ARGONNE NATIONAL LABORATORY
9700 South Cass Avenue
Argonne, Illinois 60439

PRESSURE TRANSDUCERS FOR
TREAT SODIUM LOOPS

by

L. E. Robinson and R. T. Purviance

Reactor Physics Division

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ABSTRACT

The Fast Reactor Safety meltdown program on advanced fuels in high-temperature sodium required the development of specialized instrumentation to measure transient pressure. Conventional, commercially available strain-bridge pressure transducers were successfully adapted to in-pile pressure measurement on high-temperature sodium-filled loops, through the use of a NaK liquid-column isolation technique. Developmental testing of the transduction system included steady-state and dynamic tests with a shock tube and a Mark-I integral sodium loop.

I. INTRODUCTION

Advanced phases of the Fast Reactor Safety fuel-meltdown program include exposure of fuel elements to power transients in high-temperature flowing-sodium loops placed in TREAT.¹ The very short rise-time characteristics of pressure waves generated in the liquid-metal coolant necessitated development of a specialized pressure-transduction system. Successful adaptation of commercially available strain-bridge pressure transducers resulted in a sensitive and durable sensor, which permits in-pile measurements of steep-fronted pressure pulses in high-temperature, sodium-filled systems. This report covers the initial development effort of the pressure sensor, which was directed toward transient instrumentation of the Mark-I integral TREAT sodium loop^{2,3} and the large TREAT sodium loop.⁴ The techniques that were developed are applicable to more advanced loop designs.⁵

The instrumentation techniques required extensive modifications of the basic pressure transducers. Primarily, the modifications changed the dynamic response characteristics of the transducers. Prior to modifications, the transducers possessed natural frequencies ranging from approximately 4 kHz for 1 atm full scale to 14-16 kHz for 10 atm full scale. The complete system, consisting of transducer, NaK-filled standoff tube, and the low-spring-rate isolation bellows, is highly dampened. Developmental testing of the transducer assemblies included steady-state checks and dynamic tests performed with assemblies mounted on a shock tube or on a Mark-I integral sodium loop.

II. TRANSDUCER INSTRUMENTATION DESIGN

A comprehensive listing of minimal criteria established for the design of adequate in-pile transient pressure instrumentation of the TREAT sodium loops is as follows:

1. Insensitivity to transient high-level neutron and gamma radiation fields.
2. Compatability with sodium at elevated temperatures for prolonged periods.
3. Capability of reliable operation at elevated temperatures for prolonged periods.
4. Capability of response to signal frequencies up to 1000 Hz and pulse widths as narrow as 1 msec.
5. High sensitivity to sodium pressure waves, in terms of output per psi input.
6. Linearity of pressure versus output over the full range of the sensor.
7. Miniaturization of sensor to permit close coupling with the sodium system within the space limitations of the secondary container of the integral loop.
8. Remote readout capability to permit signal transmission to the recording mechanisms in a distant control room.
9. Zero temperature drift, to accommodate the extreme temperature changes realized during thermal cycling of the loops up to 500°C.
10. Zero mounting stress on the transducer to eliminate spurious force-stress signals during experiments.
11. Zero temperature-gradient effect on operation under extreme temperature-gradient changes realized during a test.
12. Durability in thermal cycling, with the freezing-contracting effects of sodium upon the sensor eliminated.
13. Low noise, with the sensor and its excitation and signal leads adequately protected by shielding from spurious electrical pickup from ac-powered loop components and reactor accessories.
14. System containment integrity of the same order as that of the loop, and zero sodium leakage over the full range of possible loop operational conditions.
15. Mounting convenience to permit easy removal, replacement, and maintenance.

A solution satisfying the above design criteria was realized by an adaptation of commercially available transducers in wide use on conventional high-temperature systems.

