Developmental and Cryogenic Thermal Vacuum (TVAC) Testing Lessons Learned

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Agenda

- HI-TTeMP Overview
- Developmental Testing Overview
- Developing Cryogenic Testing Ability in the HI-TTeMP Lab
- Discussion of Lessons Learned and Best Practices

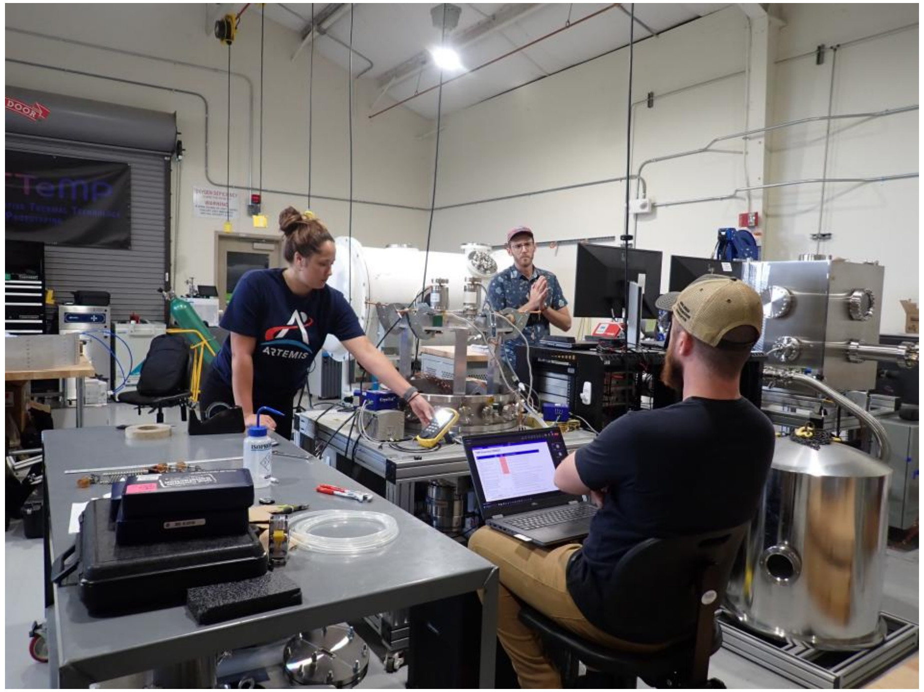
Every unexpected challenge became an improvement to the laboratory.

HI-TTeMP Overview

HI~TTeMP

Hub for Innovative Thermal Technology Maturation & Prototyping

- A thermal testing laboratory at NASA Marshall Space Flight Center focused on supporting technology development through developmental thermal testing.
- Established only a few years ago, the lab has rapidly expanded its capabilities:



Focus on developmental thermal testing	Supports technology maturation	Implement lessons learned from past test efforts	Hands on experience for engineers of all levels	Inform thermal analysis
TVAC and benchtop testing	Emphasis on rapid problem solving and iterative test development	Document lessons learned to benefit all lab users	Learning opportunity for engineers, from interns to more experienced analysts	Decrease model uncertainty with vacuum and benchtop test results

Developmental Testing Overview

The HI-TTeMP Lab primarily supports developmental thermal testing, where the objective is to

- mature technologies, develop test capabilities, reduce technical risk, and learn from each test campaign.

Verification Testing vs Developmental Testing	
Verification Testing	**Developmental Testing**
Verifies compliance with requirements	Reduces risk and matures the design earlier on
Pass/fail against defined criteria	Flexible, iterative, and learning focused
Test plans follow standards (with tailoring)	Test plans can be different depending on goal of test
Validates flight readiness	Identifies issues before qualification
Follows established procedures	Refines hardware, procedures, and test methods

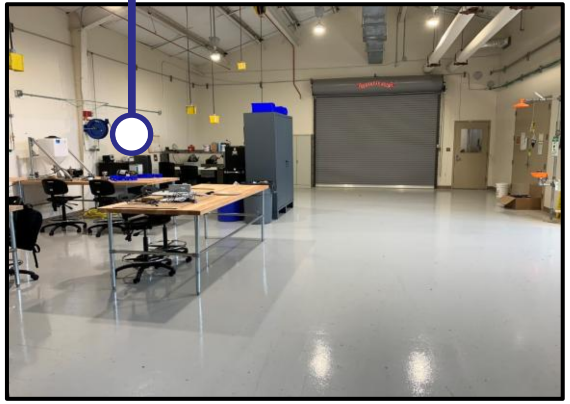
Growing Developmental Thermal Test Capability in HI-TTeMP

