AOI [2] Passive Wireless Sensors for Temperature and Corrosion Monitoring of Coal Boiler Components under Flexible Operation

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SENSORS & CONTROLS PROGRAM

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Initial Acknowledgments:

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Background:

- Operating profile of the existing coal-fired power plants has changed from high-capacity-factor (baseload) operation to *flexible operation*.

- Increased cycling operations with *increased thermal ramp rates, and rapid changes* in unit output have a major impact on reliability, efficiency and cost of the coal-fired power plants.

- Cycling causes increased wear-and-tear on high-temperature and high-pressure components, and shorter equipment lifespan due to thermal expansion/fatigue, increased corrosion and cracking.

- *Corrosion-related issues are emphasized as the major mechanism* for boiler tube failures under harsh-environments.

Background:

- Health and temperature monitoring of metal components and boiler tubes in the coal-fired power plants has technical challenges due to 500-1300ºC and high steam- and/or flue gas-related harsh-environments.

- *Downtime inspection* and *metal loss coupons* are common techniques being utilized to assess the corrosion and related failures in power plants.

  Limitations:
  - Slow response rate
  - Increased personnel required
  - Limited testing/inspections possible
  - Operating capability at various temperatures

Background:

Corrosion Sensors for Oil/NG Piping

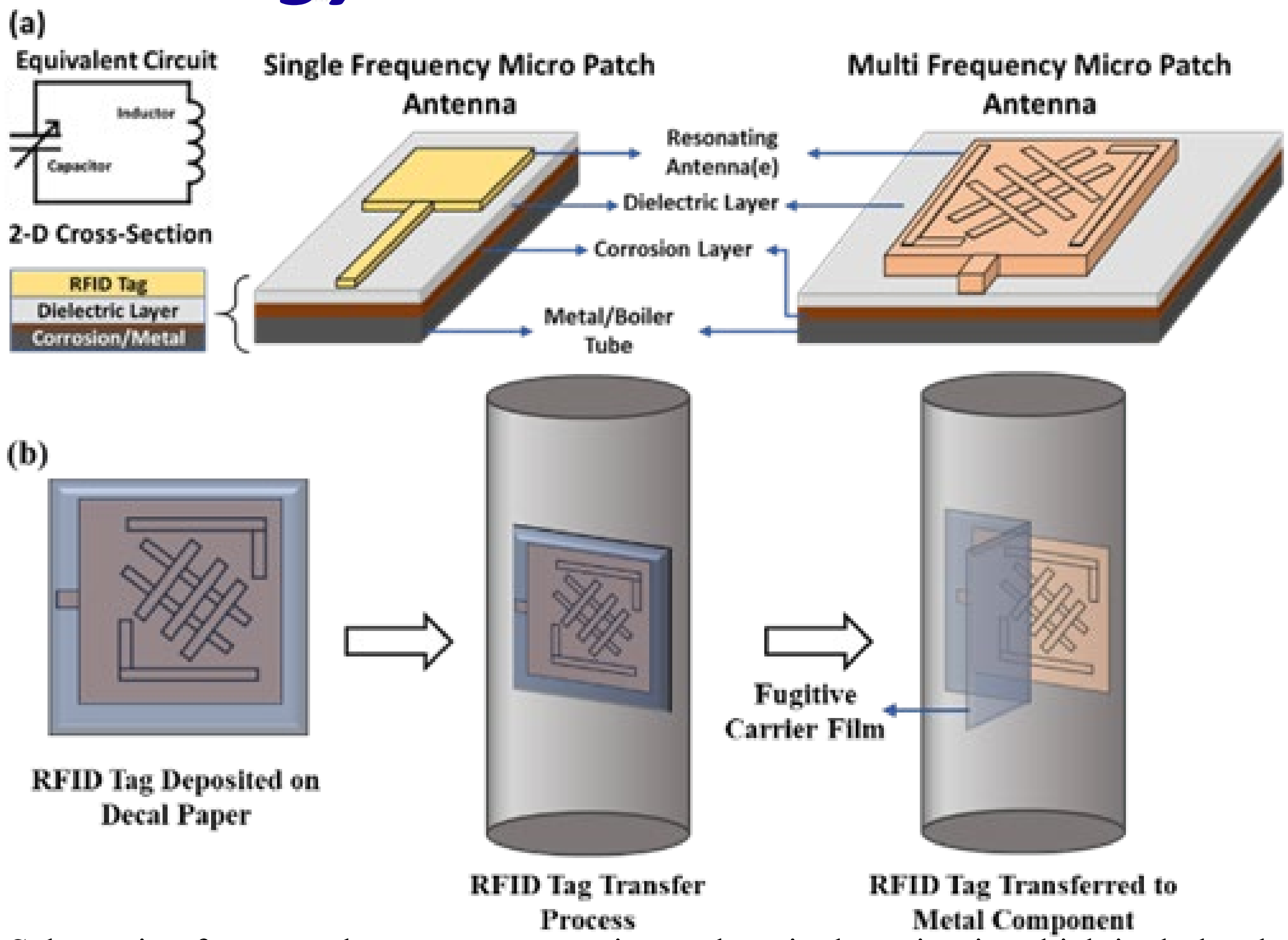
Table 1. Summary of different corrosion sensors for the oil and gas industry.

