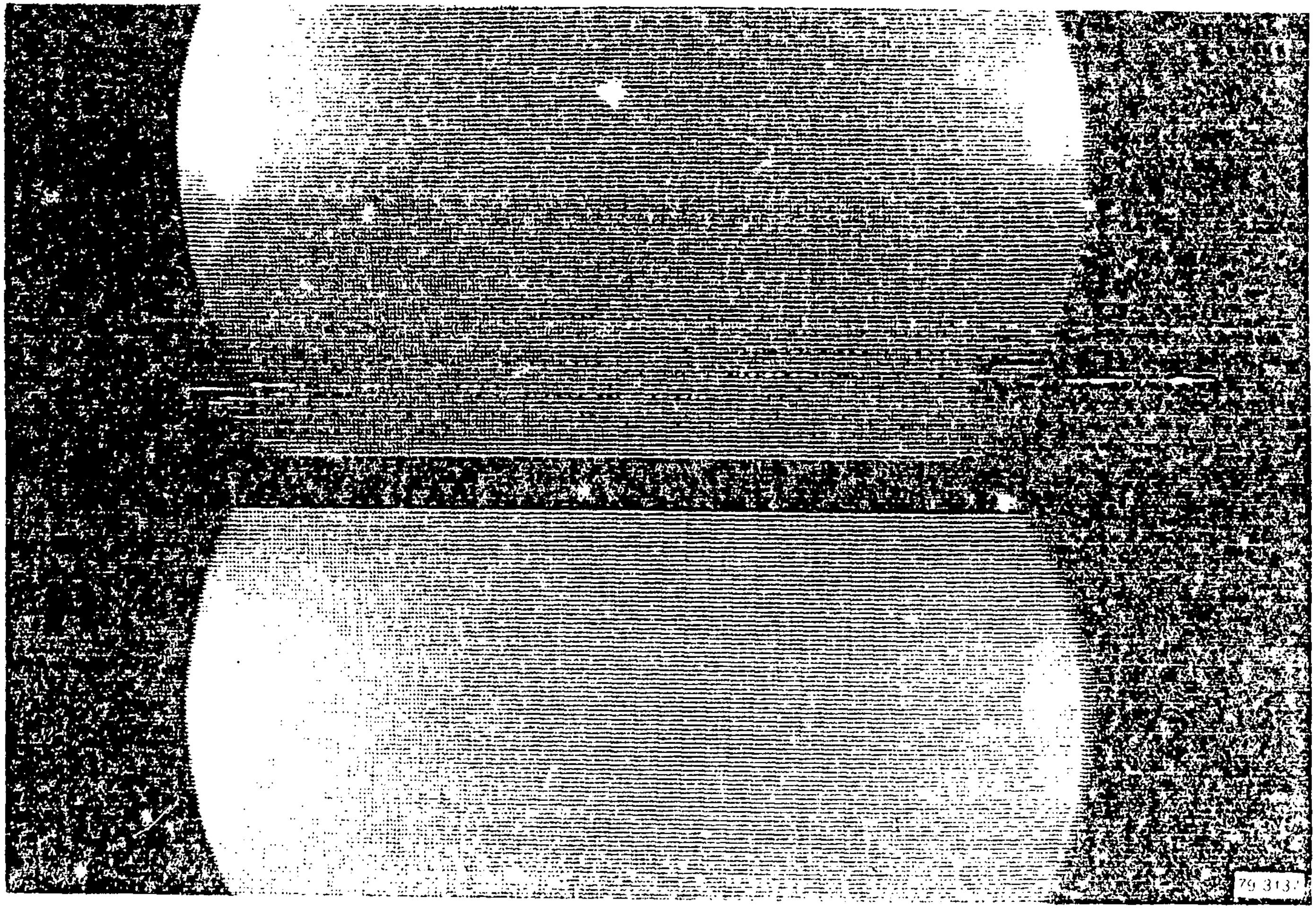

Fig. 27 A view inside downcomer pipe before blowdown with flowing water in a 3[illegible]5°C and 15.[illegible]-MPa environment. The two video fields are [illegible] s apart. The two bright objects are the tips of the fiberoptic light pipes.