2021:
HI-TTeMP Lab Established

Benchtop Test Capabilities
New Facility

2022: Expand Equipment

Vacuum Test Capabilities



2023: Began Developing Procedures

OWI
Standard Operating Procedures

2023-2024: Continued Testing and Growing

New developmental tests conducted in the lab encouraged new methods and introduced lessons learned

2024: Began Developing Cryogenic Capability

Sunpower Stirling Cycle Cryocoolers acquired, first use began

2025: Began Refining Processes

Continued development of cryogenic test capability

Troubleshooted and grew with every lesson

2026

- 4 operational thermal vacuum chambers, 1 in progress
- Benchtop thermal testing capability
- Cryogenic testing capability
- Improved instrumentation and data collection methods
- Established operating procedures

Why Developmental Testing Matters

GAIN INTUITION

Observe real world thermal behavior, integration challenges, hardware performance

MATURE TECHNOLOGIES

Refine hardware, instrumentation, and test procedures through iteration

DEVELOP ENGINEERS

Well rounded experience, make connections between theory and real life

REDUCE RISK EARLY

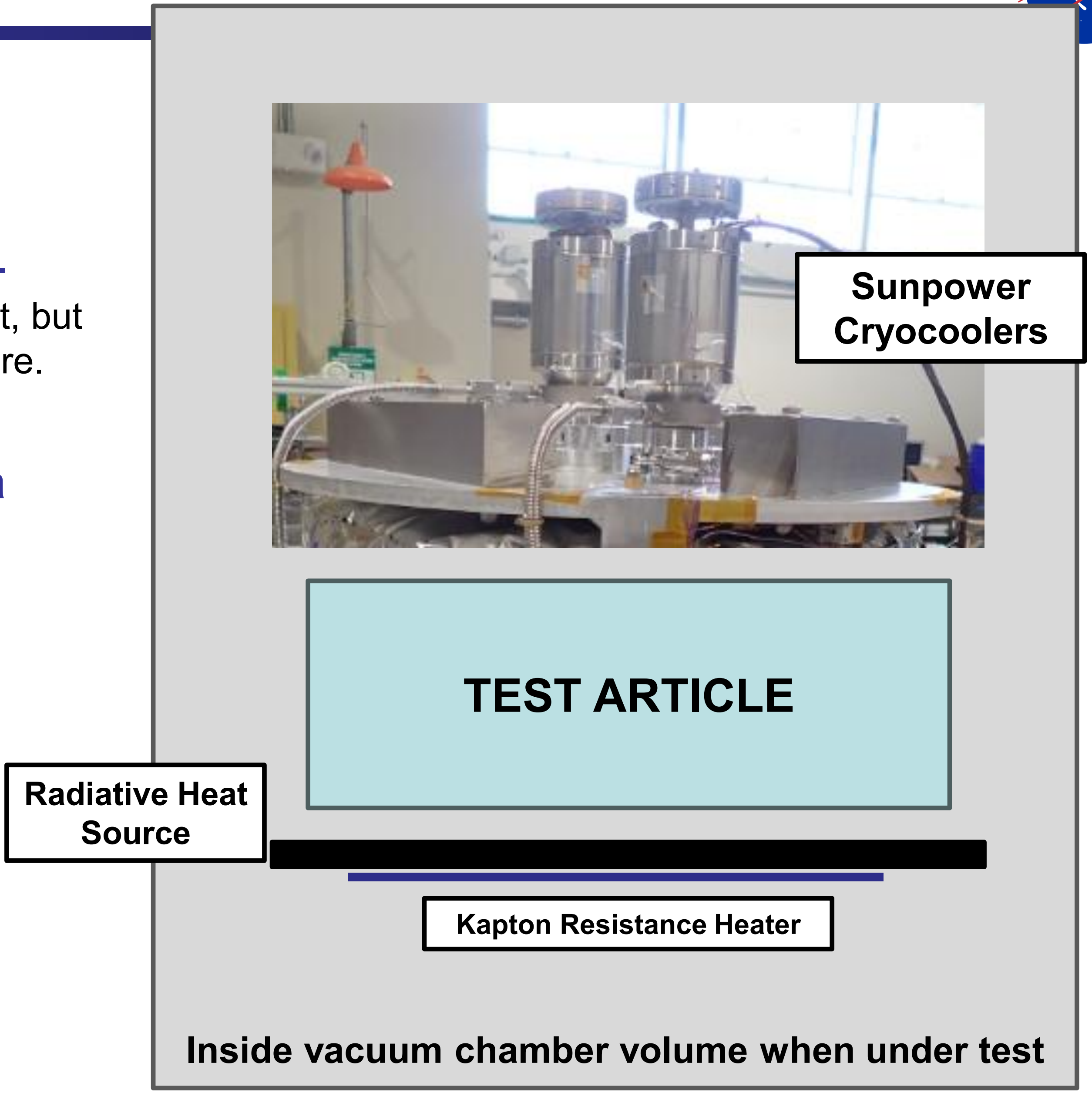
Test smaller components or perform shorter tests before full system testing

