AOI[3]: Smart Refractory Sensor Systems for Wireless Monitoring of Temperature, Health, and Degradation of Slagging Gasifiers

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Background- Gasifier Sensing Needs:

- Online monitoring sensors of refractory used in coal gasifiers under extreme conditions including high temperature (>1300°C) and high pressure (up to 1000 psi) for >20,000 hr.
- Erosive and corrosive conditions (due to slag and high pressure, in addition to various pO_2 levels) causes degradation of refractory over time.
- Ability to monitor the integrity of the refractory materials during gasifier operation would contribute significantly to improving the overall operational performance and reliability of coal gasifiers.
  - Temperature
  - Stress/strain within refractory liner
  - Spallation events
  - Refractory liner health
- Monitoring interior thermochemical conditions allows for efficient control of the gasification process.

Technology Vision:

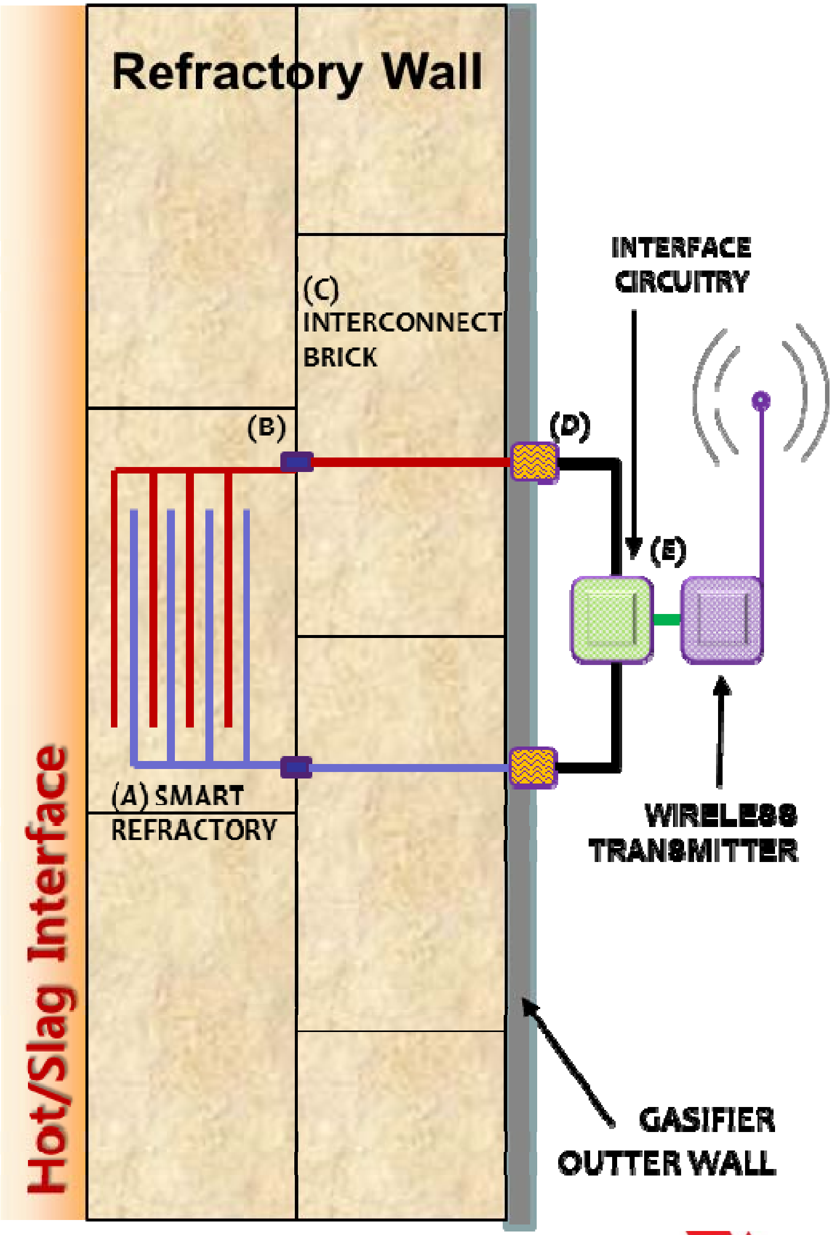
Item A represents the "smart refractory" material.

Item B is an interconnection (alignment) pin.

Item C is an interconnection brick, which will permit transfer of the signal to the exterior wall.

Item D is the sealed electrical access port to connect to the signal acquisition/processing units.

Item E is low-power electronics and wireless communication.



Program Objectives:

1) Investigate chemical/thermal stability, thermomechanical properties, and electrical properties of refractory ceramic composites at temperatures between 750-1450ºC.

2) Define processes to pattern and embed the conductive ceramic composites within refractory materials to incorporate temperature and strain/stress sensors into refractory bricks.

3) Develop methods to interface the electrical sensing outputs from the smart refractory with an embedded processor and to design a wireless sensor network to efficiently collect the data at a processing unit for further data analysis.

4) Develop algorithms for model-based estimation of temperature profile in the refractory, slag penetration depth, spallation thickness, and resultant health by using the data from the wireless sensor network.

Task Assignments:

- ☐ Task 2: *Fabrication and Characterization of Oxide-Silicide Composites.*
- ☐ Task 3 and Task 4: *Sensor Patterning and Embedding and Static and Dynamic Sensor Testing.*
- ☐ Task 5: *Data Ex-Filtration Using a Wireless Sensor Network.*
- ☐ Task 6: *Model-Based Estimation of Refractory Degradation/Temperature.*
- ☐ Task 7: *Smart Brick System DEMO in Simulated Reactor (to be completed in summer).*

Products:

1. G.A. Yakaboylu, E.M. Sabolsky, K. Sabolsky, R.C. Pillai, S. Chockalingam, M. Palmisiano, "Electrical and Thermomechanical Characterization of Silicide/Oxide Composites", *Materials Science and Technology MS&T2014, Pittsburgh, PA, USA, October 12-16, (2014)*.
2. Q. Huang, D. Bhattacharyya, E.M. Sabolsky, "Dynamic Model of a Smart Refractory Brick for Gasifier Applications", Paper 126c, *AIChE Annual Meeting*, Atlanta, GA, USA, November 16-21, (2014).
3. G.A. Yakaboylu, R.C. Pillai, S. Chockalingam, B. Armour, M. Palmisiano, K. Sabolsky, E.M. Sabolsky, "Thermal Processing and Properties of Conductive Refractory Composites for High-Temperature Electrical Applications", *International Conference and Exposition on Advanced Ceramics and Composites*, Daytona Beach, FL, USA, January 25-30, (2015).
4. B. Rumberg, D. Graham, S. Clites, B. Kelly, M. Navidi, A. Diello, V. Kulathumani, "RAMP: Accelerating Wireless Sensor Design with a Reconfigurable Analog/Mixed-Signal Platform", *Proceedings of the ACM/IEEE Conference on Information Processing in Sensor Networks (ISPN'15)*, pp. 47-58, Seattle, WA, April 13-16, (2015).
5. E.M. Sabolsky, R. Chockalingam, K. Sabolsky, G.A. Yakaboylu, O. Ozmen, B. Armour, A. Teter, D. Bhattacharyya , David Graham , Vinod Kulathumani, Close Timothy and Marc Palmisiano, "Refractory Ceramic Sensors for Process and Health Monitoring of Slagging Gasifiers", *227th ECS Meeting*, Chicago, Illinois, USA, May 28th, (2015).
6. E.M. Sabolsky , R. Chockalingam, K. Sabolsky, G.A. Yakaboylu, O. Ozmen, B. Armour, A. Teter**,** D. Bhattacharyya, David Graham, Vinod Kulathumani, Close Timothy and Marc Palmisiano, "Conductive Ceramic Composites Used to Fabricate Embedded Sensors for Monitoring the Temperature and Health of Refractory Brick in Slagging Gasifiers," *XIVth International Conference European Ceramic Society*, Toledo, Espana, 24th June, (2015).

Products:

7. R. C. Pillai, E.M. Sabolsky, K. Sabolsky, G.A. Yakaboylu, B. Armour, J. Mayer, J. Bogan, M. Raughley and J. Sayre, “Performance of high temperature ceramic-ceramic thermocouples embedded within chromia refractory bricks to monitor the health and stability of industrial gasifiers”, *Materials Science and Technology MS&T2015*, Columbus, OH, USA, October 4-8, (2015).
8. G.A. Yakaboylu, R.C. Pillai, B. Armour, K. Sabolsky, E.M. Sabolsky, “Development of Refractory Oxide/Metal Silicide Composites for High Temperature Harsh-Environment Sensor Applications”, *Materials Science and Technology MS&T2015*, Columbus, OH, USA October 4-8, (2015).
9. H. Qiao, P. Paul, D. Bhattacharyya, E.M. Sabolsky, “Dynamic Model and Estimator Development for a Smart Refractory Brick with Embedded Sensors for Gasifier Applications”, *AIChE Annual Meeting*, Salt Lake City, UT, USA, November 8-13, (2015).
10. E. M. Sabolsky, R. C. Pillai, K. Sabolsky, G. A. Yakaboylu, B. Armour, A. Teter, M. Palmisiano and T. Close, “Refractory Ceramic Sensors for Process and Health Monitoring of Slagging Gasifiers”, *ECS Trans.*, Vol 66(37), pp. 43-53 (2015).
11. R.C. Pillai, G.A. Yakaboylu, K. Sabolsky and E. M. Sabolsky, J. Bogan, J. Sayre, “Composite Ceramic Thermocouples for Harsh-Environment Temperature Measurements”, *International Conference and Exposition on Advanced Ceramics and Composites*, Daytona Beach, FL, USA, January 24-29, (2016).
12. G.A. Yakaboylu, R. C. Pillai, B. Armour, K. Sabolsky and E. M. Sabolsky, “Conductive Ceramic Composites for Fabricating High Temperature and Harsh Environment Sensors: Thermal Processing, Stability and Properties”, *International Conference and Exposition on Advanced Ceramics and Composites*, Daytona Beach, FL, USA, January 24-29, (2016).

Products:

13. G.A. Yakaboylu, R.C. Pillai, K. Sabolsky, J. Meyer, E.M. Sabolsky, J. Bogan, M. Raughley, J. Sayre, "Electroceramic Composite Sensors for Monitoring Harsh-Environment Energy Systems", *Materials Science and Technology MS&T2016*, Salt Lake City, UT, USA, October 23-27, (2016).
14. Q. Huang, D. Bhattacharyya, E.M. Sabolsky, "Estimation of Gasifier Wall Profile Using Measurements from a Wireless Sensor Network", Paper 247i, *AIChE Annual Meeting*, San Francisco, CA, USA, November 13-18, (2016).
15. G.A. Yakaboylu, R.C. Pillai, K. Sabolsky, E.M. Sabolsky, "Processing of Metal Silicide/Refractory Oxide Composites for High-Temperature and Harsh-Environment Sensing Applications", *Gordon Research Conference (GRC), Ceramics, Solid State Studies in*, South Hadley, MA, USA, July 31-August 5, (2016).
16. Q. Huang, P. Paul, D. Bhattacharyya, R.C. Pillai, K. Sabolsky, E.M. Sabolsky, "Model-Based Estimation in Gasifiers Using a Smart Refractory Brick with Embedded Sensors", *To be published in the Proceedings of 11th International Workshop on Structural Health Monitoring*, (2017).
17. Q. Huang, P. Paul, D. Bhattacharyya, R.C. Pillai, K. Sabolsky, E.M. Sabolsky, "Model-Based Estimation in Gasifiers Using a Smart Refractory Brick with Embedded Sensors", *Submitted to Industrial and Engineering Chemistry Research*, (2017).
18. Q. Huang, P. Paul, D. Bhattacharyya, R.C. Pillai, K. Sabolsky, E.M. Sabolsky, "Estimation in Gasifiers Using Smart Refractory Brick with Wireless Sensor Network", *To be submitted to AICHE Journal*, (2017).

Products:

19. A. Dilello, S. Andryzcik, B. Kelly, B. Rumberg, D. Graham, "Temperature compensation of floating-gate transistors in field-programmable analog arrays", *Proceedings of the IEEE Symposium on Circuits and Systems*, Accepted for publication, (2017).
20. G.A. Yakaboylu, E.M. Sabolsky, "Determination of a homogeneity factor for composite materials by a microstructural image analysis method", *Journal of Microscopy*, pp. 1-10, volume/issue to be assigned, (2017).
21. R.C. Pillai, K. Sabolsky, G.A. Yakaboylu, E.M. Sabolsky, "Embedded Composite Ceramic Thermocouples for Harsh-Environment Applications", *Submitted to Sensors and Actuators*, (2017).
22. G.A. Yakaboylu, R.C. Pillai, K. Sabolsky, E.M. Sabolsky, "Stability, Grain Growth Kinetics and Electrical Properties of $MoSi_2$- and WSi_2-based Electroconductive Ceramic Composites Reinforced by Al_2O_3 and ZrO_2", *Submitted to Acta Materialia*, (2017).

****8 More publications currently being prepared, 2 patents, and 2 more oral presentations in the summer/fall 2017***

Students worked/graduated:

- Rajalekshmi C. Pillai (Post-doc)
- Gunes A. Yakaboylu (PhD)
- Qiao Huang (PhD)
- Spencer Clites (MSc)
- Steven Andryzcik (MSc)
- Priyashraba Misra (MSc)
- Brian Armour (Undergraduate)
- James Meyer (Undergraduate)
- Aaron Teter (Undergraduate)

Task 2:
Fabrication and Characterization of Oxide-Silicide Composites.
(Sabolsky)

Task 2.0 Objectives:

- Investigate chemical/thermal stability, thermomechanical properties, and electrical properties of refractory silicide-oxide composites at temperatures between 750-1450°C.

Chemical Stability (XRD):

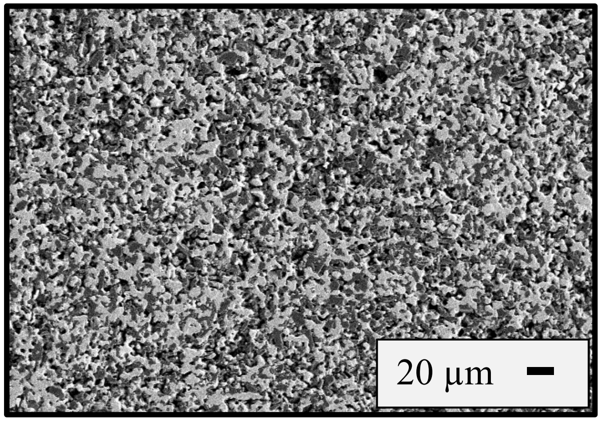
	Al_2O_3	Y_2O_3	ZrO_2	Cr_2O_3
$MoSi_2$	$MoSi_2$, Al_2O_3, Mo_5Si_3, SiO_2	$MoSi_2$, Y_2O_3, SiO_2, $Y_5Mo_2O_{12}$, Mo_3Si, Mo_3O	$MoSi_2$, ZrO_2, Mo_5Si_3	$MoSi_2$, Cr_2O_3, Cr_3Mo, SiO_2
WSi_2	WSi_2, Al_2O_3, W_5Si_3	WSi_2, Y_2SiO_5, WO_2, SiO_2	WSi_2, ZrO_2, W_5Si_3	WSi_2, Cr_2O_3, SiO_2, W_3O
$ZrSi_2$	$ZrSi_2$, Al_2O_3, ZrO_2, SiO_2	$ZrSi_2$, Y_2O_3, $Y_2Si_2O_7$, SiO_2	$ZrSi_2$, ZrO_2, SiO_2	$ZrSi_2$, Cr_2O_3, $ZrSiO_4$, Cr_3O, SiO_2
$TaSi_2$	$TaSi_2$, Al_2O_3, Ta_5Si_3, Ta_3Si, SiO_2	$TaSi_2$, Y_2SiO_5, Ta_2O_5, $Y_{10}Ta_4O_{25}$	$TaSi_2$, ZrO_2, Ta_5Si_3, SiO_2	$TaSi_2$, Cr_2O_3, $CrTaO_4$, Ta_2O_5, TaO_2
$NbSi_2$	$NbSi_2$, Al_2O_3, Nb_5Si_3	$NbSi_2$, Y_2O_3, Y_2SiO_5, Nb_5Si_3, SiO_2	$NbSi_2$, ZrO_2, Nb_5Si_3, SiO_2	$NbSi_2$, Cr_2O_3, Nb_5Si_3, $CrNbO_4$, $CrNbSi$, SiO_2
$TiSi_2$	$TiSi_2$, Al_2O_3, Ti_5Si_3, SiO_2	$TiSi_2$, Y_2O_3, $Y_2Si_2O_7$, TiO_2, SiO_2	$TiSi_2$, ZrO_2, TiO_2, SiO_2	$(Cr_{0.88}Ti_{0.12})_2O_3$, Cr_3Si, SiO_2
$CrSi_2$	$CrSi_2$, Al_2O_3, Cr_5Si_3	$CrSi_2$, Y_2O_3, Y_2SiO_5	$CrSi_2$, ZrO_2	$CrSi_2$, Cr_2O_3, Cr_3Si, SiO_2

** Prepared via mixed oxide route followed by sintering in argon atmosphere at 1400°-1600°C.*

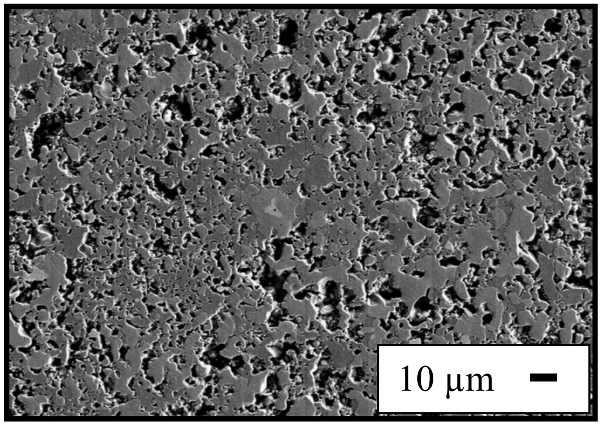
- Metal silicides show high stability in Al_2O_3 and ZrO_2 matrix only with formation of different type of silicides (Mo_5Si_3, W_5Si_3, Nb_5Si_3, Cr_3Si, etc.) and SiO_2 (highlighted).
- They partially react with Y_2O_3 and Cr_2O_3 to form undesired secondary phases.

