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Reusable Test Fixture using Induction Heating

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What's the need for a reusable test fixture?

- Development builds are expensive, ~$8,000 – $11,500 per unit
  - Design 1, 36 delivered units, 6 PVTs, total of $341,028
  - Design 2, 35 delivered units. 3 PVTs, total of $409,099
  - Design 3, 36 delivered units, 6 PVTs, total of $484,607
- Time per build
  - Contracting, build, and shipment can take up to 9 months
  - Testing can take up to 6 months, if the test labs were scheduled ahead of time
- A thermal battery may have five or more development builds that can span five or more years
- A reusable test fixture will provide multi-cell electrical performance data of new chemistries and closing forces, saving at least one development build.
  - Potential to save additional funds and time if a second iteration of the fixture can incorporate vibration testing fixtures

Thermal Battery	Number of Development Builds
Design 1	5
Design 2	5
Design 3	5
Design 4	4
Design 5	3

Reusable Fixture Design

- Over twenty concepts were sketched and presented to the design team
- Each concept needed to allow room for the field induced by the coil to access the cell stack, maintain closing force on the stack, measure the stack pressure through activation, and provide atmospheric isolation of the cell stack
- Down selection was based on discussion of the benefits and drawbacks of each design
- The activation method for the stack would be induction heating of standard heat pellets to avoid the hazards and costs associated with ignitors and heat paper, but the shape of the coil that would work for each design was variable.
- The primary difficulty in the design was ensuring there was a representative closing force while still maintaining an isolated atmosphere.

Induction Heating Technology

Induction heating is a noncontact heating method in which an electrically conductive material is placed within a varying magnetic field and heated via hysteresis (magnetic materials only) and/or induced electrical current (all conductive materials). The changing magnetic field is generated by an alternating current (AC) being passed through an electrical winding (coil/inductor).

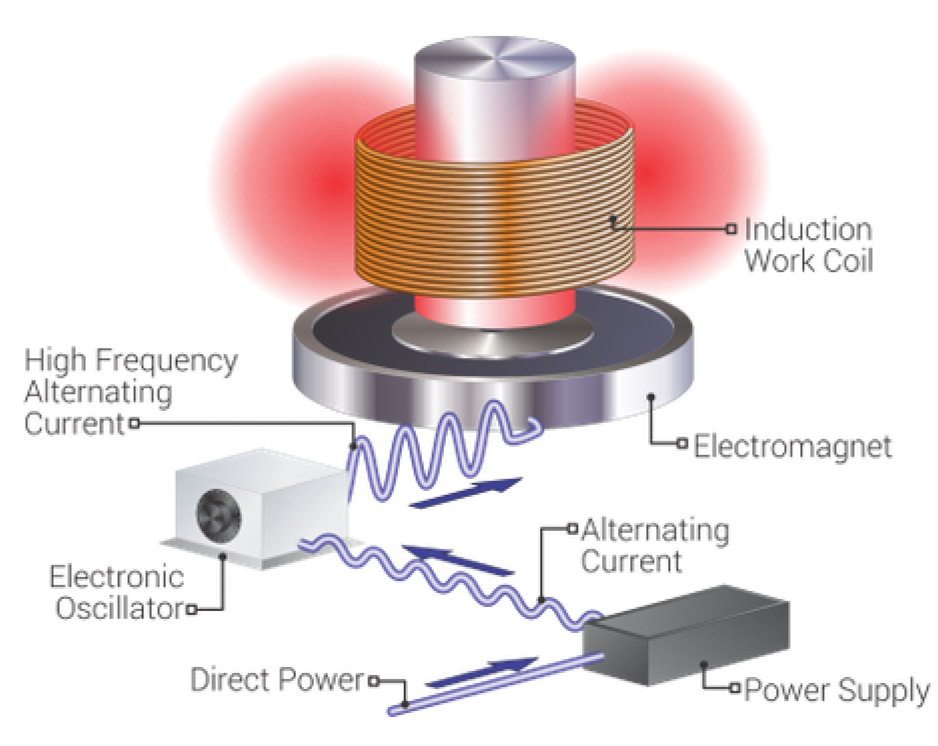
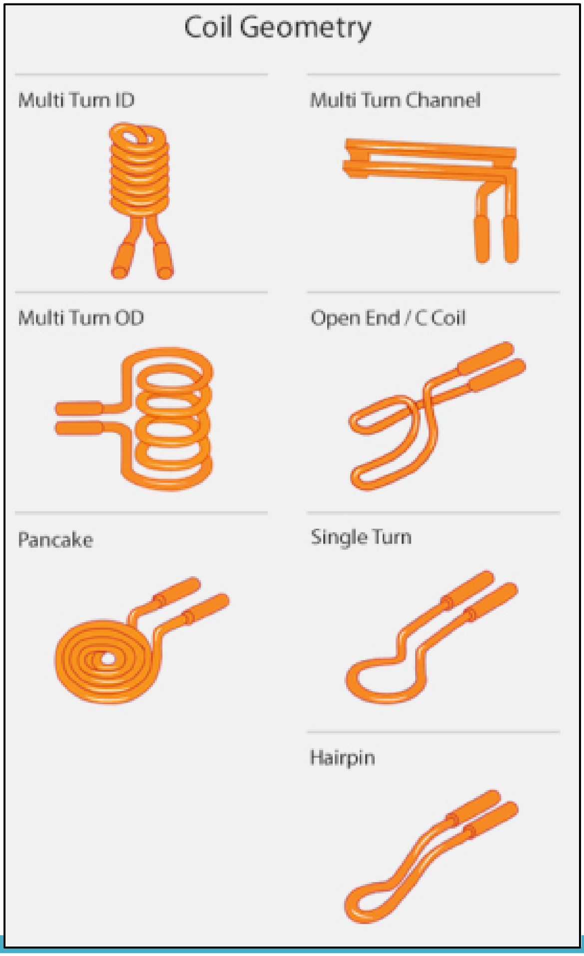
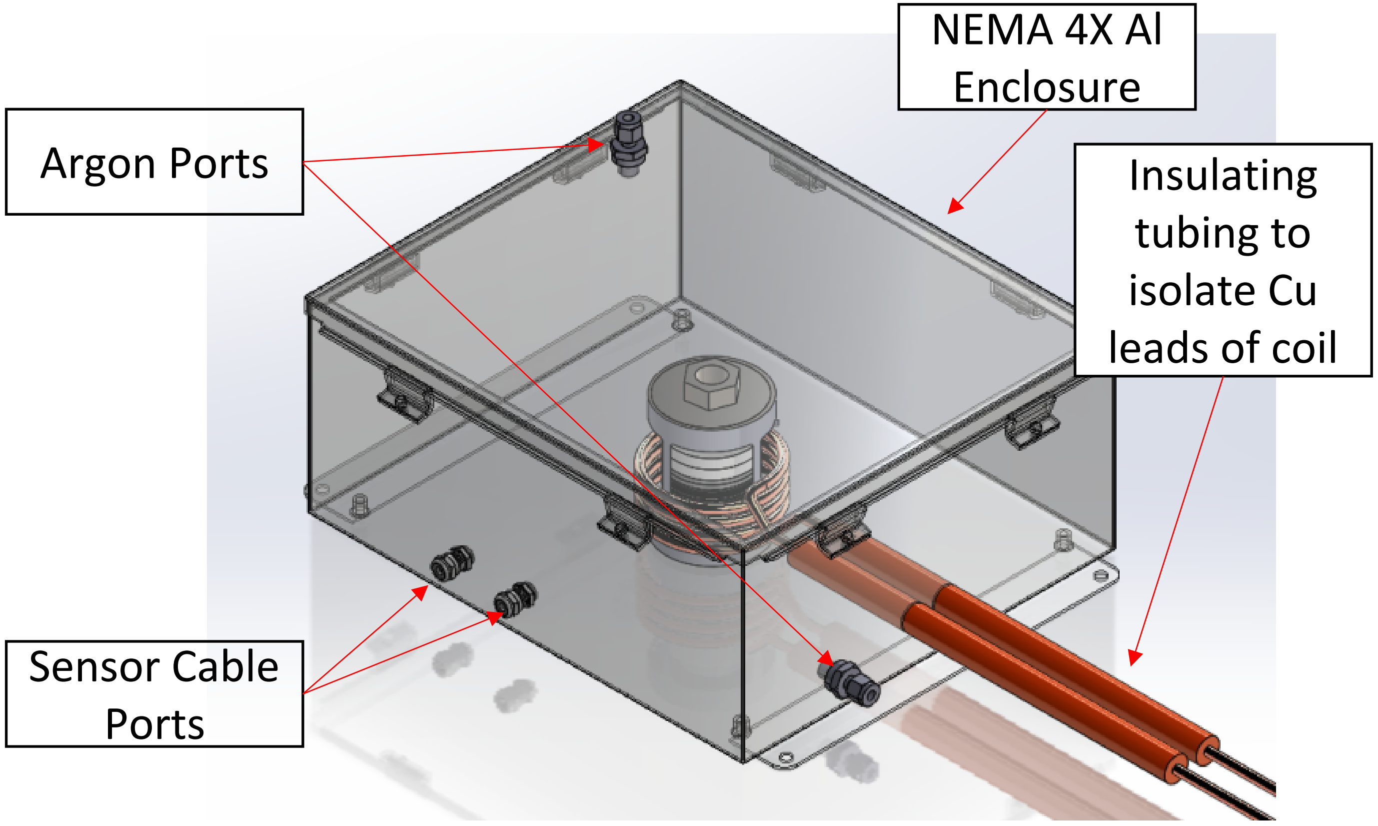


