Evaluation of the Measurement Technologies Required for the Jupiter Icy Moons Orbiter (JIMO) Reactor

David E. Holcomb, Roger A. Kisner, W. L. Bryan, and James E. Hardy

Oak Ridge National Laboratory; P.O. Box 2008, Oak Ridge, TN, 37831
E-mail: HolcombDE@ornl.gov, KisnerRA@ornl.gov, BryanWL@ornl.gov, HardyJE@ornl.gov

Abstract—*This paper provides an overview of Oak Ridge National Laboratory's (ORNL's) evaluation of the measurement technologies required for the Jupiter Icy Moons Orbiter (JIMO) reactor. The specific reactor parameters considered are neutron flux, temperature, coolant flow, and control element position. All four of the notional reactor module concepts are considered, to the extent technically relevant (i.e., liquid metal–thermoelectric, liquid metal–Brayton, heat pipe–Brayton, and direct cycle gas-cooled–Brayton).*

The mission environmental condition and the associated survival requirement assumptions are based upon the Jet Propulsion Laboratory (JPL) descriptions of the mission profile and ORNL estimation of the reactor contribution to the environment. Each reactor parameter measurement section includes a survey of the current state-of-the-art to identify candidate measurement technologies given the environmental conditions and duration of the JIMO mission and an evaluation of the potential technologies as well as the selection process rationale underlying the evaluation.

The environmental conditions and performance requirements for fore-of-shield neutron detectors require technologies significantly beyond the current commercial state-of-the-art. The most challenging mission requirement is the combination of the necessity to observe the initial reactor approach to critical with fresh, highly enriched fuel combined with the strong desirability of the capability to monitor low-power, hot reactor dynamics in space with a long-lifetime detector system. The mission background radiation environment would significantly contaminate the signals from non-fission-based detector technologies located aft-of-shield. Shielded fission counters are, therefore, a strongly preferred detector technology due to their larger signal pulse sizes (which provides the additional benefit of being able to drive longer cable lengths) and consequent signal separablility from the background space radiation.

For the duration and harsh environment of the JIMO mission, long-term minimal drift operation is the most challenging temperature measurement requirement. Temperature is a principal reactor state variable and measuring it accurately throughout the mission is required. Measurement drift is thus a principal measurement evaluation metric among the competing technologies. Almost all harsh environment temperature measurements are presently made using one of four technology classes: thermocouples, resistance thermometers, pyrometry (radiation thermometers), and ultrasonic-probe-based thermometry. This evaluation, therefore, focused on evaluating the strengths and weaknesses of these technologies for reactor coolant temperature measurement suitable under the JIMO mission profile.

A primary consideration in the selection of flow measurement technologies for recommendation is the desire to avoid introducing penetrations to the reactor pressure boundary. Thus, the evaluation is restricted to noninvasive sensor candidates. Historically, magnetic flow sensing was developed solely for use in liquid-metal applications. By contrast, ultrasonic time-of-flight has been highly developed for alternate commercial applications, but appears to be readily adaptable to liquid-metal application.

The use of magnetic conduction flow sensors minimizes contact with the flow pipe, which is desirable because of the high temperature of the contained liquid metal. The present state-of-the-art in magnetic flow sensing, based on the use of permanent magnets, can be significantly improved. Replacing the permanent magnet with an electromagnet enables the magnetic field to be turned off whenever a re-zeroing of the sensor electronics is required (thus allowing for on-line recalibration). Ultrasonic time-of-flight (TOF) flow sensing applies to both liquid and gas flow measurement. Distinguishing features of this technology are that it is noninvasive, can withstand sensor degradation, is commercially mature, and has proven high reliability. Further, ultrasonic technology has the potential for measuring both temperature and fluid density.

Twelve distinct technologies for linear and rotary position measurement have been evaluated. All successful candidate measurement technologies were required to be able to be implemented with remotely located electronics. The candidate position measurement technologies were also required to measure absolutely so that a data loss for whatever reason does not permanently corrupt the measurement value.