The strain-gauge, bridge-connected pressure transducer was chosen as the sensor, a final choice being made between three competing and operationally equivalent devices. The transducer selected had been used in high-radiation fields at steady state with good success and has a maximum operational temperature rating of 600°F. It is about 1.5 cm in diameter by about 2 cm long. Each transducer is equipped with an integral mounting flange having a cross section about 1.5 mm square. The gauges have natural frequencies of 17-20 kHz and a frequency response that is essentially flat to 3000 Hz. In the as-received condition, they exhibit no detectable departure from linearity over the full range. These gauges can be excited by a constant 5-V dc voltage applied to the Wheatstone bridge composed of two active and two inactive unbonded strain wires, supported on a star-spring mounting. The preferred method of excitation for TREAT tests is by an ac carrier wave, using a demodulator-to-analog dc output amplifier. This method tends to clarify the output of the transducer by eliminating spurious electrical noise and reducing the transducer sensitivity to the high transient radiation levels in TREAT.⁶ With either method of excitation, the full-range output of the transducer is 21.5-24.5 mV of bridge unbalance. This is more than adequate for amplifier transmission to a distant recorder and can be applied directly to millivolt indicators.

III. DESIGN FEATURES

The transducer selected was adapted to the sodium system by incorporating it into an all-welded construction of Type 304 stainless steel, the material of the loops. Although such a transducer had never been successfully installed by welding, and the manufacturer stated that such treatment would render the transducer completely inoperative, a technique for installing the transducer by welding was developed. A combination of electrical monitoring of the transducers for bridge strain due to heating, the use of specially shaped water-cooled copper chills at the weld zone, and tungsten-inert-gas weldments of short segments was the key to successful weldments. This technique has been used successfully on more than three dozen transducers.

The all-welded assembly has provision for isolating the stainless steel diaphragm of the transducer from the molten sodium of the loop by a pressure-transmitting column of NaK. The NaK, in turn, is separated from the loop sodium by a multiconvolution welded metal bellows with a very low spring rate. This bellows serves as a thermal-expansion volume compensator for the NaK column and is fabricated of AM-350 stainless steel with

a leaf thickness of 0.005 cm, a 0.025-cm-thick diaphragm closure being placed at one end and a machined weld fitting of Type 321 stainless steel at the other end. The NaK filling is accomplished by evacuating the tube and bellows region through the

filling stem, then allowing NaK to fill the voided region through a valving and NaK container system. The filling tube is pinched closed and welded shut. Figure 1 presents drawings of this assembly showing the transducer welded into place, and the isolating bellows. Figure 2 is a photograph of a finished assembly.

The finished NaK-filled assembly is flange-mounted to a short-stemmed pressure tap on the loop. The high-temperature seal against leakage of sodium is achieved through use of a solid Type 302 stainless steel O ring, in deformative compression between the mounting flanges. The O ring is of rectangular cross section, with corners rounded on a 0.031-in. radius, and is precisely fitted into 15-30° trapezoidal grooves. Seal compression is obtained by tightening the mating flanges with carbon-steel bolts.

The transducer is protected from the 500°C design temperature of the loop by enclosing the transducer with an extended-surface copper radiator, within a thin-walled jacket through which cooling gas is circulated. This arrangement also eliminates spurious signals from external temperature gradients. Figure 3 shows a typical installation.

Excitation and signal leads are brought inside the cooling

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Fig. 1. Cutaway Drawings of Pressure-transducer Standoff Assembly. Upper portion: Cooling housing section. Lower portion: Flange and bellows housing.

enclosure to the transducer connections through modified miniature tubing fittings, which provide a tight seal against excessive leakage of the coolant gas. All leads are paired (input and output) for shielding against crosstalk and stray field electrical pickup.

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Fig. 2. Pressure-transducer Standoff Assembly for Mark-I Integral Sodium TREAT Loop

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Fig. 3. Inlet Pressure-transducer Standoff Assembly on a Mark-I Integral Sodium Loop

Electrical checkout tests and pressure recalibrations were made on the completed pressure-transducer standoff assemblies, with changes in sensitivity, linearity, and zero shift noted. These tests revealed no detectable change in linearity, an average of 2.5% shift in electrical zero reference, and small losses in full-range sensitivity. With experience in NaK filling, loss in sensitivity became undetectable ($<1\%$).

Strenuous thermal-cycling tests were performed on two prototype pressure-transducer standoff assemblies. These detectors were subjected to full-range pressures while attached to a simulated sodium loop operated over a temperature range from ambient to 500°C. Operation was satisfactory, with no detectable changes in linearity and sensitivity, and with no physical change or malfunction of the assemblies.

