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Assessment of the Adequacy of ORNL Instrumentation in Reflood Test Facilities

J. E. Hardy
M.B. Herskovitz

Prepared for the
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ASSESSMENT OF THE ADEQUACY OF ORNL INSTRUMENTATION IN REFLOOD TEST FACILITIES

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ACKNOWLEDGMENTS

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EXECUTIVE SUMMARY

Instrumentation for making two-phase measurements in experimental refill-reflood test facilities was developed by Oak Ridge National Laboratory (ORNL) through the Advanced Instrumentation for Reflood Studies (AIRS) program. These unique instrumentation systems were designed to survive the severe in-vessel environmental conditions that exist during a simulated pressurized water reactor loss-of-coolant accident (LOCA). The measurements which are required for better understanding of reactor behavior during LOCAs, include two-phase flow velocity, void fraction, and film thickness and velocity. The adequacy (survivability and data quality) of the instrumentation systems installed in four experimental reflood test facilities is assessed.

The AIRS program specifically developed instruments to survive the hostile environment in a refill-reflood test vessel. Film probes were designed to measure film thickness, film velocity, and film wave velocity on the surfaces within the vessel (vessel walls or internal structures). Electrical impedance sensors were developed to sense in-vessel two-phase phenomena, in particular temperature, void fraction, and flow velocity.

In order for these instruments to function properly they must survive the extremely severe environment in which they are located. The sensors must withstand relatively short-term exposure to 800°C steam and relatively long-term exposure to 200 to 300°C steam. The probe integrity must be maintained through repetitive thermal transients of 300°C/s. To enable these instruments to be built, a unique ceramic-to-metal (cermet) seal system was developed at ORNL. In addition, a ceramic insulator developed by ORNL (patent No. 4234338) was developed after finding that no commercial insulating material met the steam compatibility, impermeability, or thermal shock requirements. This material was basically aluminum oxide containing a very fine dispersion of platinum nodules, which greatly enhanced the thermal shock resistance of the hot-pressed ceramic insulators. This ceramic insulator exhibited little or no weight change on exposure to steam at 650 to 750°C for over 100 h and has a helium leak rate of less than 0.005 mm^3/s after 25 quenches from 520°C air into water at 80°C (at 300°C/s).

The development of adequate signal conditioning electronics was also crucial in producing a functioning instrument. All the sensors developed by ORNL required the measurement of electrical impedance. The electronics were designed to measure impedance and change in impedance for a probe located in a two-phase flow field. The electrical conductivity and permittivity of steam and water are quite different; thus, as the two-phase flow regime changes, so does the electrical impedance. For the probes to be used to determine the required flow parameters, both the magnitude and phase of the impedance needed to be measured. Two circuits were designed to provide analog outputs proportional to the magnitude and phase of the probe impedance.

As stated earlier, instrumentation from ORNL was placed in four reflood test facilities. Three of these facilities are located in Japan and

operated by the Japanese Atomic Energy Research Institute (JAERI), and one facility is located in West Germany operated by Kraftwerk Union (KWU). The Japanese facilities are Slab Core Test Facility--Core I and Core II (SCTF-I and SCTF-II), and Cylindrical Core Test Facility--Core II (CCTF-II). The German experimental facility is PKL--Core II (PKL-II).

ORNL instrumentation was able to give useful, meaningful data during refill-reflood test experiments. In fact, for the first time, two-phase flow measurements of velocity and void fraction were made in an electrically heated core. In addition, velocity and void fraction data were obtained from sensors in the upper plenum and the downcomer. Film thickness measurements were made on internal surfaces in the core, upper plenum, and hot legs.

Other accomplishments achieved included development of fabrication techniques to build the required sensors. These techniques were high-temperature brazing, laser welding, and joining of components with widely different thermal coefficients of expansion.

Although some sensor failures were experienced in all the facilities, considering the severe environment, geometrical constraints and time limitations (13 months from program conception to delivery of the first sensors), the performance was very satisfactory. ORNL instrumentation gave valuable data which were useful in producing a better understanding of simulated LOCAs in refill-reflood test facilities.

HIGHLIGHTS

Instrumentation for making two-phase measurements in experimental refill-reflood test facilities was developed by Oak Ridge National Laboratory (ORNL) through the Advanced Instrumentation for Reflood Studies (AIRS) program. These unique instrumentation systems were designed to survive the severe in-vessel environmental conditions that exist during a simulated pressurized water reactor loss-of-coolant accident (LOCA). The measurements, which are required for better understanding of reactor behavior during LOCAs, include two-phase flow velocity, void fraction, and film thickness and velocity. The adequacy (survivability and data quality) of the instrumentation systems installed in four experimental reflood test facilities is assessed. Signal conditioning electronics and sensor thermocouples functioned extremely well. For the first time, two-phase flow measurements were made in-core during a simulated LOCA. Because of the harsh environment and geometrical constraints, some sensor failures were considered likely; the number actually failing in service was within expectations. An exception to this record occurred in the Slab Core Test Facility--Core 1. A chloride-ion stress corrosion problem destroyed signal cables at the vessel seal for most sensors. This problem was corrected by changing the sealant material at the vessel penetration in the subsequent facilities. Overall, the performance of the instrumentation was very satisfactory yielding valuable data during simulated LOCAs in refill-reflood test facilities.

1. INTRODUCTION

In the fall of 1977, an international agreement was initiated among the U.S. Nuclear Regulatory Commission (NRC) and its counterparts in the Federal Republic of Germany and Japan as the "International 2D/3D Refill and Reflood Analytical and Experimental Research Program." The overall objective of this tripartite program was to increase the understanding of refill-reflood phenomena during loss-of-coolant accidents (LOCAs) in pressurized-water reactors (PWRs). The specific goals of the program are to study steam binding effects during reflood, to study the reflood flow distribution in a heated core, and, finally, to study flow hydrodynamics in the core, downcomer, and upper plenum.

The analytical portion of the 2D/3D program consists mainly of a large computer code, the Transient Reactor Analysis Code (TRAC), primarily developed by Los Alamos National Laboratory (LANL). This computer code predicts reactor thermal-hydraulic behavior during a LOCA. To improve upon the accuracy of TRAC predictions, data from experimental reflood test facilities are used; three large test facilities have been constructed, one in Germany and two in Japan, to this end. To add further insight into thermohydraulic models used in TRAC and to expand the experimental data base, a second test facility, Primarkreislauf (PKL), in Germany became associated with this work.

The Advanced Instrumentation for Reflood Studies (AIRS) Program[1] at Oak Ridge National Laboratory (ORNL) was responsible for developing techniques and instrumentation to measure fluid flow in the core, de-entrainment in the upper plenum, and liquid fallback from the upper plenum into the core. To achieve this goal, liquid film thickness and velocity, along with two-phase flow velocity and void fraction, must be measured in environments never before considered amenable to such measurements. The AIRS program developed film sensors utilizing concepts first suggested at Lehigh University.[2,3] Film probes were designed to measure film thickness, film velocity, and film wave velocity on the surfaces within the vessel (vessel walls or internal structures). Electrical impedance sensors were developed to sense in-vessel two-phase phenomena, in particular temperature, void fraction, and flow velocity.

In order for these instruments to function properly they must survive the extremely severe environment in which they are located. The sensors must withstand relatively short-term exposure to 800°C steam and relatively long-term exposure to 200 to 300°C steam. The probe integrity must be maintained through repetitive thermal transients of 300°C/s. To enable these instruments to be built, a unique ceramic-to-metal (cermet) seal

system was developed at ORNL.[4] In addition, a ceramic insulator developed by ORNL (patent No. 4234338) was developed after finding that no commercial insulating material met the steam compatibility, impermeability, or thermal shock requirements. This material was basically aluminum oxide containing a very fine dispersion of platinum nodules, which greatly enhanced the thermal shock resistance of the hot-pressed ceramic insulators. This ceramic insulator exhibited little or no weight change on exposure to steam at 650 to 750°C for over 100 h and has a helium leak rate of less than 0.005 mm^3/s after 25 quenches from 520°C air into water at 80°C (at 300°C/s).

Several other techniques and procedures were developed to complete fabrication of these sensors. These techniques included laser welding of sensor subassemblies into guide tube walls, induction brazing of thermocouples through the tube wall, and furnace brazing of triaxial signal cables, thermocouples, and vent tubes.

The sensor development schedule required that the first instruments be ready within one year of the program's inception. ORNL agreed to produce the sensors on a "best effort" work condition. Thirteen months from the initial funding date instruments were ready for shipment to a foreign test facility, Primarkreislauf (PKL), in West Germany.

As sensor fabrication continued for the other test facilities, new and better manufacturing and assembly techniques were developed to improve the quality of the final instruments. However, at the end of FY 1981, all development funding was cut off.

The development of adequate signal-conditioning electronics was also crucial in producing a functioning instrument. All the ORNL-developed sensors required measurement of electrical impedance. The electronics were designed to measure impedance and change in impedance for a probe located in a two-phase flow field. The electrical conductivity and permittivity of steam and water are quite different; thus, as the two-phase flow regime changes, so does the electrical impedance. For the probes to be used to determine the required flow parameters, both the magnitude and phase of the impedance needed to be measured. Two circuits were designed to provide analog outputs proportional to the magnitude and phase of the probe impedance.

Generally, the probes are located remotely from the electronic instrumentation, 30 m or more in some cases. Interconnection between the probes and the electronics is done via coaxial cable outside the test vessel and special triaxial cable inside the vessel. Depending on cable characteristics and length, the equivalent cable capacitance can exceed 1 nF, and this capacitance value will vary as temperature transients occur in the test vessel. This cable capacitance can be three orders of magnitude higher than the desired probe impedance. However, the signal conditioning electronics provide a means to negate the cable capacitance by driving the inner cable shield and center conductor of the cable at the same potential. Thus, a capacitive charge is not built up. This

technique reduces the cable capacitance to acceptable levels for cables 30 m in length.

As state earlier, instrumentation from ORNL was placed in four reflood test facilities. Three of these facilities are located in Japan and operated by the Japanese Atomic Energy Research Institute (JAERI) and one facility is located in West Germany operated by Kraftwerk Union (KWU). The Japanese facilities are Slab Core Test Facility--Core I and Core II (SCTF-I and SCTF-II), and Cylindrical Core Test Facility--Core II (CCTF-II). The German experimental facility is PKL--Core II (PKL-II).

All facilities were designed to study thermal hydraulic behavior and core flow in a simulated PWR pressure vessel during the end of blowdown and refill and reflood phases of a postulated LOCA. The four experimental test rigs contained electrically heated rods that simulated fuel rods. During operation, the facilities were at fairly low pressure (below 0.4 MPa) but at very high temperature (up to 900°C) and were subjected to severe thermal transients (up to 300°C/s) and erosive steam-water mixtures.

2. SENSOR FABRICATION: PROCEDURES AND CHECKS

To meet the in-vessel measurement and location requirements, several different sensor configurations were designed. For the impedance probes, three types were made: (1) in-core guide tube sensors, (2) upper plenum structure sensors, and (3) string probes. These instruments are illustrated in Figs. 2.1 to 2.3, respectively. Likewise, for making film measurements at various in-vessel locations, three different probe types were configured. These are wall film probes, in-core film probes, and upper plenum structure film probes (Figs. 2.4 to 2.6, respectively).

The components used in all the sensors were fabricated of similar materials but had different configurations. The sensors had signal cables with end seals, sensor subassemblies (with electrodes), and overall housing. This housing varied from guide tubes to upper plenum structures to being an integral part of the test vessel wall. The general fabrication procedures and quality assurance checks will be described in this

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Fig. 2.1. In-core guide tube flag sensor.

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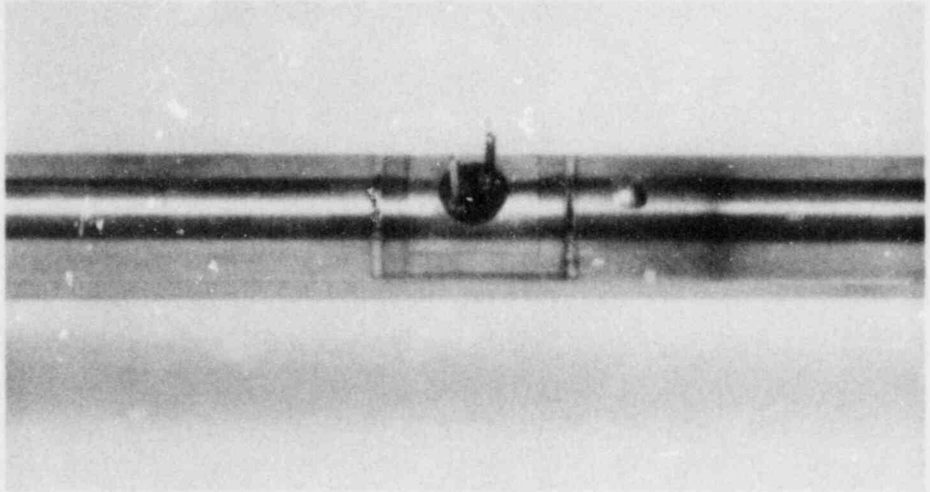

Fig. 2.2. Upper plenum prong probe.