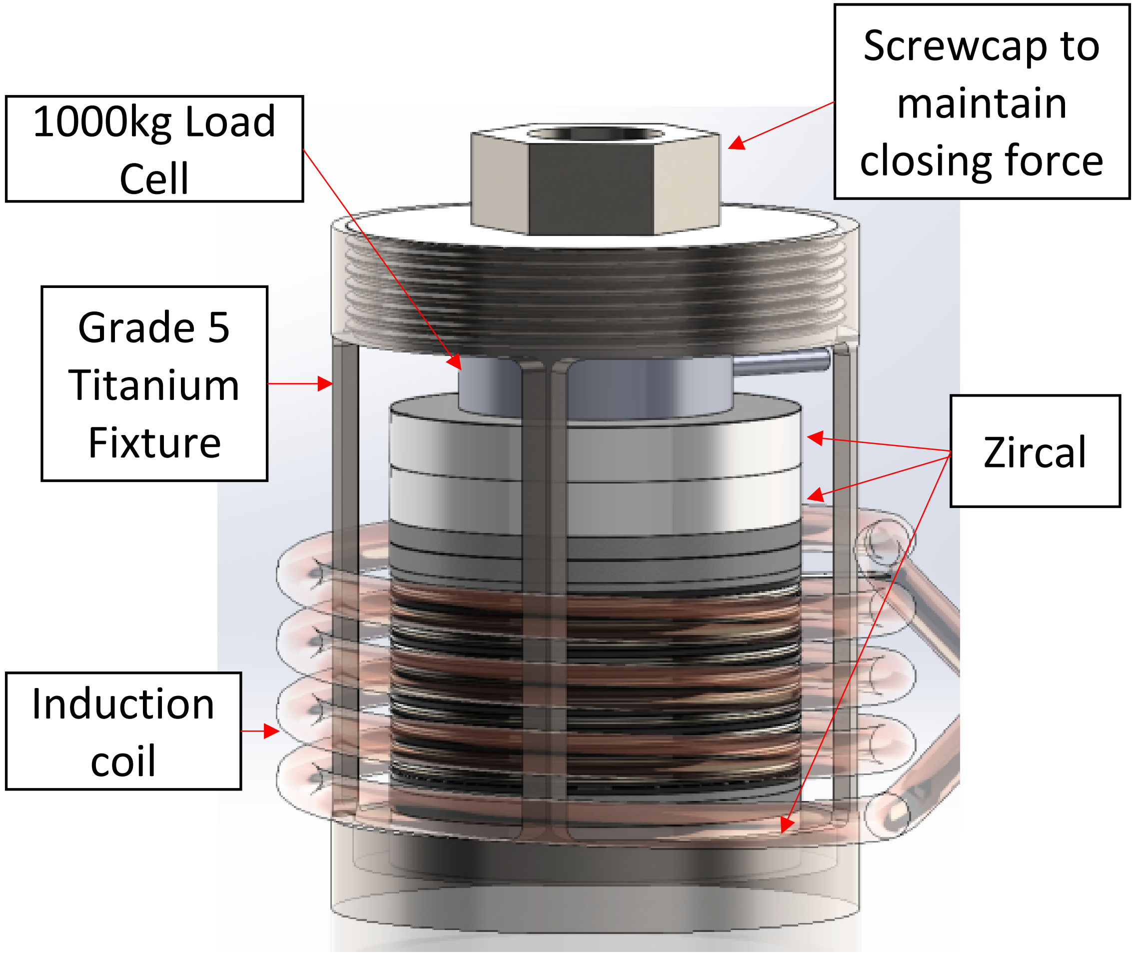
Image © 2018 EngineeringClicks



Selected Design

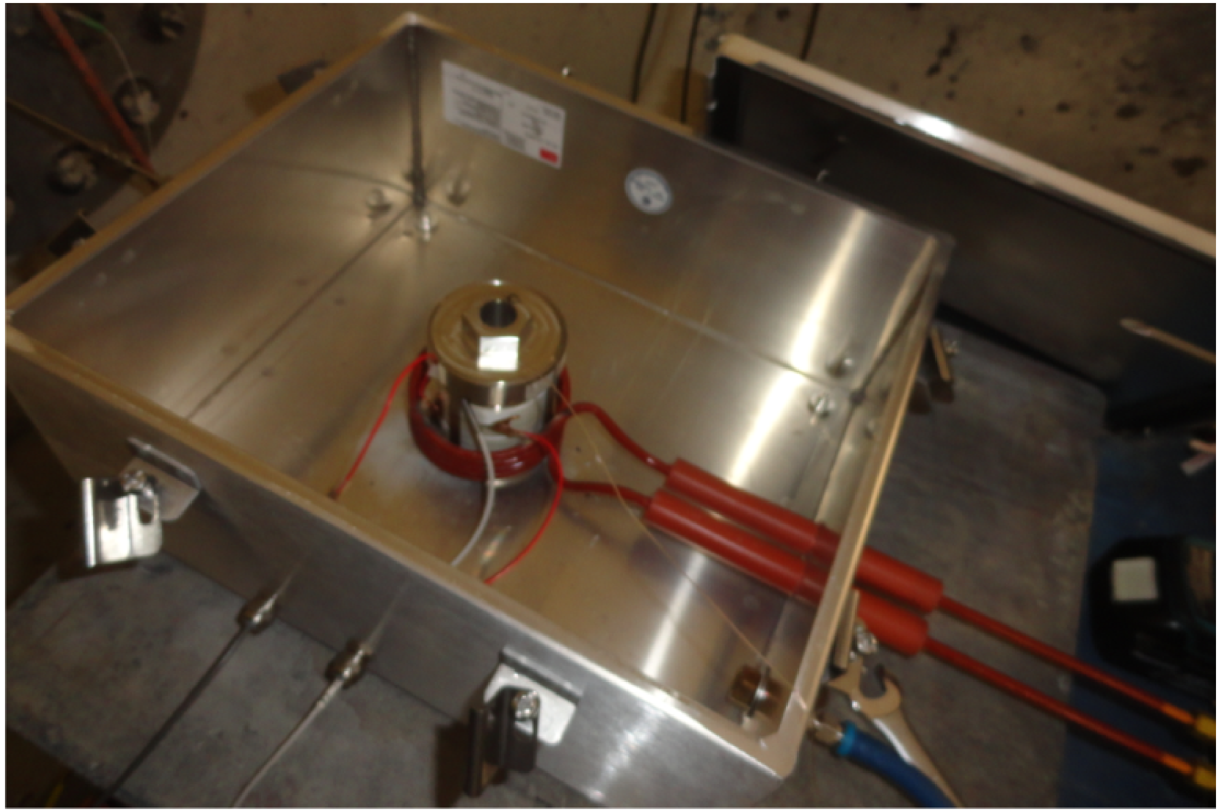
The current design became possible after separating the two functions into two different parts, the reusable test case (for atmospheric isolation) and the reusable test fixture (for applied closing force).





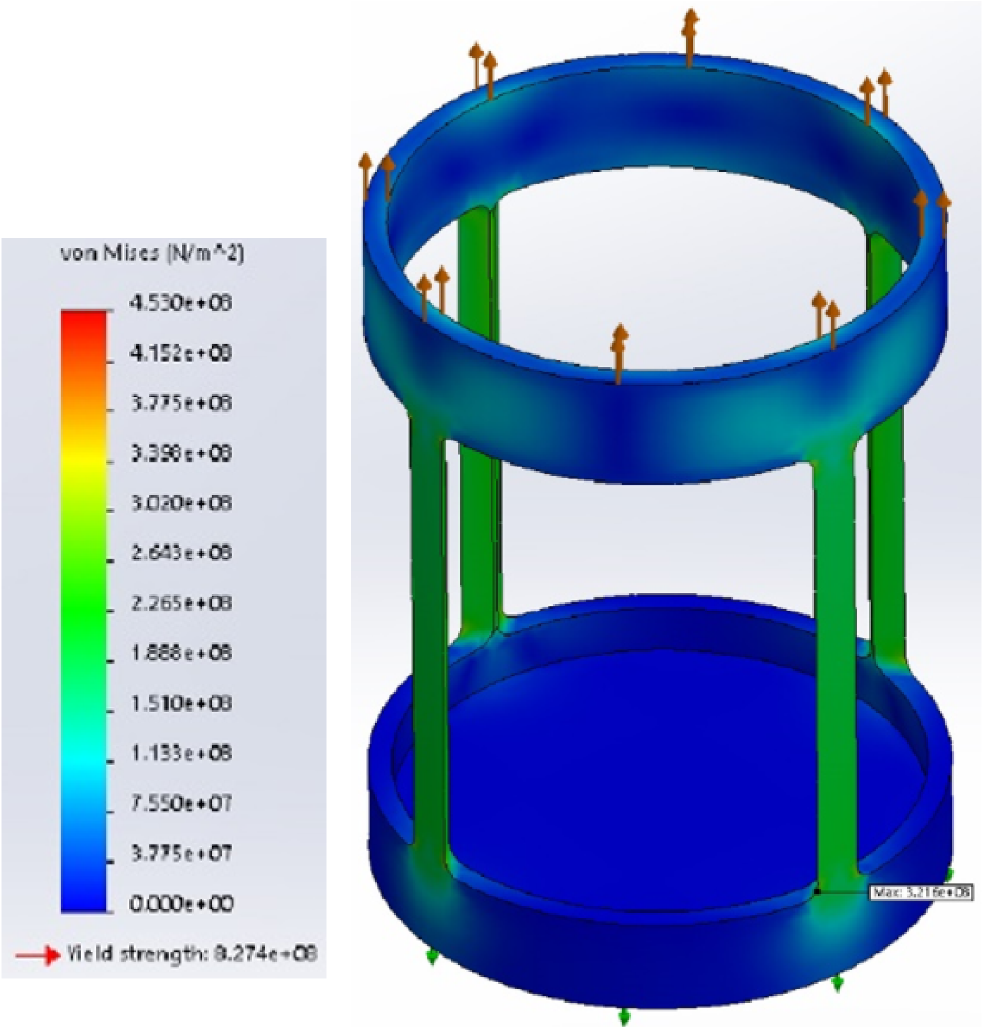
Ambrell EasyHeat 6.0 Induction Heater

- System was purchased by 7554 for unrelated testing
- Uses a water chiller and pump to circulate water through the induction coil, ensuring it is not compromised.
  - One of the tests that went into thermal runaway (FourCellMain001) resulted in molten material in contact with the coil. Additional testing with the coil was conducted without issue.
- Requires 208V 3-phase AC supply and 1.5 gal/min water supply or standalone water chiller.
- Uses two parallel 0.5μF capacitors.



Modeling

- 2000lb tension was applied to top surface
- Entire body was held at 700C
  - Tests with only the fixture in the induction coil resulted in a peak temp of 463C after heating for 22 seconds
- Bottom surface was vertically fixed but allowed to expand laterally
- Max predicted stress was 321 MPa.
- Stress in the arms of the model cage arms is similar to analytical predictions $\left(\sigma = \frac{F}{4} * \frac{1}{A_{arm}}\right)$
  - Analytical prediction of 209 Mpa
- Yield stress of Grade 5 Titanium at 533C is as low as 350 MPa



Thread Calculation

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Assumptions

- $ys_{304ss} = 34{,}083.89$ psi (at ambient)
- $ys_{Ti} = 120{,}091.25$ psi (at ambient)
- $ys_{Ti} > ys_{304ss}$, and thus the 304SS external threads are assumed to yield first.

Shear Force

- Shear Force: $f_s = \tau A_s$,

  where τ = Shear Strength

  A_s = Shear Area
- $A_s = \pi n \mathrm{L_e} \mathrm{K_{n_{max}}} \left[\frac{1}{2n} + 0.577\left(\mathrm{E_{s_{min}}} - \mathrm{K_{n_{max}}}\right)\right]$

Where n = number of thread per inch

$\mathrm{L_e}$ = Length of engagement

$\mathrm{K_{n_{max}}}$ = Maximum minor diameter of internal thread

$\mathrm{E_{s_{min}}}$ = Minimum pitch diameter of external thread

https://www.fastenal.com/content/feds/pdf/Article%20-%20Screw%20Threads%20Design.pdf

For this Test Fixture

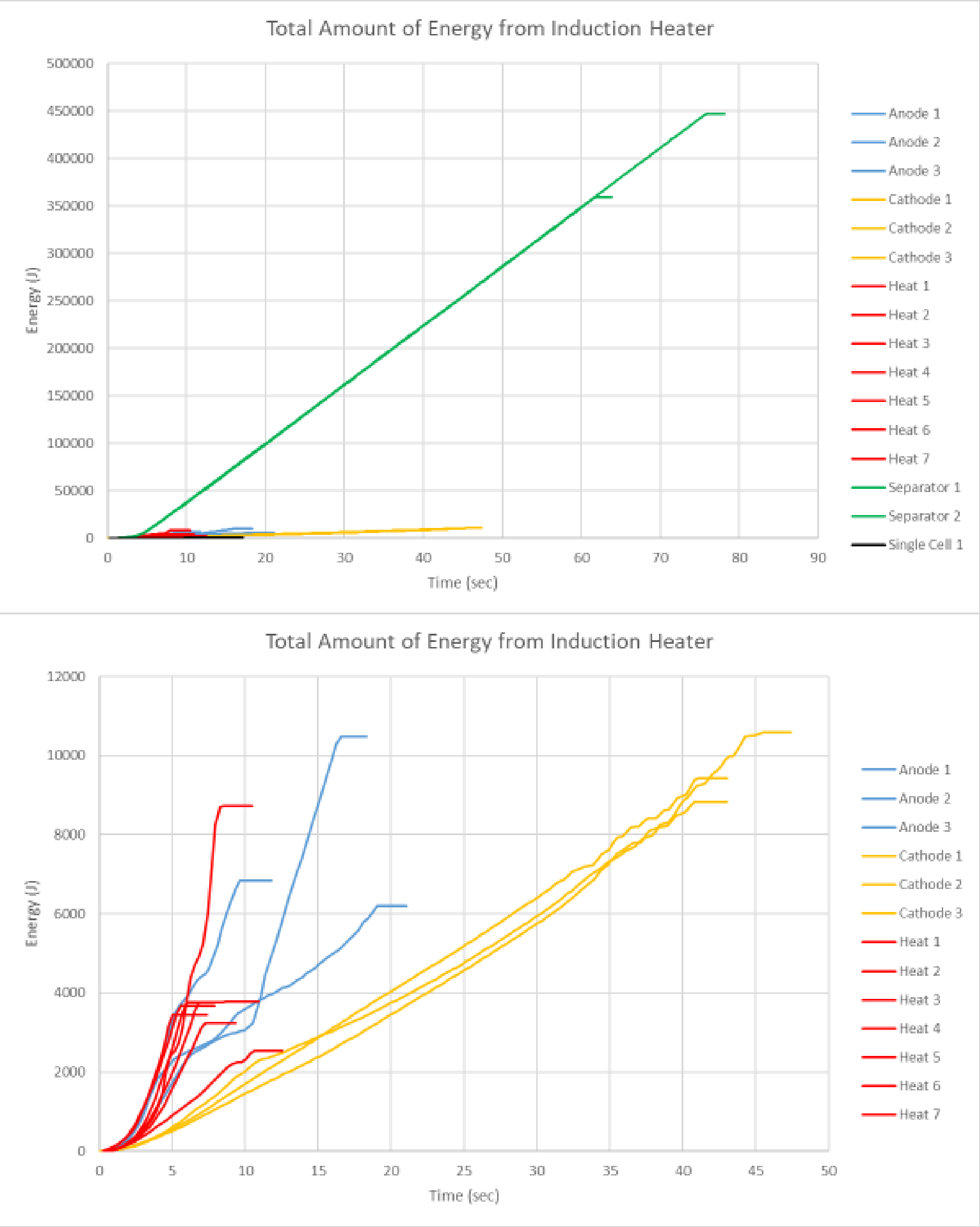
$$n = 13 \text{ threads/in}$$
$$\mathrm{L_e} = 1 \text{ in}$$
$$\mathrm{K_{n_{max}}} = 0.434 \text{ in}$$
$$\mathrm{E_{s_{min}}} = 0.4435 \text{ in}$$
$$\tau = 5.31x10^7 \text{Pa } (7{,}703 \text{ Psi}) \text{ (at 520C)}$$

