Wireless Sensors for Dry Cask Monitoring

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Overview

- Sensor Design and Fabrication
- Wireless Interrogator Development
- Sensor Radiation Testing
- Through Transportation Container Demonstration

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Waste Storage Needs

- Measure internal indicators of thermal management and containment integrity
- Pressure and Temperature
  - Internal pressure and temperature spikes indicates inadequate thermal management and potential containment rupture
- Moisture
  - Internal moisture indicates loss of containment and potential radiation leakage to the environment.
- Others
  - External Temperature, Humidity, and Chlorine Concentration
Challenges to Monitoring

Internal condition monitoring faces three main challenges

1. How to achieve wireless interrogation through metal structure?
2. How to mitigate radiation and thermal effects on sensor materials?
3. How to develop a sensor with tuned wireless response with limited material set?
Sensor Research Efforts

- Develop sensors
  - Design and model sensors compatible with material set, wireless frequency, and fabrication processes
- Low-frequency (<125kHz) wireless coupling
  - Improved power transfer through metal
  - Reduce eddy current losses within metal
- High-temperature material set to survive internal environment
  - Alumina and glass substrates with metal conductors
  - Minimize or eliminate electronics on the sensor tag
Wireless Sensor Operation

Wireless interrogation avoids thermal failure at interconnects
- Changes in the sensing element are seen as impedance changes in the reader
- Adding a diode to the sensor tag will generate harmonic frequencies – removing the return signal from the interrogator signal.
Sensor Development Tools

- Develop engineering tools to design passive wireless pressure and temperature sensors

Models developed
- Pressure sensor diaphragm
  - Analytical equations for small deflections
  - FEA (pictured to the right)
- Temperature sensor
  - Analytical equations verified via experiment
- Antenna inductance and layout
  - Analytical equations verified via experiment

\[
\delta_0 \propto P \cdot r^4
\]

\[
\frac{C}{C_0} = \mathcal{F}(\delta_0, \text{geom})
\]

\[
\frac{f}{f_0} = \mathcal{F}\left(\frac{C}{C_0}\right)
\]
Sensor designed for FR4 fabrication

FR4 – typical fiberglass epoxy used for printed circuit boards
  - Conductors plated Cu
  - Operating temperature to 200°C
  - Very mature fabrication
  - Inexpensive fabrication
Sensor Testing

- Pressure sensors were wirelessly interrogated under vacuum at room temperature.
- There was a clear resonance shift as pressure was varied.
- Resonance frequency varied between 3.4 and 5.4 MHz.
- 2MHz/atm sensitivity.
Sensor designed for LTCC fabrication
LTCC – low-temperature cofired ceramic is a glass-alumina blend ceramic tape
- Conductors are printed with co-fireable metal inks
- Operating temperature to 400°C
- Typically used for RF and wireless circuit boards
High Pressure Setup

- Sensors tested using a pressurized stainless container up to 100 psi without temperature
- SRNS is also assembling apparatus for experiments up to 200 psi and 400 °C
Wireless Pressure Sensor

8mm Sensor 200um membrane 20um gap

Decreasing resonant frequency with increasing pressure
Radiation Tolerance

- We measured the effects of “lifetime” gamma radiation on the sensor materials
  - Capacitance measurements through alumina determine change in material permittivity
  - Sheet resistance measurements of electrodes determine material resistivity
- SRNL will dose the samples
  - 4318 Curie Co$_{60}$ source
  - 2.5 x $10^6$ total rads to simulate 40 year cask life

J.L Shepherd Model 109 Cobalt Source.
Dose rate = 11,000Rads/Hr
Gamma Radiation Effect on Deposited Cu

Deposition: 200A Ti, 5000A Cu on 99.6% Alumina Substrate
Gamma Radiation Effect on Deposited Silver

Sheet Resistance with Exposure
Total: 2.7e6 Rads

Sheet Reactance with Exposure
Total: 2.7e6 Rads

Deposition: 200Å Ti, 5000Å Ag on 99.6% Alumina Substrate
Gamma Radiation Effect on Alumina Substrate

Deposition: 200A Ti, 5000A Cu on 99.6% Alumina Substrate
Wireless Development

- Demonstration of sensor communication into 1/4” thick stainless container
- Determine transmission losses in stainless container
- Use passive frequency modulation to boost signal
- Establish energy budget
- Optimize frequency
- Improve signal-to-noise
  - Harmonic generation for frequency separation
  - Switch off interrogator and listen for temporal separation
Wireless Sensor Operation

Magnetic coupling between reader coil and sensor coil
- Coupling decreases with distance and coil mismatch
The secondary containment layer from a 9975B transportation package was fitted with a reader antenna on the outside and a sensor on the inside. The container was sealed with the threaded metal lid.
1. We measured the coupling in **one direction** through the metal canister to determine an optimal RF frequency and a power budget at that frequency.
2. This energy budget will be used to calculate required interrogator power.
The diode generates a signal 20dBm over the noise floor at 2X the primary frequency. Wireless communication with a battery-free passive sensor tag in a sealed metal container is achievable given sufficient Tx power and frequency shift on the tag.
Sensor response frequency is dependent on the measurand.
Sensor response frequency is independent of the burst frequency.
But the sensor signal strength improves near resonance.
Reader Electronics

- **Electronics**
  - Electronics are removed from the sensor tag to improve survivability in austere environments
  - The reader board contains all ADC, control, and signal processing capabilities.

*Prototype Reader*

16bit ADC and microcontroller with USB power and communication.
Summary

- Demonstrated radiation hardened sensor tag
  - Need to demonstrate radiation tolerant diode
- Demonstrated sensor operation for pressure
  - Prototype temperature and pressure sensors
- Demonstrated technique for through metal communication
  - Tx requirements
  - Reader prototype
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