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

Team:
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1:30 pm

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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

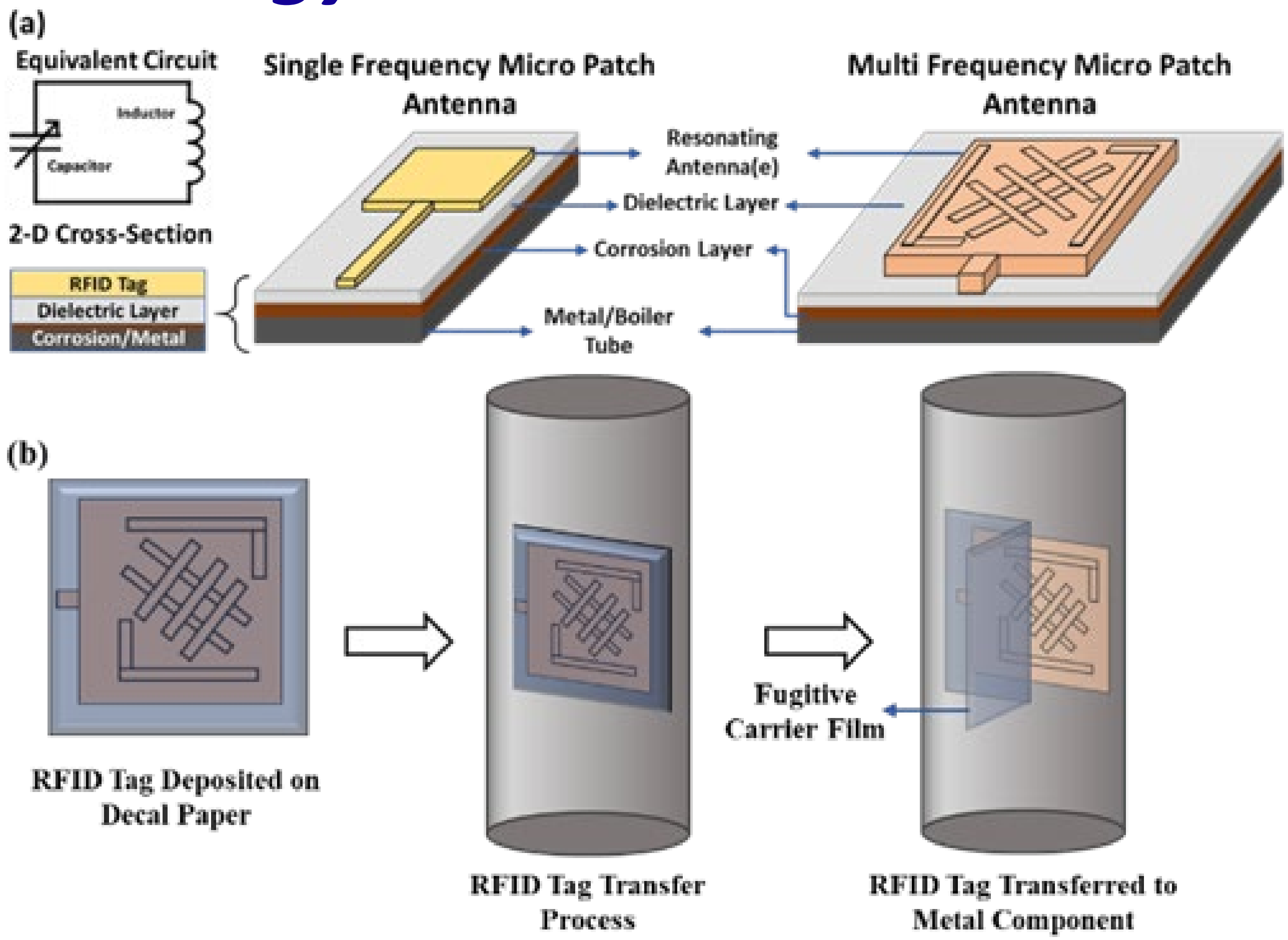
Table 1. Summary of different corrosion sensors for the oil and gas industry.

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:

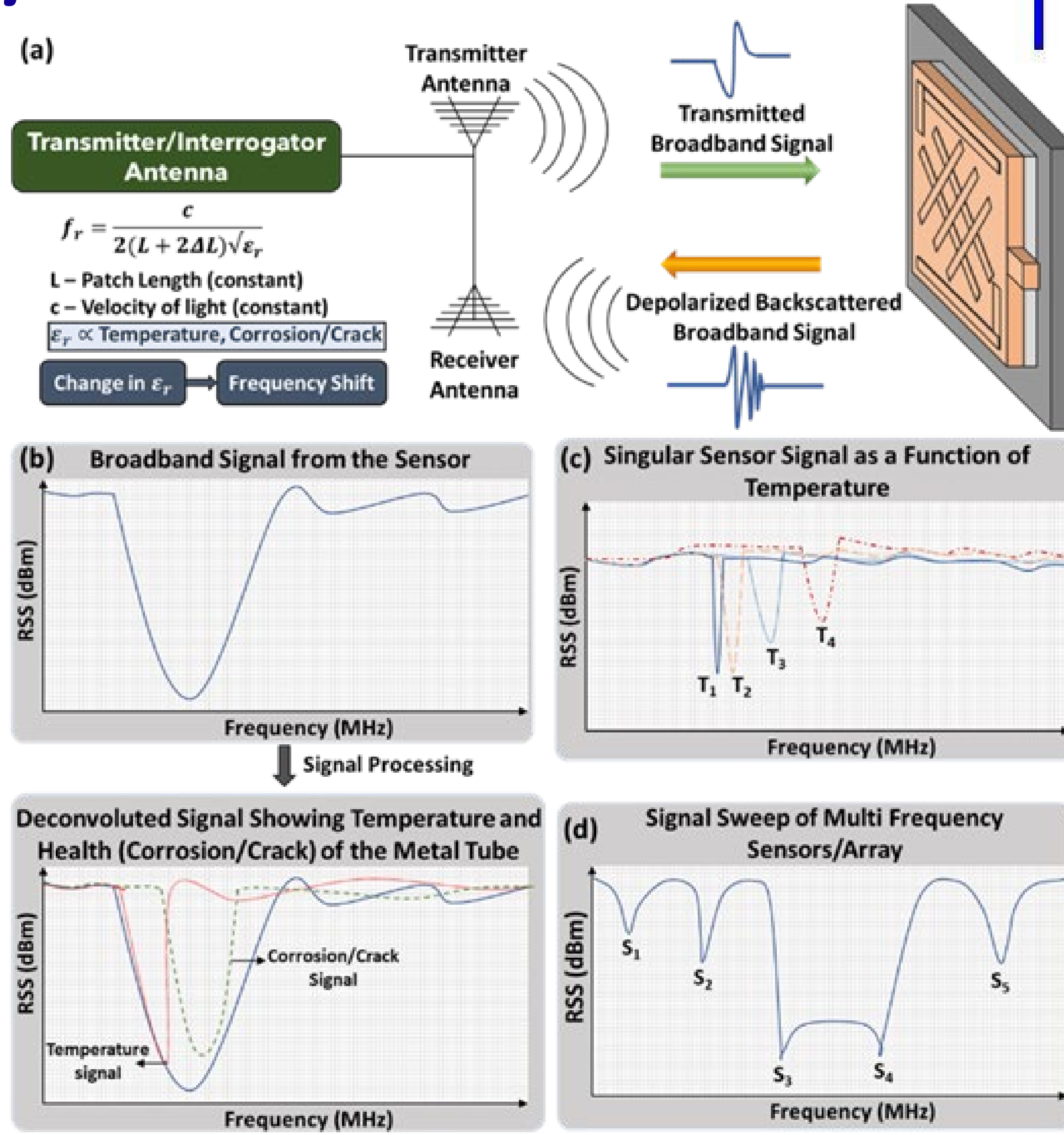
RSS= Received Signal Strength

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).