INFORM ANALYSIS

Gather data to correlate and tune models to understand their accuracy

Test Example: Background

- A project required the development of a new cryogenic TVAC testing capability to support testing of thermal protection system hardware.
  - The bulk of these lessons learned come from this test, but the topic is CUI so it will not be discussed in detail here.
- The test required a cryogenic boundary, and a radiative heat source.
- Cryogenic Source:
  - Sunpower GT Cryocooler(s)
- Radiative Heat Source
  - Kapton resistance heater applied to aluminum plate, offset to radiate heat to test article



Developing a Cryogenic TVAC Testing Capability

- The required cryogenic test capability did not yet exist in HI-TTeMP
  - Did not have the ability to accommodate the required test setup in HI-TTeMP and capture cryogenic data
- To provide test data to the project, the lab was required to develop and refine:
  - Cryogenic test and cryocooler operations, including developing procedures
  - Instrumentation strategies for components at cryogenic temperatures
  - Chamber configurations to accommodate cryocoolers and associated equipment
  - Heater application methods for components at cryogenic temperatures
  - Contamination control practices
  - Vacuum operations and processes
  - Troubleshooting and recovery methods

- Each test not only matured the hardware; it also matured HI-TTeMP's testing capabilities.
- Lessons were learned at every stage!

Lessons Learned

We encountered challenges every step of the way…

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- Planning
- Materials and Interfaces
- Contamination control
- Instrumentation
- Vacuum operations
- Cryogenic testing
- Troubleshooting
- Scheduling

Planning for Success

The quality of a test and its results is largely determined *before the chamber door ever closes*.

Planning includes

- Defining objectives
- Designing the thermal architecture
- Developing instrumentation plans and layouts
- Determining heater and sensor locations
- Performing preliminary thermal analysis
- Reviewing assumptions
- Getting experienced engineers involved

The best developmental tests are designed *collaboratively*, not independently.

