Self-Powered Wireless Through-wall Data Communication for Nuclear Environments

Advanced Sensors and Instrumentation
Annual Webinar

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Project Overview

• Goal and Objective
  The goal of this proposal is to develop novel energy harvesting and wireless through-wall communications technology for in-situ monitoring of interior conditions in enclosed metal vessels or thick concrete walls as found in dry storage canisters:
  --10mW, 1/2 SS Wall, 140C, 14.5 G Rads

• Participants (2020)
  – Lei Zuo, Virginia Tech
  – Haifeng Zhang, Univ. of North Texas
  – Nance Ericson, Roger Kisner, Kyle Reed, Oak Ridge National Laboratory

• Schedule
  – 10/2016 - 09/2020
In FY20:

- We finalized the radiation test and the characterization of the samples of all modules.
- We integrated and tested the overall system
  - Ultrasonic data communication module,
  - high-temperature radiation-hardened electronics,
  - thermoelectric energy harvesting module with power management circuit.
Technology Impact

The solution has significantly benefitted data communication through enclosed metal vessels including spent fuel canisters:

1. Cable-less and **wireless communication through a metal barrier** where RF transmission is not feasible;

2. **Energy harvesting** from nuclear radiations and heat where no other energy sources are available;

3. A detailed strategy for full realization of a high temperature, radiation tolerant **JFET electronics**;

4. Multi-layer radiation and thermal **shielding** design for the electronics working in nuclear environment;

5. Selective laser sintering **3D printing** of TE materials

6. Lab validation of the proposed overall system for **190°C**
Accomplishments (1/14): Canister environment

- Thermal and hydrodynamic analysis of the dry cask system

Heat and fluid environment in the dry cask system:

The model to estimate the decay heat within the dry cask system:

<table>
<thead>
<tr>
<th>Year (Since removal)</th>
<th>Decay (kW)</th>
<th>Gamma Spectrum (#/s)</th>
<th>Neutron Spectrum (#/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>38.44</td>
<td>2.64 x 10^{17}</td>
<td>1.02 x 10^{10}</td>
</tr>
<tr>
<td>10</td>
<td>24.52</td>
<td>1.47 x 10^{17}</td>
<td>8.4 x 10^{9}</td>
</tr>
<tr>
<td>15</td>
<td>21.07</td>
<td>1.20 x 10^{17}</td>
<td>7.0 x 10^{9}</td>
</tr>
<tr>
<td>20</td>
<td>19.00</td>
<td>1.04 x 10^{17}</td>
<td>5.9 x 10^{9}</td>
</tr>
<tr>
<td>25</td>
<td>17.31</td>
<td>9.2 x 10^{16}</td>
<td>4.9 x 10^{9}</td>
</tr>
<tr>
<td>30</td>
<td>15.85</td>
<td>8.2 x 10^{16}</td>
<td>4.1 x 10^{9}</td>
</tr>
<tr>
<td>35</td>
<td>14.56</td>
<td>7.3 x 10^{16}</td>
<td>3.4 x 10^{9}</td>
</tr>
<tr>
<td>40</td>
<td>13.42</td>
<td>6.5 x 10^{16}</td>
<td>2.9 x 10^{9}</td>
</tr>
<tr>
<td>45</td>
<td>12.40</td>
<td>5.8 x 10^{16}</td>
<td>2.4 x 10^{9}</td>
</tr>
<tr>
<td>50</td>
<td>11.49</td>
<td>5.1 x 10^{16}</td>
<td>2.0 x 10^{9}</td>
</tr>
<tr>
<td>55</td>
<td>10.67</td>
<td>4.6 x 10^{16}</td>
<td>1.7 x 10^{9}</td>
</tr>
</tbody>
</table>

**Fuel:** Westinghouse 17x17 assembly, with a total cask MTU of 15 spread over the 32 assemblies, an enrichment weight percentage of U-235 of 4%, a burnup of 45 GWd/MTU, 3 runs per fuel assembly, and an average power of 40 MW/MTU.

MCNP6
Thermal and fluid analysis of the dry cask system

Accomplishments (2/14): Canister environment

- For year 5, the temperature difference is ~70 K.
- For year 55, the temperature difference is ~13 K.