$\Rightarrow$ $f_s = 6{,}000$ lbf (at 520C)

- Represents a factor of safety of ~6 for 304SS

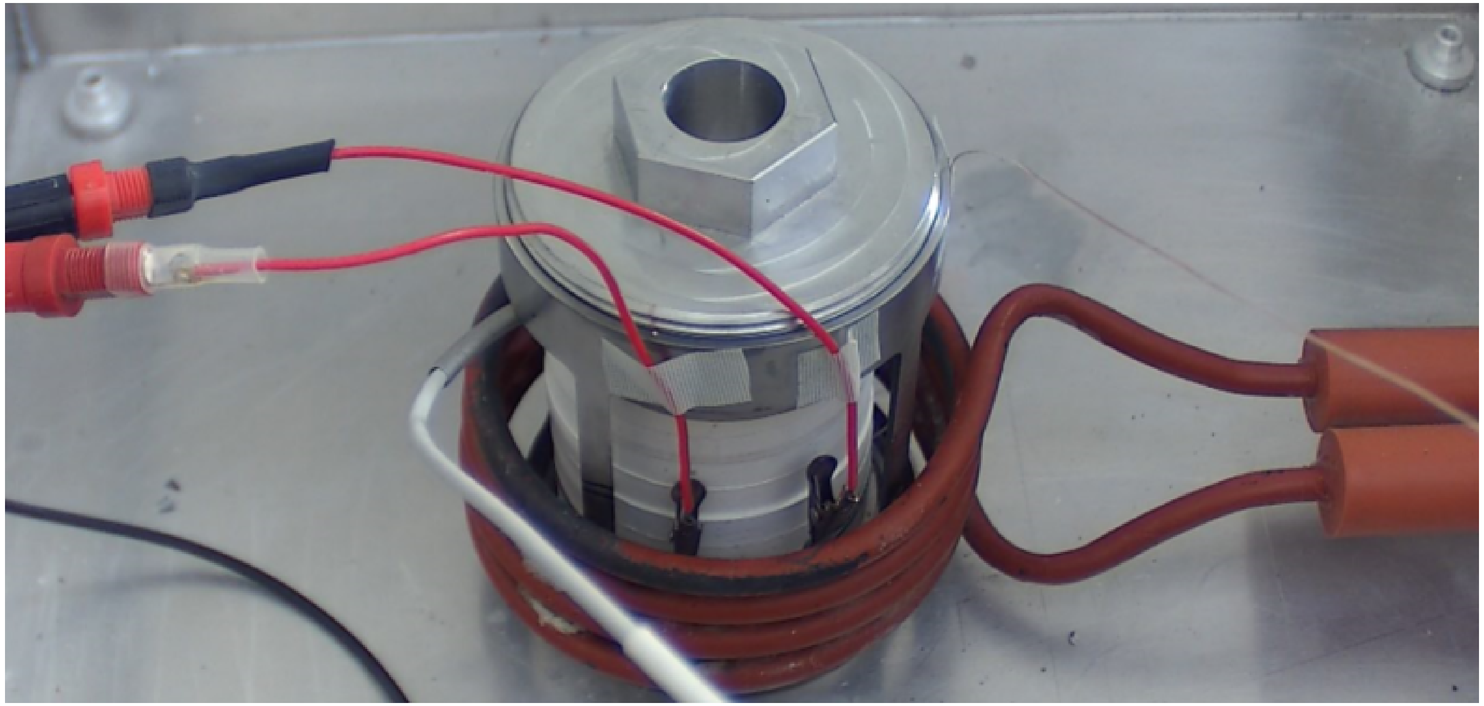
Pellet Tests in Air

- Individually tested pulse-sized heat pellets, anodes, cathodes, and separators with the same heating rate in an air environment to determine reactivity of each pellet to the induction field
  - Heat pellets ignited fastest, followed closely by the anodes
  - Separators were effectively inert
- Individual pellets tests in air indicated induction would be a suitable activation method
- Results indicated the heat pellets would ignite before the anodes, supporting proceeding with cell level tests



Single Cell Test Setup

- Leads are directly connected to the collectors.
- Thermocouple is placed in the middle of the stack on whichever pellet is desired
- Later tests used fanned wires instead of clips

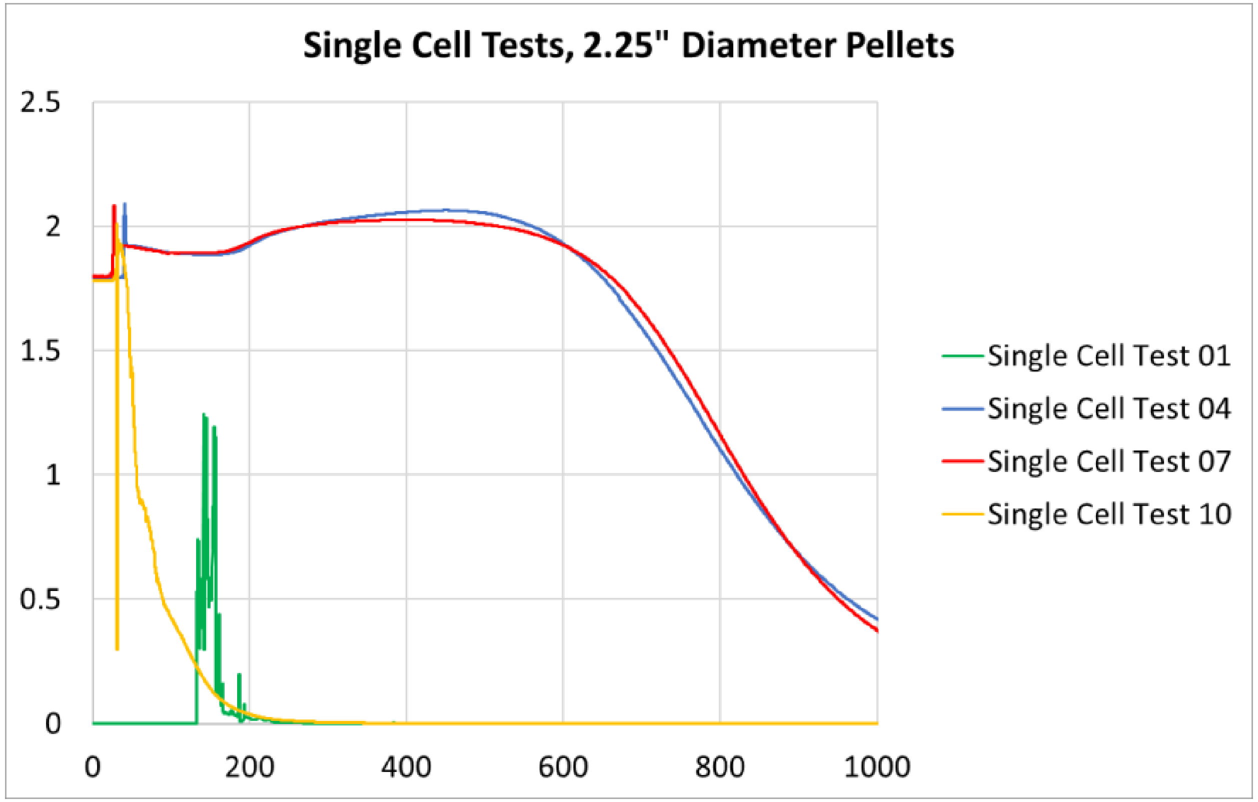


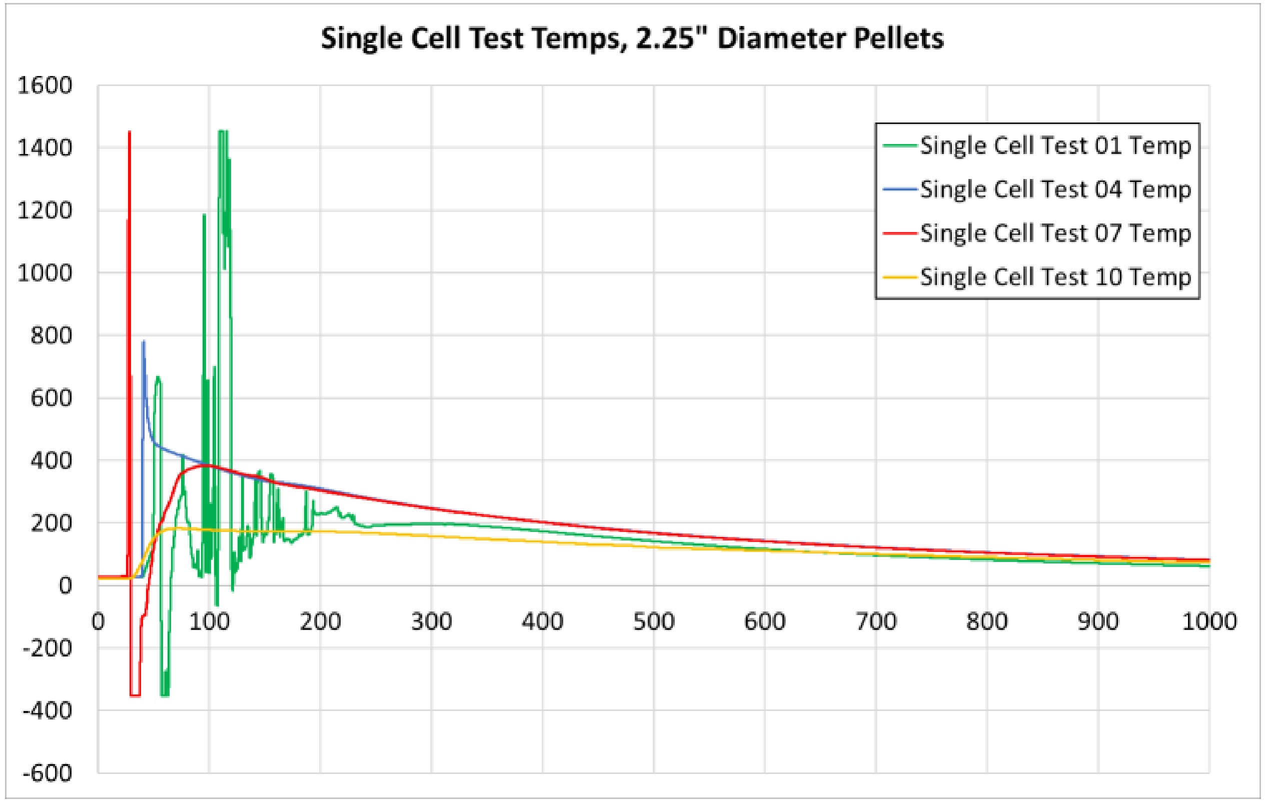
Single Cell Video

- Example of ignition, but not representative of a good test
- Ignition was in an air environment
- The cell contained components that further testing revealed to be detrimental to a consistent activation using induction