Composite Microstructures (SEM):

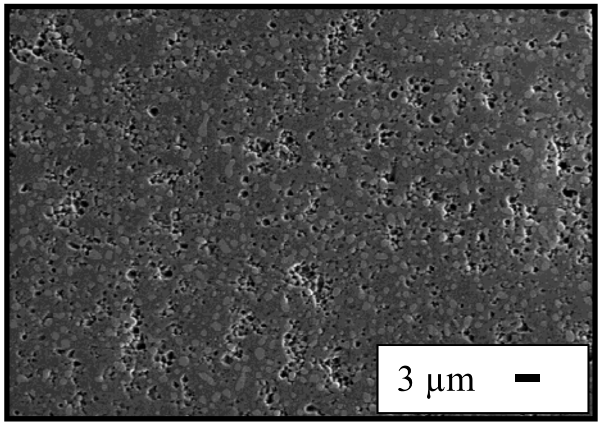
60-40 $MoSi_2$-Al_2O_3



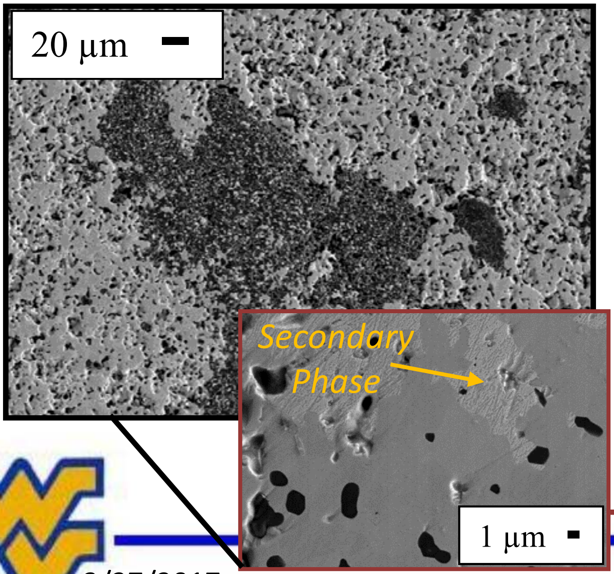
60-40 $MoSi_2$-Y_2O_3



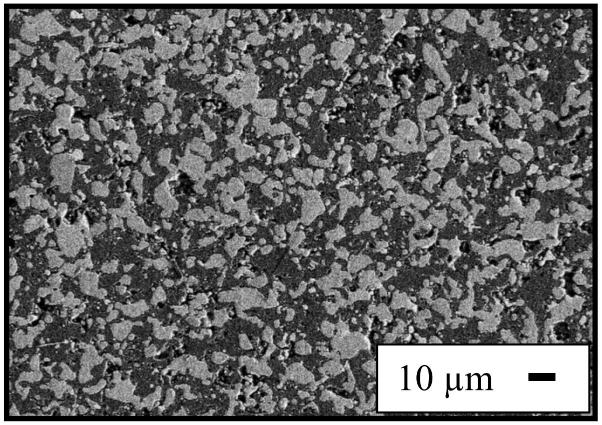
60-40 $MoSi_2$-ZrO_2



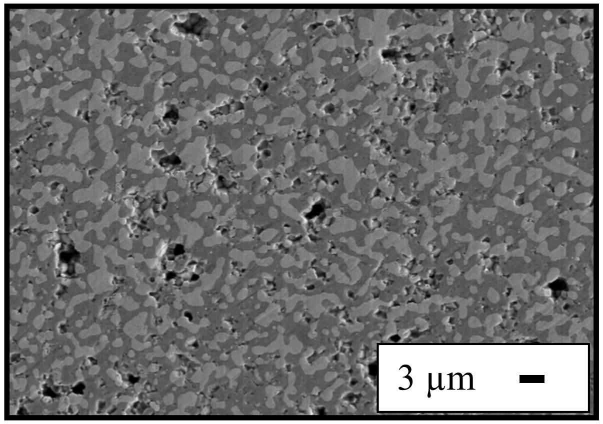
60-40 WSi_2-Al_2O_3



60-40 WSi_2-Y_2O_3



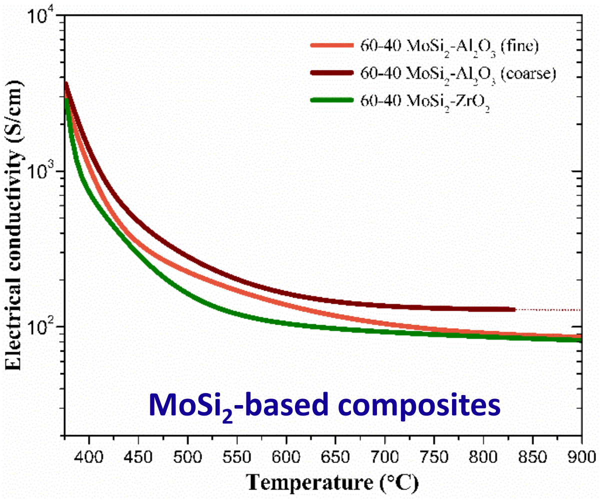
60-40 WSi_2-ZrO_2

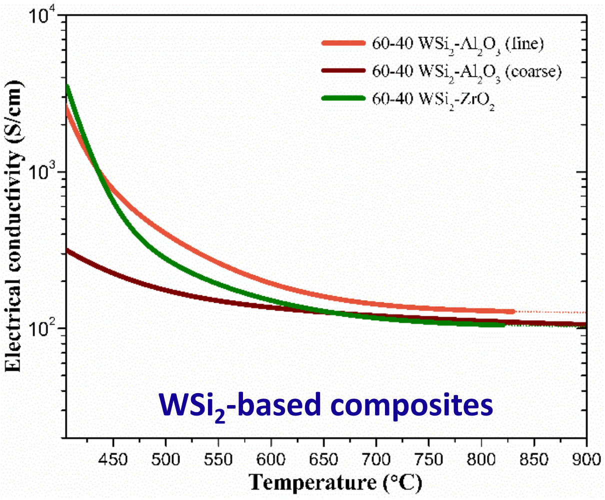


→ *Chemically etched in 1:1:1 HCl:HNO_3:H_2O*

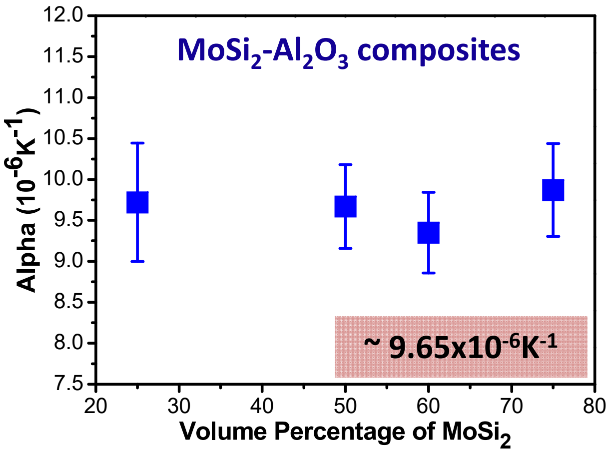
Electrical/Thermal Properties:

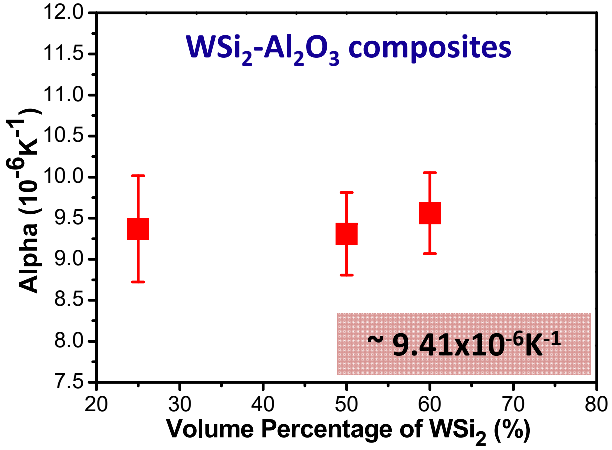
4-probe electrical conductivity up to 900°-1000°C





CTE (100°-1000°C)





Conductivity (S/cm) at 900°C

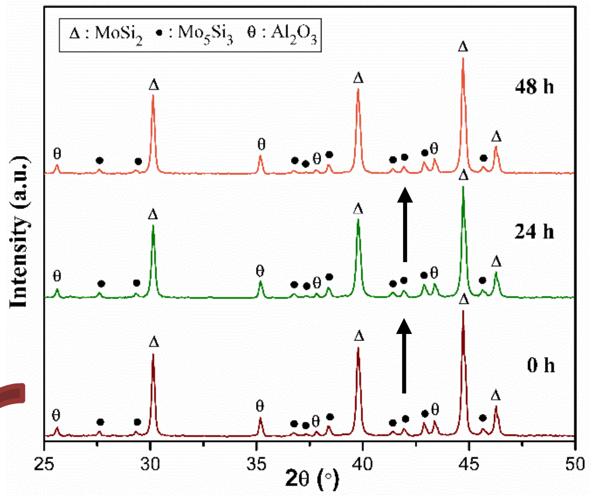
	20-80 vol%	*60-40 vol%*		
	$MoSi_2$-Al_2O_3 (fine)	**$MoSi_2$-Al_2O_3 (fine)**	**$MoSi_2$-Al_2O_3 (coarse)**	**$MoSi_2$-ZrO_2**
	8.83	86.01	128.36	81.91
	Other composites	**WSi_2-Al_2O_3 (fine)**	**WSi_2-Al_2O_3 (coarse)**	**WSi_2-ZrO_2**
	No percolation	126.64	105.91	102.76

- 60-40 $MoSi_2$-Al_2O_3 (coarse) and WSi_2-Al_2O_3 (fine) exhibited higher electrical conductivity at 900°C.
- Density, particle distribution/size and secondary phase highly influenced the physical properties.

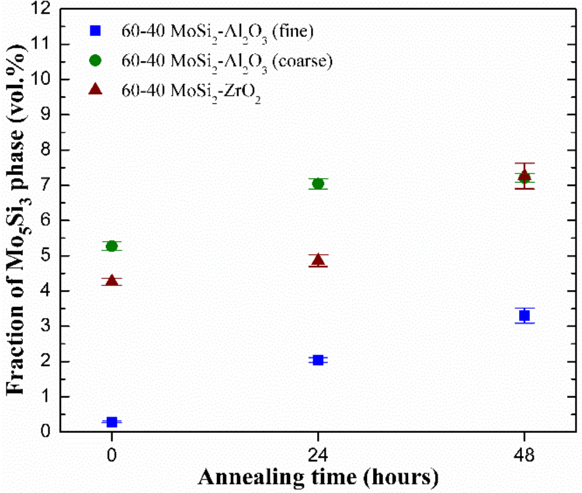
Thermal Stability – Grain Growth:

Thermal stability at 1400°C

MoSi$_2$-Al$_2$O$_3$ composites



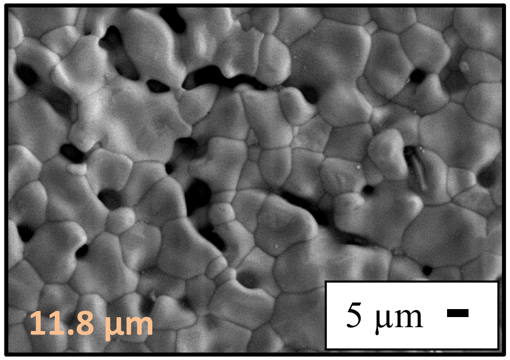
Increase in the fraction of Mo$_5$Si$_3$



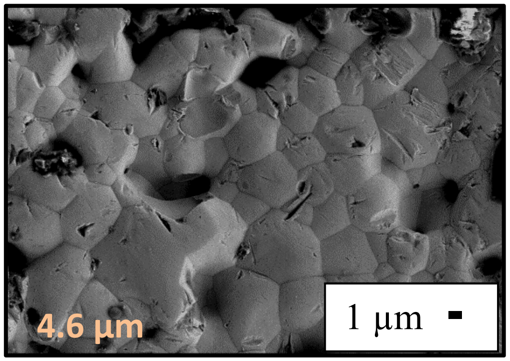
Grain growth kinetics at 1400°C

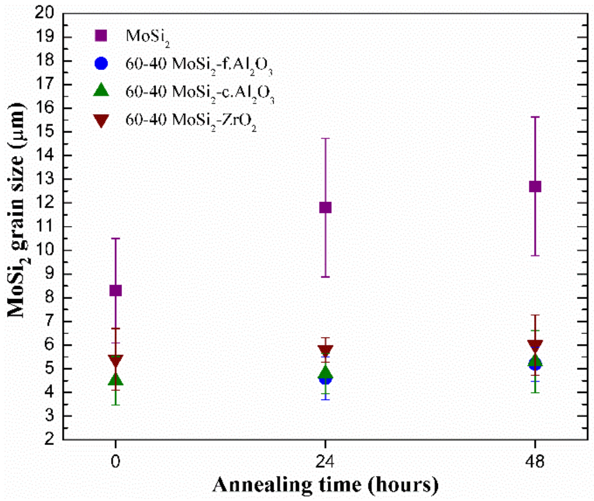
After 24h annealing

Pure MoSi$_2$



MoSi$_2$-Al$_2$O$_3$





- They showed high thermal stability at 1400°C up to 48h, only with formation of 5-3 silicide and silica phases.
- The rates of grain growth were highly decreased by grain boundary pinning effect.

Task 2 Conclusions and Future Work:

- Metal silicides show high chemical/thermal stability in Al_2O_3 and ZrO_2 matrix (with occasional formation of sub-silicides).
- Electrical conductivity of composites characterized with various silicide content → *consistent performance transferred to sensor design and fabrication task.*

Future Work:

- Alternative compositions (Cr-silicides, etc.) and designs will be investigated to prevent the reaction between silicide/oxide composites and Cr_2O_3.
- Process parameters will be optimized by correlating the homogeneity (D index) with the physical properties of the composites (percolation, etc.) at high temperatures.

Task 3: Sensor Patterning and Embedding.(Sabolsky/HWI)

Task 4: Static and Dynamic Sensor Testing of Smart Refractory Specimens. (Sabolsky/HWI)

*US Provisional Patent Number 61/941,159

Task 3 Objectives:

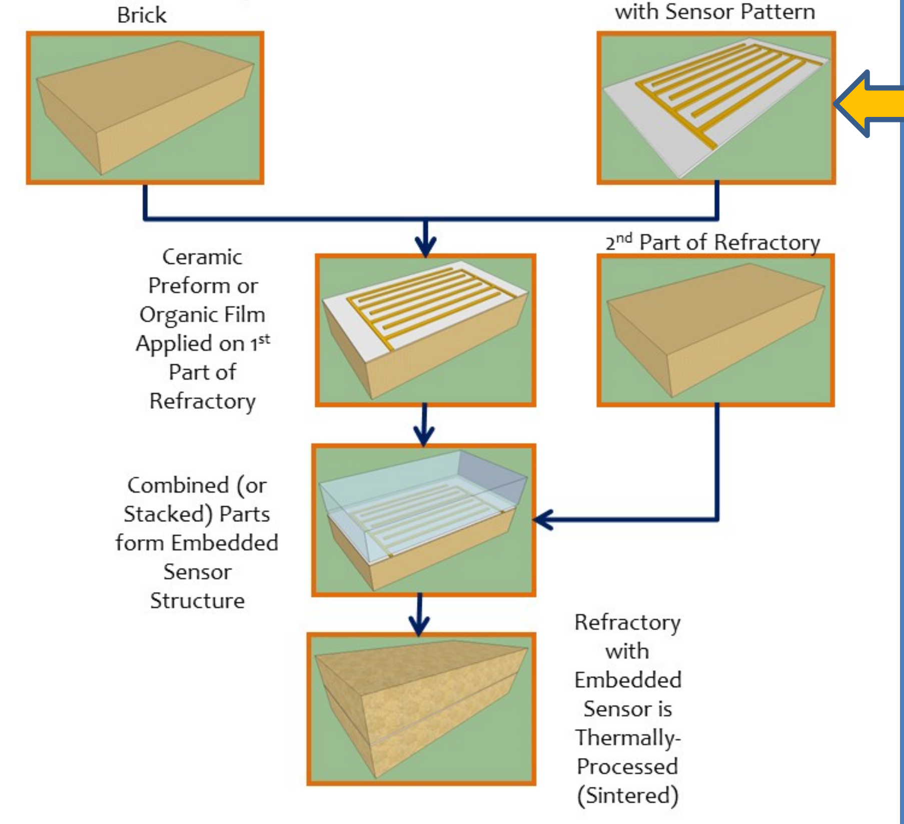
- To develop methods for patterning technology the ceramic composites within the refractory matrix.