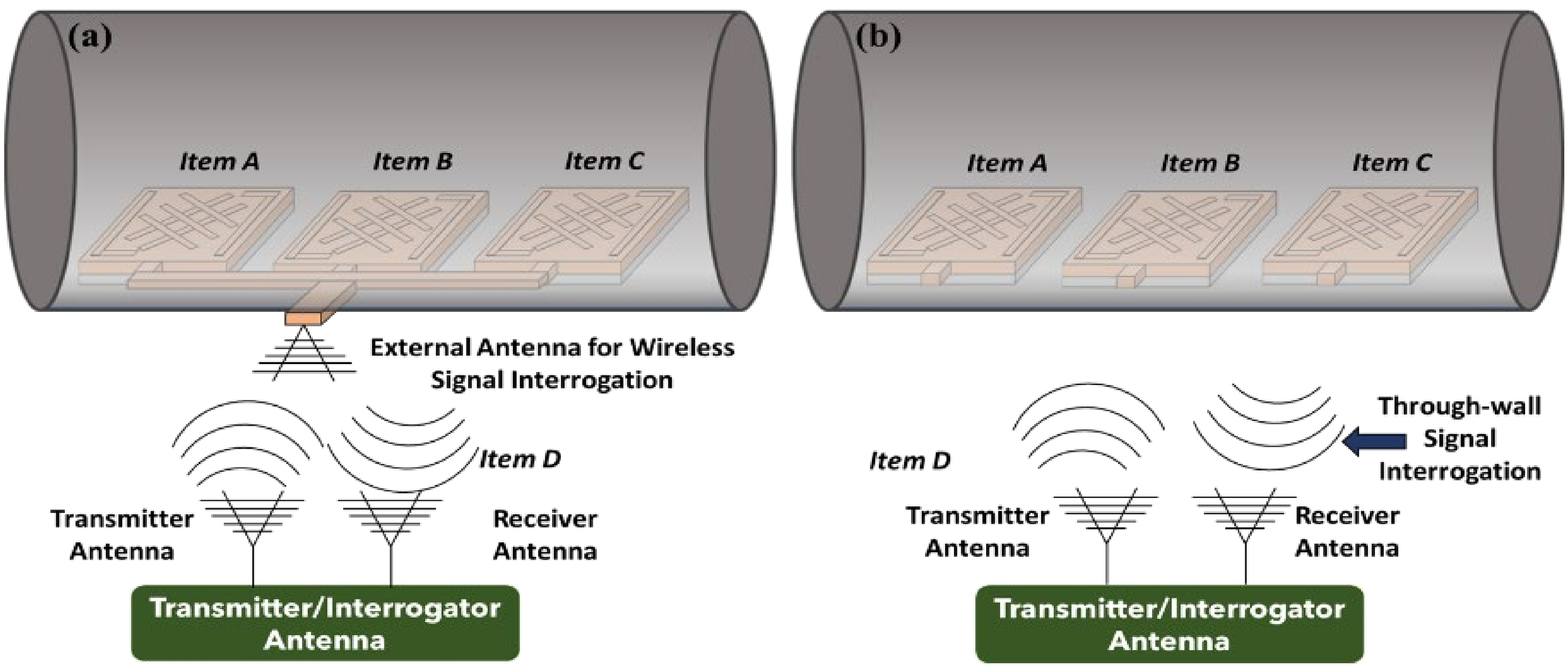
Item (d)= Multi-frequency signature read for multi-sensor array measured by interrogator antennae.



The Technology:

Internal Interrogation Antenna

Through-wall Interrogation Antenna



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**.

R&D Team

Dr. Edward M. Sabolsky (WVU Mechanical Engineering) will act as PI of the program (both technical and administrative), and will be responsible for materials and sensor development.

Dr. Daryl Reynolds (WVU Electrical Engineering) will lead the signal collection and processing, and later electronics development for boiler demo.

Brian Jordan (WVU MAE-MS&E- PhD Student1) will complete materials development, sensor fabrication, and metal corrosion characterization work.

Graduate Student (WVU Electrical Engineering- PhD Student2) will complete modelling and signal analysis work, which includes signal collection and processing.

Chad Hufnagel (Longview Power, WV) *Plant manager who will* coordinate the demonstration work with WVU.

Task Assignments

Task 1.0 Project Management and Planning.
Sabolsky

Task 2.0 Passive RFID Sensor Design and Initial Benchtop Testing.
Reynolds (PhD2-TBD) $\Rightarrow$Modelling and RT testing of sensors printed on plastic or similar.

Task 3.0 Fabrication of Wireless Sensors and Development of Inexpensive Transfer Process
Sabolsky (PhD1-Jordan) $\Rightarrow$Materials development, sensor pattering, and transfer of design to complex surfaces.

Task 4.0 Cyclic Passive Wireless Sensor Testing.
Sabolsky/Reynolds (PhD1-Jordan, PhD2-TBD)$\Rightarrow$Low/high temperature sensor testing within corrosive environment with interior antenna (as well as baseline characterization of metals).

Task 5.0 Through-Wall Signal Transmission for RFID Wireless Sensor Testing.
Reynolds (PhD2-TBD)$\Rightarrow$Data acquisition, signal processing

Task 6.0 Implementation of Passive Wireless Sensor Arrays into Power Plant Demonstration.
Sabolsky/Reynolds (PhD1/PhD2/Post-Doc) $\Rightarrow$Sensor testing/demonstrations

SUMMARY of TECHNICAL TASKS and MILESTONES

Task 1.0– Project Management and Planning. (Sabolsky)

Task 1.0– Project Management and Planning:

- Manage and direct the project in accordance with a Project Management Plan to meet all technical, schedule and budget objectives and requirements.

- Management of project risks will occur in accordance with the risk management methodology delineated in the Project Management Plan in order to identify, assess, monitor and mitigate technical uncertainties as well as schedule, budgetary and environmental risks associated with all aspects of the project.

Task 1.0 Current Status:

- Funding strings released by university (Sept. 29th).
- Hiring process initiated:
  - PhD1 arrive at WVU on Sept. 1, 2020 waiting on DOE approval ***(Brian Jordan-FN UK)***
  - PhD2 (TBD) will not start until Jan. 15, 2021
- Work not initiated to date waiting on student FN approval.

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

Task 2.0 – RFID Sensor Design and Initial Benchtop Testing.