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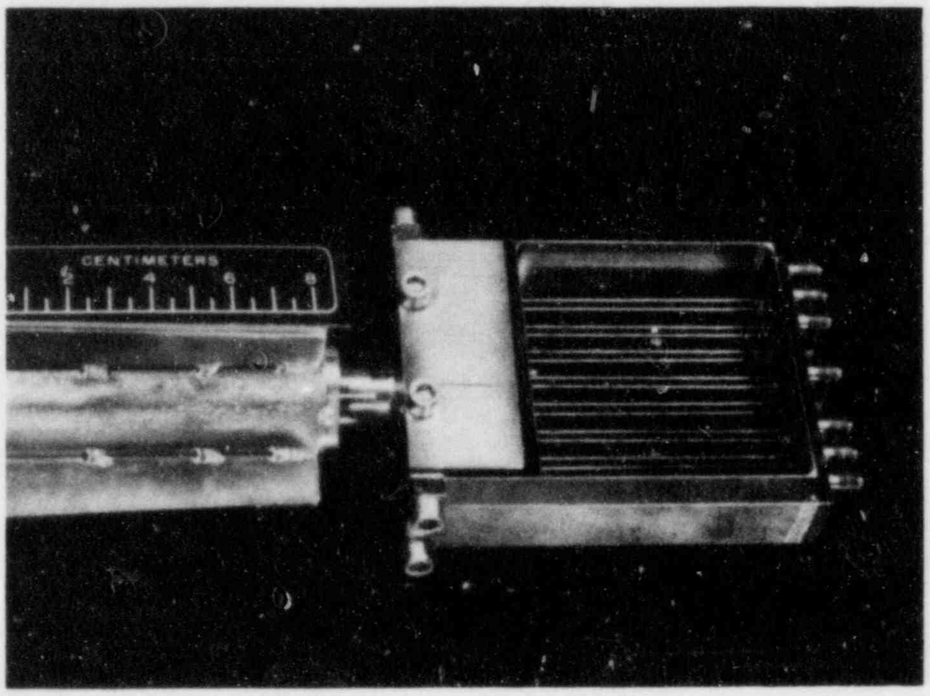

Fig. 2.3. String probe for downcomer or vent valve location.

section. Some steps may vary for a particular sensor design, but the overall plan is essentially the same for each probe.

All parts to be used in the sensor fabrication are dimensionally inspected, and all materials are verified before and after each step in the process.

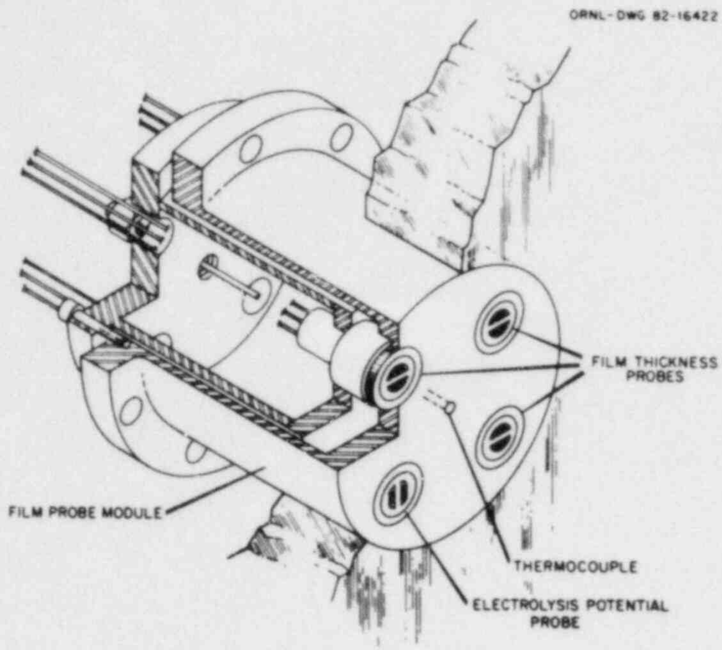

Fig. 2.4. Core and upper plenum wall film probe assembly.

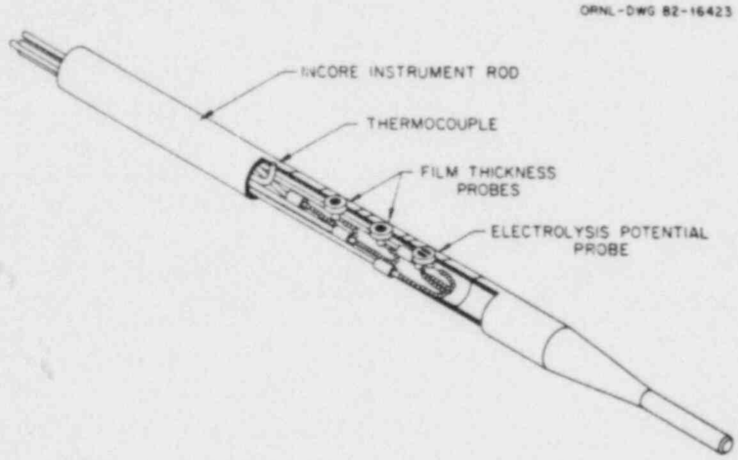

Fig. 2.5. ORNL-built in-core film probe.

2.1 CABLES

The triaxial signal cables (up to four for some probe types) were cut from a spool to a specific length. A bevel was machined in both cable ends. After this machining, cable electrical parameters were measured to check the integrity of the cables. These electrical parameters included the cable capacitance, capacitive loss, and resistance. These measurements indicate insulation quality between the conductor and the two shields, the continuity of each, and the absence or occurrence of any shorts. This step is done for each signal cable cut.

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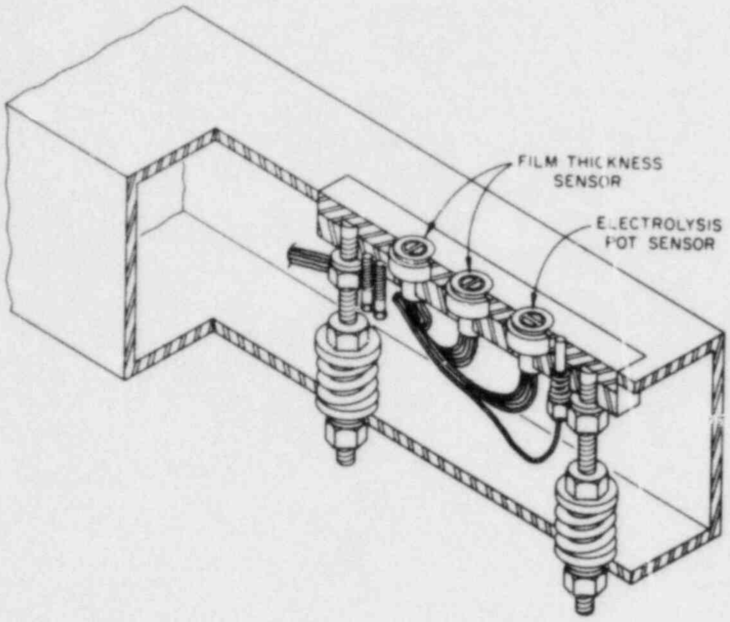

Fig. 2.6. Upper plenum structure film probe.

To protect the cable insulation from absorbing moisture at the sensor end and degrading the insulation, thereby changing the electrical output from the sensors, a cable end seal was developed.[4] The seal may be exposed to severe thermal conditions, nearly as harsh as those experienced by a sensor. The design of the end seal is illustrated in Fig. 2.7. The two criteria for a good cable end seal were leak tightness and high electrical resistance. After installing a seal, a preliminary leak test was performed by pressurizing externally with 0.34 MPa gauge of helium for 30 s, and then quickly removing the pressurization fixture and immersing the brazement in alcohol. The absence of bubbles in this test indicated a probable leak rate of less than 1×10^{-6} cm^3/s. If large leaks were observed, the cable was rebrazed. The final leak check consisted of pressurizing the seal area in a small fixture at a pressure of 0.41 MPa gage of helium and holding for 10 min to allow helium to penetrate any leak. The fixture was quickly removed and the part connected to a mass spectrometer. Five randomly selected samples were given 50 thermal shock tests from 520°C air into 80°C water and then inspected for leaks. Although some leakage was detected in all five samples, the amount of leakage was less than the maximum allowable limit. The electrical integrity of the cable was also monitored and found to be intact after the thermal shock testing. A finished cable end seal is pictured in Fig. 2.8.

2.2 SUBASSEMBLIES

Another step in probe fabrication was the making of the sensor subassemblies.[4] A subassembly was made up of cerment insulators, platinum electrode support plugs, a platinum transition piece, and a stainless steel frame. These subassemblies would be machined and inspected for

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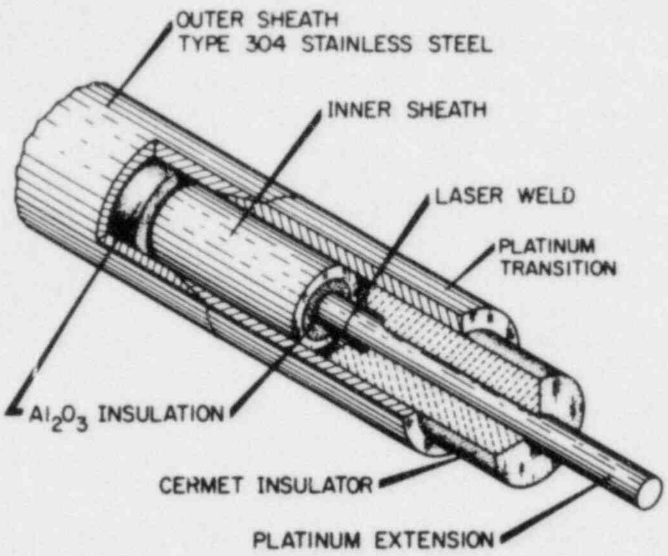

Fig. 2.7. Design of end seal for 3.18-mm-diam (0.125 in.) stainless steel triaxial cable.

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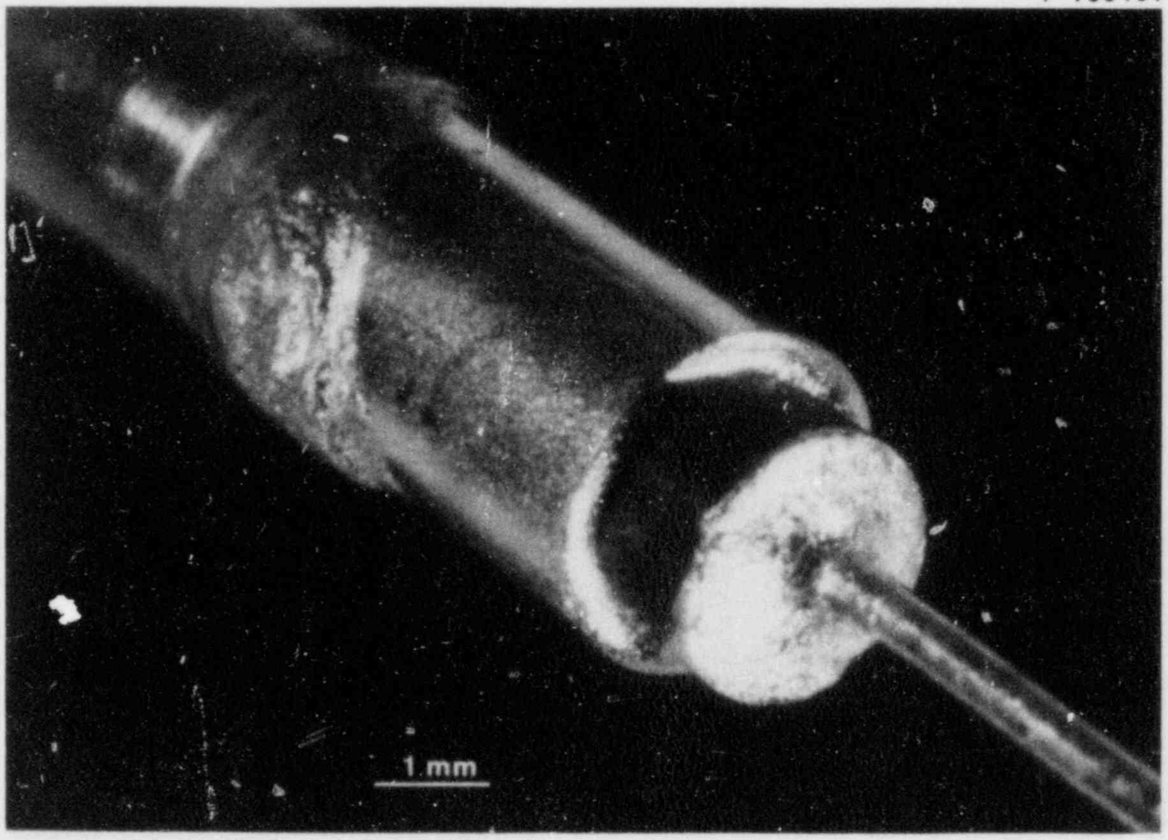

Fig. 2.8. Cable end seal after brazing with a direct brazing filler metal ($^{49}Ti-^{49}Cu-^{2}Be$).

leaktightness and electrical properties before being joined into their final housing. When a subassembly was fabricated, it was checked for leakage and electrical integrity. The components and a completed subassembly for an in-core flag probe is shown in Fig. 2.9. Upon passing the appropriate tests, a subassembly was ready to be joined to its housing. This was accomplished by using a pulsed ruby laser welder and a series of overlapping spot welds to make a helium-leaktight joint. These welds were inspected for leakage while still at the laser console by pressurizing the rod with 0.17 MPa gauge helium and immersing the sensor area in alcohol. Figure 2.10 depicts a flag probe sensor array installed in a guide tube. Samples of the different probe type assemblies were thermally shocked and checked for leakage and electrical usability. The results of these tests were considered very good (see Sect. 2.5).