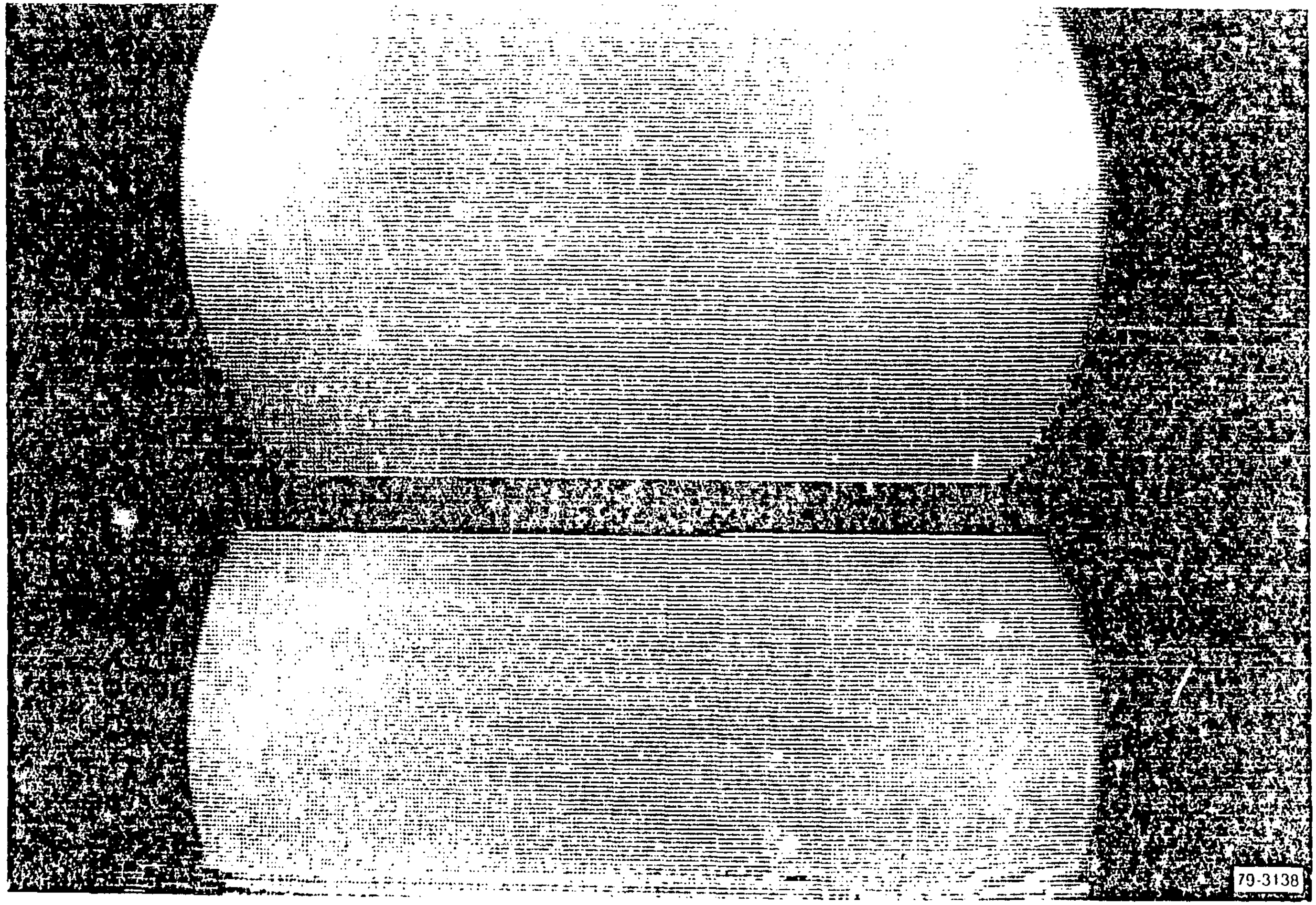

Fig. 28 Wisps of steam shown in downcomer pipe at blowdown.