Sensor	Temporal	Spatial	Advantages	Disadvantages
Corrosion coupon	A few months	Point sensor	Gold standard, Simple, Easy to operate	General corrosion, Not real-time
Electrical resistance probe	Real-time	Point sensor	Real-time, Remote sensing compatible	Uniform corrosion, Electrical based
Electrochemical sensor	Real-time	Point sensor	Various in-situ electrochemical techniques	Electrical based, Mostly for conductive liquids
Ultrasonic sensor	Real-time	Point sensor, PIG	Non-intrusive	Not sensitive to small thin features
Magnetic flux leakage sensor	Real-time	Point sensor, PIG	Nondestructive	Limited for surface detection
Electromagnetic sensor	Real-time	Point sensor, PIG	Nondestructive, Inner wall features	Not sensitive to small defects
Pipeline inspection gauge	Every 5–7 years	Run through pipes	Comprehensive sensing/logging, Long distance	Costly, not frequent
Optical fiber sensors	Real-time	Distributed linear sensors	Distributed sensing for a long distance, Multi-parameter	Cost of interrogation instrument
Passive wireless sensors	Real-time	Ubiquitous point sensors	Small size, Passive, Wireless capability, Low cost	Wireless telemetry in attenuating media

- Many are intrusive but some non-intrusive
- Most are costly (especially for instrumentation)
- Many not sensitive to small defects
- Difficult to implement many with wireless data acquisition

Sensors **2019**, *19*, 3964; doi:10.3390/s19183964

The Technology:



Item (a): Schematic of proposed sensor cross-section and equivalent circuit, which includes the single and mult-frequency micro-patch RFID tag printed onto ceramic barrier layer which will insulate and bond sensor to the metal specimen.

Item (b): Representation of peel-and-stick deposition approach to transfer the chipless RFID tag sensor to metal component.

The Technology:

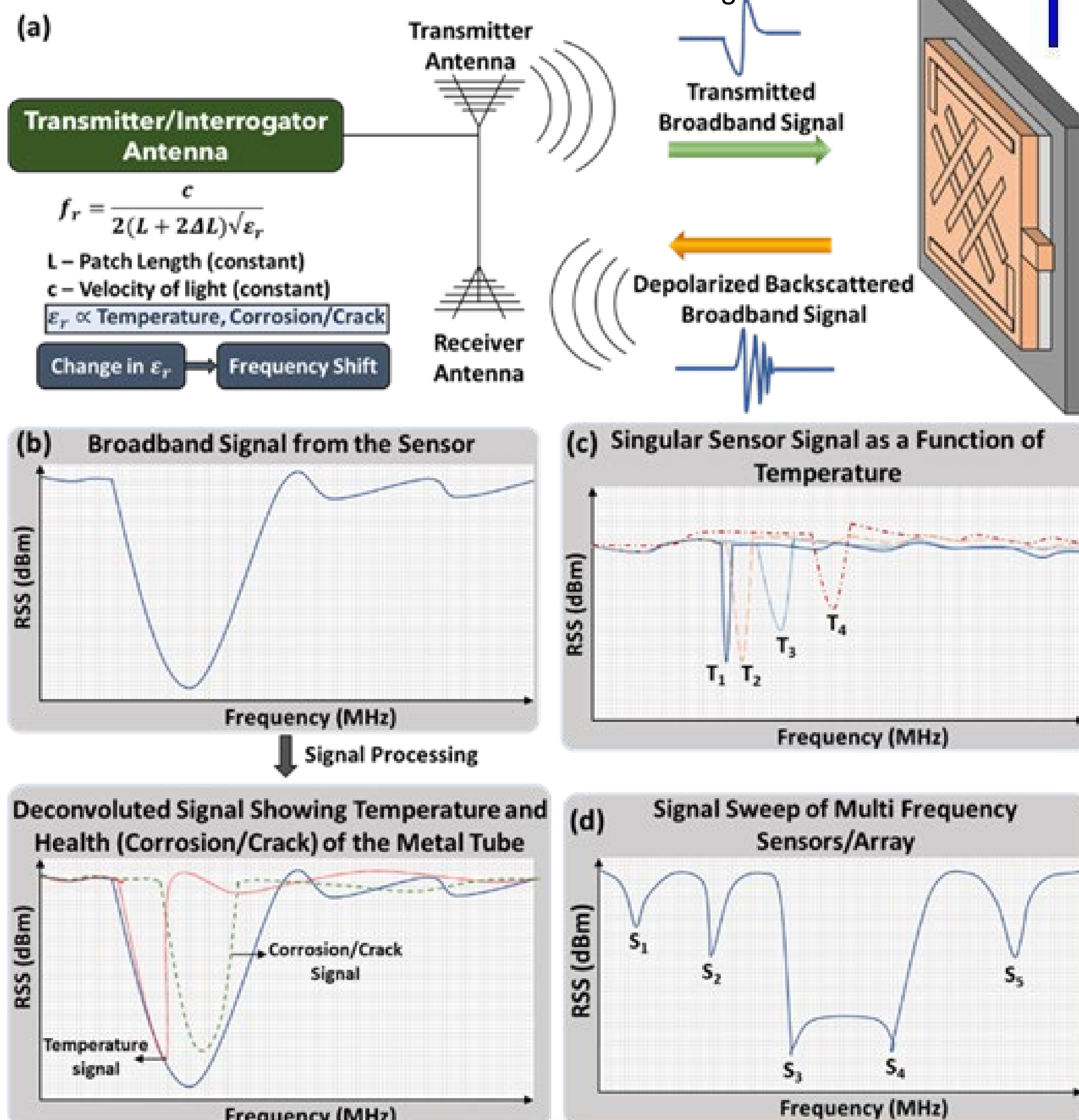
RSS= Received Signal Strength

Item (a)= *General Schematic*

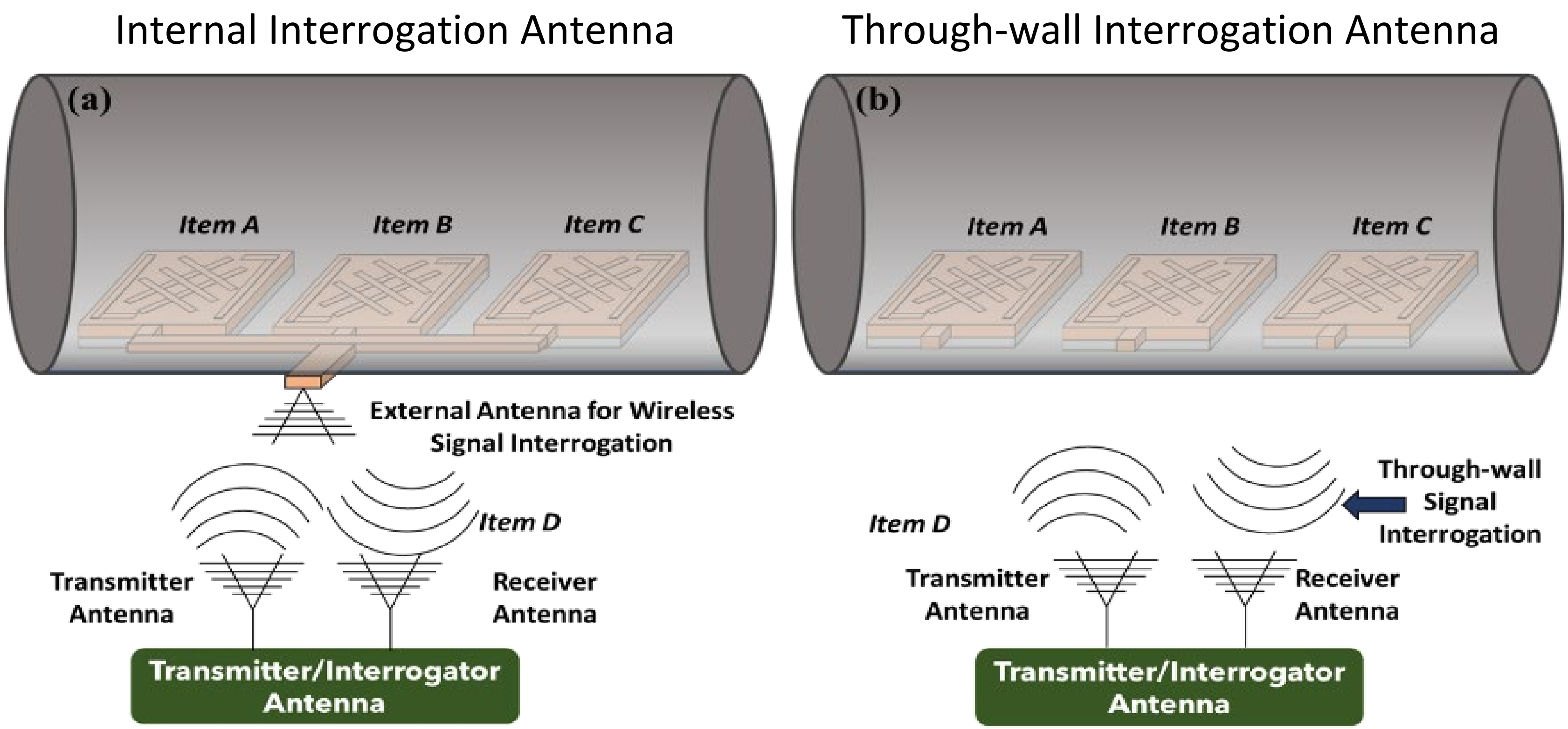
Item (b)= Received broadband signal and deconvoluting step to separate temperature and corrosion/crack information.

Item (c)= Frequency shift for reflected power for singular sensor to change in sensing parameters (temperature).

Item (d)= Multi-frequency signature read for multi-sensor array measured by interrogator antennae.



The Technology:



Item A-C: Each sensor pattern will have a different dimensions/geometry which permits the sensors to couple at a different frequency band.

Item D: Represents the interrogator antenna that will be used to broadcast and read the reflected power from the RFID sensors.

Program Objectives:

The specific project objectives are as follows:

1) **Design passive (chipless) wireless RFID patch** and interrogator antennas which will be implemented in a wide frequency band for high-temperature sensing of corrosion and crack propagation at temperatures up to 1300°C;
2) **Develop materials and methods to fabricate a microstrip patch antenna sensor** composed of a robust conductive material pattern and interlayer ceramic coating (incorporate this sensor into a "peel-and-stick" preforms that will efficiently transfer and bond to the metal specimens of interest);
3) **Investigate the wireless RFID sensor response in accelerated high-temperature and high steam environments**, and correlate corrosion and cracking mechanisms (and kinetics) with response of the sensors;
4) **Investigate the wireless signal acquisition and processing of data** transferred in various configurations by multiple sensors within the same environment and through-wall transmission of the signal by a singular RFID sensor;
5) **Demonstrate monitoring the health of metal components in service within a coal-fired power plant**.

Task Assignments:

Task 1.0 Project Management and Planning. (Sabolsky)

Task 2.0 Passive RFID Sensor Design and Initial Benchtop Testing. (Reynolds)

Task 3.0 Fabrication of Wireless Sensors and Development of Inexpensive Transfer Process (Sabolsky)

Task 4.0 Cyclic Passive Wireless Sensor Testing. (Sabolsky/Reynolds)

Task 5.0 Through-Wall Signal Transmission for RFID Wireless Sensor Testing. (Reynolds)

Task 6.0 Implementation of Passive Wireless Sensor Arrays into Power Plant Demonstration. (Sabolsky/Reynolds)

= Tasks initiated (but behind schedule) due to student visa issues and FN review

= Tasks not slated to start until Year 2

SUMMARY of TECHNICAL TASKS and MILESTONES

Task 2.0 – RFID Sensor Design and Initial Benchtop Testing. (Reynolds)

Task 2.0 – RFID Sensor Design/Initial Benchtop Testing:

•***Subtask 2.1: Passive Wireless Design (Q1-6)***

- Design appropriate RFID sensor using ANYSIS Maxwell modelling package.
- Chipless RFID microstrip patch antenna design, where the geometry of the conductive pattern on the specimen and the dielectric properties (and thickness) of insulating layer will alter the frequency behavior (which is proportional to temperature variation, corrosion, and corrosion induced cracking).

•***Subtask 2.2: Wireless Sensor Fabrication on Polymer/Ceramic Substrates and Benchtop Testing (Q3-5)***

- Screen/ink-jet printing techniques will be used to fabricate the sensors using metallic (Ag, Pt, etc.) inks on polymer or non-conductive substrates. Both the sensors and interrogator designs will be tested at low temperature (<100°C) both outside and inside the proposed metal tubes.
- Sensors/antenna pairs will be tested parallel to each other at various lengths, offset distances, and related orientations.

