Development of Low-Power Wireless Sensor Network of Conductivity Probes for Detection of Corrosive Fluids Inside Pressure Vessels and Piping

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Project Objectives

1. Develop the electronic components necessary to power and connect an array of conductivity sensors via a low-power, wireless sensor network (WSN).

2. Design, prototype and test conductivity probes compatible with standard access fittings and integrated into corrosion coupon holders.

3. Engage a significant number of students in the development of technology that is relevant to the pipeline industry and introduce them to the roles and responsibilities of producers and regulators (e.g. PHMSA) in the oil and gas sector.

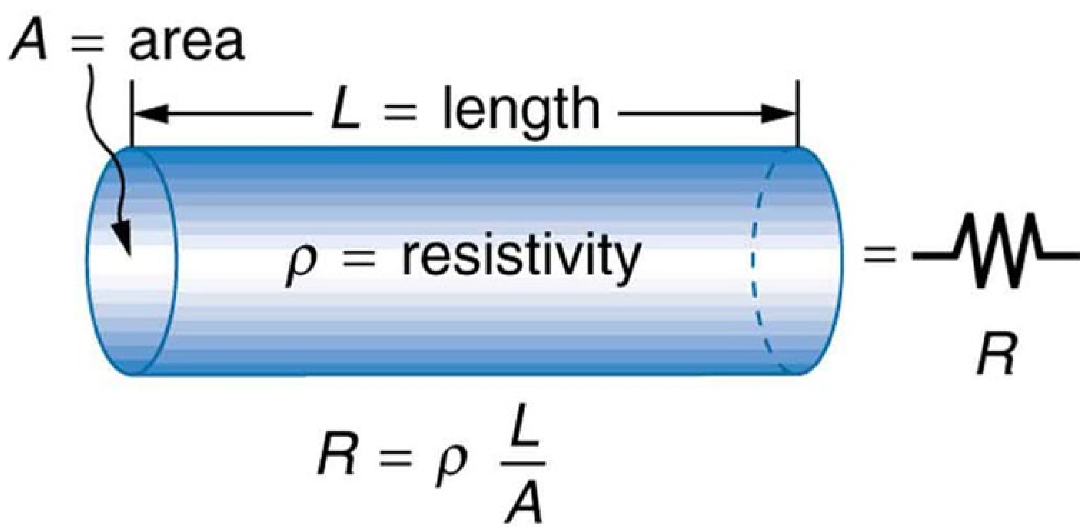
Background

I. Electrical Conductivity

$$V = IR$$

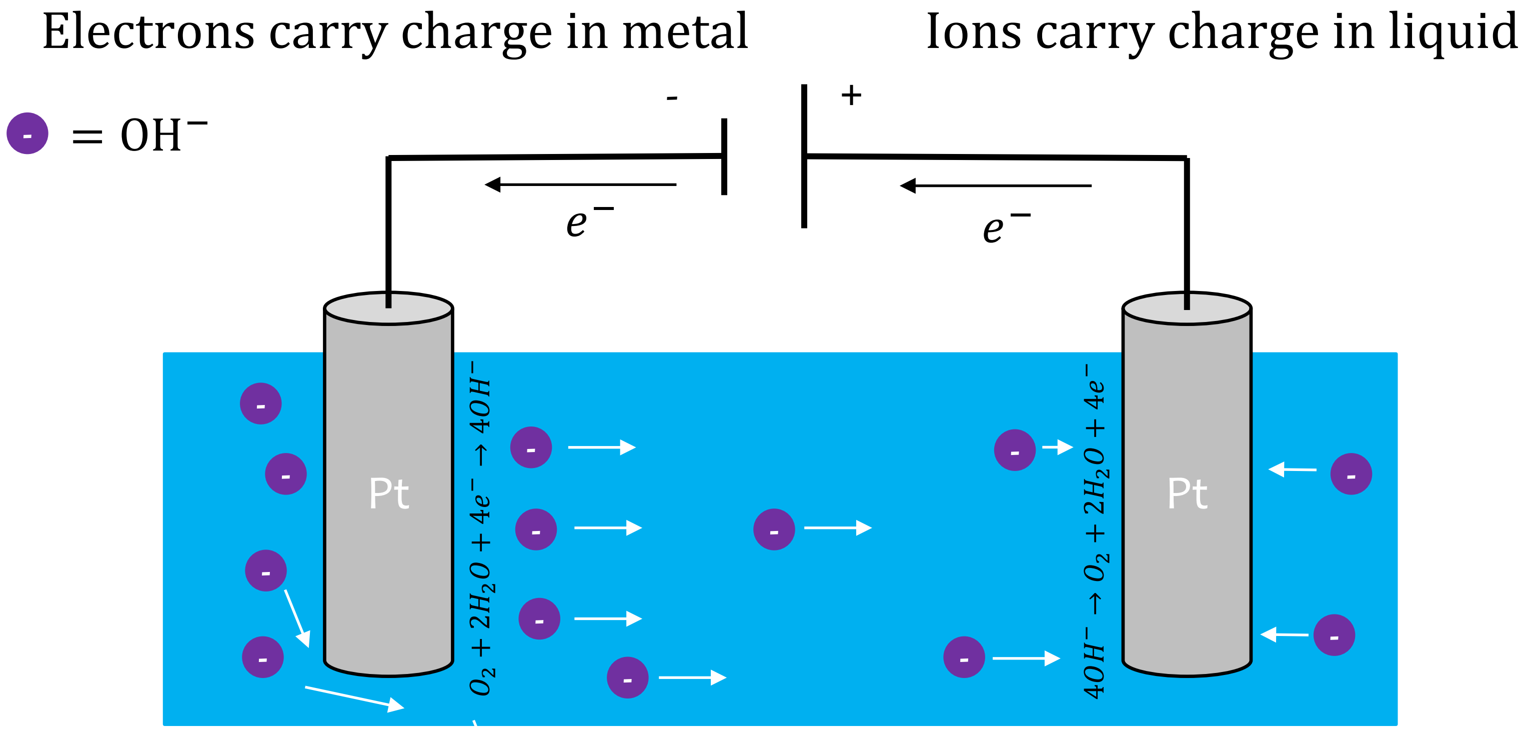
$$\rho = R\frac{A}{l}$$

$$\sigma = conductivity = \frac{1}{\rho}$$



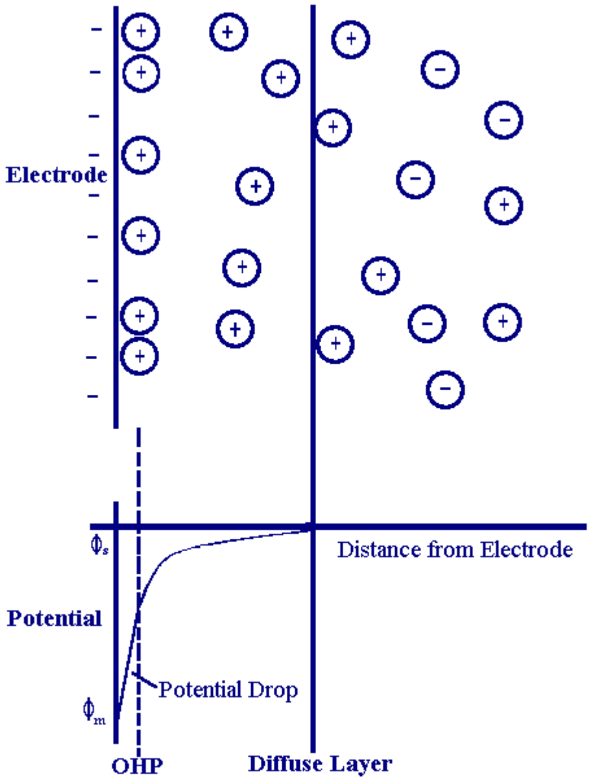
Background

II. Electrical conductivity of fluids (electrolyte)



Background

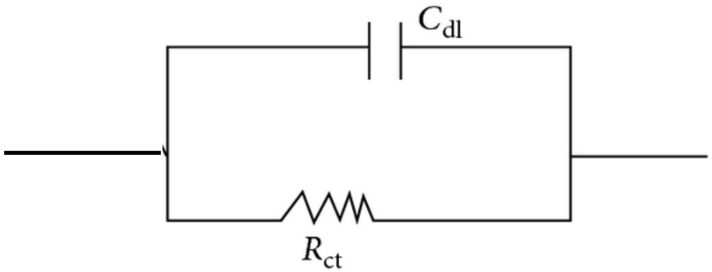
III. Double layer, polarization, equilibrium potential

