CONF-791037-13

MASTER

SENSOR FOR MEASUREMENT OF FUEL ROD
GAS PRESSURE DURING LOSS OF FLUID TESTS

DISCLAIMER

This book was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

T. R. Billeter

May 1979

IEE Nuclear Science Symposium
October 1979, San Francisco, Calif.

HANFORD ENGINEERING DEVELOPMENT LABORATORY
Operated by Westinghouse Hanford Company, a subsidiary of
Westinghouse Electric Corporation, under the Department of
Energy Contract No. EY-76-C-14-2170

COPYRIGHT LICENSE NOTICE

By acceptance of this article, the Publisher and/or recipient acknowledges the U.S. Government's right to retain a nonexclusive, royalty free license in and to any copyright covering this paper.

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

SENSOR FOR MEASUREMENT OF FUEL ROD GAS PRESSURE DURING LOSS-OF-FLUID-TESTS*

T. Roger Billeter

Hanford Engineering Development Laboratory
Richland, Washington 99352

SUMMARY

Qualification tests have been conducted of a measurement system for determining the pressure of certain fuel rods in the loss-of-fluid-test (LOFT) reactor. Because of physical size (0.35-in. OD by 5.5-in. length) and operational characteristics, an eddy current device was selected as the most promising measurement transducer for the application. The sensor must operate at pressure up to 17.2 MPa (2500 psig) and at temperatures up to 800°F. During the reactor transient caused by loss of coolant flow, sensor temperature and applied pressure will vary rapidly and significantly. Consequently, qualification tests included subsection of the sensor to rapid depressurization, temperature transients, and blowdowns in an autoclave, as well as to calibrations and various slow temperature cycles.

Calibration data show the sensor responds linearly for applied pressure, but with both temperature-dependent sensitivity and zero pressure output signal. Temperature compensation of signal output values was achieved with use of a derived temperature-dependent algorithm to transform the dc output voltage to indicate pressure. Because of the very rapid (up to 100°F/s) temperature changes imposed, the sensor erroneously indicated pressure by a maximum of 18% of reading during some transient tests. In addition to the influence of magnitude and rate of temperature change on the observed pressure measurement error, a very significant factor pertains to the spatial distribution of the temperature field immediately adjacent to the sensor envelope. As proven during 700 hours of qualification tests, precision and stability of the sensor should be satisfactory for LOFT. Particular responses of each of the tested units to imposed transient stimulus may be determined by reference to a summary table of acquired data.

INTRODUCTION

This report summarizes development and qualification testing of pressure measurement instrumentation intended for use in the LOFT reactor. Certain of the nuclear fuel rods in the reactor will be pressurized. Consequently, during the transient test the gas pressure within those fuel rods will vary rapidly and significantly. One constituent characterizing events within the reactor during loss-of-coolant is an accurate measurement of fuel rod pressure. Characteristics of candidate pressure sensors, each based on different physical operating principles, were evaluated during initial work phases. Supported by this evaluation, a sensor using eddy current techniques was judged to most nearly satisfy operating and physical characteristics specified for the LOFT pressure sensor.

Two units were initially subjected to development tests. Relying on results obtained during those initial tests, a revised sensor was designed and used during subsequent tests of qualification units. All units have been subjected to multiple iterations of a series of tests. Most tests were completed with the sensor installed in a laboratory oven; however, some tests

required use of an autoclave. Brief descriptions of each test in the series are presented.

In general, the sensor described in this report should be useable in severe environments up to 2500 psig and 800°F. Although the sensors will survive rapid variations of both temperature and pressure, data output during the transient may not accurately reflect the applied pressure, especially due to temperature gradients existing along the sensor during rapid temperature variations. As an overall purpose, the described work should characterize the pressure sensor sufficiently well to later facilitate interpretation of data obtained during planned transient tests in the LOFT reactor.

SENSOR REQUIREMENTS

Within the instrumented fuel bundle for LOFT, the pressure sensor can be located either as an integral part of the fuel rod or as an attachment to auxiliary structures in close proximity. However, if the pressure sensor is not a part of the fuel rod, a small-diameter tube must be used to transmit the rod pressure to the measurement location. Because of the difference in environment for sensors located inside and outside of the fuel rod, the specifications for each is different, as noted in Table I. Sensors located within the fuel rod experience less severe temperature transients, but must be physically smaller. Because of space constraints within the reactor, direct attachment to the fuel rod is the preferred sensor location.