Planning: Combination of Analysis and Testing

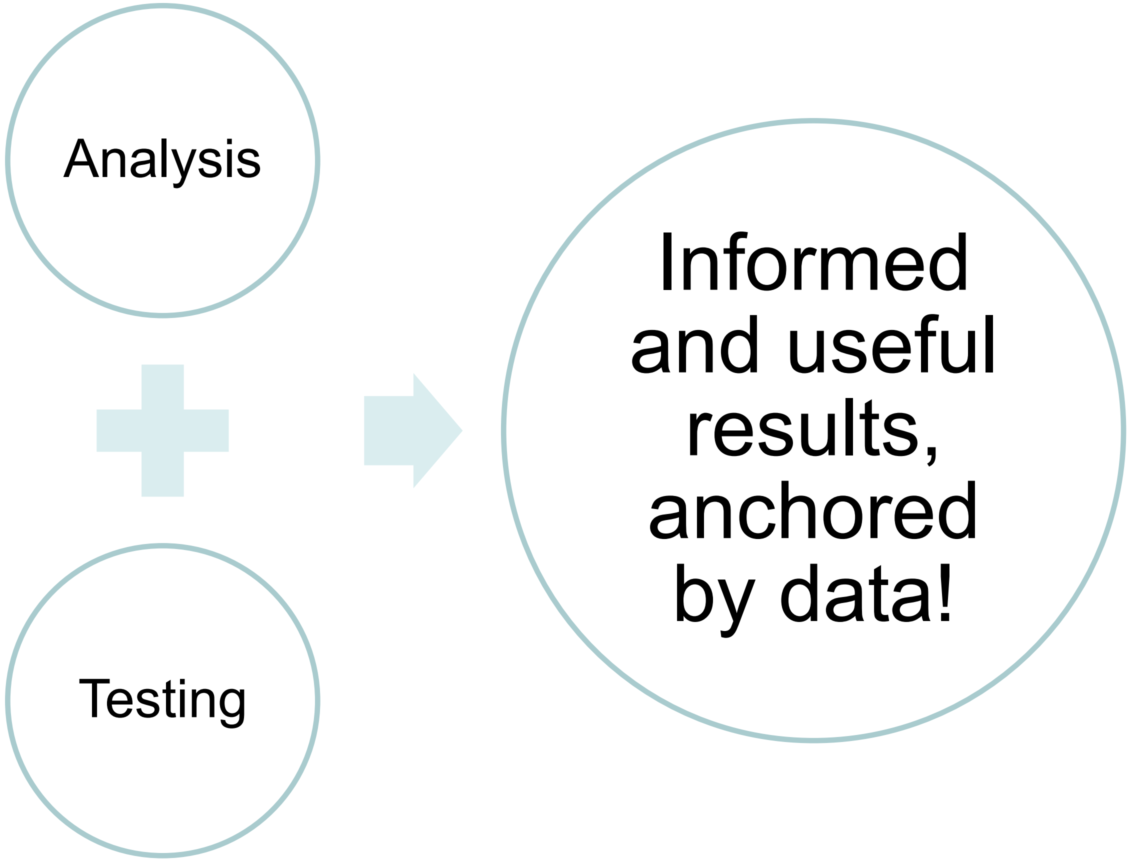
Analysis without testing leaves uncertainty.
Testing without analysis limits understanding.

Preliminary Analysis Helps Testing:

- Predict expected temperatures
- Identify critical sensor locations
- Determine heater sizing
- Evaluate boundary conditions
- Estimate testing timeline
- Increase confidence before hardware is built
- Determine data needed to be collected

Testing Helps Analysis:

- Validate assumptions
- Improve model fidelity
- Identify unknowns
- Refine contact conductance
- Refine material properties
- Improve future predictions



Example of the importance of collaboration between test engineers and analysts:

Initial test concept developed by the thermal testing team

Based on engineering intuition, previous testing experience, and project requirements.

Experienced thermal analysts, test engineers, and subject matter experts reviewed the concept to ensure the test would produce meaningful, representative data.

The review challenged key assumptions and balanced test practicality with analytical fidelity, resulting in a significantly improved test design.

~3 months invested in redesign before fabrication

- More representative boundary conditions
- Improved ability to calculate calorimetry and track heat flows
- Higher confidence in test results and model correlation
- Avoided costly redesign after fabrication and testing

Lessons Learned

We encountered challenges every step of the way…

Planning

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Materials and Interfaces

Contamination control

Instrumentation

Vacuum operations

Cryogenic testing

Troubleshooting

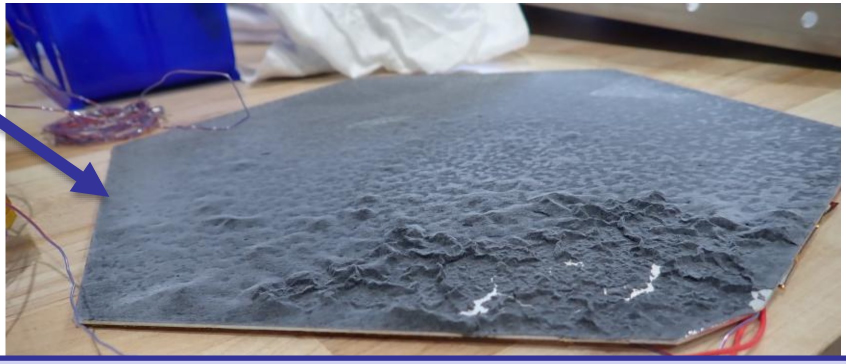
Scheduling

Materials: Adhesives

Carefully prep surfaces, test all adhesives (especially expired ones if applicable), and check temperature limits before using or applying to test hardware