Thermoelectric energy harvesting

$$P_{\text{max}} = \frac{N\alpha_P N^2 \Delta T^2}{4R}$$
Accomplishments (3/14): Energy harvesting

• Thermoelectric energy harvesting: Experimental and simulation results

(a) The experimental setup in the lab, (b) The energy harvester, and (c) the oil channel to simulate the helium environment.

(a) fluid velocity contours, (b) temperature profile in TEG, and (c) electrical potential profile in TEG

<table>
<thead>
<tr>
<th>Cases</th>
<th>$\Delta T$</th>
<th>Power Experiment (mW)</th>
<th>Power Simulation (mW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Year 55</td>
<td>12.8</td>
<td>46.3</td>
<td>93.9</td>
</tr>
<tr>
<td>Year 50</td>
<td>13.7</td>
<td>56.1</td>
<td>106.1</td>
</tr>
<tr>
<td>Year 45</td>
<td>14.5</td>
<td>66.7</td>
<td>118.8</td>
</tr>
</tbody>
</table>

$dP = 4.06\sim12.9\ mW$  \hspace{1cm} Experiment uncertainty

• Goal: $P \geq 10\ mW$
Accomplishments (4/14): TEG radiation test

- Radiation Test

1. Radiation chamber at Westinghouse

2. Samples (~124 Mrads)
   - Co-60 gamma radiation source
   - Experimental setup in the chamber

Thermoelectric Energy Harvester

3. Seebeck

4. Electrical

Thermal

- The accumulated gamma dosage is 124 Mrads.
- No significant changes were observed after the gamma irradiation.

Thermoelectric materials: No obvious changes after 124 M Rads
Accomplishments (5/14): TEG power management

- Power management circuit

Voltage profiles of the super-capacitor and the energy management circuit output
Accomplishments (6/14): Through-wall communication

- Test of the ultrasonic through wall transmission at elevated temperatures

Fig. 2. Through wall communication modulus in a oven.

Fig. 3. Through wall communication result (carrier wave frequency=100 kHz)
Accomplishments (7/14): Through-wall communication

- PZT-LDV Through-Wall Communication Experiment

1.5in Steel Wall Setup

Laser Doppler Velocimetry (LDV)
Accomplishments (8/14): Through-wall communication

- PZT-LDV Through-Wall Communication Experiment

Results of PZT-LDV Through-Wall Comm.

<table>
<thead>
<tr>
<th>Experiment #</th>
<th>Piezoceramic Transducer Type</th>
<th>Wall Type</th>
<th>Fundamental Resonance Frequency</th>
<th>Maximum Carrier Frequency</th>
<th>Maximum Data-rate/Baud-rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>TRS200HD</td>
<td>Aluminum 0.25 in</td>
<td>8.949 kHz</td>
<td>-&gt;8.949 kHz</td>
<td>10 bps</td>
</tr>
<tr>
<td>2</td>
<td>TRSBT200</td>
<td>Aluminum 0.5 in</td>
<td>11.3 kHz</td>
<td>-&gt;1.755 Mhz</td>
<td>155 kbps</td>
</tr>
<tr>
<td>3</td>
<td>TRSBT200</td>
<td>Steel 1.5 in</td>
<td>109.94 kHz</td>
<td>-&gt;1.25 Mhz</td>
<td>115 kbps</td>
</tr>
</tbody>
</table>

Successful Transmission of Binary Text Data Every Time

up to 115 kbps
Accomplishments (9/14): Ultrasound transducer radiation test

- Radiation Test (Ultrasonic Data Transmission)

- The radiation test has been completed in Westinghouse company. The test started from Apr 23, 2019 and end on May 21, 2019.

- The total of 101 Mrad has been applied to the TRS 200 transducer and receiver.

- The Labview program works well during the test period.

