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FFTF SODIUM SERVICE
PRESSURE MEASUREMENT:
STATE-OF-THE-ART REPORT

December 1968

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UC-80, Reactor Technology

FFTF SODIUM SERVICE PRESSURE
MEASUREMENT: STATE-OF-THE-ART REPORT

By

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December 1968

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FFTF SODIUM SERVICE PRESSURE MEASUREMENT

STATE-OF-THE-ART REPORT

INTRODUCTION

This report defines the present level of technology of pressure instrumentation for liquid metal test facilities and nuclear systems, and outlines the characteristics of selected commercial models. The instruments are evaluated in relation to their potential for sodium service use in the Fast Flux Test Facility (FFTF).

Information presented was obtained through the facilities of the Atomic International Liquid Metal Information Center and the PNL Library, and from information solicited from transducer manufacturerers and users.

This report is not intended to define the state-of-the-art for the complete spectrum of pressure instrumentation. Transducers not considered are those with temperature limitations of less than 600 °F and those designed for low pressure or vacuum service.

SUMMARY AND CONCLUSIONS

A state-of-the-art survey was conducted to determine pressure instrumentation technology. This survey provides a basis for the evaluation and development of pressure instrumentation for FFTF sodium in vessel and piping service.

Information obtained indicates that current pressure measurement technology is not sufficiently developed to provide devices suitable for FFTF in vessel applications. However, commercial devices, with unestablished reliability, are available for FFTF sodium piping pressure measurements. It is concluded; (1), Strain gage, linear variable differential transformer, and variable impedance electromechanical transducers may be used for sodium piping system applications and for use in an in-vessel NaK volumetric scheme if the

temperature compensated range can be increased, radiation effects minimized and temperature sensitivity reduced; (2), A NaK volumetric transducer may be used for in-vessel applications if the envelope size of the sensing element can be reduced and the temperature effects minimized; (3), NaK volumetric and force balance transducers may be used for pressure piping applications if sufficient proof testing is performed to verify operating capabilities and to establish reliability.

DISCUSSION

FFTF is an integrated system intended for fuels and materials evaluation studies. This complex includes a fast reactor core and several heat removal systems. From the standpoint of pressure measurement, each of these systems present unique requirements, and each represents a different range of proposed operating conditions and instrumentation criteria.

At the present time, operating conditions and criteria for the two major categories of FFTF transducer applications; namely, in-vessel and sodium piping, have not been definitely established. However, based on present scope, in-vessel conditions and criteria include the following: primary sodium coolant temperature to 1200 °F and closed loop sodium coolant to 1400 °F; pressure ranges from 0-3 psig to 0-150 psig; neutron and gamma flux levels to 8×10^{15} n/cm²/sec; and 1×10^{10} R/hr, respectively; system accuracy within 3% over full pressure range; envelope size of sensor of 1-in. diameter, 3-in. length; response time of less than 2 sec; electrical leads exiting the reactor; and a cost which permits replacement at scheduled intervals. Operating conditions and criteria for sodium piping include primary sodium coolant temperatures to 900 °F; pressure ranges from 0-10 psig to 0-150 psig; gamma levels to 5×10^5 R/hr; system accuracy

within 2% over the full pressure range; and response time of less than 3 sec.

While it is recognized that many techniques exist to measure pressure, this report will be limited to those which have potential FFTF use. For convenience, these instruments will be categorized according to their principle of operation; namely: electromechanical, volumetric, and force balance.

ELECTROMECHANICAL TRANSDUCERS

Severity of operating environments experienced in the nuclear industry has in the past limited the use of electromechanical transducers for pressure measurement. With special adaptation, electromechanical units are in use at EBR-II and in the SNAP-8 and NERVA projects.^{1,2} Electromechanical transducers are devices which convert the physical phenomena of pressure, using a force summing member, into mechanical deflection and ultimately into a proportional electrical signal using a conversion element.

Force-summing members normally consist of thin flat or convoluted diaphragms or bellows.

Conversion units for potential FFTF transducers employ variable resistance and variable inductance design principles. For convenience, transducers using the variable resistance principle are referred to as strain gage transducers and those employing the principle of variable inductance are referred to as linear variable differential transformer (LVDT) transducers and variable impedance transducers.