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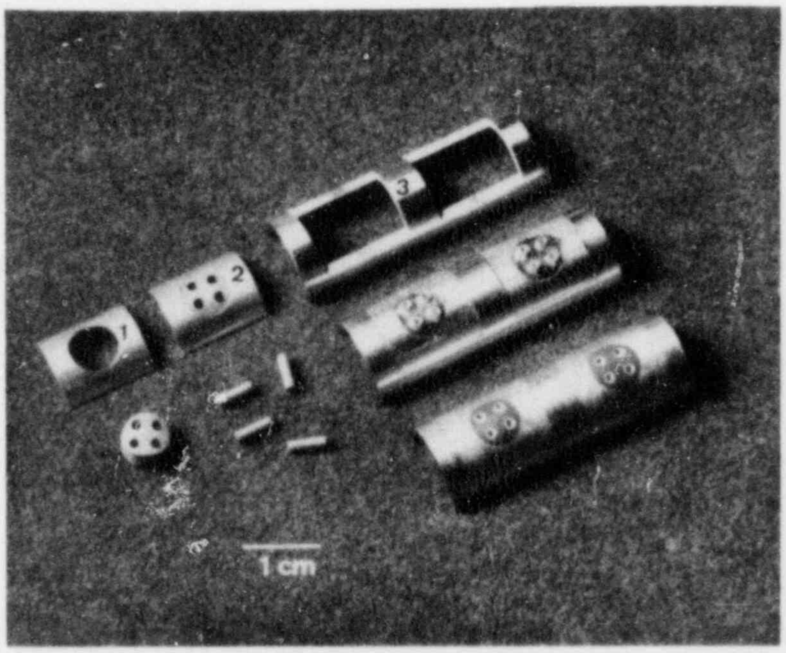
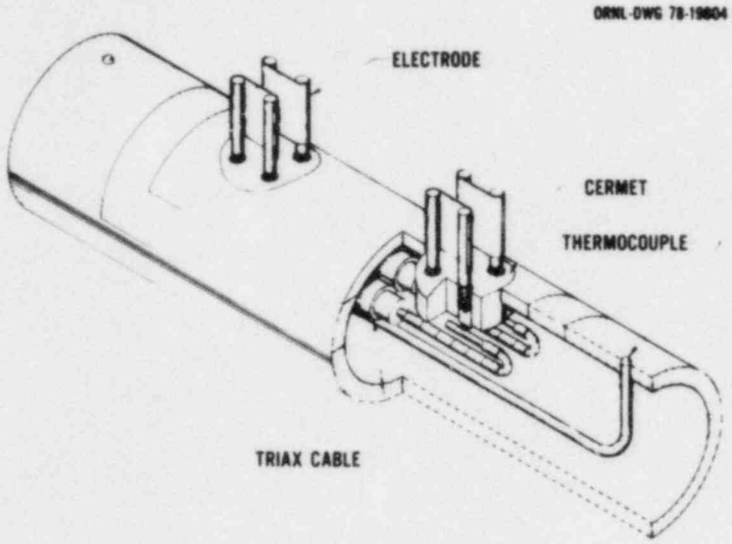


Fig. 2.9. Flag probe sensor subassembly
(1) platinum expansion transition piece,
(2) cermet insulator, (3) stainless steel frame.

2.3 UPPER ROD TERMINATIONS

One final problem was left for guide tube sensors (in-core and upper plenum impedance type). This was the closure of the guide tube at the upper end through which up to eight triaxial cables, four thermocouples, and a vent tube passed.[4] The design of the upper rod termination is shown in Fig. 2.11 and pictured in Fig. 2.12.



In-Core Guide Tube
Impedance Measurement Assembly
Flag Probe Sensor

Fig. 2.10. Flag probe subassembly and thermocouple installed in a guide tube rod.

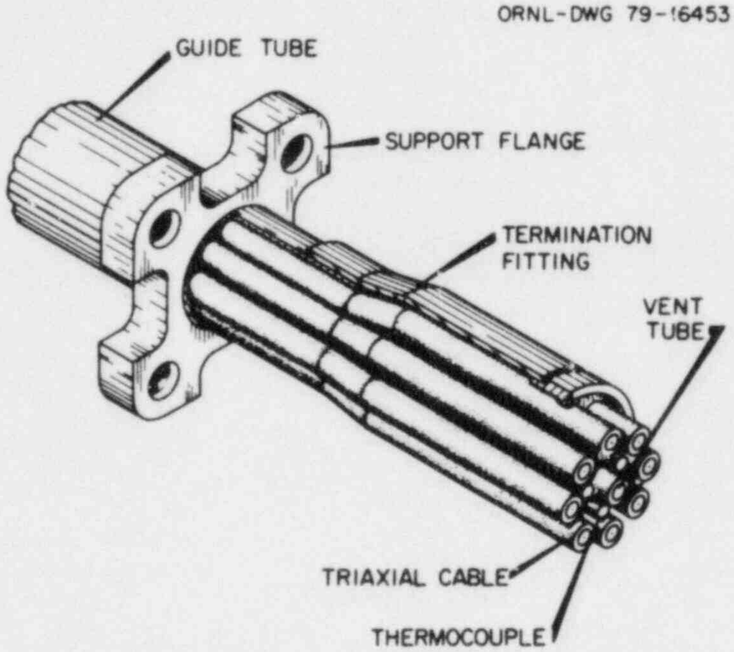


Fig. 2.11. Upper rod termination of an instrumented guide tube assembly. All the joints are brazed simultaneously in a resistance-heated furnace with a commercial nickle-based filler metal (B_2Ni-3). The support flange is tack-welded in place after brazing.

Y-160148

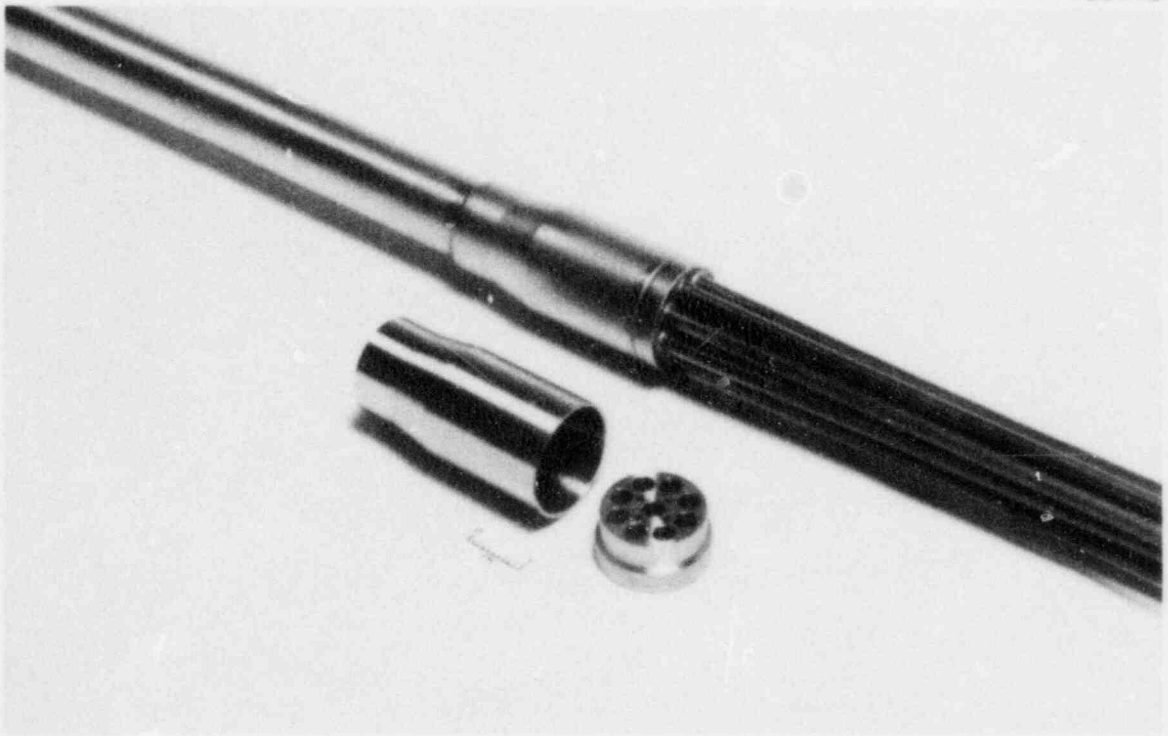


Fig. 2.12. Upper rod termination components and brazed assembly.

2.4 FINAL ASSEMBLY OPERATIONS

After the upper rod termination had been brazed, the sensor subassemblies were then laser welded in the housing. A completed instrumented guide tube assembly is shown schematically in Fig. 2.13. The tapered lower end plug and rod support bracket were gas tungsten-arc welded into position. At this stage the instrument was ready for final electrical and leak-check tests.

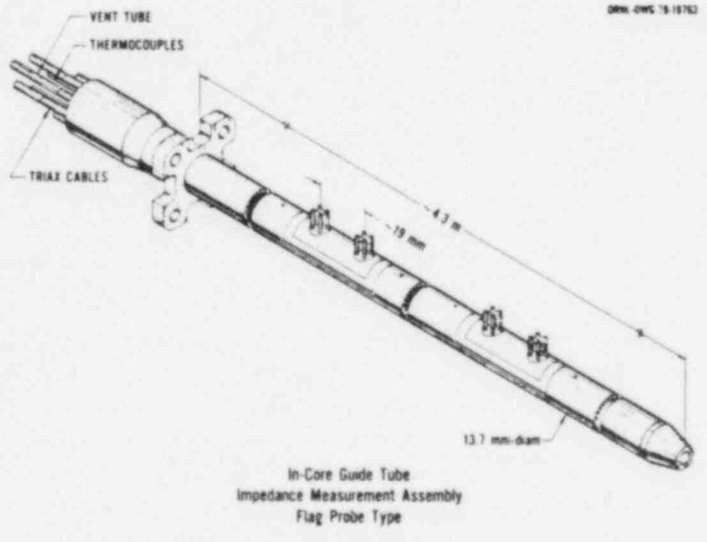


Fig. 2.13. Flag probe impedance measurement assembly.

A comprehensive helium leak test, which checked the end plugs and the sensor subassemblies, was performed. Also electrical cable measurements were recorded. If these tests were passed, the exposed signal cable ends were seal welded, and the entire sensor package readied for shipment.

The criteria for a "good" instrument are listed in Tables 2.1 to 2.3. To improve on probe performance, the leak rate values were made more stringent for the instruments fabricated for SCTF-II and CCTF-II. These stricter values are listed in Table 2.3.

Table 2.1. Electrical parameter requirements for a good sensor

Insulation resistance	$>1 \times 10^6$ ohms
Loss	<0.010

Table 2.2. Leak rate limits for sensors in SCTF-I and PKL-II

Subassembly	1×10^{-5} std cm^3/s of helium
Cable end seal	5×10^{-7} std cm^3/s of helium

Table 2.3. Leak rates limits for sensors in CCTF-II and SCTF-II

Subassembly	6×10^{-7} std cm^3/s of helium
Cable end seal	2×10^{-9} std cm^3/s of helium

2.5 QUALITY ASSURANCE TESTING

To evaluate how well the instruments were meeting the leak-rate limits listed in Table 2.3, a statistical analysis was made on 12 CCTF-II in-core flag probes. Both the cable end seal and subassemblies were tested.

A helium gas leak rate test was made on the cermet-to-metal end seal of each of the 96 1.6-mm-OD triaxial cables used in the fabrication of the 12 flag probes (8 cables per probe). Twenty-seven cermet end seals had a leak rate in the range of 10^{-9} std cm^3/s of helium and 69 cermet end seals had a leak rate in the range of 10^{-10} std cm^3/s, with a mean leak rate of 8.1×10^{-10} and a standard deviation of 1×10^{-9}. A histogram of the measured leakage is shown in Fig. 2.14. These data indicate that excellent cable end seals were being fabricated since the maximum allowable leakage was 2×10^{-9} std cm^3/s of helium.

A helium gas leakage test was also performed on the 24 subassemblies installed in the 12 probes. Two subassemblies had a leak rate in the range of 10^{-6} std cm^3/s of helium; 5 subassemblies leaked in the range of

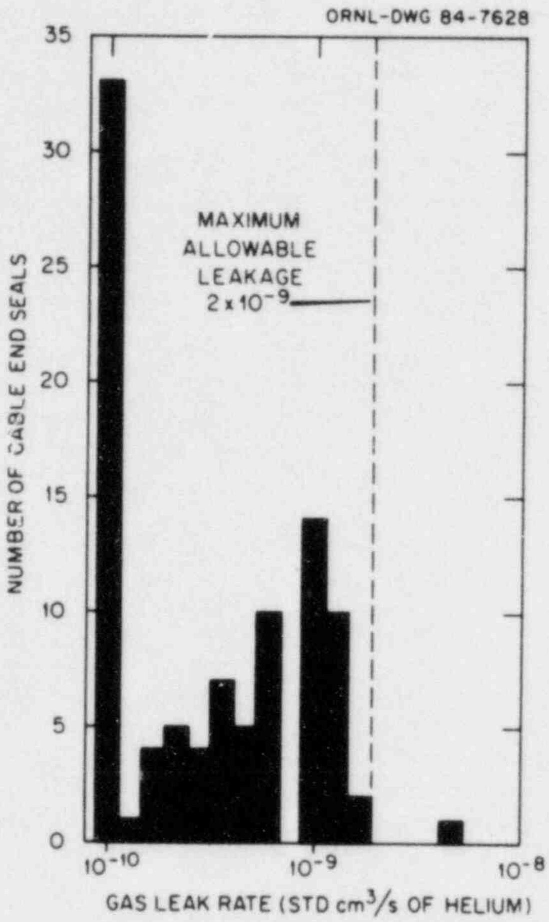


Fig. 2.14. Gas leakage distribution for triaxial cable end seals--CCTF-II.

10^{-7}; 5 subassemblies were in the range of 10^{-8}; and 12 subassemblies had a leak rate of approximately 10^{-9}. The mean leak rate was 2.3×10^{-7} with a standard deviation of 5.45×10^{-7}. A histogram of the leak rates is shown in Fig. 2.15. These data indicate that good subassemblies were being fabricated because the mean of 2.3×10^{-7} is less than the construction specification of 6×10^{-7} std cm^3/s of helium.