I. INTRODUCTION

Four different reactor types were evaluated for the Jupiter Icy Moons Orbiter (JIMO) mission. The instrumentation and controls (I&C) technology requirements for each reactor type formed part of the evaluation. All of the reactor concepts considered included fast-spectrum, highly enriched uranium cores. The JIMO spacecraft in fully deployed form was to feature a main body with a ~25-m boom with the reactor located at its tip. Immediately aft of the reactor along the boom was a shadow shield to protect the remainder of the spacecraft from the reactor-generated radiation. The power generation components were located further aft from the shield. The system electronics were planned to be deployed in a shielded box within the main body of the spacecraft.

JIMO mission I&C components must be designed to survive (1) prelaunch vehicle integration, (2) launch, (3) Low Earth Orbit (LEO), (4) rendezvous and docking, (5) interplanetary transfer trajectory injection, (6) spacecraft mission configuration expansion, (7) power and propulsion subsystem start-up, (8) Earth to Jupiter transfer, (9) Jovian orbit capture, and (10) Icy Moons capture and maneuvering phases. The changes in environment through these phases are dramatic. In terms of radiation exposure, JIMO components go from a prelaunch, very low radiation environment to a LEO cosmic radiation environment, through the Earth magnetosphere's trapped ion radiation belts, back to a cosmic radiation environment, to a reactor-generated mixed neutron and gamma-ray radiation environment with cosmic radiation contribution and finally into the intense Jovian magnetosphere's trapped ion environment with combined reactor and cosmic radiation during the science portion of the mission. In terms of temperature variations, JIMO components will go from an essentially climate controlled environment to the seasonal climate conditions of the Florida Atlantic coast to the 4 K cold vacuum of space prior to reactor start-up coupled with periodic solar heating as the spacecraft transits the Earth's shadow, and then up to a reactor core temperature of up to 1500 K at full power. Reactor module measurement components will be exposed to a somewhat lesser range of these extreme temperatures through engineered controls.

The measurement electronics would be required to survive a combined reactor, space, and Jovian radiation environment. This includes a combined neutron (fast and thermal), energetic proton, energetic heavy ion, energetic electron, gamma ray, and cosmic ray doses. Jet Propulsion Laboratory (JPL) provided calculated estimates of space-originating radiation and shielding requirements to protect science electronics in the body of the spacecraft.[1] A 2.54-mm aluminum electronics enclosure is included in the design assumptions. The total ionizing dose anticipated within the electronics vault is anticipated to be 60 Gy (Si). A radiation design variance assumption of 2.0 is specified in the same JPL memorandum, so the total ionizing dose assumption within the electronics vault is 120 Gy (Si). Again employing the 2.54-mm aluminum enclosure, the mission module lifetime displacement damage dose design assumption is specified as 8.6×10^{12} neutrons/cm^2 (1-MeV equivalent) or 1.7×10^{13} neutrons/cm^2 (1-MeV equivalent) using the prescribed factor-of-two design uncertainty.

II. REACTOR POWER LEVEL (NEUTRON FLUX)

The chief objective for observing the reactor initial approach to critical is avoiding prompt criticality because this is highly stressful. Observing the reactor subcritical neutron multiplication with fresh, high-enrichment uranium fuel requires the highest detector sensitivity of any portion of the JIMO mission, as ^{235}U produces almost no spontaneous neutron emission. The necessary detector sensitivity varies strongly with whether a start-up neutron source is present. The specific detector sensitivity required varies considerably with the particular reactor design as the different candidate reactors have significantly different aspect ratios and thus different control element worths per unit insertion length (or degree of rotation). Additionally, the detector sensitivity will be significantly impacted by the hardness of the neutron spectrum of the selected reactor, since the neutron conversion cross-sections of interest for detectors are much larger for lower energy neutrons. The hardness of the neutron spectrum at the detector locations varies with both the details of the core and shield composition and arrangement. It is possible to locally enhance the thermal flux by encasing the neutron detectors in a moderator. Monte Carlo Neutron Particle (MCNP) calculations indicate that encasing a fission chamber located immediately aft of the shield (based on a reference 520-kW liquid-metal cooled Brayton-cycle model) in a layer of hydrogenous moderator ~3 cm thick increases the net fission rate from a ^{235}U-based detector by a factor of ~35. In addition to observing the low-temperature initial approach to critical, the neutron flux sensors will also be required to measure the reactor dynamical response produced through low-power, hot critical physics testing. This means that the high-sensitivity flux monitors are required to perform for at least the first few months of reactor operation.