- Ex: Applied silver Teflon tape to shroud walls to achieve ε=0.81 on interior surface.
  - Tape delaminated from surfaces entirely undergoing vacuum at cryogenic temperatures
- Ex: Radiative heater plate painted with Aremco 840-M cracked and peeled under vacuum and near cryogenic temperatures
  - Plate was painted > 3 years ago, could have degraded over time
  - Plate was stored in non-humidity-controlled lab
  - We have no knowledge of how the surface was prepped before painting
- Both failures could have resulted from
  - Poor surface prep
  - Degraded/expired adhesive
  - Operating outside of temperature ranges

Problem: High E surface treatment (Silver Teflon tape) delaminated



Problem: Aremco coating failed under test

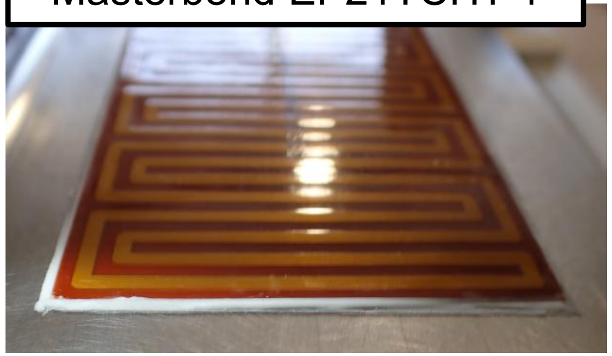
Solution: Improve surface prep, find more compatible treatments/coatings/adhesives

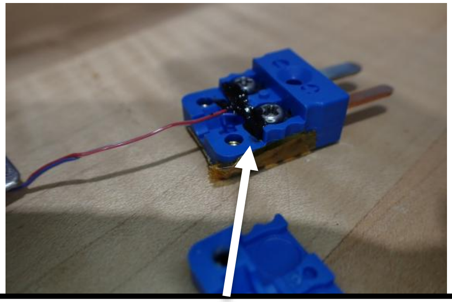
Materials: Epoxy/Adhesive Selection

- Some common epoxies used in thermal vacuum testing
  - Master Bond EP21TCHT-1 – Thermally conductive, cryogenic compatible epoxy with low outgassing characteristics; well suited for applications where good thermal coupling is required
  - Master Bond EP29LPSPAO – Low outgassing epoxy with good thermal conductivity and cryogenic compatibility
  - 3M Scotch-Weld 2216 – Flexible, general-purpose structural adhesive with relatively easy handling and cure; useful when compliance through thermal cycling is beneficial
  - Stycast 2850 FT/GT – Thermally conductive, electrically insulating epoxy commonly used for potting, encapsulation, and instrumentation applications
- Key parameters to consider during a trade study
  - Coefficient of thermal expansion (CTE) and CTE mismatch
  - Thermal conductivity / Electrical conductivity or insulation requirements
  - Operating temperature range / cryogenic compatibility
  - Vacuum compatibility and outgassing
  - Bond strength and flexibility
  - Cure temperature and cure time
  - Working life / handling requirements
  - Bondline thickness and surface preparation
  - Reworkability / removal requirements
- Use analysis to support material selection
  - Even simple Thermal Desktop models can quantify the impact of adhesive thermal conductivity, bondline thickness, and contact resistance
  - Analysis can help determine whether a higher-performance adhesive provides a meaningful thermal benefit for the application

Scotchweld 2216

Masterbond EP21TCHT-1





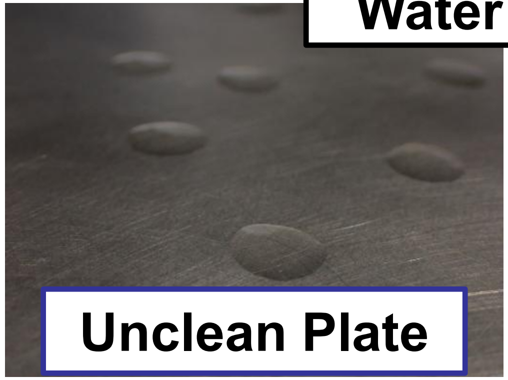
Stycast 2850 FT Cat 9

Adhesive or epoxy selection should be treated as a trade study because no single epoxy is ideal for every application.

