An experimental wireless, in-vessel neutron monitor is being developed to measure the reactivity of an advanced breeder reactor as the core is loaded for the first time to preclude an accidental criticality incident. The environment is liquid sodium at a temperature of \(\sim 220^\circ C\), with negligible gamma or neutron radiation. With ultrasonic transmission of neutron data, no fundamental limitation has been observed after tests at \(230^\circ C\) for \(\sim 2000\) h. The neutron sensitivity was \(\sim 1\) count/s-\(\nu\), and the potential data transmission rate was \(\sim 10^4\) counts/s.

I. Introduction

An experimental in-vessel monitor was designed and fabricated and is being further developed to ultrasonically transmit reactivity data from advanced breeder reactors. Since such reactors have potentially high reactivity cores, their initial fuel-loading operation will require careful surveillance as the core is loaded to preclude an accidental criticality incident.

An in-vessel neutron detector is preferred to an ex-vessel detector because it is closer to the fuel elements and is not shielded by blanket assemblies. Thus, data from an in-vessel detector are received at a greater rate (up to \(10^6\) counts/s for this model) and are more easily interpreted. Also, with an in-vessel detector, the neutron source required to make the subcriticality measurements can be reduced in size and possibly eliminated.

A wireless, completely remote in-vessel detector can be located at any core position, giving much greater versatility to the measurements. In addition, the wireless detector does not need expensive instrument thimbles and does not inhibit the motion of fuel handling equipment.

The in-vessel environment for this initial start-up monitor is liquid sodium at a temperature of about \(220^\circ C\). No existing neutron monitor has the wireless capability and adequate sensitivity for this application. The experimental model described herein has been successfully tested at \(230^\circ C\) for \(\sim 2000\) h.

II. Wireless Neutron Monitor Concept

The current concept of the wireless neutron monitor system is shown in Fig. 1. In the sodium-filled reactor vessel (\(0.6\) m diam \(\times 18\) m high), the neutron monitor is positioned in the reactor core region within a dummy fuel element. The ultrasonic transmitter is mounted at the top end of the dummy element where it can transmit signals along an unobstructed path through the sodium to a receiver which is also immersed in the sodium.

III. Instrumentation

A diagram of the instrumentation is shown in Fig. 2. A fission counter senses the neutrons, and the resulting electrical pulses are processed by a pulse amplifier and a bandpass filter with single-pole upper and lower cut-off frequencies (RC-CR filter). Electronic noise and alpha pile-up noise are rejected by a discriminator. The discriminator output pulses trigger a driver circuit which excites a 2-MHz ceramic crystal to create an ultrasonic burst for each neutron pulse exceeding the discriminator threshold level. The primary electrical power, which will be derived from a radioisotopic thermoelectric generator, is transformed by a dc-ac converter to positive and negative 10 V levels to bias the fission counter and to drive the active circuitry.

The total quiescent power of the instrument is \(\sim 0.56\) W at a temperature of \(230^\circ C\). The ultrasonic driver is expected to require \(0.14\) W at an output pulse rate of \(10^4\) counts/s. The radioisotope source requirement is 8.0 V at \(1.0\) W.

A. Fission Counter

A commercial fission counter (Reuter-Stokes model ASN-10A) with a 4-ma electrode spacing, \(0.005\)-cm\(^2\) of sensitive area, and a \(300^\circ C\) maximum operating temperature was selected for our use. These counters were required for our special application, and the availability of the counter eliminated a costly in-house fabrication program. However, some special alterations were needed to ensure adequate performance (voltage...)}
The transducer will contain a PZT-5A ceramic crystal similar to that used by the Hanford Engineering Development Laboratory (HEDL)\(^1\) in their under-sodium viewing systems. It is attached to the transducer face-plate with either a Pb-Sn-Ag solder alloy or a high temperature epoxy. Both have been successfully tested.

The transducer is driven by two VMOS transistors in parallel, with the power being obtained directly from the primary power source. A 2.5-mF Teflon capacitor is currently used as an energy storage element to reduce the ripple on the primary power source.

The crystal impedance is integrated into a resonant tank in the drain circuits of the VMOS transistors. A step-up transformer wound on a high-temperature ferrite toroid reduces the amplitude of the voltage pulses on the drain circuitry.

D. DC-DC Converter

The dc-dc converter\(^5\) is an astable multivibrator that drives an n-channel VMOS switch (two in parallel) in a dual-coil switching regulator. A dielectrically isolated, IC, differential operational amplifier in conjunction with a 6.9 V zener diode (an emitter-to-base junction of a Diodes D1524 dielectrically isolated transistor) senses the positive 10 V output variations and adjusted by the end of the VMOS (on-time is fixed). Integration in the operational amplifier determines the dominant pole of the forward loop. The astable circuits comprise dual, dielectrically isolated, pnp and npn transistors, Inter i1137 sm. 11-27, respectively.

The coil is a high-permeability, silicon-steel toroid with a Curie temperature of 730°C and is wound with 30 gauge, Teflon-insulated copper wire. The switching frequency is 60 kHz, and 10-µF electrolytic capacitors reduce ripple to acceptable value for a total load of 12.5 mA for a positive and negative 10 V output.

The internal, drain-substrate, p-n junction diode of n-channel VMOS transistors are used as rectifiers. At 230°C, the forward drop is 0.3 V, with a leakage current of <200 µA, and a reverse voltage of 60 V.