STRAIN GAGE TRANSDUCERS

Strain-gage pressure transducers have been developed to the stage where commercial models are readily available. A review of transducer literature indicates these devices have the following capabilities:

- Temperature: Readily available transducers are operable at temperatures to 400 °F. Recently developed units have been designed for operation to 750 °F.
- Radiation: With the use of standard materials, the neutron and gamma tolerances are 10^{13} n/cm² and 10^8 rad respectively; where radiation hardening is a factor in the transducer design, the neutron and gamma tolerances have been increased to 10^{18} n/cm², and 10^9 rad, respectively.
- Linearity and Hysteresis: 1% of full range output at rated excitation
- Thermal error: 0.02% full scale/°F
- Response time: 3 microseconds full scale
- Size: Less than 1.50 in. in diameter and 3 in. in length

The operating principal of a strain-gage transducer is based on the resistance change of a strain gage, attached directly or indirectly to the force summing member. This resistance change is proportional to the measured pressure.

Advantages of this type device are its wide range of application and miniature size. The disadvantages are the low signal output (normally less than 100 millivolts) and radiation sensitivity.

Bonded strain-gage transducers (Figure 1) utilize a Wheatstone bridge configuration consisting of four resistive elements that are bonded with either organic or ceramic adhesive to a rigid insulating base wafer. For temperatures between 400 and 600 °F the transducers contain copper-nickel wire that is bonded to a bakelite or glass fiber carrier base material with phenolic or bakelite adhesive.^{3,4} Frequently used in this same temperature range is a copper-nickel foil utilizing ceramic bonding. When temperature conditions are expected to approach 600 to 700 °F, the common practice is to employ the unbonded strain-gage technique. This type transducer, shown in Figure 2,

FIGURE 1. *Bonded Strain Gage Transducer*

FIGURE 2. *Unbonded Strain Gage Transducer*

utilizes a four active arm Wheatstone bridge strain gage coupled to a force-summing diaphragm. The materials of construction include platinum alloys for the strain gage windings, sapphire for the supporting post and small amounts of Inconel-X, boron-free glass, and ®Ceramacite.⁵

Strain gage pressure transducers can be used in radiation environments only when the basic materials have been carefully selected. There are five types of damage which must be considered:

- Weakening of the bond between the bridge legs and the base;
- Breakdown of the insulation between the bridge-leg terminals and the metal support of the base
- Changes in the resistance of the resistant element
- Changes in sensitivity of gage factor due to aging and flexing
- Changes in lead-in insulating resistance.

Reviewing reports of various radiation effect experiments conducted with strain gage pressure transducers, it appears that some are capable of operating in a nuclear environment involving neutron flux levels from 10^{15} to 10^{18} n/cm² and up to 10^9 rads of gamma radiation.^{3,5}

It is generally concluded in these reports that due to the difference in construction and the variation of manufacturers' processes, each transducer must be carefully studied to determine the mechanism of damage that places limitation on the use of a certain transducer in a nuclear environment.

Of major concern in the use of strain gage pressure transducers in the FFTF is the error induced by ambient temperature variations and temperature gradients, although this is not as significant as the temperature and radiation tolerances.

® Consolidated Electrodynamics Corp., Monrovia, California

Ambient temperature errors are of two kinds: First, the zero setting may shift and second, the calibration factor, or sensitivity may change.

To minimize thermal zero shift, the first requirement is to select mechanical components to ensure that thermal expansions nearly balance. Since differential expansion cannot be totally eliminated, that which remains is normally electrically compensated using temperature sensitive resistors. Using these techniques, the error induced by zero shift can be held to 0.01% of full range/°F.^{6,7}

To minimize thermal sensitivity error, transducer components are selected which exhibit a minimum change in modulus of elasticity as a function of temperature. Since only a limited amount of correction can be made by design procedures, electrical compensation using temperature sensitive resistors is also employed. Thermal sensitivity error of approximately 0.01% of full range/°F over the temperature compensated range can be expected.⁶

In addition to the effects of ambient temperature variations on strain gage transducers, temperature gradients can cause errors which far exceed those previously predicted. Normally, the resistors used to compensate for material temperature dependency are located near the electrical connections.⁷ The temperature that these resistors experience during transient temperature conditions differs from that experienced by the force-summing member and conversion element. Consequently, it is sometimes advantageous to remove the compensating resistors as the error induced by temperature gradients on a compensated transducer may far exceed the error due to temperature dependency of the materials used.