IV. DYNAMIC TESTING

A. Shock-tube Tests

To determine if the NaK-filled system could respond to a fast-traveling pressure wave, a shock tube was built and used to test the standoff transducer assemblies. Two TREAT large loop transducer assemblies, one 5 cm long and one 60 cm long, were tested on the shock tube. The 5-cm-long standoff assembly provided a good comparison, because its bellows and standoff length compared closely with those of the 5-cm integral-loop transducer assembly. The 5-cm integral-loop assemblies were not run on the shock tube because their curvature prevented mounting them directly on the shock tube.

Two pressure-tap ports were located directly opposite each other on the sides of the pressure tube, located at a distance from the shock-tube diaphragm calculated to be sufficient to ensure that a pressure wave produced by bursting the diaphragm would be fully developed. A transducer was mounted on one of the pressure ports and served as a monitor. The standoff transducer unit to be tested was mounted on the other port.

Experiments were run with 1 atm of air inside the test chamber, and some tests contained a volume of Welch Duoseal oil extending 5 cm above the transducer ports. Reservoir pressures ranged from 7 to 12 atm at the time of diaphragm rupture. The output of the transducers was recorded on an oscilloscope and a high-speed oscillograph. Figures 4-6 are typical oscilloscope results of tests performed without oil in the shock tube. In all three cases, the initial pressure in the reservoir was 11.6 atm. Table I gives detailed results of these tests. The figures show the ability of the highly damped standoff assemblies to reduce excitation of the transducer natural frequency. Oscillograph recordings of the 170-psig pressure bursts closely matched the oscilloscope photos.

Fig. 4

Oscilloscope Trace of Monitor Transducer Output in Shock-tube Test. Horizontal scale is marked in 0.5-msec divisions (origin is at left).

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Fig. 5

Oscilloscope Trace of 5-cm Standoff Transducer Assembly Output in Shock-tube Test. Horizontal scale is marked in 0.5-msec divisions (origin is at left).

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Fig. 6

Oscilloscope Trace of 60-cm Standoff Transducer Assembly Output in Shock-tube Test. Horizontal scale is marked in 0.5-msec divisions (origin is at left).

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TABLE I. Results of Tests with No Oil in Shock Tube

	Monitor (Fig. 4)	5-cm Standoff Assembly (Fig. 5)	60-cm Standoff Assembly (Fig. 6)
Initial pressure peak, atm	6.1	6.0	4.0
Rise time of initial peak, μ sec	50	300	~500
Measured peak of reflected wave, atm	9.0	9.0	9-10
Elapsed time from first peak to reflected wave, msec	2.2	2.2-2.5	2.2-2.5
Natural frequency of transducer, kHz	15-16	12	8-16

The output of the 5-cm standoff assembly closely matched that of the monitor for the initial pressure wave. The 60-cm standoff assembly showed about 75% of the actual initial peak. After the initial pressure wave, both standoff assemblies closely followed the 400-Hz natural frequency of the gas chamber.

The shock-tube experiments for the fluid-dampened conditions showed results similar to those of the empty-vessel experiments.

Vacuum-pump oil was put into the shock tube to a level 5 cm above the testing pressure ports. Because of the low compressibility of the oil, the reservoir pressures had to be reduced to the 7-atm range. Shocks initiated by reservoir pressures of 11.6 and 8.5 atm, with the shock tube filled with oil, shattered the bridge wires of both the monitor transducer and a 5-cm standoff assembly. The latter unit showed a rise time of less than 300 μ sec and recorded an estimated pressure of 20 atm at the time the bridge wires failed.

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Fig. 7. Oscillograph Recording from Shock-tube Tests with Oil. Reservoir pressure: 6.9 atm. (a) Monitor, (b) 5-cm standoff assembly, (c) 60-cm standoff assembly.

Figure 7 shows tracings of oscillograph records of the monitor, the 5-cm standoff assembly, and the 60-cm standoff assembly for shock-tube tests with the oil, performed with reservoir pressure of 6.9 atm. The response of the 5-cm assembly is close to that of the monitor; however, the response of the 60-cm assembly is considerably degraded from that of the short standoff assembly.