The design assumption for neutron flux monitoring is that following the initial ascent to power, the reactor power will never be reduced below a small house load (1% full power used in the design estimate). The front surface of the shield low-energy neutron flux is anticipated to be on the order of 10^9 neutrons/cm^2-s. For 15 full-power years, this corresponds to a low energy fluence of 5×10^{17} neutrons/cm^2. The aft of shield, full-power low-energy (<100-MeV) neutron flux is expected to be roughly 500 neutrons/cm^2-s. For an unshielded fission chamber, the fissions induced by energetic protons (Europa orbit flux and spectrum) are somewhat less but roughly equivalent to those induced by the neutrons for energies < 100 meV, but are only about 4% of the total, full-power, neutron-induced fissions.

A front side of the detector may be required to operate at up to the hot-leg design basis accident maximum temperature excursion (likely 1450 K). This is substantially beyond commercial state-of-the art. Aft-of-shield neutron detectors can employ more standard, commercially available, high-temperature neutron detector materials. The neutron pulse measurement electronics should be able to be located 30 m from the sensors (in the electronics vault). Fission chambers are distinctly advantageous in this respect due to their larger electronic pulse sizes resulting from the larger amount of energy (80–100 MeV for a fission chamber, versus 1.5 MeV for a ^{10}B-lined ion chamber, or 800 keV for a ^{3}He ion chamber). Ion chambers also tend to be operated at higher voltages ~1500 V vs ~500 V for a fission chamber to obtain larger signal pulses due to gas amplification. Larger electric fields are more stressful on electrical cables, and higher voltage power supplies tend to be less reliable than their lower voltage counterparts.

It is preferable that a single detector channel covers the entire range of reactor operation from shutdown (prior to initial criticality), to hot very low power critical experiments, to full-power operation. The combined high-sensitivity requirement for start-up operations and the relatively large full-power low-energy neutron flux along with the desirability to employ only one set of amplifier electronics for the detector system provides motivation for employing an extended range counting system.

Higher temperature tolerant gas-filled detectors are the only viable detector class for fore-of-shield deployment. A fore-of-shield detector is required for reactor start-up. Fission chambers, ^{10}B-lined ion chambers, and ^{3}He detectors without hydrogenous or fluorine-based quench gases are potential candidates. Due to their larger pulse sizes, fission chambers are preferred for pulse mode long-cable deployments such as the initial start-up of the JIMO reactor. Helium-3—argon ion chamber would be the secondary choice for a fore-of-shield neutron detector. The aft-of-shield neutron detector likely could be a commercially available component closely resembling a high-temperature-tolerant, high-sensitivity fission counter encased in a neutron moderator layer. Ion chambers are not strong candidates for aft-of-shield deployment due to the large amount of background that would be caused by the Jovian environment. The second choice for an aft-of-shield deployment would be to replicate the extremely high-temperature fission chamber from the front side of the shield.

III. REACTOR COOLANT TEMPERATURE

Temperature is one of the most important variables measured to verify proper operation of a reactor. The consequences of reactor operation (particularly low-mass space reactors without the large thermomechanical margins characteristic of their terrestrial counterparts) outside of their design temperature range can be catastrophic in certain situations even for relatively small, short-term deviations. Further, the requirement for accurate temperature measurement tends to be more rigorous later in the reactor's design life when its structural materials have accumulated most of their anticipated radiation damage. However, temperature measurements are likely to have the highest uncertainty after long-term operation. Both the high temperatures and radiation environments of nuclear reactors over time cause the physical properties of even extremely durable component materials of high-temperature thermometers to drift. The requirement for high-accuracy measurement combined with the inevitable drift in the material properties of temperature transducers results in high merit being placed on temperature measurements that depend on invariant, fundamental phenomena.

The particular temperature measurement requirements vary between reactor types as well as with the particular design choices of a specific reactor. The accuracy requirements used in the evaluation were ±1.5% of reading or ±10 K whichever is greater at the nominal reactor operating temperature of 1375 K with design basis transients to 1650 K over the anticipated life of 15 years with a 10-s response time. Additionally, prior to reactor start-up, the spacecraft will be orbiting Earth. Consequently, it will experience low-temperature thermal cycling as it passes into and out of the Earth's shadow.

