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A Unique Concept for Liquid Level and Void Fraction Detection in Severe Fuel Damage Tests

Prepared by R. D. Tokarz, S. L. Crowell, F. E. Panisko

Pacific Northwest Laboratory
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ABSTRACT

This report describes a direct-contacting liquid level and void fraction detection system that is being developed by Pacific Northwest Laboratory. The measurement technique could be used in the severe fuel damage tests that will be conducted at the Power Burst Facility, Idaho Falls, Idaho, and at the ESSOR reactor, Ispra, Italy. The detection system could also be retrofitted for commercial operating reactors to provide definitive thermal-hydraulic information. The technique can provide unambiguous, real-time data on liquid level and void fraction during normal reactor operation as well as during shutdown and accident conditions.

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This report describes a direct-contacting liquid level and void fraction detection system that is being developed by Pacific Northwest Laboratory. The measurement technique could be used in the severe fuel damage tests that will be conducted at the Power Burst Facility, Idaho Falls, Idaho, and at the ESSOR reactor, Ispra, Italy. The detection system could also be retrofitted for commercial operating reactors to provide definitive thermal-hydraulic information. The technique can provide unambiguous, real-time data on liquid level and void fraction during normal reactor operation as well as during shutdown and accident conditions.

SUMMARY

Pacific Northwest Laboratory (PNL) is developing a unique concept for detecting liquid level and void fraction conditions in pressurized condensable fluid. The detection system is a combination of state-of-the-art devices that amplify the differences in mass flow rate through the sensing system when conditions change within the fluid.

The basic concept of the sensing device is described, and the two main configurations--a single sensing orifice and multiple sensing orifices--are evaluated. Prototype testing of the device was conducted using a package steam generator and a single sensing orifice. Additional testing was done using a Freon void fraction generator and both single and multiple sensing orifices. From the results of the testing it appears that the liquid level detection system is capable of providing discrete and unambiguous real-time information on liquid level and an indication of the existence of a void fraction.

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Pacific Northwest Laboratory (PNL) is developing a unique concept for detecting liquid level and void fraction conditions in pressurized condensable fluid. The detection system is a combination of state-of-the-art devices that amplify the differences in mass flow rate through the sensing system when conditions change within the fluid.

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INTRODUCTION

Since the incident at Three Mile Island (TMI), the emphasis on fuel behavior test programs has shifted from large-break loss-of-coolant accidents (LOCAs) to small-break LOCAs. The occurrence at TMI clearly demonstrated that a small pipe break in a pressurized water reactor (PWR) coupled with instrumentation inadequacies and operator error can devastate a nuclear reactor core.

Severe fuel damage (SFD) programs in the United States and the European Common Market countries have been initiated to learn more about the effects of small-break accidents. Results from these test programs will probably have a far-reaching impact on future nuclear plant design and licensing criteria and should ultimately result in safer nuclear power plants that are either operated or controlled to preclude an accident similar to the one at TMI.

Pacific Northwest Laboratory (PNL)(a) is currently working under contract with the U.S. Nuclear Regulatory Commission (NRC) to design and fabricate two instrumented test assemblies for SFD studies to be conducted in the Power Burst Facility (PBF) at Idaho Falls, Idaho, by EG&G Idaho, Inc. PNL may also provide similar design and fabrication support and analytical services for the small-break LOCA tests to be conducted in the ESSOR reactor(b) at Ispra, Italy. These latter tests are sponsored by the European communities with some NRC support. Since it will be important to control the water level in the test assemblies, PNL is developing a unique system to detect liquid level and void fraction for possible use in the PBF and ESSOR.

This report first reviews the PBF and ESSOR test programs to provide necessary background information. The unique liquid level and void fraction sensing system that is being developed at PNL is then described. If used in PBF and ESSOR, this system could improve the quality of data collected and provide an additional measure of safety in SFD experiments. The device could also be installed in commercial PWRs and boiling water reactors (BWRs) to

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(a) Operated for the U.S. Department of Energy (DOE) by Battelle Memorial Institute.

(b) Super Sara Test Program (SSTP).

provide definitive thermal-hydraulic measurements. It is capable of providing discrete and unambiguous real-time readouts of liquid level and void fraction. Calculations that support the results of laboratory testing of the prototype device are also provided in the Appendix.

BACKGROUND

The test program that PNL is conducting for the PBF and the similar Super Sara effort are described in this section, and test objectives and requirements are discussed.

POWER BURST FACILITY TEST PROGRAM

The small-break LOCA tests planned for the PBF test program are all high-temperature SFD tests (see Table 1). The current plan calls for five tests with peak temperatures and heating rates targeted to exceed 2300K to obtain UO_2 dissolution by the molten Zircaloy cladding. Other test parameters include temperature rise rate, cladding cooldown rate, and rod internal pressure.

SUPER SARA TEST PROGRAM

The Euratom (EEC) test program includes 21 tests in both large- and small-break categories. The small-break phase of the program is further divided into three classifications that cover varying degrees of bundle blockage due to 1) fuel rod deformation, 2) Zircaloy cladding oxidation and subsequent bundle rubble bed formation, and 3) cladding melting, fuel dissolution, and subsequent bundle rubble bed formation by resolidification.

Recent changes have redefined the program with increased emphasis on tests at high temperatures where severe bundle damage will result. The original small-break test matrix is illustrated in Figure 1. The new emphasis will be directed toward Type 3 tests (see Table 2).

For type 3 tests, the system will be depressurized until ΔP across the cladding is ~0 MPa; and the rod cluster will gradually be uncovered until the desired peak cladding temperature is reached. The system will then be depressurized until the rods rupture. Extensive cladding deformation in the form of ballooning may occur prior to rupture for small strain rates as long as the circumferential temperature gradient is very small. Cladding inside diameter/outside diameter (ID/OD) oxidation will occur following rupture, and hydrogen

TABLE 1. Power Burst Facility Severe Fuel Damage Tests

Test	Rod Pressure, MPa	Peak Cladding Temperature, K	Cladding Temperature Rise, K/sec	Test Termination
SFD-ST	3	2300	0.5	Slow cooldown
SFD-1	3	2300	4.0	Slow cooldown
SFD-2	3	2300	0.5	Quench
SFD-3	3	2300	4.0	Quench
SFD-4	3	2300	(a)	Quench

(a) Same as Three Mile Island (TMI)-2.

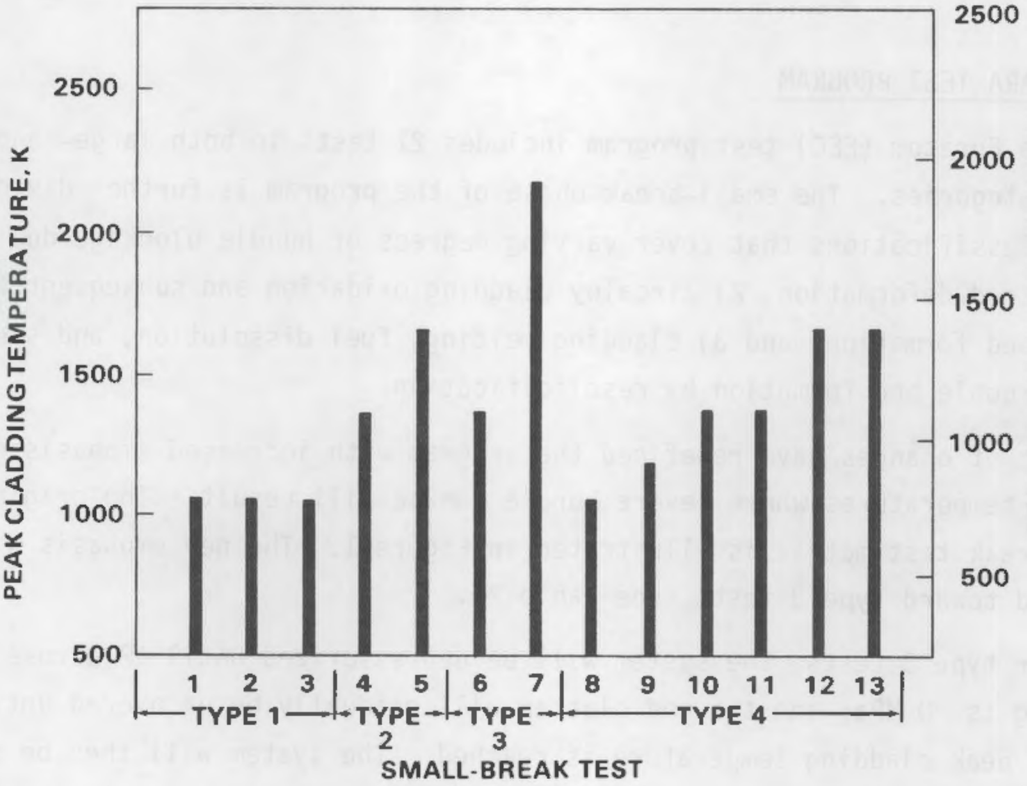


FIGURE 1. Original ESSOR Super Sara Peak Cladding Temperatures for the Small-Break Tests

TABLE 2. Redefined ESSOR Super Sara Small-Break Test Plan

Test No. and Type	Rod Behavior
1, 2, and 3[(a)] (Type 1)	Deformation and rupture; peak cladding temperature ≃ 1100K (same as original)
4 and 5 (Type 2)	Oxidation, embrittlement, fracturing, and fragmentation; peak cladding temperature ≃ 1600K (same as original)
6 and 7 (Type 3)	Deformation and rupture followed by ID/OD oxidation and fragmentation; peak cladding temperature ≃ 1900K (different from original)
8[(b)] through 13 (Type 4)	Simultaneous deformation, oxidation, embrittlement, melting, fracturing, and fragmentation; peak cladding temperature ≃ 2300K (different from original)

(a) System pressure oscillating for Test 3.
(b) Rods preoxidized for Test 8.

sorption on the ID could occur. Hydride formation will depend on the cooldown rate. If the oxidation embrittlement is severe, the cladding may fragment during cooling.