• ***Subtask 2.3: Advanced Signal Processing Methods for Deconvoluting the Wireless Response (Q4-11)***

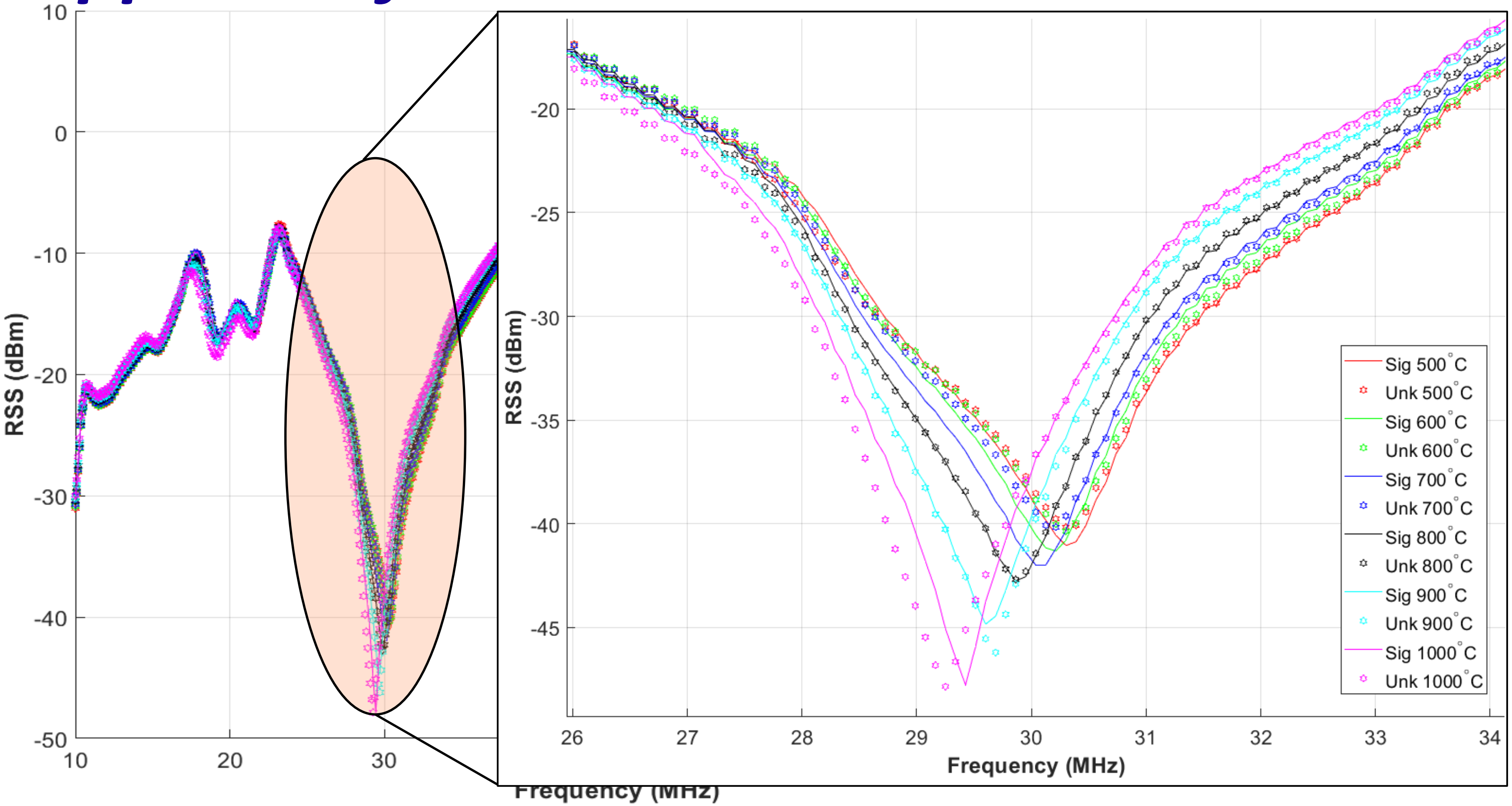
- Define signal processing method (such as Non-Parametric (NP) Methods and Parametric Modelling (PM) Methods) to define the measurement parameters (T, c, s) separately, and modeling their interactions to build a model for defining corrosion and crack events during testing.

Approach for Task 2:

- **Temperature Sensing for Harsh Environments:**
  - We have designed, fabricated, and tested chipless RF temperature sensors for harsh environments
  - RLC-based design produced in software, fabricated using various methods on a variety of substrates and "inks"
  - We can measure temperatures over 1000C
  - **Works when material properties are unknown or when material properties or the environment change over time.** For example: the material changes after repeated temperature cycling or the sensor is moved to a new location with new RF interference.
  - Our approach is adaptive and non-parametric (don't need to track a resonant frequency)
- **Approach for Signal Processing**
  1. Transmit a frequency sweep (say 10-80 MHz)
  2. Measure backscatter energy from the sensor at each frequency creating a frequency response vector **r**
  3. Compare **r** to a database of frequency response signatures taken at known temperatures
  4. Choose the database signature that is "most similar" to **r**
  5. At regular intervals or after known changes, obtain new signatures.

Converts temperature measurement into a classical signal matching problem!

Approach for Task 2:



- ❖ Actual sample frequency responses : signatures (-----) and unknowns (oooo)
- ❖ We can easily see the different responses at each temperature
- ❖ We are *not* tracking peaks: we look for ANY kind of variability

Approach for Task 2:

•Signal Processing Approach: adaptive, robust, and non-parametric

- Convert temperature sensing into signal matching
- When something changes, just get new signatures
- Leverage signal processing toolsets from RADAR/SONAR, digital communications, biometrics, maching learning/deep learning…
- Optimal matching algorithm depends on "noise" or "channel" model: (**s** is the signature)

  r=s+n (additive noise model)