A similar statistical analysis was performed on the measured leak rates for 28 sensor assemblies fabricated for SCTF-II. One hundred and twelve cable end seals were tested and gave a mean leak rate of 3.12×10^{-10} with a standard deviation of 6.03×10^{-10}. The end seal leak rates are plotted in Fig. 2.16. The low leak rates indicate that excellent cable seals were produced.

A helium leak test of 43 subassemblies installed in 14 film probes and 11 impedance probes yielded a mean leak rate of 3.5×10^{-9} std cm^3/s and a standard deviation of 7.7×10^{-9} (see Fig. 2.17). This data infers that very good cermet-to-metal seals were obtained on the subassemblies.

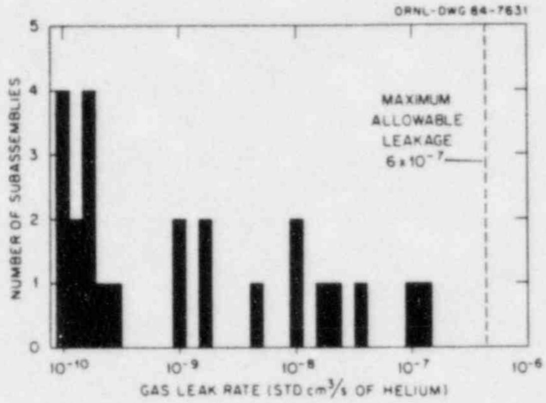


Fig. 2.15. Gas leakage distribution for subassemblies cermet to metal seals--CCTF-II.

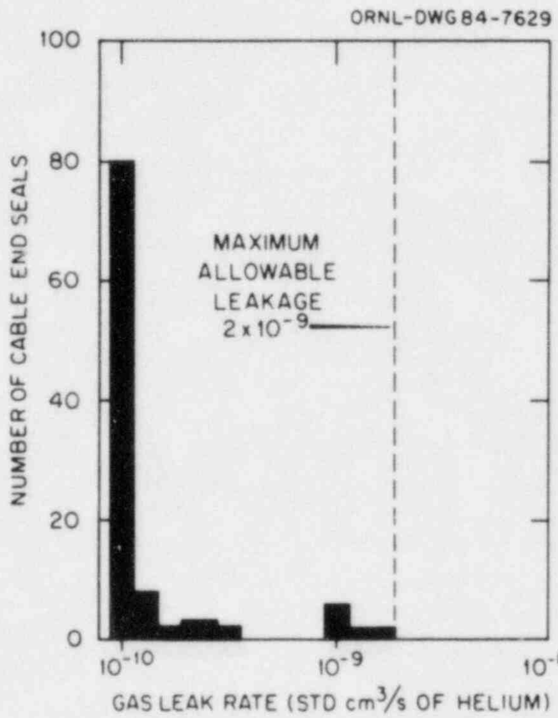


Fig. 2.16. Gas leakage distribution for triaxial cable end seals--SCTF-II.

2.6 THERMOCOUPLES

A chromel-alumel thermocouple with a stainless steel sheath was placed at each sensor location. The thermocouple was 1 mm in diameter with a nominal time response of 0.25 s. The thermocouple was attached to the

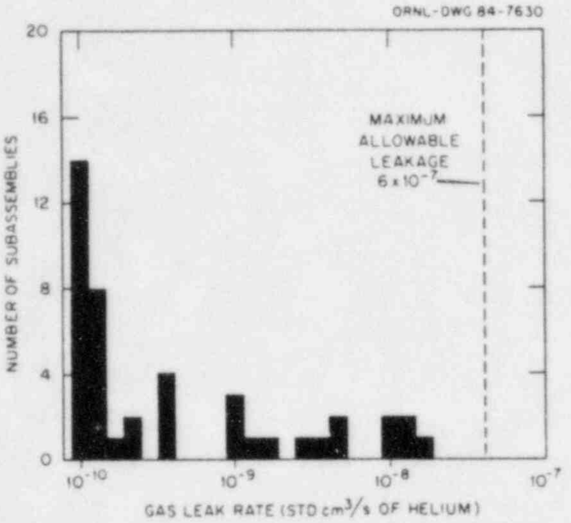


Fig. 2.17. Gas leakage distribution for subassemblies cermet to metal seals--SCTF-II.

surface by induction brazing in a helium atmosphere. The thermocouple braze was inspected visually and by helium pressurization and alcohol immersion. These brazed joints proved to be very successful, both from leak tightness and electrical-integrity standpoints.

3. SHIPMENT AND INSTALLATION AT A FACILITY

After final assembly and seal-welding the exposed signal cable end to prevent moisture absorption by the cable insulation, the probes were prepared for shipment to the foreign facilities. The sensors were carefully placed into specially designed wooden shipping crates. These crates were made to protect the instrument from rough handling and to support the sensors to prevent twisting or sagging that might damage a seal.

Upon arrival in a foreign country, the instruments were visually inspected for any damage. All deliveries for the four facilities arrived in good condition. The instruments were then shipped to the appropriate facility for installation.

At the facility site, leak tests were not possible, but electrical integrity checks were made. At this point, the electrical tests were most important because seal leaks could not be repaired in the field and the data quality depended on the electrical signal quality. Electrical parameter measurements were made and recorded when the instruments were uncrated. The instruments were installed into their appropriate positions and their signal cables fed out through the vessel walls.

At this point, the signal cable seal weld was cut off and the final terminations were made. This final termination consisted of connecting the triaxial cable to a connector which linked to a soft cable that ran to the signal-conditioning electronics. After making the connection to the soft cable connector, the connection was potted with epoxy to prevent moisture from entering the triaxial cable. Before the potting was done, a final set of cable electrical parameters were measured.

Of the 142 sensors installed in the four test facilities, all but two were functioning at completion of installation. The two inoperable sensors had sustained severe damage when they were accidentally dropped during installation.

4. SENSOR SURVIVABILITY

Periodically, electrical cable parameters were measured for the installed sensors. The cable data enabled an evaluation of the survivability of the probes as a function of time and number of tests performed. The number of official tests that the instruments were subjected to was well documented. However, before any "official" tests were run and between "official" tests, numerous thermal cycles occurred in the test facilities. These thermal cycles were generated by partial system checkout tests, hydro tests, and shakedown tests during facility checkout. So, although sensor failure sometimes occurred after a few recorded experiments, the sensor had been thermally cycled twenty or more times. The specifications called for the probes to survive 25 thermal shocks.

The track record of the sensor thermocouples was excellent. Although the probe thermocouples were located throughout the vessel, with some in extreme environments, their performance was most encouraging. For the 142 sensors installed in the four facilities, all thermocouples functioned and are functioning up to specifications.

4.1 SCTF-I

The sensor survival history for SCTF-I is tabulated in Tables 4.1 to 4.5. ORNL delivered a total of 46 measuring stations for SCTF-I. In February of 1981, ORNL learned of an unexpected corrosion problem with the triaxial cable sheaths. By the end of the shakedown test in April 1981, 9 of the 46 measuring stations were inoperable and 14 additional stations were marginal (Table 4.1). Marginal status means that the sensor is able to produce data, but if the cables degrade any further, the station will become unusable. The triaxial cables had corroded badly on these failed and marginal measurement stations. Investigation into the cable problem uncovered a stress-corrosion failure mode caused by high chloride ion concentration in the Conax grafoil sealing material. The Conax seals were used where the sensor signal cables exited the vessel. By the completion of the fifth test, Run 509, the sensor status had changed significantly (Table 4.2). Only ten stations were operable with an additional four as marginal. In October 1981, six core wall film modules were replaced. After Run 514, ten tests, the status was as listed in Table 4.3. A total of 18 sensors produced some useful data with 28 stations totally inoperable. After three more tests (after Run 517), the tally on sensor operability is shown in Table 4.4, which shows that only six wall film probes were functioning well, and an additional ten were able to produce some usable data. The final status recorded is listed in Table 4.5. This status was taken in September 1982, after 20 official tests were conducted. At this time sixteen stations could produce meaningful data while 30 stations had failed.

Table 4.1. ORNL sensor status for SCTF-I after the shakedown test (April 24, 1981)

Sensor type	Number installed	Good	Marginal	Bad
In-core flag probes	8	3	3	2
In-core film probes	6	0	2	4
Wall film probes	14	5	6	3
Upper plenum structure film probes	6	3	3	0
Prong probes	8	8	0	0
String probes	3	3	0	0
Reference cond. probe	1	1	0	0
Total	46	23	14	9

Table 4.2. ORNL sensor status for SCTF-I after Run 509 (June 23, 1981)

Sensor type	Number installed	Good	Marginal	Bad
In-core film probes	6	0	0	6
In-core flag probes	8	0	0	8
Wall film probes	14	3	2	9
Upper plenum structure film probes	6	3	0	3
Prong probes	8	3	0	5
String probes	3	0	2	1
Reference cond. probe	1	1	0	0
Total	46	10	4	32

The mode of failure for these sensors was most probably a moisture leak into the signal cables near the sensor end. Moisture in the signal cables would cause a high loss value and make the probe impedance impossible to measure. For the moisture to enter the signal cable, a double seal had to break down: the seal at the sensor-surface interface and the cable end seal. It should be noted that most of the probe failure occurred in the core where the environment was most severe.

4.2 PKL-II

Twenty-five measuring stations were installed into the PKL-II test facility. Although this facility did not come on line till mid-1982, the ORNL sensors were the first production models completed in the fall of 1978. The sensor status just before the first "official" test is shown

Table 4.3. ORNL sensor status for SCTF-I after Run 514 (October 28, 1981)

Sensor type	Number installed	Good	Marginal	Bad
In-core film probes	6	0	0	6
In-core flag probes	8	0	0	8
Wall film probes*	14	10	0	4
Upper plenum structure film probes	6	3	0	3
Upper plenum prong probes	8	2	0	6
String probes	3	0	2	1
Reference cond. probe	1	1	0	0
Total	46	16	2	28

*Six wall film probes modules were replaced in early October 1981.

Table 4.4. ORNL sensor status for SCTF-I after Run 517 (December 17, 1981)

Sensor type	Number installed	Good	Marginal	Bad
In-core film probes	6	0	0	6
In-core flag probes	8	0	0	8
Wall film probes	14	6	3	5
Upper plenum structure film probes	6	0	3	3
Prong probes	8	0	0	8
String probes	3	0	3	0
Reference cond. probe	1	0	1	0
Total	46	6	10	30

in Table 4.6. Because of the time the sensors sat in a humid environment and the thermal cycles run, several probes had failed. After the completion of six tests, the status was as tabulated in Table 4.7. Most of the inoperative sensors were located in the core where the worst thermal conditions exist. The failure mechanism was surmised to be moisture in the signal cables the same as described in the SCTF-I sensors.

4.3 CCTF-II

Thirty-nine sensors were installed at CCTF-II in September of 1981 with two bad in-core flag sensors caused by installation problems (dropped

Table 4.5. ORNL sensor status for SCTF-I (September 1982)

Sensor type	Number installed	Good	Marginal	Bad
In-core film probes	6	0	0	6
In-core flag probes	8	0	0	8
Wall film probes	14	5	4	5
Upper plenum structure film probes	6	0	3	3
Upper plenum prong probes	8	0	0	8
String probes	3	0	3	0
Reference cond. probe	1	0	1	0
Total	46	5	11	30

Table 4.6. ORNL sensor status for PKL-II (June 30, 1982)

Sensor type	Number installed	Good	Marginal	Bad
In-core flag probe	8	4	0	4
In-core prong probes	4	2	0	2
Wall film probes	4	4	0	0
Upper plenum flag probe	4	2	0	2
String probe	3	3	0	0
Reference cond. probe	2	2	0	0
Total	25	17	0	8

Table 4.7. ORNL sensor status for PKL-II (April 1983)

Sensor type	Number installed	Good	Marginal	Bad
In-core flag probes	8	0	0	8
In-core prong probes	4	2	0	2
Wall film probes	4	3	0	1
Upper plenum flag probes	4	1	0	3
String probes	3	3	0	0
Reference cond. probe	2	2	0	0
Total	25	11	0	14

during installation). After the first shakedown test, the tally of the ORNL instrumentation is shown in Table 4.8. After six runs, the status had not changed. By September of 1982 (6 tests later), the survivability record stood as shown in Table 4.9. At this point, 25 of the 39 measuring stations could produce valid data. By May 1983, ten tests had been completed and the sensor status was as listed in Table 4.10. Twenty-five probes were still functioning. The final status taken was in October 1983 (after 20 tests). This status showed that 23 stations could give useful information (Table 4.11). The high loss values recorded for the failed sensors again indicated moisture pickup in the cables.

Table 4.8. ORNL sensor status for CCTF-II after Run 053 (March 1982)

Sensor type	Number installed	Good	Marginal	Bad
In-core flag probes	24	19	0	5
Upper plenum structure film probes	4	3	1	0
Hot leg film probe	4	4	0	0
Prong probes	4	4	0	0
String probes	2	2	0	0
Reference cond. probe	1	1	0	0
Total	39	33	1	5

Table 4.9. ORNL sensor status for CCTF-II (September 1982)

Sensor type	Number installed	Good	Marginal	Bad
In-core flag probes	24	8	2	14
Upper plenum prong	4	4	0	0
String probes	2	2	0	0
Hot leg film probes	4	3	1	0
Film probes	4	2	2	0
Reference cond. probe	1	1	0	0
Total	39	20	5	14

4.4 SCTF-II

Oak Ridge National Laboratory placed 32 sensors into SCTF-II in August 1983. At the completion of the installation phase, all 32 probes were functioning as expected (Table 4.12).