TEST OBJECTIVES AND REQUIREMENTS

The PBF and Super Sara test programs are both designed to achieve the following basic objective:

- to characterize fuel rod damage and bundle coolability in terms of cladding oxidation and melting, UO_2 dissolution, movement, freezing, and fuel rod fragmentation.

To accomplish this objective, it will be necessary to use highly instrumented test assemblies capable of yielding useful information on bundle behavior during the imposed transient.

Test Objectives

The PNL effort, which is performed as part of the NRC Severe Core Damage Test Subassembly Procurement Program, will provide two highly instrumented test assemblies for use in small-break LOCA tests to be conducted in the PBF at Idaho Falls, Idaho. The test sequence will progress from the initial reduction in coolant flow and onset of boiling through cladding melting and redistribution of liquified fuel rod material, followed by quench and fuel rod fragmentation. The hydrodynamic and heat transfer characteristics of the rubble bed will then be examined. Experimental objectives for the small-break LOCA project are to:

- examine the primary fuel rod damage mechanisms and the controlling processes during system conditions of decreased pressure and superheated steam cooling
- examine the hydrodynamic and heat transfer characteristics of a rubble bed formed from previously molten and/or fragmented fuel rods.

Because it is not economically feasible to perform a sufficient number of tests in the PBF to systematically evaluate all aspects of fuel rod behavior and damaged core coolability, the tests are structured to provide the most relevant damage over the complete range of anticipated fuel rod behavior. The data obtained from these tests will be used to bench mark out-of-pile data and computer codes that are necessary to complete a systematic evaluation of fuel rod behavior during the types of transients expected.

Detailed test objectives that have been defined to insure that the more general primary experimental objectives are attained include:

- evaluate the effect of cladding ballooning and rupture on oxidation, hydrogen uptake, embrittlement, and fuel rod meltdown
- confirm existing Zircaloy cladding oxidation correlations at temperatures above 1773K and the embrittlement and fuel rod fragmentation criteria at quench temperatures
- characterize fuel rod fragmentation when quenched

- determine the extent of UO_2 dissolution by molten Zircaloy, and characterize the redistribution and solidification of liquified fuel rod material
- monitor fission product release during heatup, and evaluate the effect of UO_2 dissolution and fragmentation on fission product release
- evaluate the hydrodynamic and heat transfer characteristics of the rubble bed with respect to fuel rod fragment size and coolant flow rate.

The types of severe fuel rod damage mechanisms that could be expected during various small-break LOCAs include cladding ballooning, rupture, oxidation, melting, UO_2 dissolution on molten Zircaloy, and ultimately UO_2 melting. The cladding melting may occur at lower temperatures due to eutectic reactions with iron and/or nickel, both of which are present in fuel assemblies in stainless steel end fittings and control rod cladding as well as in Inconel spacer grids. Vibration and thermal stresses can cause the oxygen-embrittled cladding and UO_2 to crack and fracture. The amount of damage depends upon the high-temperature heating rate, the time at high temperature, the amount of oxygen available (from steam) for Zircaloy, and eventually the cooling rate.

A peak cladding temperature of at least 2300K was selected to insure that the Zircaloy will melt. The cladding temperature rise rate will be varied to obtain differing degrees of cladding oxidation prior to exceeding the Zircaloy melting temperature. At 0.5K/sec, the cladding should totally oxidize before reaching 2250K; at 4.0K/sec, less than 50% of the cladding will oxidize and the remainder of the cladding will melt. Considerable UO_2 may be dissolved as the Zircaloy melts and contacts the UO_2. These heatup rates will be held constant until the desired peak temperature is reached. The third temperature rise will approximate the calculated cladding temperature history during the conditions that have been postulated for the TMI accident. The time at peak temperature will be adjusted to obtain the desired degree of cladding oxidation.

Cladding cooldown will be either slow (by radiation to the flow shroud) or rapid (quench). The slow cooldown will minimize thermal shock and preserve the test bundle geometry for post-test examination; and the quench, which is more typical of postulated commercial reactor behavior, will fragment the test rods. The postquench flow rate will be varied to examine the hydrodynamic and heat transfer characteristics of the test bundle rubble bed. The as-fabricated test rods will be prepressurized to approximately 3 MPa to induce cladding ballooning and rupture during the heatup phase of the tests. Two lower priority tests have been identified with an initial fuel rod prepressurization of only 0.1 MPa. During these tests, the cladding will collapse onto the UO_2 fuel pellets, thus maximizing the potential fuel/cladding chemical interaction.

Test Train Operational Requirements

The test conditions for the proposed SFD tests will be more severe than any encountered in previous PBF tests because of the very high temperatures, the presence of molten cladding and dissolved UO_2, and the relatively long time required to perform the tests. The test train must be designed to withstand these severe conditions and provide the necessary containment to prevent damage to the test loop.

The following system operational requirements will be necessary to perform a test. After preconditioning, the reactor power will be decreased to about 0.1 MW, and the system pressure will be held constant at about 7 MPa. The coolant flow to the test bundle will be reduced or shut off, and the test bundle will uncover by boiling. When the coolant reaches the desired level near the bottom of the bundle, the coolant flow will be increased (and/or adjusted as necessary) to maintain the desired liquid level. Reactor power will be increased to initiate cladding heatup. After reaching a peak cladding temperature of at least 2300K, the test will be terminated, which will consist of reactor shutdown followed by a slow cooldown to preserve the bundle structure for post-test examination or a quench with coolant to fragment the highly embrittled fuel rods. Tests subjected to a quench may also include a series of low-flow tests to evaluate the hydrodynamic and heat transfer characteristics of the rubble bed.

During some of the tests, significant molten fuel rod material will be formed, which will redistribute into lower regions of the test train. This liquified material must be contained within the test vessel.

During these SFD tests, it will be important to control the water level in the test assembly. There now exists a method that can measure and therefore control this water level. With the system being developed at PNL, it is possible to characterize the water in the assembly during SFD tests and provide a real-time instrument display that includes definition of liquid level and the presence and extent of the void fraction in the assembly.

LIQUID LEVEL AND VOID FRACTION DETECTION SYSTEM

The unique detection system that is described in the remainder of this report is composed of state-of-the-art components that can provide a real-time readout of the liquid level in a fuel assembly. In this section the basic detection system is defined, and the two configurations that were tested are described. In the first configuration, a single measuring orifice provides liquid level information and it is assumed that there is no void fraction. In the second configuration, multiple measuring orifices provide definitive information on the location and extent of the coolant void fraction as well as on liquid level. In-reactor applications in the PBF and ESSOR fuel damage test programs are described, the results of prototype testing are presented, and opportunities for futher development are discussed.

DEFINITION OF DETECTION SYSTEM

The basic concept consists of an orifice (I) located in the test assembly, a connecting tube or pipe that passes through the closure head to a condenser section and then to a second orifice, and a flow control valve (see Figure 2). The second orifice (II) includes appropriate pressure taps to enable the use of a differential pressure transducer to measure the mass flow rate.

To explain the functional characteristics of this device, it is assumed that there is no void fraction generated in the assembly and that the assembly pressure is constant at 7 MPa. Both orifices have been arbitrarily chosen to be 1 mm in diameter. With these assumptions in mind, only two conditions can exist for the sensing device. For calculational purposes, a 1.4-MPa pressure drop from the pressure vessel to the flow control valve was arbitrarily chosen. The 1.4-MPa pressure drop is shared equally by the two orifices while the condenser is cooling the liquid. The differential pressure transducer is seeing a nominal 0.7-MPa pressure drop, and the mass flow rate through the sensor is nominally 345 kg/hr.