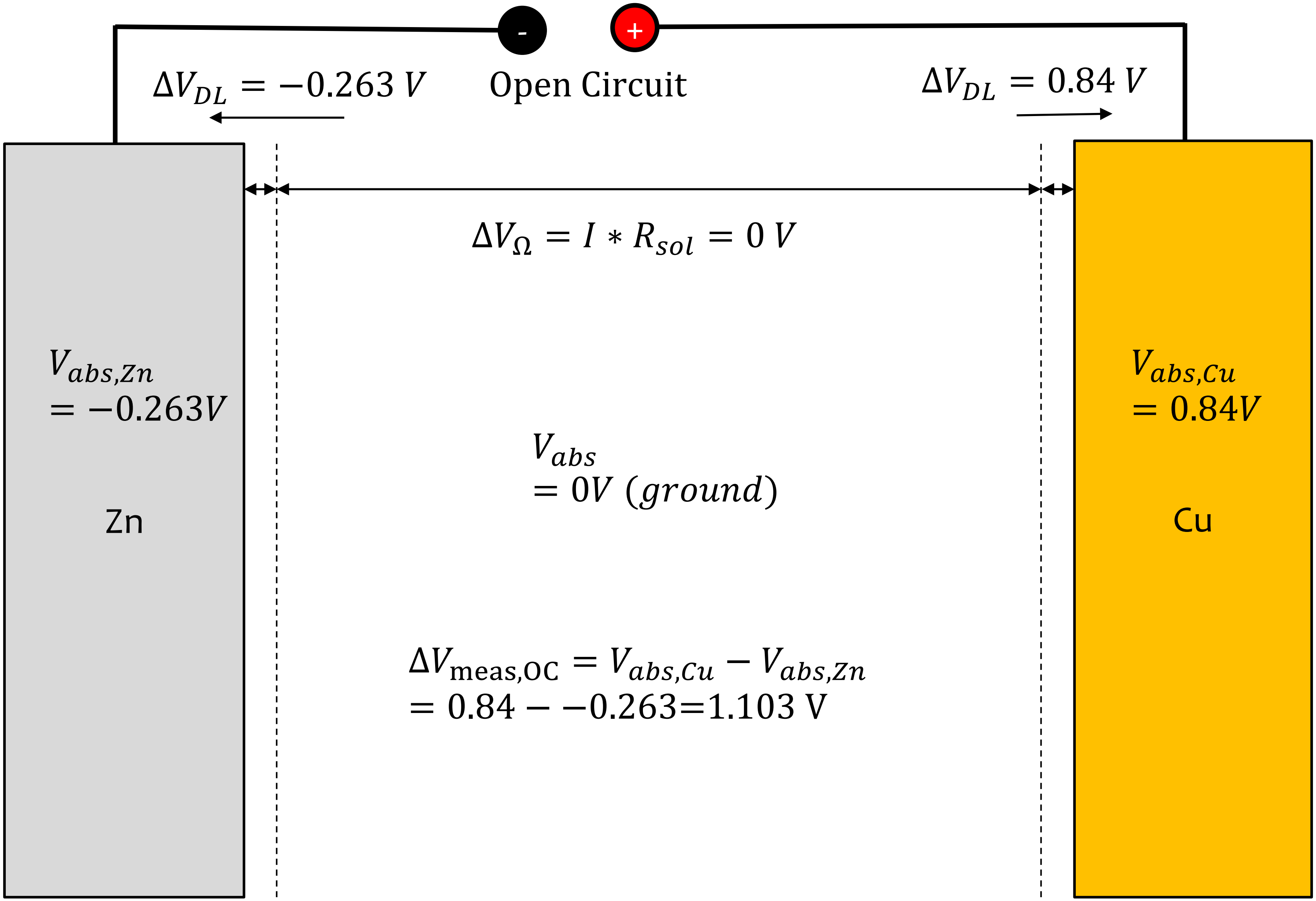


Double layer will exist at any conductor/electrolyte interface

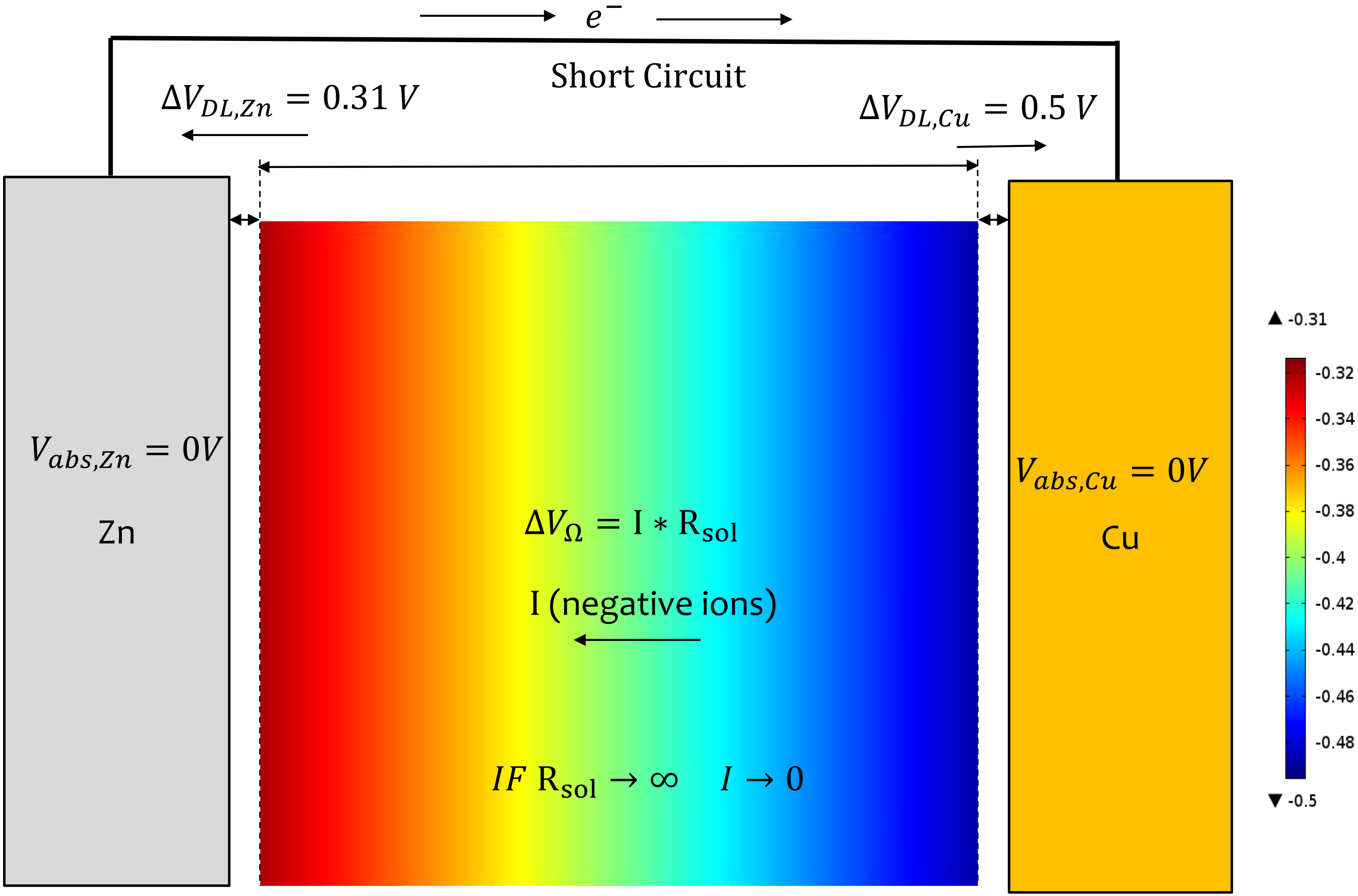
Double layer is very small (on the order of nanometers)

Behavior can be effectively modeled with a capacitor/resistor:





-
+
$\Delta V_{DL} = -0.263\ V$
Open Circuit
$\Delta V_{DL} = 0.84\ V$
$\Delta V_{\Omega} = I * R_{sol} = 0\ V$
$V_{abs,Zn} = -0.263V$
Zn
$V_{abs} = 0V\ (ground)$
$V_{abs,Cu} = 0.84V$
Cu
$\Delta V_{\text{meas,OC}} = V_{abs,Cu} - V_{abs,Zn} = 0.84 - -0.263 = 1.103\ \text{V}$



e^-
Short Circuit
$\Delta V_{DL,Zn} = 0.31\ V$
$\Delta V_{DL,Cu} = 0.5\ V$
$V_{abs,Zn} = 0V$
Zn
$V_{abs,Cu} = 0V$
Cu
$\Delta V_{\Omega} = \mathrm{I} * \mathrm{R}_{\mathrm{sol}}$
I (negative ions)
$IF\ \mathrm{R}_{\mathrm{sol}} \to \infty \quad I \to 0$
▲ -0.31
-0.32
-0.34
-0.36
-0.38
-0.4
-0.42
-0.44
-0.46
-0.48
▼ -0.5

Background

Key takeaways:

- Corrosion reactions are electrochemical and require electrical current to flow between two sites.
- No current flow = no corrosion,   No electrolyte = no current flow = no corrosion
- The ability to detect the presence of an electrolyte can give a warning for corrosion
- Potential (voltage) gradient over the double-layer is not instantaneous, but may approach a steady state value over time.
- Potential (voltage) gradient due to resistance (AKA Ohmic) is instantaneous.
- When we study corrosion we are primarily interested in the double-layer potential gradient.
- When we make conductivity/resistivity measurements we are interested only in the Ohmic potential gradient.

Background

IV. Conductivity / Resistivity Measurements

Steady State:

- Wenner (4-pin)
- Dissimilar metal comparison (galvanic cell)

Transient:

- Current Interrupt (Instant Off)
- AC (alternating current), Electrochemical Impedance Spectroscopy (EIS)

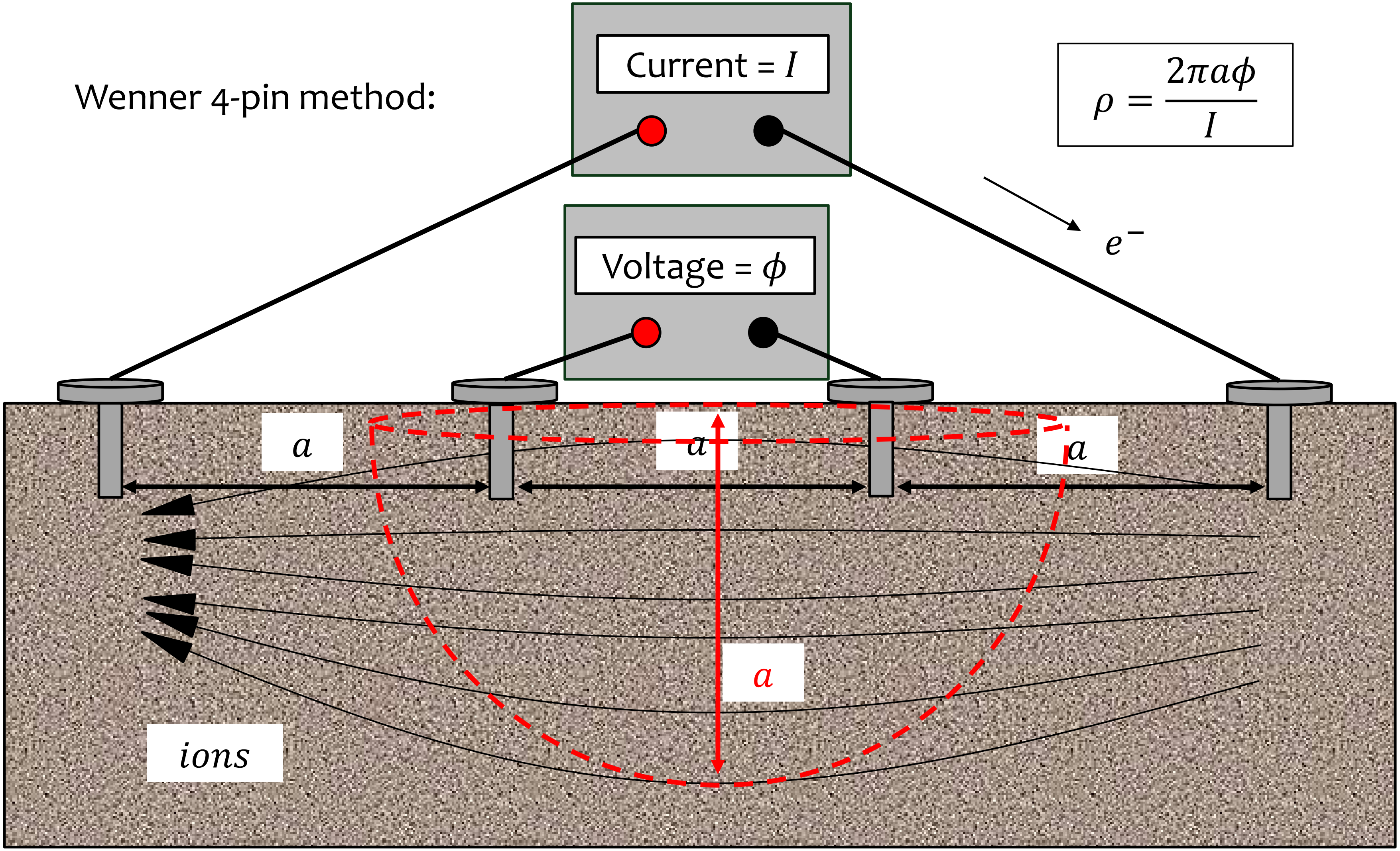
Results:

- Quantitative (e.g. 10 $\mu S/cm$) .... 1 Siemen (S) = 1 Ω^{-1}
- Semi-Quantitative (e.g. low, medium, high)
- Binary (e.g. conductive or not conductive)

Measuring electrolyte resistivity:

Wenner 4-pin method:

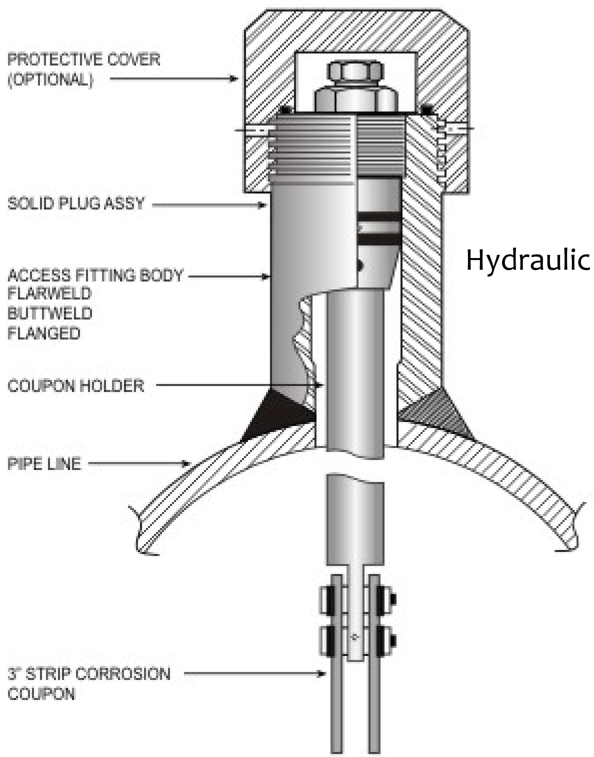
$$\rho = \frac{2\pi a \phi}{I}$$



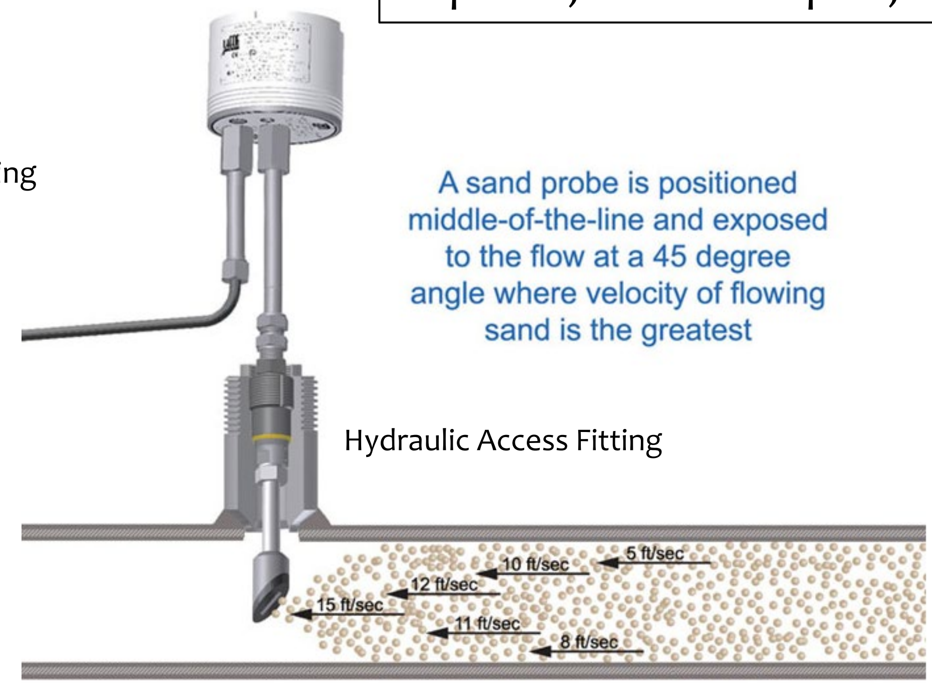
Background

V. How do we access the inside of an operational pipeline?

Manufacturers: Cosasco, Caproco, Metal Samples,…



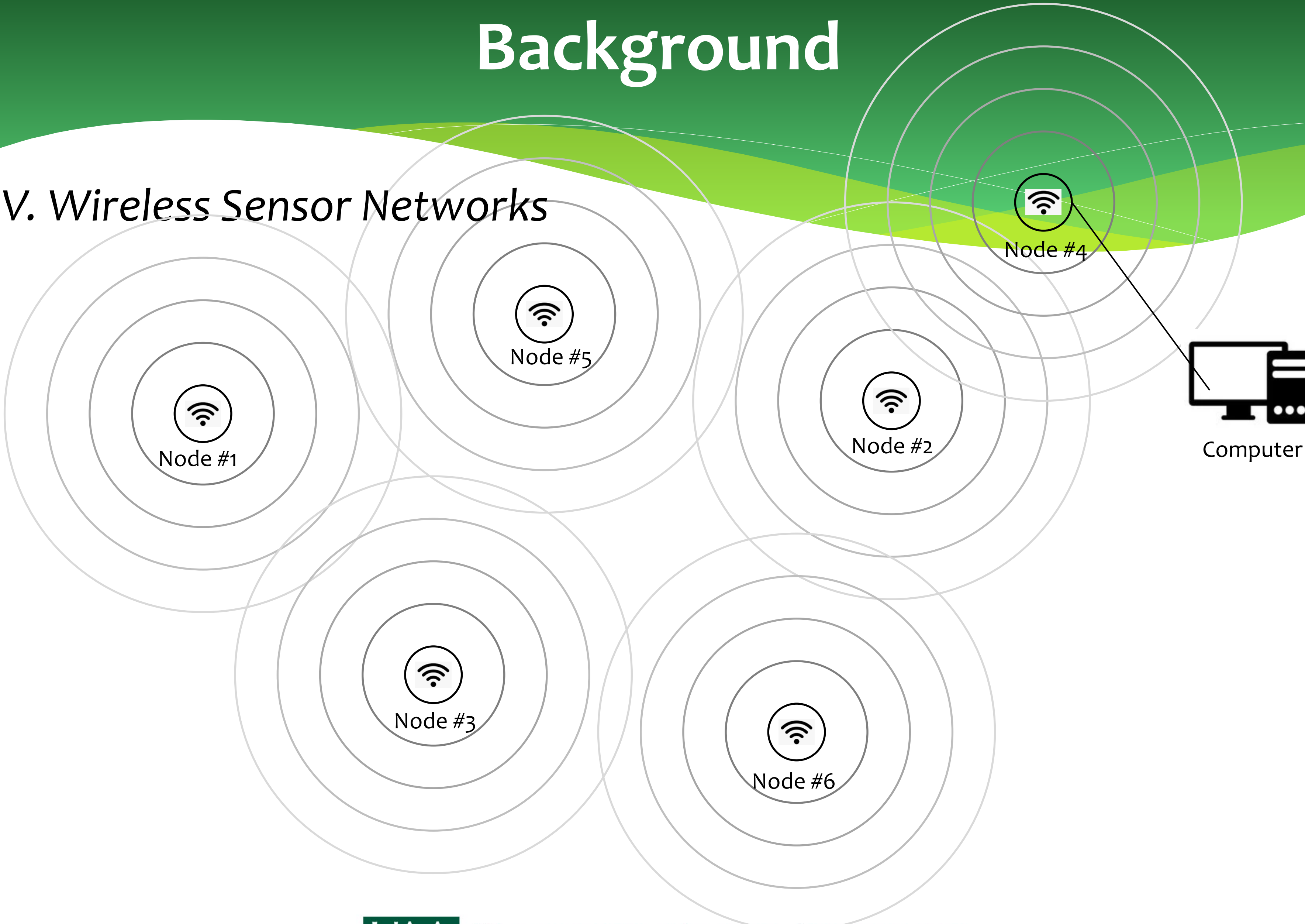
Hydraulic Access Fitting



Hydraulic Access Fitting

Background

V. Wireless Sensor Networks



Background

V. Wireless Sensor Networks

Pros:
- Each node can be independently powered by energy harvesting devise
- Lack of wired power/coms
- Resilient network if arranged in a mesh (multiple communication pathways)
- Relatively low cost

Cons:
- Limited computational power and precision of nodal microprocessor
- Relatively low temporal resolution
- Potentially slow data propagation rates
- May require (expensive) certification to operate in potentially explosive atmosphere (e.g. ATEX, IECEx, NFPA 70, CSA C22.1, etc.)

Project Team

Dr. Matthew Cullin, UAA, ME (PI)

Dr. Raghu Srinivasan, UAA, ME (co-PI)

Dr. Todd Petersen, UAA, EE (co-PI)

Dr. John Lund, Western Washington University, EE (co-I)

1 Graduate student (M.S.)

12 Undergraduate ME and EE students

Industry Working Group (BPAK, Hilcorp, LLC / Harvest AK, LLC)

Summary

I. Probe analysis and design

A. Conductivity sensing element (electrodes)

B. Access-fitting-compatible probe body

C. Test vessel

II. Conductivity measurement technique development

III. Energy harvesting element design and analysis

IV. Wireless Sensor Network (WSN) integration and testing

I-A: Analysis/design of conductivity sensing element

Design Requirements

Support 2- and 4- electrode measurement techniques

1000 psig operating pressure

$200°F$ operating temperature

Ability to be integrated into corrosion coupon holders (hydraulic access fitting)

Support low-power operations

Resist or support detection of electrode fouling

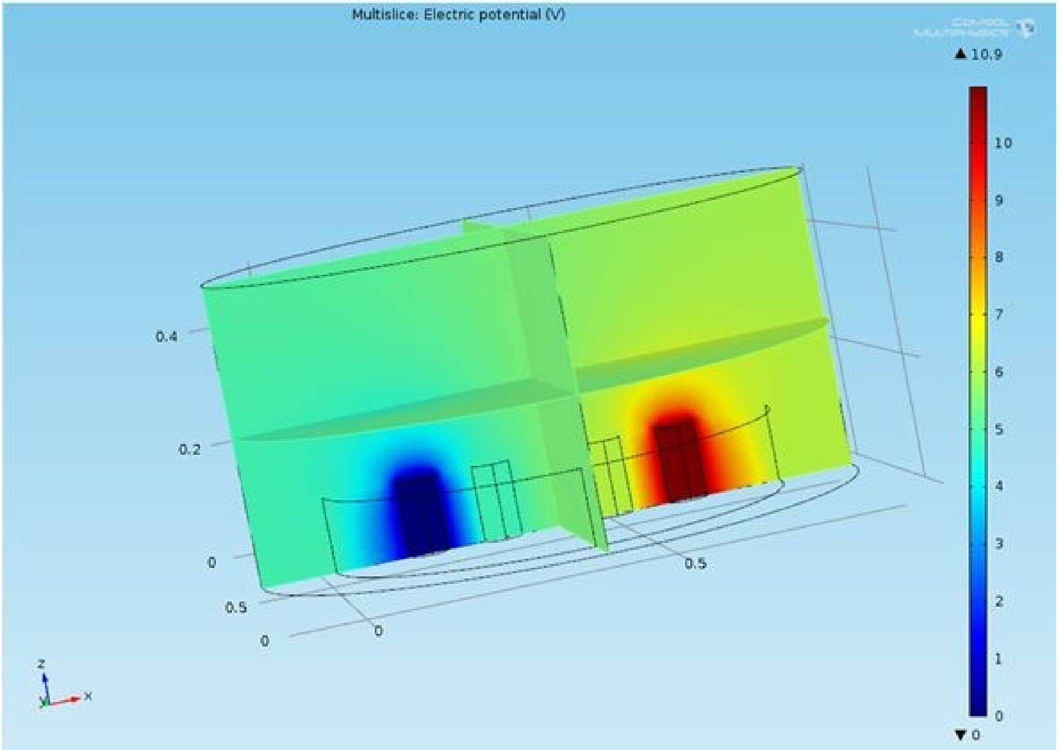
I-A: Analysis/design of conductivity sensing element