Table 4.10. ORNL sensor status for CCTF-II after Run 060 (May 1983)

Sensor type	Number installed	Good	Marginal	Bad
In-core flag probes	24	5	6	13
Upper plenum structure film probes	4	3	1	0
Hot leg film probes	4	3	1	0
Prong probes	4	4	0	0
String probes	2	0	1	1
Reference cond. probe	1	1	0	0
Total	39	16	9	14

Table 4.11. ORNL sensor status for CCTF-II (October 1983)

Sensor type	Number installed	Good	Marginal	Bad
In-core flag probes	24	4	5	15
Upper plenum structure film probes	4	3	1	0
Hot Leg film probes	4	3	1	0
Prong probes	4	4	0	0
String probes	2	0	1	1
Reference cond. probe	1	1	0	0
Total	39	15	8	16

Table 4.12. ORNL sensor status for SCTF-II after installation (August 1983)

Sensor type	Number installed	Good	Marginal	Bad
In-core flag probes	4	4	0	0
In-core film probes	6	6	0	0
Wall film probes	14	14	0	0
Upper plenum prong probes	4	4	0	0
String probes	3	3	0	0
Reference cond. probe	1	1	0	0
Total	32	32	0	0

Following numerous system checkout tests that included thermal cycling of the vessel (and ORNL probes), a high temperature calibration test was performed. In addition to these experiments, several hydro tests were conducted. The instrumentation status after these runs but before an "official" test is listed in Table 4.13. For this stage in the test schedule, the probe status revealed the highest percentage of functioning sensors as compared to the other previous reflood test facilities. This result can be, at least partly, attributed to the excellent degree of seal leaktightness obtained during fabrication of these SCTF-II instruments.

Table 4.13. ORNL sensor status for SCTF-II after high-temperature acceptance test (December 1983)

Sensor type	Number installed	Good	Marginal	Bad
In-core flag probes	4	3	1	0
In-core film probes	6	4 1/2*	0	1 1/2*
Wall film probes	14	14	0	0
Upper plenum prong probes	4	4	0	0
String probes	3	2	1	C
Reference cond. probe	1	1	0	0
Total	32	28 1/2	2	1 1/2

*One of the two probe sensors was good.

5. SENSOR DATA QUALITY

The assessment of data quality can be done from two viewpoints. One way is to judge the data with respect to measurement limits, calibration values, and statistical values (e.g., standard deviation). The second method is to judge the data against other appropriate instrumentation values; for example, impedance-probe void fraction versus differential pressure cell-determined void fraction.

For the ORNL instrumentation, the first viewpoint assessment is easily accomplished. The sensor voltage output can be reviewed for correct magnitude and sign; steam-only and water-only calibration points can be checked; and statistical values can be studied for their reasonableness. The second viewpoint, however, is not such a simple task. Comparing the sensor output to expected values can be done without much trouble. Is the void fraction between 0 and 1? Is the measured velocity physically possible? Is the film thickness a positive value? These questions can be easily answered, but comparing the results to other instrumentation data can be difficult. The reasons are as follows:

1. The ORNL instrumentation takes local measurements. Measurement volumes are very small. Most other instrumentation is global in nature with fairly large sampling volumes.
2. Many of the ORNL measurements are unique. For instance, film thickness and film wave velocity are not measured by any other instruments in the reflood test facilities.

So, to assess the ORNL instrumentation, the data are reviewed for reasonableness as compared to measurement ranges, calibration values, and statistical quantities. Furthermore, the output data are judged on physical credibility and against either similar instrumentation or events occurring during a test (e.g., liquid level increases, core quench, etc.).

5.1 SCTF-I: SYSTEM PERFORMANCE

As noted earlier, many sensors failed because of stress corrosion in SCTF-I. Unfortunately, all the in-core flag and in-core film probes were lost before any data were obtained. Some results were obtained from the wall film probes in the core and upper plenum regions; data were also obtained from the upper plenum prong probes.[5]

Film probes measured film thickness and film wave velocities. In general, the film thickness measurements were consistent between probes

in similar locations and the magnitude and changes in thickness correlated to events during the reflood experiment. The onset of a film on the core wall began at the beginning of reflood (water entering the core), approximately 120 s. Illustrations of these points are shown for core wall and upper plenum structure probes in Figs. 5.1 to 5.4. Direct comparisons to other instruments were not possible since no other film-sensing probes were installed in the reflood facilities. Film velocity results were not very promising. The electrolysis potential probe was too sensitive to other factors such as local fluid conductivity to produce a usable film velocity measurement. Wave velocities showed a very poor coherence leading to no consistent or reliable value (Fig. 5.5). Coherence is an estimate of the signal sensed at one location and then the next. A high coherence infers that the perturbations sensed by one film sensor are generally measured by the second probe. Low coherence

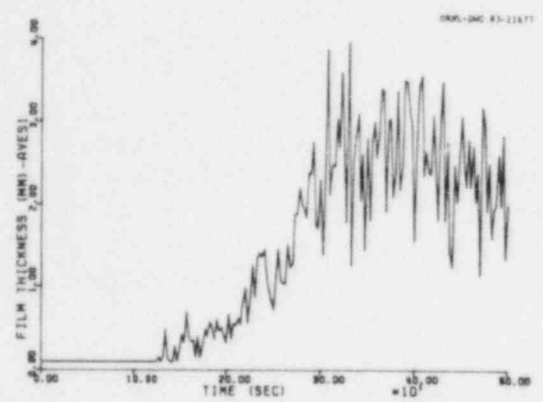


Fig. 5.1. Film thickness measurement (R1) for core wall film probe UP01E82 during Run 508.

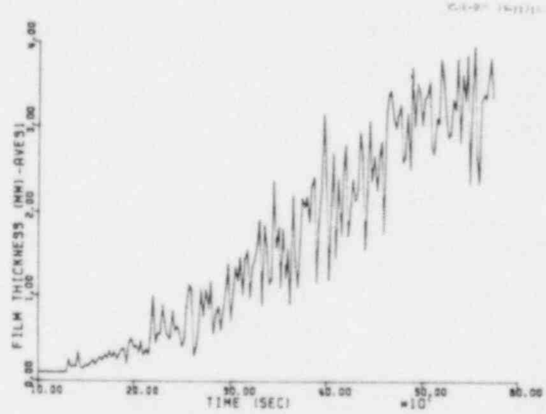


Fig. 5.3. Film thickness measurement (R1) for upper plenum structure film probe UP02L81 during Run 508.

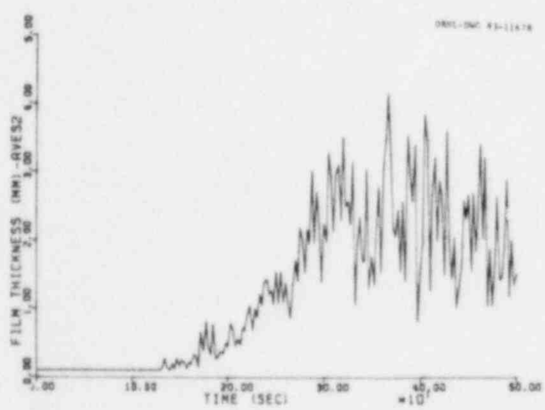


Fig. 5.2. Film thickness measurement (R2) for core wall film probe UP01E82 during Run 508.

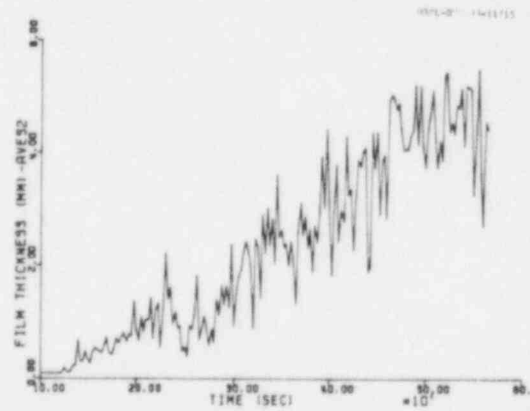


Fig. 5.4. Film thickness measurement (R2) for upper plenum structure film probe UP02L81 during Run 508.

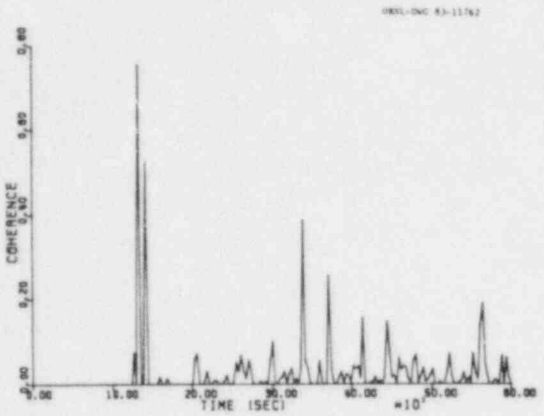


Fig. 5.5. Coherence for core wall film probe UP01E82 during Run 509.

(<0.1) indicates a significant amount of randomness between sensor levels. The low coherence for the film sensors was probably caused by cross flow and not by a faulty sensor or the measurement technique.

Upper plenum prong probes gave void fraction results consistent with each other and with flow events in the upper plenum. The consistency obtained between prongs at the same elevation in the upper plenum is shown in Figs. 5.6 and 5.7. Comparison to collapsed liquid level showed qualitative agreement but not quantitative agreement. These results were not unexpected since the collapsed liquid level was measured by very global differential pressure (dP) transducers. The measurement volume ratio of dP cells to prong probes is approximately 10^7 to 1. Prong probe data did show agreement in magnitude and trend with INEL-supplied upper plenum gamma densitometers. The densitometers were choral measurements at one elevation and thus, not as global as measurements as the collapsed liquid level (measurement volume ratio of 10^3 to 1).

The downcomer was blocked by a plate for the tests analyzed by ORNL. Therefore, no meaningful data were recorded. The string probes, however, were functional during the entire test series.

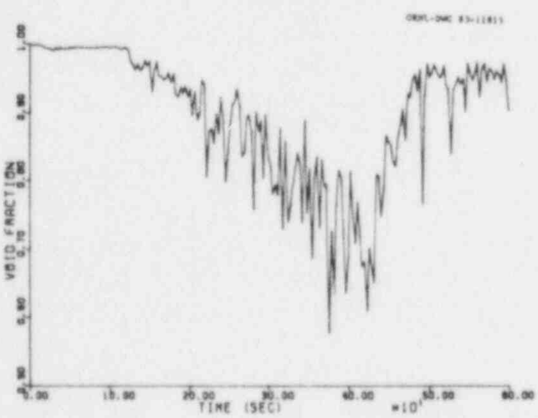


Fig. 5.6. Void fraction values for upper plenum prong probe UB02L21 during Run 509.

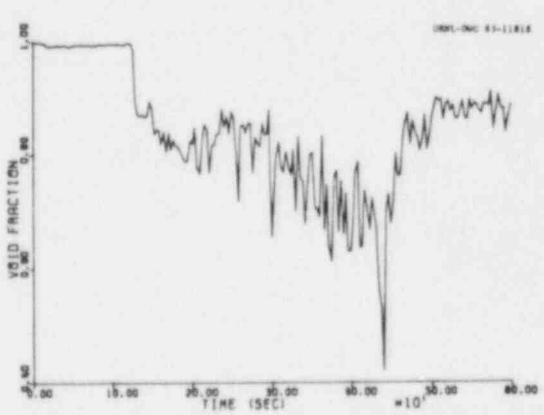


Fig. 5.7. Void fraction values for upper plenum prong probe UB02L41 during Run 509.

5.2 PKL-II: SYSTEM PERFORMANCE

ORNL sensors, similar in design and function, were installed in various locations within the test vessel.[6] ORNL sensor data have been analyzed for two tests from PKL-II, Test IIA-9 and IBSIIA-6. Test IIA-9 was a 200% cold leg break simulation with cold leg injection only. IBSIIA-6 was also a 200% cold leg break but had cold and hot leg injection as modes of emergency core cooling (ECC) injection.

The film probes gave reasonable film thickness values (Figs. 5.8-5.9). The film wave velocity measurement was not very successful. Once again low coherence was the cause.

In-core flag and prong probes produced mixed results. Comparison of a void fraction measurement for prong probe IP7UM and IP6OM with a dP measurement showed good results prior to rewetting of the impedance probe (Figs. 5.10 and 5.11). After rewetting the impedance gave a lower void fraction than did the dP transducer. This result was probably caused by a film on the unheated impedance probe rod producing a locally lower void fraction than that sensed by the more global dP transducer. Steam velocity measurement values by IP6OM showed good agreement with a turbine meter 10 mm above the tie plate (Fig. 5.12).