Temperature sensors will be employed both as a primary reactor state-variable monitor as well as to assess the condition of the reactor functional components (shield, control rod drives, etc.). For some reactor designs, it may be advantageous to monitor the reactor temperature fore-of-shield as a diagnostic of the condition of the reactor materials or for rapid control responses. However, most of the temperature sensors will be located aft-of-shield in a lower (although still aggressive) radiation environment. Reactor coolant measurements at a minimum will be made on the hot leg and cold leg of the primary coolant as well as along the coolant legs (for initial coolant thaw monitoring for the liquid-metal reactor option). Additionally, both the structural and mechanical components of the reactor system will likely be thermally monitored. Notably the fore-of-shield flux monitor will have its temperature measured prior to start-up to ensure that it is within an operable temperature range when performing the initial reactor approach to criticality.

The exterior layer of the temperature probe sheath will vary with reactor material type. The use of SiC as a structural material would necessitate very different sheath materials than a refractory alloy system. The thermal probes require good thermal contact with the structure whose temperature is being measured, which generally means a weld or braze type contact. Temperature measurement probe sheaths are a critical component for both attachment and proper sensor functioning. Sheath materials are often the source of impurity atoms that cause sensor drift and/or premature sensor failure. The design assumption for each of the measurement alternatives discussed is that the measurement electronics will be located within the electronics vault of the mission module. This means that the separation between the transducing elements and the measurement electronics is roughly 30 m.

Temperature measurement needs to be evaluated on an entire channel basis. Obviously, a highly accurate transducer that cannot be read out is of little use. Virtually every known physical and chemical phenomenon is influenced by temperature, and many of them have at some point been exploited to measure temperature for some particular application. However, temperature measurements in harsh, high-temperature environments are presently almost exclusively performed by one of four methods: thermocouples, resistance thermometry, pyrometry, or ultrasonic thermometry.

At the high temperatures anticipated for space reactor applications, small-diameter mineral-insulated, metal-sheathed thermocouples both experience drift and insulation shunting errors. Long-term exposure to high temperatures and radiation combines to cause drift in the thermoelement Seebeck coefficient. One of the primary drift mechanisms for thermocouples at high temperatures is interdiffusion of the sheath and thermoelement alloy metals, so to the extent possible a closely matching thermoelement alloy sheath should be used for thermocouples above ~850 K. Impurities in the insulators are another source for atoms to alter the thermoelements. Oxide insulators having purity as high as possible are recommended.

Aft-of-shield radiation-induced drift, at reactor coolant temperature (1375 K nominally), is not anticipated to be as significant as the thermally induced drift.[2] The direct current (dc) gain of the readout instrumentation needs to be very stable because the thermocouple output voltage is very low (on the order of 20 mV for the types of thermocouples that could be used at temperatures up to 1650 K). Any offsets in the input of the sensing amplifiers or inaccuracies in the reference temperature voltage will cause error in the reading. As high-gain dc circuits, thermocouple readouts are particularly vulnerable to radiation exposure.

Very pure, well-annealed platinum is most commonly used to form the resistive element in high-accuracy resistance thermometers. The resistive element performs transduction of local temperature to a resistance value, which is then measured by an electronic circuit. Uncertainty comes from every component along the signal path; however, the single greatest source of measurement error comes from the resistive element itself. The temperature calculation depends on precisely knowing the element's temperature-to-resistance transfer function over the full range of measurement. The transfer function exhibits resistance variations arising from several sources. Time-at-temperature leads to corrosion and diffusion of contaminants into the element. Similar processes impact the insulative wire supports. In addition, vibration leads to fatigue and creep. Initial, built-in stress from fabrication processes is relieved throughout the sensor's operating life producing a progressive resistance shift. All of these influences lead to measurement drift.

Resistance temperature detectors (RTD) must be periodically calibrated to maintain low uncertainty of temperature measurement. For most terrestrial industrial applications, calibration by human intervention is routinely employed. Johnson noise thermometry (JNT) is a technique to accomplish the recalibration without human intervention. JNT measurement is applied in parallel to the RTD lead wires and the resistance measurement circuit without altering the traditional resistance measurement circuit.