Task 4 Objectives:

- To test the electrical performance of the smart refractory brick (with embedded thermocouple or thermistor sensors).
- To investigate corrosion/erosion kinetics in static and dynamic tests on smaller prototype and full-size smart cups and bricks (at WVU and HWI).
- To implement and test methods for data collection on initial prototypes.

Smart Refractory Fabrication:

General Smart Refractory Processing Method



1st Part of a Refractory Brick

Ceramic Preform or Organic Film with Sensor Pattern

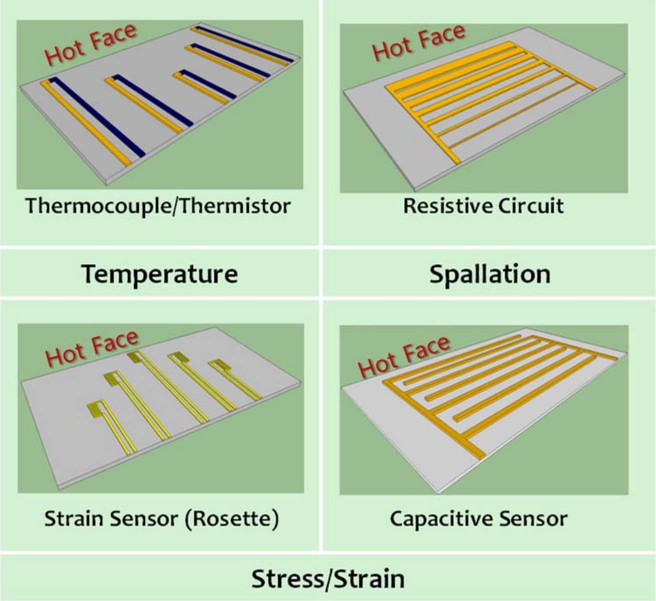
Ceramic Preform or Organic Film Applied on 1st Part of Refractory

2nd Part of Refractory

Combined (or Stacked) Parts form Embedded Sensor Structure

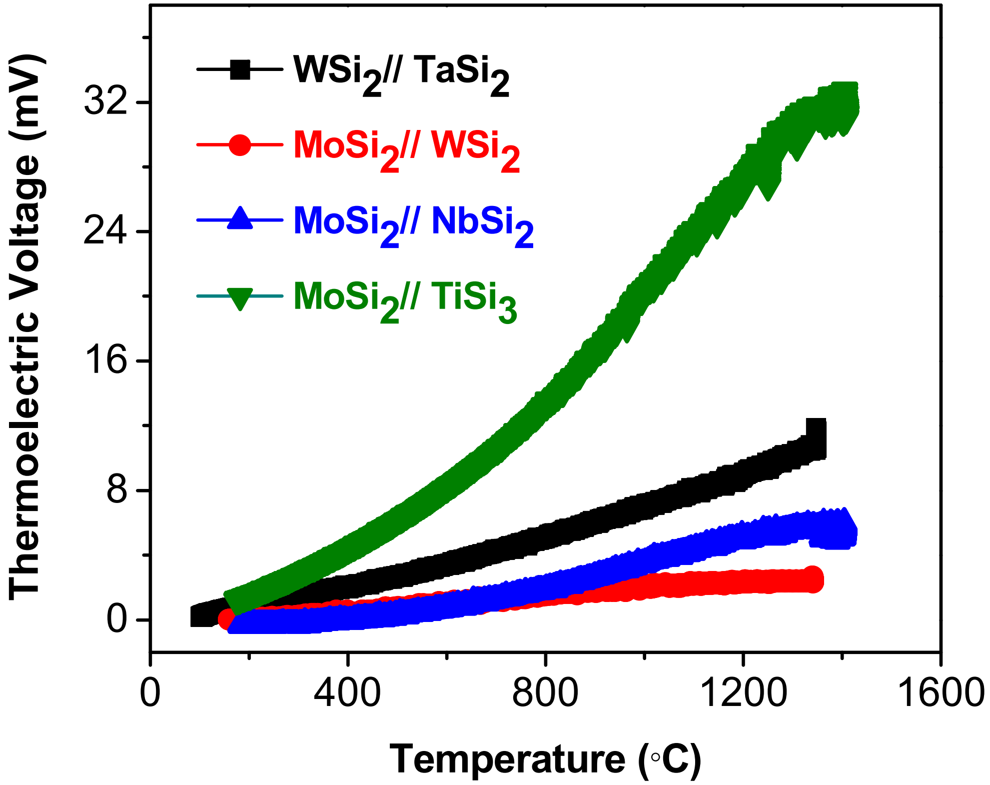
Refractory with Embedded Sensor is Thermally-Processed (Sintered)

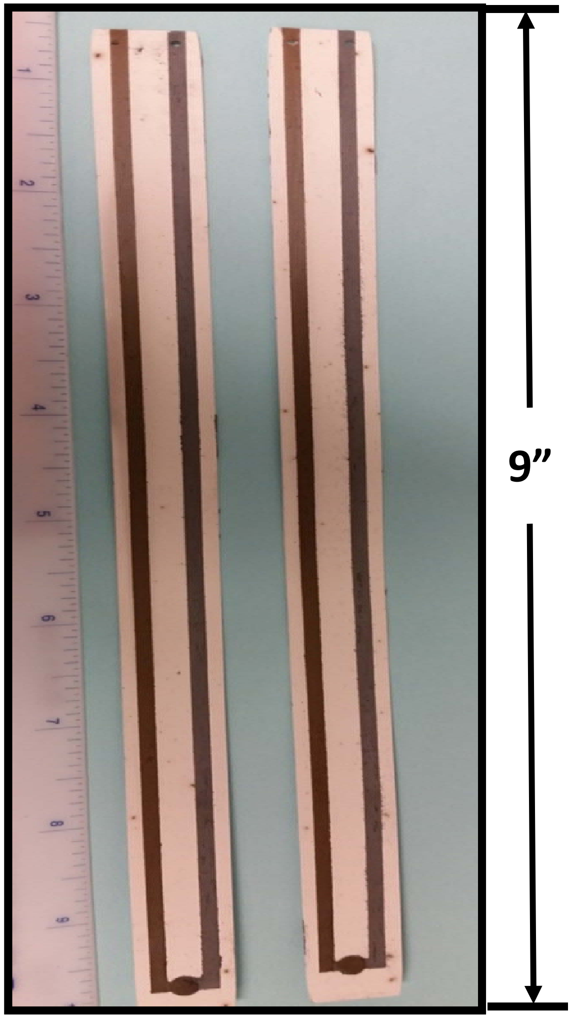
Examples of Sensor Preforms



Thermocouple/Thermistor	Resistive Circuit
Temperature	**Spallation**
Strain Sensor (Rosette)	Capacitive Sensor
Stress/Strain	

High-Temperature Thermocouple Performance:



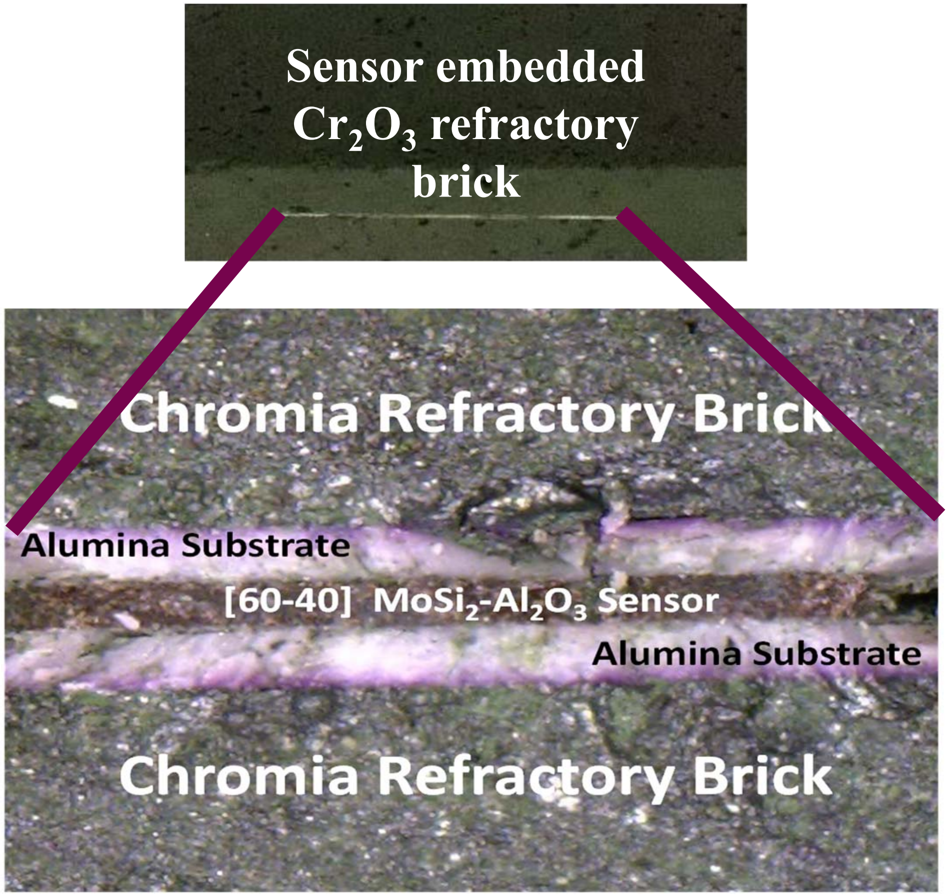


Various thermocouple compositions studied at 1500 °C

90 vol% silicide and 10 vol% oxide

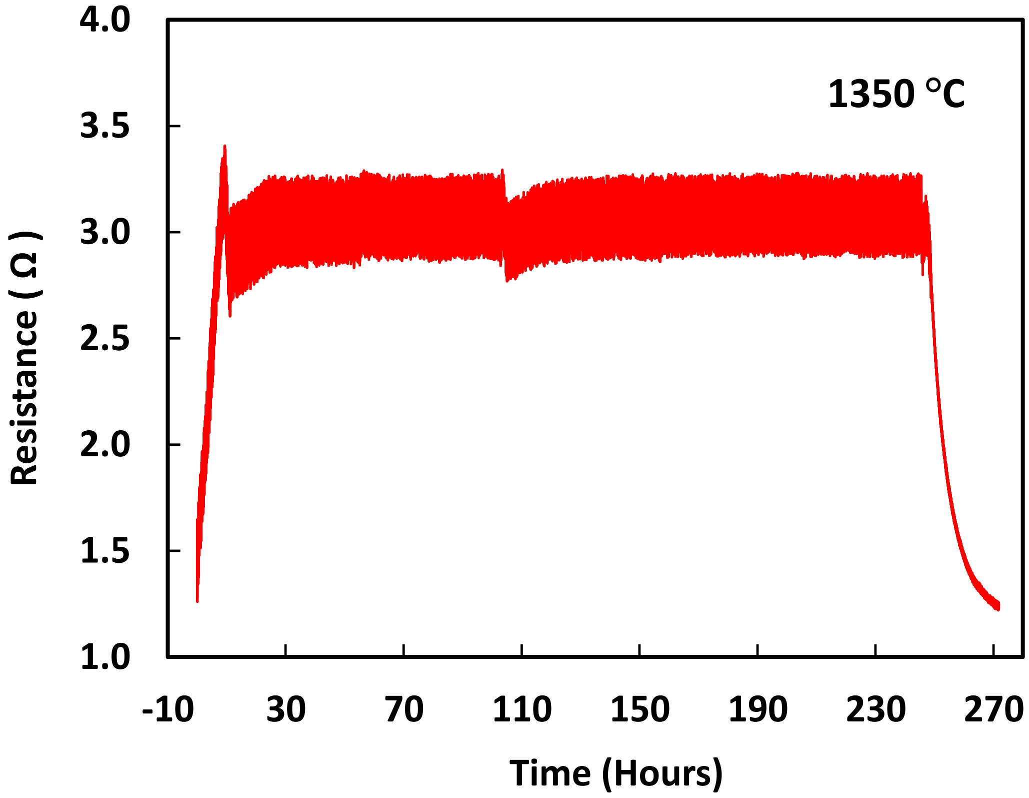
The thermocouple with composition $MoSi_2$ //$TiSi_2$ exhibited 34 mV at 1400 °C

Smart Refractory Microstructure:



- Monoliths of sensors were fabricated via tape casting, laminated and sintered at 1500 °C. These laminates were embedded in the Cr_2O_3 brick while slip casting and co-sintered at 1500º C in Argon atmosphere.

Embedded Thermistor: Smart Chromia Brick



Performance of thermistor [60-40] vol% $MoSi_2$-Al_2O_3

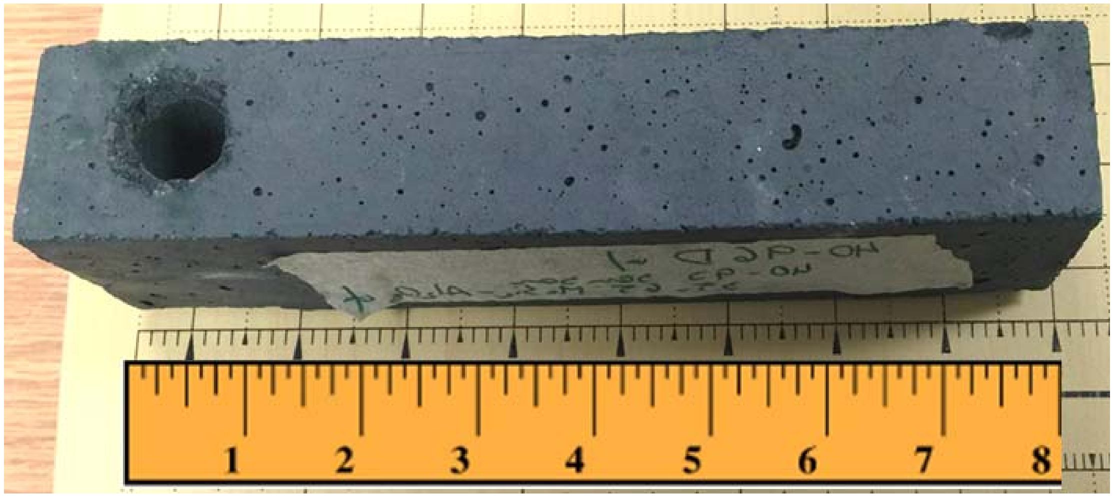
Thermistor embedded smart brick in the testing furnace

- The temperature sensor (thermistor) with composition (60-40) vol% $MoSi_2$-Al_2O_3 embedded within the Cr_2O_3 refractory exhibited stable behavior for more than **250 hours at 1350 °C** in argon atmosphere.

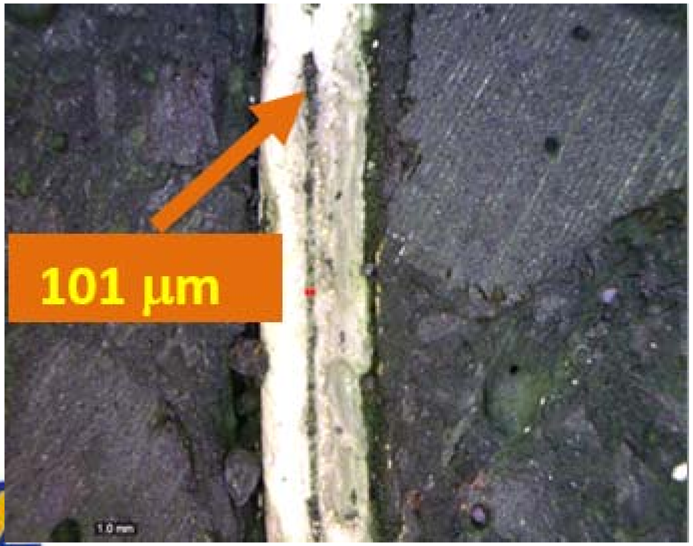
Embedded Thermocouple: Smart Chromia Brick

- Sensor preform embedded HWI high-chromia formulation.
- Sensor embedded below opening to insert slag composition for corrosion testing.