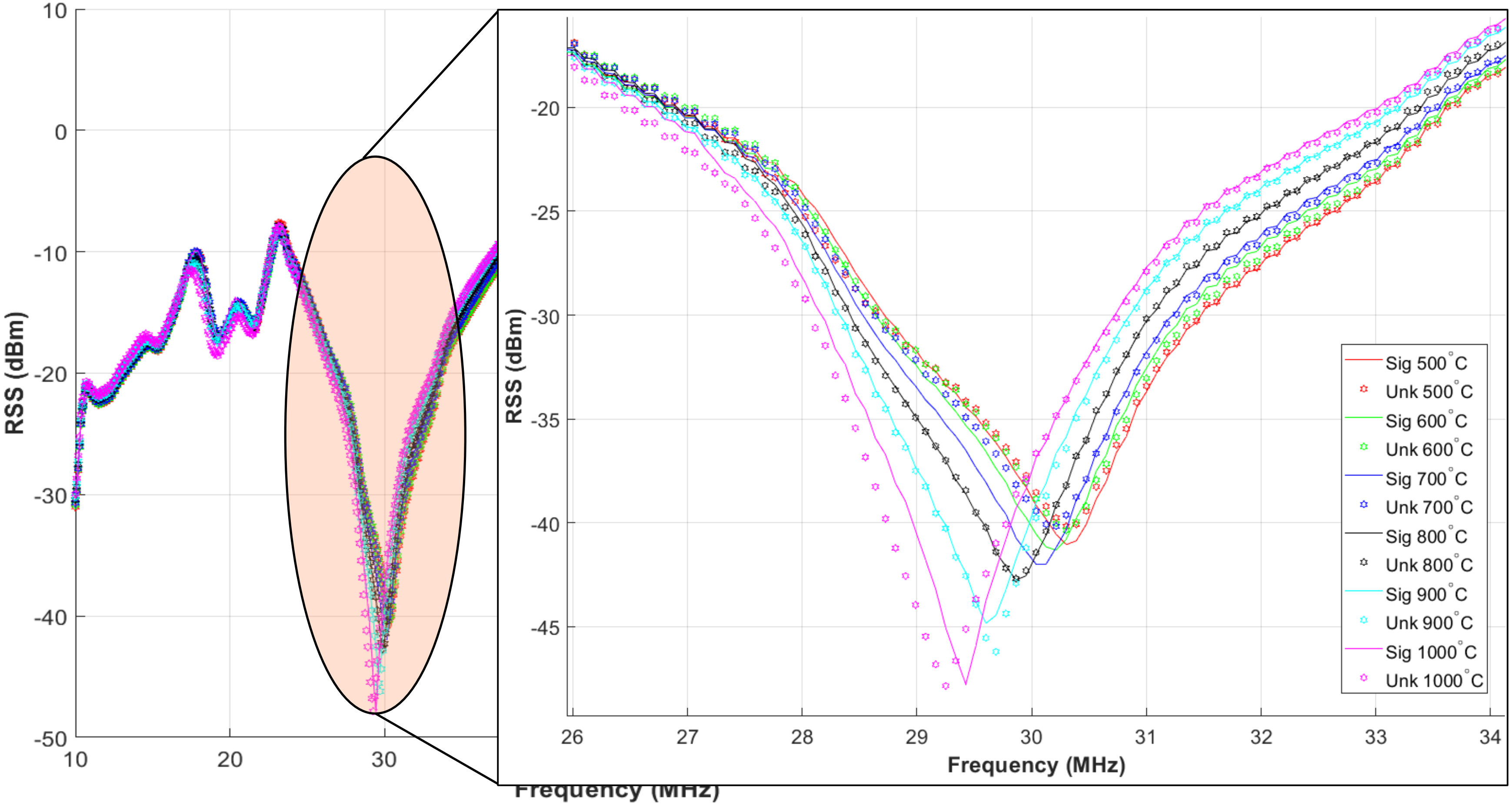
- ***Subtask 2.1: Passive Wireless Design (Q1-6)***
  - Design appropriate RFID sensor using ANYSIS Maxwell modelling package.
  - Chipless RFID microstrip patch antenna design, where the geometry of the conductive pattern on the specimen and the dielectric properties (and thickness) of insulating layer 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.

Task 2 Related Previous Work (I/III):

- Temperature Sensing for Harsh Environments (funded by DoE):
  - 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)
- How does it work?
  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.

  Coverts temperature measurement into a classical signal matching problem!

Task 2 Related Previous Work (II/III):



- 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

Task 2 Related Previous Work (III/III):

- 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.**

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.

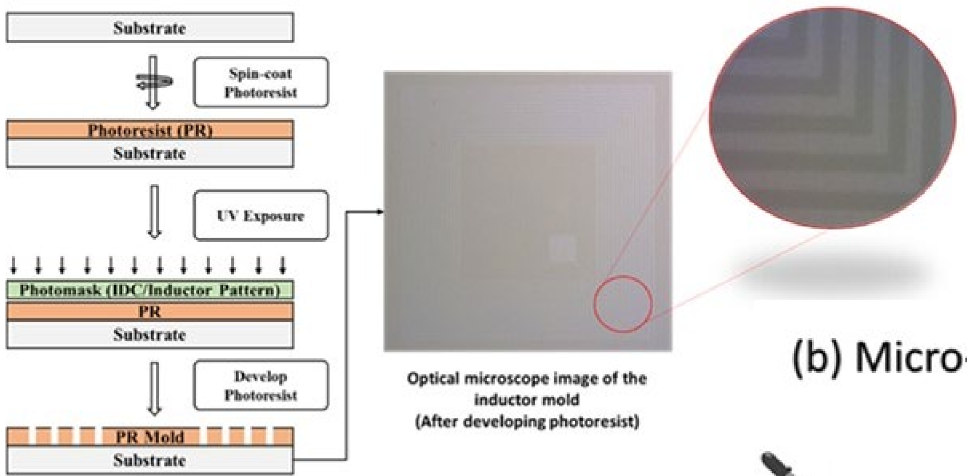
Task 3.0 – Direct-Writing (2D/3D Patterning) of Refractory and Sensor System.

- ***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°-1300°C in varying atmospheres in WVU's existing automated sensor test stands. Baseline electrical performance will be assessed.

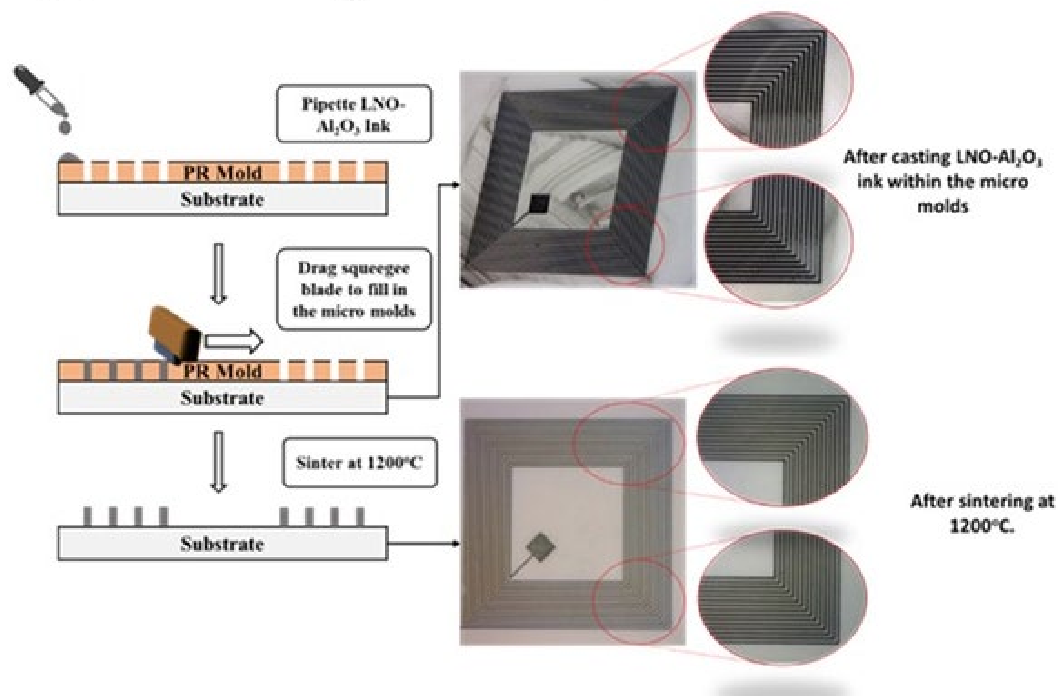
Task 3 Related Previous Work:

(a) Photolithography Process to Create Micro-molds



- Methods developed at WVU to pattern miniature RF-circuits with high-temperature electroceramics.
- Microcasting can produce features to 25-50 μm resolution.

(b) Micro-casting Process to Fabricate Wireless Sensor



Two-step process:

a) Use photolithography to fabricate micromolds on alumina substrates.