Condition 1--when the vessel is full of liquid or at least the sensing orifice (I) is in liquid--is depicted in Figure 3. For Condition 2 (see

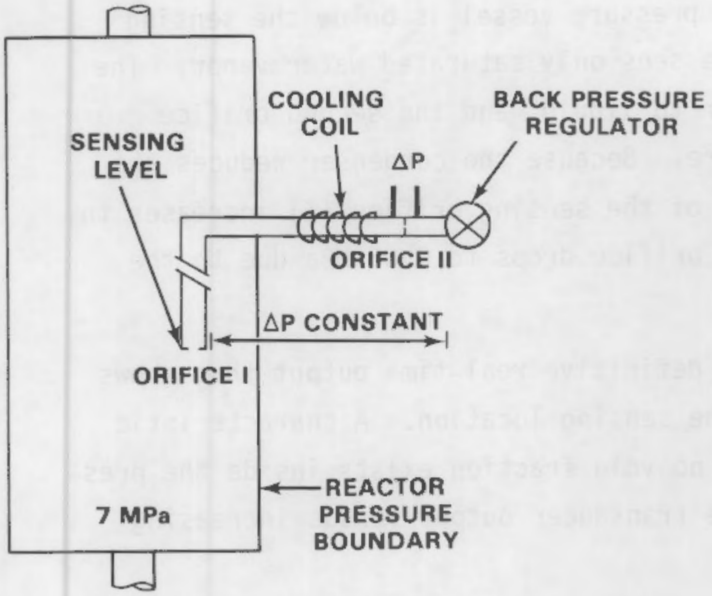


FIGURE 2. Basic Concept of the Liquid Level and Void Fraction Detection Device

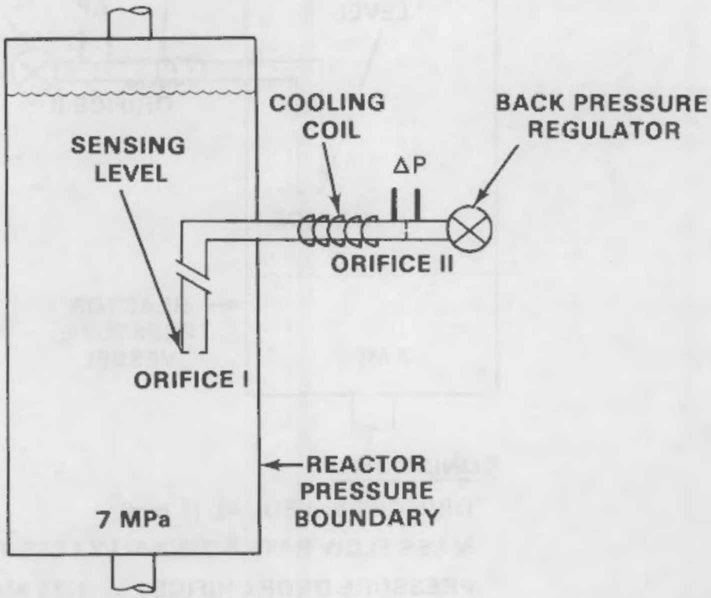


FIGURE 3. Condition 1: Liquid Level Above Sensing Level

CONDITION I

ORIFICE I & II EQUAL (1 mm)

MASS FLOW RATE NOMINALLY 344 kg/hr

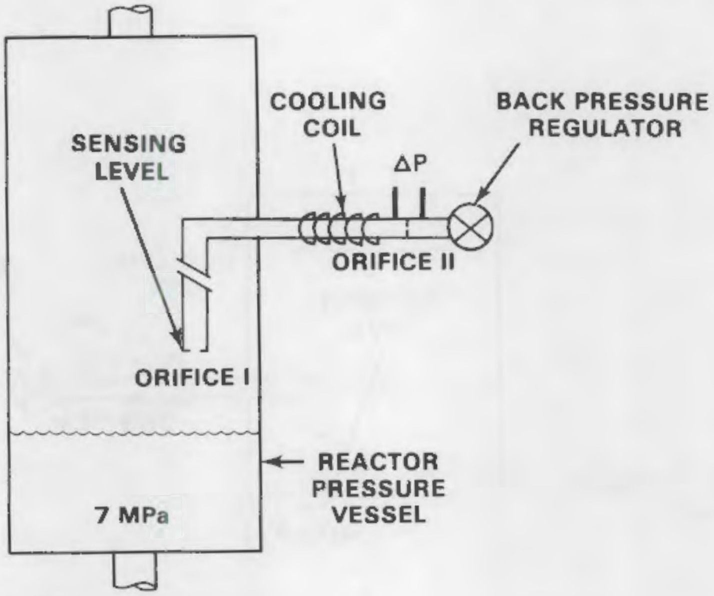
PRESSURE DROP ORIFICE I = 0.7 MPa

ORIFICE II = 0.7 MPa

(WATER FLOW IN BOTH ORIFICES)

Figure 4), the liquid level inside the pressure vessel is below the sensing orifice; therefore, the sensing orifice sees only saturated water vapor. The condenser cools and condenses the vapor to liquid, and the second orifice still sees liquid at a fixed temperature. Because the condenser reduces the volume of the vapor, the pressure drop of the sensing orifice (I) increases to a nominal 1.35 MPa while the measuring orifice drops to 0.05 MPa due to the much reduced mass flow rate.

This basic device then provides a definitive real-time output that shows the presence or absence of liquid at the sensing location. A characteristic curve can be defined that assumes that no void fraction exists inside the pressure vessel. The differential pressure transducer output versus increasing



CONDITION II

ORIFICE I & II EQUAL (1 mm)

MASS FLOW RATE NOMINALLY LESS THAN 45 kg/hr

PRESSURE DROP ORIFICE I = 1.35 MPa

ORIFICE II = 0.05 MPa

SATURATED STEAM FLOW IN ORIFICE I

WATER FLOW IN ORIFICE II

FIGURE 4. Condition 2: Liquid Level Below Sensing Level

fluid temperature is plotted in Figure 5. The first portion of the curve from 25°C to T_1 is solely a linear function of the change in the density of the liquid as it heats.

T_1 is defined by the pressure drop from the vessel to the flow control valve and the sizes of the orifices. It is the temperature and pressure at which flashing begins in the first orifice. As flashing occurs and is subsequently condensed downstream, the pressure drop in the system becomes a more complex function of liquid and vapor densities and becomes nonlinear from T_1 to $T_{saturation}$. It should be noted that if the liquid level drops below the sensing orifice at any point along this curve, the mass flow rate and the pressure drop across the measuring orifice will drop to the nominal 0.05-MPa value, indicating the drop in liquid level.

If the temperature of the liquid goes to $T_{saturation}$ and the presence of a void fraction is ignored or suppressed, then point P_1 in Figure 5 is a definitive value that represents the condition of the liquid at the sensing level in the vessel. Without the existence of a void fraction, the sensor has only two conditions--P_1 and P_2. P_2 provides a distinctive output

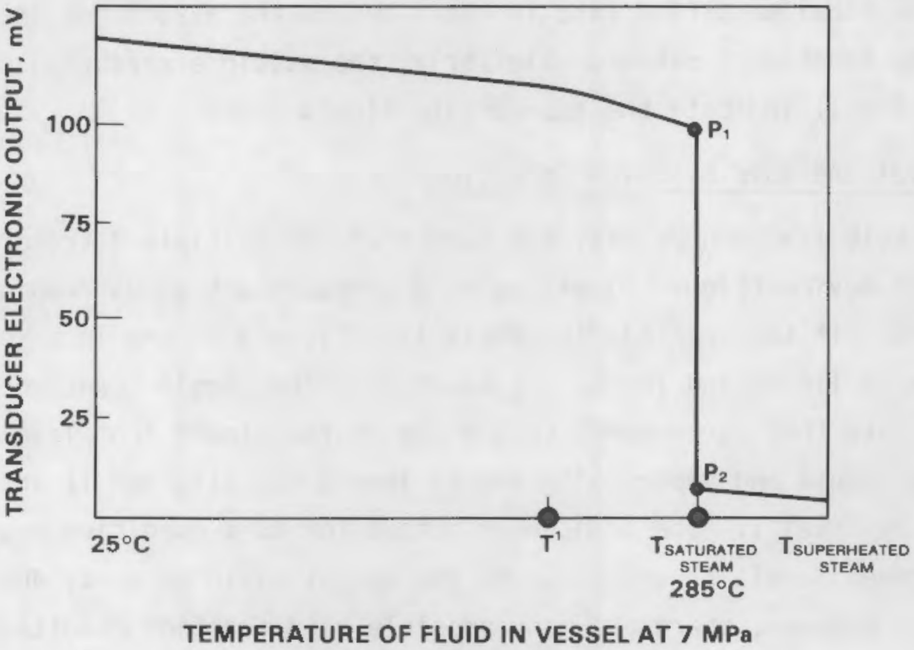


FIGURE 5. Transducer Output

indicating that the liquid level is below the sensing elevation. From P_2, the steam becomes superheated as the temperature increases and the transducer output becomes a linear function primarily related to the density change of the steam as its temperature increases.

DESIGN CONFIGURATIONS

Liquid Level Detection

The previous description of the basic function of the detector referenced a sensor with one detector orifice and one measuring orifice. To better measure liquid level, two improved configurations can be used. One of these configurations (see Figure 6) consists of multiple detector orifices and one measuring orifice with a single differential pressure tranducer. The second configuration (see Figure 7) consists of both multiple detector and measuring orifices, each having a differential pressure transducer.