Single Cell Tests in Air

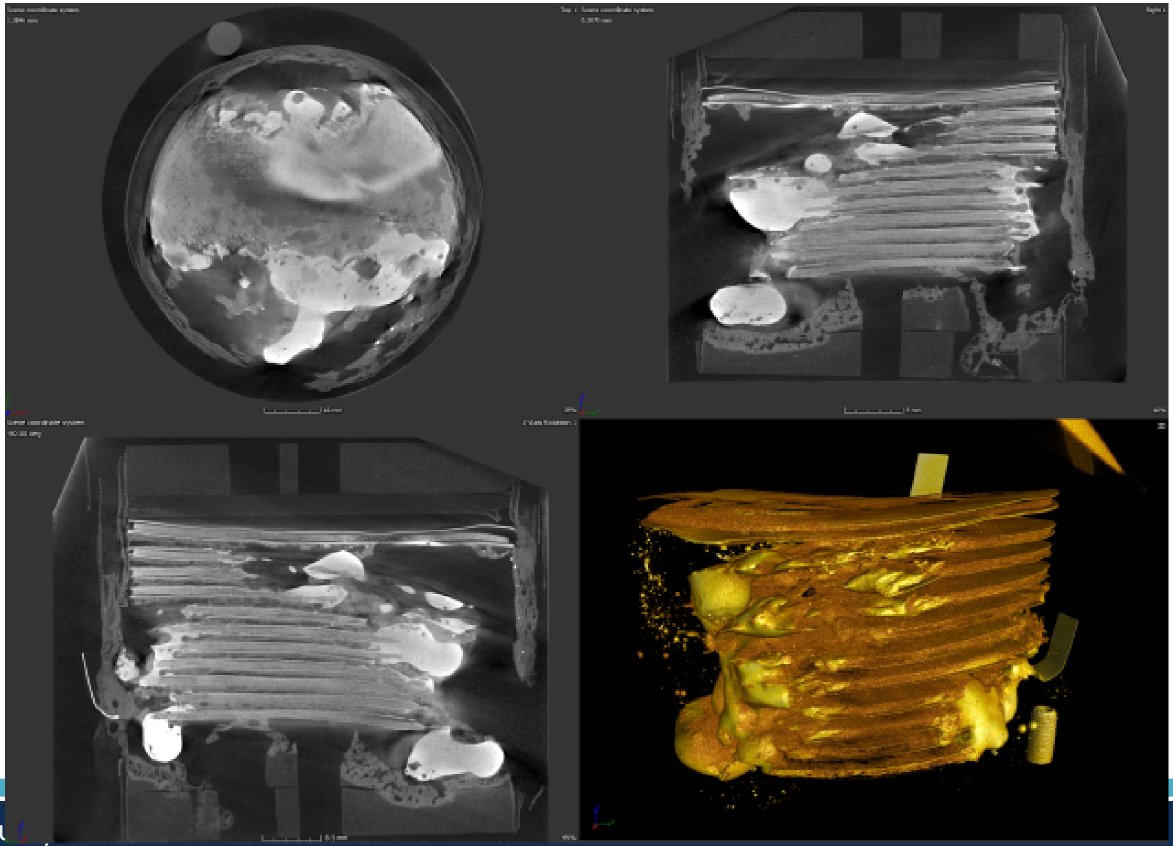
- Tests were conducted between May and July of 2020 by Nate Johnson and/or Greg Peacock
- Cells were either 0.75” diameter (May tests) or 2.25” diameter (June and July tests)
- Chaotic temperatures and voltage indicate thermal runaway of the cell
- Good activations on tests 04 and test 07
- Test 10 did ignite the heat pellet but it is unclear why the temp stayed so low

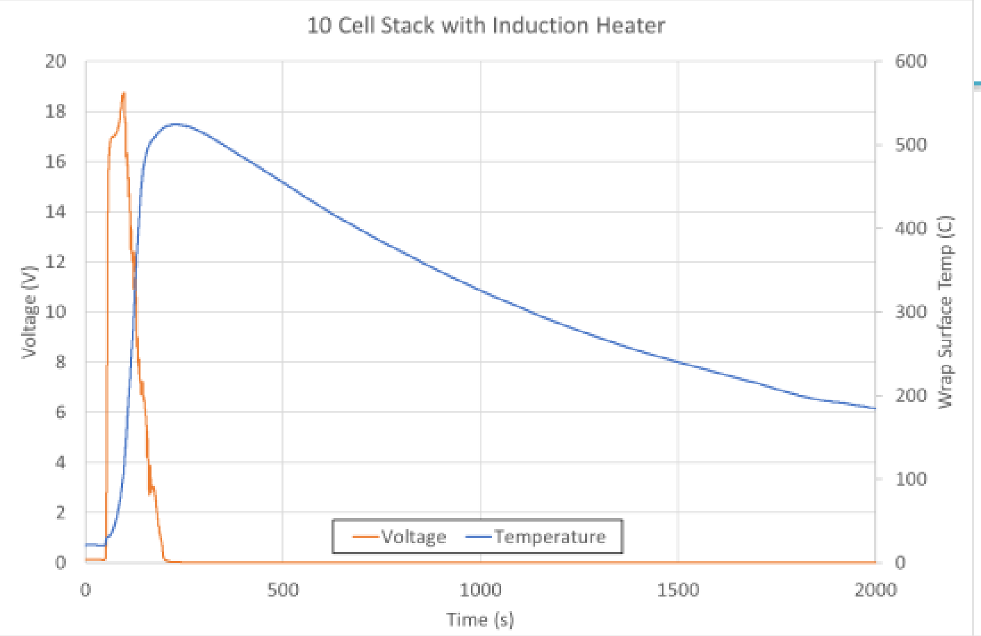


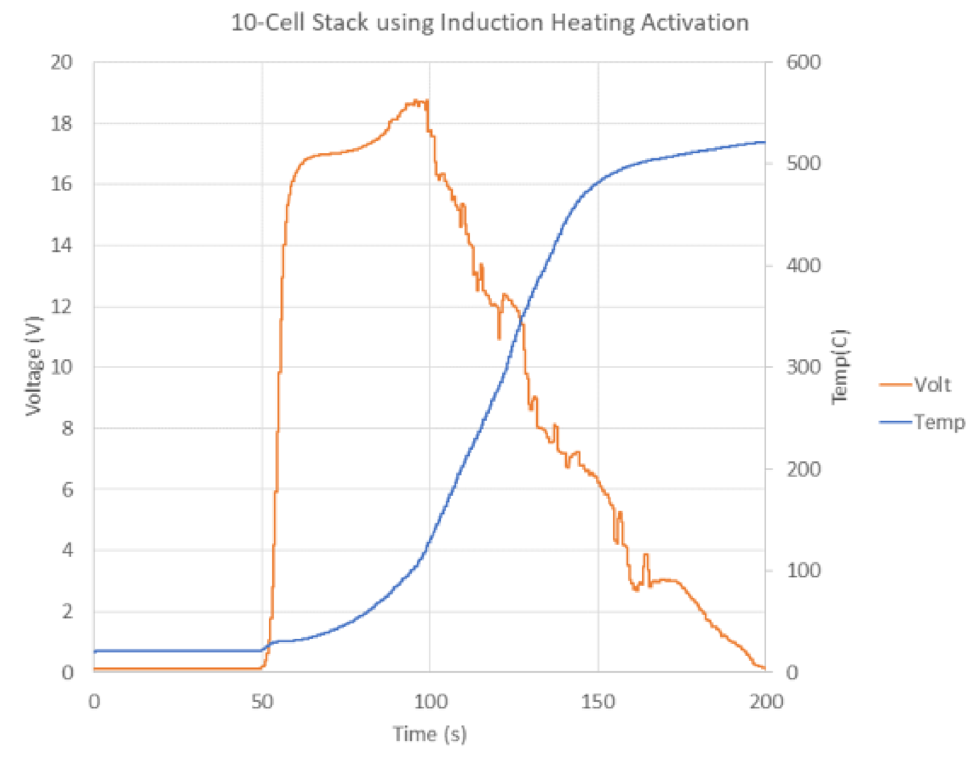


10 Cell Stack Test in Argon

- Activated on May 14th by N. Johnson
- Stack was composed of normal 2.25” pellets
- TC was placed on the external surface of the wrap
- The stack went into runaway, but the containment case prevented any gases from escaping and the coil and fixture were used many times after this event

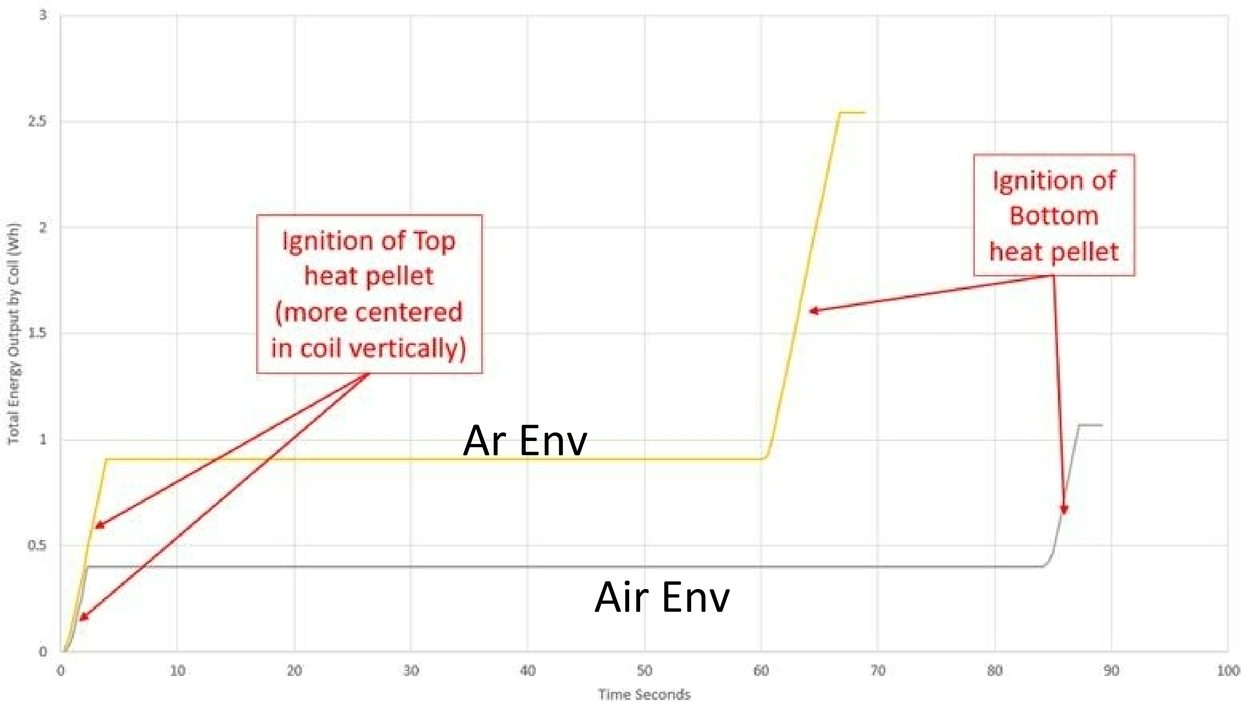






Troubleshooting

- An additional 40 tests were performed to isolate the impact of the induction field, materials in the field, argon vs gas atmosphere, and collector material
- Results:
  - Argon atmosphere creates a fuel-starved environment. Tests conducted in air are not relevant to performance in an Argon atmosphere.
  - Stainless Steel collectors act as a 'getter' of the EMF, resulting in more thermal energy in the cell than would be produced from a normal heat pellet activation.
  - The induction heater must be set to a constant power output rather than a desired temperature ramp rate.
  - A resistor needs to be put in parallel to the electrical leads to bleed off the capacitance that would otherwise build up. This resistor should be removed after stack activation, likely by Labview virtual relay in the second revision of the test setup.