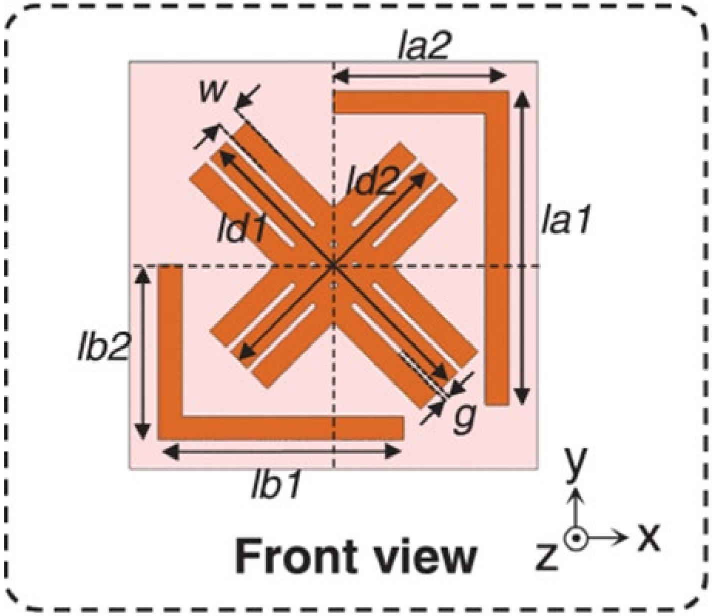
  r=s*h+n (linear filter distortion)

  …
- We obtain excellent results using correlation (optimal for additive white Gaussian noise) and minimum absolute error.
- It's possible that better results could be obtained by better channel modeling or by learning approaches, but **not needed.**

- **This new project provides new challenges!**
- **Our experience puts us in a position to succeed.**

Initial Patch Sensor Design (Sensor 1):

- Patch antenna design was based upon previous work.

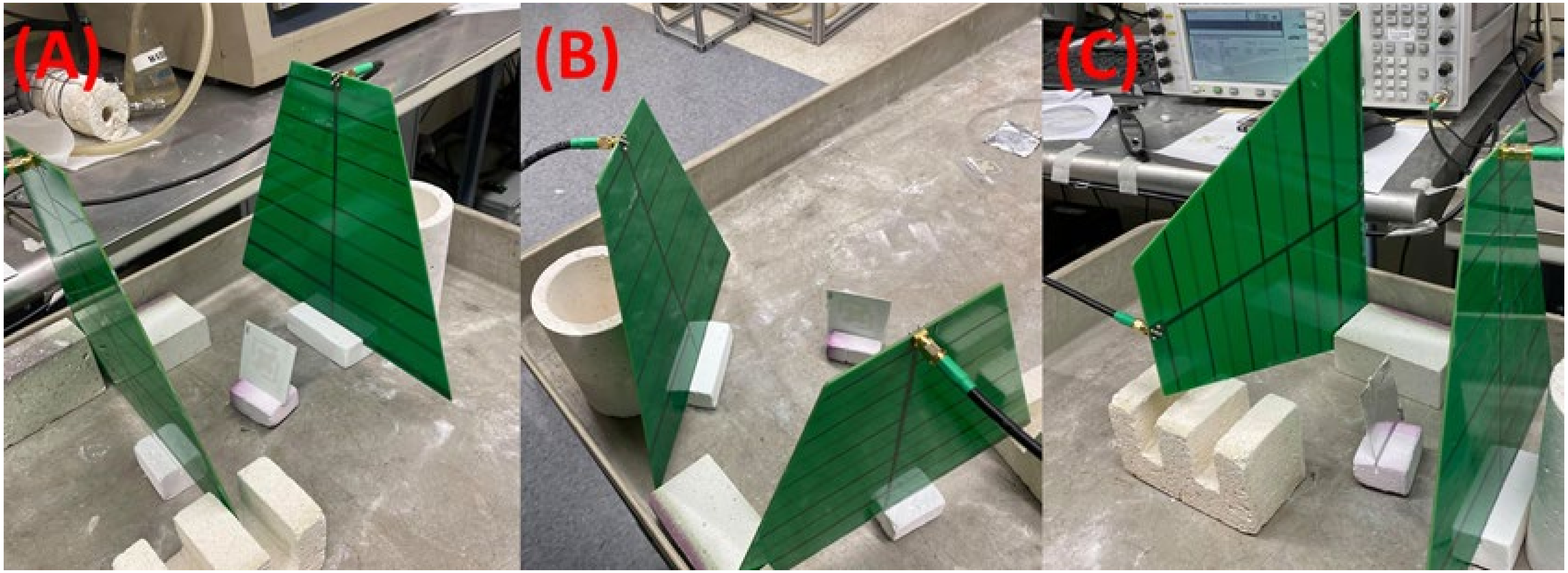


- Multi resonance peaks are achieved with this design.
- Five peaks are achievable in the range of 1.5-5Ghz.

g	*h*	*la1*	*la2*	*lb1*	*lb2*	*ld1*	*ld2*	*t*	*w*
0.5	1.52	27	15	21	15	28	23	0.035	2