In Figure 6, the individual detector orifices (labeled I, II, III, IV, and V) are connected to a single line through the closure head and ultimately to a single measuring orifice and differential pressure transducer. The output for this device is shown in Figure 6. Each level change will cause an appropriate drop in the total mass flow rate in the line and the associated incremental drop in the transducer output. Similarly, the multiple measuring device shown in Figure 7 will indicate the appropriate liquid level.

Liquid Level and Void Fraction Detection

If a void fraction exists, the output of the multiple detector/single measurement device (Figure 6) will give a somewhat ambiguous reading as shown in Figure 8. If the orifices at levels II, III, and IV are in a void fraction, level V is in liquid and level I is in vapor. The single transducer will see a mass flow rate that corresponds to the sum of the liquid from level V plus the sum of the liquid and vapor collected by levels IV, III, and II and the vapor collected by level I. The transducer output for this condition would probably settle between levels II and III, and the output would be noisy due to condensing vapor. However, there are many possible void fraction conditions that may

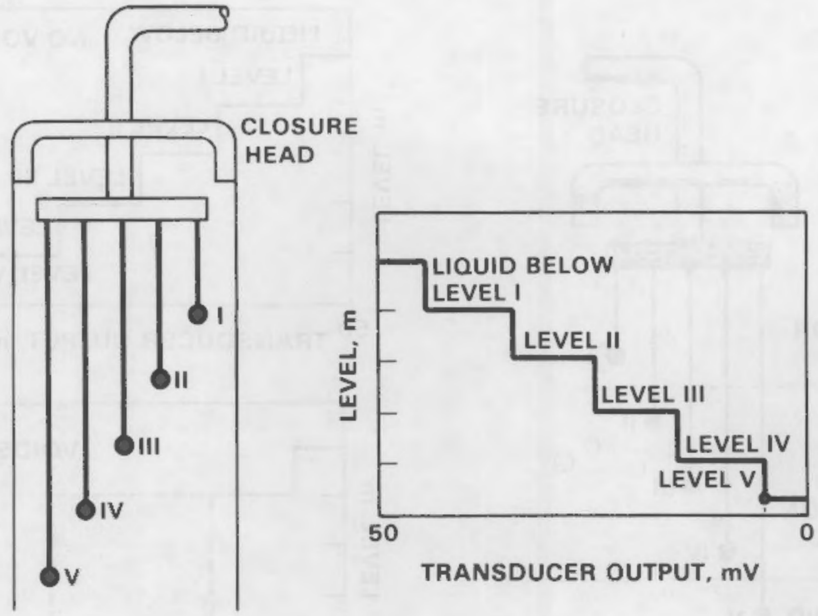


FIGURE 6. Multiple Level Detector Using a Single Measuring Orifice

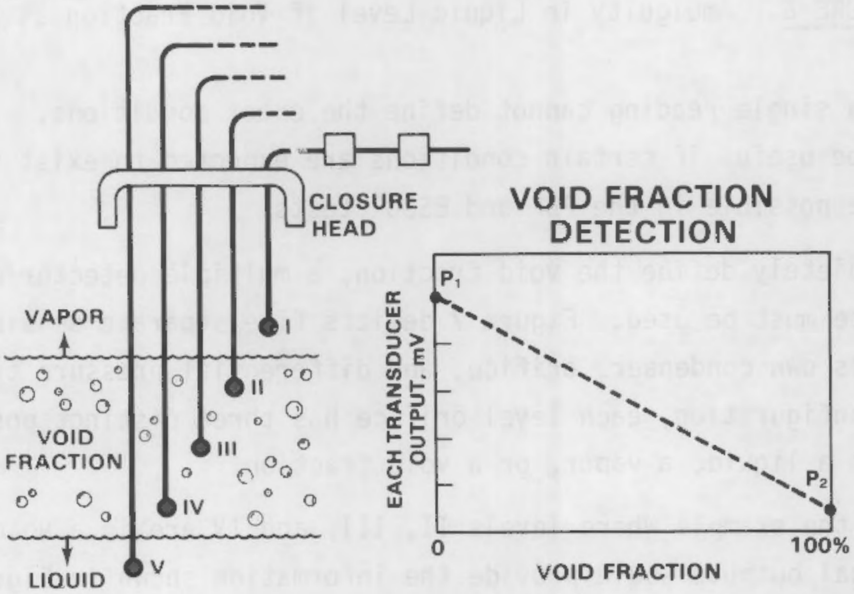


FIGURE 7. Liquid Level and Void Fraction Detection Using Multiple Measuring Orifices

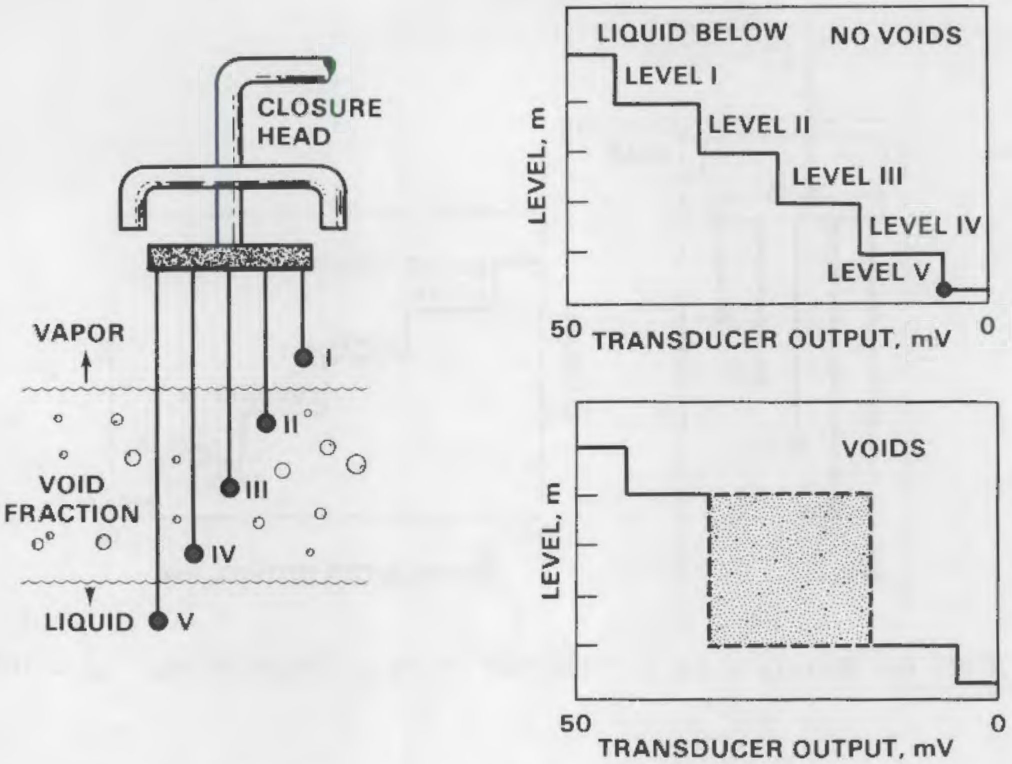


FIGURE 8. Ambiguity in Liquid Level if Void Fraction Is Present

occur, and a single reading cannot define the exact conditions. This detection system can be useful if certain conditions are expected to exist in the system, which may be possible in the PBF and ESSOR tests.

To completely define the void fraction, a multiple detector/multiple measuring device must be used. Figure 7 depicts five separate sensing systems, each with its own condenser, orifice, and differential pressure transducer. With this configuration, each level orifice has three distinct possible conditions: in a liquid, a vapor, or a void fraction.

Taking the example where levels II, III, and IV are in a void fraction, the individual outputs would provide the information shown in Figure 9. The transducer output for level V is smooth and indicates liquid flow, and the sensor at level I is indicating vapor and the output is smooth. Sensors at levels IV, III, and II are somewhere between the liquid and vapor outputs and their signals will be slightly noisy. Since the internal heat of the fuel assembly is generating the void fraction, zero void fraction occurs between

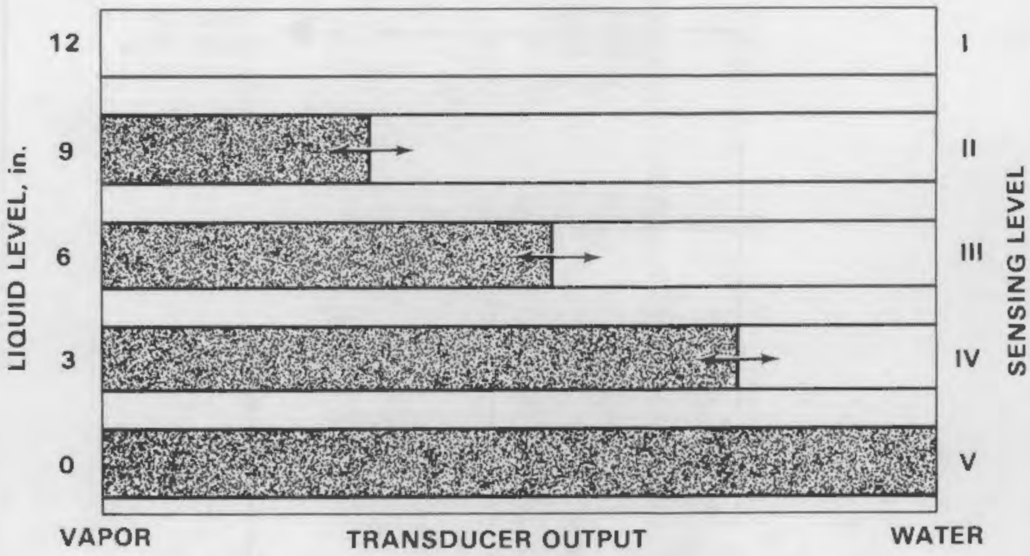


FIGURE 9. Transducer Output Graphic Display

levels V and IV and the void fraction increases with increasing elevation until a froth front occurs between sensors II and I. Therefore, the absolute magnitude of sensors IV, III, and II will be in descending order (see Figure 9).