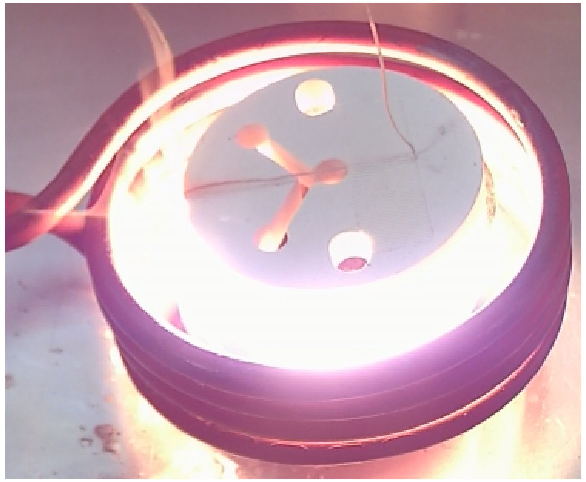
Collector Material

- Ignition of heat pellets is typically within 11 seconds in argon
- Aluminum had the lowest peak temperature, but melted after heat pellet ignited
- Future collectors should be titanium

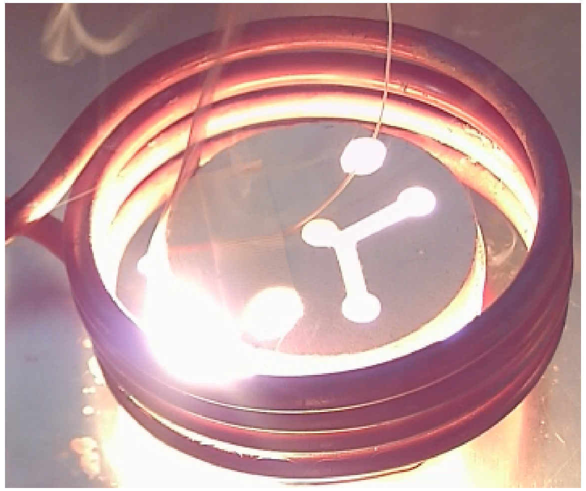
Heating Collector Materials in Argon

	Max. Temp (°C)	Thickness (in)	Heating Time (sec)
Grafoil	2292	0.0155	~2
Stainless Steel	2291	0.005	~2
Copper	840	0.01	22
Titanium	594	0.125	22
Aluminum	545	0.0005	22

*Coil was set to maximum current during tests



Stainless Steel in Air



Grafoil in Air

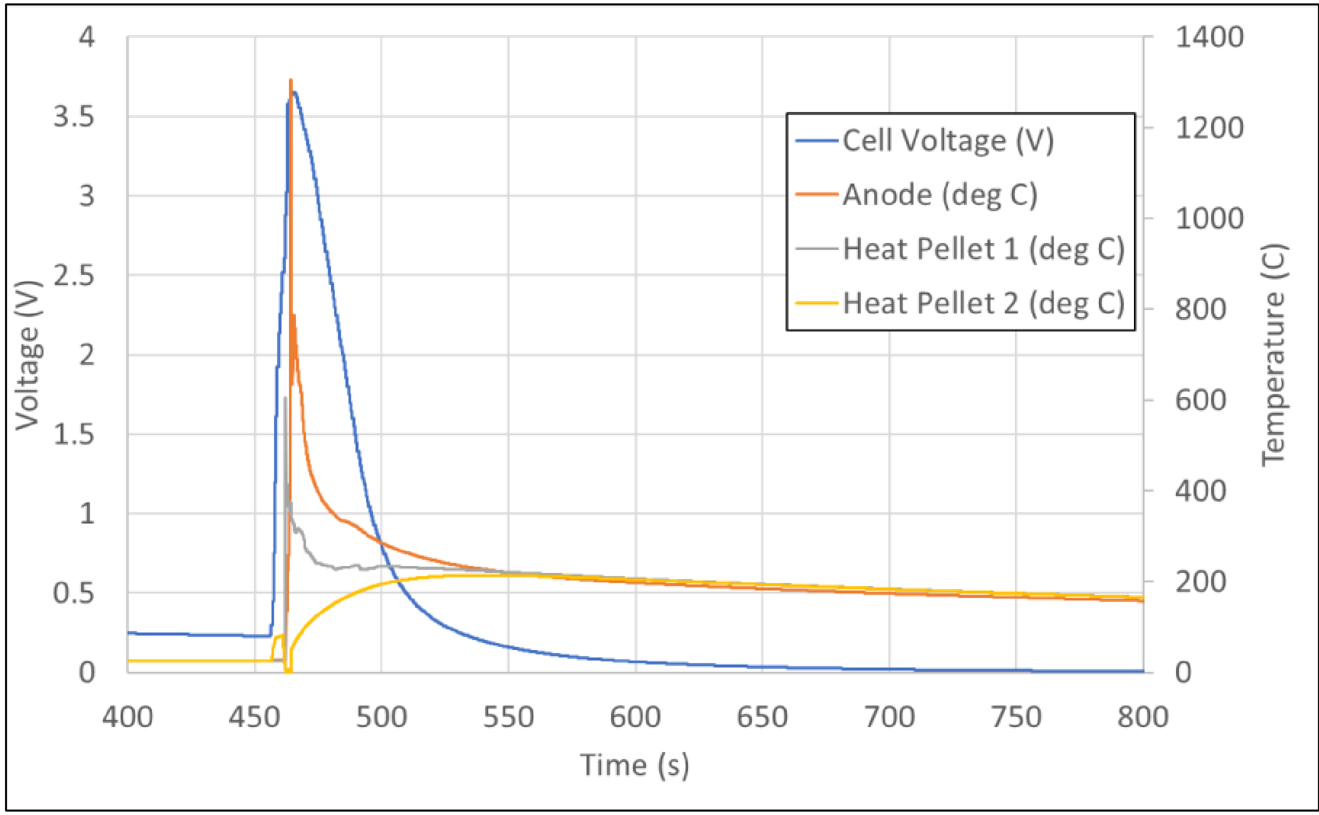
Repeat Double Cell Test

Test Conditions

- Titanium Collectors (blank RTB base plates) were used instead of 304SS
- 100 Ohm Resistor in parallel with the voltage leads to blead off the capacitance on the leads
- 1000lb closing force
- Induction coil set to constant power output, remained on until a temperature spike was observed

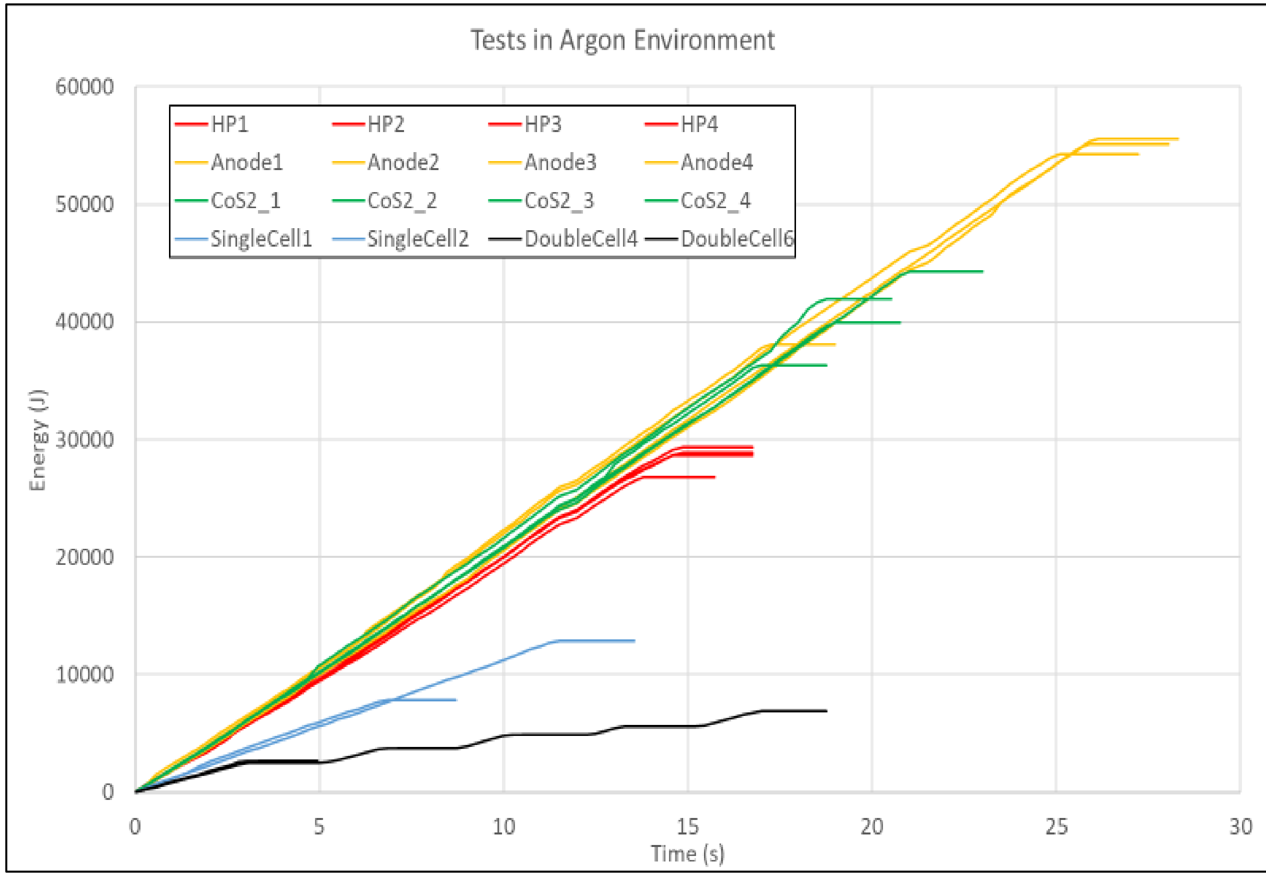
Results

- Voltage output was consistent with FeS_2 cells and line resistance
- Smooth temperature response and rapid voltage drop is likely due to the 100ohm resistor still in parallel with the leads
- One heat pellet did not ignite
- Anode showed a very high temperature spike but did not induce thermal runaway