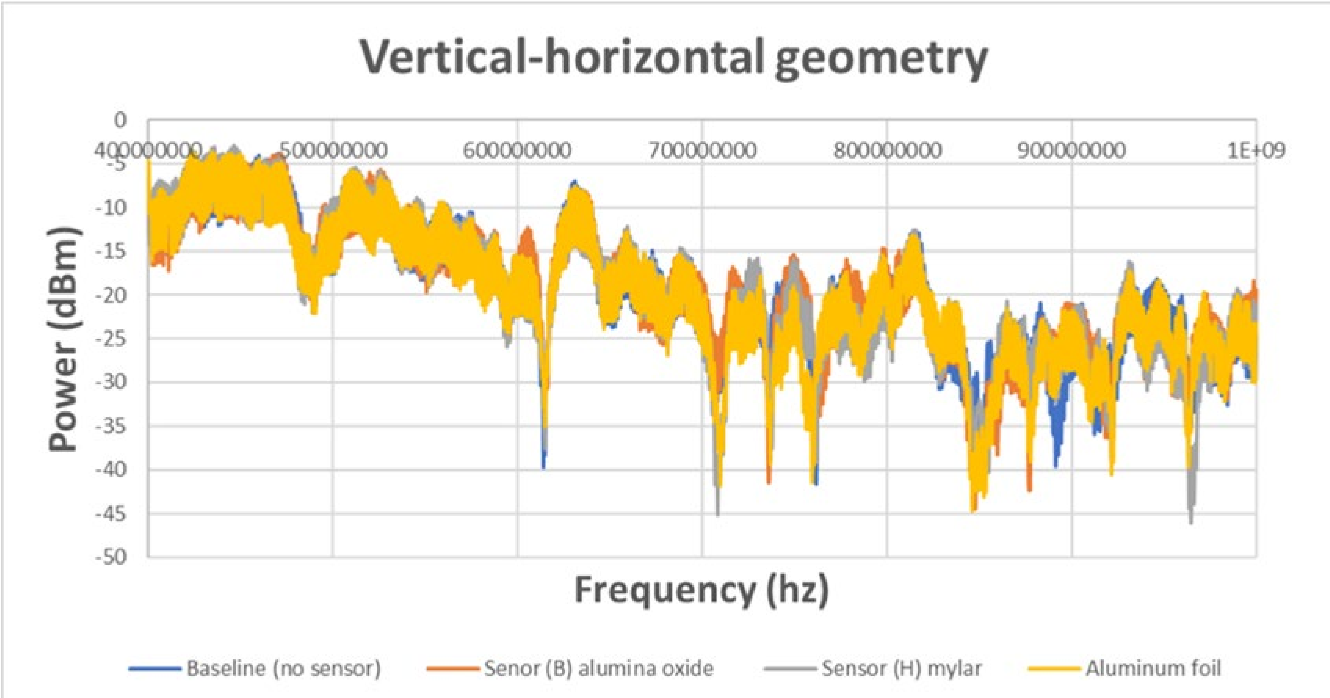
REF: Marindra, A. and Tian, G., 2019. Multiresonance Chipless RFID Sensor Tag for Metal Defect Characterization Using Principal Component Analysis. *IEEE Sensors Journal*, 19(18), pp.8037-8046.

Initial Low-Temperature Wireless Testing of (Sensor 1):



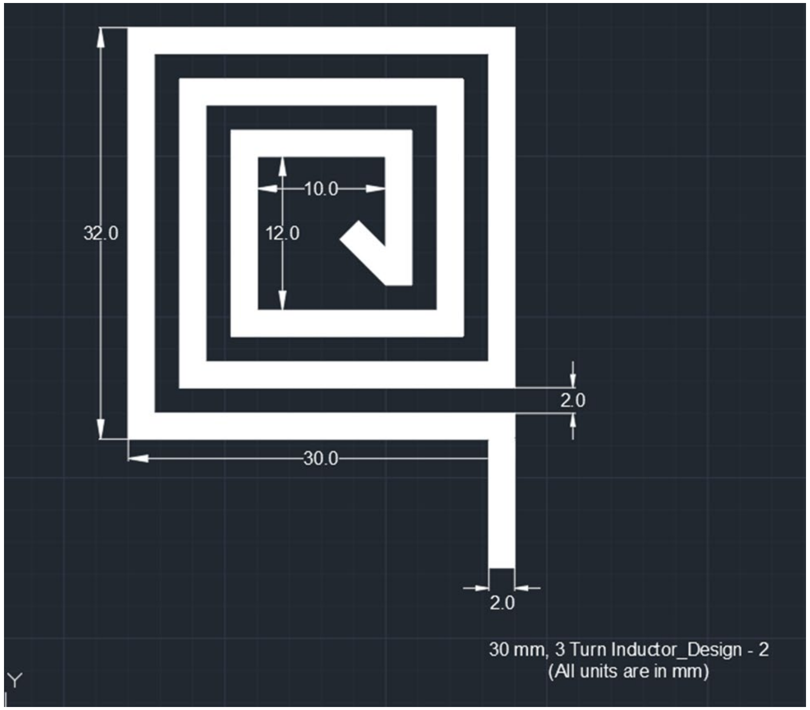
- The patch antenna design was printed on three different material, alumina, mylar and transparency film.
- Signals were collect at room temperature in three different geometries.
- Signal was scanned in the range of 0.4-1Ghz.

Example of Initial Sensor Signal (Sensor 1):



- No resonance peaks were identified for first baseline test for initial sensor geometries.
- Signals for all sensor designs generally followed baseline signal.
- Further modelling investigation is required at a higher frequency ranges.

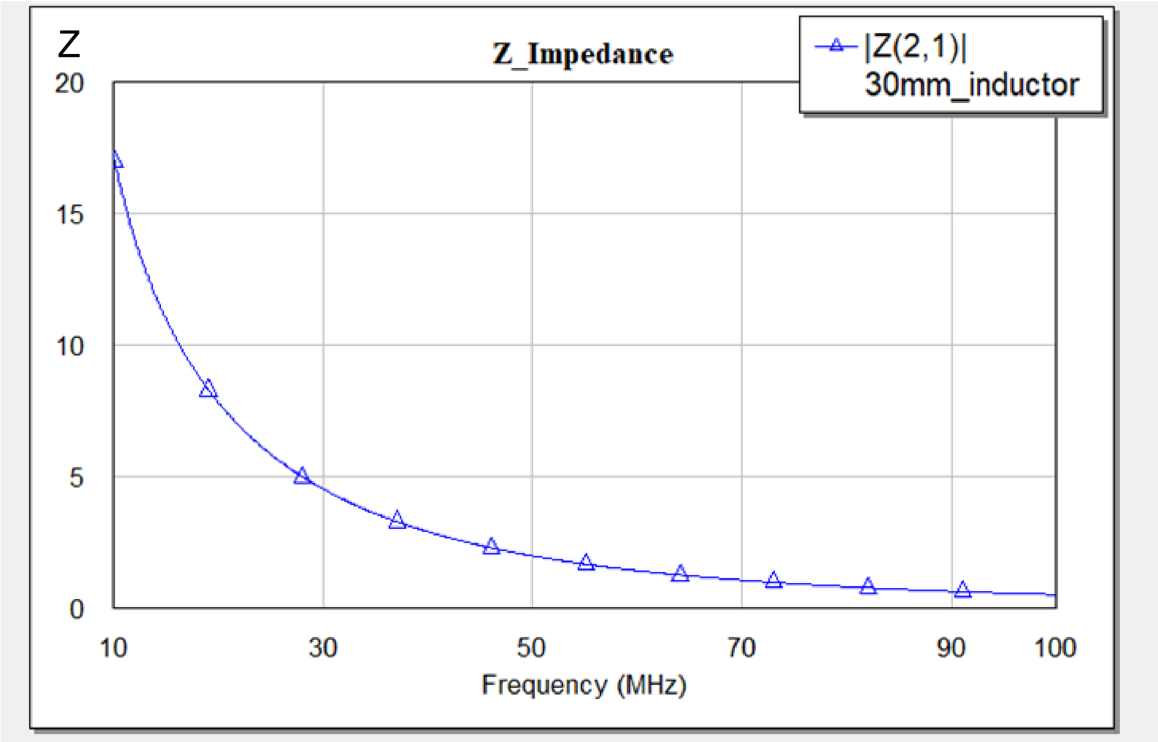
AWR modelling (Sensor 2):