Functionally, the described pressure sensor provides a measurement of fuel pin plenum gas pressure. This measurement is useful for determining fuel pin failure by detecting a loss of pressure in the fuel pin plenum and also for characterizing the rate of depressurization. Sensors placed inside the fuel rod gas plenum must be small enough to fit within a nominally 0.37-in. inside diameter, 0.025-in. wall cladding of the nuclear fuel. For most of its service life, the sensor will operate at 2000 psig and 650°F. During imposed transients, the pressure sensor will be exposed to rapid variations of temperature and pressure of the plenum gas.

In addition to the requirements noted in Table I, the sensor is expected to withstand vibration loads prevalent during the transient and to have a lifetime of 1000 effective full-power hours.

SENSOR DESCRIPTION

The principle of operation of the sensor depends upon interaction between a metal plate (target) and the electromagnetic field of an adjacent coil. Proximity of the target and coil affect the impedance of the coil due to eddy current effects. Consequently, a transducer, with relative separation between a coil and an adjacent target dependent upon pressure applied to the transducer, may be designed to yield a signal proportional to applied pressure. Two metal targets, connected

* Work supported by United States Nuclear Regulatory Commission

TABLE I
PRESSURE SENSOR PERFORMANCE
REQUIREMENTS AND OPERATING ENVIRONMENT

PERFORMANCE		
Range:	Atmosphere to 17.2 MPa (2500 psig)	
Accuracy:	3% of reading or ± 172 kPa (± 25 psi), whichever is larger	
Resolution:	± 69 kPa ($\pm$ psi)	
Response Time:	250 msec	
OPERATING ENVIRONMENT:	INSIDE FUEL ROD	EXTERNAL MOUNT
Flow	None	15 ft/sec, 60 lbm/ft ³
Media	Helium/fission-product gas/ UO ₂ water vapor (10 ppm)	LOFT water chemistry
Radiation	2×10^{13} n/cm ² sec. 2×10^8 R/hr	2×10^{13} n/cm ² sec. 2×10^8 R/hr
Pressure	Atmosphere to 17.2 MPa (2500 psig)	Atmosphere to 17.2 MPa (2500 psig)
	$\frac{dp}{dt} = 2.4$ MPa/sec (350 psi/sec)	17.2 MPa (2500 psig) 722 kPa/sec (105 psi/sec)
Temperature	70 to 650°F 850°F for 100 sec. $\frac{dT}{dt} = 10^\circ\text{F/sec.}$	70 to 605°F 800°F for 100 sec. $\frac{dT}{dt} = 260^\circ\text{F/sec.}$

via a push rod to a bellows and spring-supported diaphragm, move in unison relative to two adjacent coils. The coils excited with a 500 kHz signal source, comprise two arms of a balanced four-arm bridge. Pressure applied to the diaphragm causes displacement of the two metal targets relative to the energized coils, thereby changing the coil impedance. The resulting bridge imbalance yields a pressure-dependent signal output. As the maximum displacement of the diaphragm/target assembly approximates .005 inch to .007 inch, the pressure range of a particular sensor design mainly depends upon physical characteristics of the support springs. Physically, the sensor envelope is 0.23-inch in diameter by about 5.5-inches long. However, for the LOFT design, a 0.35-inch diameter outer copper shell was attached to the envelope for the purpose of reducing temperature gradients created during the severe temperature transients concomitant with loss-of-coolant. A 16-foot length of two-conductor, magnesia-insulated, 1/16-inch Inconel-shielded cable connected to signal conditioning electronics acts as the signal transmission cable for the pressure sensor.

TEST FACILITIES AND PROCEDURE

Qualification testing consists of a 500-hour series of static and dynamic tests conducted in a laboratory oven followed by 200 hours of transient and static tests in an autoclave of 6.4 litre capacity. Vibration of the sensor at critical frequencies concludes the qualification test rigor.

During tests, data output is acquired and plotted using an HP 3052A data acquisition system. Reference pressure values originate from a Setra Model 204 capacitive pressure transducer and a model 301C readout, both maintained at laboratory temperature.

OVEN

During initial tests, sensors (as illustrated with the attached signal cable by Figure 1) were placed in-

FIGURE 1. Test Pressure Sensor With Attached Signal Cable.

side a laboratory oven with a 1/4-inch pressurizing tube connecting the test device with the high-pressure argon gas supply. A schematic of the test facility (Figure 2) shows components required for performance of required tests. For the fastest depressurization, a holder for a burst disk connects to the pressurizing line at point "A". Pressure variations for calibrations and other tests result from adjustment of the high-pressure regulator at the supply gas cylinder. Inside the tube furnace, the assembly of the test article plus coolant lines, temperature monitors, and other components was oriented as shown in Figure 3. In addition to the oven

FIGURE 2. Schematic of Facility for Testing Pressure Sensor.