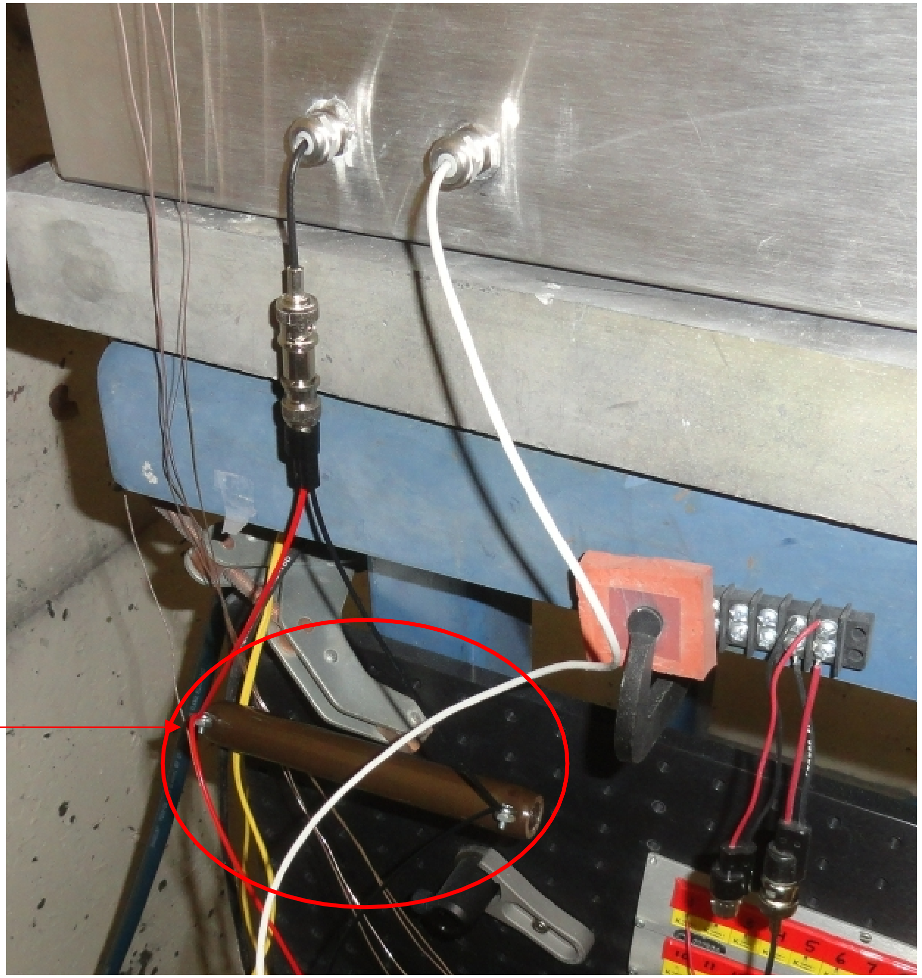
Tests in Argon

- Additional testing was conducted between Dec 12 and Dec22, 2020
- Individually tested main-sized heat pellets, anodes, CoS_2 cathodes, and cells with the maximum current setting in an argon environment to determine reactivity of each pellet to the induction field in an inert environment
  - Heat pellets ignited fastest
  - Anode and cathode tests were arbitrarily ended after the test duration had significantly exceeded the heat pellet tests
    - Anode and cathode did not show significant degradation
- Results indicate heat pellets activate faster to induction fields when surrounded with additional cell components



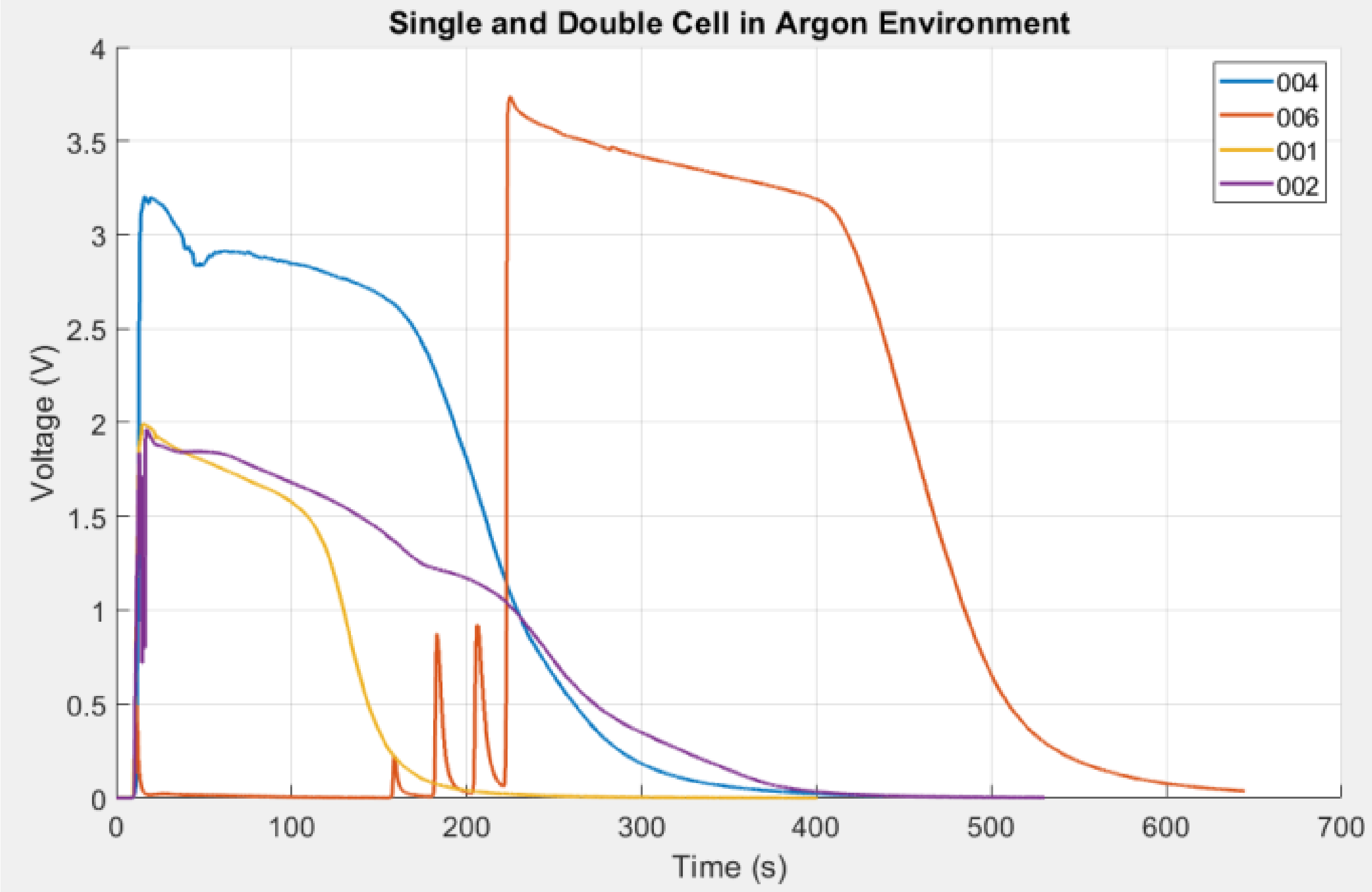
Modified Test Setup for Cell Level Tests

- A 5Ω resistor was placed in parallel with the voltage monitoring system to bleed off the capacitance that would build up on the leads
  - Without a resistor, the voltage before activation could be as high as 1.6V (for a single cell) which would mask the actual activation of the cell
- Titanium collectors and electrodes were used instead of stainless steel for the majority of tests
  - One double cell test still used stainless steel to test pulsing the heater after Ti collectors were consumed



Cell Level Tests

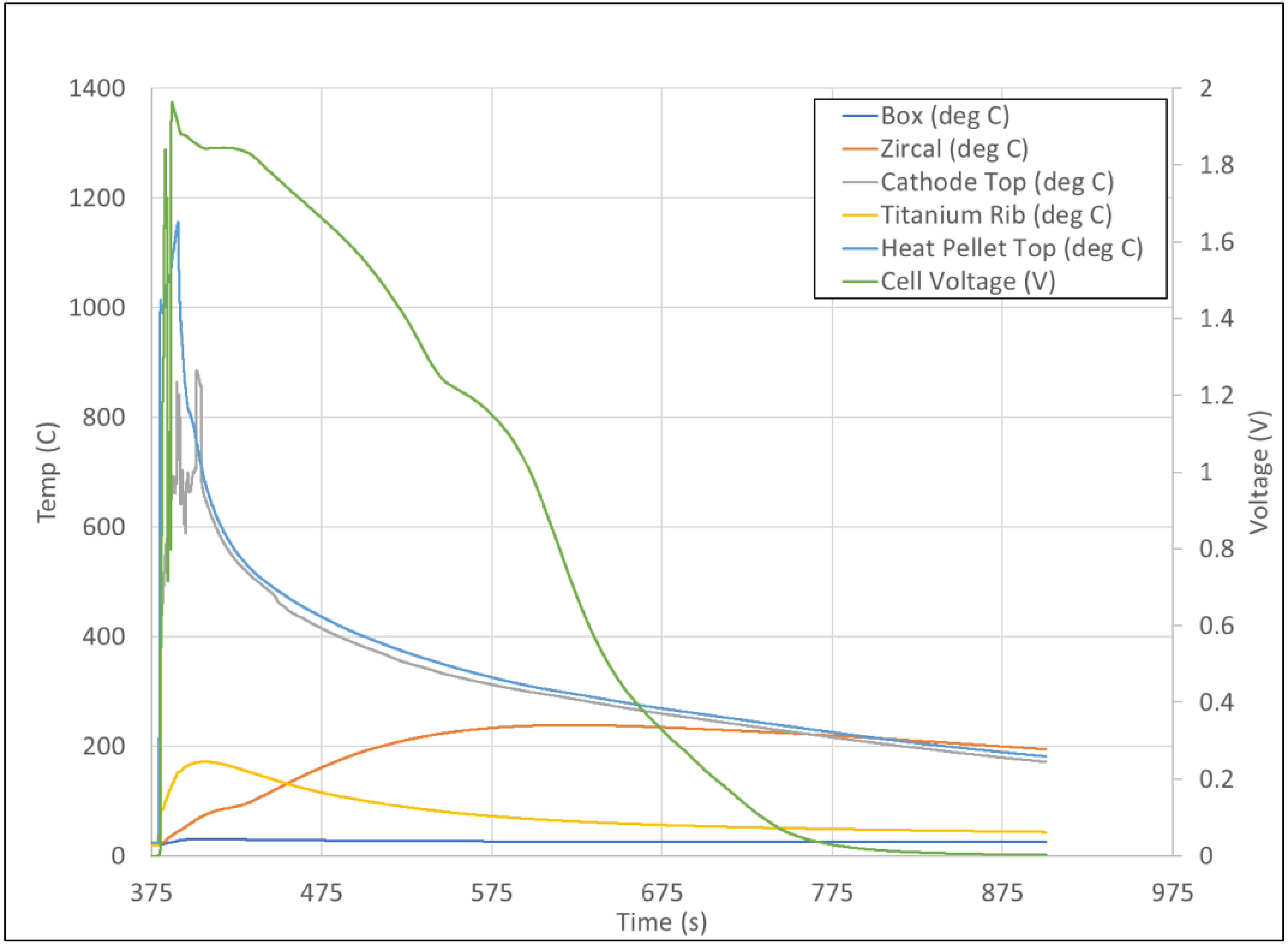
- Two single cell tests and six double cell tests were conducted
- Single cell activations were simple and showed excellent discharge curves
  - Single cells would activate (show voltage) concurrently with the heat pellet temperature spike
- Double cell tests were more difficult to achieve correct activation
  - Four tests went into thermal runaway most likely due to user error
  - One heat pellet would activate, but full voltage of the stack was not observed. Thus the heater was left on for a longer duration which would easily send the stack in runaway when the heat pellet activated
- Test 006 showed an excellent activation after pulsing the induction heater.
  - Test 006 used stainless steel collectors and electrodes



Note: Peak values below the theoretical voltage may be due to oxidation of the pellets, line resistance, and activation under 5Ω load.