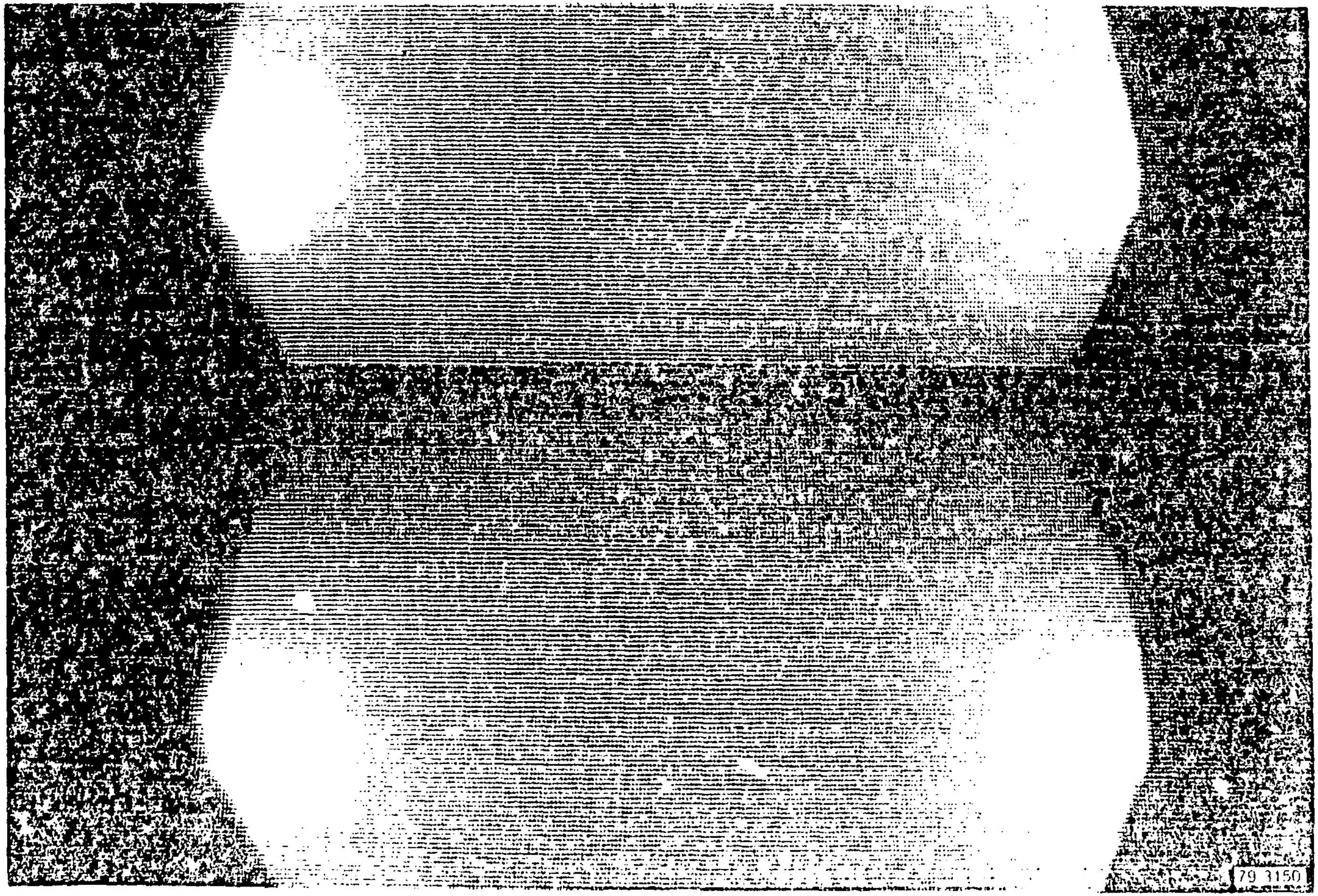

Fig. 29 Only steam is present in the downcomer pipe which is void of any cooling water.