- The results show **no significant signal degradation** has been observed even when the high radiation dose is applied.
Accomplishments (10/14): Electronics for sensing & communication

- **JFET-Based Electronics System Schematic**
Accomplishments (11/14): Electronics radiation test

- Radiation Test (Electronics)

Drift due to RG17 BNC cable with TPFE insulation or ceramic capacitors
Accomplishments (12/14): Electronics radiation test

JFET Design Revision

- In FY19 (Year 3), a set of JFET boards were successfully irradiated to \(2 \text{ Mrad} \) TID at Westinghouse with a Cobalt-60 source (Pittsburgh, PA)
- The radiation dose uniformity decreases across the board as the dose rate is increased due to the initial board and source geometries
- \(~500 \text{ krad/hr}\) can be achieved if the electronics are placed inside the source cylinder (shown on right)
- Revised JFET PCBs (shown below) were designed to fit inside the Westinghouse (Pittsburgh) Cobalt-60 source

Revised JFET circuit enabling placement inside the Co-60 source for 100 MRad dose test

- The revised JFET boards will be tested inside the source cylinder to \(\geq100 \text{ Mrad}\) or to failure
- Only a single sensor oscillator was placed on the board
- Other variability was removed from the design
- Connections are soldered directly to the board
- A tab was added on the board to better facilitate PCB placement and removal from the center of the source
- A notch was cut in the board to attach a cable tie for cable strain relief
Accomplishments (13/14): Radiation & thermal shielding

Radiation and thermal shielding for the electronics

Must survive internal $\gamma$ radiation dose rate of $\sim$33 krad/h for 50-year storage cycle ($\sim$14.5 Grad TID) $\Rightarrow$ **Shielding by a factor of $\sim$150**

<table>
<thead>
<tr>
<th>Materials layers</th>
<th>Thermal conductivity (W/(m*K))</th>
<th>Thickness (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel</td>
<td>50.2</td>
<td>2</td>
</tr>
<tr>
<td>Fiber glass</td>
<td>0.1</td>
<td>10-20</td>
</tr>
<tr>
<td>Copper</td>
<td>400</td>
<td>10</td>
</tr>
<tr>
<td>W-B4C</td>
<td>141.5 (Estimated by weight ratio)</td>
<td>25 (safe value for radiation shielding)</td>
</tr>
</tbody>
</table>

Boundary conditions (according to simulation results):
Ambient temperature: 480 K (207°C)
Wall temperature: 410 K (137°C)
**Target: <150 °C** at the internal surface (423 K)

Temperature distribution in the shielding block

60mm, 210 kRads

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Accomplishments (14/14): System integration & test

• System Integration and High-Temperature Durability Test

Survived 190 C, failed 195C
Conclusion: Self-Powered Wireless Through-wall Data Communication for Nuclear Environments

Goal: 10mW, 1/2 SS Wall, 140C, 14.5 G Rads

- A thermoelectric energy harvester: existing temperature gradient in the canister. Compact (8 × 8 × 6 cm), thus can be easily installed. 94 mW even after 50-years of canister storage, Bi2Te3 124 M Rads radiation dose

- Ultrasonic data communication: 1.5 inches metal wall, Operation up to 180 C with TRS BT 200, 101 M rads. A novel laser-ultrasonic data communication system with good data transmission rate 115 kbps

- Multi-sensor and communication electronics system has been developed for in-cask monitoring based on Si JFETs, successfully tested to a radiation dose of 2 M Rads total dosing. The electronics survived at 190C

- A system integration test and high-temperature durability test were done.

- Radiation tests were done in Westinghouse hot cells: 124M, 101M,

- The W-B4C was identified as the radiation shielding material for both gamma and neutron shielding, 1 inch is enough.
• Publications

1. **Self-powered Wireless Through-wall Data Communication for Nuclear Environments.** Yongjia Wu, Lei Zuo, Suresh Kaluvan, Haifeng Zhang, Milton Nance Ericson, Kyle Reed, Roger A Kisner. the 11th Nuclear Plant Instrumentation, Control and Human-Machine Interface Technologies (NPIC&HMIT), Feb 2019, Orlando FL


Q&A: Self-Powered Wireless Through-wall Data Communication for Nuclear Environments

**Energy harvester:** 100mW, 124 MRads

**Ultrasound communication:** 100kbps, 180C, 101 Mrads

**Electronics:** FM, 190C, 2 Mrads