JNT measures temperature based on first-principles physics that derives a temperature value from the random noise generated by an electrical resistance. Johnson noise is caused by the random thermal motions of electrons in any material. JNT has been applied to in-core temperature measurement for more than 30 years [3] and more generally, Johnson noise has been used for temperature measurement for more than 50 years. [4] JNT has recently been employed in space on the International Space Station (ISS). [5]

Temperature may be determined by radiation thermometry because the radiance emitted by an object is a function of its temperature. If an object behaves as a blackbody, its temperature can be determined from the emitted radiance using Planck's law. In the case of a non-blackbody, knowledge of the object's emittance is required to obtain its temperature. Provided the emittance of the surface is well characterized, radiation thermometers can be very accurate and precise. Pyrometers can provide grossly errant measurements of temperature for situations involving varying emittance of the radiating object or any other factor that attenuates or distorts the photon path. Light emission from reactor components needs to be transmitted to the measurement electronics located in the electronics vault. Fore-of-shield reflective optics are required for the light guide to survive the radiation field.

A highly stable, relatively radiation tolerant, spectrally sensitive light measurement system is required for the pyrometer. Traditionally, optical measurements in high-radiation environments have been made using vacuum-tube-based video cameras because of their very high radiation tolerance.

Probe-type, pulse-echo ultrasonic thermometry is applicable to space-reactor temperature measurement. These ultrasonic thermometers operate by measuring the speed-of-sound in a metal wire or rod, which is a known function of temperature. By launching a compressional wave down a cylindrical rod waveguide, the transit time can be measured as the wave travels from the launch location to a point of reflection then returns to the detection location. The temperature can be calculated from the transit time. By creating abrupt impedance shifts (such as notches) at predetermined locations, temperature measurement over multiple zones is made possible.

Probe-based ultrasonic temperature measurements have been applied to nuclear reactor core temperature measurements including nuclear thermal rocket propulsion since the late 1960s. [6] Piezoelectric or electromagnetic acoustic transducers are typically employed to generate and receive the ultrasonic pulses. The drift in the ultrasonic temperature measurement arises from two principal sources: (1) radiation and temperature-induced mechanical changes in the sensing element and (2) drift in the electronics timing and gain characteristics. Radiation hardness of electronics is slightly more of an issue than for some of the other competing techniques because of the accurate timing required for precision measurements.

The overall technology recommendation was to pursue developing both a more stable thermocouple measurement circuit and to pursue developing JNT to the point where it may be practically applied to demanding field applications.

IV. REACTOR COOLANT FLOW

A primary consideration in the selection of flow measurement technologies for recommendation is the desire to avoid introducing penetrations to the reactor pressure boundary. Thus, the recommended sensor candidates are noninvasive. To prioritize the gas flow measurement technologies, many attributes and the importance of those attributes were considered to assist in determining the suitability of the identified technologies. Many of these are in addition to the considerations identified in the guidelines, such as the maturity level of the technology, the relative simplicity or complexity of the technology, the ability of the method to tolerate transducer degradation, or the accessibility of the technology. Other considerations include the availability (or lack thereof) of suitable measurement transducers for the high-temperature and radiation conditions, or transducers that cannot be thermally isolated and must undergo development to withstand the full-flow pipe temperature. This affects the development effort, and ultimately the feasibility of the technology.

Based on of the assessment of liquid-metal flow-sensing technologies, two methods were recommended for consideration: (1) the magnetic conduction flow sensor and (2) the ultrasonic time-of-flight sensor. Historically, magnetic flow sensing was developed solely for use in liquid-metal applications. By contrast, ultrasonic time-of-flight has been highly developed for alternate commercial applications, but appears to be readily adaptable to liquid-metal application.