Upper plenum flag probes gave fair (void fraction) results. The flow seemed to be very oscillatory in the upper plenum and caused the void

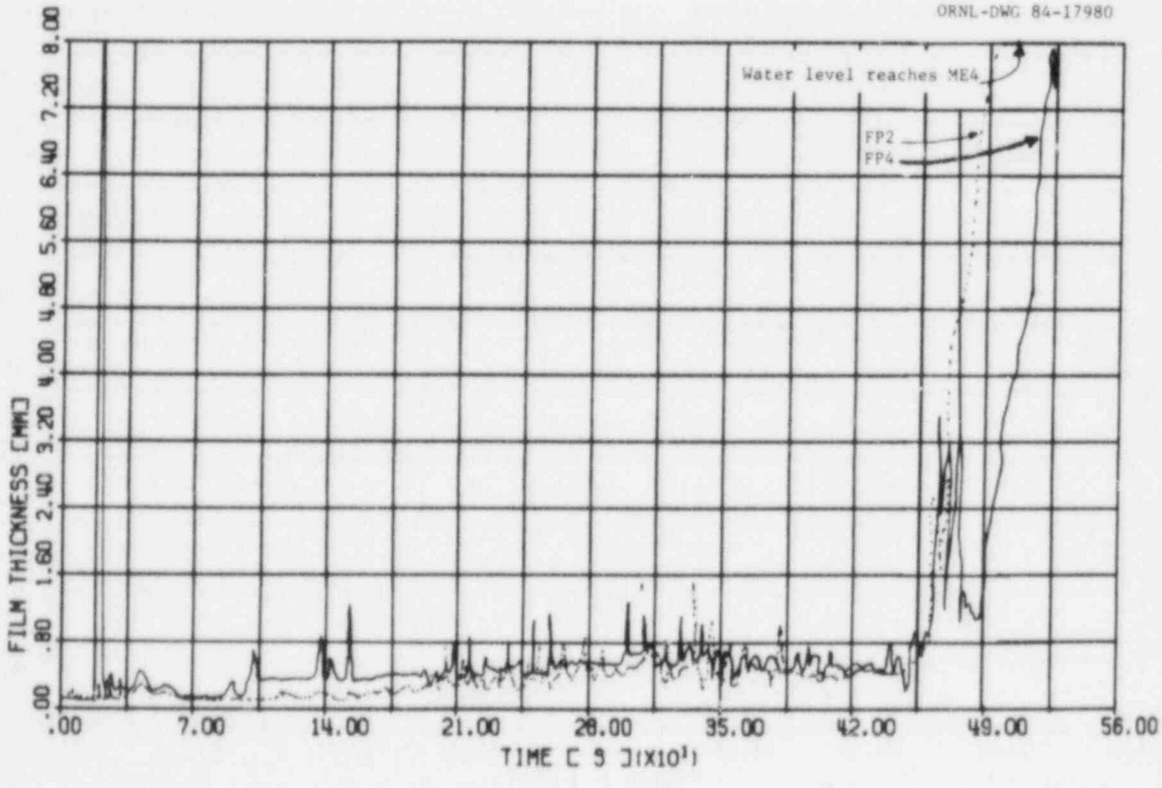


Fig. 5.8. Comparison of film thickness measurement for film probes FP4 and FP2 during Run PKL II A-9.

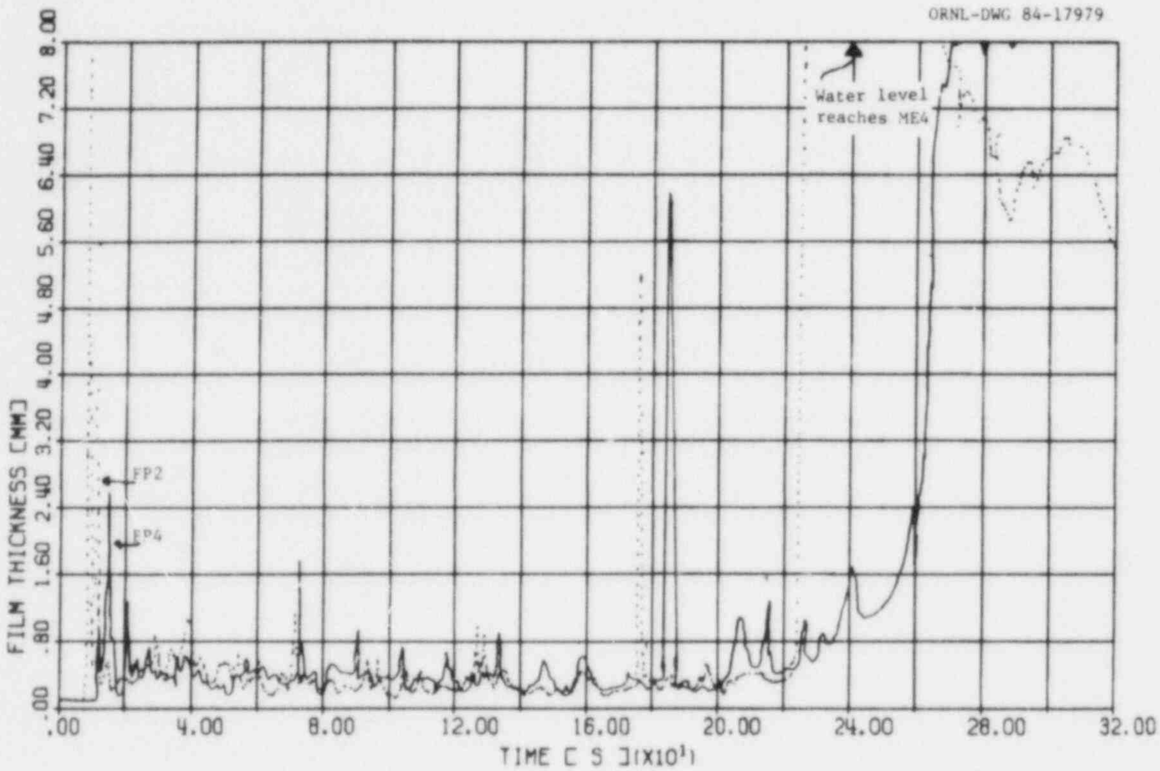


Fig. 5.9. Comparison of film thickness measurement for film probes FP4 and FP2 during Run PKL II A-6.

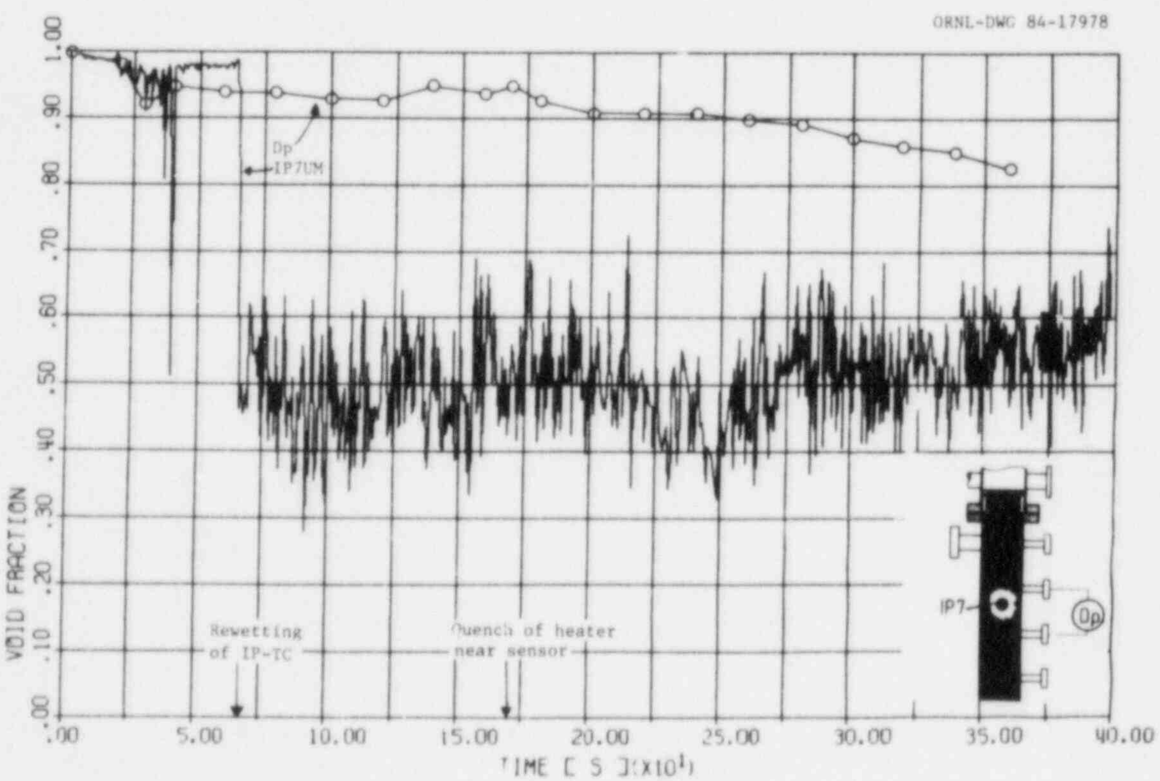


Fig. 5.10. Comparison of void fraction measurement for in-core prong probe IP7UM and a dP transducer during Run PKL II A-9.

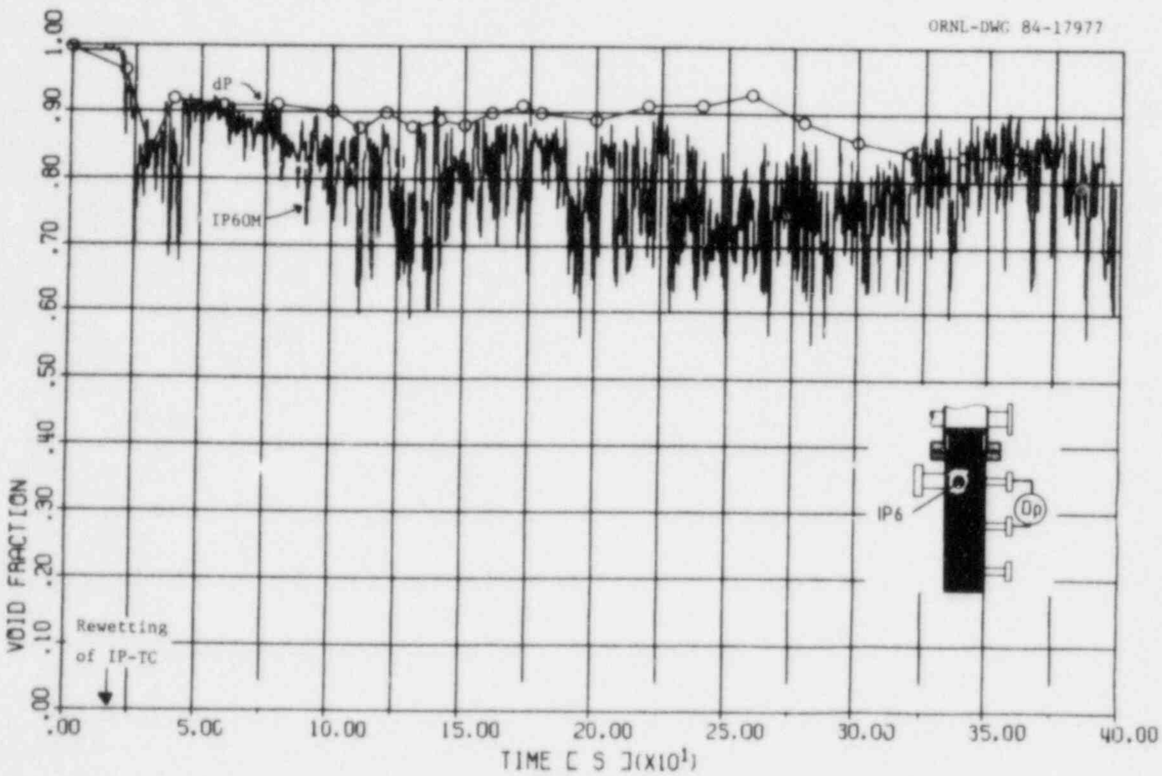


Fig. 5.11. Comparison of void fraction measurement for in-core prong probe IP60M and dP transducer during Run PKL-II A-9.

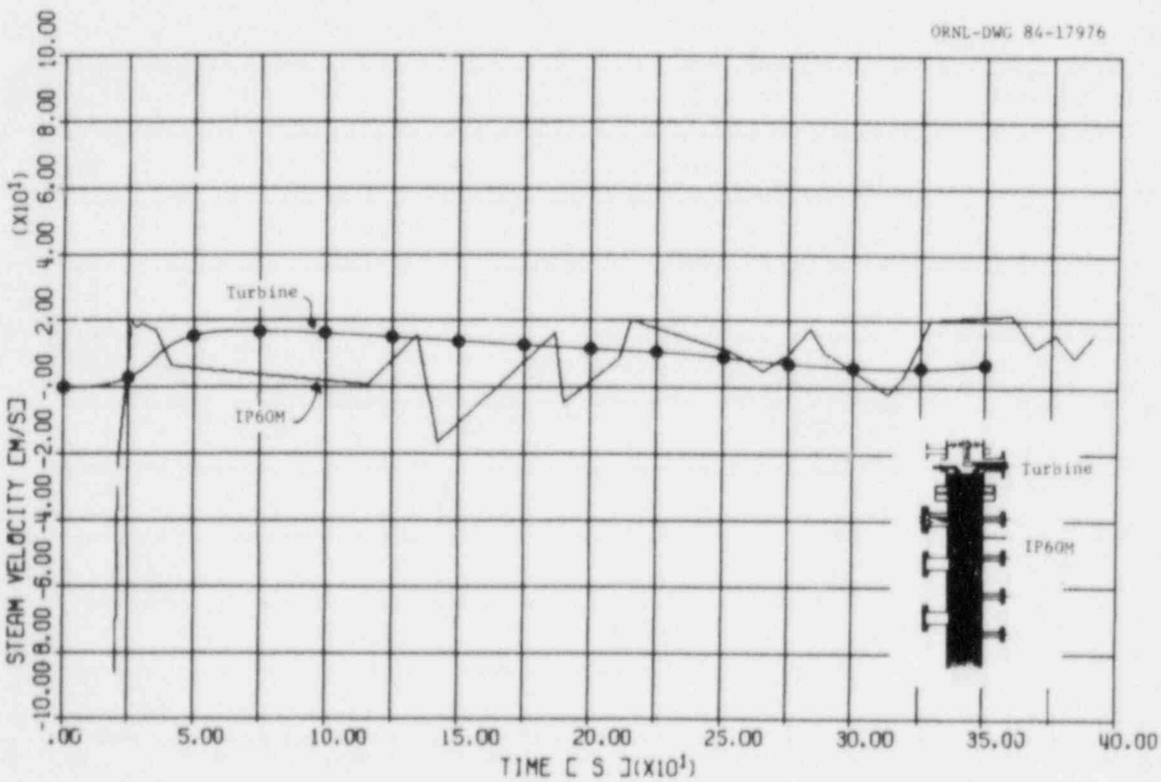


Fig. 5.12. Comparison of steam velocity measurement for in-core prong probe IP60M and a turbine meter during Run PKL-II A-9.

fraction data quality to be reduced. Using a criterion that at least 50% of the data must be good for each averaging interval, many points were found to be "bad." The results of this data validation are shown in Fig. 5.13. Very low coherence results in no velocity data from the upper plenum flag probe.