Approach

COMSOL Multiphysics modelling

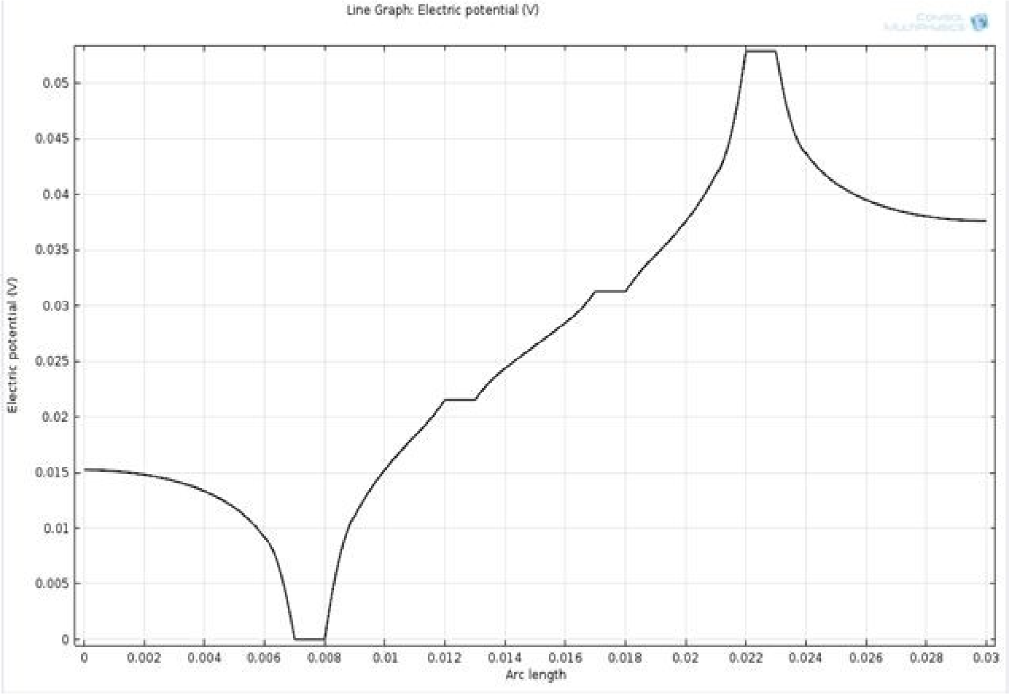
Explore electrode size, shape, and spacing options in terms of impact on:

- Probe sensitivity
- Pipeline operations (e.g. pigging, coupon holder integration)
- Power consumption
- Electrode fouling



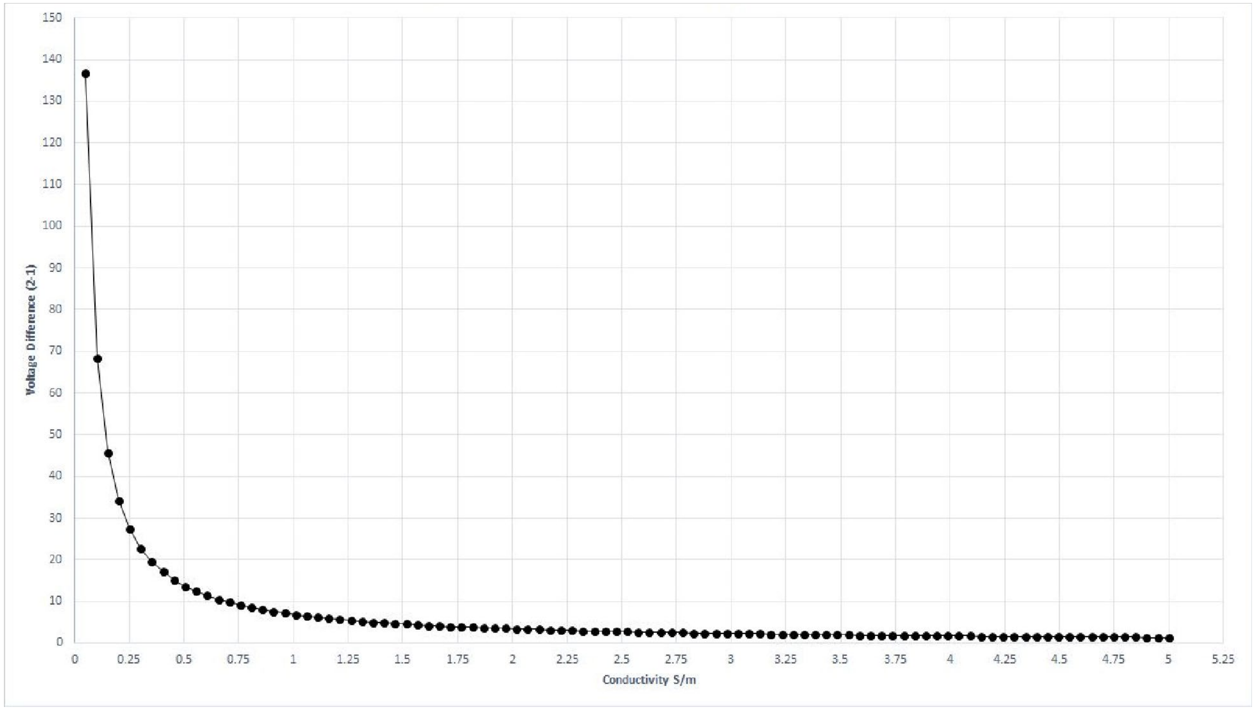
I-A: Analysis/design of conductivity sensing element

Results
Potential distribution across linear configuration flush electrodes



I-A: Analysis/design of conductivity sensing element

Results
Sensitivity analysis
100 mA



I-A: Analysis/design of conductivity sensing element

Design

3 mm diameters electrodes

linear configuration

5 mm center-to-center spacing

Electrode material: nickel alloy (e.g. C-276)

Electrode seals: glass

I-B: Analysis/design of probe body

Design Requirements

Ability to integrate corrosion coupon holder

1000 psig operating pressure

$200°F$ operating temperature

Corrosion resistant alloy

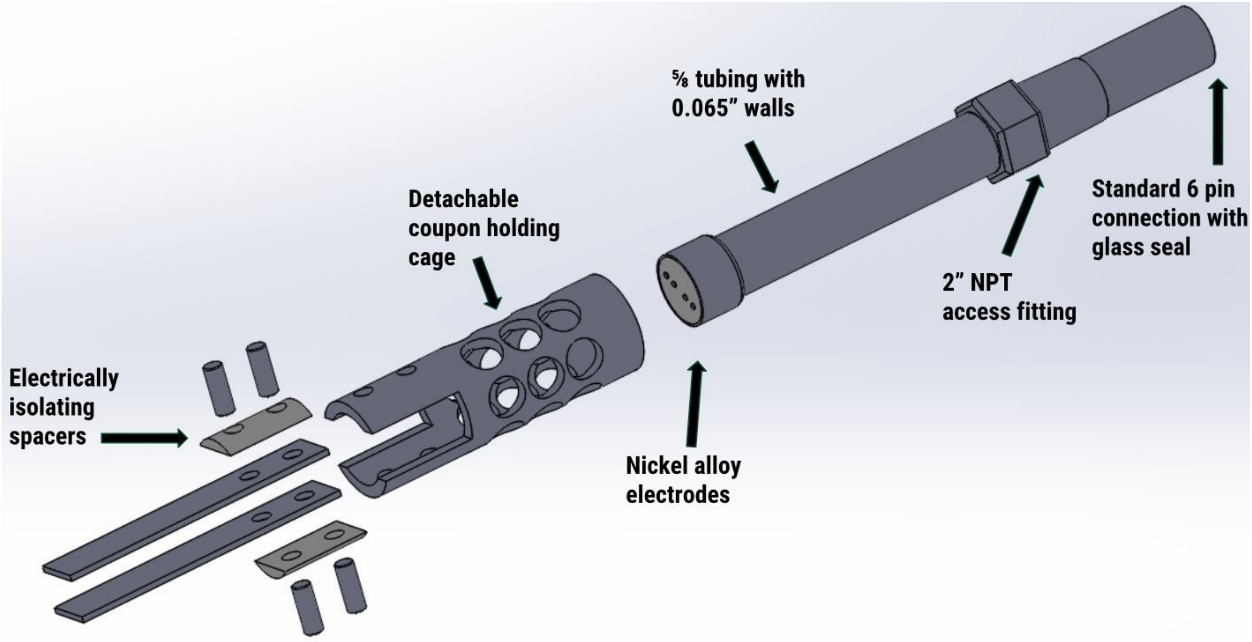
Installation in 2-inch hydraulic access fitting

Resist drag forces for 100% oil @ 15 ft/s

I-B: Analysis/design of probe body

Design

Detachable (optional) corrosion coupon holder



I-B: Analysis/design of probe body

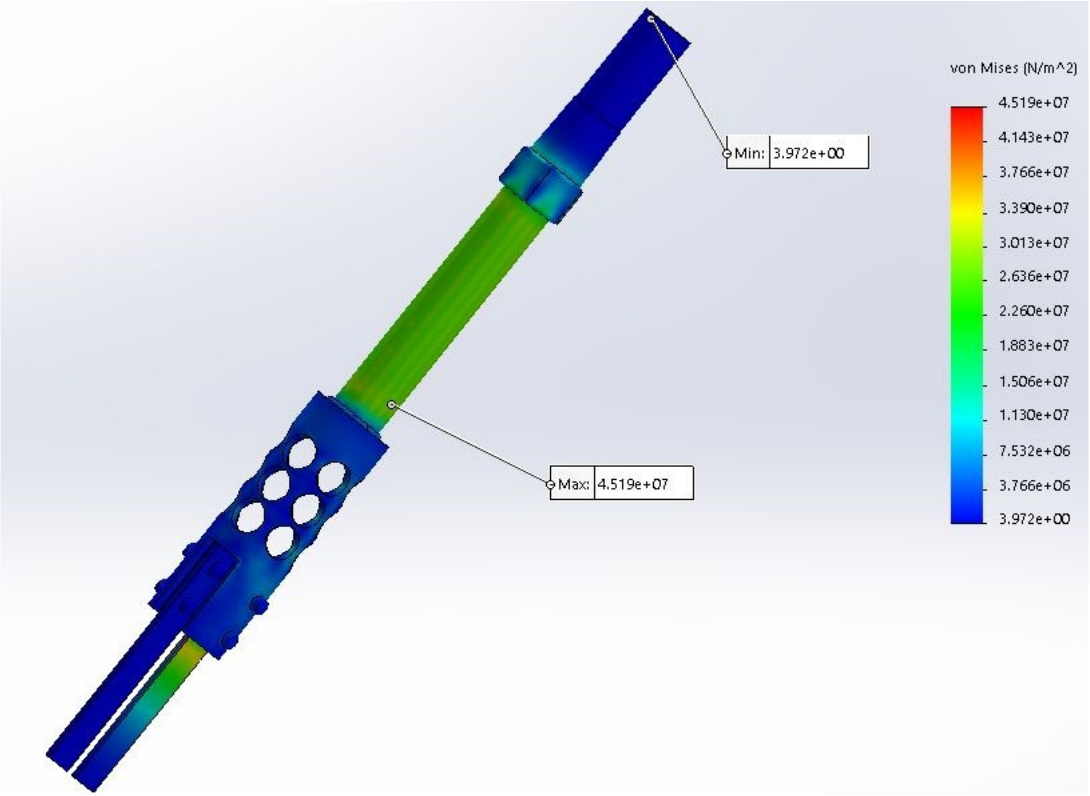
Design

FEA stress analysis

316L body

Coupons perpendicular to flow

FOS = 3.8



I-B: Analysis/design of probe body

Design

316L body material

Primary glass seals (electrodes) and secondary glass seals (wire bulkhead)

Rohrback Cosasco Inc. confirmed the ability to manufacture and incorporate into their adjustable positioning

Cost: $2000 (prototype), $700 for each additional unit

Full prototype not pursued due to limitations of integrating WSN electronics in explosive atmospheres.