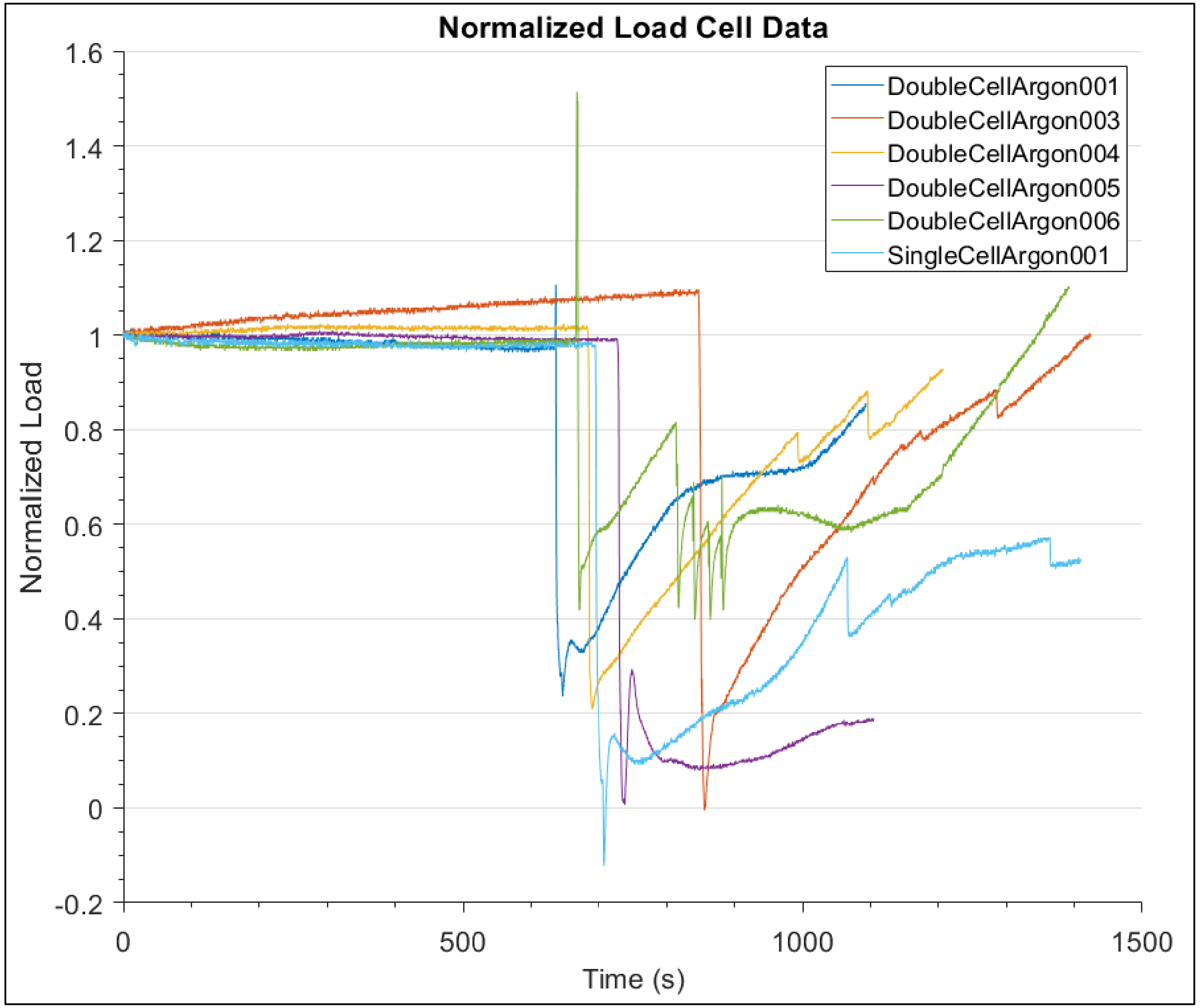
Internal Cell Temperature Measurements

- The geometry of the test fixture allows internal cell temperatures to be measured
- The heat produced by the heat pellet and subsequent reactions is more representative than currently available single cell test configurations



Load Cell Response

- Applied loads were normalized for analysis, but did not exceed 30 lbs
- Large loads applied with Texture Analyzer are possible and will be used for stack testing
- Load cell records at 50Hz and captures the phase change of the electrolyte
- Stack pressure rapidly drops at activation but increases with time, perhaps due to expansion of the axial insulation as it heats up



Preliminary Conclusions

- Can use induction heating to activate a thermal cell stack
- Can use the reusable test fixture to quickly test thermal cell designs at realistic closing forces
  - Will yield stack force during active performance
- Can measure internal cell temperatures at as many points as needed
- Successful testing of NiAl thin films using induction heating
  - Details were not included in this presentation
- Test fixture and case is robust to thermal runaways, reducing the risk of testing fringe chemistries

Future Work

- Full stack testing with 10 cells in argon environment, titanium collectors, and resistor in parallel controlled by a relay
- Interface of Maccor tester with the setup to allow loads to be applied
  - We anticipate using alligator clips to connect the leads. This will add line resistance, but in a simple series cell stack, it is simple to calibrate the tester to account for the increase.
- Purchase induction heater system and perform testing in 894 fumehood
- Investigate the responsiveness of the ignition time and/or energy to the percentage of iron in the heat pellets
- Develop control software to automate the induction heating such that heating pulses are terminated once a sufficient voltage is detected
- Iterate the fixture and case design to allow for testing in a vibration cell
- Iterate on the coil design to target specific areas and/or materials in the stack that may be more susceptible to EMF heating

Backup Slides

Problem Solving: Project Charter

Project Lead: Greg Peacock, 07547 & Nathan Johnson, 07547 **Other Team Members:** Chris Apblett, 07500; Chris Esquibel, 07547; Teal Harbour, 07546

Project Title: Reusable Test Fixture using Induction Heating

The Defect

Each development cycle for thermal batteries require 6-9 months to contract, build, and receive thermal batteries with new formulations that then must be tested to understand the new formulations' effect.

The Risks

Describe risks to the program that might arise from the defect. Include likelihood and severity (Likelihood / severity)

- The long lead times that currently exist in the development of thermal batteries raises the potential for cost over-runs and schedule delays.
  - Likelihood: Medium   Severity: Medium - High
- Future thermal batteries will likely require multiple design iterations to produce the desired performance, the extent of which can vary between design requirements.
  - Likelihood: High   Severity: Medium

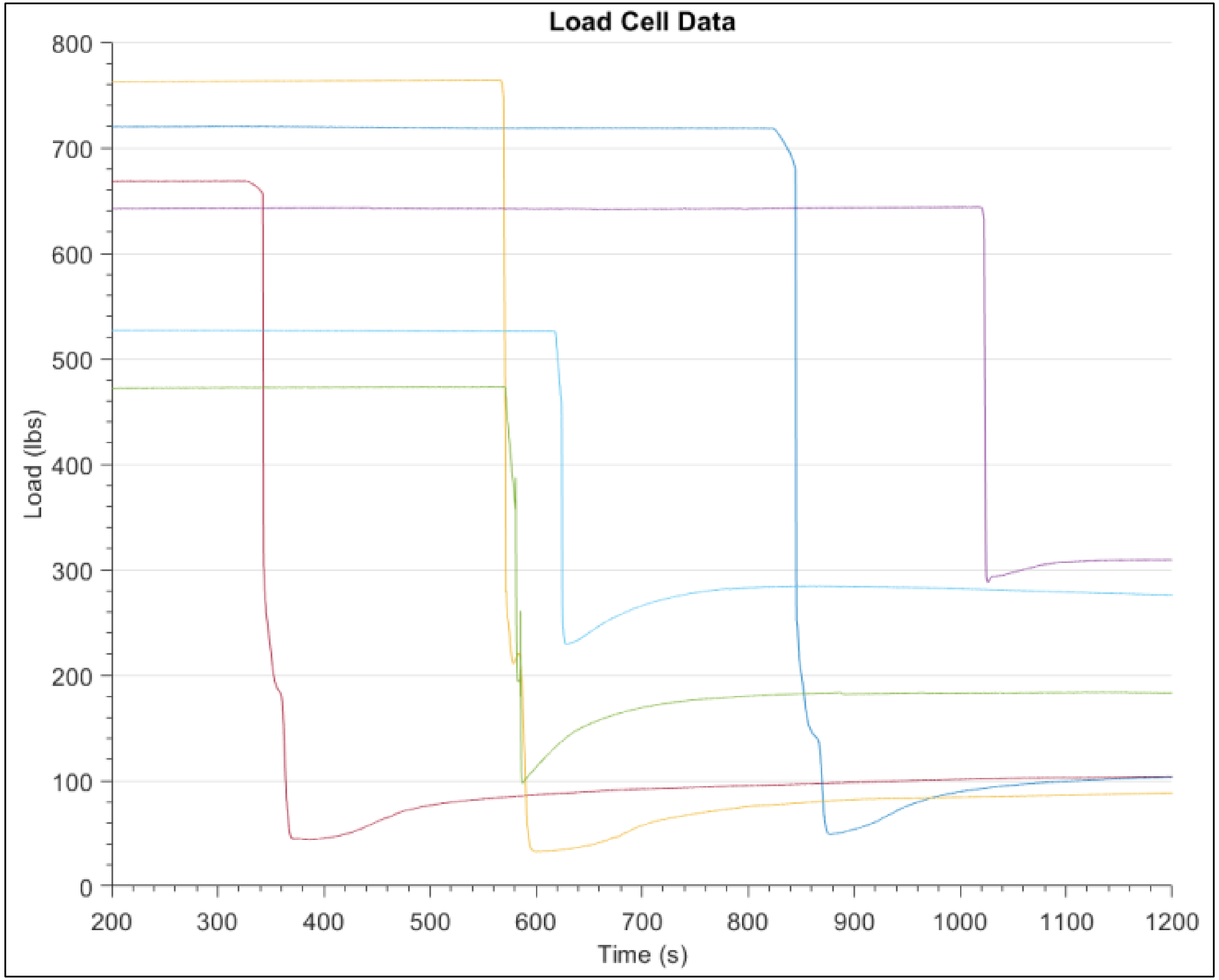
The Goal(s)

Reduce the risks by developing a test fixture that:

- Doesn't require hazardous pyrotechnics, ESD sensitive materials, or long lead times.
- Will allow representative closing forces to be employed and for the cell stack to be loaded with the mission's electrical requirements.
- Will be reusable without major cleaning or modification.

