INSTRUMENT PROBE FOR MEASURING TEMPERATURE AND PRESSURE IN THE UPPER
PLENUM OF THE EBR-II REACTOR VESSEL

by

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ABSTRACT

Instrumentation has been installed to measure temperature and pressure of sodium in the upper plenum of the EBR-II reactor vessel. The instrumentation includes eight thermocouples, positioned at eight different elevations, and two pressure detectors. These instruments are mounted in a thimble-like probe, which replaces a plug in an auxiliary hole designed for the fuel-handling gripper. The probe extends from the operating floor of the reactor building through the primary-tank cover and the reactor vessel cover.

During the first year of operation seven thermocouples and the two pressure detectors operated satisfactorily. Immediately after installation, one thermocouple was found to be defective. The performance of these sensors was similar enough to instrumentation now in use in the plant protective system to permit their use as substitutes should the remaining initial-design devices fail.

Temperature measurements revealed a temperature gradient of 27 to 48°F from the bottom to the top of the upper plenum. Thermocouples 3 and 5 near the mid-elevation point indicate temperatures nearest the average reactor outlet temperature. The transient response, measured on a reactor scram, indicates lag times for these thermocouples of 4 and 2.5 sec, respectively. If 90% of the temperature change on a scram is assumed to be a step change, thermocouples No. 3 and No. 5 respond as though they have time constants of 10.1 and 6.3 sec, respectively.

Calibration of the pressure transmitter requires a correction because of gas trapped in the line from the upper plenum to the pressure sensors. With this correction, the calibrations match those of the original pressure sensors. Transient response

measured during a flow-coastdown test of the primary pumps indicated that the time constant is well below 1 sec.

I. INTRODUCTION

This report describes the design and performance, through the first year of operation, of an instrumented probe for measuring temperature and pressure of sodium in the upper plenum of the EBR-II reactor vessel. The probe was installed in January 1969 to provide spare sensors that would be available if the remaining suitable sensors in the primary tank failed. The original sensors in the primary tank are inaccessible for replacement. Several of the original temperature sensors and one of the two original pressure sensors have failed in service. Other sensors provided in the original design have been used as substitutes in the plant protective system.

The probe has eight thermocouples and two pressure sensors. To reach the upper plenum, the probe extends from the reactor-building operating floor through the rotating cover of the primary tank and through the reactor-vessel cover. It replaces a dummy plug that formerly occupied an auxiliary gripper hole.

II. DESIGN AND INSTALLATION

The instrument probe is a one-piece assembly 23-1/2-ft long, weighing 1060 lbs. See Fig. 1. It is mounted in the auxiliary gripper hole by use of a spring suspension. Figure 2 shows the orientation of the probe with respect to the reactor and the upper plenum. Radially, the probe is above grid position 14D6. The thermocouples are numbered such that thermocouple No. 1 is at the bottom of the probe and No. 8 is at the top.

A flanged connection is welded to the top surface of the primary-tank rotating plug. Welded to this main flange is a bellows. The other end of the bellows is welded to another, smaller, flange at the top of the probe to make a leak-tight seal. Four bolt-and-spring assemblies extend upward from the main flange to the probe flange to provide spring suspension and permit minor adjustment of the vertical position of the probe.

Fig. 1. Instrument Probe for Measuring Temperature and Pressure in the Upper Plenum of the EBR-II Reactor Vessel

Fig. 2. Orientation of Probe in EBR-II

The diameter of the body of the probe (the thimble) is increased immediately below the main flange. The thimble is filled with a shield plug in its upper portion, which extends through the primary-tank rotating plug. A spiral groove is cut into the shield plug to accommodate thermocouple leads and capillary tubes.

The diameter of the probe is decreased below the shield plug and pressure sensors so that it fits the hole in the reactor-vessel cover. A multiple-groove labyrinth type of seal, similar to those used on the control rods, is provided where the probe passes through the reactor-vessel cover.