During normal reactor operation, transducer temperature gradients result from gamma radiation. This energy raises the

temperature of the transducer components to a level dependent on the component size and heat capacity. If results of gamma heating are not considered in the transducer design, large errors may occur.

Commercially available strain gage pressure transducers, which typify the state-of-the-art, are manufactured by Consolidated Electrodynamics Corporation (CEC) and Statham Instruments, Inc.

The CEC, Model 4-361 pressure transducer is designed to operate in a high temperature nuclear environment. This unit is temperature compensated from 77 to 600 °F and is operable between -423 and 700 °F. Combined linearity and hysteresis effects are within $\pm 0.75\%$ of full range output at rated excitation.⁶

Materials used in this transducer are compatible with neutron and gamma radiation levels to 10^{18} n/cm²; 5×10^9 R.^{3,5,8}

In tests conducted by Phillips Petroleum Corporation,⁹ 17 CEC transducers of various pressure ranges were exposed to a radiation pulse for a 13 μ sec duration at a radiation level of 1.4×10^{15} thermal neutrons and 9×10^{10} R/hr gamma radiation. The results of these tests showed that transducer sensitivities to transient radiation were generally less than 10% of full scale output at rated pressure. However, because of the differences between individual transducer sensitivities, it was not possible to state which type of transducer was best suited to the radiation environment or to predict the exact sensitivity of any transducer from knowledge of the performance of similar transducers.

Changes in operating characteristics of Model 4-361 when subjected to neutron and gamma radiation is given in "Summary of Radiation Test Effects."⁵

Statham Instrument Co. Models PA 732 and PG 732 pressure transducers were specifically designed for radiation service.

These instruments have a temperature compensated range to 600 °F and a combined linearity and hysteresis error of less than $\pm 0.75\%$.^{6,10}

Irradiation tests have been conducted on Statham pressure transducers with results similar to those for CEC, Model 4-361.^{9,11}

Statham Instruments also manufactures a semiconductor transducer which is a bonded strain gage with doped silicon as the gage material. Using techniques similar to electronic microcircuitry, these transducers are manufactured by a vacuum deposition process. This type device is operable to 600 °F and has been chosen as the reference design for Project NERVA.^{10,11}

DIFFERENTIAL-TRANSFORMER AND VARIABLE IMPEDANCE

Pressure transducers incorporating conversion units using variable impedance and LVDT principles are commonly used to measure pressure in rocket engine propellant systems, wind tunnels, missile supporting systems and to measure air shock associated with nuclear detonations.¹² The capabilities of readily available and recently developed LVDT's and Variable Impedance Transducers are as follows:

- Temperature: Standard models are operable at temperatures to 450 °F. Recently developed units are designed for operation at temperatures to 1000 °F.
- Radiation: Conventional transducers can withstand neutron exposures to 1×10^{14} n/cm² and gamma exposures of 4×10^6 rads without excessive damage; upgraded transducers are expected to have neutron and gamma tolerance of approximately 1×10^{18} n/cm² and 1×10^9 rads, respectively.
- Linearity and Hysteresis: 2% of full range output
- Thermal error: 0.01% full range/°F

- Response time: 2 μ sec full
- Size: 2 in. diam - 3 in. long

The LVDT Transducer (Figure 3) is a device which produces an electrical output signal proportional to the displacement of a movable core. This movable core is of magnetic material and is directly attached to the force-summing member. Other components of the LVDT transducer consist of a number of coils axially spaced on a cylindrical coil form through which the core is positioned. When the primary or center coil is energized with alternating current, voltages are induced in the secondary coil. The secondary coils are connected in series opposition so that the two voltages of the secondary circuit are opposite in phase; the net output of the transducer is therefore the difference between these voltages.