Surface Preparation Best Practices

- Surface preparation is just as important as adhesive selection.
  - Never skip cleaning or abrasion steps.
- Clean surface properly
  - Degreaser, Acetone, IPA
  - Water droplet test
- Abrade surface with appropriate grit sandpaper/Scotchbrite pad to ensure proper adhesion of epoxy

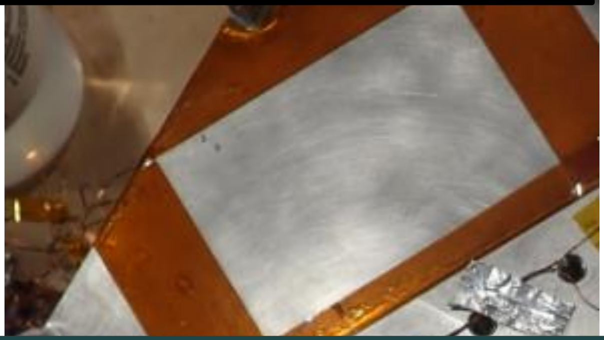
Water Droplet Test



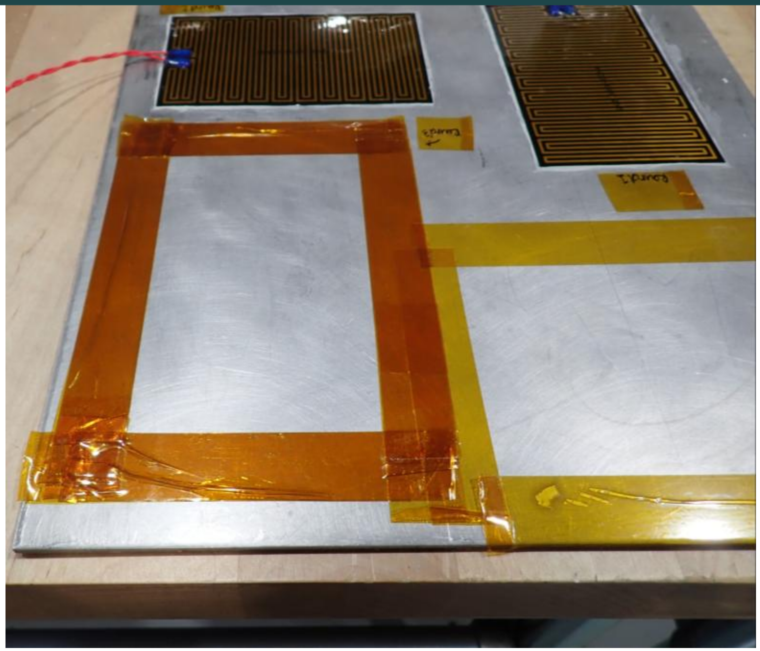
Unclean Plate

Clean Plate

Abrasion of Surfaces



Abraded heater areas, also abraded underside of heaters before application to help with adhesion