Eight thermocouples are positioned so as to measure the temperature at eight different elevations in the upper plenum. The junction of each thermocouple is metallically bonded to a button that projects into the coolant stream. A thin-walled tube is welded between the button and the main body of the probe. The tube and button are similar to a conventional thermocouple well. The tube reduces heat transmission from the main body of the probe and thus prevents the temperature of the main body from influencing the button temperature. The junction and leads are 18-gauge chromel-alumel, and the insulating material is commercial-standard fiber glass. Leads are routed up through the thimble and terminate at a cold-junction compensator box outside the thimble near the pressure transmitters.

From near the top thermocouple button, a tube that is open to the primary sodium leads upward to the pressure sensors, which are Barton NaK-filled devices inside the thimble. Capillary tubes run from the sensor bellows to the transmitter bellows. All parts are of Type 304 stainless steel. Maximum rated pressure of the sensors is 200 psig, and working temperature is 700 to 900°F. Both sensors have a working range of 0-10 psig, corrected for the difference in elevation of the sensors.

Because of space limitations the pressure-sensor bellows cannot be located in the bottom of the instrument probe. Therefore, they are mounted in a staggered arrangement immediately above the first step in the probe thimble. The midpoint of the two pressure sensors is 62.3 in. below their transmitter bellows, which is 73.2 in. above the bulk-sodium liquid level.

The sensor is about 12 ft above the reactor outlet plenum. During installation of the probe, gas was trapped in the line connecting the sensor

and the plenum. No provision was made in the probe now installed to purge this trapped gas, which introduces a pressure-dependent error in the output signal. A spare instrument probe fabricated after the first unit was installed has a purge tube to release trapped gas and thus eliminate the error.

The possibility of leaks in the probe thimble or pressure-sensor lines was considered in the design. A leak probably would result in destruction of the thermocouples because of shorting, but the leaking sodium would be contained within the thimble. A probe wire was installed near the bottom of the thimble to indicate any leaks.

Motion-limit switches are provided for interlocks in the lifting circuit for the reactor-vessel cover. When the cover is raised (during fuel handling) these switches will detect movement of the probe due to its binding in the cover.

Before installation, the instrument probe was leak-tested with helium and given a pre-operational checkout, which included calibration of the instrumentation. A special written procedure was prepared for removing the dummy plug and installing the probe. The dummy plug was constructed so that it could be installed or removed in two sections. Because the instrument probe could not be so designed, it was installed as a unit. This installation, which was made possible by removing several structural members from one side of the control-rod-drive superstructure, was completed without difficulty.

III. PERFORMANCE

The instrument probe was installed in February 1969. Of the eight thermocouples and two pressure sensors, all except one (thermocouple No. 4) have operated satisfactorily for more than a year. Immediately after the probe was installed, thermocouple No. 4 was found to be defective.

A. Thermocouples

After pre-installation testing, the response of the thermocouples at both steady-state and transient conditions was evaluated.

1. Pre-installation Testing

The thermocouples were tested before the probe was installed in the reactor. A temporary thermocouple was placed on the outside of each button on the probe with contact with the button being assured by spring pressure. The probe was heated at one end (at the No. 8 thermocouple) by placing a pipe over the tip and wrapping the pipe with an electrical resistance heater. By varying the current to the heating element, four temperature conditions were established. Equilibrium conditions were attained at each of the four heating rates. Temperatures were measured with a high-precision potentiometer simultaneously on the external temporary and internal permanent thermocouples. Differences between the external and internal temperature measurements were caused, at least in part, by temperature gradients in the test heating arrangement; the probe was too large to permit use of a calibration furnace. Table I compares the thermocouple measurements at each of the four heating rates.

When the temporary external thermocouples were tested in a heated sand-bed type of calibration furnace, they read within $\pm 2^{\circ}\text{F}$ of the reference resistance thermometer.