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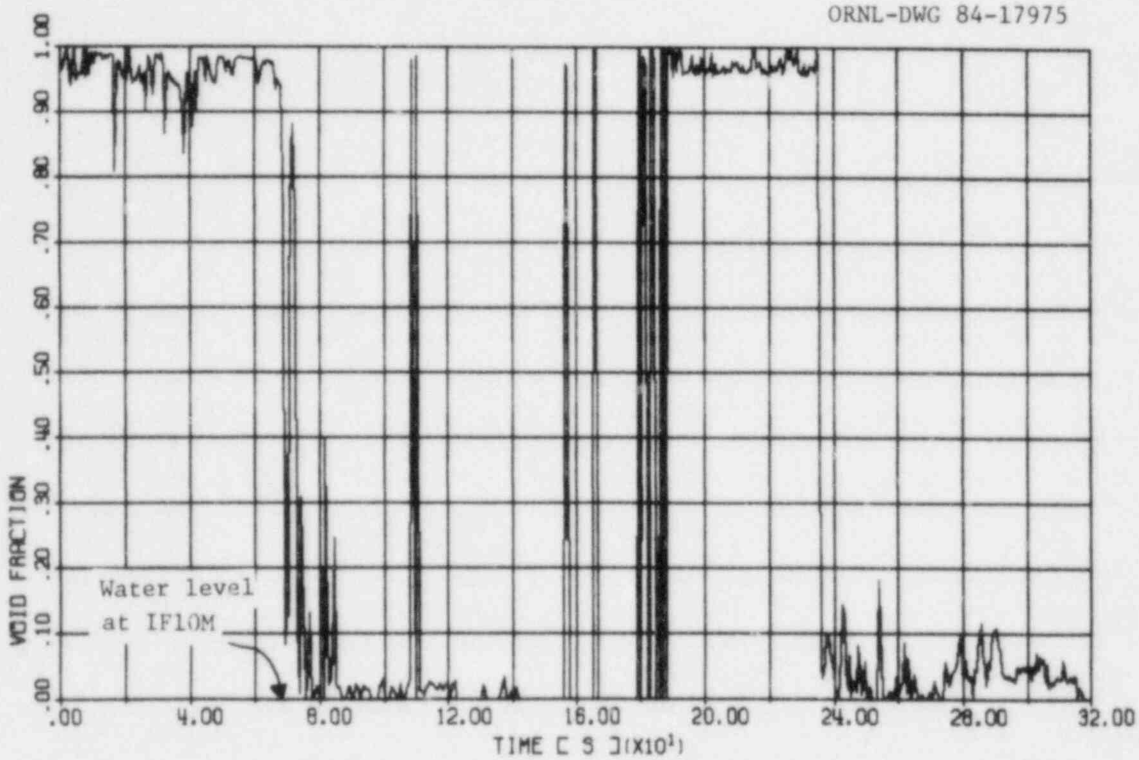

Fig. 5.13. Void fraction measurement for upper plenum flag probe IF10M with data qualification during Run PKL-II A-6.

The string probe data were difficult to analyze because of the amount of water on the probe frame and cermet at the beginning of the test (Fig. 5.14). All three string probes showed an initial void fraction of 0.60 to 0.70. This can be corrected somewhat by changing some software parameters. The results of this typed correction is shown in Fig. 5.15. Usable velocity information was not obtained from any of the string probes. This poor performance may have been caused by the oscillatory flow in the upper plenum.

5.3 CCTF-II: SYSTEM PERFORMANCE

Four reflood tests have been analyzed for the ORNL-CCTF instrumentation. Detailed results will be given in an upcoming report. Some general conclusions will be given in this section.

For the in-core flag probes, void fraction results were consistent for probes at the same core level and agreed in trend with thermal-hydraulic conditiors in the core (Figs. 5.16-5.18). Some of these conditions were initial droplet flow, local rod quench, and a substantial period of slug-like flow. Flow velocities in the core could not be compared to other instrumentation to judge reasonableness, but the range of values measured was within expected limits of 0 to 15 m/s (Fig. 5.19).

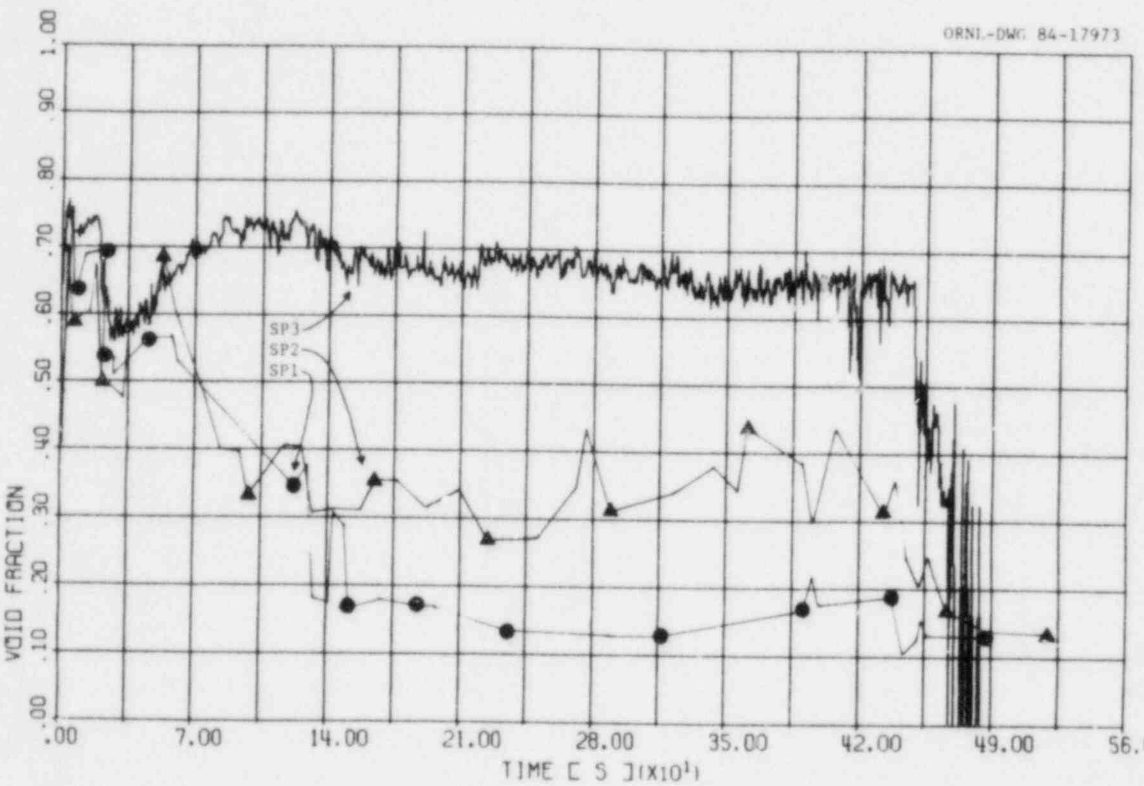

Fig. 5.14. Comparison of void fraction measurement for string probes SP1, SP2, and SP3 during Run PKL-II A-9.

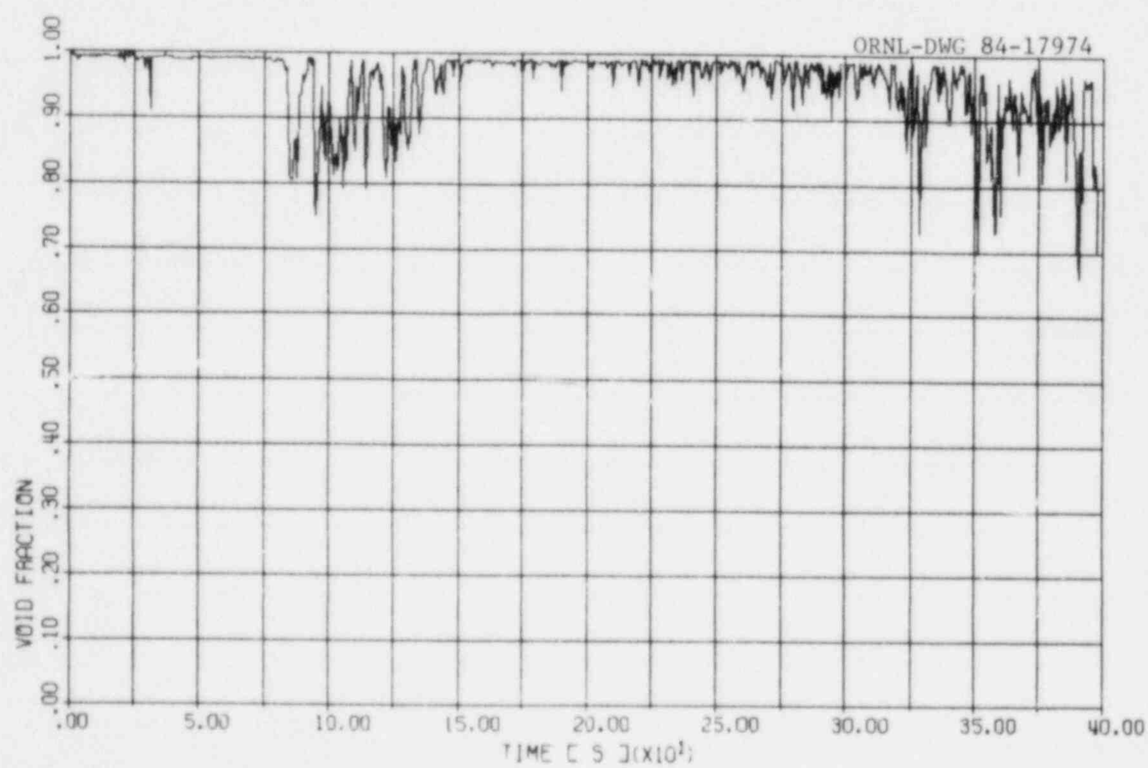

Fig. 5.15. Void fraction measurement for string probe SP3 using modified parameters during Run PKL-II A-9.

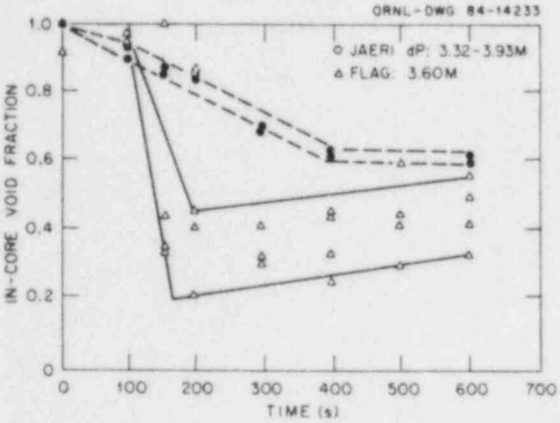

Fig. 5.16. In-core void fraction comparison between flag probes at the 3.6-m level and JAERI dP sensors covering the range of 3.32 to 3.93 m during CCTF-II Run 053.

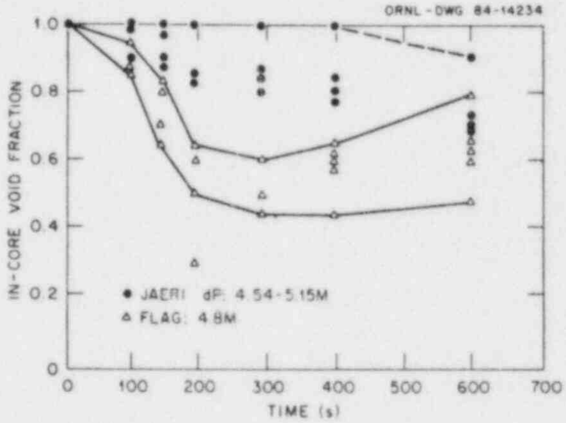

Fig. 5.18. In-core flag probe NB19NB2 void fraction with thermal-hydraulic core conditions noted during CCTF-II Run 055.

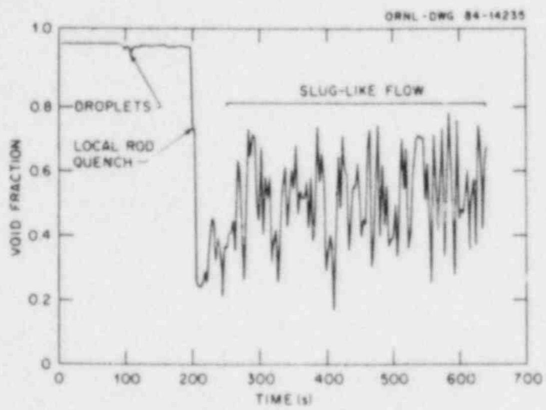

Fig. 5.17. In-core void fraction comparison between flag probes at the 4.8-m level and JAERI dP sensors covering the range of 4.54 to 5.15 m during CCTF-II Run 053.