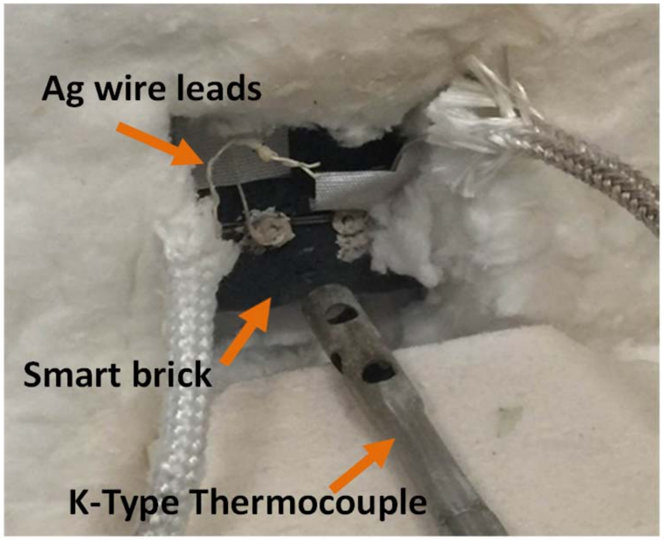
Long TC embedded Chromia Refractory Brick



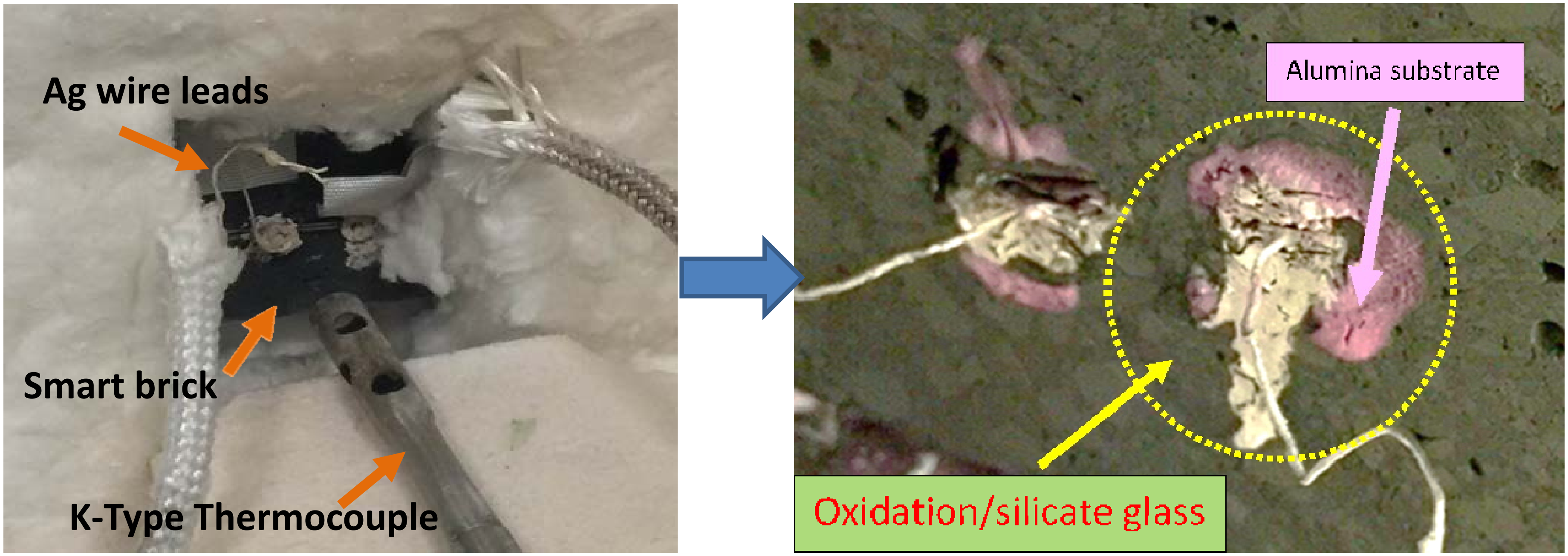
Thin Embedded TC Sensor



Interfaced Smart Brick



Current Issue: Brick Interconnection



- Loss of electrical connection to bricks during testing.
- Metal lead delamination due to wetting limitations and Pt-Si alloy formation.
- Phase oxide formation in locations that are not embedded causing drift in response.

Efforts are focusing on better understanding the issue and developing the proper ceramic and/or metal connections.

Alternative Sensor Materials

(Heading towards Demonstration Task)

Risk Mitigation:

- Two alternative oxide compositions initiated in August 2016.
- Fabrication and testing completed, and new bricks for summer Task 7 DEMO being manufactured at HWI.

Approach:

High conductivity electrode material, **La_2NiO_4 (LNO)** and **$Sr(Ti,Nb)O_3$ (STNb)** was evaluated as alternative sensor materials, stable in air and slightly reducing atmospheres.

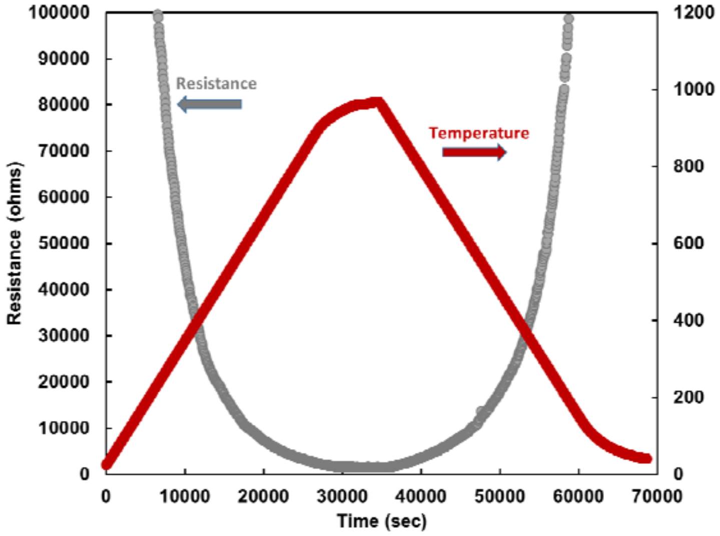
- Stable interconnect junction and does not react with Pt leads.
- Synthesized at WVU by solid state processes.
- Screen printed on and within zirconia, and embedded within high-chromia bricks.

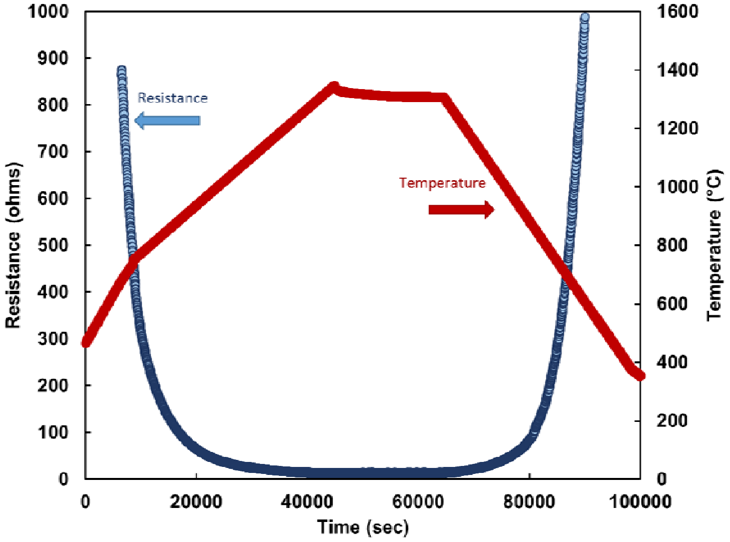
Screen printed sensor material on green YSZ

Oxide sensor material co-sintered in zirconia.

Alternative Sensor Material: La_2NiO_4

- **La_2NiO_4** (LNO)- High p-type semi-conducting material.
- Initial LNO thermistor sensors showed an increase resistance during 5 hr hold.
- Increased sintering temperatures de-stabilized microstructure and caused variable response.

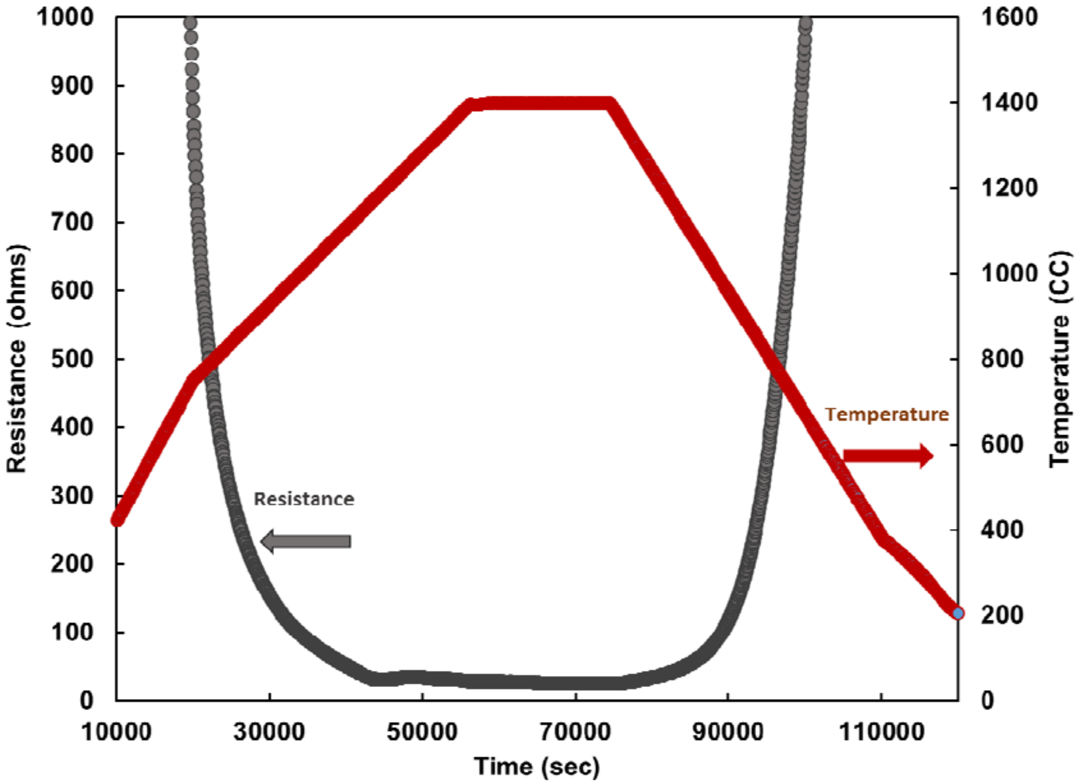

LNO sensor tested to 1000°C


LNO sensor tested to 1350°C

Alternative Sensor Material: La_2NiO_4

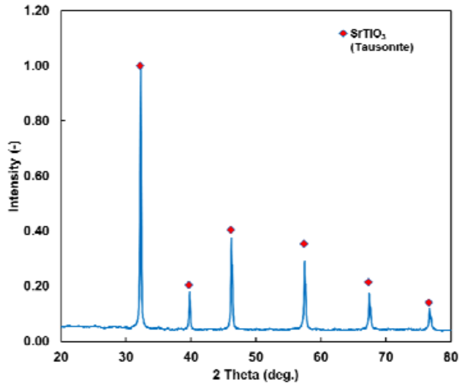
- Coarser (more aggregated sensor material, >10 µm average particle size) currently being tested to show stable high-temperature response.
- The thermistor tested to 1400°C showed nice stability.

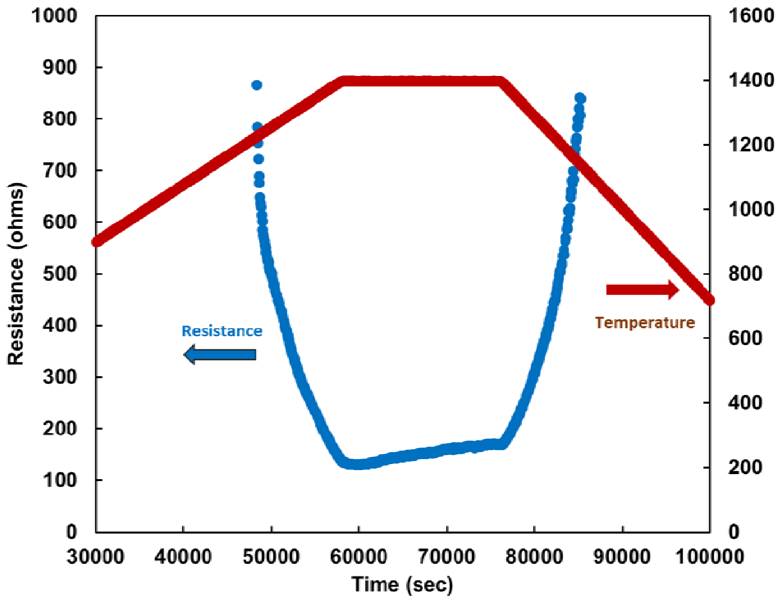
YSZ imbedded thermistor imaged over light box



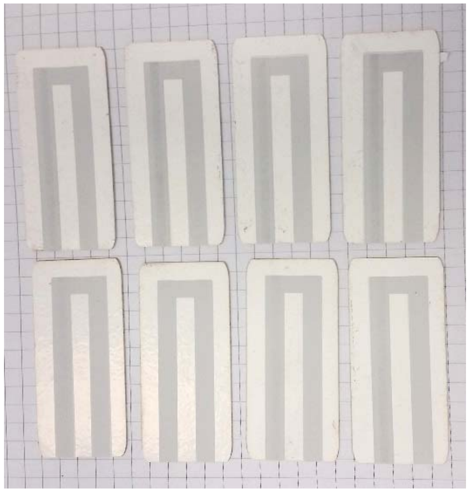
Alternative Sensor Material: $Sr(Ti_{0.8}Nb_{0.2})O_3$

- **$Sr(Ti_{0.8}Nb_{0.2})O_3$** (STNb) - High n-type semi-conducting material.
- The thermistor was fabricated using zirconia substrate
- Thermistors were sintered at 1450°C and tested to 1400°C





Screen printed sensor material on green zirconia



Task 3 and 4 Conclusions and Future Work:

- All-ceramic thermocouple and thermistor preforms (and smart bricks) were fabricated and successfully tested, but issues with interconnection.
- Two new alternative oxide-based systems also being investigated in parallel to show full brick and system demonstration.

Future Work:

- Optimize method to interconnect to embedded sensors (in order to stabilize sensor signal and sensor long-term response).
- Complete fabrication and testing of all-oxide based sensor preforms in smart brick architecture.
- Scale-up all sensor preforms and smart refractory brick for **FULL-TECHNOLOGY DEMO IN TASK 7**.

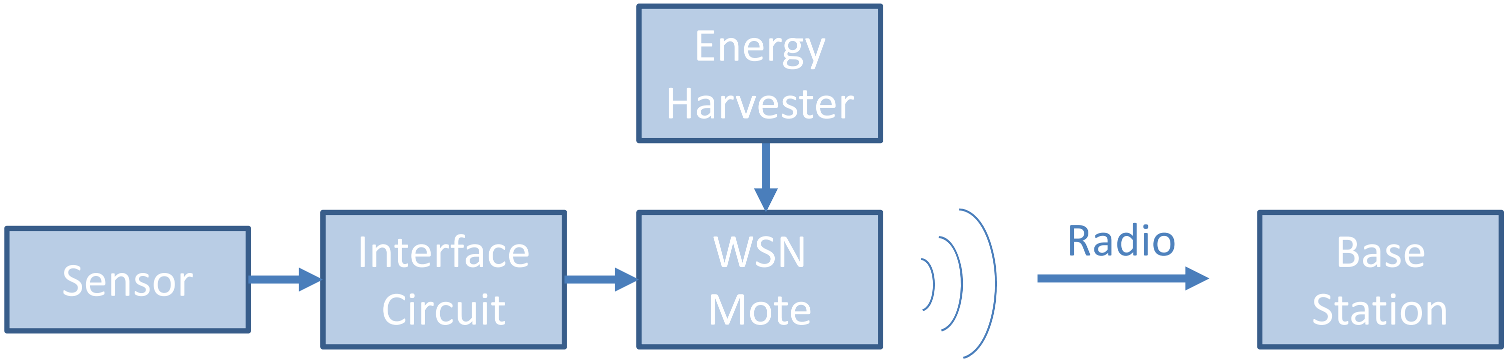
Task 5:

Data Ex-Filtration Using a Wireless Sensor Network.