2. Response

Typical sodium temperatures indicated by the seven functional thermocouples during 50-MWt operation are given in Table II. When the power level is reduced to zero, the temperatures indicated by the thermocouples returned to 700°F . The indicated temperature varies linearly with power. During run 33 the power and the flow were reduced by a factor of about 2; the temperatures were the same as for conditions at full power and flow.

a. Steady-state Response

For run 33A the sodium temperature indicated by thermocouple No. 8 was higher by 46°F than that for No. 1. The calculated subassembly outlet temperature in the outer blanket (over which the probe is located) was $700\text{--}710^{\circ}\text{F}$, well below the temperature of 829°F indicated by the No. 1

TABLE I. Results of Pre-installation Test of Probe
(Temperatures in °F)

Thermocouple No.	Heat Rate, amp							
	0		5		10		12	
	Thermocouple Int.	Ext. Test	Thermocouple Int.	Ext. Test	Thermocouple Int.	Ext. Test	Thermocouple Int.	Ext. Test
1	78.0	73.75	212.0	210.5	481.5	472.5	662.0	610.0
2	79.5	74.5	220.6	216.0	503.0	490.5	649.0	631.0
3	80.3	74.5	225.0	221.5	512.0	500.5	659.0	641.5
4	81.0	76.0	226.0	221.0	512.0	498.0	658.0	638.0
5	81.5	76.3	226.0	221.5	509.5	497.0	653.5	637.0
6	82.0	76.5	224.0	230.0	503.0	492.0	647.0	630.0
7	81.5	76.9	219.0	217.0	490.0	482.0	635.0	623.0
8	81.5	77.0	211.0	215.0	446.0	474.0	606.0	610.5

TABLE II. Coolant Temperatures Recorded by Probe at Full Reactor Power

Thermocouple No.	Coolant Temperatures, °F			
	Run 33A	Run 36A	Run 38A	Run 42
	3-10-69 50 MWt	7-7-69 50 MWt	9-23-69 62.5 MWt	5-15-70 50 MWt
1	829	814	853	825
2	837	815	854	823
3	844	829	858	826
4	---	---	---	---
5	858	829	878	846
6	860	846	881	856
7	873	862	880	857
8	875	862	880	857
T.C.8-T.C.1	46	48	27	32

(lowest) thermocouple. Mixing of coolant in the upper plenum as described in the following paragraph causes this difference. The reading of 844°F for thermocouple No. 3 was closest to the average reactor outlet temperature of 847°F. Measured subassembly outlet temperatures for core subassembly rows 1, 2, and 3* were below 850°F, except for three controlled-flow experiments. Subassembly outlet temperatures for rows 4,** 5, and 6 ranged from 850 to 899°F. Each thermocouple has a different temperature within the range given.

These results indicate that the lower half of the upper plenum provides the flow space for the low-velocity flow of the cooler sodium from the outer blanket. The coolant is warmed either by convective heat transfer or by mixing with higher-temperature coolant from the core. Flow in the upper half of the upper plenum apparently is from the core, where the higher-temperature and higher-velocity coolant originates. Such an interpretation is consistent with the results of the flow studies by Franklin Institute.¹

Thermocouples 7 and 8 are in the region of essentially static sodium between the reactor-vessel cover and the upper baffle, which is attached to the cover. Gamma heating in the cover and baffle may cause the higher temperatures sensed by these thermocouples. Temperatures of coolant from rows 4, 5, and 6 are similar to those read on thermocouples 7 and 8. To reach thermocouples 7 and 8, sodium would have to flow up through the clearance openings around the control-rod drive shafts and through a clearance gap of about 1/16 in. between the cover and the baffle. This explanation, however, is believed to be improbable because of the low pressure gradients.

Loading changes cause changes in measured temperatures, as can be seen from Table II. Experiments have flow rates ranging from 1 to 100% of the normal flow in a core position. Although the flow rates are selected to produce a temperature difference between adjacent subassemblies of no more than 100°F, the flow patterns in the upper plenum probably change, depending on the location of the experiments.

* Row 1 is the core center, and rows of higher number proceed radially outward.

** Defective thermocouple.

¹ D. T. Rymsa and G. P. Wachtell, Flow Model Study of the EBR-II, July 15, 1958 to December 2, 1960, Report F-A2201, Franklin Institute.