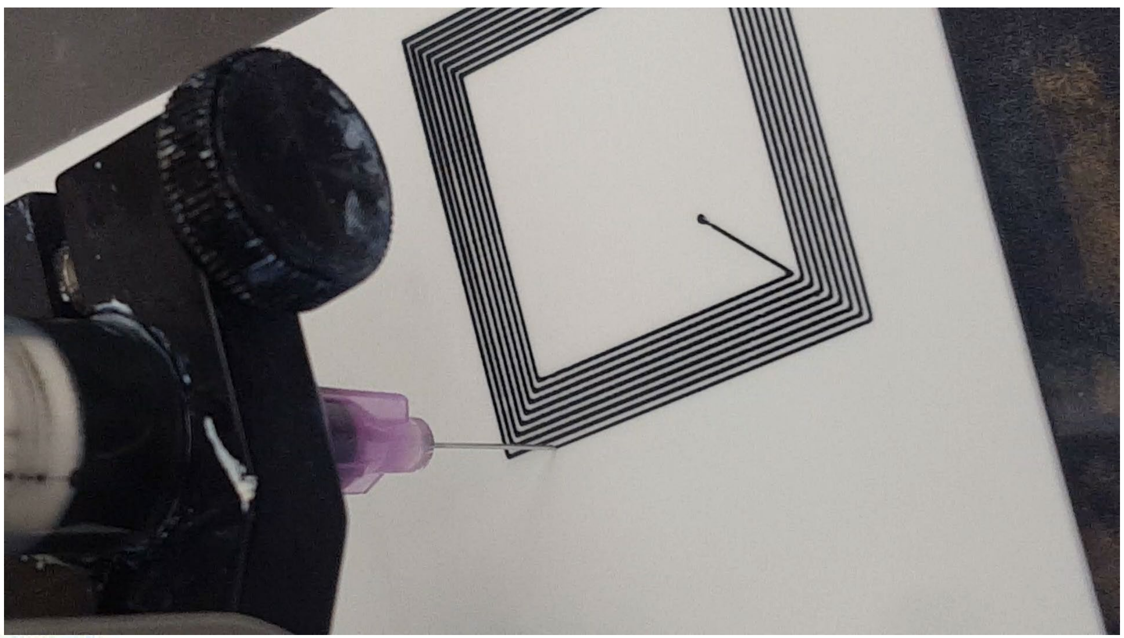
b) Cast electroceramic suspension in molds and fire to high-temperature to burn-off mold and bond pattern.

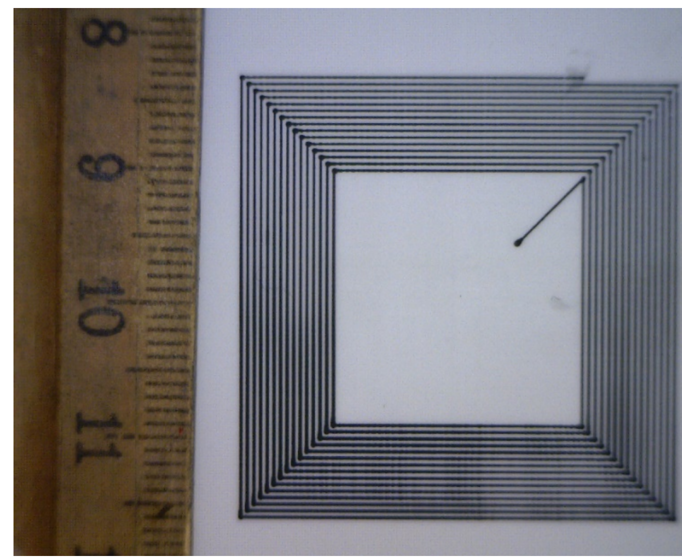
Task 3 Related Previous Work:

- **Parameters:**
  - **Ink: 30 vol.%**
  - **Nozzle: 27 gauge (200 µm).**
  - **Print speed: 9 mm/s.**
  - **Line width : ~210 µm.**
  - **Line spacing: 350 µm.**

<u>Direct Writing of RF-circuits:</u>

- Robotic direct-writing methods developed to 2D/3D print circuits.
- Usually larger feature size, but can rapidly alter pattern and inks





- **Larger form factor sensor (150 x 150 mm) was fabricated on alumina.**

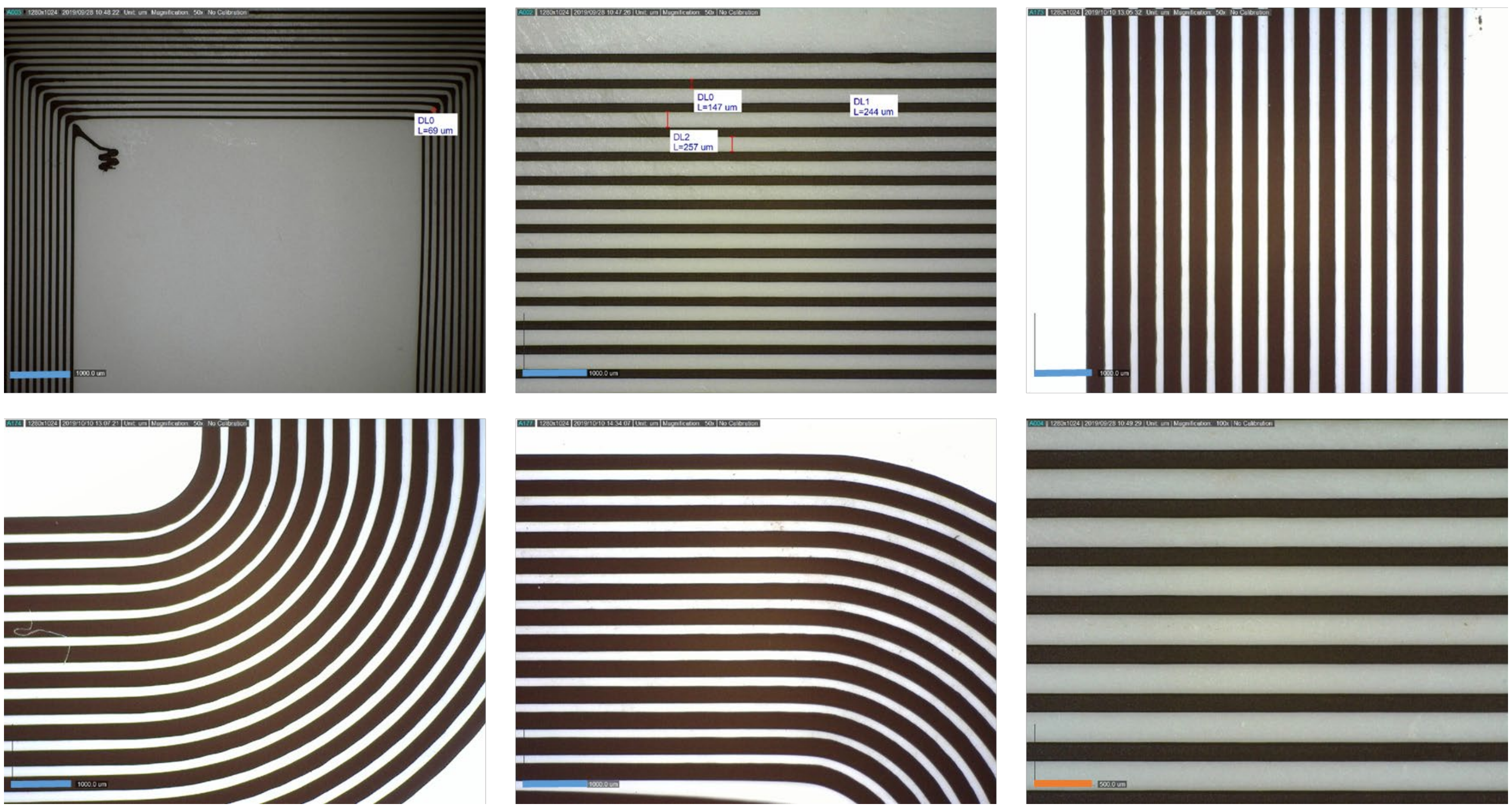
Task 3 Related Previous Work:

Direct Writing of RF-circuits:

- Robo-casting produces repeatable patterns at the >100 µm for metals and ceramic inks.
- Saves time in redesign since new photo-mask are not needed.