This configuration of the detection system should provide sufficient information to define the real liquid level and the area of void fraction. While we make no claims at this time that the concept will in fact measure void fraction, that question is being investigated in laboratory studies.

LIQUID LEVEL DETECTION IN POWER BURST FACILITY OR ESSOR

In the SFD tests scheduled for PBF and ESSOR, the desired liquid level and the likely area of void fraction can be reasonably defined for each test. A very real constraint of these tests is bringing tubes out of the closure head. In addition, the space used for tubes in the closure head limits the available space for instrument leads from the test assembly.

These constraints favor the single tube/multiple orifice device. If this device were to be used, the configuration shown in Figure 10 is recommended: a 1/4-in. diameter line through the closure head, passing through the bypass flow to the bottom of the fuel assembly, then into the fuel assembly area.

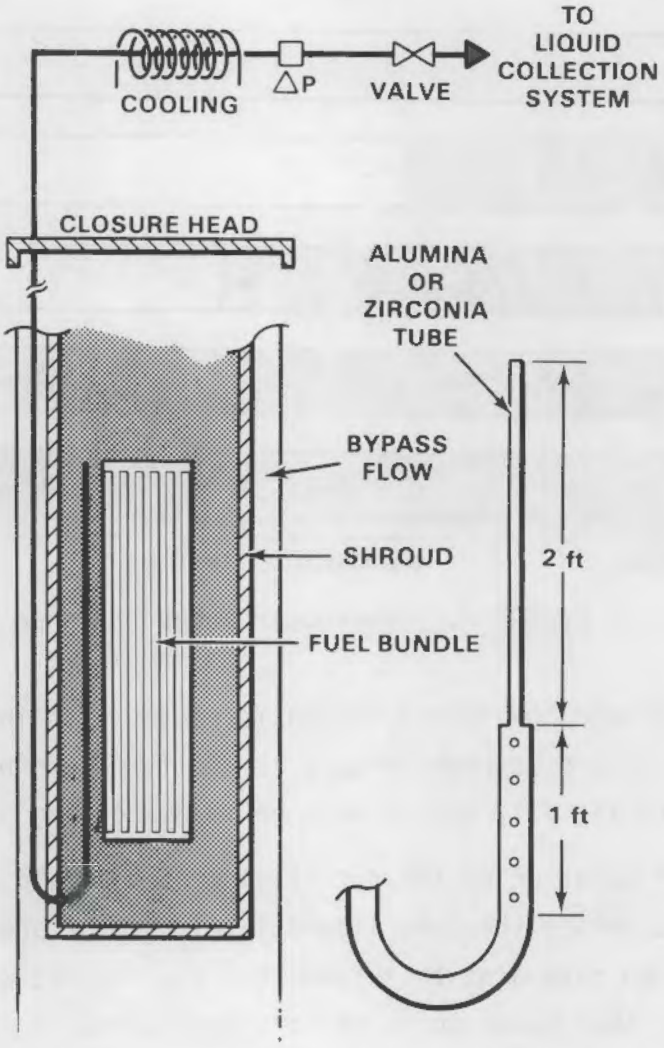


FIGURE 10. Power Burst Facility Liquid Level Detector

Five orifices are equally spaced along the tube from zero elevation to the 1-ft elevation. The 1/4-in. line is then terminated in a 2-ft length of alumina or zirconia tube with a fixed and appropriately sized ID. In this configuration, the first orifice is at the top of the active core and there are enough orifices in the liquid level area to provide sufficient information on the movement of the level as well as added information to recognize and anticipate the effect of a change in control settings.

If the decision is made to characterize the liquid level and void fraction completely, six 1/16-in. lines could replace the single system in the test train (see Figure 11).

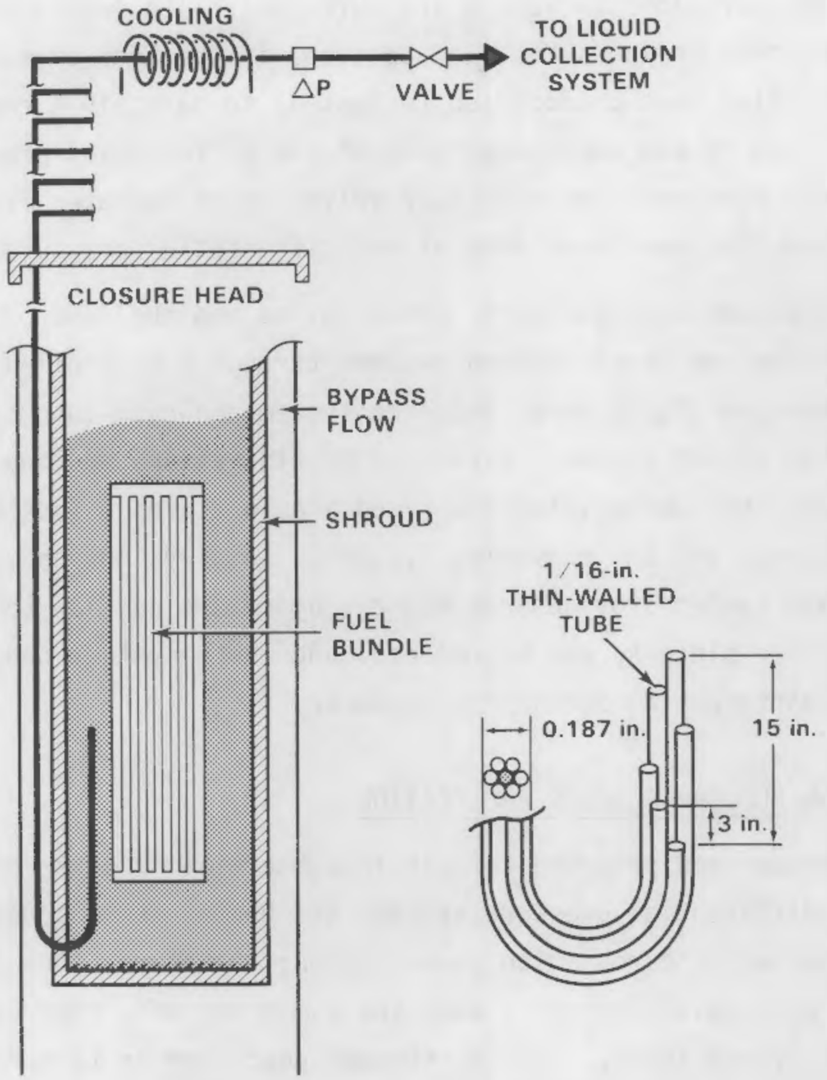


FIGURE 11. System for Defining Liquid Level and Void Fraction

OPERATION OF THE SENSOR IN A CHANGING PRESSURE ENVIRONMENT

Throughout the discussion of the operation of the liquid level-void fraction detection systems the loop or supply pressure has been maintained at 7 MPa (1000 psi). This pressure level has been used because the PBF-SFD tests will be run at this pressure and there is no need to compensate the output of the sensors. In a commercial reactor environment, the pressure may range from 15 MPa (2200 psi) down to very low pressures in certain accident conditions. Any sensor proposed for use in nuclear reactors must provide unambiguous output that is free of errors due to pressure and temperature changes; therefore, sensor configurations include a pressure-controlled regulator valve that reacts to a major drop in pressure. In addition, if the loop pressure changes, this regulator valve must be modified (adjusted) to maintain a constant pressure from the loop to the downstream side of the differential pressure transducer. For control purposes, the regulator valve can be operated from a pressure signal from the downstream side of the differential pressure transducer.

In a second configuration, these valves and the control system are removed by connecting two level sensing systems through a controlled pump. Fluid is pumped from one liquid level scanning system and back into the reactor vessel through the second system. With this configuration, no liquid is removed from the vessel, the pump maintains a fixed pressure drop across the two liquid level sensors, and the measuring system is totally independent of reactor pressure. This system provides redundancy; by reversing flow through valving, the potential for plugging can be reduced; and both systems can be operated with a single differential pressure transducer.