The use of magnetic conduction flow sensors minimizes contact with the flow pipe, which is desirable because of the high temperature of the contained liquid metal. The present state-of-the-art in magnetic flow sensing, based on the use of permanent magnets, can be significantly improved. Magnetic flow sensors based on the use of permanent magnets have been used extensively on liquid-metal flow loops since the early 1950s. Replacing the permanent magnet with an electromagnet enables the magnetic field to be turned off whenever a re-zeroing of the sensor electronics is required (thus allowing for on-line recalibration). Using of a built-in magnetic flux monitor/integrator, the strength of the magnetic field can be monitored, correcting for degradation in the magnetic permeability of the electromagnet. Additional significant performance improvements in the magnetic flow sensor are likely to result from implementing either alternating current (ac) or pulsed-dc modes of operation.

In the liquid-metal magnetic flow sensor, a magnetic field is established in a direction perpendicular to the direction of fluid flow. The motion of an electrically conductive fluid in the transverse magnetic field generates an electromotive force (emf) in the direction perpendicular to both the magnetic field and the flow direction (Faraday's Law). However, the emf induced in the fluid is partially shunted by the metal wall of the flow pipe, which is stationary and therefore does not experience a similar emf. The emf induced in the liquid metal results in a circulating current flow, across the fluid channel and returning in the walls of the flow pipe. If the electrical resistivity of the flow pipe is comparable to that of the liquid metal, most of the flow-induced emf appears in the pipe wall and can be measured with electrodes installed on the outside of the pipe wall. The emf so detected is a fixed fraction of the flow-induced emf in the liquid metal, with the exact proportion determined by the relative resistivities of the liquid metal and the pipe material, as well as the wall thickness and pipe diameter. The magnitude of the induced emf increases linearly as the cross product of the flow velocity and the magnetic field strength, multiplied by the diameter of the pipe. Magnetic flow sensors are well suited to the measurement of bi-directional flow, as only the sign of the induced emf changes when the direction of flow is reversed. For high-temperature applications, the current carrying magnetic field coil must be thermally insulated from the flow pipe, and designed to tolerate moderate temperatures and the radiation environment. Because the magnetic field is produced using a current in a coil, no magnetic materials are subjected to thermal and radiation stresses, and the only parameter that varies with temperature is the diameter of the flow pipe. A major concern with permanent magnets is that the strength of the magnetic field can undergo changes over long periods, either due to prolonged exposure at elevated temperature near the maximum rating for the magnet, or due to radiation, shock, or other environmental factors, thereby degrading the sensitivity of the flow sensor. Permanent magnets can be prestressed to some of these factors to minimize subsequent changes due to similar mission-related stresses. Ideally, the strength of the magnetic field should be measured continuously to maintain the calibration of the flow sensor. Magnetic flow sensors are relatively insensitive to changes in the flow velocity profile and swirl. However, it is generally advisable to allow five upstream pipe diameters to assure that flow conditions are well established.

Ultrasonic time-of-flight (TOF) flow sensing is a preferred option for both liquid and gas flow measurement. Distinguishing features of this technology are that it is noninvasive, can withstand sensor degradation, is commercially mature, and has proven high reliability. Further, ultrasonic technology has the potential for measuring both temperature and fluid density. The most significant technical challenge for ultrasonic measurements is the long-term stability of transceiver and waveguide to pipe interface (both mechanically and acoustically). This is recommended to be the focus of the environmental tolerance testing for the selected components.

The backup gas flow measurement technology is a vortex shedding flowmeter with clamp-on strain gages. However, this technology is unproven for the harsh JIMO mission environment, and strain gages may not be sufficiently sensitive to work with gas pressure pulses. An additional technical challenge for the nonultrasonic gas flow measurement option is development of the additional gas density measurement technology to convert volumetric flowrate to mass flowrate (if pressure sensors are not employed on the primary piping).

For a clean liquid metal with single-phase flow ultrasonic TOF is an established measurement technology. In this method, the propagation time delay of ultrasonic pulses is measured in both the upstream and downstream directions inside the flow pipe. The propagation time delay depends on the velocity of sound in the fluid, as well as the flow velocity of the fluid. The fluid flow velocity is inferred from the difference in the upstream and downstream propagation time delays. Ultrasonic flow sensing works well for sensing low flow velocities (excellent rangeability), as well as bi-directional flow. Because the speed of sound changes with temperature, this method can also be used to measure fluid temperature, if the speed of sound in the liquid metal, as a function of temperature, is known.