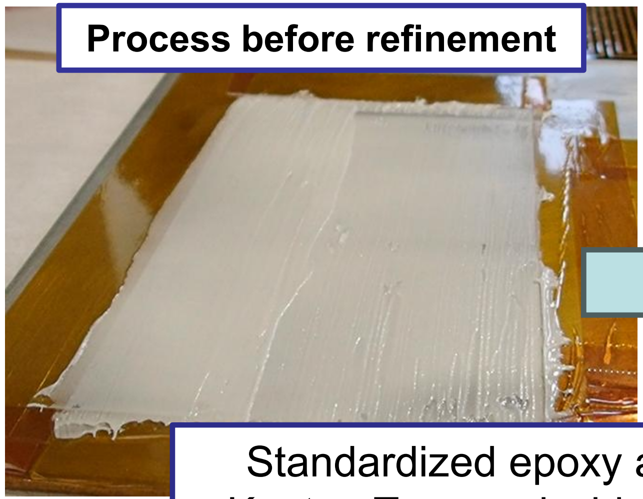


Materials: Adhesives and Kapton Heater Application

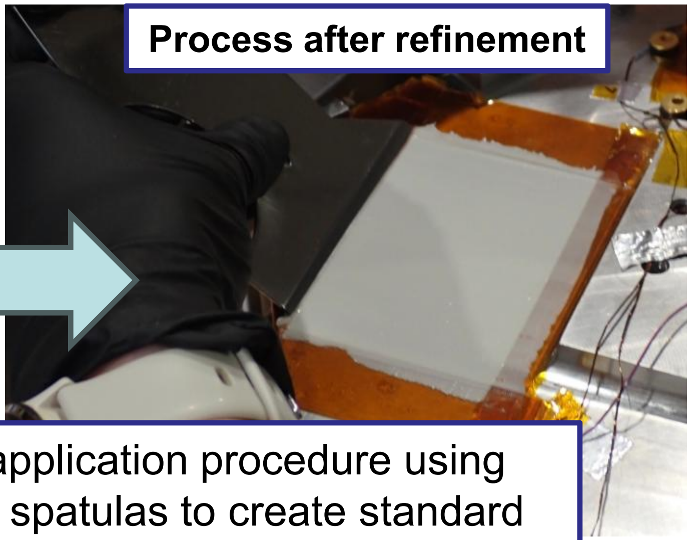
- Match the adhesive to the environment.
  - Cryogenic epoxy
  - Epoxy suited to use with Kapton
    - Masterbond EP21TCHT-1
- Validate bond methods and material itself before committing to the test article.
- Standardize the preparation process for repeatability.
- Contact manufacturer with questions about products

Problem: Kapton PSA heaters delaminated from stainless steel surface at cryogenic temperatures multiple times

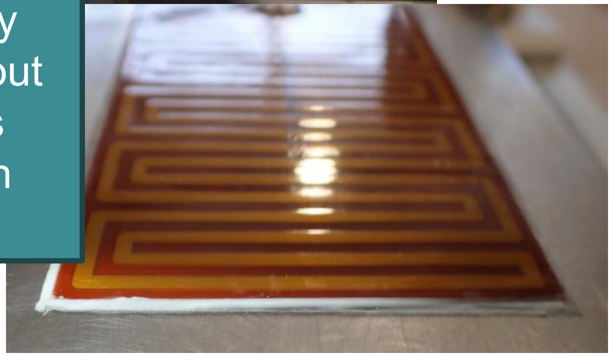
Process before refinement



Process after refinement



Standardized epoxy application procedure using Kapton Tape and wide spatulas to create standard bond line thickness. Improved application by practicing and using proper tools



Solution: Thoroughly tested and checked out cryogenic epoxy as adhesive for Kapton heaters

Thermal Interfaces

- Examples of common materials used in HI-TTeMP lab
  - Grafoil
  - PGS (Pyrolytic Graphite Sheets)
  - Kapton Tap
  - ULTEM
- Conduct trade studies during design phases to select and implement thermal interface materials
  - Key Parameters to consider during trade study:
    - Conductivity
    - Material compatibility with vacuum
    - End goal of interface
      - Adhesive interface vs Insulative face vs Conductive Face

Lessons Learned

We encountered challenges every step of the way…

- Planning
- Materials and Interfaces
- Contamination control
- Instrumentation
- Vacuum operations
- Cryogenic testing
- Troubleshooting
- Scheduling

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Contamination Control

- Removed non-vacuum-compatible materials
  - Instrumentation strain relief changed to steel clamps instead of rubber
  - Covering sharpie written labels with layer of Kapton tape
  - Rebuilding cryocooler cables since cryocoolers run inside vacuum, vendor provided cables are made of plastic
  - Utilizing Kapton insulated wires
- Implemented bakeout to test procedure
  - Bakeout begins when pumps are turned on
  - Test article reaches temperature a few degrees higher than highest goal temperature to ensure all contaminants are off-gassed
- Cryogenic shroud utilized
  - Shroud reached cryogenic temperatures first so remaining contaminants cooled to shroud instead of cryogenic components attached to test article