COMMERCIAL NUCLEAR REACTOR APPLICATION

Other devices proposed for use in commercial nuclear reactors (for example, differential pressure systems and heated thermocouple systems) cannot be used while circulation pumps are on; therefore, they cannot detect the presence of a void fraction. When the pumps are off, they can detect only the collapsed liquid level. The PNL concept described in this report will provide unambiguous indications during all reactor operating and accident conditions. It will detect the presence of a void fraction and define its extent whether the circulation pumps are on or off. In addition, it will provide discrete output readings of the existence of liquid or vapor at any sensing level that is totally independent of vessel pressure.

PROTOTYPE TESTING

The detection system was initially tested on a package steam generator with a sight glass. The pressure chamber held about 3.8 l of water, and the steam generator had 3 kW of heat input. The heaters were activated by a settable pressure switch. The sensing system was made from 1/4-in. stainless steel tubing with 0.05-mm orifices. Rather than using a differential pressure transducer, the downstream side of the measuring orifice was exhausted to atmosphere.

The single sensing orifice was placed in the pressure vessel through a pipe fitting in the top of the steam generator, and the steam generator pressure was set to 0.3 MPa. The condenser consisted of a coil of 1/4-in. stainless steel tubing immersed in an ice bath. Tests were conducted with the sensing system as the only bleed on the steam generator, followed by tests while bleeding liquid from the blowdown valve, and then by bleeding steam from the pressure relief valve. These three types of tests should have resulted in a liquid level being generated without a void fraction, with a minimum void fraction, and with a high void fraction, respectively. In each case, the sensing system accurately defined the liquid level. In the second and third cases, the system also indicated the existence of the void fraction prior to liquid level by indicating a reduction in the mass flow rate seen by the measuring orifice and the increase of noise on the flow signal. However, even in the high void fraction case, the difference in the mass flow rate in the void fraction and the liquid level was clear.

The problem with these tests arises from two factors: One cannot observe the void fraction, and constant pressure of the steam generator system cannot be maintained during the tests. Because of these problems, a void fraction generator that operates with Freon was fabricated (see Figure 12). The system consists of a glass column 2 in. in diameter by 22 in. high with a pressure gage and vent valve at the top for removing noncondensable gases. A helium-pressurized container of Freon 11 was used to supply liquid Freon to the bottom inlet. Although Figure 12 shows a 1/4-in. sensing line with six 0.05-mm orifices, extensive testing of both single and multiple orifices has been conducted in this generator. Three 100-W cartridge heaters located at the bottom of the column are driven by variable ac voltage. The multiple level single-probe tests were conducted by filling the column with liquid Freon 11 and closing the inlet and outlet valves. The heaters were turned on at 60 power, and the sensing system was opened when the system pressure

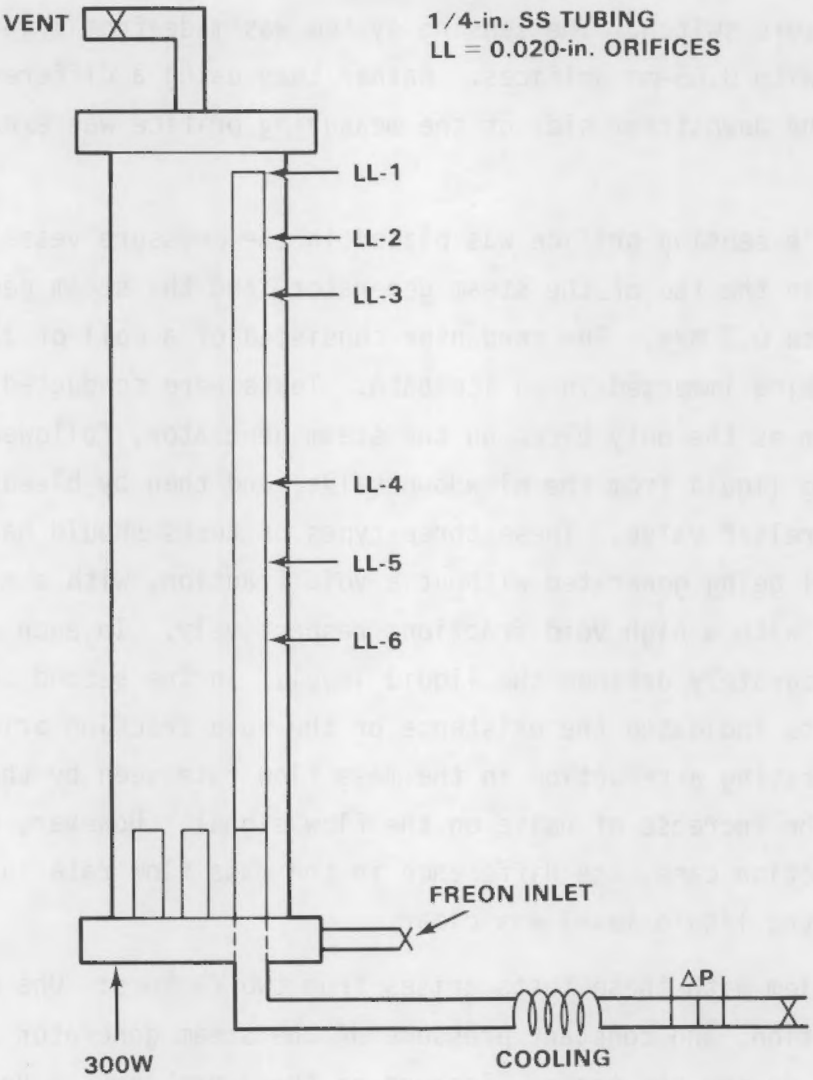


FIGURE 12. Freon Void Fracton Generator

reached 0.14 MPa. During this test, a significant void fraction was generated in the column. Figure 13 shows the sensor output as the liquid level dropped and the relative magnitude of the noise signal created by the void fraction. The void fraction noise was largest when the column was full and decreased as the liquid level dropped.

In addition to laboratory testing, two liquid level sensors are being installed in the boil-off tests being conducted at PNL in support of the SFD program. The test system is being inserted in the 189D high-pressure water

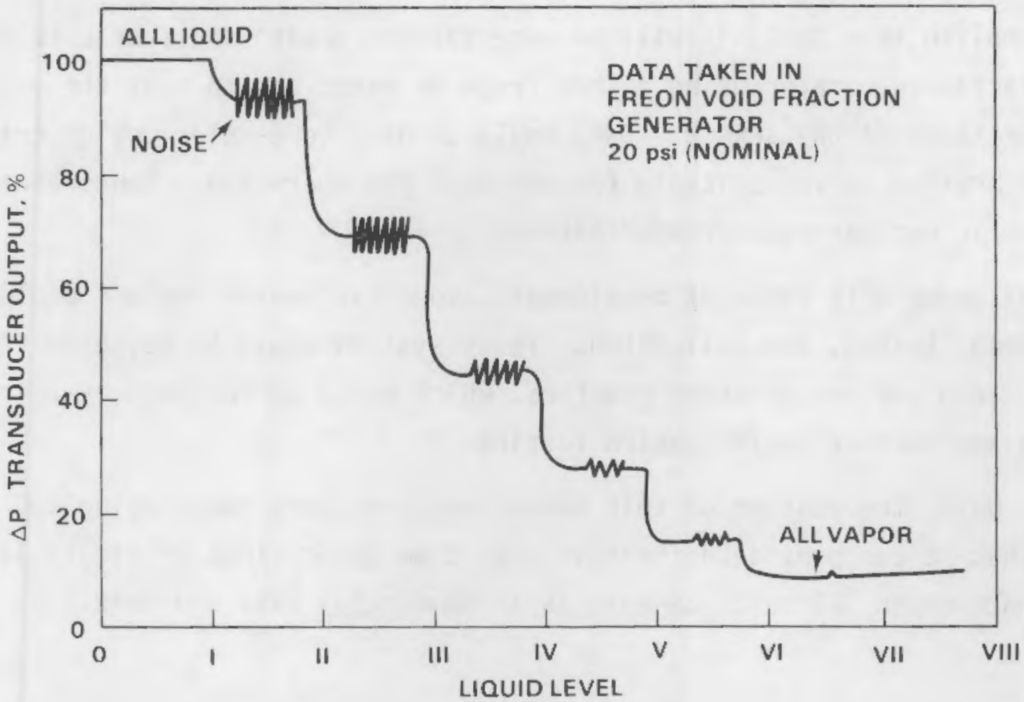


FIGURE 13. Laboratory Test of Single Liquid Level Sensor with Multiple Orifices

loop. The test assembly consists of nine electrically heated rods in a vertical section, and the tests will be performed at 7 MPa and 285°C water. The water will be boiled off slowly using the heated rod assembly; steam temperatures are expected to reach 650°C during the test. Each liquid level device consists of a single 1/8-in. diameter stainless steel tube with three 0.05-mm ID orifices that are 6 in. apart on the rods.

FURTHER DEVELOPMENT OPPORTUNITIES

The development work presently under way at PNL on the liquid level device may be sufficient to allow its use in the SFD tests. The device is directly applicable to use in nuclear reactors to provide real-time readout of liquid level as well as void fraction detection. It may also be capable of discrete measurement of void fraction.