Variable-impedance pressure transducers, as shown in Figure 4, utilize a non-magnetic force summing diaphragm and a single active coil excited by a radio-frequency (rf) generator. As the diaphragm with its surface perpendicular to the coil axis is moved toward one end of the coil, an induced current is generated in the diaphragm and the electrical characteristics of the coil change. The magnitude of this induced current increases as the diaphragm is moved closer to the coil. Since energy is dissipated as the induced current flows through the resistance of the diaphragm, the power furnished from the rf generator increases as the diaphragm moves toward the coil. The variations of induced current in the diaphragm as a function of its position correspond to variations in both the effective resistance and inductance, which the inductor represents as a load on the generator.

Advantages of the LVDT and variable impedance transducers are their inherent temperature stability over wide ranges (77-1000 °F), high output signal (140 MV - 2 V dc) and miniature size. The disadvantages are radiation sensitivity and the necessity of signal conditioning units.

FIGURE 3. *Differential Transformer Transducer*

FIGURE 4. *Variable Impedance Transducer*

Results from research conducted with a wide variety of conventional LVDT and inductance type transducers indicate that most transducers can withstand integrated fast neutron exposures of 1.1×10^{14} n/cm² and gamma exposures of 4.2×10^6 rads without excessive physical damage or changes in electrical characteristics.^{3,4} When levels of ionizing and nuclear radiation are increased to 4×10^{15} n/cm² and 4.3×10^8 rads gamma, mechanical damage became apparent in the form of case rupture, caused by gas evolution of potting compounds.^{3,4}

Radiation tolerances for upgraded high temperature LVDT and variable impedance transducers have not been established conclusively by tests. However, their tolerances have been estimated to be approximately 1×10^{18} n/cm² and 1×10^9 rads.¹³ These units use ceramic bobbins, gold, silver, platinum, platinum alloys, or beryllium copper as the coil materials; Inconel X, Carpenter A-286 or stainless Type 17-4 PH as the diaphragm materials and small amounts of aluminum oxide, zirconium oxide and ®Secon Type "D" ceramic insulation.

Common to all electromechanical transducers and of concern in the use of the LVDT and variable impedance transducers for FFTF applications, is the system error induced by ambient temperature variations and temperature gradients. Cause of these errors is similar to those outlined for strain gage transducers, however, the compensating mechanisms differ substantially.

Variable impedance transducers use an inactive coil for temperature compensation. The active and inactive coils are so located in the transducer housing that balanced impedance exist except when the diaphragm associated with the active coil deflects with pressure. Using an inactive coil, the thermal zero shift is limited to 0.02% of full range/°F and thermal sensitivity to less than 0.003% of full range/°F.¹²

®Secon Metals Corp., White Plains, New York

An LVDT temperature compensating scheme utilizes a temperature sensitive resistor located in the transducer to provide a reference current. The algebraic sum of the currents of the secondary transformer is then compared to the reference current to obtain the system output as a function of pressure. Thermal zero and thermal sensitivity shift expected is approximately 0.004% of full range/°F.¹⁴

Commercially available LVDT and variable impedance transducer which typify the state-of-the-art are manufactured by Consolidated Controls Corporation (CCC) and Kaman Nuclear.

Kaman K-3011 variable impedance pressure transducers have been specifically developed for pressure measurements in high temperature (1000 °F) liquid metal systems. According to the manufacturer, the operating temperature range of this instrument is from 77 to 1000 °F. The zero shift and non-linearity are less than 0.03%/°F and ±1% of full range output, respectively. Tested radiation tolerance of this device is undocumented. This transducer, when used with the Kaman M-100 series matching network, may be separated from the electronic circuitry and recording equipment by distances up to 1000 ft.

Consolidated Controls Corp., (CCC) Series 41M LVDT type transducers have been developed to provide accurate pressure readings under the most severe applications, including nuclear radiation. These units are claimed to be unaffected by nuclear radiation, are operable from -430 to 900 °F, and can maintain a 1% accuracy over extreme temperature spans.¹⁴

The electronic circuitry, necessary to supply excitation to the transformer and to rectify and condition the output signal, is packaged separately for use outside the severe environment.