E. Primary Power Source

Because of its ruggedness and proved performance in numerous space problems, a radioisotopic generator is being considered for the primary power source. Plutonium as \(238\text{PuO}_2\) in a 1-cathode generator, and silicon-germanium forms the thermocouple junctions. The liquid sodium serves as the "cold leg" of the generator system. For an electrical power output requirement of 1.6 W, a heat source of \(<125 \text{ W/kg}\) is considered adequate. Contracts are being prepared for the procurement of this source.

IV. Hybrid Thick-Film Circuits

Fabrication Details

The AFD circuit and the dc-dc converter are fabricated with thick-film technology on 51- by 51-mm (2" by 2-in.) and 32- by 32-mm (1.25- by 1.25-in.) 96A alumina substrates, respectively. Figures 2 and 3 are photographs of these two thick-film circuits. The AFD circuit (Fig. 2) was operated at temperatures near 230°C for nearly 2800 h. The metallization is gold (Du Pont 9910). The thick-film resistors are screened.
The capacitors contained in these two circuits are monolithic, ceramic capacitor chips with 50- to 100-V ratings. The bypass and decoupling capacitors were formed from a high-dielectric-constant material (X7R), but filter and compensation capacitors were formed from a more stable, low-dielectric material (NPO). A gold-germanium alloy solder (360°C mp) was used to make electrical connections to the capacitor chips and to the external wires of the substrate using a reflow technique. Later, a parallel-gap welder was obtained to make the external connections with a 25- by 500-μm (0.001- by 0.020-in.) nickel ribbon.

V. Description of the Experimental Monitor

The experimental monitor is shown in Fig. 5. Its construction does not represent the construction that would be used in the prototype monitor. Instead, it was designed to facilitate data taking and to accommodate modifications and improvements as they became apparent during the testing program. From left to right in the figure is the fission counter wrapped in an electrically insulating Teflon jacket to protect the shell of the counter, which is maintained at a negative 10 V biasing potential, followed by the APD module, the dc-dc converter, and the transformer for the ultrasonic transmitter. At the extreme right is an oil-filled test chamber with a transmitter and receiver crystal at opposite ends. The entire system is mounted on a high-temperature, printed circuit board (Du Pont Pyralin) with a small number of discrete resistors (Oaddock) and ceramic capacitors (San Fernando Electric). The resistors, capacitors, and the hybrid thick-film modules were attached with 90% lead-10% tin solder. A test pulse, dc and pulse monitor points, oil drain and fill tubes, and thermocouples are all brought out of a flanged end of the assembly. The entire assembly, ~1.0 m (40 in.) long, is installed in a cylindrical enclosure, giving a pressure tight containment for an inert cover gas.

VI. Test Results and Discussion

The results of the temperature tests of the experimental monitor are summarized in Table 1. The performance of the solid-aluminum electrolytic capacitors was poor, a result not expected based on previous work in high-temperature electronics. Preliminary tests were made in air up to 275°C for hundreds of hours, showing only a slight degradation of performance. The cause of the capacitor failure is believed to be outgassing from oil that leaked out of the ultrasonic test chamber. The oil initially used in the tests possessed inadequate high-temperature properties. Also, the high porosity of the printed circuit board material prevented an adequate clean up of the test assembly.

Two failures of aluminum wire bonds at the gold metallization of the dc-dc converter were the first experienced after nearly 300 successful bonds on other hybrid circuits. This failure rate is not considered excessive at this time, and no changes in our bonding procedures are planned.

Integral bias response obtained for two measurements at ~230°C and covering a time span of nearly 1600 h show only slight differences. Projection of the 1.0 count/s noise curve threshold to the neutron curve shows an ~75% counting efficiency for the monitor.
Fig. 5. Photograph of the experimental wireless, initial core-loading neutron monitor (externally powered).

Table 1. Summary of performance of neutron monitor components

<table>
<thead>
<tr>
<th>Component</th>
<th>Hours at 230°C</th>
<th>Performance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fission counter</td>
<td>2500</td>
<td>More than adequate</td>
</tr>
<tr>
<td>AFU module</td>
<td>2800</td>
<td>Adequate ²</td>
</tr>
<tr>
<td>DC-DC converter</td>
<td>324</td>
<td>Adequate ³</td>
</tr>
<tr>
<td>Ultrasonic transmitter</td>
<td>2200</td>
<td>More than adequate</td>
</tr>
<tr>
<td>Solid-aluminum electrolytes</td>
<td>176</td>
<td>Not adequate ⁴</td>
</tr>
<tr>
<td>Printed circuit board, with discrete resistors and ceramic capacitors</td>
<td>2800</td>
<td>More than adequate</td>
</tr>
</tbody>
</table>

² Some drift in pulse gain (or amplitude of test signal) not seen in prior 2100-h tests at 250°C.
³ Maximum time to failure.
⁴ Failures caused by two faulty wire bonds at substrate metallization.
⁵ Does not include a gated oscillator.
⁶ Capacitor failure from outgassing effects.

VII. Problem Areas

The failure of the solid-aluminum electrolytics must be resolved. Although the prototypical neutron monitor will not contain an oil source, the apparent sensitivity of these capacitors to outgassing must be determined.

Presently, we are working on a design for a gated, 2-MHz oscillator that will provide the input drive signal for the transmitter. Tests are still to be made on the cylindrical ultrasonic beam generator. The concept for this ultrasonic beam generator is shown in Fig. 6.

VIII. Conclusions

Temperature tests on an experimental assembly of an initial-core-loading neutron monitor show no unsolvable problems. Failure of solid-aluminum electrolytics because of off-gassing indicates a need for a vapor-free environment for these devices. Bond failure on the dc-dc converter substantiates the need for pretesting of all hybrid thick-film modules.

IX. References


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