To assess the capabilities of the device for use in nuclear reactors, it will be necessary to complete more extensive testing in various configurations and to address the problems involved in retrofitting into existing reactors.

To accomplish this goal, it will be necessary to design and fabricate a new void fraction generator using either Freon or water and to test the various configurations of the sensor. Data would be used to develop design criteria and calibration curves suitable for use with the operational constraints involved in nuclear reactor applications.

Following this phase of development, specific sensor designs could be fabricated, tested, and calibrated. These systems would be designed for retrofitting into various existing reactors, which would be followed by third-party testing and nuclear qualification testing.

To date, the testing of this sensor has been very encouraging and indicates that it can provide definitive real-time indications of liquid level and void fraction in SFD tests as well as in commercial BWRs and PWRs.

APPENDIX

LIQUID LEVEL AND VOID FRACTION DETECTION SYSTEM CALCULATIONS

APPENDIX

LIQUID LEVEL AND VOID FRACTION DETECTION SYSTEM CALCULATIONS

The following calculations were performed to illustrate the ideal behavior of the liquid level and void fraction detection system. All minor effects were neglected to show a simple representation of system operation. Laboratory tests using Freon (R-11) indicate that the calculations and experimental data generally agree.

Since the level detector may be used in SFD tests, conditions and constraints appropriate for PBF and ESSOR were used as input for the calculations. The required orifice diameters and pressure drops were determined and then reviewed for practicality.

CONSTRAINTS AND OPERATING CONDITIONS

The constraints and operating conditions that would apply for a SFD experiment include maximum flow rate, system pressure drop, and steam conditions.

If the level detector pulls too much steam (or liquid) out of the vessel, it could have a significant effect on the level, which would be a concern as the liquid level falls. A maximum flow limit of 10 lb/hr has been set for the level where three orifices are exposed to vapor and three to liquid.

The detector is designed to produce $\Delta P_1 = \Delta P_2$ at the all-liquid condition. Although it is desirable to minimize pressure drop to limit the flow rate, the total pressure drop must be large enough to be controllable and ΔP_2 must be large enough to be measurable. A total pressure drop of 10 psi was chosen, which will result in a reasonable ΔP_2 readout of 0 to 5 psi. The PBF and ESSOR experiments will be run at 1000 psi. Since two phases will be present, the steam can be considered saturated at 285°C.

ASSUMPTIONS

The following assumptions are based on neglecting the effects of head loss in the line and condenser, static head, and change in static head. These factors are not negligible, but they need not be considered in this basic illustration of the system. Static head from 3 ft of water will approach 1 psi at test conditions. This effect could be largely compensated for by varying the inlet orifice sizes.

At this time, assume that 1) all sensing orifices have the same diameter and 2) the pressure drop is equal across all sensing orifices. At the all-liquid condition, this pressure drop is equal to $\Delta P_{total}/2$ or 5 psi.

For steam flow, an expansion factor would normally be introduced into the orifice equation because the flow is compressible. In this case the steam passes from a 1000-psi region to a 995-psi region. Since the expansion ratio is very close to one, it is neglected in steam flow calculations.

In level detector calculations, the presence of a void fraction is not considered. That is, a given orifice will see either all vapor or all liquid depending on the liquid level. It is suggested from experimental data that the presence of a void fraction would tend to smooth out the calculated step function response. Void fraction is considered in calculations for a two-orifice detector (see text Figure 2).

The equations used for these calculations are for standard square-edged orifices, and a 0.6 flow coefficient was always used. Published data show "C" constant at this value for Reynold's numbers over 1×10^4 and orifice-to-line diameter ratios less than 0.3. Experimental data are needed to confirm flow coefficients for these small orifice diameters.

Any effects caused by liquid flashing to steam as it passes through sensing orifices are neglected. It is assumed flashing would not affect mass flow rate.

LEVEL DETECTOR CALCULATIONS

The orifice arrangement is presented in text Figure 6. Mass flow through a standard square-edged orifice is expressed as:

$$\dot{m} = CA_o\sqrt{2g_c\Delta P\rho} \tag{1}$$

where $\dot{m}$ = mass flow
C = flow coefficient
A_o = orifice area
ΔP = pressure drop across orifice
ρ = fluid density.

Since there are six sensing orifices, mass flow is considered as the sum of six individual flows. From earlier assumptions, A_o and ΔP are equal throughout and it is also assumed that C remains constant at 0.6. The only flow variable among orifices is density, where either ρ_{vapor} or ρ_{liquid} will apply. Thus, the total mass flow into the sensing orifices may be expressed as:

$$\dot{m}_1 = CA_1\sqrt{2g_c\Delta P_1}\left[n_v\sqrt{\rho_v} + \left(n_t - n_v\right)\sqrt{\rho_l}\right] \tag{2}$$

where A_1 = inlet orifice area
n_v = number of orifices exposed to vapor
n_t = total number of sensing orifices
ρ_v = vapor density
ρ_l = liquid density.

The mass flow through the measurement orifice is given as:

$$\dot{m}_2 = CA_2\sqrt{2g_c\Delta P_2\rho_l} \tag{3}$$

The fluid density through the second orifice would probably be greater than that for saturated liquid; the condenser will subcool the liquid. For these calculations, however, it is assumed that the condenser removes just enough heat to condense the vapor. This error would be eliminated by measuring the fluid temperature at the measurement orifice. Since $m_1 = m_2$, Equations (2) and (3) are equal.

$$C_1 A_1 \sqrt{2g_c \Delta P_1}\left[n_v \sqrt{\rho_v} + (n_t - n_v)\sqrt{\rho_l}\right] = C_2 A_2 \sqrt{2g_c \Delta P_2 \rho_l} \tag{4}$$

For the all-liquid condition, $\Delta P_1 = \Delta P_2$ by design; therefore, $A_2 = n_t A_1$ (inlet flow area = outlet flow area).

When $n_t A_1$ is substituted for A_2, A_1 cancels and:

$$\sqrt{\Delta P_1}\left[n_v \sqrt{\rho_v} + (n_t - n_v)\sqrt{\rho_l}\right] = \sqrt{\Delta P_2 \rho_l}\, n_t \tag{5}$$

Solving for $\Delta P_1 / \Delta P_2$,

$$\frac{\Delta P_1}{\Delta P_2} = \frac{n_t^2 \rho_l}{\left[n_v \sqrt{\rho_v} + (n_t - n_v)\sqrt{\rho_l}\right]^2} \tag{6}$$

Since $\Delta P_1 + \Delta P_2 = \Delta P_t$ (a constant by design),

$$\Delta P_2 = \frac{\Delta P_t}{\left(1 + \dfrac{\Delta P_1}{\Delta P_2}\right)} \tag{7}$$

An HP calculator program was written to solve for ΔP_2 as a function of n_v (see Table A.1). The program output is plotted in Figure A.1 as is the output calculated for Freon (R-11) saturated at 90°F. Program results are tabulated in Table A.2.

Orifice size was not a factor in ΔP_2 readout. The orifices must still be sized to meet the 10-lb/hr flow limit at $n_v = 3$. Output orifice size can be determined by solving for A_2 in Equation (3) (from Table A.2, $\Delta P = 3.5$).

$$\dot{m}_2 = C A_2 \sqrt{2 g_c \Delta P_2 \rho_l} \tag{8}$$

$$10\ \text{lbm/hr} = 0.6\ A_2 \sqrt{2\left(32.2\ \frac{\text{lbm ft}}{\text{lbf sec}^2}\right)\left(3.5\ \text{lbf/in.}^2\right)\left(46.3\ \frac{\text{lbm}}{\text{ft}^3}\right)\left(144\ \text{in.}^2/\text{ft}^2\right)} \tag{9}$$

TABLE A.1. HP Program - Level Detector (solves for ΔP_2 as a function of n_v)

Store Input:

STO 1 = ρ_v
STO 2 = ρ_l
STO 3 = n_t
STO 4 = ΔP_t

To Run Program:

n_v
R/S

Program Steps:

Step	Entry	Step	Entry
1	STO 5	18	÷
2	RCL 3	19	1
3	g x^2	20	+
4	RCL 2	21	g 1/x
5	x	22	RCL 4
6	RCL 3	23	x
7	RCL 5		
8	–		
9	RCL 2		
10	f $\sqrt{x}$		
11	x		
12	RCL 5		
13	RCL 1		
14	f $\sqrt{x}$		
15	x		
16	+		
17	g x^2		