Functional prototype of sensing element constructed instead

I-C: Analysis/design of test vessel

Original intent: to test full prototype of probe

Modified intent: pressure vessel design exercise for ME undergraduate students

Design Requirements

1000 psig operating pressure

$200°F$ operating temperature

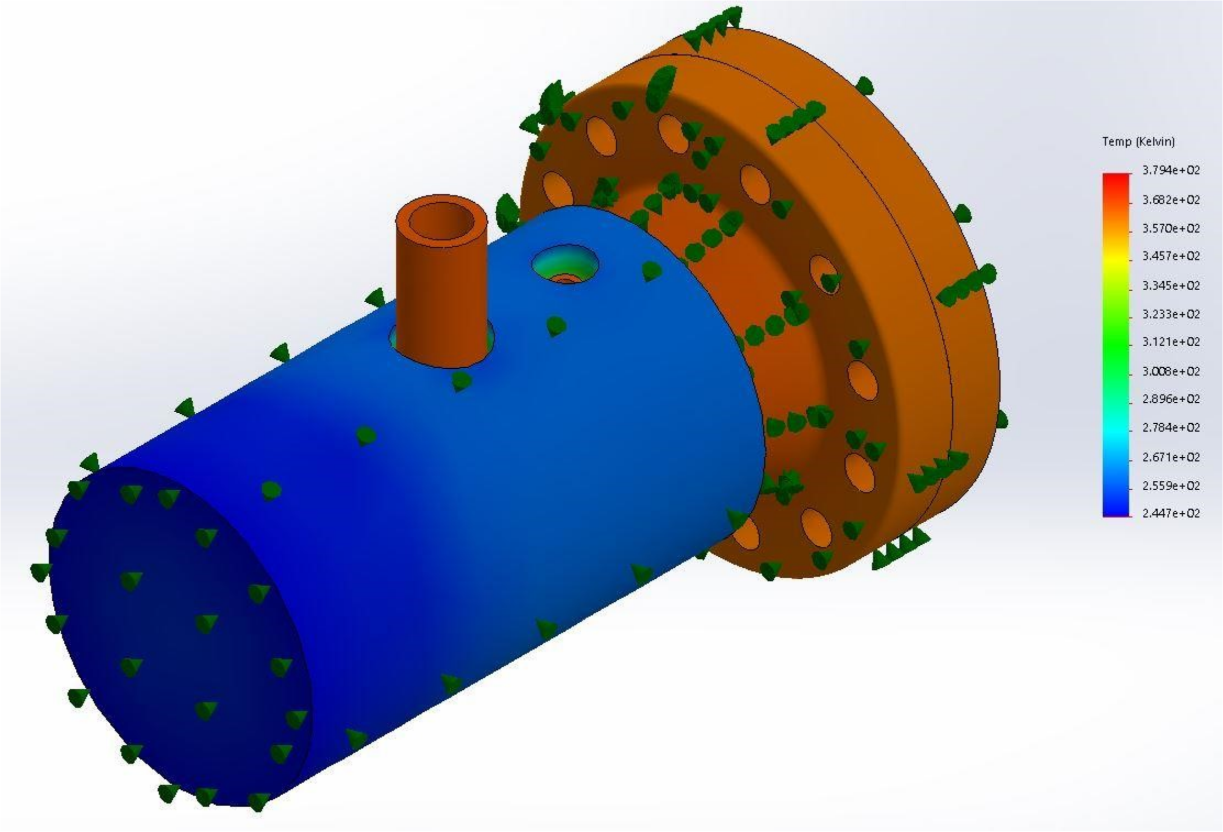
2-inch hydraulic access fitting

Working fluid: water

I-C: Analysis/design of test vessel

Design

Thermal analysis (FEA)

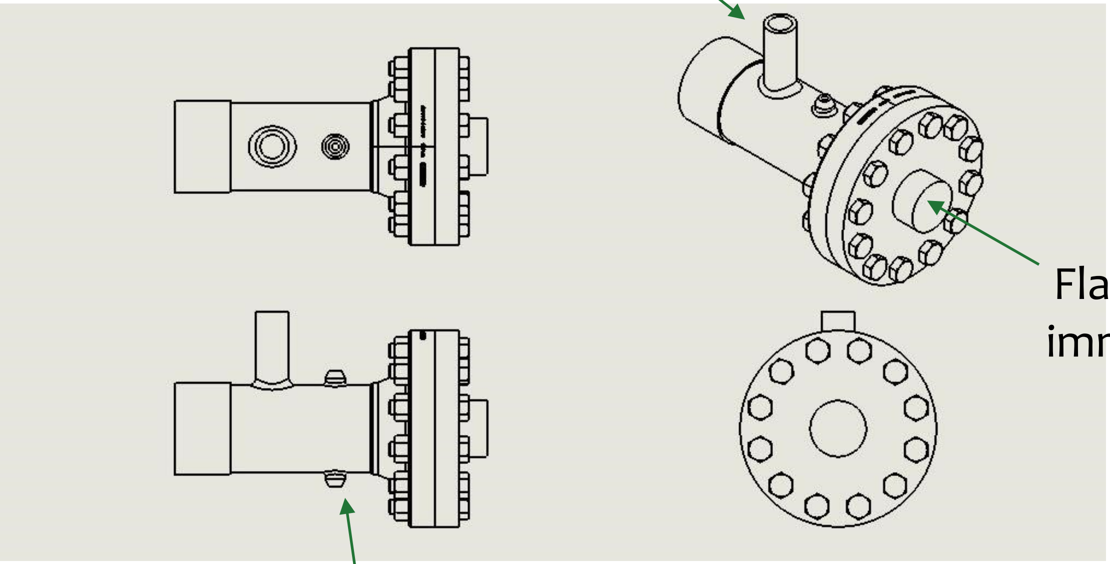


I-C: Analysis/design of test vessel

Design

Final design (insulation not shown)

2-inch access fitting



Flange-mounted immersion heater

½-inch threadolet fittings (2x)

I-C: Analysis/design of test vessel

Design Summary

Design-by-rule based (ASME B31.4)

API 5L Grade A

NPS 6 Sch. 40 pipe body and end cap

Standard access fitting and threadolets

Class 600 flange

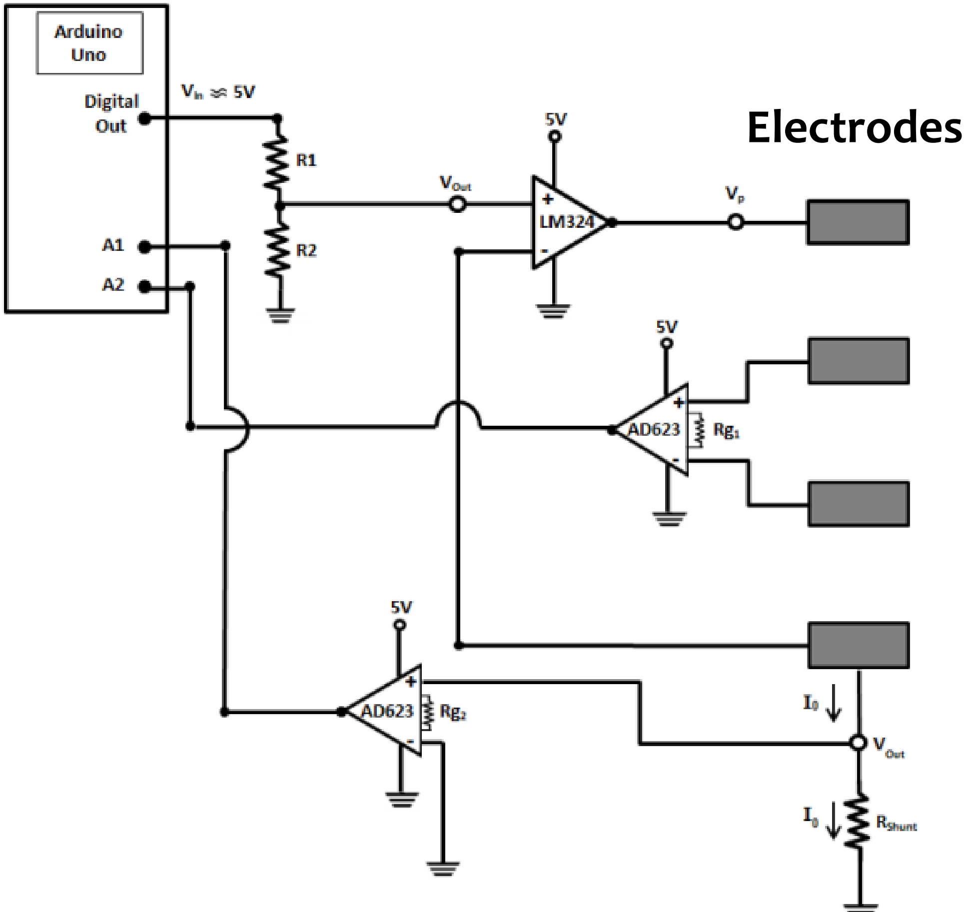
750W (120 VAC) heater, 1.25-inch NPTM connection

Designed under the supervision of piping engineer from BPXA

II: Conductivity measurement technique development

4-electrode circuit diagram

- When digital out is high, voltage divider (R1, R2) determines the magnitude of a constant current source acting between the outer electrodes via LM324 buffer op amp.
- One differential instrumentation op amp (AD623) reads the voltage between the inner electrodes
- A second differential instrumentation op amp (AD623) reads the voltage over a shunt resistor, to verify the current.



II: Conductivity measurement technique development

Method #1: Wenner (steady state)

- Apply fixed current between outer electrodes
- Monitor voltage across inner electrodes and wait for it to settle (steady state)
  OR
  Perform calibration experiments and choose a fixed time delay for a single reading
- Read instantaneous current (shunt resistor) immediately after potential reading
- Use value of steady state current and inner electrode potential to back calculate resistance.
- Use probe factor (calibration) to determine resistivity/conductivity of fluid.

II: Conductivity measurement technique development

Method #1: Wenner (steady state)

Pros

- Programmatically simple to implement
- Larger sample sets can be taken at steady state to reduce the effects of noise
- Provides quantitative conductivity data

Cons

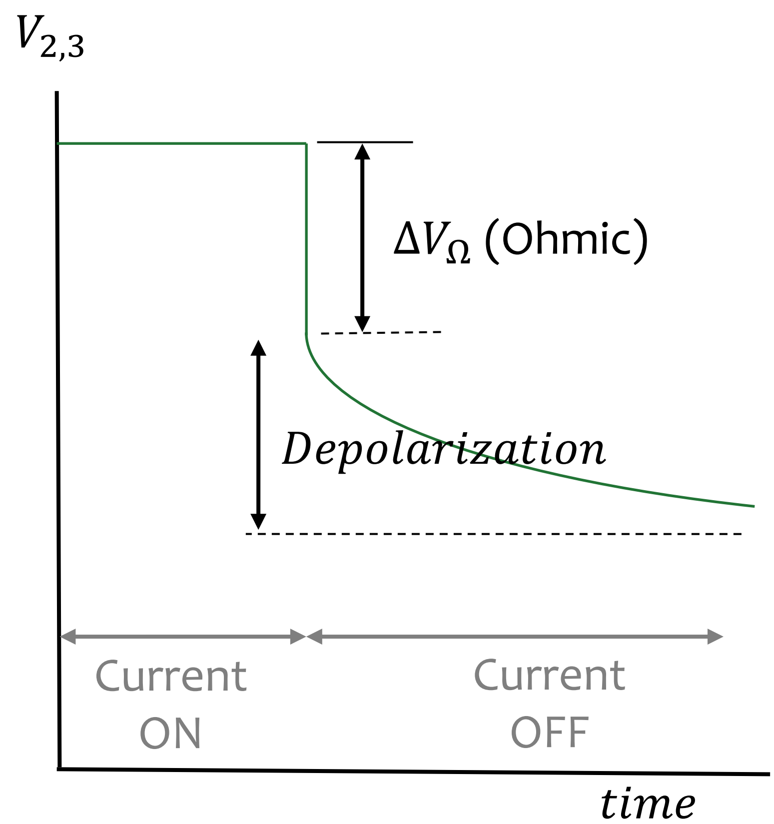
- Relatively large amount of energy required per measurement
- Can produce significant ionic concentration gradients over time in stagnant solutions (drift)

II: Conductivity measurement technique development

Method #2: Current interrupt (instant off)

Use Wenner method, but with the following modifications:

- Interrupt current by driving the digital out to low/zero (add a pull down resistor)
  OR
  Using a transistor to switch current source off
- Quickly record inner electrode potential after interrupt to determine the instant change (step).
- Use value of current just before interrupt and instant potential step magnitude (Ohmic) to back out an effective resistance.