In experimental programs conducted by NASA, CCC Model 41M operated satisfactorily in a liquid metal system at

temperatures to 750 °F and pressures to 300 psia.¹⁵ Output of the instrument over the full pressure range was 0-160 mV dc; time response of approximately 0.002 sec; and accuracy was rated at $\pm 1/2\%$ (at low temperature) to $\pm 2-1/2\%$ (at high temperature) of full range over the 0-750 °F operating temperature span.

VOLUMETRIC TRANSDUCERS

Commercially available volumetric transducers have been widely used in the nuclear industry where temperatures of the process media exceed 1000 °F, radiation levels at the point of pressure measurement are high, size restrictions do not exist, and response time is not critical.¹⁶⁻²¹

The capability of volumetric transducers is somewhat dependent on the application, length of capillary and type of transmitter; however, the following is representative of the capability of readily available units.

- 1) Temperature: With mercury as the fill fluid, temperature at the sensing element is limited to 650 °F; with NaK as the fill fluid, pressure measurements can be made at temperatures to 1400 °F.
- 2) Radiation: Since all electrical components and radiation sensitive materials are remotely located, radiation tolerance is based on the materials used for the contacting seal only. Commonly used materials have been tested to 10^{23} n/cm² with no serious degradation.
- 3) Linearity and Hysteresis: 1% full scale
- 4) Thermal effects:* 0.002 psi/°F at contacting seal; 0.001 psi/ft/°F along capillary; 0.003 psi/°F at transmitter.
- 5) Response time: 3 sec full scale
- 6) Size. Contacting seal, 5.125 in. in diameter, capillary line 0.1875 in.; transmitter dimensions, 6 in. x 8 in. x 4 in.

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* Thermal effects for volumetric transducers are fixed with the system design and are independent of the pressure range.

The basic elements of such a volumetric transducer, as shown in Figure 5, consists of a transmitter, providing a pneumatic or electrical signal output, a process media contacting seal, and a fluid filled interconnecting line between the seal and the transmitter. Materials of construction include Type 316 SS or Hastelloy-B as the contacting seal; and Type 304 SS for the pneumatic or electrical actuating element.²² The fill fluid commonly used is a mixture of sodium and potassium (NaK). This material is used because of its high boiling point of 1443 °F, low freezing point of approximately 12 °F, and satisfactory temperature coefficient of expansion.

Advantages of a volumetric transducer are its ability to provide pressure measurements where process temperatures of 1200 °F exist and its insensitivity to radiation. The disadvantages are the size of the contacting seal (approximately 5 in. in diameter); size of the transmitter (6 x 8 x 4 in.); temperature limits of the transmitter (300 °F), and slow response time (1 sec/10 ft of capillary).

FFTF in-vessel pressure measurement requirements have been defined, which include size restriction of sensing element or contacting seal to 1 in. diam; termination within the reactor of all leads excluding electrical, and response time of the system of less than 3 sec. At present, no commercially available volumetric transducers fulfill these requirements. However, it appears that with suitable upgrading, a NaK volumetric transducer can be developed which would satisfy FFTF in-vessel pressure measurement requirements.

Major problems to be solved include:

- Material compatibility and size limitation of the contacting seal
- The effect of temperature gradients along the capillary line and at the contacting seal

FIGURE 5. *Fluid Filled Capillary System*

- Response time
- Transient behavior
- Size limitation of the transmitter.

To obtain a satisfactory contacting seal it is necessary that (a) the material selected exhibit mechanical properties where large deflections can be obtained with minimum stress; (b) the corrosion rates of the material be tolerable when exposed to high-temperature liquid metal; (c) the material compatibility with other reactor components be satisfactory; and (d) the geometry of the unit be compatible with the process flow channel. In addition, the contacting seal unit must have sufficient volumetric displacement capacity to absorb by its outward movement the increased volume of NaK caused by heating the seal and capillary by the process media. This must be accomplished without overstressing the seal and without introducing serious nonlinear effects on the system's calibration.

Heating a liquid filled closed system implies an increase in internal pressure, and a NaK filled instrument is no exception. The effect of ambient temperature is of utmost concern in obtaining suitable instrument accuracy. With a fixed contacting seal geometry and capillary length, the temperature effect on the system calibration can be minimized by limiting the volume of NaK that is heated.