B. Response Testing with an Integral Sodium Loop

Early phases of testing standoff transducer assemblies showed they were sensitive to mechanical vibration shocks. To determine the frequency and order of magnitude resulting from a known shock, we performed another series of tests. An additional goal, of equal importance, was that of characterizing natural frequencies associated with the loop proper.

An integral loop was suspended from a gantry with reservoir pressure tanks mounted directly above the loop opening, and a quick-opening solenoid valve served as a pressure transfer mechanism. Test parameters included

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An integral loop was suspended from a gantry with reservoir pressure tanks mounted directly above the loop opening, and a quick-opening solenoid valve served as a pressure transfer mechanism. Test parameters included

pressure inputs from 1 to 60 psig. Fluid levels of 740 and 1640 cc of oil were used to provide comparisons with empty-vessel results. In normal use, the loop is filled with approximately 740 cc of sodium. In some of the loop tests, the loop was isolated mechanically by using a rubber hose approximately 5 cm long to connect the loop to the solenoid valve. The integral sodium loop and TREAT large loop transducer assemblies were tested on the Mark-I integral loop using an unmodified transducer as a monitor. Under the three conditions of no oil and 740 and 1640 cc of oil, all transducer assemblies showed good response to pressure inputs from the solenoid. Rise times investigated ranged from 10 to 160 msec.

The first experiments were performed with the solenoid valve coupled directly to the loop. With the high oil filling, frequencies of about 25 and 100 Hz were impressed on the output of the standoff assemblies. Only the 25-Hz signal was seen on the monitor transducer. Decreasing the oil volume to 740 cc increased the signal from about 25 to about 125 Hz. With the loop empty and undamped by oil, the signal shifted to approximately 400 Hz. Because of this shift with loop liquid level, the signal was attributed to vibration of the loop proper. The 100-Hz frequency, which was seen only on the standoff assemblies and did not shift appreciably with loop level, was

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Fig. 8. Oscillograph Recording of Output from 60-cm Standoff Assembly Excited Mechanically by Direct-coupled Solinoid Valve. Maximum amplitude: $\pm 0.5\%$. Full-scale transducer output. No pressure, empty loop.

due to vibration in the standoff assemblies. This signal could be excited mechanically by tapping the loop lightly. Figure 8 shows the output from mechanical excitation for the 60-cm standoff assembly on an empty loop. (This case gives the maximum excitation. Typically, with a pressure signal and dampening of the loop by 740 cc liquid, the signal is $\leq 1\%$ of full scale.) Banding the transducer tightly to the loop increased the frequency of the signal somewhat and increased its rate of decay. Isolating the loop with the rubber hose essentially eliminated the 100-Hz frequency.

Figure 9 is a drawing of a typical oscillograph recording from the dynamic loop tests. It

was obtained with a 5-cm standoff assembly, 740 cc of oil, and a maximum pressure of 0.6 atm. The solenoid valve was not isolated from the loop. Superimposed on the resonances of about 100 and 125 Hz is a signal of about 2000 Hz; for this standoff assembly, this result is in qualitative agreement with a predicted natural frequency of 2455 Hz calculated for an idealized model of the assembly.⁶

112-7560

Fig. 9. Oscillograph Recording of Output from 5-cm Standoff Assembly on Unisolated Integral Loop

to prevent actual pressure from the pump), and no 120-Hz signal was seen on the transducer output. Figure 10 shows the signal from the test-section inlet and outlet pressure-transducer assemblies on the Mark-I integral sodium loop for a test-section pressure drop of approximately 0.24 atm (corresponding to a 3-m/sec flow upward through the test section).

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Fig. 10. Oscillograph Recording of Inlet and Outlet Transducer Assemblies on Mark-I Integral Loop, Showing Pulsating Output of AC Electromagnetic Pump

Testing with the complete loop showed that there was a much greater effect on response from the mounting location than from the length of the standoff. The inlet transducer assembly (mounted directly on the inlet flow tube) responded as indicated in Fig. 9. However, an outlet assembly, which is not mounted directly on the outlet of the test section, but is on the outer pipe surrounding the concentric counterflow loop body,^{2,3} has much poorer response. A solenoid-initiated burst, producing a rise time of approximately 10 msec at the inlet assembly location, produced an output signal from an outlet transducer assembly delayed by about 25-50 msec behind that from the inlet assembly.

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