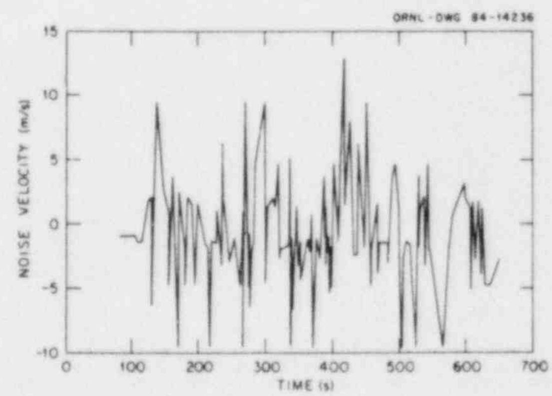

Fig. 5.19. In-core flow velocities as measured by a flag probe NB07NB1 during CCTF-II Run 055.

Figures 5.20 and 5.21 illustrate typical film thickness values obtained from the hot leg film probes. The upper pipe sensors did not measure a film during the entire test (Fig. 5.20), and the lower probes "saw" only a very thin film for part of the test (Fig. 5.21). The upper plenum structure film sensors agreed within modules, at similar elevations, and with flow events in the upper plenum. These points are shown in Fig. 5.22 through 5.24, respectively.

Upper plenum prong probes measured the fluid phenomena occurring during the test very well. These sensors showed the first presence of liquid

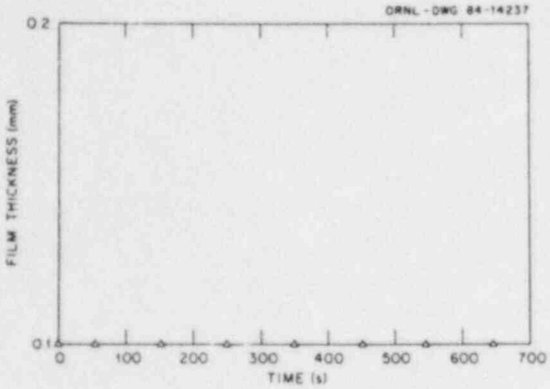

Fig. 5.20. Upper pipe film probe NP01H film thickness measurement in a hot leg during CCTF-II Run 055.

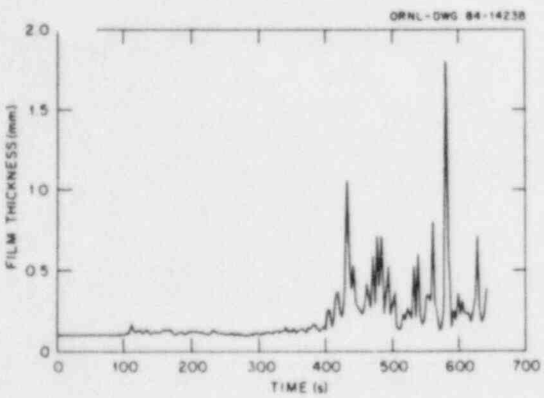

Fig. 5.21. Lower pipe film probe NP02H film thickness measurement in a hot leg during CCTF-II Run 055.

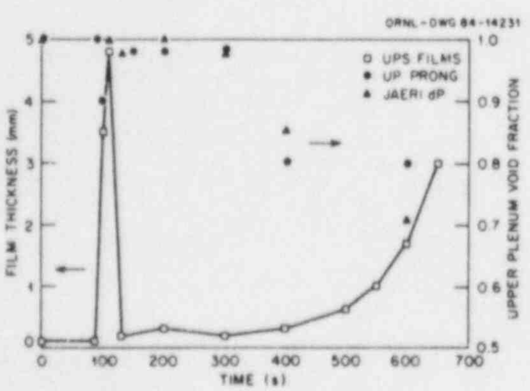

Fig. 5.24. Film thickness measurement for an upper plenum structure film probe compared to an upper plenum prong probe and JAERI dP sensor during CCTF-II Run 053.

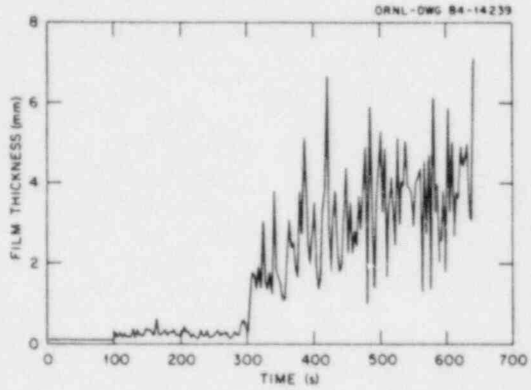

Fig. 5.22. Film thickness measurement for an upper plenum structure film probe NP19NI1 (AVES1) during CCTF-II Run 055.

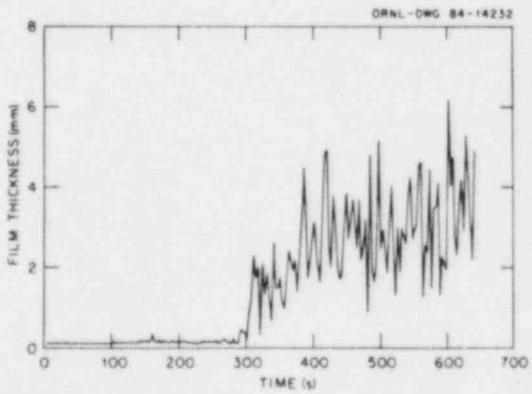

Fig. 5.23. Film thickness measurement for an upper plenum structure film probe NP19NI1 (AVES2) during CCTF-II Run 055.

and the void fraction stratification in the upper plenum (higher α with increasing elevation). The lower-level prong probes agreed very well with upper plenum JAERI dP cells. These items are shown graphically in Figs. 5.25 and 5.26.

The string probes were located in front of vent valves in the upper plenum. For the tests analyzed, the valves were blocked. This fact lead to very high void fractions in the vicinity of the vent valves. The void fraction measured by the string probes agreed with this as shown in Fig. 5.27.

The data quality for CCTF-II was judged to be very good for both impedance probes (void fraction and flow velocity) and film probes (film thickness). Once again film velocities were not measured with any degree of success. As with SCTF-I, the problems lie in the flow conditions and not with the sensor status.

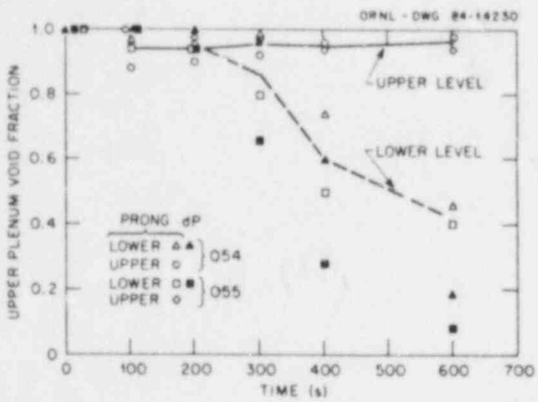

Fig. 5.25. Upper plenum prong probe void fraction measurements for both elevations during CCTF-II Runs 054 and 055 compared with a JAERI dP transducer measurement.

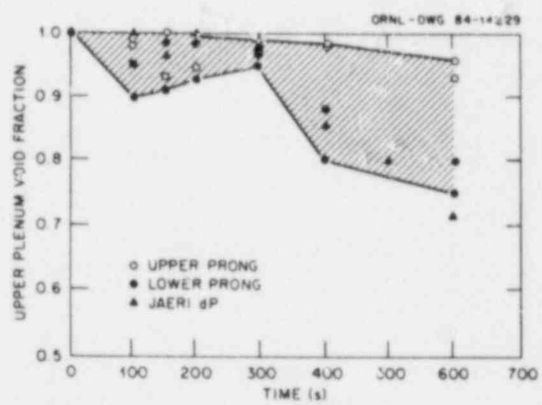

Fig. 5.26. Comparison of void fraction measurement for upper plenum prong probes and JAERI dP transducers during CCTF-II Run 053.

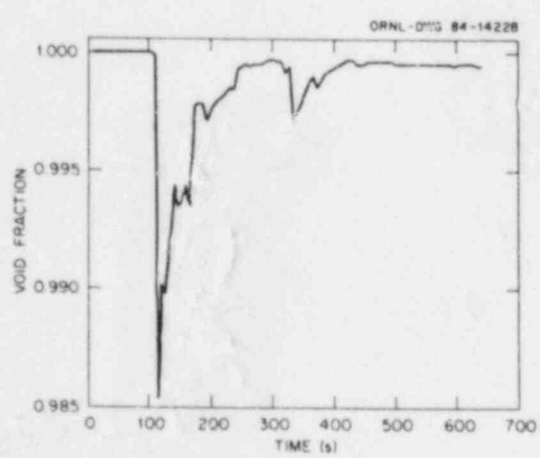

Fig. 5.27. Vent valve string probe NSU6NV1 void fraction measurement at a blocked vent valve during CCTF-II Run 053.

5.4 SCTF-II: SYSTEM PERFORMANCE

At the time this report was written, SCTF-II had just begun its initial test series and data were not yet available from any of the instrumentation.

6. SIGNAL-CONDITIONING ELECTRONICS

Signal-conditioning electronics were developed for both impedance-type sensors and the film probes. Depending on the particular sensor, some variations in the electronics were required. For example, wall film probes measured film thickness using the ratio of output from two "D" shaped electrodes while in-core film probes utilized an electrode-to-ground circuit configuration to measure film thickness.

The basic principles of operation for the impedance-type signal-conditioning electronics are explained below. The signal-conditioning electronics provide one analog output signal proportional to the magnitude of the probe impedance and another analog output proportional to the angle or phase of the probe impedance. The total electrical circuit can be divided into two major parts. One part, the Roberts loop,* generates the analog signal proportional to the magnitude of the probe impedance. In the Roberts loop, the probe is excited by a 100-kHz signal and is arranged in the feedback of a voltage control circuit. The output voltage that drives the probe acts to maintain a constant current through the probe and is thus proportional to probe impedance. The circuit diagram and more details of the operation of the Roberts loop are contained in *AIRS Electronics System*, Part F.[7] The second major portion of the system is the phase detection circuit,[7] which takes the probe signal and converts it to a pulse train. The width of this pulse train is proportional to the phase difference between the probe signal and a reference signal. The reference signal is provided by a 100-kHz oscillator. The phase signal is integrated and displayed as an analog output.

The film-thickness electronics operated as follows.[8] The electronic circuit is affected by both the electrode-to-electrode conductance and the electrode-to-ground conductance. (Because the electronics operates at a low frequency (2 kHz) and a liquid film is relatively high in conductivity, the conductance component dominates the probe signal. For all practical purposes, the capacitive terms are negligible.) Because of the different electrode-to-electrode and electrode-to-ground spacing, the effects of liquid conductivity are effectively cancelled out. The output ratio of electrode-to-electrode divided by electrode-to-ground is a function of film thickness only. An oscillator delivers a 2 kHz voltage which is applied to the inner sheath to minimize stray capacitance in long cables.

The electrolysis potential electronic module uses a 100-V dc source, which is applied across the electrodes. The current flow is sensed

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*Designed by M. J. Roberts, a staff member at ORNL.

through a precision resistor and is amplified and transmitted through a low-pass filter. Current from the electrosis process is correlatable to a film velocity.

For the sensors used in the four reflood test facilities, a total of 160 electronic modules were fabricated. With the exception of a few minor repairs the electronic systems at all the facilities have functioned extremely well. By using the ORNL-provided repair/troubleshooting manual, most of the minor repairs could be made by facility personnel.

Overall, the electronic/signal conditioning systems have been an unqualified success.

7. CONCLUSIONS

Oak Ridge National Laboratory instrumentation was able to give useful, meaningful data during refill-reflood test experiments. In fact, for the first time two-phase flow measurements of velocity and void fraction were made in an electrically heated core. In addition, velocity and void fraction data were obtained from sensors in the upper plenum and the downcomer. Film thickness measurements were made on internal surfaces in the core, upper plenum, and hot legs.

Other accomplishments achieved included development of a ceramic-metal (cermet) to be used as an electrical insulator and seal with the sensor. An insulator that could withstand the environmental conditions that occurred during the experiments was not available commercially. The AIRS program developed this cermet within one year of program inception. Also, sensitive, stable, and reliable signal-conditioning electronics were developed to measure small probe impedances in the presence of large cable capacitances and an extremely noisy environment. The final achievement was the establishment of fabrication techniques to build the required sensors. These techniques were high-temperature brazing, laser welding, and joining of components with widely different thermal coefficients of expansion.

Although some sensor failures were experienced in all the facilities, considering the severe environment, geometrical constraints and time limitations (13 months from program conception to delivery of the first sensors) the performance was very satisfactory. ORNL instrumentation gave valuable data that were useful in producing a better understanding of simulated LOCAs in refill-reflood test facilities.

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13. ABSTRACT (200 words or less)

Instrumentation for making two-phase measurements in experimental refill-reflood test facilities was developed by Oak Rige National Laboratory (ORNL) through the Advanced Instrumentation for Reflood Studies (AIRS) program. These unique instrumentation systems were designed to survive the severe in-vessel environmental conditions that exist during a simulated pressurized water reactor loss-of-coolant accident (LOCA). The measurements include two-phase flow velocity, void fraction, and film thickness and velocity, and are required for better understanding of reactor behavior during LOCAs. The adequacy (survivability and data quality) of the instrumentation systems installed in four experimental reflood test facilities is assessed. Signal conditioning electronics and sensor thermocouples functioned extremely well. For the first time, two-phase flow measurements were made in-core during a simulated LOCA. Because of the harsh environment and geometrical constraints, some sensor failures were considered likely; the number actually failing in service was within expectations. An exception to this record occurred in the Slab Core Test Facility -- Core 1. A chloride-ion stress corrosion problem destroyed signal cables at the vessel seal for most sensors. This problem was corrected by changing the sealant material at the vessel penetration in the subsequent facilities. Overall, the performance of the instrumentation was very satisfactory yielding valuable data during simulated LOCAs in refill-reflood test facilities.

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