FIGURE 3. Component Placement for Pressure Sensor Temperature and Pressure Transient Tests.

(shown in the background) used for heating the sensor, two adjacent tube furnaces (Figure 4) placed collinearly contain the signal cable which is bent to allow heating of three five-foot sections.

AUTOCLAVE

All qualification units were subjected to 200 hours of tests in a 6.4-litre autoclave. Prior to installation each unit was welded into a pressurizable enclosure to permit independent adjustment of the autoclave or the sensor pressure. Also, the enclosure simulates the thermal barrier afforded by a LOFT fuel rod. Next, about 12 feet of signal cable are wound on a 5-inch diameter mandrel and secured for insertion within the autoclave. Figure 5 illustrates components of the test unit mounted within the autoclave head. Fast response thermocouples measure temperatures within the enclosure near the sensor and also adjacent to the enclosure envelope--essentially the autoclave environment temperature.

During blowdowns, pressurized water usually at 650°F and 2700 psig is exhausted via a manually operated valve. The rate of expulsion of water/steam depends upon the area of the exhaust orifice. Most blowdowns were conducted with maximum attainable exhaust orifice area, although some were rate limited by restricting the exhaust area. For the majority of blowdowns, the exhaust valve was closed and the autoclave feed water pump activated immediately after depressurization. Output signal amplitude variations were measured during the

FIGURE 4. Ovens for Controlling Signal Cable Temperature. Oven for Sensor in the Background

FIGURE 5. Encapsulated Sensor and Signal Cable Mounted for Tests in Autoclave.

blowdown transient and for the following 15 minutes while water partially refilled the autoclave.

During time intervals between blowdown tests, the sensor signal output was monitored to determine its stability for relatively long time durations. During these times, sensor temperature and pressure were maintained constant at about 1850 psig and 650°F.

TEST RESULTS AND INTERPRETATIONS

As shown in the calibration summary of Figure 6, each sensor responds nearly linearly for pressure variations to 2500 psig and within the temperature range 75 to 800°F. Practically no signal hysteresis occurs for increasing ("*" data points) or decreasing ("+" data points) pressure. Calibration data obtained at the beginning and end of tests in the laboratory oven show the sensors continue to yield repetitive data after undergoing 500 hours of testing, an indication that long term signal drift remains limited.

FIGURE 6. Output Signal Amplitude for Pressure Applied to Test Unit. Sensor and Cable Heated.

Calibration data from each sensor show that as temperature increases, sensitivity decreases; however, behavior of the value of zero pressure output signal appears to be a characteristic particular to each sensor. Nevertheless, as each sensor output signal relates in a temperature-dependent way to the applied (reference) pressure, an algorithm was developed for each sensor to transform output signal values to indicated pressure. The algorithm, derived from calibration data, accounts for the variations of sensitivity and zero pressure signal output with temperature. Curves obeying second degree polynomial equations essentially describe the observed variation of sensitivity and zero pressure output signal with temperature. Transform algorithms derived from each of the calibration summaries verify that the sensor yielded repetitive calibration data nearly independent of conditions existing for the three different test conditions. Specifically, these conditions include the following: (1) the sensor only heated; (2) the sensor and cable heated; and (3) the sensor encapsulated in the pressurizable enclosure and installed inside the autoclave. The derived algorithm (Equation 1) transforms signal output data to indicated pressure as noted on the ordinate of data plots which occur subsequently:

$$P = \frac{E - K(T)}{M(T)} \quad (1)$$

where P is the indicated pressure, E is the sensor dc output voltage, and K(T) and M(T) are the temperature-dependent values of zero pressure output and sensitivity, respectively. Plots of K(T) and M(T) derived from each set of calibration data relate to coefficients (noted as A₀, A₁, and A₂) by the general equation:

$$K(T) = A_0 + A_1T + A_2T^2 \quad (2)$$

$$M(T) = A_0 + A_1T + A_2T^2 \quad (3)$$

where T is temperature and the values of the coefficients for (2) and (3) are distinct values for each set of calibration data.