As printed

Blue Scale – 1000 um
Orange scale – 500 um



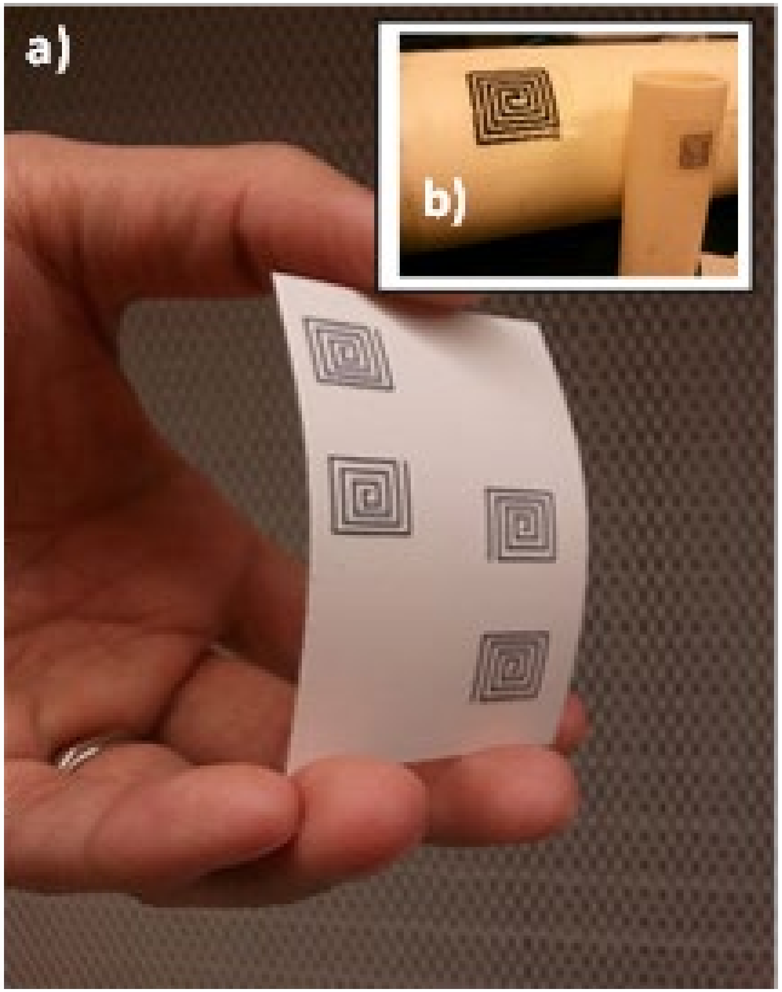
Task 3 Related Previous Work:

Decal Transfer:

- WVU team developed their own decal formulations.
- Wet-transfer process where water releases polymer with design to be transferred.
- Multi-layer patterns will be required (where insulator and metal design must be co-deposited).

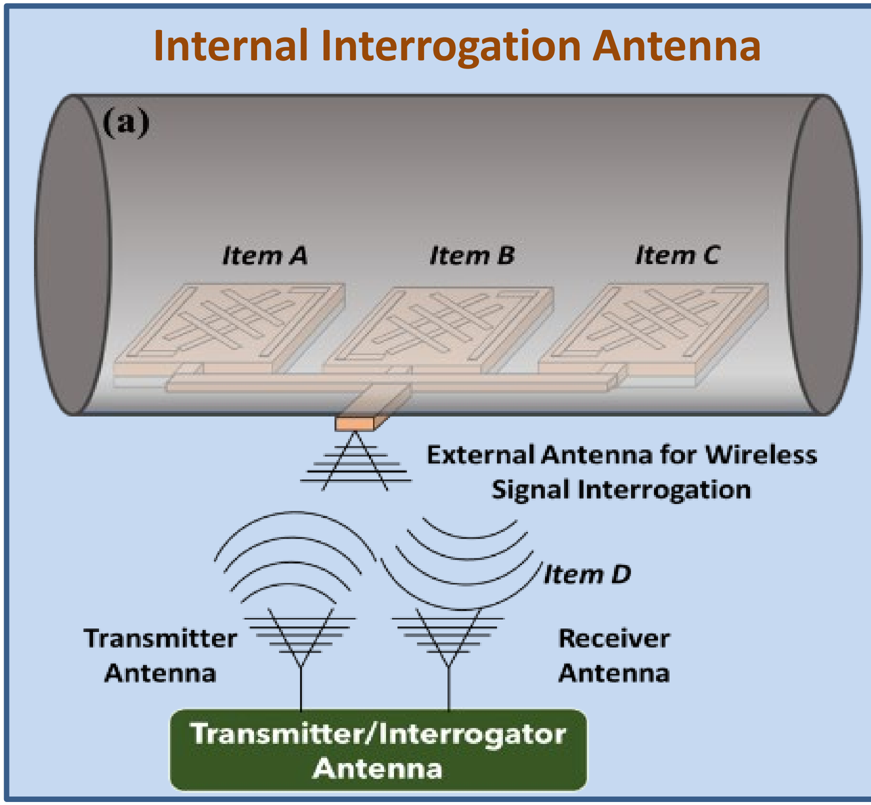
Possible issues:

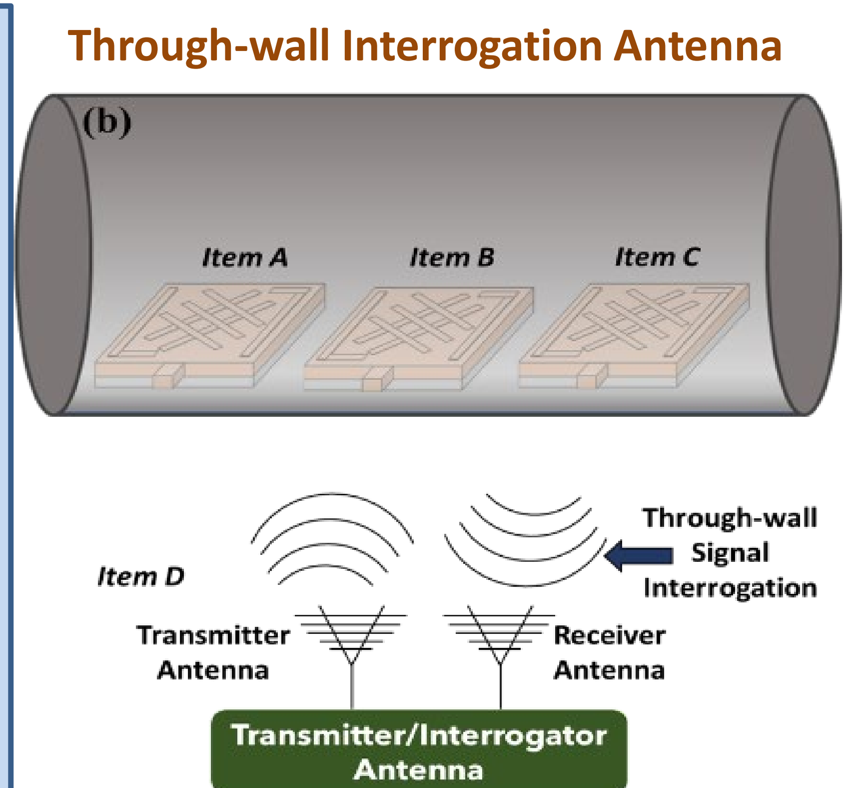
- Heating localize area may be need for in-field deposition (i.e. deposit within previously installed piping or assembly).
- Possible local control of heating environment may be needed.



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

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.