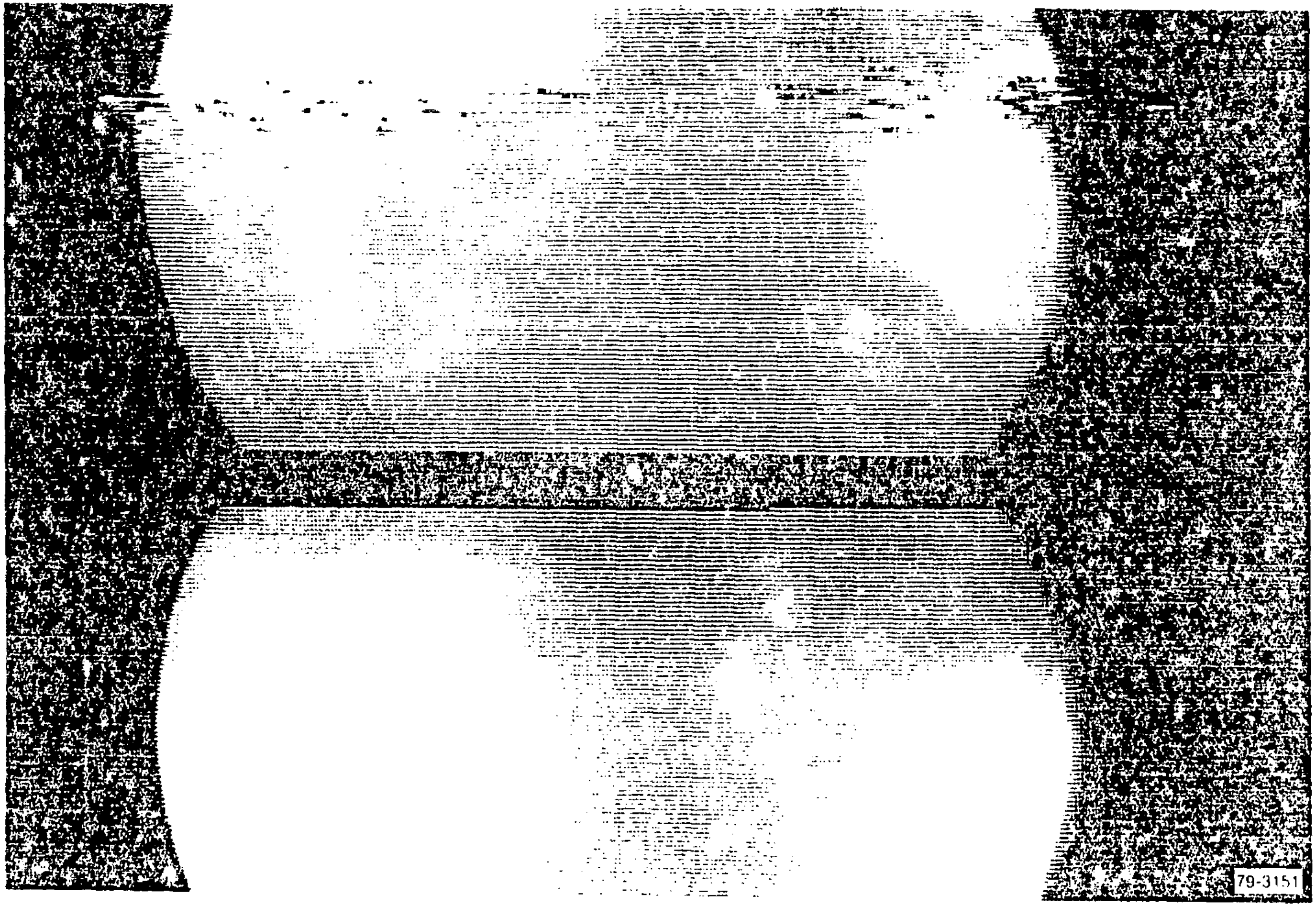

Fig. 30 Cooling water is being injected into the downcomer pipe and boiling from pipe wall.