3-turn inductor
30 mm thickness
2 mm turn separation

- A second sensor design (Sensor 2) was proposed of an LRC circuit.
- Advancing the Wireless Revolution (AWR) modelling package used from Cadence Design Systems, Inc.
- Various number of inductor turns, inductor geometries, and conductive materials (i.e. conductivities) were placed into the model and evaluated at 50 MHz.

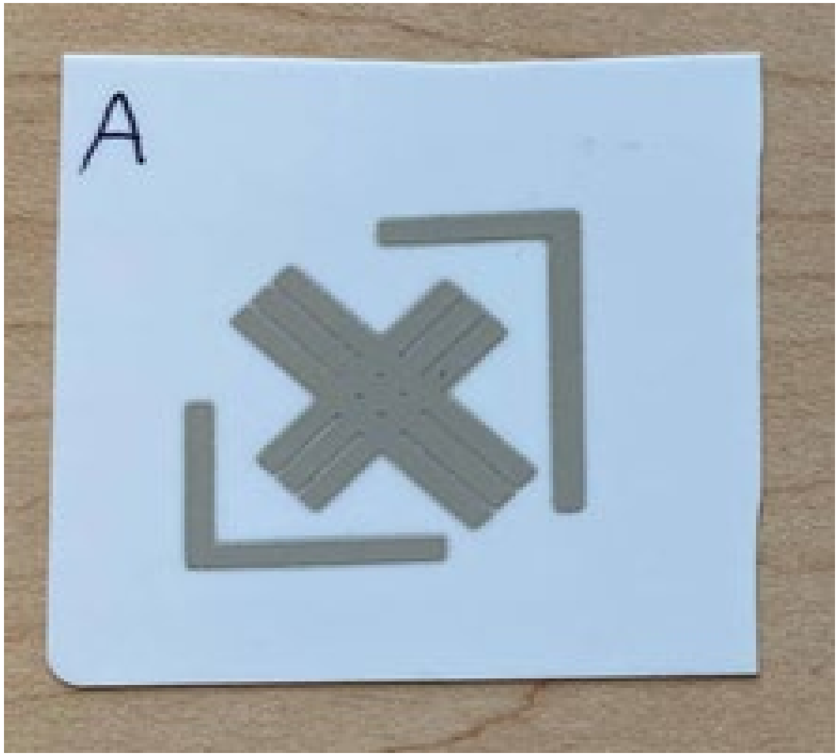
Impedance Modeling for LC-sensor (Sensor 2):



- The impedance was modelled using the AWR software for Sensor 2 design (seen above).
- The impedance trends are used within the AWR model to define the expected resonant frequency Sensor 2 with various geometrical factors.

Fabrication of Sensor 1 and Sensor 2:

- Sensor 1 was printed on various substrates.
- Room temperature testing was completed with variable substrates.
- Sensor 2 was successfully modelled and fabrication has begun.
- Fabrication details will be in Task 3.



(Sensor 1 design printed on alumina with a silver based ink)

Task 3.0 – Fabrication of Wireless Sensors and Development of Inexpensive Transfer Process. *(Sabolsky)*

Task 3.0 – Fabrication of Wireless Sensors and Development of Inexpensive Transfer Process:

- ***Subtask 3.1- Investigation of Various Material Systems for the Wireless Sensor Fabrication***
  - *Refractory metals and electroceramic oxides* will be for operation at 500°-1300°C, varying humidity levels, and pressure developed in the system.
  - *Electrical/Physical properties:* Electrical conductivity, corrosion resistance, chemical/thermal stability, susceptibility to temperature, electric and magnetic field.

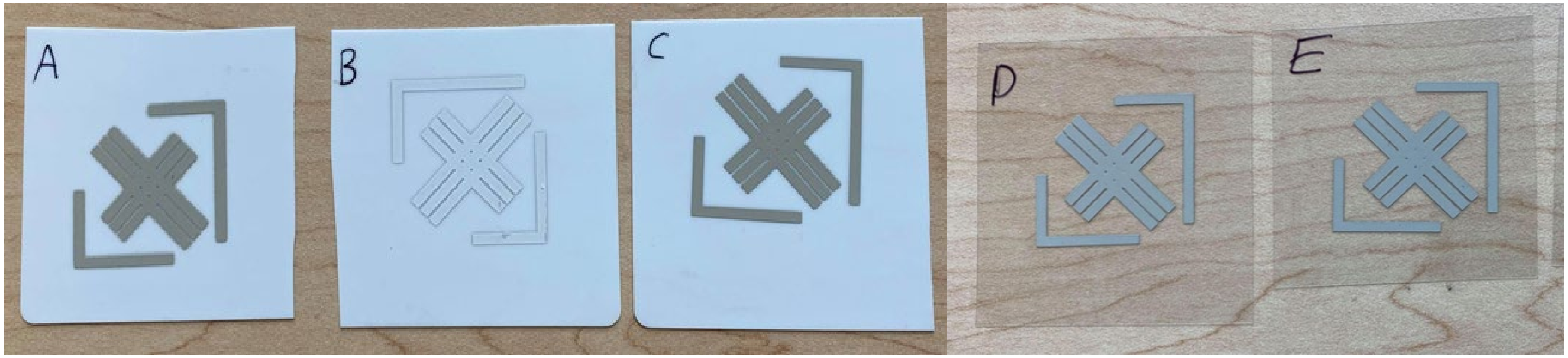
- ***Subtask 3.2 Fabrication of RFID and Patch Antenna Sensors Directly onto Planar Metal/Ceramic Substrates***
  - Sensor designed in Task 2 will be *fabricated onto a planar metal/ceramic substrate* with the materials system.
  - Several patterning and deposition techniques (direct ink writing, micro-casting, screen-printing) will be investigated based on the geometrical form factor of the sensor/arrays.