One general approach used to reduce this volume is to minimize the capillary bore size to a point not adversely affecting system response time and where plugging problems are not incurred. Normal capillary bore sizes in commercial instruments vary between 0.030 and 0.090-in. depending upon the application. Capillary bore and length provide the major flow restricting element in this system. Response time, as a function of the capillary size and system parameters, can be predicted mathematically.²⁵ A typical time response for

a volumetric transmitter with a 0.093 in. ID capillary tube is approximately 1 sec/10 ft of capillary. The relationships derived in reference 24 and 25 indicate that the tube diameter has a pronounced effect on the transient behavior. Pressure oscillations can be minimized without introducing any signal delay if a system is properly damped.

The choice of a transmitter design to permit use of the smallest possible seal unit is one that will require the least sensor displacement with full range pressure input. The transmitter portion of the system is designed to have a spring rate at least 100 times that of the seal unit. Locating the transmitter in a more favorable temperature and radiation environment will permit maintaining system calibration despite extreme temperature changes at the seal unit. Selection of a transmitter will vary according to the application; however, upgraded electromechanical transducers are prime candidates.

Commercially available NaK volumetric transducers which typify the state-of-the-art are manufactured by Taylor Instrument Co., and ITT-Barton Equipment. Transducers manufactured by Taylor Instrument Company are a commonly used alkali metal pressure measuring device for high temperature use.¹⁹ A number of Taylor transducers have been evaluated at ORNL and have been used at EBR-II, S.C.T.I., and Enrico Fermi.^{27,28} Reports on the use of these transducers indicate that the majority performed satisfactorily. However, failures did occur at EBR-II when the capillary bore became plugged; and in some uses, the instruments could not be recalibrated to determine transducer errors.

The Barton Model 305 Sealed System, a differential pressure system, consists of a remotely located differential pressure unit, two sections of capillary and two sensor assemblies. The sensor bellows, capillary tubes and differential pressure unit housing are filled with NaK to form the sealed system. According

to the manufacturer, the temperature capabilities are 1200 °F at the contacting seal and 400 °F at the differential pressure unit.

FORCE BALANCE TRANSDUCERS

Force or null balance transducers have been developed primarily for nuclear applications.²⁹⁻³⁵ This type transducer permits operation over a wide temperature range without serious temperature error since, with essentially zero displacement, changes in the spring constant of the contacting seal does not affect the transducer accuracy.

A search of available literature indicates that the two types of force balance transducers, which are distinguished by their application, namely, in-vessel or pressure piping, have the following capabilities.

- Temperature: In-vessel units have operated satisfactorily at temperatures to 1000 °F; pressure piping units have been designed to operate at temperatures to 1600 °F at the contacting seals.
- Radiation: Since radiation sensitive components are remotely located for in-vessel units, the radiation tolerance is limited by the materials used for the contacting seals and the electrical contacts. Materials commonly used have been tested to 10^{23} n/cm² with no serious degradation. Since high radiation levels are not expected in pressure piping, no radiation tolerance has been established.
- Linearity, Hysteresis and Thermal effects: Undefined for in-vessel transducers; ±2% of full range for pressure piping units.
- Response time: Undefined for in-vessel; <10 μsec, pressure piping.
- Size: 0.25-in. diam for in-vessel; 2 in diam, 16 in. length, for pressure piping.

The principle of operation of one of the more recently developed in-vessel null balance transducers, as shown in Figure 6, is the separation of two electrical contacts by inert gas; one contact located on a stationary probe and the other attached to a pressure sensing diaphragm. The electrical contact is so adjusted that with slight excess of pressure on the contact side of the diaphragm, the contact will open. At the instant of contact opening, the pressure is equal to the process pressure plus the slight differential pressure required to open the contact. The differential pressure is usually small relative to the process pressure and can be disregarded.

Operation of a typical pressure piping force balance transducer, as shown in Figure 7, is based on the use of an LVDT to measure the deflection of a force-balancing spring. The spring, which is connected by means of a rod to the process media contacting bellows, limits the deflection of the bellows to approximately 0.05 in.³⁶

Advantages of the force or null balance transducer is its ability to operate over wide temperature ranges with little temperature error, and for in-vessel, its insensitivity to radiation and miniature size.