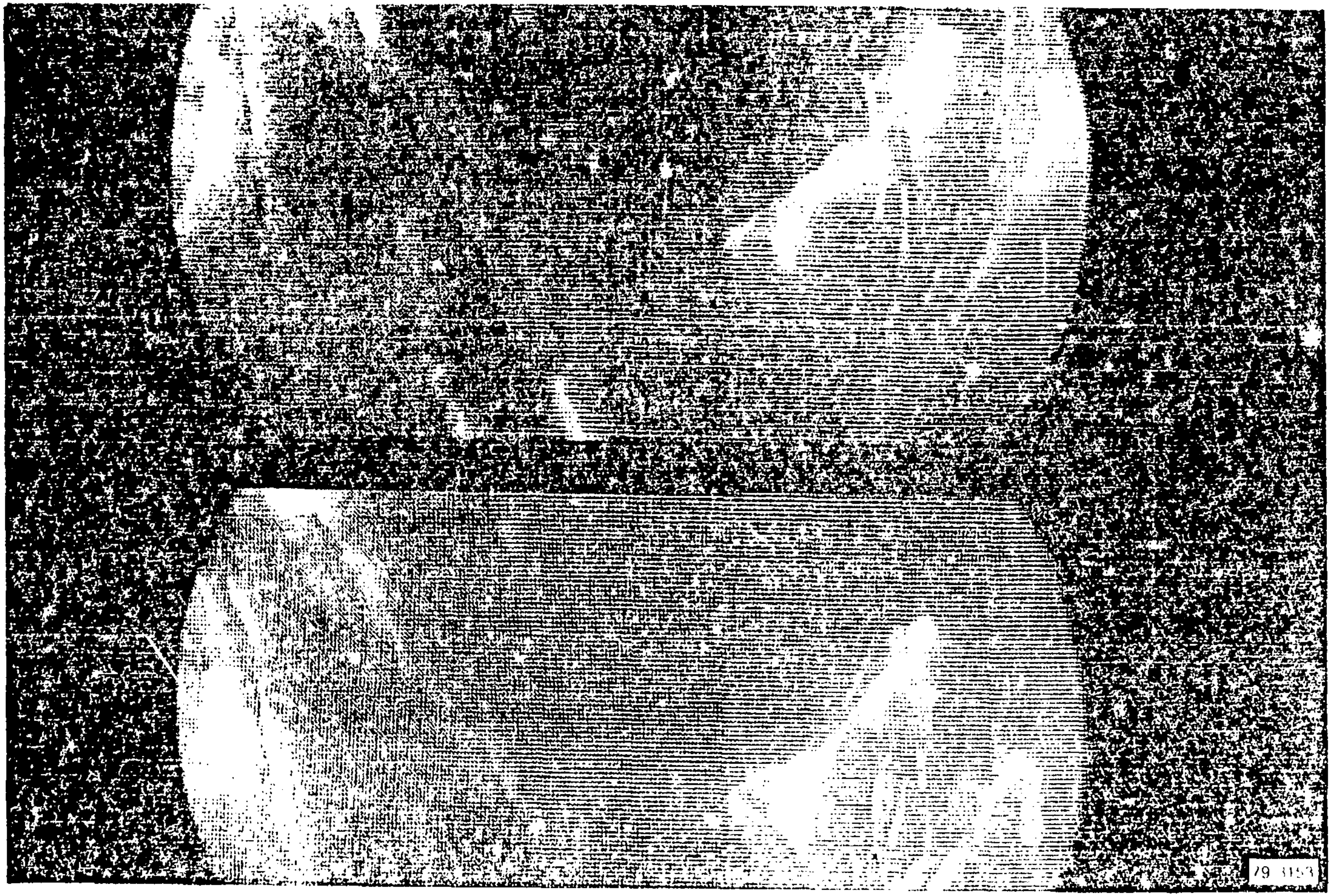

Fig. 31 Downcomer pipe is approaching quench as a great quantity of cooling water has been injected.