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

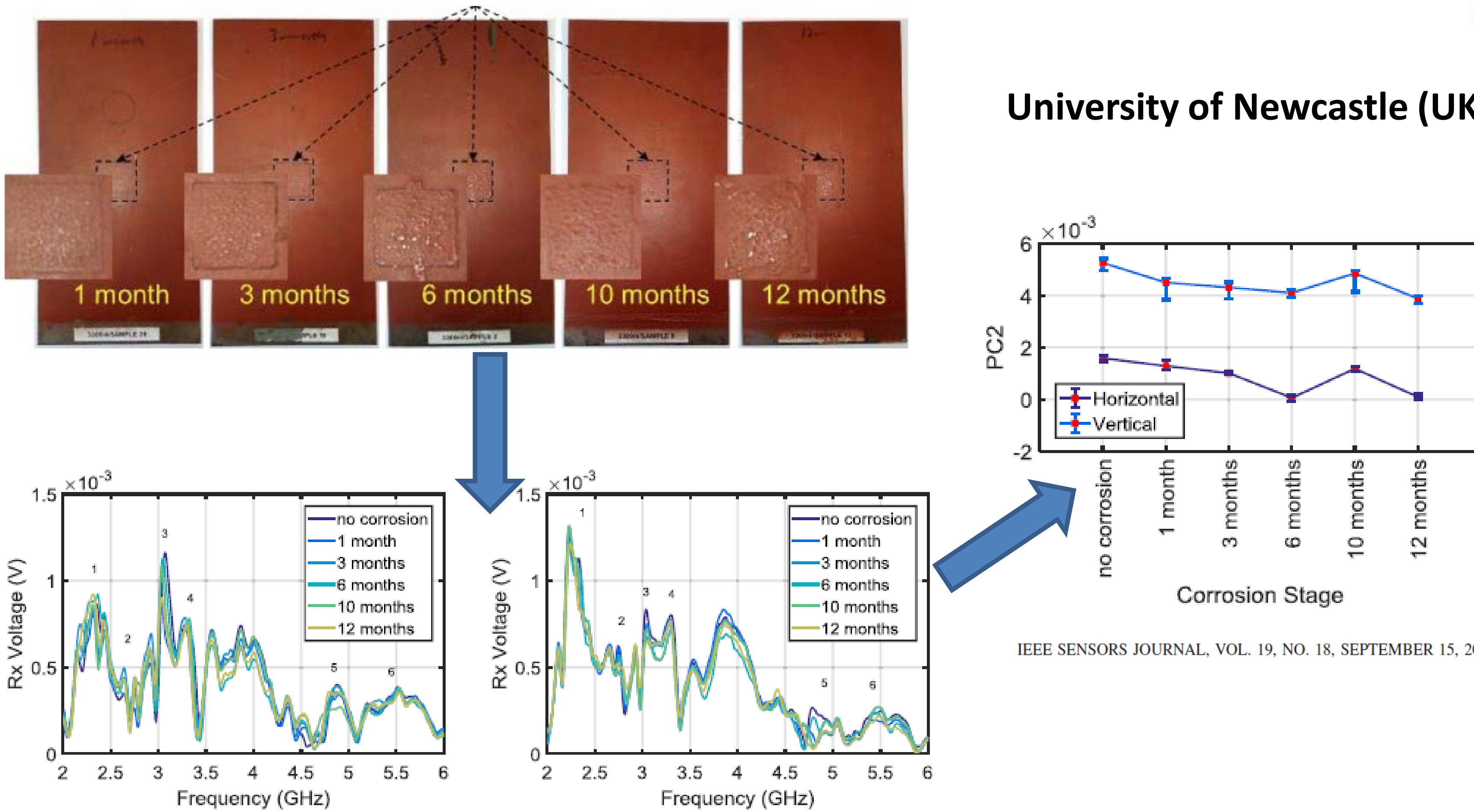
- ***Subtask 4.1- Temperature and Corrosion Induced Crack Testing of Singular Passive Wireless Sensors***
  - ***Singular passive wireless sensors*** will be deposited onto flat metal sheets (e.g. 316 and 330 grades).
  - Interrogator antenna will be placed in different orientations (and distances) to corrosion specimen. (Isothermal and cyclic crack tests will be completed over 1-8 weeks at temperatures of 500-1300°C with various humidity levels).

- ***Subtask 4.2- Performance Evaluation of Wireless Sensor Arrays at Low Temperature***
  - ***Passive wireless sensor arrays*** will be initially tested within a closed metal tubing system *up to 500°C* to identify the issues with high-temperature experiment.
  - Interrogator antenna design and placement (as function of distance from the RFID sensors) will be evaluated. Simultaneous testing of multiple sensors (with different geometry parameters) for spatial investigation along the tube will be completed.

Subtask 4.3- ***Performance Evaluation of Wireless Sensor Arrays at High Temperature***

- Similar to Subtask 4.2.
- The high-temperature test stand (with humidity control) will be used for testing the passive wireless sensor arrays *to 500-1300℃* with various humidity levels.

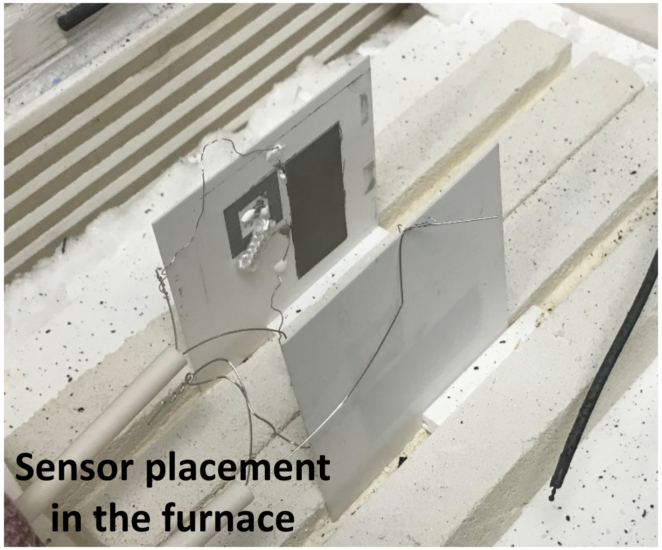
Task 4 Related Work (from Literature):



IEEE SENSORS JOURNAL, VOL. 19, NO. 18, SEPTEMBER 15, 2019

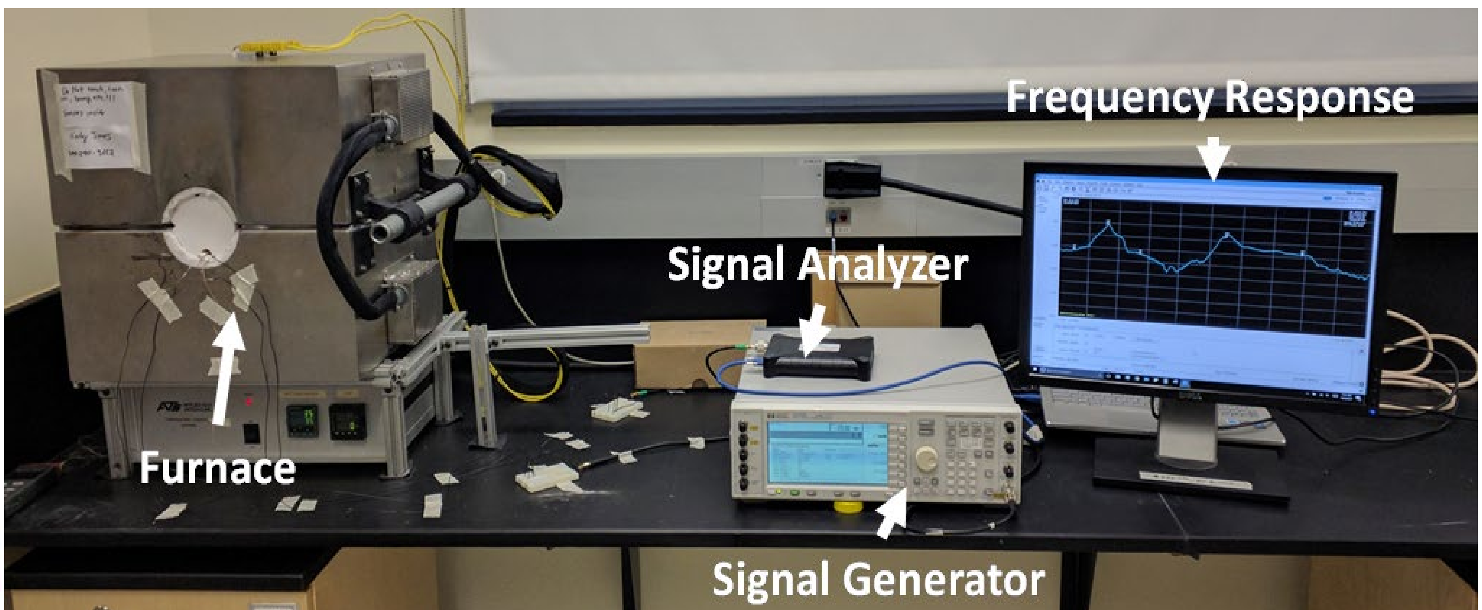
- Deposited patch antennae onto mild steel.
- Tested at room temperature in “marine environment”.
- Correlation between signal and corrosion rate/mechanism not established.