(Graham/Kulathumani)

Task 5 Objectives:

- To develop methods to interface the electrical sensing outputs from the smart refractory with an embedded processor
- To design a wireless sensor network to efficiently collect the data at a processing unit for further data analysis



Energy Harvester

Sensor

Interface Circuit

WSN Mote

Radio

Base Station

Electronics interfacing – Approach:

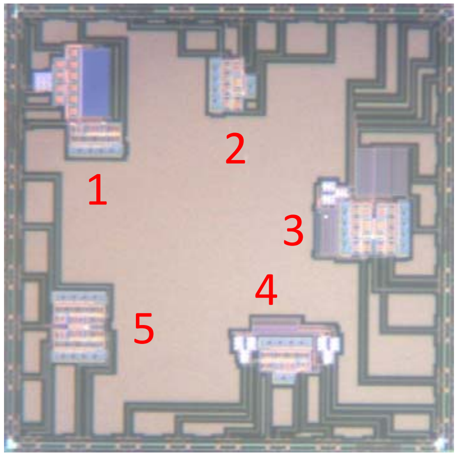
Aim: To reliably collect data from the sensors embedded within the smart bricks and interface them to wireless sensor nodes for communication

Approach:

(i) Iterative approach to sensor interface circuitry in parallel with the sensor development
  a) Initial sensor interface circuitry using off-the-shelf circuitry
  b) Move to integrated circuits for lower-power and more compact solutions

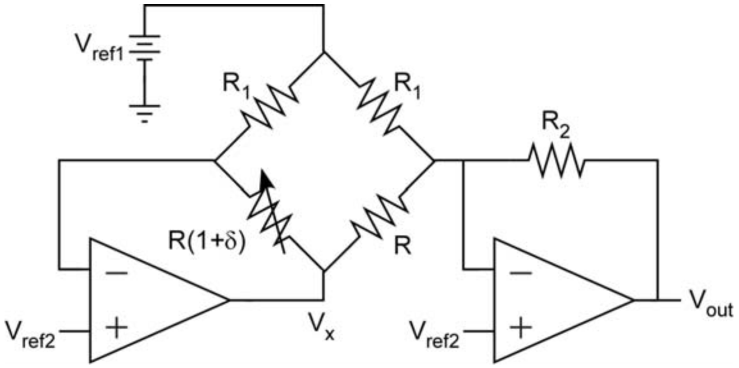
(ii) Investigate energy harvesting using thermoelectric devices to help power the sensor motes and interface circuitry

Custom Integrated Circuit:

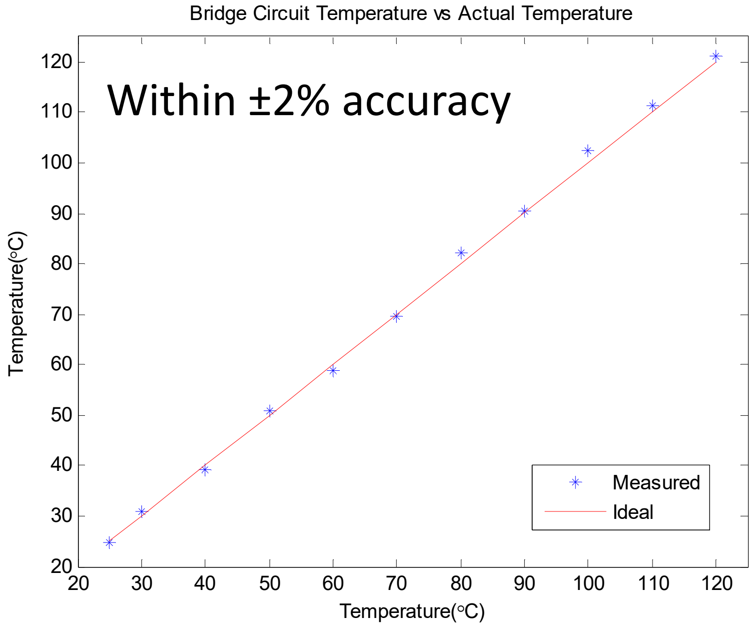


1. Cold-Junction Compensator
2. Thermocouple Amplifier
3. Capacitive Sensor
4. Thermocouple Amplifier V2
5. Wheat-Stone Bridge

Resistance-Based Sensor



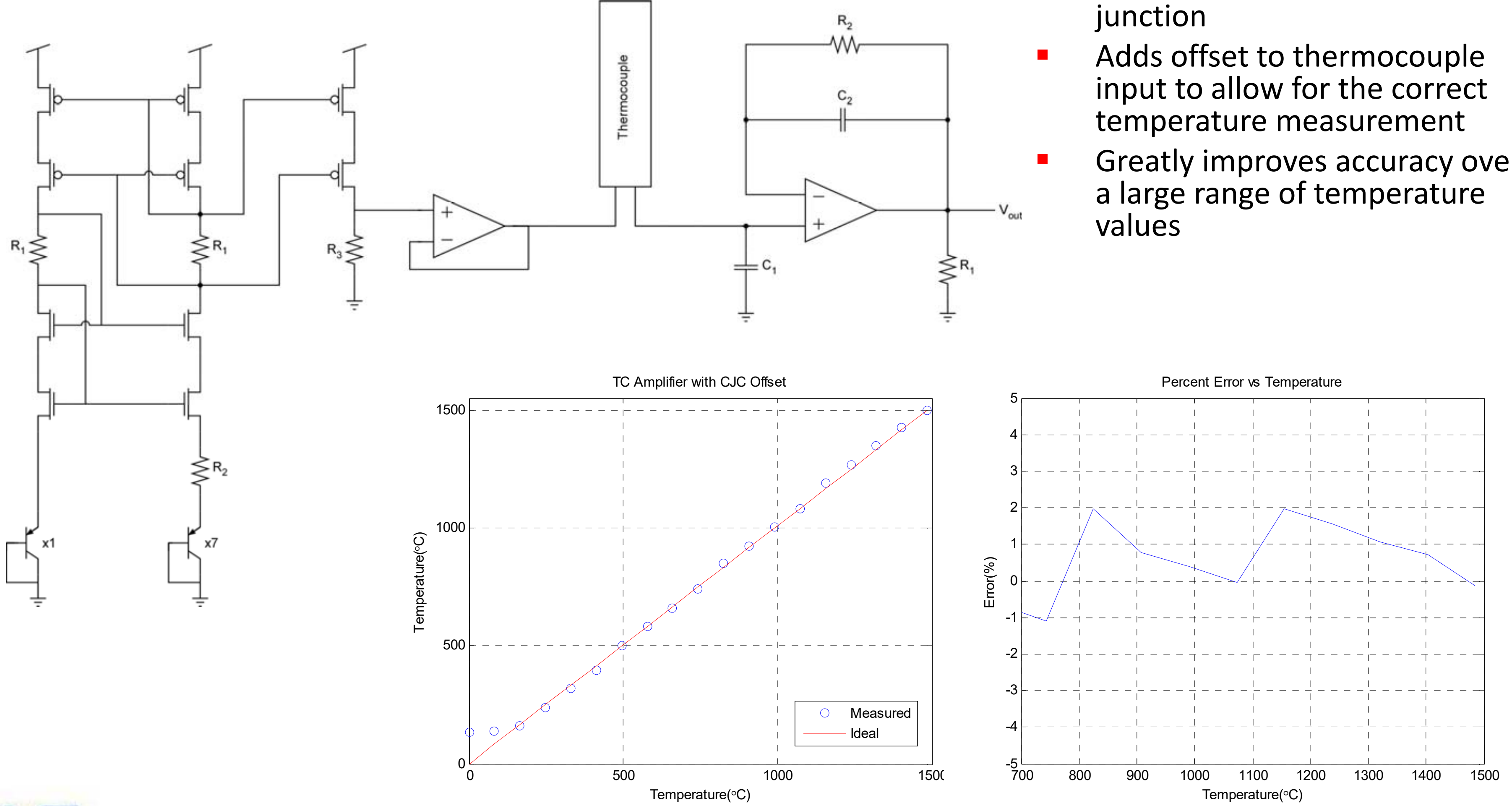
$$V_{out} = V_{ref2} + \frac{R_2}{R_1}\delta\left(V_{ref1} - V_{ref2}\right)$$


Bridge Circuit Temperature vs Actual Temperature

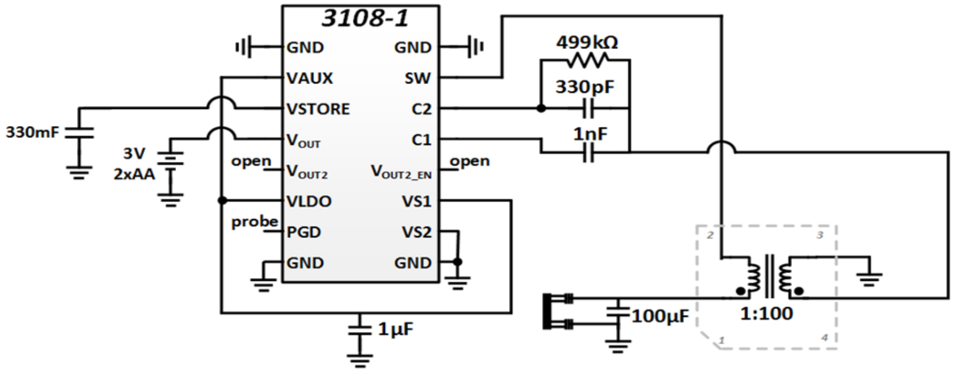
Within ±2% accuracy

Circuits for Thermocouple-Based Sensors:

- Compensates for measurement error at thermocouple cold junction
- Adds offset to thermocouple input to allow for the correct temperature measurement
- Greatly improves accuracy over a large range of temperature values



Circuits for Energy Harvesting:

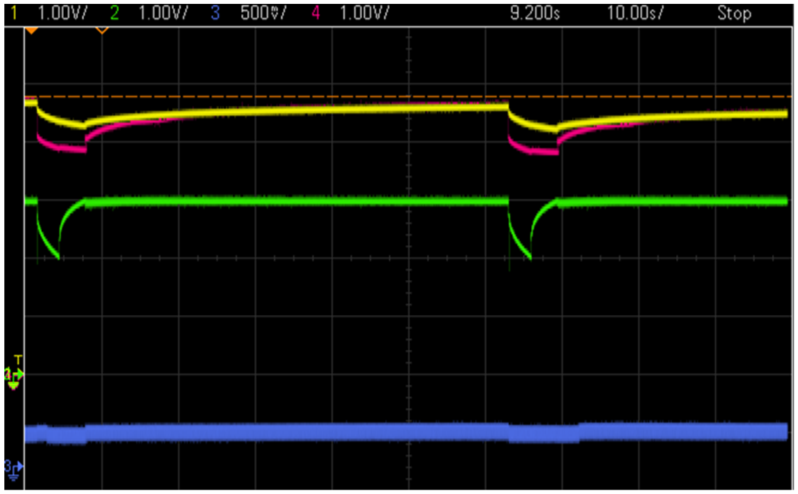


- Leverages COTS-based DC/DC converter circuit (LTC3108)
- Start-up Sequence shows the output of Thermoelectric Generator, LDO Regulator, Storage Buffer, and V_{OUT}.
- The Mote Experiment was done using a TelosB. The results shown are 10 minutes into the test. Once a minute, the TelosB turned on and was powered by the energy harvesting system for a 5 second radio transmission.

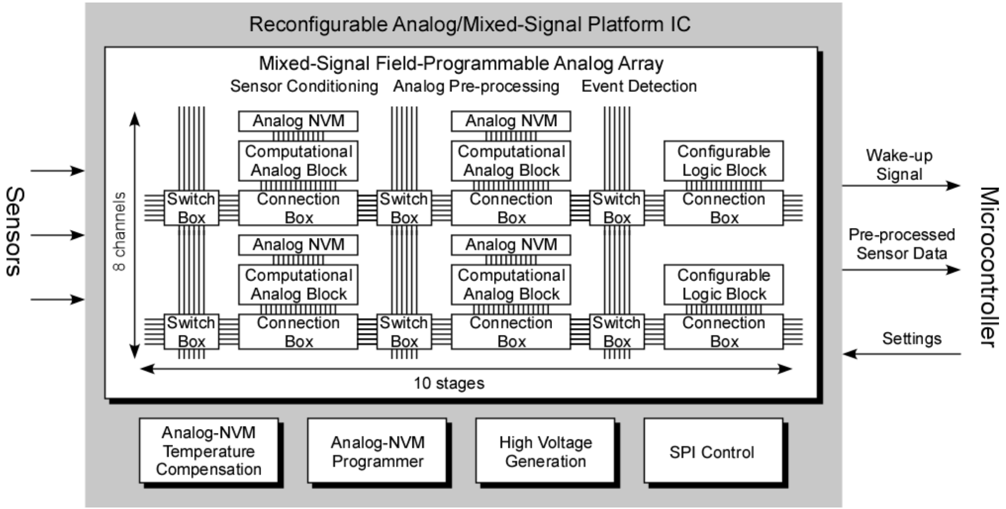
V_{OUT} – System Output
Storage Buffer – Energy Storage Output
LDO Regulator – Internal Regulator Output
TEG – Thermoelectric Generator Output

Start-up Sequence

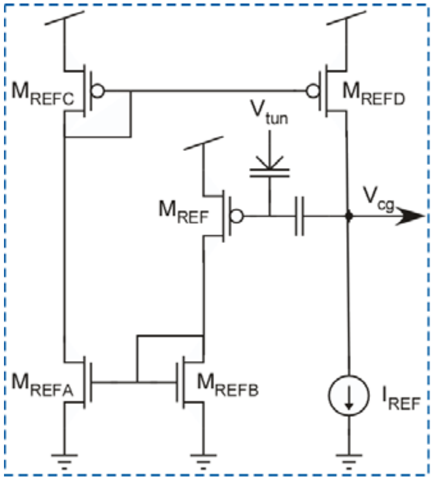
Mote Experiment: Testing Results

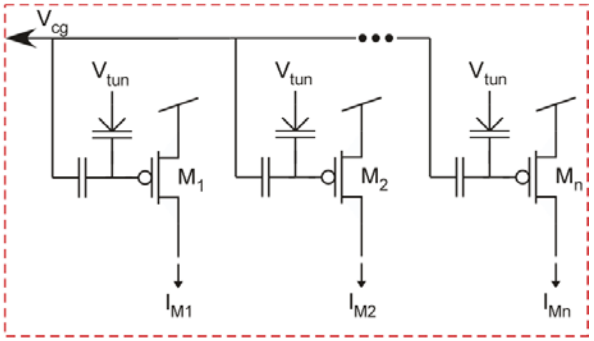


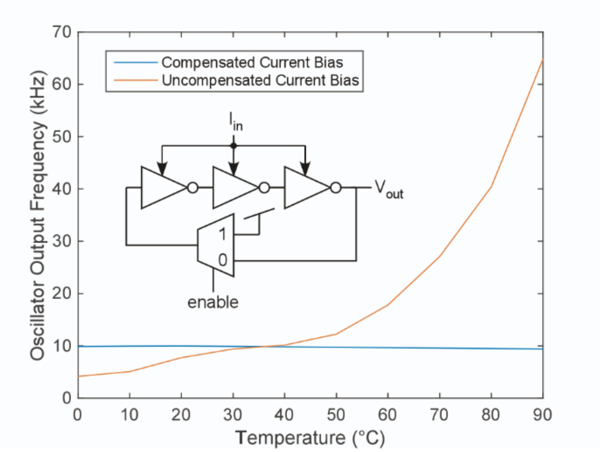
Reconfigurable Circuits:



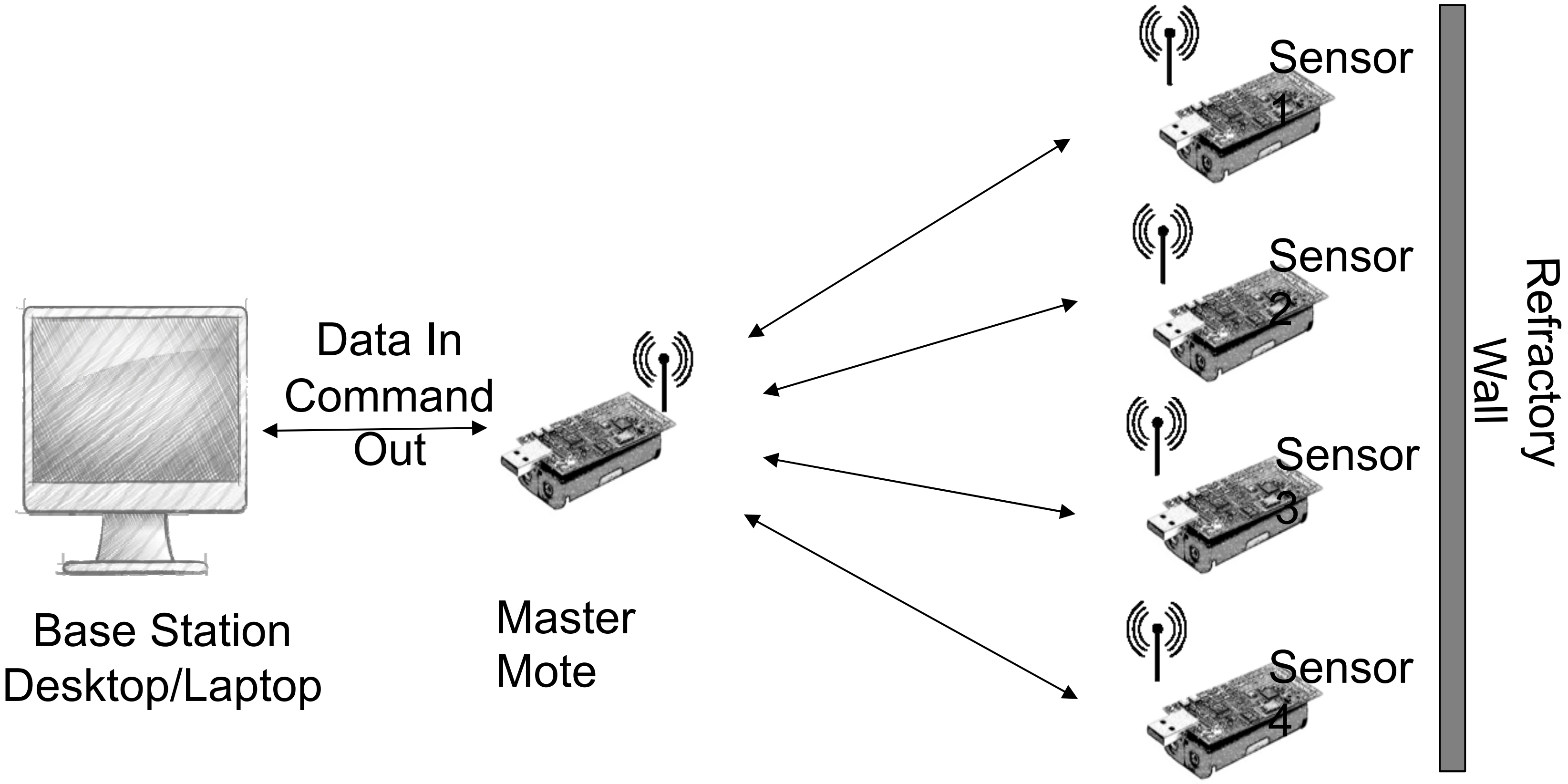
- Maintain flexibility—in-the-field updates to sensor-interfacing circuits
- A variety of sensor interface circuits can be constructed from a single chip
- Internal temperature compensation using floating-gate transistors