For slow variations of sensor temperature between 650 and 250°F, the indicated pressure conforms within about ±2% of the reference (applied) pressure. In contrast, accelerated cooling of the sensor by directing cold nitrogen gas over its exterior results in significant pressure measurement errors. Figure 7 illustrates the response of the sensor as its temperature decreases with atmospheric pressure applied. A maximum negative error of 50 psi and a maximum positive error of 75 psi occur at respective elapsed times (after start of test) of 52 seconds and 175 seconds. The errors most likely result from sensor coil temperature differences which effectively unbalance the bridge, resulting in a signal output variation even though the applied pressure remains nearly constant. The minimum sensor temperature of 360°F occurs 39 seconds after application of the cooling gas. At that time, interruption of coolant gas flow allows the sensor to reheat to the initial temperature. Data is obtained for a total of about 18 minutes--time for the sensor to return to temperature equilibrium. Alphanumeric notations along the data curve specify the time elapsed after initiation of the test. The rate of data acquisition becomes intermittently slower as the test progresses.

FIGURE 7. Response of Sensor at Ambient Pressure for Rapid Decrease of Temperature.

The sensor responds to rapid cooling regardless of the magnitude of applied pressure, as shown by the variation of indicated pressure as noted in Figures 7 and 8. As occurred with zero applied pressure, the sensor yields an indicated pressure greater than the applied pressure by 11% eighty seconds after test initiation. Maximum rate of temperature change occurs 43 seconds

FIGURE 8. Response of Pressurized Sensor for Rapid Temperature Variation.

FIGURE 9. Rate of Temperature Change for Test Illustrated by Figure 8.

after application of the coolant. Figure 9 shows temperature rates occurring during the test. Table II giving a summary of test results witnessed for all test sensors during transient tests in the laboratory oven indicates operational responses to be expected for rapid temperature change. Subsequent to each temperature transient and after reaching thermal equilibrium, each sensor yielded an output signal closely equal to its initial value, an indication that transient tests do not cause permanent signal offset.

Both rapid and relatively slower depressurization of the sensors caused responses shown in Figure 10. In all cases, the sensors respond to the 1850 psi reduction of pressure. The maximum rate of pressure reduction, limited by the size of tubing and valve orifice area along the exhaust path, apparently prevents accurately determining the intrinsic response speed of the sensor; however, even though limited by exhaust capacity, a demonstrated 10 to 90% time response of about 40 milliseconds easily satisfies the requirement of 250 milli-

TABLE II

ERRORS INDUCED BY TEMPERATURE TRANSIENTS

Sensor Serial No.	S/N-01	S/N-03	S/N-04
TEST NO. 1			
Start Error	-7.6%	-1.3%	-1.6%
Maximum Error	-16% @ 48 s.	+13.7% @ 121 s.	+16.8% @ 96 s.
3% Error	<151 s; >195 s.	<60 s; >277 s.	<38 s; >210 s.
Max. Temp. Rates	-29°F/s; +12°F/s	-11°F/s; +3°F/s	-23°F/s; +6°F/s
TEST NO. 2			
Start Error	-7.5%	-2%	-1.5%
Maximum Error	-13.7% @ 52 s	+12% @ 168 s	+15.4% @ 88 s
3% Error		<57 s; >400 s	<40 s; >210 s
Max. Temp. Rates	-21°F/s; +12°F/s.	-10°F/s; +5°F/s	-14.5°F/s; +7°F/s
TEST NO. 3			
Start Errors	+19 psig	-1.1%	
Maximum Error	-50 psi @ 52 s. +75 psi @ 175 s.	+13% @ 85 s.	
3% Error	Not Applicable	<31 s; >244 s.	
Max. Temp. Rates	- 20°F/s; +4°F/s	-13°F/s +4°F/s.

FIGURE 10. Time Response of Sensor for Rapid Depressurization Via a Burst Disk.

seconds for LOFT use. For comparative purposes, one data trace shows time response of the SETRA reference pressure transducer (specified to respond at a 100 Hz rate) during depressurization.

For each of the sensors, very minor signal variations as shown in Figure 11 occur during heatup from 75 to 800°F of 16 feet of signal cable. Ideally, the indicated pressure should remain unchanged, for both the applied pressure and temperature of the sensors remain constant during these tests. As used in LOFT, the signal cable will be routed in a compact bundle with many other cables along the structure supporting the fuel assemblies. Consequently, the temperature along the cable will be nonuniform and probably less than the maximum temperature imposed during these tests.