II: Conductivity measurement technique development

Method #2: Current interrupt (instant off)

Pros

- Provides quantitative conductivity data
- Greater accuracy and repeatability than single point Wenner measurement

Cons

- Potentially time / energy intensive waiting for voltage to settle
- Programmatically more difficult to implement
- Relatively sensitive to noise and microcontroller timing delays

Method #3: AC Impedance

- Apply a high-frequency (100-500kHz), low amplitude (5mV) AC potential waveform between 2 electrodes.
- Measure the amplitude of the resulting current signal (shunt)
- Calculate the impedance (resistance)
- Can use third electrode as pseudoreference to improve accuracy or multiplex to test for electrode fouling

II: Conductivity measurement technique development

Method #3: AC Impedance

Pros

- Provides quantitative conductivity data
- Fast measurement, requires minimal energy**
- Do not need to separate Ohmic and polarization components

Cons

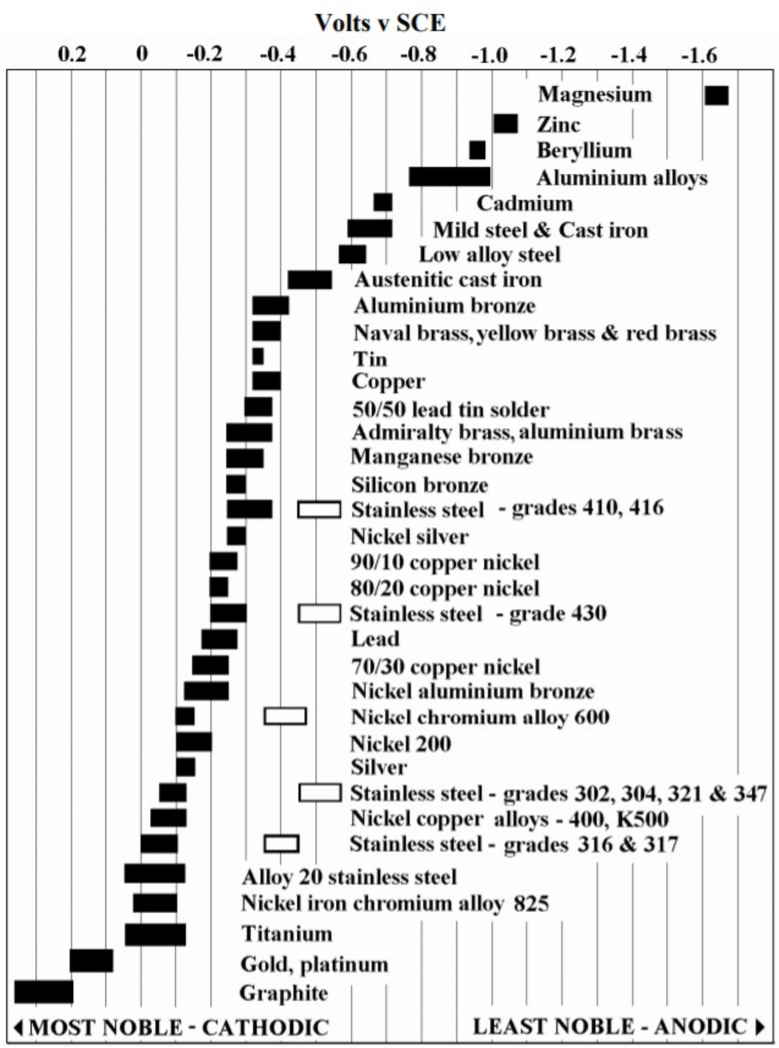
- Additional electronic components required
- Sensitive to noise (for low-amplitude signal)

**additional electronics may significantly increase power

II: Conductivity measurement technique development

Method #4: Dissimilar metal comparison

- Build sensing element with dissimilar metals having a significant difference in corrosion potentials (e.g. nickel and aluminum)
- Measure the potential between the electrodes.
- If liquid is non-conductive, voltage will float, or, be zero if a large pull-down resistor is wired in parallel.
- If liquid is conductive, a positive voltage will develop
- 4 electrode probe can be multiplexed (E1 to E3, E2 to E3, E1 to E4, E3 to E4) to detect electrode fouling.



II: Conductivity measurement technique development

Method #4: Dissimilar metal comparison

Pros

- Passive measurement. Very low energy consumption.
- Rapid measurement (ms)
- Programmatically trivial to implement

Cons

- Qualitative (threshold) or semi-quantitative with calibration
- Sensitive to noise

II: Conductivity measurement technique development

Test Results

Arduino Uno w/ fixed resistors

Actual Resistance (Ω)	Current (mA)	ΔV (mV)	Experimental Resistance (Ω)	Absolute Error (%)
47	0.105	1	9.51	79.77
100	0.105	7	66.60	33.40
180	0.105	15	142.72	20.71
330	0.105	31	294.96	10.62
680	0.105	67	637.45	6.26
1500	0.105	156	1484.30	1.05
3000	0.105	317	3016.18	0.54
4700	0.105	490	4662.23	0.80
6800	0.105	725	6898.19	1.44
7500	0.105	791	7526.17	0.35
8200	0.105	873	8306.37	1.30
10000	0.105	1059	10076.11	0.76
15000	0.079	1183	15009.00	0.06

Large errors at low resistance values due to resolution limits of A/D converter (10-bit). Very small voltage over inner electrodes.

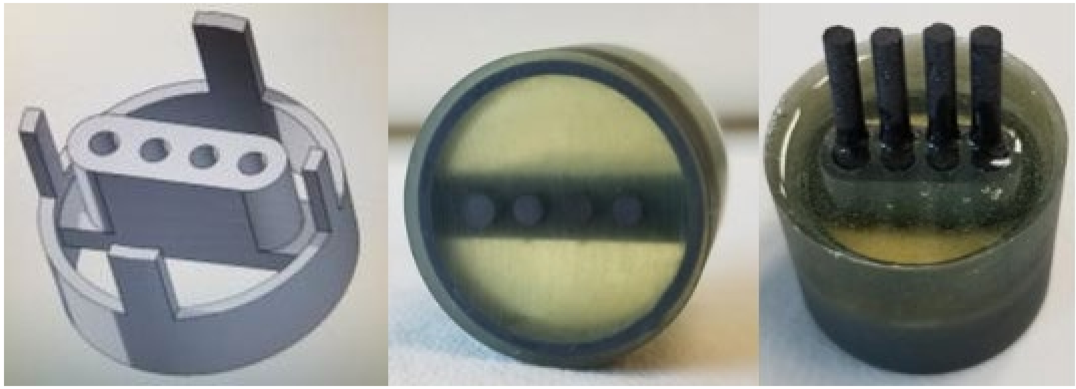
Op amp unable to supply target current at high resistance value.

II: Conductivity measurement technique development

Functional prototype of sensing element

Graphite electrodes (3 mm) @ 5 mm OC

Epoxy mount



II: Conductivity measurement technique development

Test Results

Arduino Uno stock solutions

Actual Conductivity (μS/cm)	Measured Conductivity (μS/cm)	Absolute Error (%)
186	185	0.54
686	629	8.26
1183	1151	2.70
2328	2961	27.21
5080	6296	23.93
7910	7391	6.56
10990	14813	34.79
41000	14483	64.68

Reference Conductivities:

Seawater: $50{,}000\,\frac{\mu S}{cm}$

Fresh water: $50 - 1500\,\frac{\mu S}{cm}$

Distilled water: $0.5 - 5\,\frac{\mu S}{cm}$

Gain can be set to provide better accuracy for high conductivity solutions, but requires additional noise reduction (filtering) and decreases the lower LoD.

II: Conductivity measurement technique development

Dissimilar metal probe

- Functional prototypes created using:

    1. Copper – aluminum electrodes in epoxy (500 - 600 mV)

    2. Carbon steel - nickel electrodes in epoxy (300 - 400 mV)

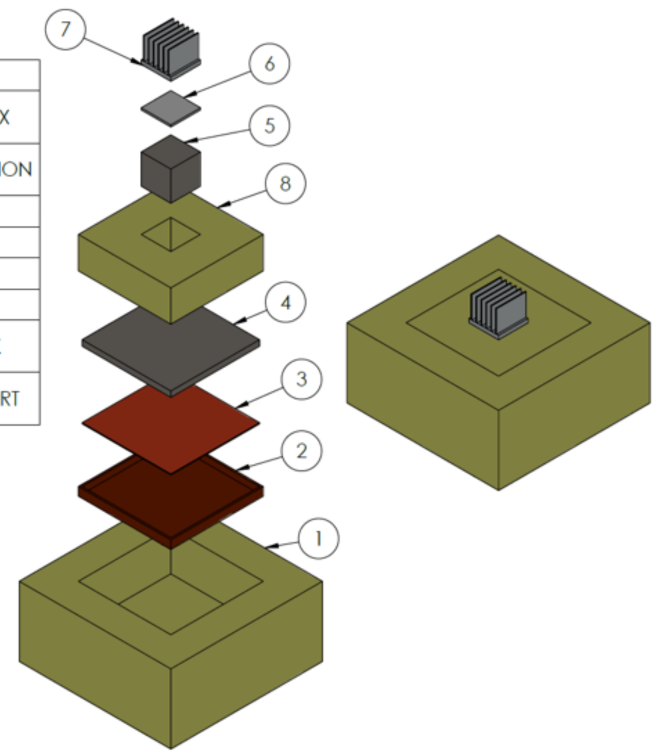
- Same dimensions as graphite-epoxy probe

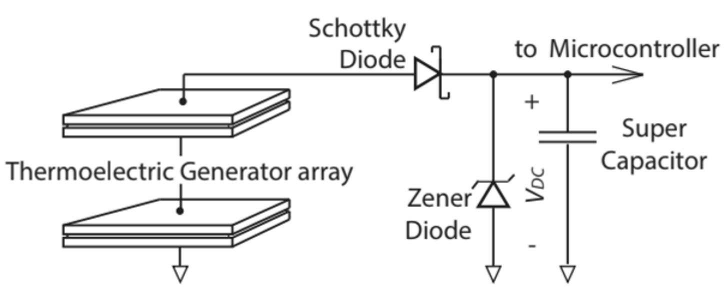
III: Energy harvesting element design and analysis

Thermoelectric generator (Peltier junction)