Task 4 Related Previous Work (WVU):

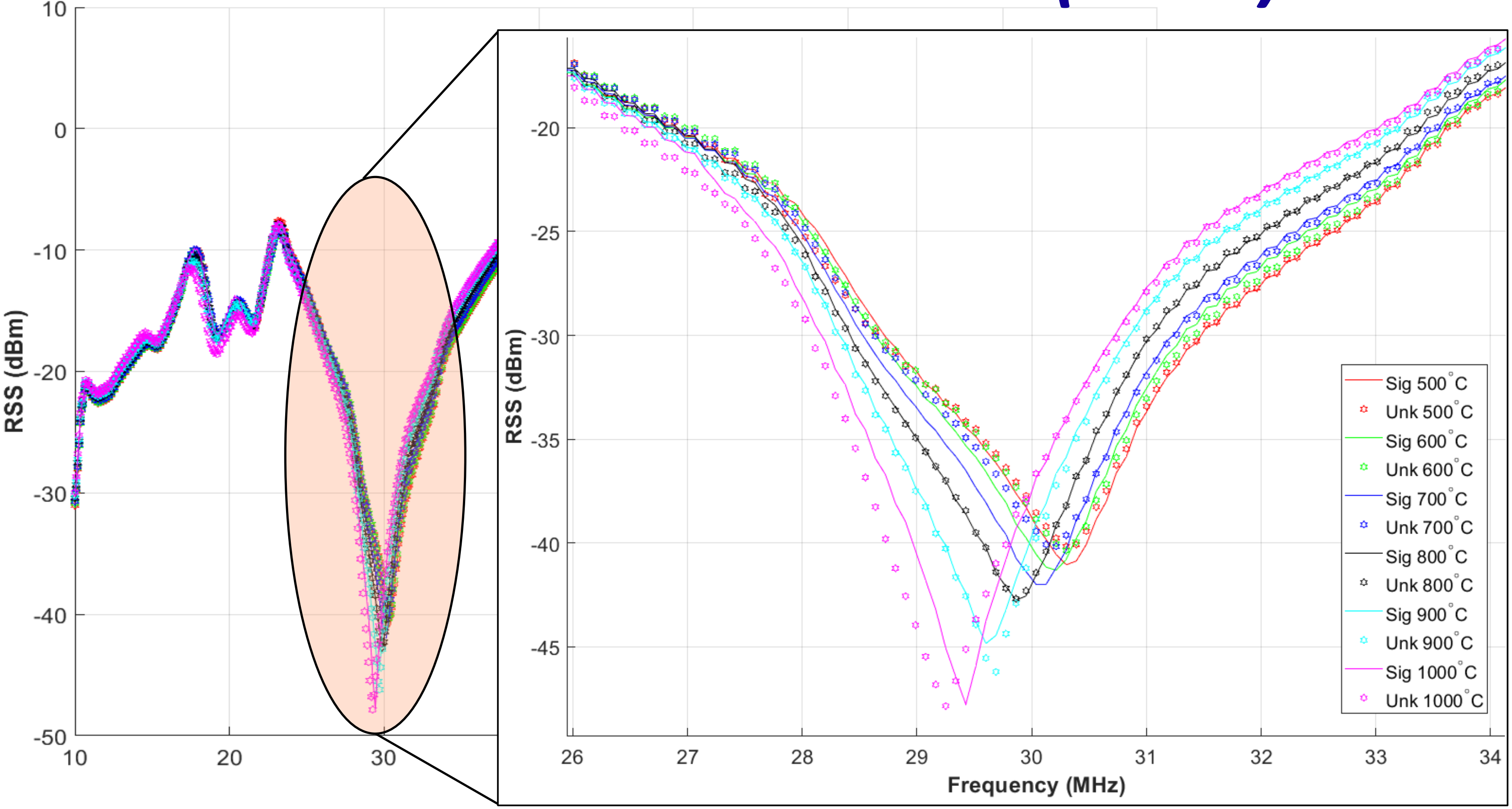


Passive Wireless Temperature Measurement:

- A pair of sensors were used to characterize the wireless signal response.
- One is connected to signal generator and the other to signal analyzer.
- Distance between the sensors ~10 cm.



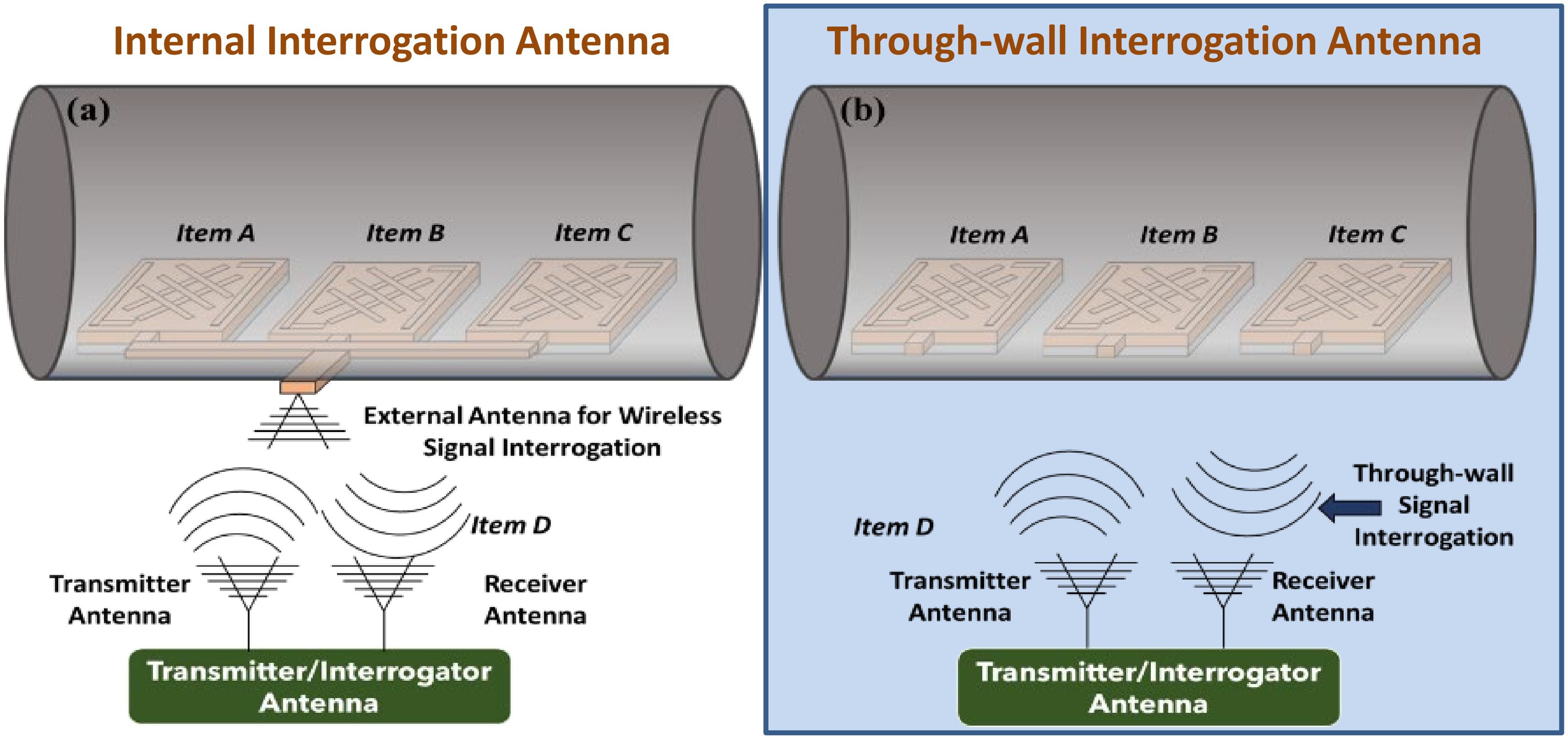
Task 4 Related Previous Work (WVU):



- Temperature signatures of the sensor from 500 – 1000^{o}C.
- The resolution was improved and sensor show highly distinguishable wireless response.
- Temperature signatures are unique and distinguishable with a sensitivity of 3.5 kHz/^{o}C.

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

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.