Initial tests in the autoclave include calibration at temperatures of 75, 250, 400, and 650°F. As verifiable from the calibration plot of Figure 12, these data conform closely with calibration data obtained prior to sensor installation in the autoclave. Rapid temperature variations during maximum and controlled-rate blowdowns cause the sensors to indicate pressure inaccurately as shown in Figure 13. For data obtained (from all test sensors) during a maximum-rate blowdown, maximum errors of +14% and -11.3% of reading occur at times during the transients. The sensors remain within the LOFT specified accuracy limits of 3% for a period of about 13 seconds after initiation of a depressurization which creates temperature change rates up to -100°F/s, ten times as severe as expected to occur at the pressure sensor location during transients in the LOFT reactor. Even for controlled blowdowns, temperature change rates were up to 25°F/s, yet the pressure indicated by the sensor deviated by less than ±3% of reading as shown in Figure 14. Pressure measurements higher by 192 psi and lower by 57 psi than the applied pressure were observed during the test duration.

Table III summarizes data typical of the sensor response for the transient tests. Of significance, regardless of comparative rates, errors observed during tests in the autoclave were generally less than those caused by coolant gas in the oven facility. This further emphasizes the importance of minimizing temperature gradients in the sensor vicinity. In the autoclave, the pressurizable container enclosing the sensor provides a thermal mass tending to reduce gradients near

the sensor.

FIGURE 11. Effect on Sensor Output Signal of Heating Attached Cable.

FIGURE 12. Sensor Calibration After Installation of Sensor and Cable Into Autoclave.

On the basis of detailed, lengthy, and severe testing performed with pressure sensors intended for the LOFT reactor, the following conclusions appear warranted.

- All sensors yielded linear signal outputs for increasing pressure up to 2000 psig. Zero pressure output and sensitivity must be determined for each sensor by calibrations at specific temperatures.
- For improved accuracy, a temperature-compensating algorithm must be derived to transform output signal to indicated pressure. The second degree polynomial algorithm approximates the temperature dependence of the zero pressure output and sensitivity.

FIGURE 13. Sensor Response for Maximum Rate Depressurization in Autoclave.

FIGURE 14. Response of Test Unit for Controlled Rate Depressurization in Autoclave.

- Each sensor responds with distinctive characteristics to imposed temperature transients. Inaccuracy should be anticipated whenever the applied stimulus results in temperature differences between the two sensor coils. However, for temperature rates up to 100°F/s, the sensors have exhibited maximum errors less than 18% of reading. Furthermore, the maximum error usually occurs subsequent to reaching the maximum applied temperature rate. Because of this event sequence, quite accurate pressure measurements should result during initial phases of the LOFT blowdown.
- The exact response of the sensor to temperature transients depends upon the rate and magnitude of the imposed temperature excursion and significantly upon the complex spatial temperature field existing adjacent to the sensor envelope.
- Each sensor and associated signal conditioning electronics should be calibrated and subsequently used as an integral measuring unit, thus avoiding measurement errors caused by variations of electronic units.
- The sensor continued to give stable indications of pressure for periods of 72 hours at temperatures of 650°F and for applied pressure of about 1650 psig.
- Temperature variations of only the 16-foot signal cable affect the magnitude of the sensor output signal and result in nominal errors equivalent to 2% of sensor reading.
- For rapid depressurization, the intrinsic time response of the sensor easily satisfies requirements (less than 250 milliseconds) for LOFT.

TABLE III
ERRORS INDUCED BY TRANSIENTS IN AUTOCLAVE

Sensor Serial No.	S/N-01	S/N-03	S/N-04
TEST NO. 1			
Start Error	+1.2%	0.1%	-0.7%
Maximum Errors	-8.8% @ 19 s +12.5% @ 72 s	-11.3% @ 21 s +3.5% @ 62s	-7.2% @ 15 s +14% @ 56 s
3% Error	12 s	13 s; 39 s	13 s; 128 s
Max. Temp. Rates	-68°F/s; +22°F/s	-86°F/s; +45°F/s	-70°F/s; +28°F/s
TEST NO. 2			
Start Error	+1.5%	0.8%	-0.6%
Maximum Errors	-8.1% @ 19 s +13.5% @ 66 s	± 3%	-3% @ 20 s + 10% @ 61 s
3% Error	12 s		20 s; 117 s
Max. Temp. Rates	-65°F/s; +21°F/s	-26°F/s; +60°F/s	-24°F/s; +22°F/s