- Utilize temperature gradient between warm, insulated pipe and ambient air

ITEM NO.	PART DESCRIPTION
1	FOAM INSULATION BOX
2	SILICONE HEATER ISOLATION
3	STRIP HEATER
4	STEEL PLATE
5	STEEL BLOCK
6	PELTIER JUNCTION
7	ALUMINUM HEAT SINK
8	FOAM INSULATION INSERT

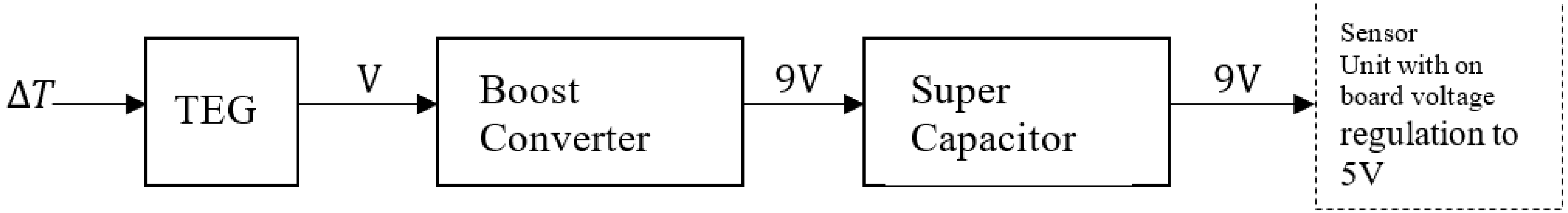




III: Energy harvesting element design and analysis

Thermoelectric generator (Peltier junction)

- Need voltage boost converter to charge super capacitor



Peltier units tested: *Thermonamic TEC1-12706* and Marlow *TG16-6 82078*

Boost converters tested: *Maxim MAX630 and the Texas Instruments TL499A*

III: Energy harvesting element design and analysis

Peltier resistive load benchtop testing ($\Delta T \approx 40°C$)

TEC1-12706

Load Resistance	Test 1 (V_g)
10Ω	1.058 V
100Ω	1.065 V
1kΩ	0.8126 V
10kΩ	0.7221 V
100kΩ	0.7171 V

TG12-6 82078

Load Resistance	Test 1 (V_g)
10Ω	1.067 V
100Ω	1.117 V
1kΩ	1.56 V
10kΩ	1.325 V
100kΩ	1.265 V

Short duration tests (<15 seconds) per point

III: Energy harvesting element design and analysis

Two TG12-6 82078 units in series

Load Resistance	Test 1 (V_g)
10Ω	1.10 V
100Ω	2.07 V
1kΩ	2.32 V
10kΩ	2.75 V
100kΩ	2.49 V

III: Energy harvesting element design and analysis

Boost regulator testing w/ power supply input

MAX630

$V_{in} = 2.3\ V$

0.5F super capacitor load

Not viable due to excessive charge times and high minimum input voltage

Charge/Discharge	MAXIM (V_{in} = 2.3V) 0.5F cap
Dt 0.0V - > 2.0V	20:01.7 (min:sec)
Dt 2.0V - > 3.0V	28:56.5
Dt 3.0V - > 4.0V	13:46.8
Dt 4.0V - > 5.0V	16:51.4
Dt 5.0V - > 6.0V	19:40.2
Dt 6.0V - > 7.0V	24:34.7
Dt 7.0V - > 8.0V	36:19.2
Dt 8.0V - > 9.0V	50:52.0
Dt 9.0V - > 3.0V	00:57.7
Dt 3.0V - > 0.5V	02:16.1
Dt 0.5V -> 90mV	03:52.8
Dt 90mV -> 50mV	02:12.0
Dt 50mV -> 25mV	03:51.8

III: Energy harvesting element design and analysis

Boost regulator testing w/ power supply input

TL499

$V_{in} = 1.5\ V$

0.5F super capacitor load

Charge/discharge times are acceptable

Charge/Discharge	TL499 (Vin = 1.5V), 0.5F cap
Dt 0.0V - > 9.0V	100.68s
Dt 9.0V - > 4.5V	38.33s

Boost regulator w/ 2x series Peltier

TL499 – 2X TG12-6 82078

$\Delta T = 40°C$ 0.5F super capacitor load

Voltage (V_O)	Time (H:M:S)
0.2317 V	0:00:00
0.442 V	1:02:52
0.442 V	Test was ended

- Stall in charging due to thermal saturation of Peltier junction
- Peltier junction unable to produce enough voltage/current to continue charge
- Cycling as boost regulator cut in and out (min voltage)

III: Energy harvesting element design and analysis

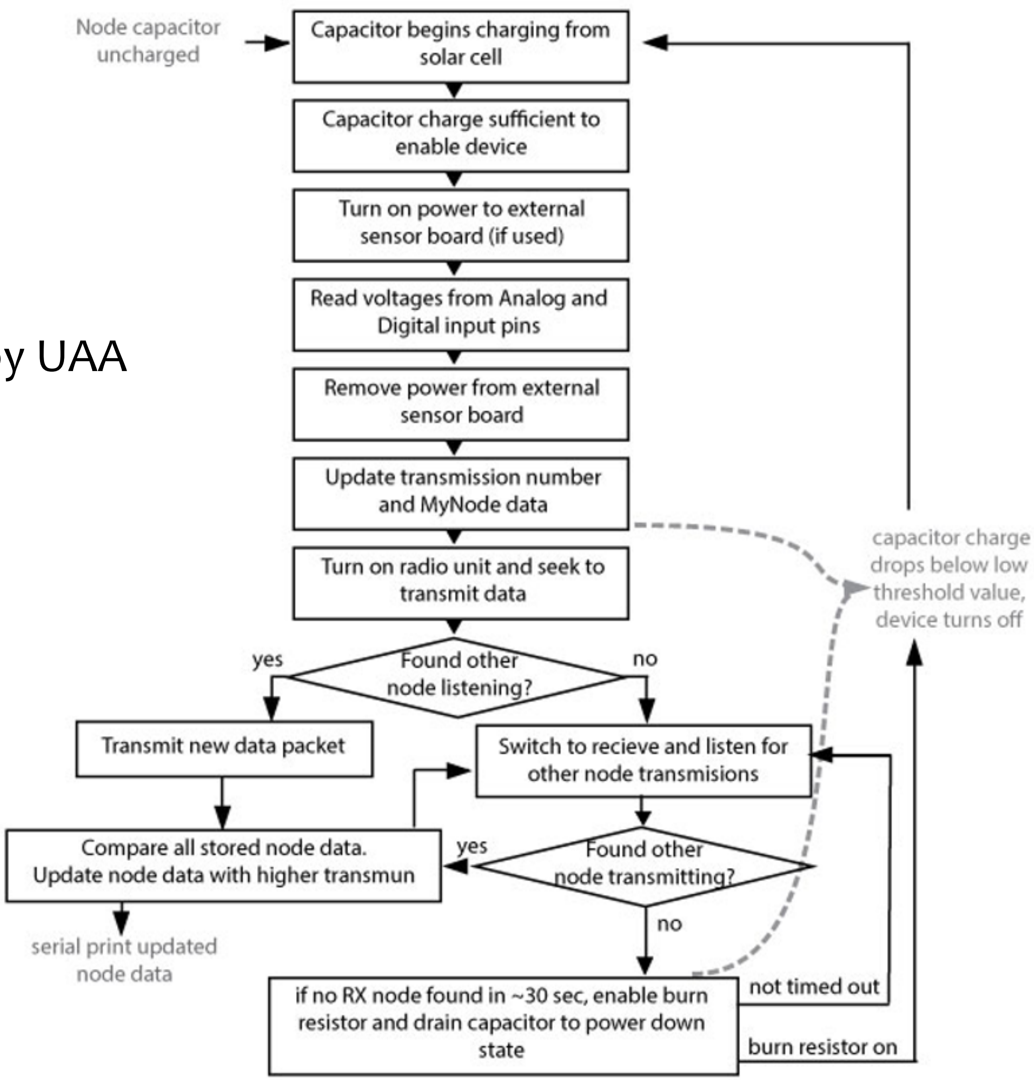
Takeaways:

- Large heat sinks and/or active cooling likely required for viable TEG energy harvesting from warm (140-200 $°F$) insulated pipes.
- Additional electronics and or larger footprint TEG's required for reasonable charge times.
- Serious concern from industry partners about large perforations in insulation
- Only viable for insulated, warm lines
- Solar charging a better option

IV: Wireless Sensor Network (WSN) integration and testing

Zensor^{TM}

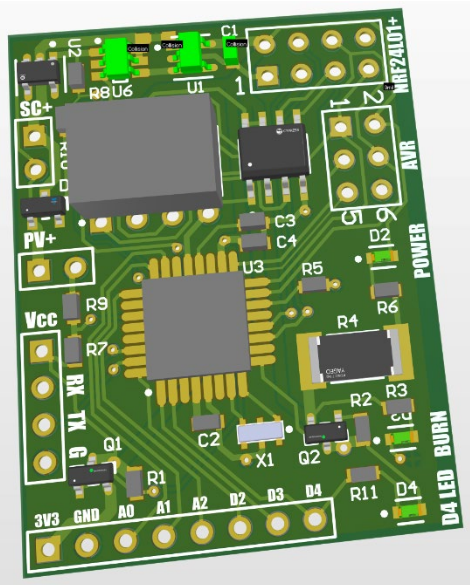
Patent owned by UAA

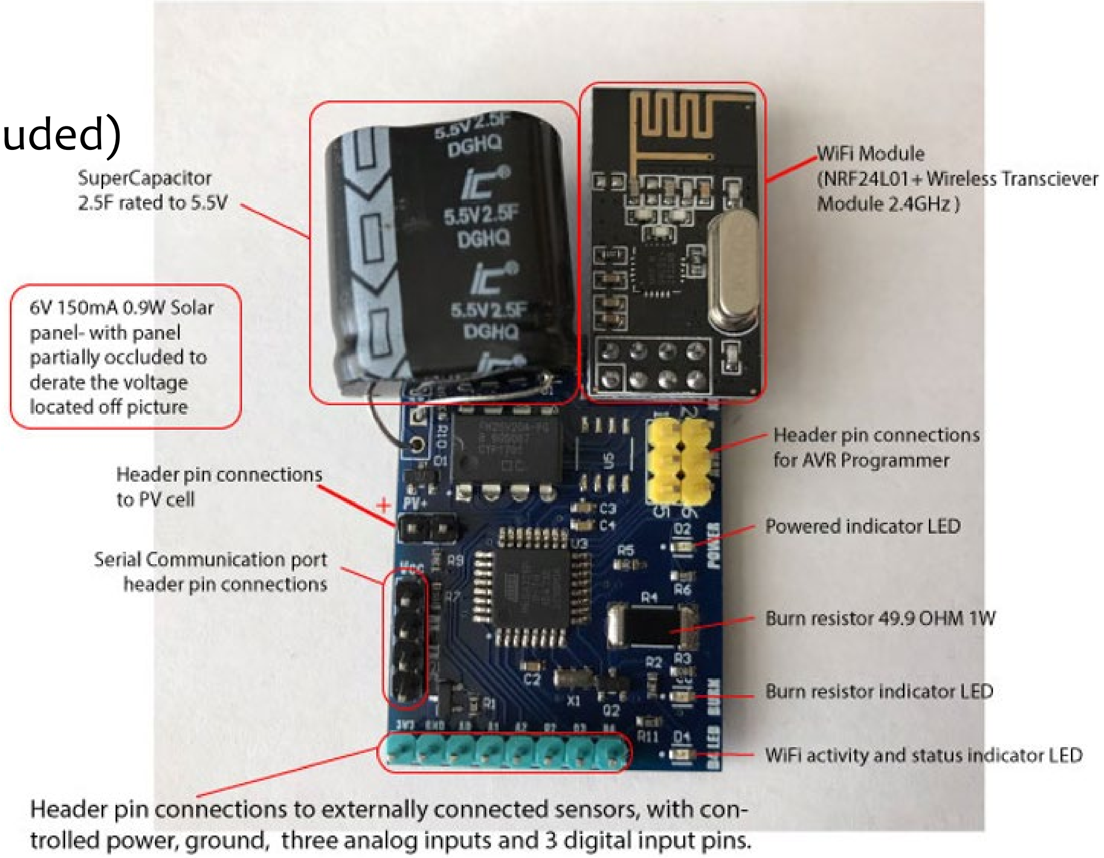


IV: Wireless Sensor Network (WSN) integration and testing

- Designed to support conductivity measurement

- $13 / board (node)
  (solar cell, enclosure not included)





IV: Wireless Sensor Network (WSN) integration and testing

All nodes have solar cells mounted vertically pointing to the bottom of the page, or roughly South.