Changes in temperature with time for each thermocouple in relation to thermocouple No. 1 are illustrated in Figs. 3 through 8. There is some correspondence between variations. Temperatures were recorded on a high-speed recorder for run 36. The variation is 10-17°F for thermocouple No. 1, with less variation for the thermocouples higher in the plenum. Thermocouples 7 and 8 show very little variation, probably because they are above the upper baffle in nearly stagnant sodium.

The temperatures measured by thermocouples No. 5, 6, 7, and 8 are affected by the control-rod bank position. During run 38A this position was changed from 11 in. to 14 in. Temperatures recorded by thermocouples No. 5, 6, 7, and 8 increased by 3, 3, 5, and 7°F, respectively, and the subassembly outlet temperature above the outer-blanket position 16E9 increased by 6°F at the same time. The flow discharged from the control-rod subassemblies is discharged 3 in. higher in the upper plenum when the rods are raised from 11 in. to 14 in. With control rods down, the flow discharge is at the same height for control rods as for all other subassemblies. This change in height probably changes the flow-mixing pattern and thus changes the temperatures at the upper end of the probe and above row 16.

If a thermocouple on the probe were used in the reactor shut-down circuit, the measuring circuitry would have to provide for some smoothing or averaging of data. Further, the trip value for full-power condition would have to be adjusted for each loading change. This adjustment could be made by noting the temperature measured when the temperature in the secondary-sodium system indicates that the reactor is at full power and then making the adjustment.

b. Transient Response

The time constants of thermocouples Nos. 3 and 5 were measured by connecting the thermocouples to the post-incident-recall system. When a reactor scram occurred, an analog recording was made of flux and temperatures. Of the total temperature change on a scram, 90% is assumed to be a step change. The other 10% is decay heat. A time lag of 2.5 sec for thermocouple No. 5 and 4.0 sec for thermocouple No. 3 was observed. The thermocouples respond as though they have time constants of

Fig. 3. Temperature Variation During Steady-state Operation at 50 MWt
(Measured by Thermocouples No. 1 and No. 2)

Fig. 4. Temperature Variation During Steady-state Operation at 50 MWt
(Measured by Thermocouples No. 1 and No. 3)

Fig. 5. Temperature Variation During Steady-state Operation at 50 MWt
(Measured by Thermocouples No. 1 and No. 5)

Fig. 6. Temperature Variation During Steady-state Operation at 50 MWt
(Measured by Thermocouples No. 1 and No. 6)

Fig. 7. Temperature Variation During Steady-state Operation at 50 MWt
(Measured by Thermocouples No. 1 and No. 7)

Fig. 8. Temperature Variation During Steady-state Operation at 50 MWt
(Measured by Thermocouples No. 1 and No. 8)

6.3 sec for thermocouple No. 5 and 10.1 sec for thermocouple No. 3. The lag measured for the reactor outlet temperature (original thermocouple 507BK) was 4.6 sec and the time constant was 6.7 sec.

B. Pressure Transmitters

The pressure transmitters, as installed, give values for pressure that differ from those measured by the operating instrument.* Figure 9 indicates the measuring conditions for the new probe schematically. The original-design pressure sensor is mounted in the primary sodium. The difference in measured pressures between the new and old sensors is caused by helium trapped in the probe pressure-sensing line between the pressure sensors and the reactor outlet plenum.

1. Pre-installation Testing

The pressure transmitters were tested by using air for the input pressure. They met the manufacturer's specifications.

2. Steady-state Response

When the primary pumps are off, gas trapped in the probe pressure-sensing line extends from the sensor bellows down to an elevation determined by the quantity of gas trapped and the static pressure resulting from the bulk-sodium level. This pressure in the sensor line is 11 ft, 22 in. When the pumps are turned on the gas is compressed, so that for normal operation the trapped gas is contained entirely within the sensor-bellows chamber. This compression results in a pressure-dependent error in indicated pressure.

The error due to the trapped gas approximates a straight-line function from zero pressure up to the pressure at which the sodium enters the sensor bellows. Above this pressure, the error is nearly insignificant. Figures 10 and 11 show the increase in upper-plenum pressure with increased primary system flow, as recorded by the probe's pressure transmitters and

*The operating instrument is the one remaining sensor for measuring upper-plenum pressure of those provided in the original design.