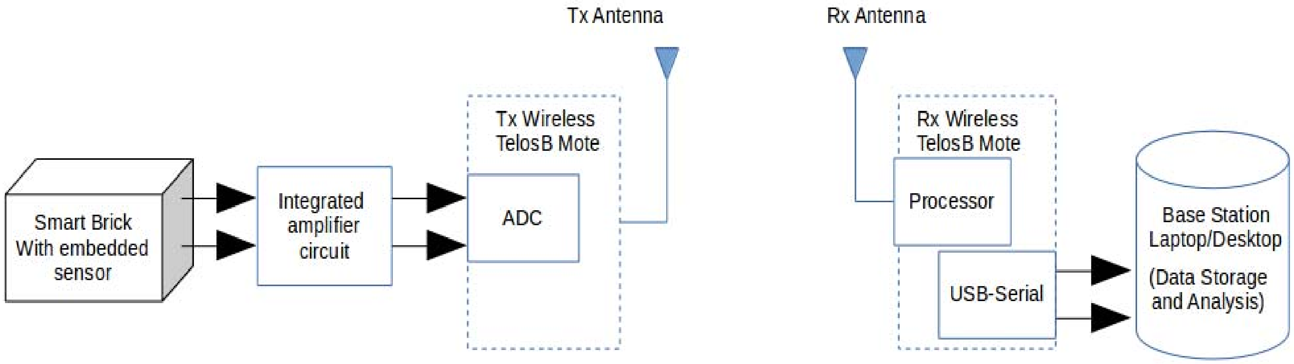


Wireless sensor network overview:



- Collect refractory sensor data over wireless medium
- (data ex-filtration)
- Enable remote configuration of parameters
    - (over-the-air programming)

Previous work



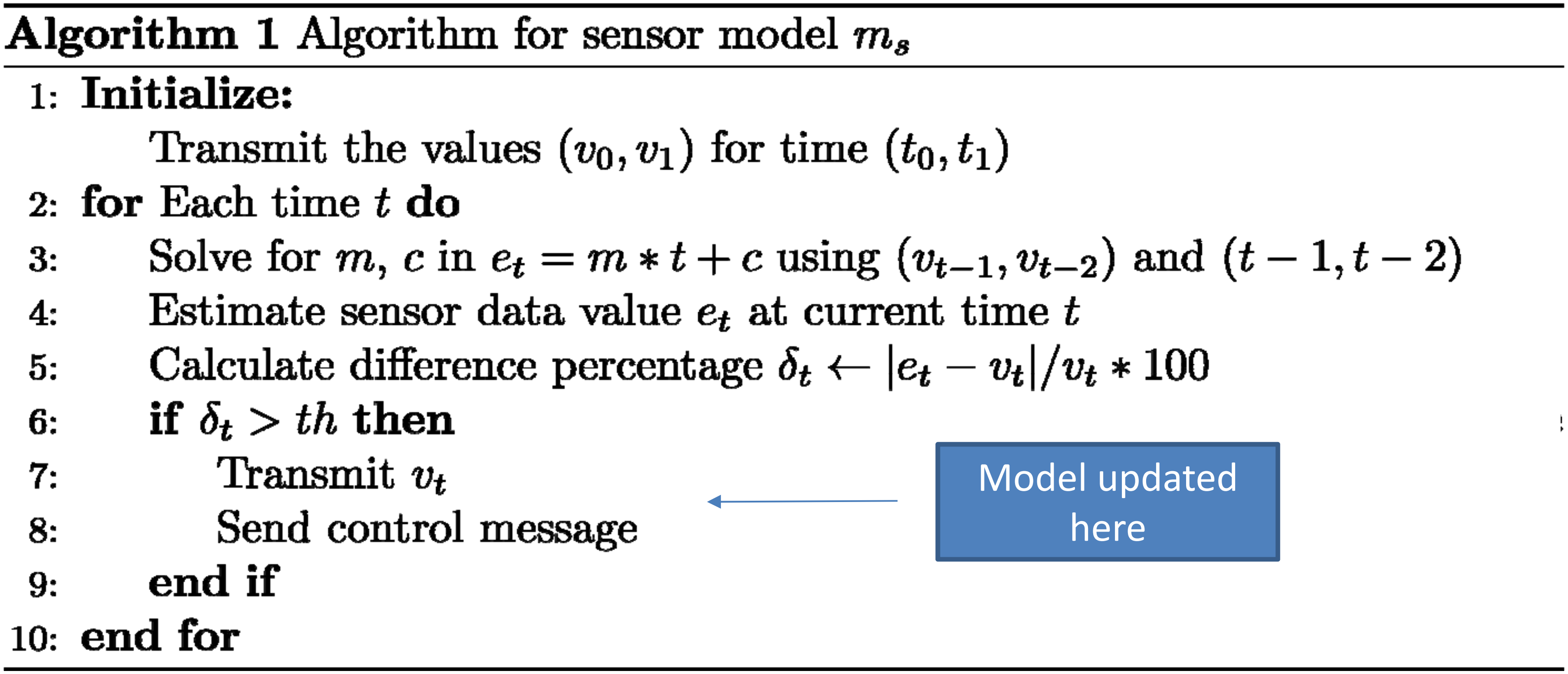
- Assembled full signal chain
  - Smart bricks with embedded sensors were interfaced with a wireless mote yielding a complete signal chain comprising
    - the smart brick,
    - resistance measurement / amplifier circuit,
    - and wireless data transmission.
- Verified wireless signal chain performance on smart brick prototype
- Developed visualization tools and sensor parameter control interface
- Tested network performance at scale using network simulator

Current work: Model based strategies

- **Goal: Talk less, convey more information**
  - Critical for scaling system to large network sizes
  - Use information-centric models to compress data being transmitted

- **Linear estimation based data reduction**
  - Sender computes dynamic linear estimator based on sampled data
  - Transmits linear estimator
    - Only if estimation error exceeds a preset threshold
  - Receiver uses most recent linear model to estimate sensor data
  - Only models communicated
    - Not data

Algorithm for sensor

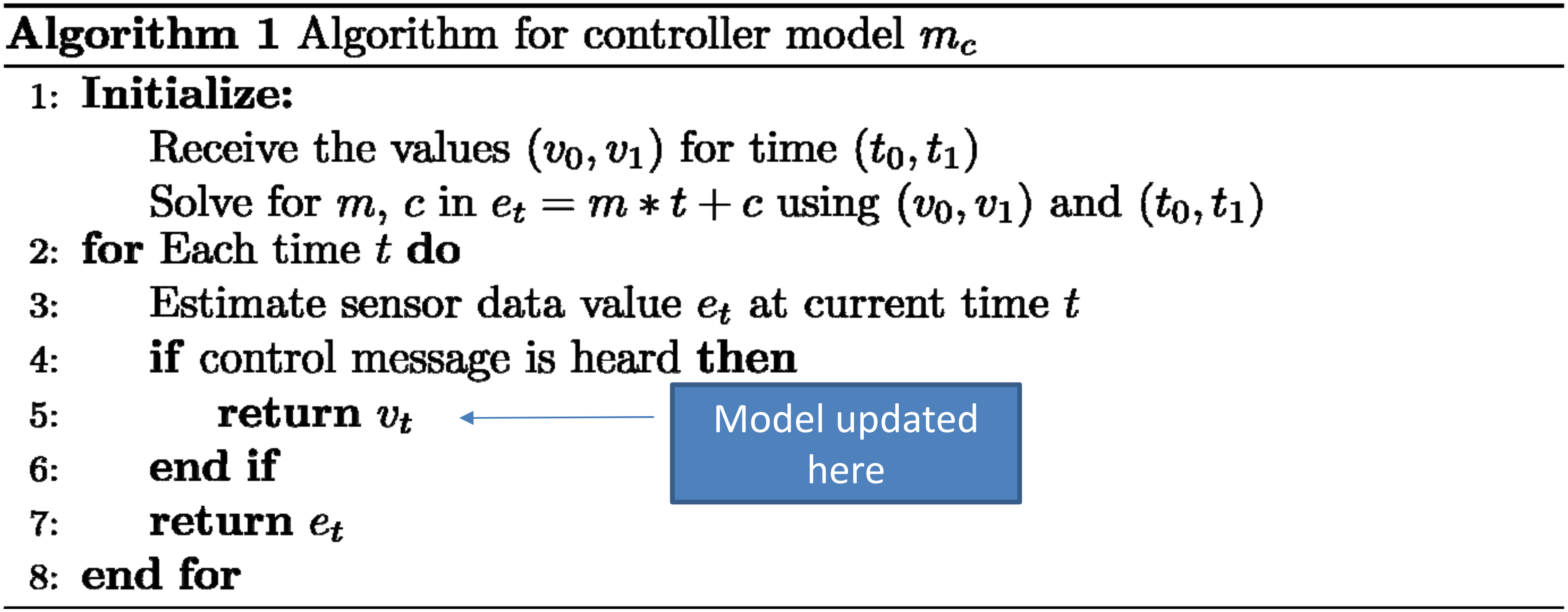


Algorithm 1 Algorithm for sensor model m_s

```
Initialize:
    Transmit the values $(v_0, v_1)$ for time $(t_0, t_1)$
for Each time $t$ do
    Solve for $m$, $c$ in $e_t = m * t + c$ using $(v_{t-1}, v_{t-2})$ and $(t-1, t-2)$
    Estimate sensor data value $e_t$ at current time $t$
    Calculate difference percentage $\delta_t \leftarrow |e_t - v_t|/v_t * 100$
    if $\delta_t > th$ then
        Transmit $v_t$
        Send control message
    end if
end for
```

Model updated here

Algorithm for receiver / controller



Algorithm 1 Algorithm for controller model m_c

```
Initialize:
    Receive the values $(v_0, v_1)$ for time $(t_0, t_1)$
    Solve for $m$, $c$ in $e_t = m * t + c$ using $(v_0, v_1)$ and $(t_0, t_1)$
for Each time $t$ do
    Estimate sensor data value $e_t$ at current time $t$
    if control message is heard then
        return $v_t$
    end if
    return $e_t$
end for
```

Model updated here

Evaluation setup

- Sensor Network Simulated with sensor model and controller model

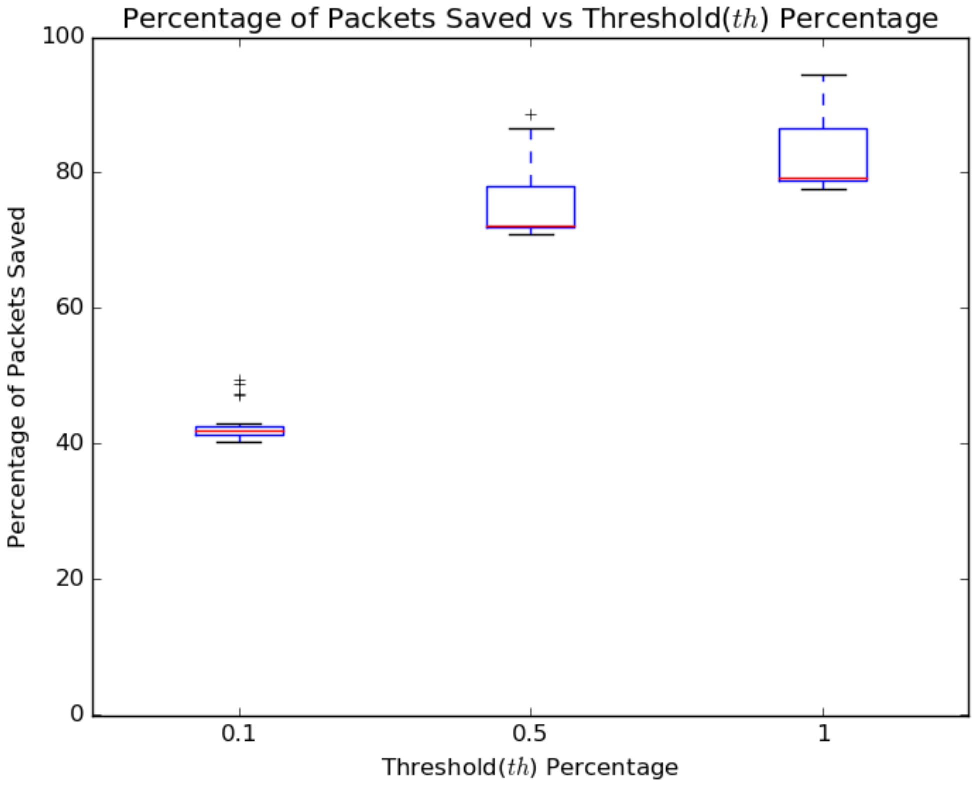
- Data from Mica2Dot sensors with weather boards deployed at Intel Berkeley Research Lab
    - Mimics ***slow changing, low sampling rate phenomena*** like the smart brick monitoring
    - The data was sampled once every 31 secs and collected between February 28th and April 5th, 2004

- The model is validated for three different threshold percentage values i.e. *th = 0.1, 0.5, 1* for all 54 sensors

- System also evaluated under simulated packet drops

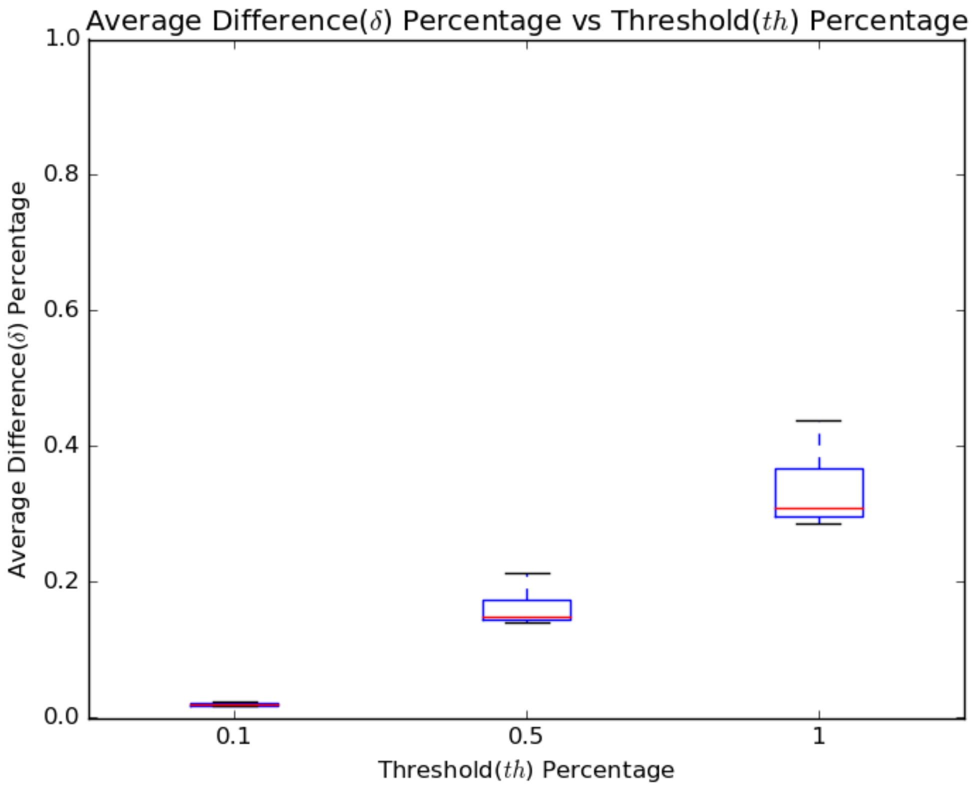
Results (1)

- Percentage of packets saved as function of allowed error
- Even with an error of 0.1%, *about 40% packets saved*



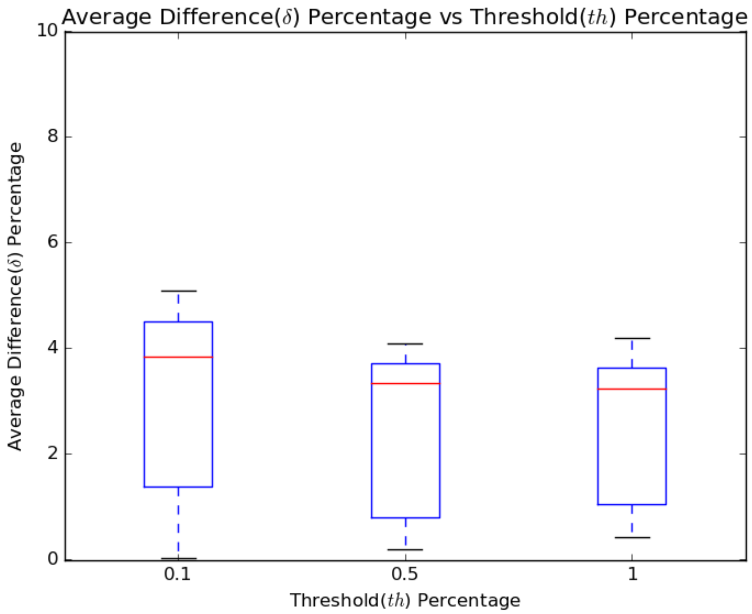
Results (2)