The disadvantages of an in-vessel force or null balance transducer is the requirement for long interconnecting gas lines and slow response time, and for a pressure piping unit the disadvantages are the physical size, and the necessity to maintain components, other than the contacting bellows, at temperatures below 400 °F. Commonly used materials of construction for the contacting diaphragm or bellows include Inconel-X, Type 316 SS and 17-4 PH, Monel, or nickel.

To create a near pressure balance or to restrict deflection of the contacting member, an inert gas (normally helium), or a

FIGURE 6. Force Balance Transducer for In-Vessel Use

FIGURE 7. Forcing Balance Pressure Transducer for Use on Pressure Piping

mechanical mechanism is used. This mechanism consists of a calibrated ring, compression spring, or compression bellows of stainless steel, Inconel-X, or phosphor bronze. Where a calibrated ring is used, linearity for deflection versus load of 1% full range has been attained. The accuracy of the pressure piping transducer, however, is not only dependent on the type of calibrated mechanism, but also on the accuracy of conversion unit. This unit, similar to those used in electromechanical transducers, is temperature sensitive and an error of 0.001% full range/°F can be expected.

Force balance transducers have been designed for in-vessel applications; however, to date these units have been limited to measurement of fuel pin fission gas buildup. Since this measurement is necessary only periodically, no effort has been expended to provide a unit where continuous data is available or where response time is critical.

Commercially available force balance transducers, limited to pressure piping units, are manufactured by MSA Research and Moore Products. In-vessel transducers have been fabricated by Atomics International and General Electric.^{30,31,37}

MSA Research standard pressure transducers are designed to detect the pressure in a high temperature liquid metal system. These units, for pressure piping applications, use Inconel-X for the contacting bellows and Ni-Span C for the force balancing spring. A linear variable differential transformer, manufactured by Automatic Temperature Control Company, is used to detect the spring deflection. According to the manufacturer, these transducers have pressure ranges from 0-10 psi, either gage or absolute; are operable at temperatures to 1600 °F, and have an accuracy to within ±2%. Greater accuracy can be obtained if the unit can be calibrated in place at operating temperatures.

Moore Products Model 15 pneumatic pressure transmitter is designed for continuous operation at temperatures to 800 °F. These units have, however, operated at temperatures to 1400 °F and would be expected to operate satisfactorily for one year at 1200 °F. They are constructed of Type 316 SS, with a maximum operating pressure of 225 psi at 1000 °F. According to the manufacturer, it is expected that linearity of 0.5% of full scale can be achieved.

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APPENDIXGLOSSARYPressure Range

Pressure range or rated pressure is defined as the maximum difference in pressure between the transducers rated design pressure and reference chambers within the transducer.

Residual Unbalance

Residual unbalance or zero balance is defined as the electrical output of the transducer at zero gage or absolute pressure, rated excitation and room temperature

Sensitivity

Sensitivity is defined as the algebraic difference between the output voltage of the transducer at rated pressure, rated excitation, room temperature, and the residual unbalance

Calibration Curve

Calibration curve is defined as a plot of the transducers output voltage as a function of pressure for one continuous ascending and descending positive pressure

Linearity

Linearity is defined as the maximum deviation of any data point on the calibration curve from the best straight line

Hysteresis

Hysteresis is defined as the difference between the output of a transducer for ascending positive pressure and the output for a descending positive pressure for one cycle

Temperature Calibration

Temperature calibration is the recording of the stabilized zero and full range output readings at (1) room temperature, (2) lower extreme of the compensated temperature range, (3) center of the compensated temperature range and (4) upper extreme of the compensated temperature range

GLOSSARY (contd)Thermal Zero Shift

Thermal zero shift is defined as the quotient of the difference of the output between any two zero values obtained in Steps 2, 3, and 4 of temperature calibration and the algebraic difference of the compensated temperature range. Thermal zero shift is expressed as a percentage error per thermal degree.

Thermal Sensitivity Shift

Thermal sensitivity shift is the quotient of the maximum deviation between any two full range output values obtained in Steps 2, 3, and 4 of the temperature calibration and the algebraic difference of the extremes of the compensated temperature range. Thermal sensitivity shift is expressed as a percentage error per thermal degree.

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