Task 3.0 – Direct-Writing (2D/3D Patterning) of Refractory and Sensor System:

- ***Subtask 3.3- Development of Inexpensive Transfer Process and Baseline Testing***
  - *Methods to transfer the sensor to the active energy system component* (*flat substrates*).
  - The work will investigate (but not be limited to): the effect of ink/paste characteristics on wetting and transfer of the patterns, organic overlay effect on "sticking" to metal surfaces, pyrolysis of fugitive under- and over-lay coatings, bonding of print after carrier pyrolysis.

- ***Subtask 3.4- Direct Transfer of Sensor to Metal Tubing and Thermal Processing Development***
  - *Three (3) initial sensor configurations* (without passive communication circuit) will be designed, with focus on temperature, corrosion, and corrosion induced crack tests.
  - Electrical performance testing of the sensors *directly transferred on metal tubing or curved substrates via transfer process* will be completed at 500^{o}-1300°C in varying atmospheres in WVU's existing automated sensor test stands. Baseline electrical performance will be assessed.

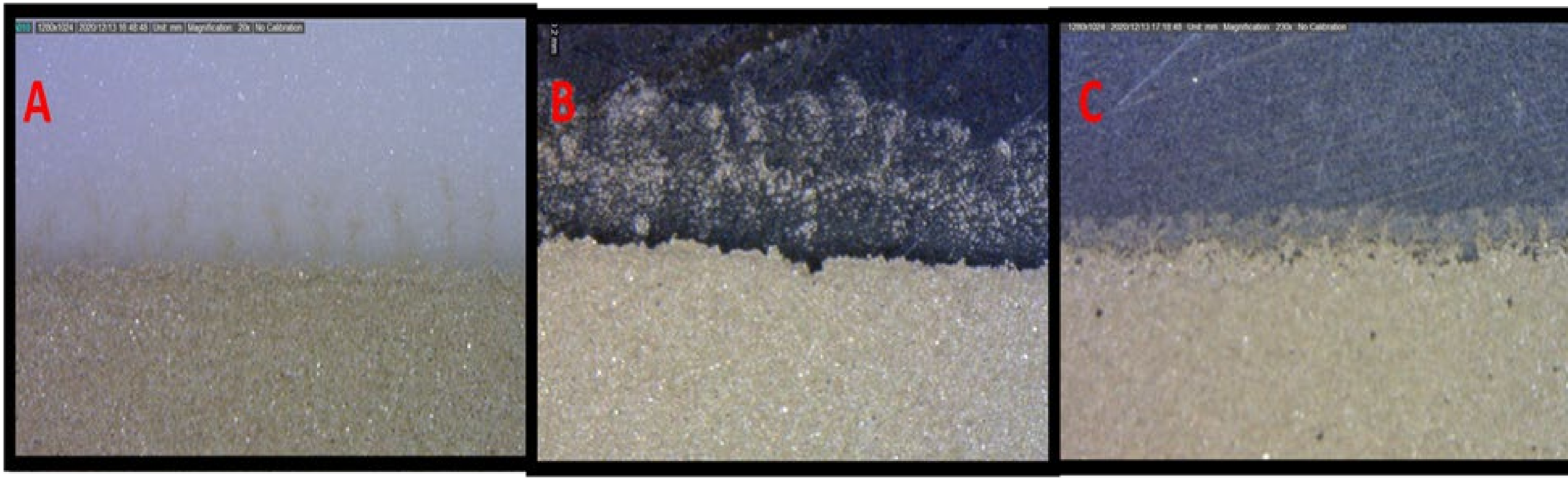
Fabrication of Sensor 1 on Various Substrates:



Sample substrate	Resistivity (Ω)
(A) alumina oxide RT	47.1
(B) alumina oxide (sintered)	0.3
(E) transparency film	32
(H) mylar	21

- Sensor 1 design was screen printed on three different substrates, alumina, mylar and a transparency film with silver ink.
- Sensor B was sintered at 500C for two hours removing the organic binders.
- Resistivity measurements of all sensors were then collected.

Boundary Investigation of Sensor 1:



- Boundaries to the substrate where then investigated under a microscope.
- From the figure we can confirm the silver ink bonded best to the alumina substrate.

Brief Task Descriptions Not Initiated as Schedule in SOPO:

Task 4.0 – Development of Embedded Interconnection Design and Smart Anchor Testing

Task 5.0 – Through-Wall Signal Transmission for RFID Wireless Sensor Testing (Reynolds/Sabolsky)

Task 6.0 Implementation of Passive Wireless Sensor Arrays into Power Plant Demonstration (WVU/Longview)

* Tasks will be initiated in Year 2 of the program (i.e. next work quarter).

Near-Term Future Work:

In the coming months we plan to:

- Investigate different dielectric substrates and conductor inks for Sensor 1 and Sensor 2.
- Investigate the corrosion mechanisms of three boiler grade steels, SS304H SS347H and SS347HFG, before baseline sensor testing.
- Corrode steels at high temperatures and humidity with various coatings and barrier layers over 100 h.
- Slit-ring resonator circuit was also selected as Sensor 3, modelling will begin on AWR software.
- Room temperature and high temperature testing of all three sensor designs.

Acknowledgments:

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Questions

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