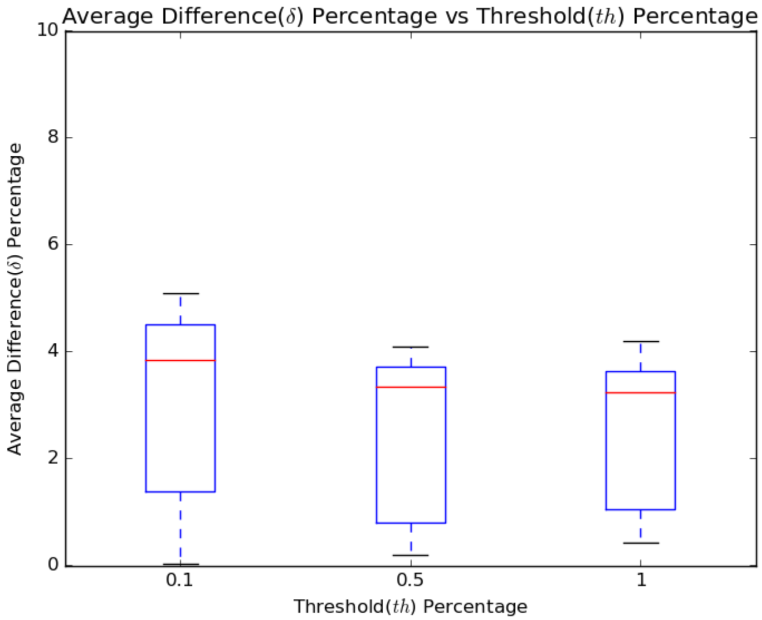
- Actual observed error vs preset error threshold
- Actual observed errors are *actually much lower*



Results (3)

- Impact of data loss
  - Note that **model data more significant than raw data**





- Notice that errors are about 2-5% when crucial model data is lost
- *But sending less data is actually likely to reduce data loss due to reduced interference*

Task 5 Conclusions and Future Work:

- Analog interface section
    - Developed an integrated circuit for sensor interfacing
    - Demonstrated the potential of using energy harvesting
    - Exploring using reconfigurable analog systems for providing long-term flexibility

- Wireless sensor network
    - Model based data reduction techniques are being explored
    - This can help reduce data rate without compromising with information required for analyzing system characteristics
    - Linear model based estimator yielded 40% savings with <1% error rate
    - Plan to continue exploring other model based ideas for data reduction e.g. Change based strategy

Task 6.0:
Model-Based Estimation of Temperature Profile and Extent of Refractory Degradation.
(Bhattacharyya)

Task 6 Objectives:

- To develop algorithms for model-based estimation of temperature profile in the refractory, slag penetration depth, spallation thickness, and resultant health by using the data from the wireless sensor network

Motivation & Approach:

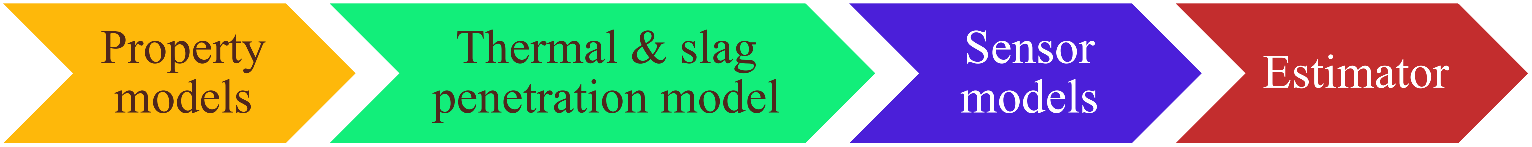
Motivation:

- Typical correlation based approaches are inadequate
- Stiff temperature gradient along the sensor length
- Change in thermal and electrical properties over time due to slag penetration

Model-based approach:

Variable of interests:

- Temperature
- Extent of slag penetration



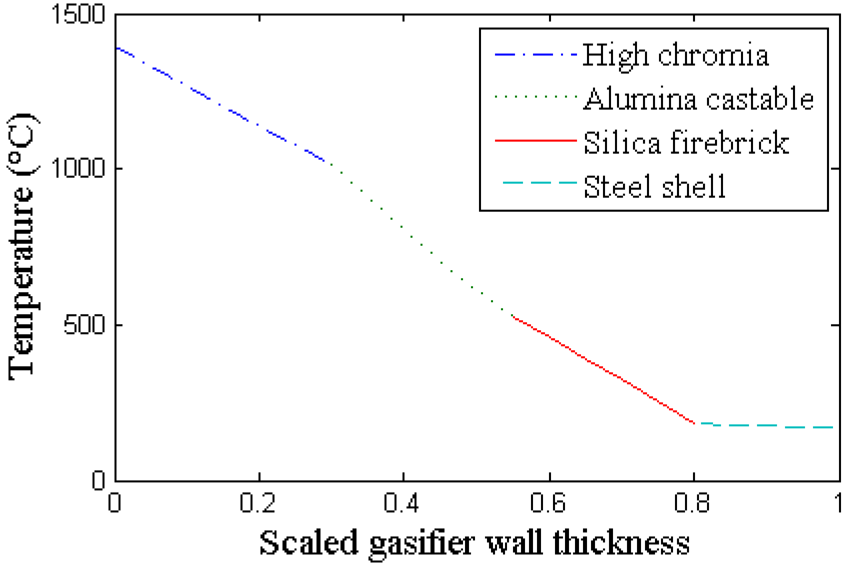
Property models

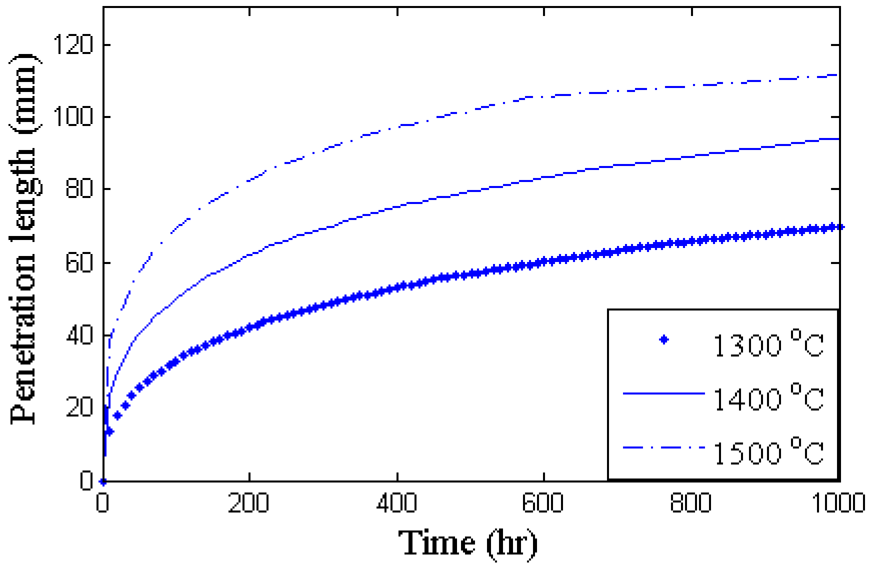
Thermal & slag penetration model

Sensor models

Estimator

Properties and Process Models





Properties (thermal, mechanical, electrical) Models

- For slag, sensor, and refractory materials
- For slag-infiltrated refractory

Process Models:

- Thermal model:
- Slag penetration model:

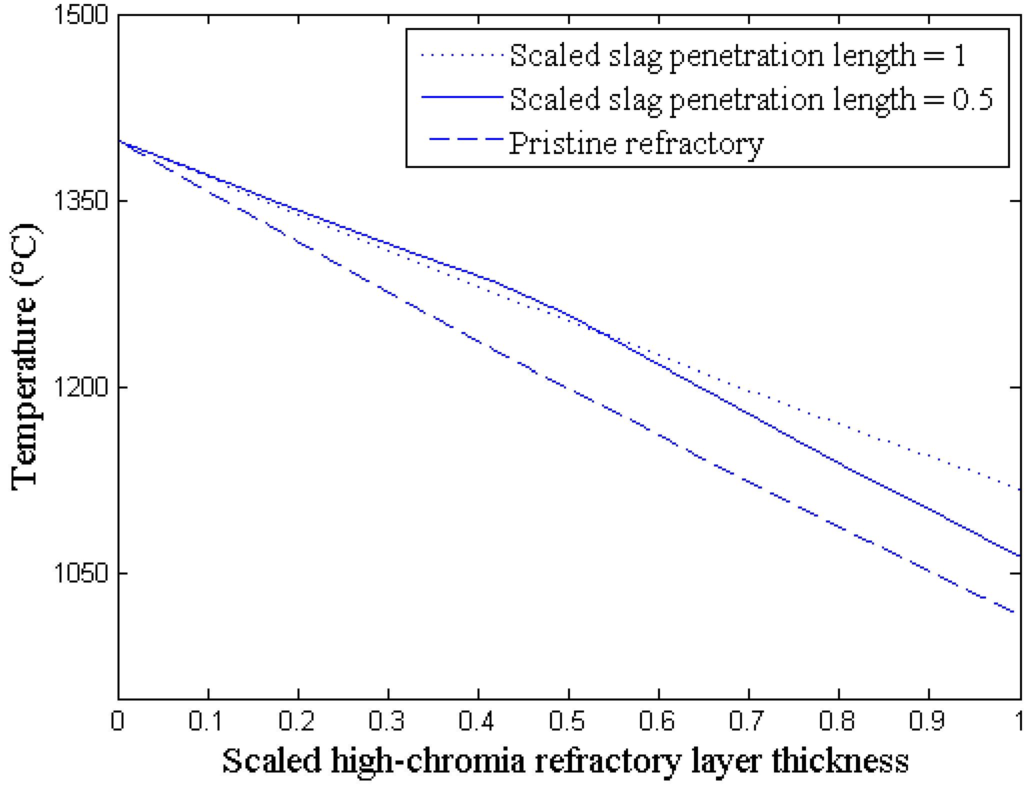
❖ Capillary pressure

❖ Simplified Poiseuille's law

Effect of Slag Penetration on Wall Temperature

Steady state temperature profiles:

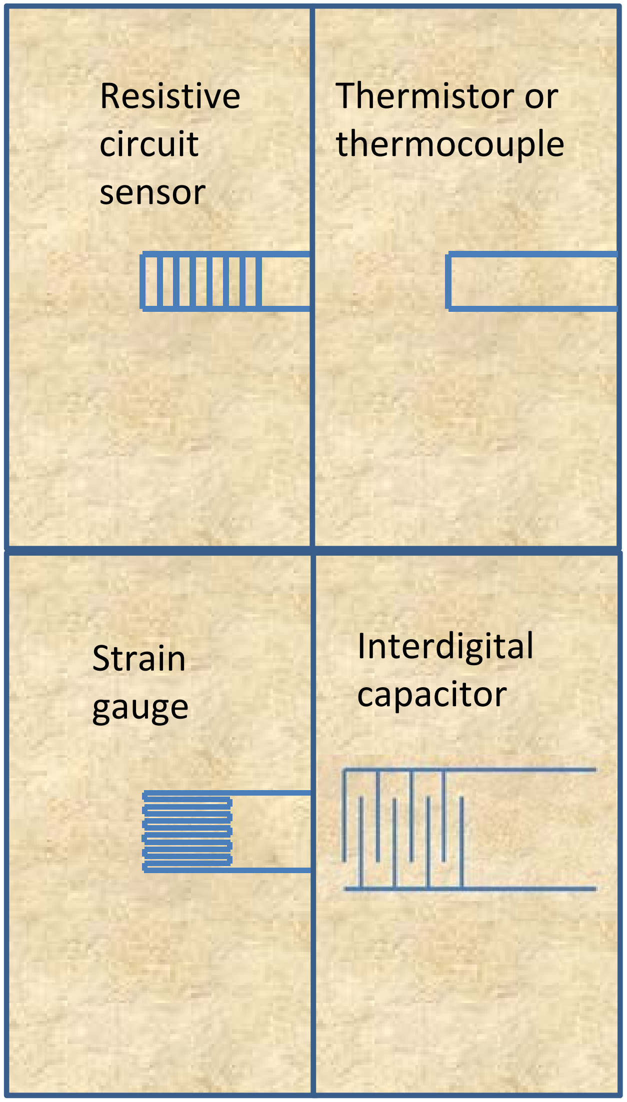
- ✓ Property models for slag penetrated refractory
- ✓ Slag penetration model



Sensor Models:

Five different types of sensors:

- Interdigital capacitor (IDC)
- Strain gauge
- Resistive circuit
- Thermistor
- thermocouple



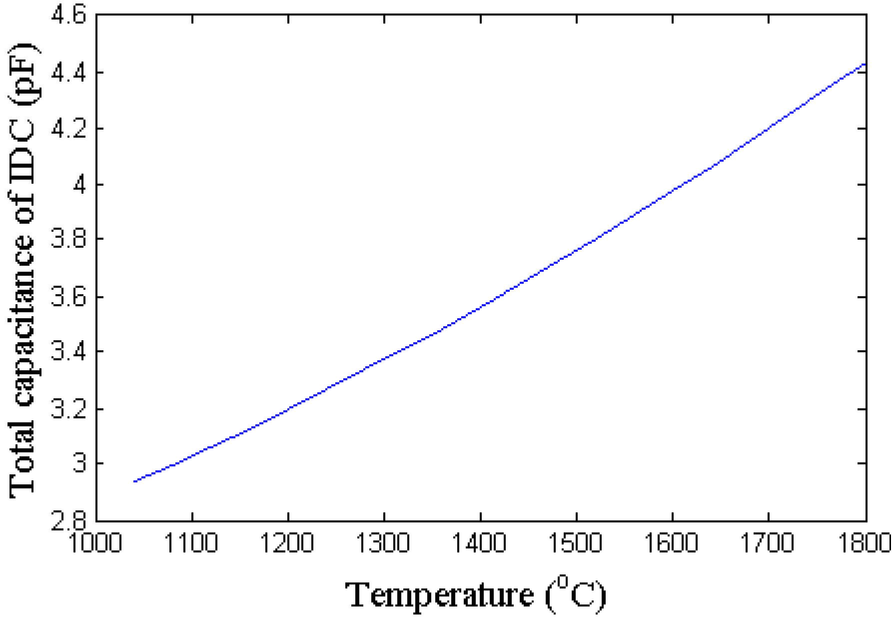
Resistive circuit sensor

Thermistor or thermocouple

Strain gauge

Interdigital capacitor

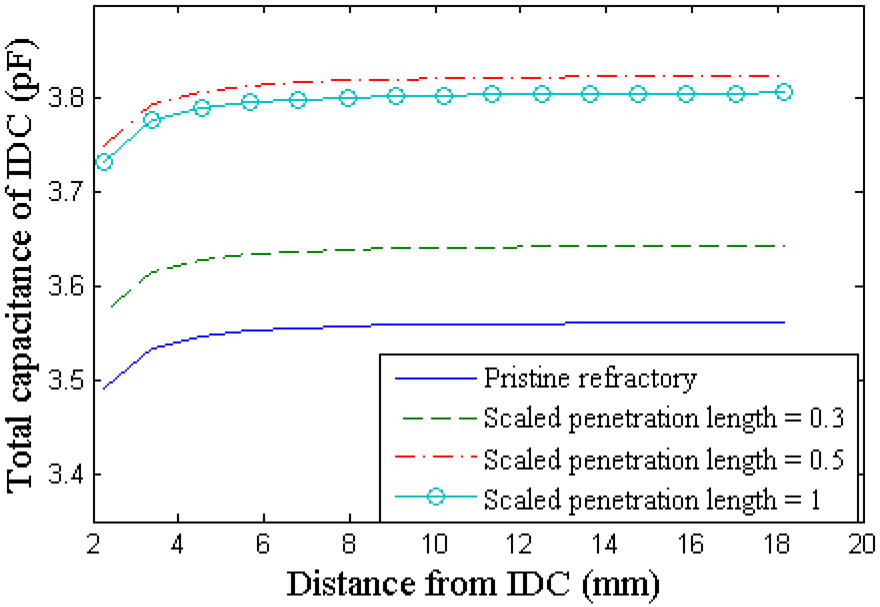
Interdigital Capacitor (IDC) Sensor Model:



Sensitivity to the hot face temperature

Sensitivity to slag penetration

- ➢ Composite property model
- ➢ Slag can only fill the pores



* Igreja R, Dias C J. Analytical evaluation of the interdigital electrodes capacitance for a multi-layered structure[J]. Sensors and Actuators A: Physical, 2004, 112(2): 291-301.