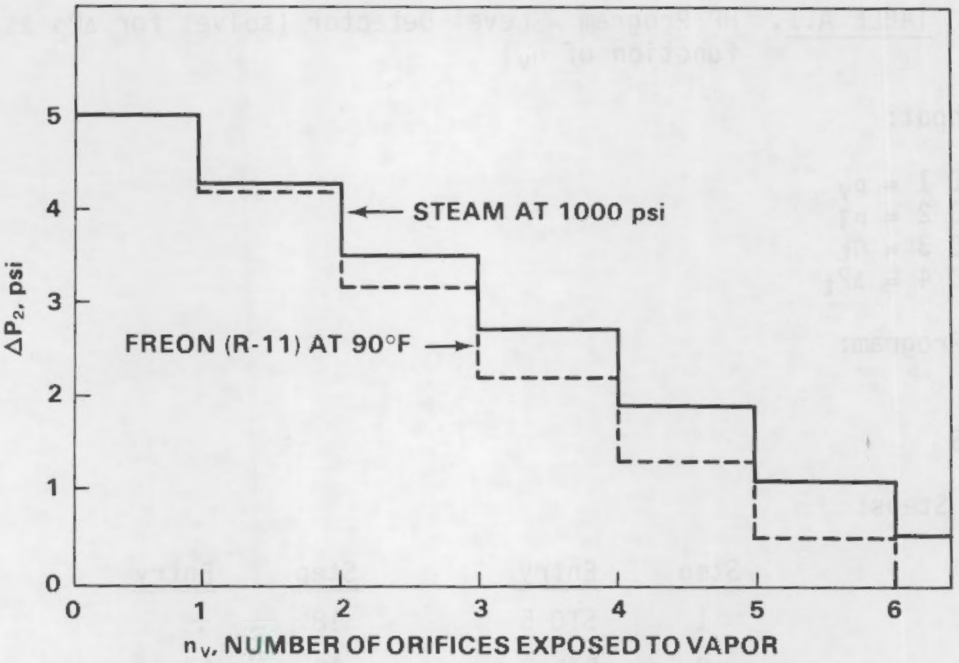


FIGURE A.1. Liquid Level Detector Output for Steam and Refrigerant (R-11)

TABLE A.2. Level Detector Output

	ΔP_2, psi	
n_v	Steam at 1000 psi	Freon (R-11) at 90°F
0	5.0	5.0
1	4.3	4.2
2	3.5	3.2
3	2.7	2.2
4	1.9	1.3
5	1.1	0.5
6	0.5	0.05

$$(10\ \text{lbm/hr})(1\ \text{hr}/3600\ \text{sec}) = (736\ A_2\ \text{lbm/ft}^2\text{-sec})(1\ \text{ft}^2/144\ \text{in.}^2)$$

$$A_2 = 5.43 \times 10^{-4}\ \text{in.}^2$$

$$d_2 = \left(\frac{4\ A_2}{\pi}\right)^{1/2}$$

$$d_2 = 0.026\ \text{in.} \qquad (10)$$

Since $A_2 = 6A_1$

$$d_2^{\,2} = 6d_1^{\,2}$$

$$d_1 = \sqrt{\frac{d_2^{\,2}}{6}}$$

$$d_1 = 0.0107\ \text{in.} \qquad (11)$$

Inlet orifices would need to be just ten-thousandths of an inch in diameter to meet the flow limit. Practical problems would arise with these small sizes. Filters would probably be designed into the system to control plugging.

VOID FRACTION DETECTOR CALCULATIONS

These calculations are based on the system shown in text Figure 2. The square-edged orifice equation can be more conveniently used with specific volume, v, instead of density.

$$\dot{m} = CA\sqrt{\frac{2g_c \Delta P}{v}} \qquad (12)$$

When two phases exist, specific volume may be expressed in terms of quality, x:

$$v = xv_g + (1 - x)v_f \tag{13}$$

For two-phase flow Equation (12) becomes Equation (14).

$$\dot{m}_1 = CA_1\sqrt{\frac{2g_c\Delta P_1}{xv_g + (1 - x)v_f}} \tag{14}$$

The use of Equation (14) is controversial since reviewers feel two-phase flow cannot be characterized this simply. However, early testing has produced data that agree at least in form with Equation (14).

At the second orifice,

$$\dot{m}_2 = CA_2\sqrt{\frac{2g_c\Delta P_2}{v_f}} \tag{15}$$

By design $A_1 = A_2$ and by continuity $\dot{m}_1 = \dot{m}_2$. By neglecting the variation in C and combining Equations (14) and (15),

$$\frac{\Delta P_1}{\Delta P_2} = \frac{xv_g + (1 - x)v_f}{v_f} \tag{16}$$

Equations (16) and (6) can be used to solve for ΔP_2.

$$\Delta P_2 = \frac{\Delta P_t}{1 + \frac{\Delta P_1}{\Delta P_2}} \tag{17}$$

To solve for ΔP_2 as a function of void fraction (α), α must be converted to quality.

$$x = \frac{1}{1 + \left(\frac{1 - \alpha}{\alpha}\right)\frac{v_g}{v_f}} \tag{18}$$

Equation (18) was derived from the more straightforward expression for quality given below:

$$x = \frac{\dfrac{\alpha}{v_g}}{\dfrac{\alpha}{v_g} + \dfrac{(1-\alpha)}{v_f}} = \frac{\text{vapor mass}}{\text{vapor mass} + \text{liquid mass}}$$

A calculator program was written to solve for ΔP_2 as a function of α (see Table A.3). The output is shown in graphical and tabular form in Figure A.2 and Table A.4, respectively. The program was also run for Freon (R-11) at conditions used in laboratory tests.

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TABLE A.3. HP Program - Void Fraction Detector (solves for ΔP_2 as a function of void fraction, α)

Store Input:

STO 1 - v_g
STO 2 - v_f
STO 3 - ΔP_t

To Run Program:

α (0 to 1.0)
R/S

Program Steps:

Step	Entry	Step	Entry
C	Solve for Quality	19	1
1	STO 4	20	+
2	CHS	21	RCL 2
3	1	22	x
4	+	23	+
5	RCL 4	24	RCL 2
6	÷	25	÷
7	RCL 1	C	Solve for ΔP_2
8	x	26	1
9	RCL 2	27	+
10	÷	28	g 1/x
11	1	29	RCL 3
12	+	30	x
13	g 1/x		
14	STO 5		
C	Solve for $\Delta P_1/\Delta P_2$		
15	RCL 1		
16	x		
17	RCL 5		
18	CHS		

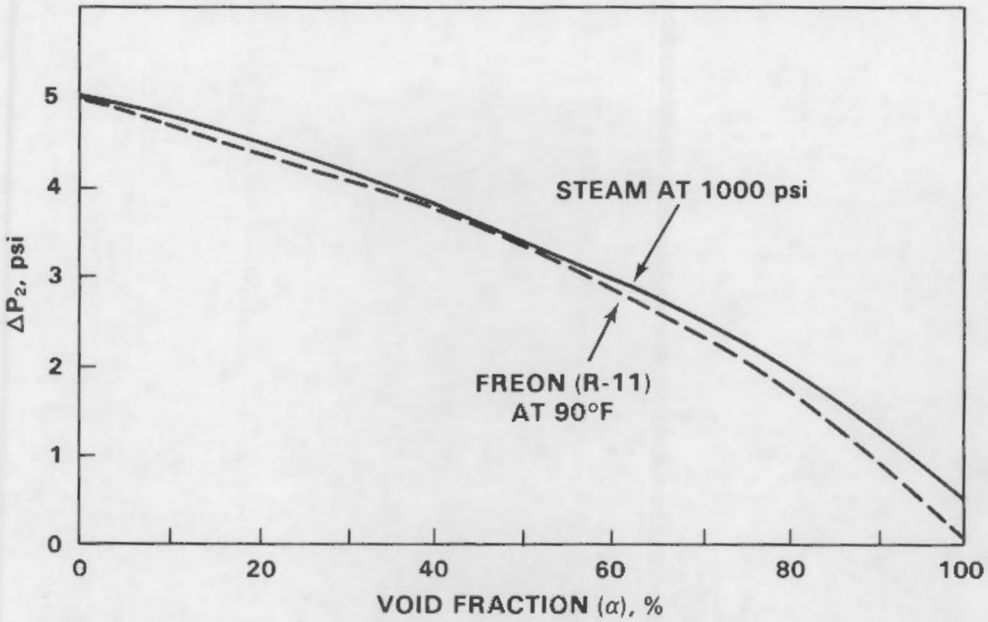

FIGURE A.2. Void Fraction Detector Output for Steam and Refrigerant (R-11)

TABLE A.4. Void Fraction Detector Output for Steam and Refrigerant (R-11)

Void Fraction, α	ΔP_2, psi Steam at 1000 psi	ΔP_2, psi Freon (R-11) at 90°F
0	5.0	5.0
0.1	4.8	4.7
0.2	4.5	4.4
0.3	4.2	4.1
0.4	3.8	3.8
0.5	3.4	3.3
0.6	3.0	2.9
0.7	2.5	2.3
0.8	1.9	1.7
0.9	1.3	.9
1.0	0.5	0.05

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16. ABSTRACT *(200 words or less)*

This report describes a direct-contacting liquid level and void fraction detection system that is being developed by Pacific Northwest Laboratory. The measurement technique could be used in the severe fuel damage tests that will be conducted at the Power Burst Facility, Idaho Falls, Idaho, and at the ESSOR reactor, Ispra, Italy. The detection system could also be retrofitted for commercial operating reactors to provide definitive thermal-hydraulic information. The technique can provide unambiguous, real-time data on liquid level and void fraction during normal reactor operation as well as during shutdown and accident conditions.

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