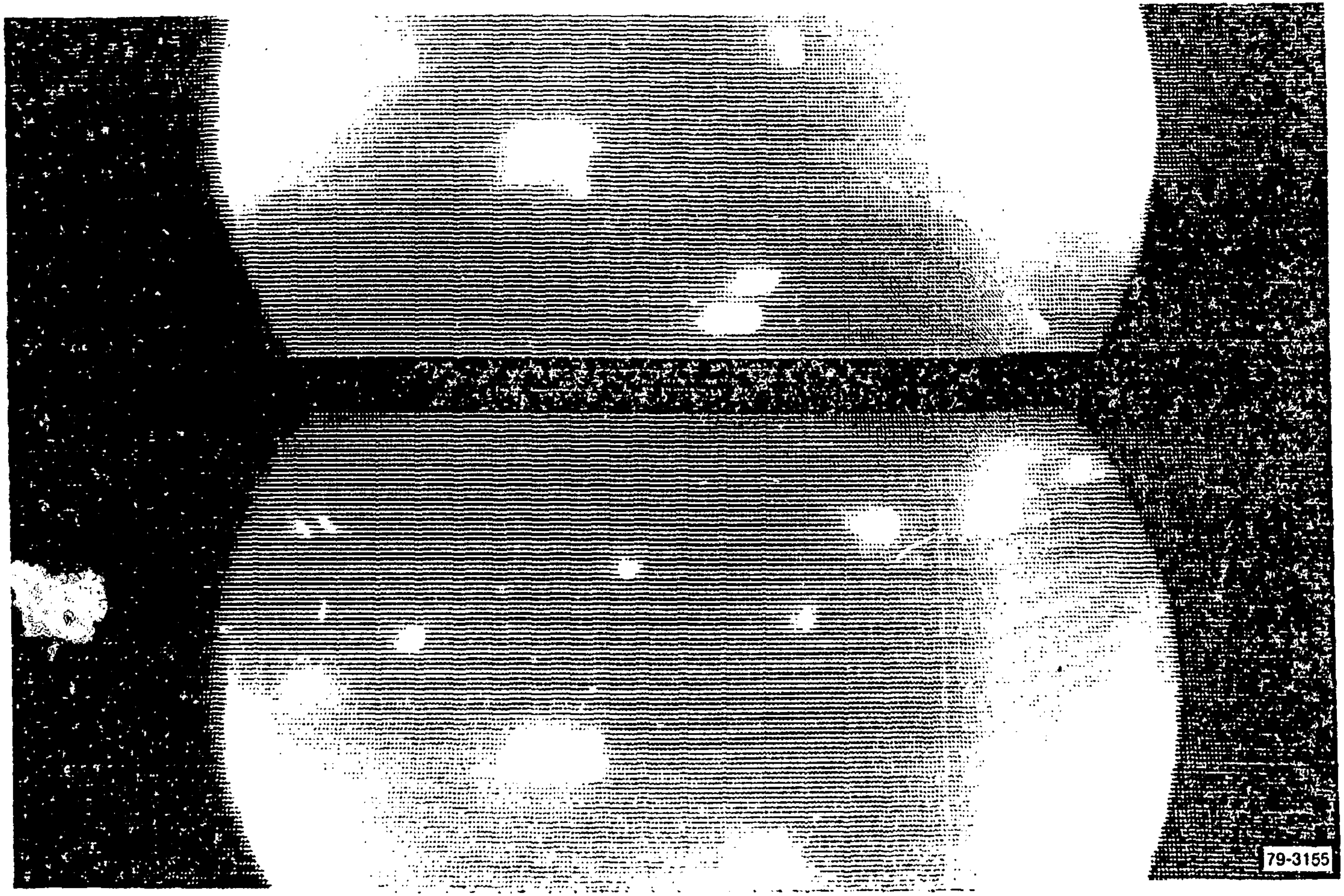

Fig. 32 Downcomer pipe contains almost all water with slow velocity steam bubbles still present.

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