Estimation:

Methods:

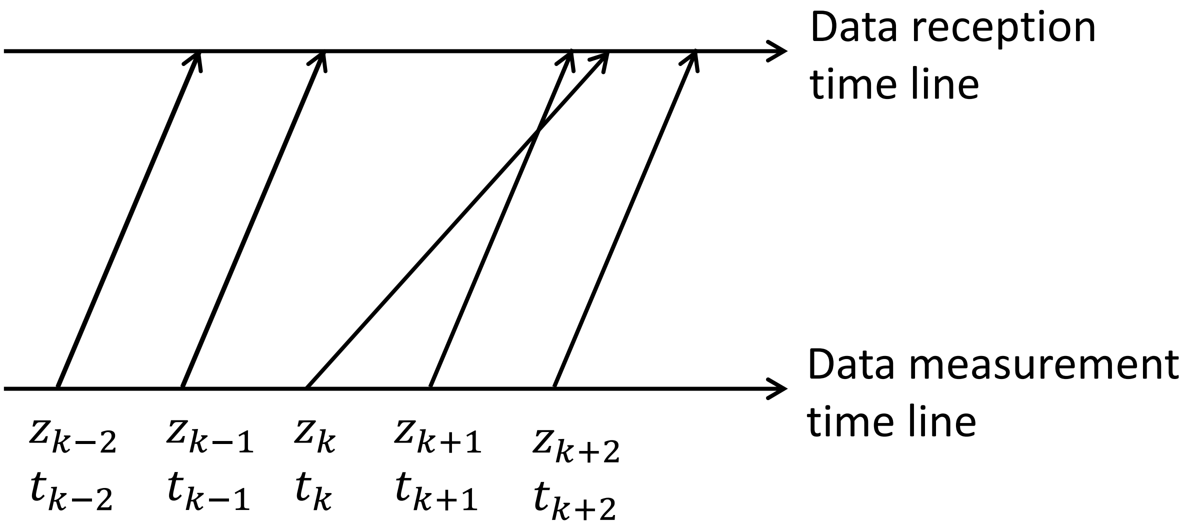
- Traditional Kalman Filter (TKF)
- Extended Kalman Filter (EKF)
- Unscented Kalman Filter (UKF)

Difficulties:

- Differential Algebraic Equations System
- Out-of-sequence measurements due to the wireless sensor network
- Multi-rate estimation
  - slag penetration: slow process
  - temperature: relatively fast process

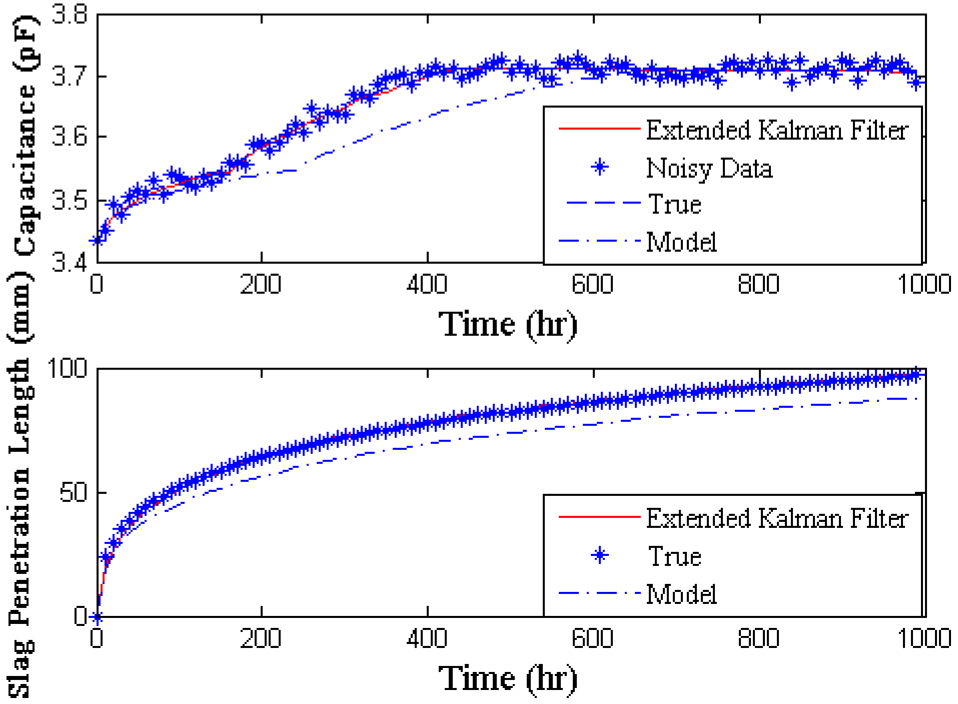
Wireless Sensor Network:

Out-of-sequence measurements (OOSM):



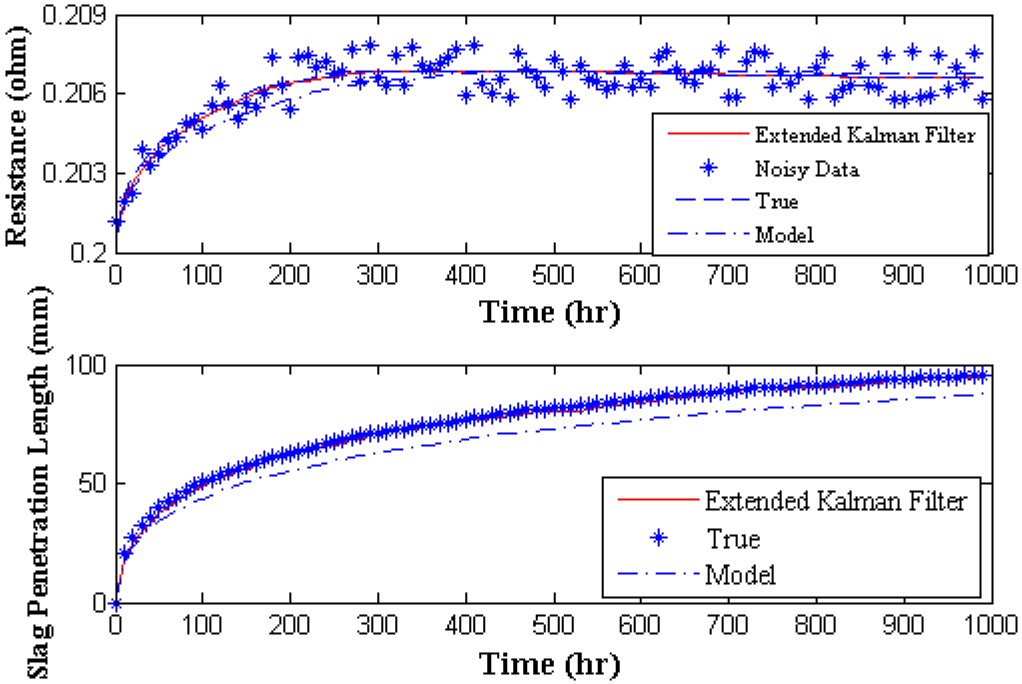
- A random time delay due to communication delay
- Goal: Update the current states by using the measurements that arrive late

Estimations of the Extent of Slag Penetration Using IDCs:

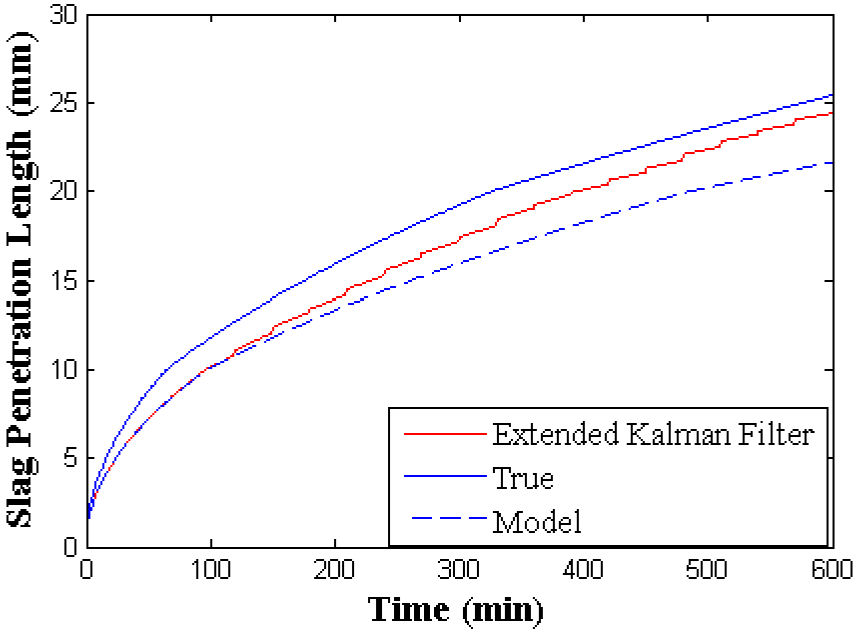


- Constant hot face temperature
- Complex effect of slag penetration on:
  1. Temperature profile
  2. Dielectric constant

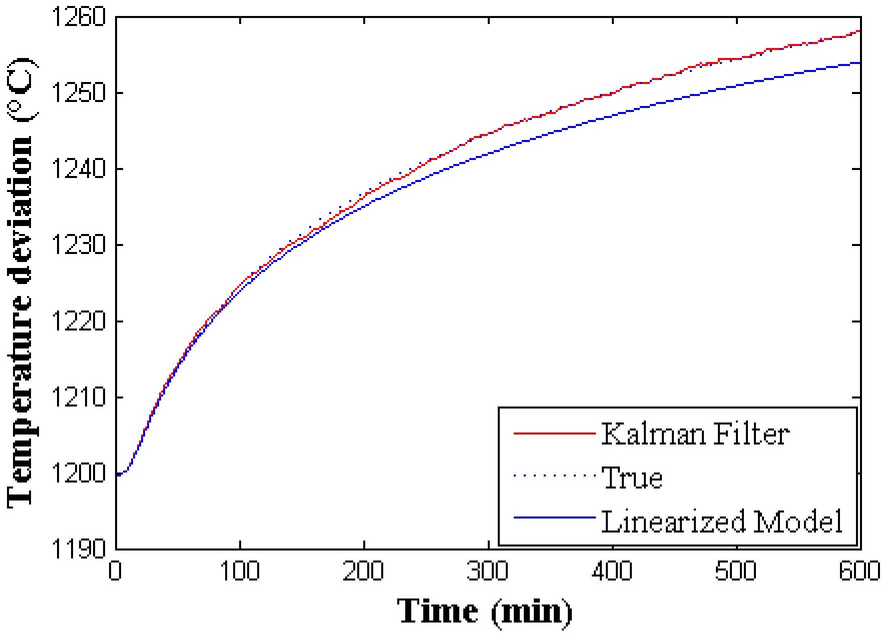
Estimations of Extent of Slag Penetration Using Thermistors:



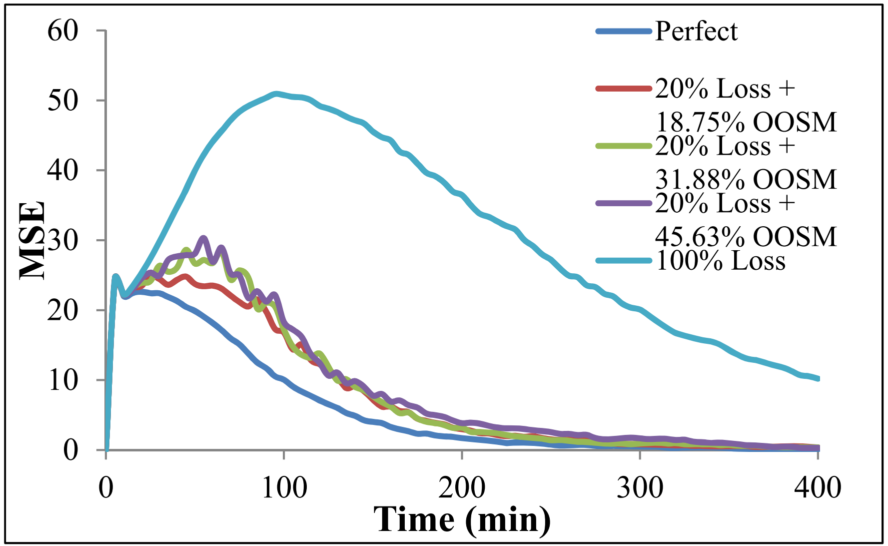
Estimation of Multi-Rate KF:

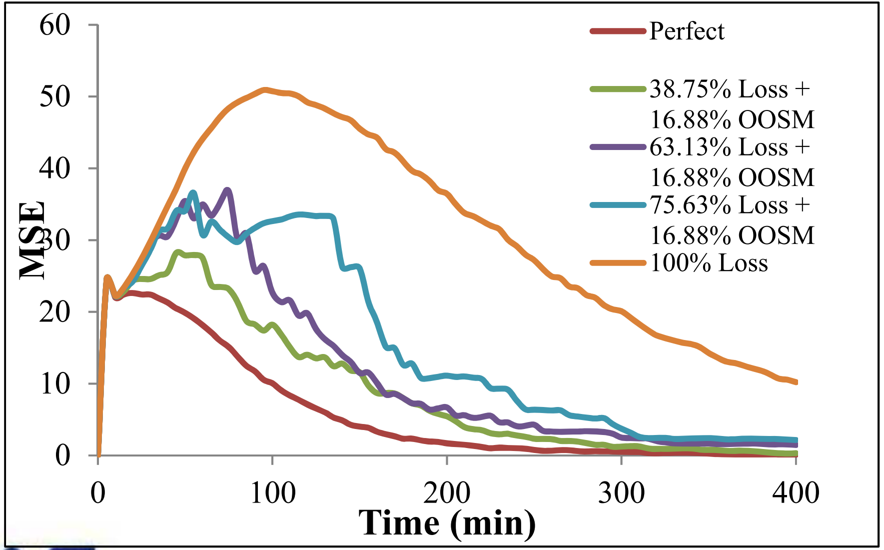


- Both thermistors and IDCs are used
- Both temperature and slag penetration length are estimated



Estimations of Temperature with OOSM:



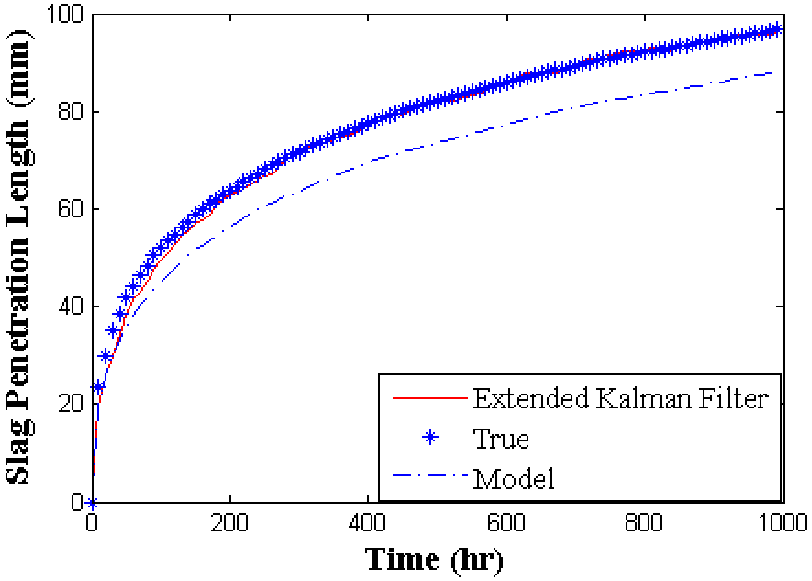


- The OOSM algorithm can successfully make use of the measurements that are received out-of-sequence.

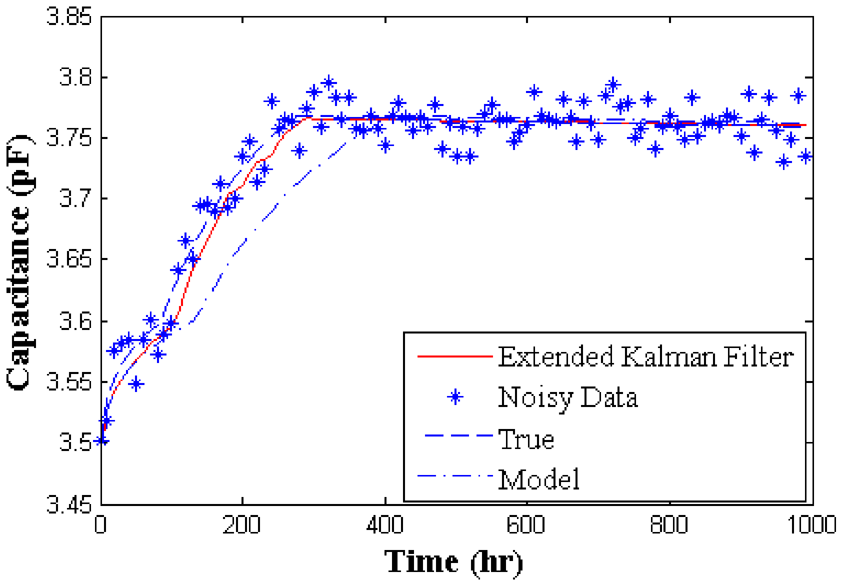
$$MSE = \frac{1}{N}\left(\sum_{i=1}^{N}(\hat{x}_i - x_i)^2\right)$$

- Effect of a lossy measurement network evaluated- estimation accuracy decreases as the data loss rate increases

Estimations of Slag Penetration with OOSM:



- 6 IDCs are embedded on the centerline (# of sensors is decided by the sensitivity study)
- EKF
- One-lag delay measurements



Task 6 Conclusions and Future Work:

- An algorithmic framework that can use the measurements from the smart refractory bricks through a wireless network to estimate the temperature profile and slag penetration depth in a gasifier has been developed.

- Further validation and testing of developed models and algorithms using experimental data are in progress

Acknowledgements:

- We would like to thank **U.S. Department of Energy (DOE)** for sanctioning this project **DE-FE0012383**.
- Dr. Maria Reidpath, U. S. Department of Energy, is greatly appreciated for her insight and valuable guidance.
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- Thanks are also due for Ms. Raughley Margaret and Mr. Joshua Sayre, HarbisonWalker International for the technical support.
- Kindly acknowledge Faculty and staff of West Virginia University for their support.