Fig. 9. Measurement of Pressure with the Instrument Probe

by the operating pressure transmitter RI-PT-520A. The curve obtained from the probe's transmitters is normalized to the normal full-flow condition of 5.84 psig as indicated on the operating instrument. Figure 11 also shows the curve for a corrected response. The corrected curve is in reasonable agreement with that of the operating instrument. The corrected values were obtained as follows. Comparing the curves in Figs. 10 and 11 identifies the pressure at which the sodium enters the sensor bellows as about 2.7 psi, the point at which the two curves intersect. From this value and the volume of the 11.9 ft of the pressure-sensor line, it was determined that the trapped gas occupies about 7.7 ft of the line when the pumps are off. This information was used to generate the correction curve given in Fig. 12. Both sensor bellows are connected to the sensor line and are at different elevations. This arrangement introduces some variation in the correction and shows that the error is very small in the range where the instruments will be required to function if they are to be used in the plant protective system.

3. Transient Response

A flow-coastdown test was conducted to compare the transient characteristics of the operating pressure transmitter with those of the two instrument-probe transmitters. No attempt was made to evaluate the absolute response time of these transmitters. However, these data show that all three devices have similar response times for reactor operating conditions and that the time constants are well below 1 sec.

In Fig. 13, curve a shows the core flow as it changes with time when the power to the primary pumps is shut off. The signal is supplied by a core-inlet electromagnetic flowmeter. There are two core flowmeters and two blanket flowmeters. The signals from both core flowmeters were essentially the same.

Curve b in Fig. 13 shows the relative pressure recorded by the operating instrument. As expected, the pressure is proportional to the square of the flow. The upper-plenum pressure is about 6 psig at 100% primary flow. The flow is reduced from 100% to 25% within 14 sec after pump shutoff, and the upper-plenum pressure is reduced from 100% to 10% in a corresponding time.

Fig. 10. Variation in Upper-plenum Pressure with Total Flow of Primary Sodium
(Measured by the Instrument Probe)

Fig. 11. Variation in Upper-plenum Pressure with Total Flow of Primary Sodium
(Measured with the Operating Meter)

Fig. 12. Pressure Correction for Gas Trapped in Sensor Line of the Instrument Probe

Fig. 13. Response-time Test of Sensors of the Instrument Probe

Curve c in Fig. 13 shows the pressure recorded by one of the instrument-probe transmitters. The second transmitter produced nearly identical data. From time zero on the graph to 5 sec, the transmitted signal is reduced from 100% to nearly 0. This reduction corresponds to a pressure drop from 6 psig to about 1.4 psig. The signal does not extend to 0 psig because no correction has been made for the gas trapped in the pressure-sensing line.

The plant protective system includes a shutdown trip from overpressure in the upper plenum (7.5 psig). Response times of the instrument probe and the operating instrument for overpressure appear similar for pressure changes from 6 to 4 psig.

CONCLUSION

The temperature and pressure sensors have performed satisfactorily for more than a year. They measure conditions in the coolant immediately above the reactor fuel. Changes in coolant temperature caused by changes in reactor power level are proportional to the power level. Response time is nearly the same as that of the temperature measurement now used in the protective system. The pressure sensors are nearly the same as those of the original design in the range of intended use. Changes in pressure caused by changes in flow can be measured with the same accuracy and speed of response as with the original instrumentation.

Use of these devices in the plant protective system requires that several factors be considered. The temperature measured by any probe thermocouple is not precisely equal to the average reactor outlet temperature and may change with loading changes. In the protective circuit, the thermocouple will protect against overpower if the trip point is adjusted according to the temperature that the thermocouple measured at full power. This value can be determined by comparison with other devices to measure reactor power level. Steady-state variation in the temperature measured is large enough that some smoothing of data may be required to prevent unnecessary reactor trips. Setting of the pressure trip must take into account the effect of the trapped gas in the pressure sensing line.