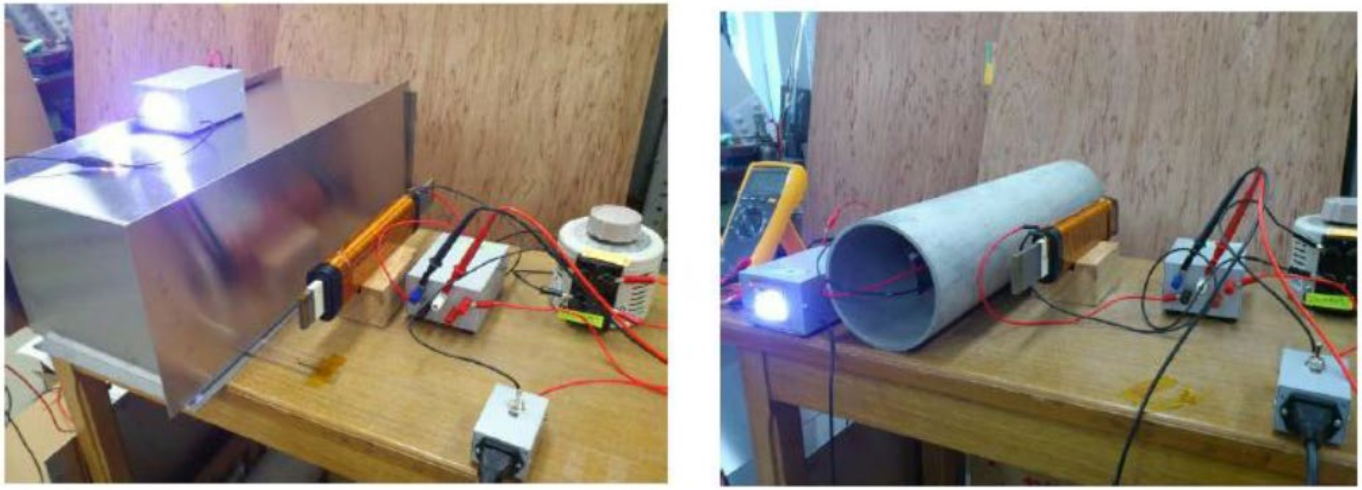
Item D: Represents the interrogator antenna that will be used to broadcast and read the reflected power from the RFID sensors.

Task 5.0 – Through-Wall Signal Transmission for RFID Wireless Sensor Testing

- ***Subtask 5.1- Through-Wall Performance Evaluation Sensors at Low Temperature***
  - Singular and array sensors will be fixed parallel to the metal tube wall (but not deposited to the wall).
  - Non-magnetic metal tubes with various thicknesses (1-5 mm) and composition will be utilized. The interrogator antenna will be placed outside the closed tube, and the relative signal transfer efficiency will be measured (*up to 500^{o}C*).

- ***Subtask 5.2- Through-Wall Performance Evaluation of Sensors at High Temperature***
  - Sensor/antenna pairs that show the best performance in Subtask 5.1 for a specific tube thickness and composition will be tested in the high-temperature (*up to 1300^{o}C*) test stand.
  - Similar isothermal and cyclic steam exposure used in Subtask 4.1 and 4.3 will be completed for the sensors directly deposited onto the metal tube.

Task 5.0 Previous Work (from literature):



(a) (b)

Figure 4. Experimental demonstration setups (a) power transfer through a space enclosed by stainless steel metal walls of 1 mm thick; (b) power delivery through a metal pipe of 5 mm thick, from Yamakawa *et al.* [12] (Open Access).

University of Tokyo (Japan)

Sensors **2015**, *15*, 31581–31605

- Magnetic resonance coupling through-non-magnetic metal-wall (1-3 mm sheet or pipe).
- Resonance frequency at kHz-MHz range for high quality factor.
- Roughly 40% power transmitted through 1 mm thick at distance of 12 cm.
- Nearly 10% power transmitted through 5 mm thick.

WVU has no previous work in this area, and will initiate this study in Task 5 of this work.

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

Task 6.0 *Implementation of Passive Wireless Sensor Arrays into Power Plant Demonstration* .

- ***Subtask 6.1- Wireless Array Sensors in Power Plant Demonstration***
  - Deposit the chipless RFID sensors onto the surface of the metal components provided by the plant collaborator.
  - Component will be ***placed into service***, and interrogator antenna to monitor the corrosion during isothermal/cyclic operation.
  - ***Either along-wall or through-wall data transfer will be completed*** depending on results from Task 4. The test duration will be dependent upon the collaborating plant and availability of the monitoring equipment.

<u>Current Collaborator:</u>
Longview Power LLC.
1375 Fort Martin Rd, Maidsville, WV 26541

<u>Future Collaborator:</u>

- Longview declared bankruptcy in April (may effect future collaboration).
- Year 3 will discuss with NETL and other power plants for potential other collaborators for demo.

Task/*Milestone*	Project Timeline											
	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10	Q11	Q12
Task 1. Project Management and Planning (PI: Sabolsky)												
Task 2. Passive RFID Sensor Design and Initial Benchtop Testing (Co-PI: Reynolds)												
Subtask 2.1: Passive Wireless Design (Q1-Q6)												
Subtask 2.2: Wireless Sensor Fabrication on Ceramic Substrates and Benchtop Testing (Q2-Q6)												
→M 1: Downselect initial sensor designs and pass over to Task 3			*	June 2021								
Subtask 2.3: Advanced Signal Processing Methods for Deconvoluting the Wireless Response (Q4-Q11)												
Task 3. Fabrication of Wireless Sensors and Development of Inexpensive Transfer Process (PI: Sabolsky)												
Subtask 3.1: Investigation of Various Material Systems for the Wireless Sensor Fabrication (Q2-Q6)												
→M 2: Defined basic ceramic composition for initial sensor fabrication			*	June 2021								
Subtask 3.2: Fabrication of RFID and Patch Antenna Sensors Directly onto Planar Metal/Ceramic Substrates (Q3-Q9)												
→M 3: Fabricate initial wireless sensors to initiate testing in Task 4				* Sept 2021								
Subtask 3.3: Development of Inexpensive Transfer Process and Baseline Testing (Q4-Q9)												
→M 4: Demonstrate direct transfer of sensor design to planar substrates						*						
Subtask 3.4: Direct Transfer of Sensor to Metal Tubing and Thermal Processing Development (Q4-Q11)												
→M 5: Demonstrate direct transfer of sensor design to curved substrates							*					
A: Demonstrate that the RFID sensor and signal processing methodology for planar metal specimen at >750°C								**A**	Aug 2022			

Task/*Milestone*	Project Timeline											
	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10	Q11	Q12
Task 4. Cyclic Passive Wireless Sensor Testing (PI: Sabolsky)												
Subtask 4.1: Temperature and Corrosion Induced Crack Testing of Singular Passive Wireless Sensors (Q4-Q7)												
→M 6: Define signal-temperature-corrosion relation for planar metal specimens								*	Aug 2022			
Subtask 4.2: Performance Evaluation of Wireless Sensor Arrays at Low Temperature (Q6-Q8)												
→M 7: Demonstrate sensor array evaluation at low temperatures									*			
Subtask 4.3: Performance Evaluation of Wireless Sensor Arrays at High Temperature (Q7-Q11)												
→*M 8*: Demonstrate sensor array evaluation at high temperatures										*		
B: Demonstrate that the RFID sensor and signal processing methodology using a sensor array										**B**	Dec 2022	
Task 5. Through-Wall Signal Transmission for RFID Wireless Sensor Testing(PI: Sabolsky)												
Subtask 5.1: Through-Wall Performance Evaluation of Sensors at Low Temperature (Q7-Q9)												
Subtask 5.2: Through-Wall Performance Evaluation of Sensors at High Temperature (Q8-Q11)												
→M 9: Demonstrate testing of through-wall performance evaluation at high temperature											*	Mar 2022
Task 6. Implementation of Passive Wireless Sensor Arrays into Power Plant Demonstration (PI: Sabolsky) (Q10-Q12)												
→M 10: Discussion and identification of metal component with power plant									Mar 2022		*	
→M 11: Discussion and identification of metal component with power plant												*
***Milestone:* →*M #* *Go/No-Go:* *A* *Task Connector* →**												