The ultrasonic TOF flow sensor is an excellent example of a nonintrusive flow technology, because the ultrasonic signals can be coupled through the wall of an existing section of coolant piping. To adapt this technique for use at high temperature, the ultrasonic transducers must be thermally isolated from the coolant flow pipe. This can be accomplished by inserting an acoustic waveguide between the ultrasonic transducers and the flow pipe. The acoustic waveguide must be sufficiently long to provide the necessary thermal isolation, and details of the attachment of the acoustic waveguide to the flow pipe are critical to assure that the ultrasonic signals are adequately and reliably coupled. If the speed of sound varies significantly with temperature, this will alter the refraction angle at the pipe-fluid interface, which could alter the distance that the signal travels, or even cause the signal to miss the receiver. These effects require compensation. Ultrasonic flow sensing is moderately sensitive to changes in the velocity profile, and large scale structures in the flow. It is generally recommended that a straight section of pipe equivalent to 10–20 upstream pipe diameters be used to assure that flow conditions are well established.

V. CONTROL ELEMENT POSITION

Both linear and rotary position measurement systems have been evaluated because both were candidates for different reactor concepts. The top criteria for down selection of measurement technologies are high-temperature and radiation survivability, lifetime, reliability, uncertainty, and response time. All successful candidate measurement technologies were also required to be able to be implemented with remotely located electronics. Finally, the candidate position measurement technologies were required to measure absolutely so that a data loss for whatever reason does not permanently corrupt the measurement value. A numerical weighting method was devised to rank-order the candidates since there were so many candidate technologies to be evaluated. As expected, no single technology displays characteristics and performance metrics that make it clearly superior to the other technologies. It is prudent to favor commercial technologies, which have a path to adaptation for space nuclear applications, and especially technologies that have been previously used successfully in high-temperature and radiation environments.

The leading candidate linear position measurement is the linear variable differential transformer (LVDT). Correspondingly, the leading candidate for rotary position measurement is the resolver. The recommended backup position measurement for both linear and rotary position measurement is capacitive position sensing. Linear and rotary capacitors are very mature technology; however, their use as a position measurement instrument is not as commercially developed as LVDT or resolver technology. Commercial use and maturity factored strongly in the technology selection although commercially available models do not meet the mission requirements. Although significant effort will be required to develop, test, and make them ready for deployment, the level of effort should be less than most of the other technologies.

The LVDT consists of a ferromagnetic core that passes through a three-winding transformer: a primary and two secondary windings. The primary winding is excited with a constant sine-wave current. Voltages measured in the two secondary windings differ in proportion to the inductive coupling provided by the ferromagnetic core. The difference in the secondary voltages is proportional to the linear position of the core. The ferromagnetic core is attached to a control element shaft, and thus the control element's position is measured. LVDT accuracy is temperature dependent, and the measurement stroke is typically limited to a few centimeters. This would need to be extended for control-rod motion.

Position measurement by rotary resolver is based on a rotary transformer that changes output with shaft position. A resolver consists of stator and rotor windings. Control element shaft position measurement is accomplished by coupling the resolver rotor to the control element shaft; the stator is mounted to a fixed structure, which becomes the reference. The rotor windings are excited by a sinusoidal electrical signal that induces current flow in the stator windings. The stator winding outputs are in quadrature (90-degree phase angles). The ratio of the stator signals determines the rotor angle. Resolvers have a significant temperature response shift for which compensation must be provided.

VI. CONCLUSIONS

A principal difference between space and terrestrial nuclear reactors is the ability to periodically recalibrate and if necessary replace reactor instrumentation. An additional key difference for space reactor deployment is the lack of a well-conditioned environment for the measurement electronics. Thus, the measurement circuitry needs to be considered along with the transducer technology. The combined extreme environment service conditions and the required service lifetime constrain the technology choices for the JIMO reactor. This technology evaluation is, therefore, limited to the particular mission profile of the JIMO reactor, and different mission requirements will likely change the technology recommendations.

ACKNOWLEDGMENTS

This work was performed under the sponsorship of NASA's Project Prometheus and directed by DOE/NNSA Naval Reactors. Opinions and conclusions drawn by the authors are not endorsed by DOE/NNSA Naval Reactors.

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