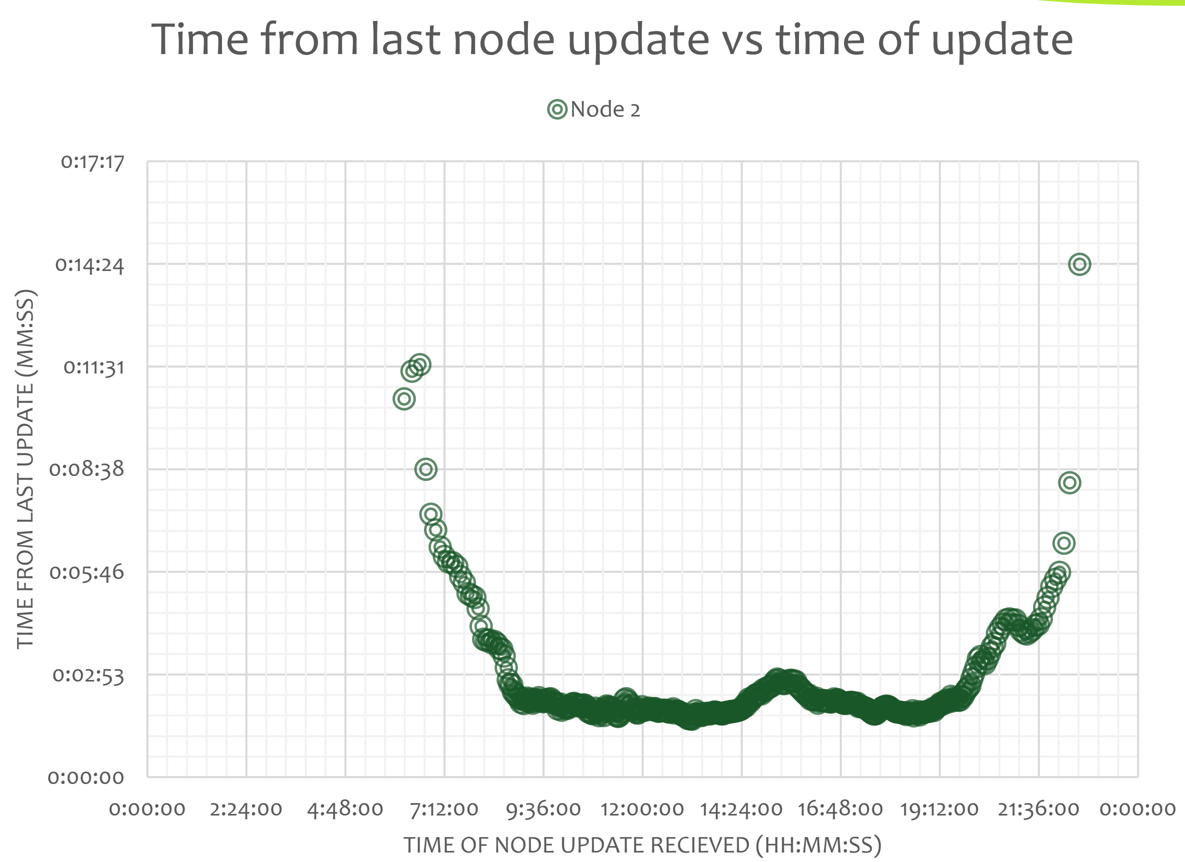
● Approximate WSN node location

N - Node number

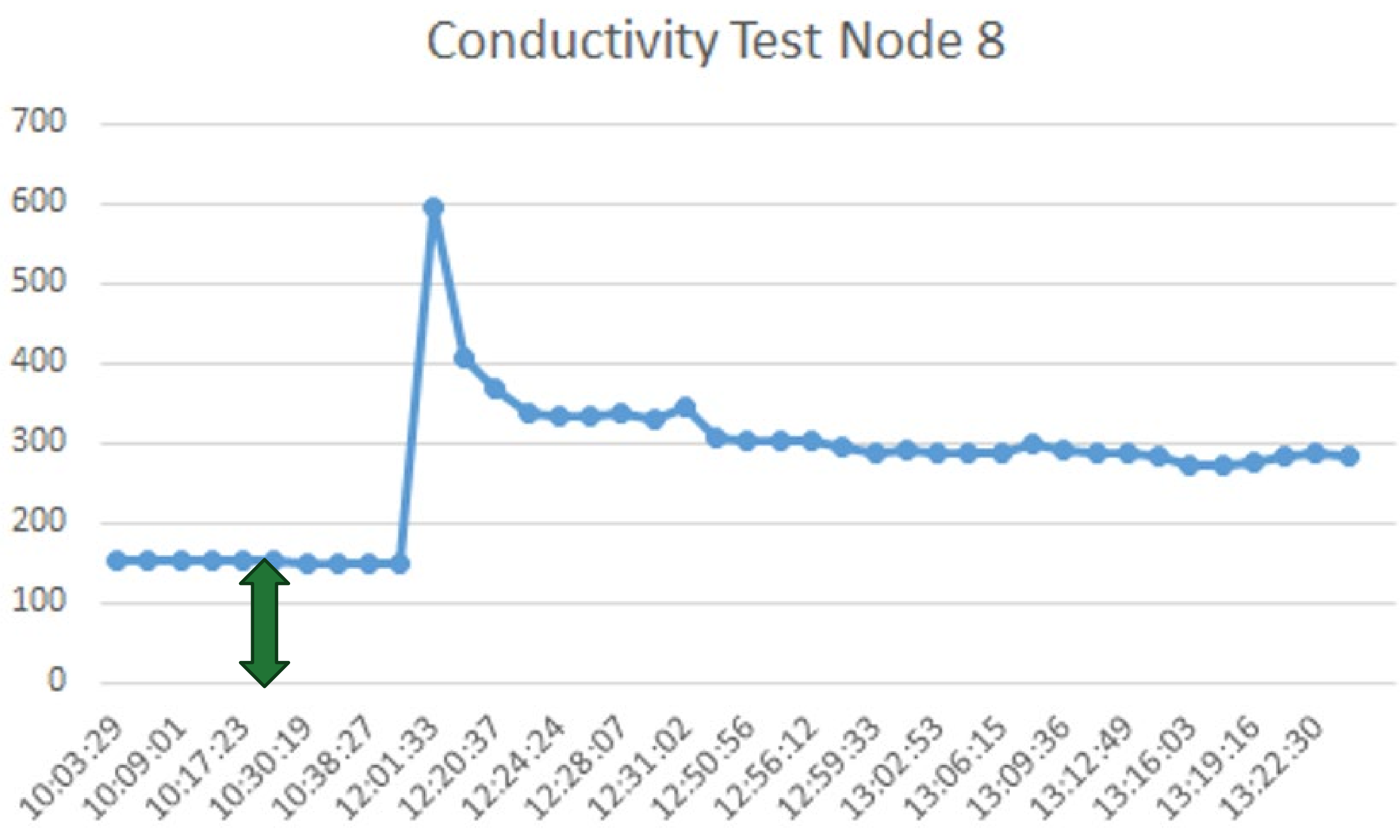
IV: Wireless Sensor Network (WSN) integration and testing

- Salt on sensor with lip (hold water)
- Rain triggers conductive readings
- Galvanic / binary sensor (steel – Ni)

IV: Wireless Sensor Network (WSN) integration and testing



IV: Wireless Sensor Network (WSN) integration and testing



Offset caused by noise

Wire pickups (unshielded)

IV: Wireless Sensor Network (WSN) integration and testing

Performance:

Direct sunlight: ~ 1 min/sample

Diffuse sun / overcast: 3-20 min/sample

Average current draw (@ 3.3V):

Measurement: 1-4 mA measurement
Radio transmitting: 14 mA
Listening mode: <1 mA

Average transmission rate: 20 – 300 ft/min (0.23 – 3.4 mph)

IV: Wireless Sensor Network (WSN) integration and testing

The good:

- Performance characteristics are reasonable for intended application
- Boards functioned reliably outside of user-error (bad solder joints)
- Galvanic sensor provided repeatable and discernable indication of electrolyte

IV: Wireless Sensor Network (WSN) integration and testing

The not-so-good:

- Noise from radio picked up by analog inputs
  Solution: low pass filter, separate grounded enclosure, shielded / twisted pair wiring

- Occasional errors from crowded radio frequencies
  Solution: better error checking than simple checksum

- Downtime / low sample rates during dark/overcast periods
  Solution: secondary RC – transistor circuit (instead of cap burndown)

Publications / presentations / theses / reports

R. Srinivasan, M. Cullin, T. Petersen, C. Forbes, "Testing of a Low-Power Wireless Sensor Network of Conductivity Probes to Detect of Corrosive Fluids in Pipelines (C2021-16380)," CORROSION 2021. April 18-22, 2021.

R. Srinivasan, M. Cullin, T. Petersen, C. Forbes, "Development of a Low-Power Wireless Sensor Network of Conductivity Probes to Detect Corrosive Fluids in Pipelines (C2020-14502)," CORROSION 2020. June 14-18, 2020. Cancelled (due to COVID-19). Reviewed, accepted, and published.

C. Forbes. "Development of a Low-powered Wireless Sensor Network of Conductivity Probes to Detect the Presence of Fluids That Cause Internal Pipeline Corrosion." M.S. thes., University of Alaska Anchorage, 2020.

C. Forbes, K. M., L. M., M. W., B. A., M. C.. "Conductivity Probe Design." Final report and presentation ME A438. Presented to / approved by Mechanical Engineering Department, 2019.

M. A., B. B., L. C., M. M., R. H. "Pressure Vessel Design." Final report and presentation ME A438. Presented to / approved by Mechanical Engineering Department, 2019.

T. Petersen, J.S. "Low Power Conductivity Sensor." Report for project-sponsored Summer UGRA, 2020.

T. Petersen, M. Cullin, K.T. "Wireless Sensor Network of Conductivity Probes." Report for project-sponsored Summer UGRA, 2021.

Student Engagement

- engaged 12 undergraduate engineering students in design work related to the project

- supported 1 graduate student to develop the conductivity sensing element and measurement procedure

- supported three summer undergraduate research assistantships

- facilitated a program for practicing engineers from BP Alaska to mentor the undergraduate design teams associated with the project

- helped encourage one student to enter the pipeline industry (Hilcorp AK)

Future Work

- Application to Corrosion Under Insulation, water ingress detection
- Explore certification to operate in potentially explosive atmospheres
- Application to oil conductivity (time-of-wetness) monitoring for buried pipelines
- Application to specialized cleaning pigs designed to separate oil and water
- Expanded energy harvesting techniques (vibration-based)