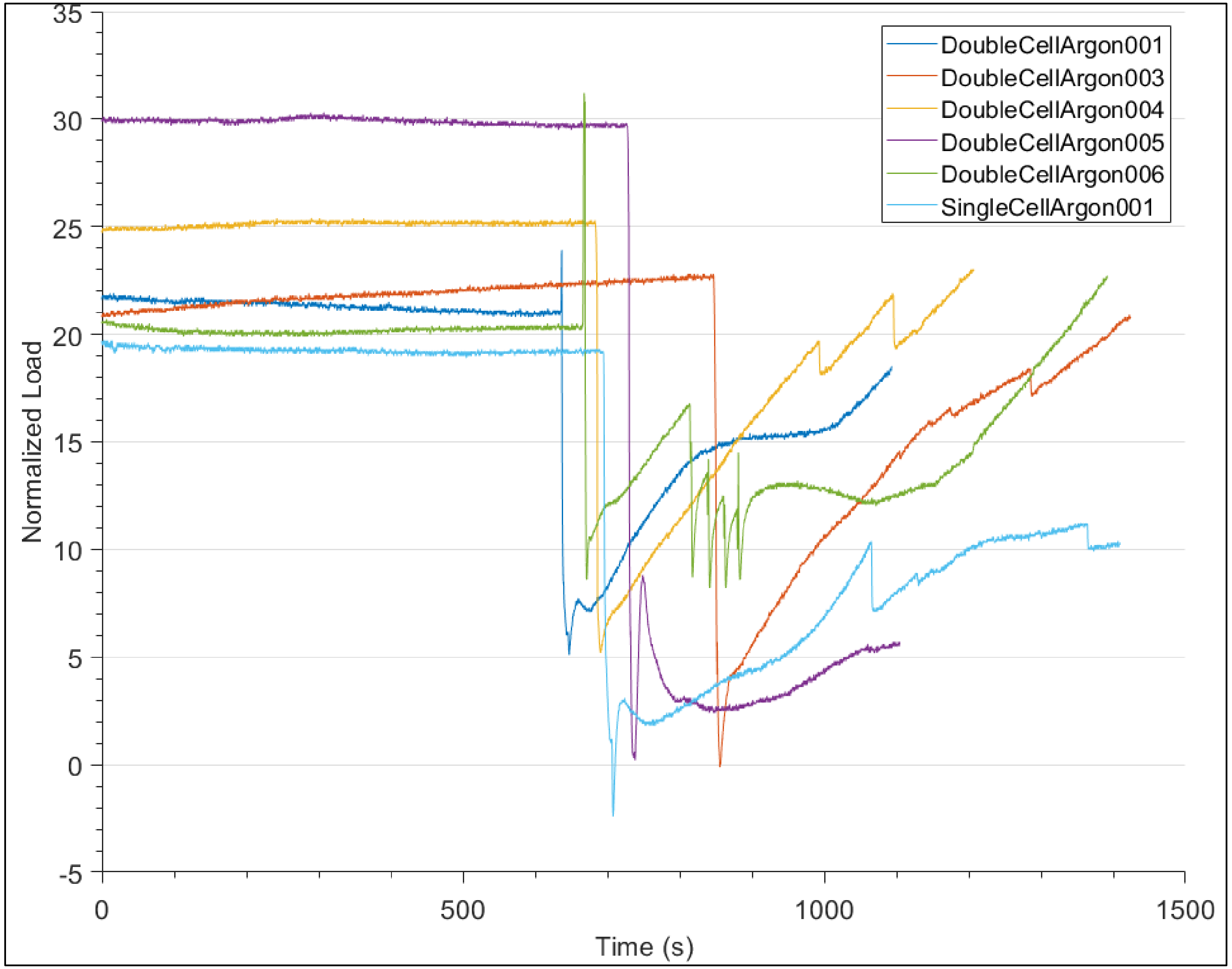
Load Cell Response

- Applied loads were not consistent during tests, ranged from hand tightened to ~1,000lb.
- Large loads applied with Texture Analyzer in 132, then the screw cap is torqued down using a wrench.
- Load cell records at 50Hz and captures the phase change of the electrolyte.
- The plot is intended to show the ability to measure the stack force, not to draw conclusions from. Future tests will use a consistent stack force to accurately measure the response.

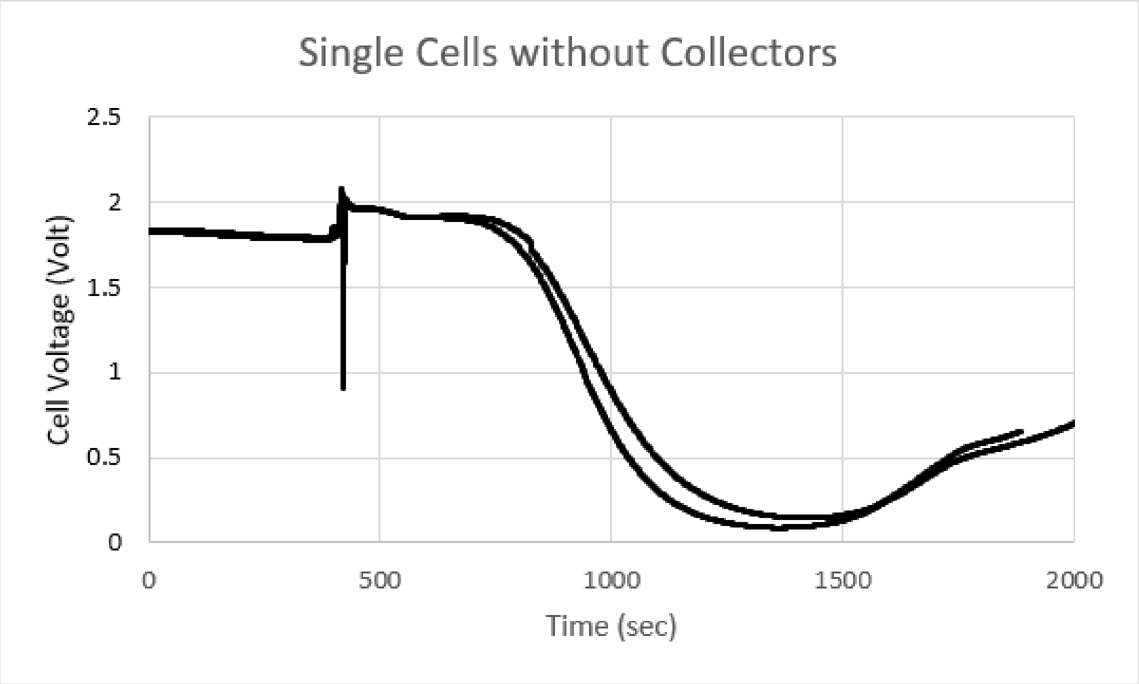


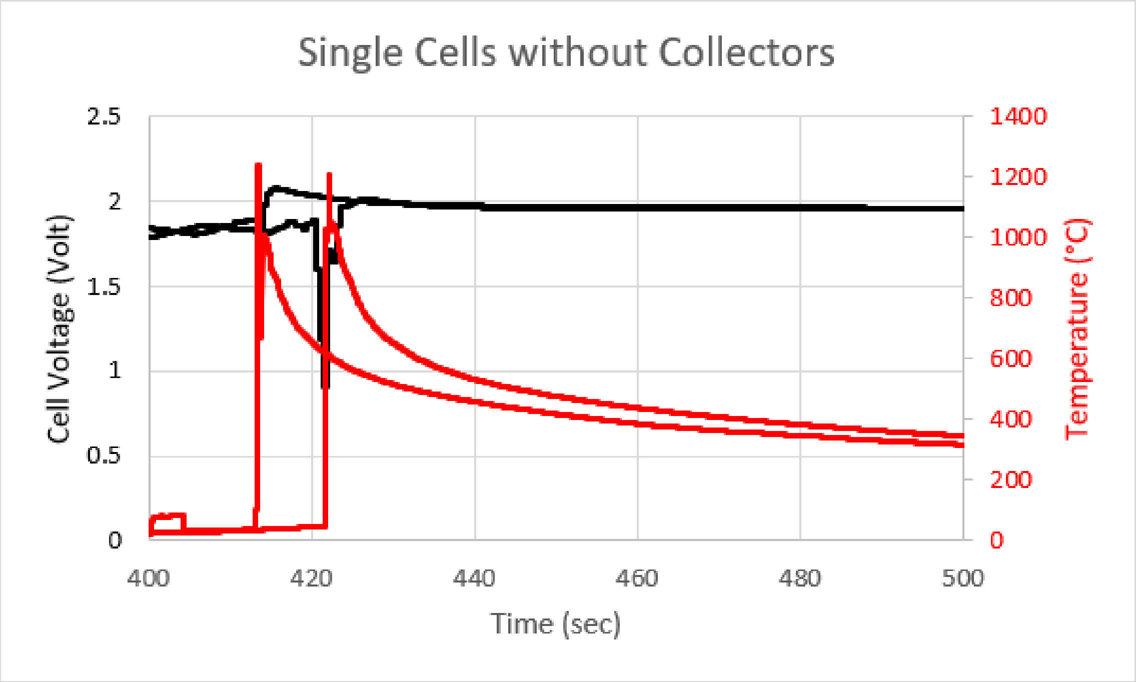
Load Cell Response

Load Cell data without normalizing to the first recorded value



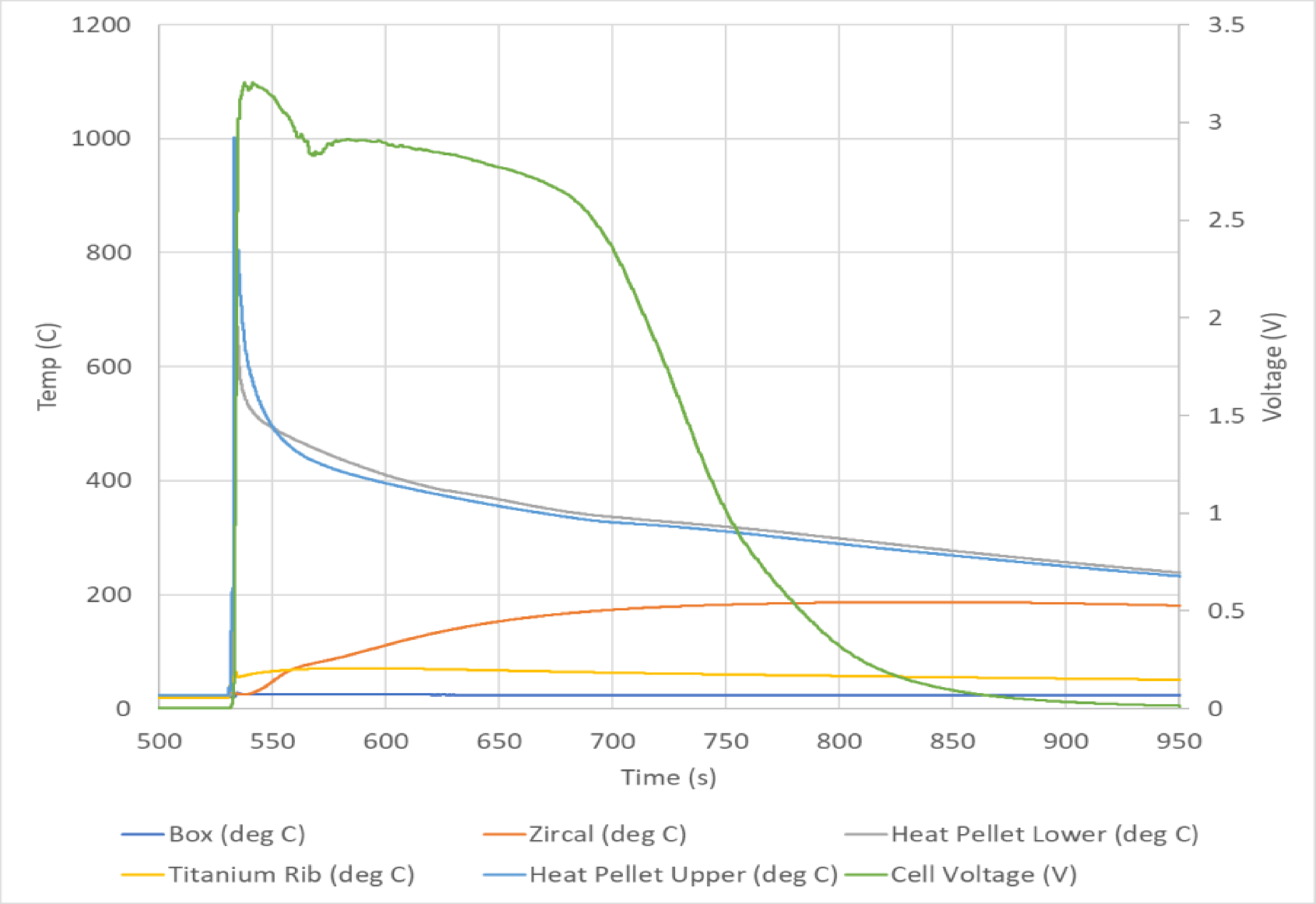
Data Analysis – Single Cells without Collectors





Test	Potential OCV	Recorded Max Voltage	Voltage Prior to Test	Voltage 10 sec after "Ignition"	Voltage when Temp is 350C (Heat Pellet)	Max Temp (Heat Pellet)	Time between "ignition" and 350C	Time Coil was On	Enegry Output of Coil
	(Volt)	(Volt)	(Volt)	(Volt)	(Volt)	(deg C)	(sec)	(sec)	(Joule)
1Cell_18	1.98	2.02	1.84	1.98	1.95	1209.2	75	21.6	40497
1Cell_19	1.98	2.08	1.82	2.01	1.97	1239.3	65	21.5	42770
2Cell_1	3.96	4.05	3.73	3.86	3.85	737.9	2	10.6	13408
2Cell_2	3.96	3.90	3.89	3.83	3.74	818.4	2	9.7	12140
2Cell_3	3.96	3.87	3.84	3.73	3.57	998.8	34	10.8	13447
2Cell_4*	3.96	3.65	0.56	3.24	3.61	604.5	2	7.5	9032

Double Cell Test 4



Double Cell Test 6