Lessons Learned

We encountered challenges every step of the way…

Planning

Materials and Interfaces

Contamination control

Cryogenic testing

Vacuum operations

Instrumentation

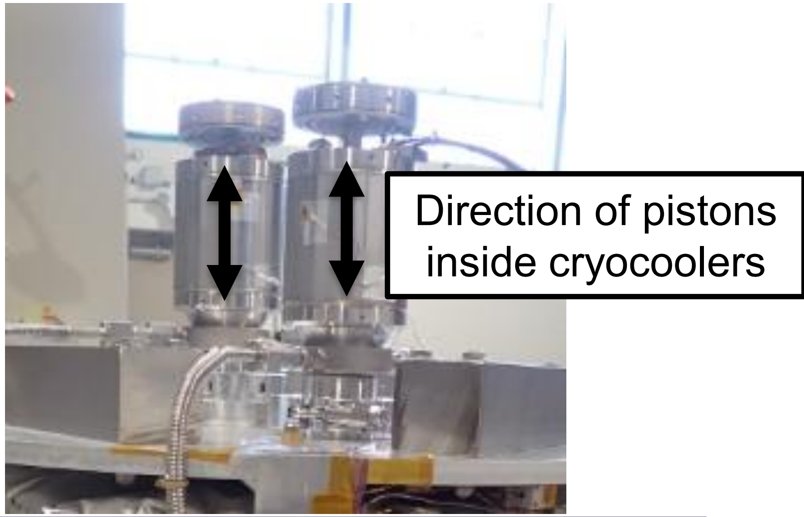
4

Troubleshooting

Scheduling

Instrumentation in Cryogenic Tests

- Instrumentation is a critical component of TVAC testing
  - Report temperature data at desired location(s)
  - Essential to understand heat transfer through components
  - Loss of data from sensors can render a test ineffective
- Types used in HI-TTeMP
  - Silicone Diodes
    - Preferred for cryogenic temperatures
  - Thermocouples (Type T, Type K, etc.)
  - RTDs
- Relation to cryogenic test:
  - Due to the vibrations caused by the cryocoolers:
    - We experienced loss of sensors, delamination of tape, breaking of wires, etc
    - Following charts show some lessons learned and solutions to these issues



Problem: Cryocoolers vibrate when operating and are rigidly mounted to frame. This is source of some sensors lost

Instrumentation Improvements and Lessons Learned

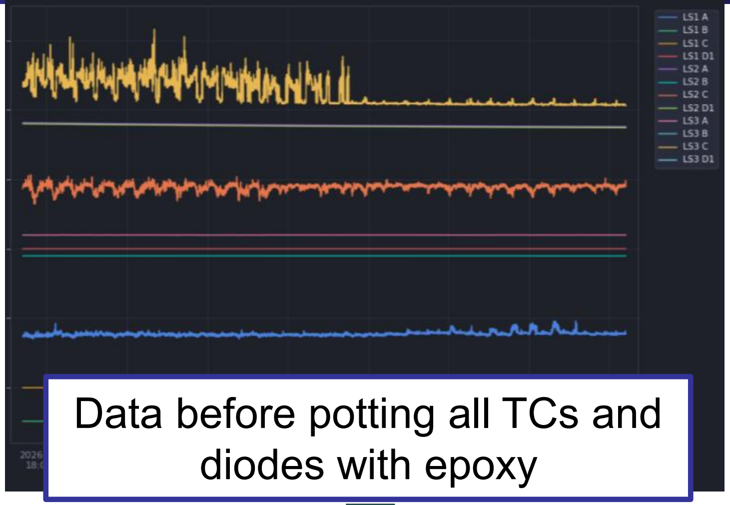
Mechanical Protection

- Pot sensors and thermocouples to improve retention under vacuum
- Use PEEK braided sleeving to reduce abrasion and organize wiring
- Protect wires from sharp edges and provide adequate strain relief
- Replace vacuum-incompatible rubber strain reliefs with metal clamps

Organization & Repeatability

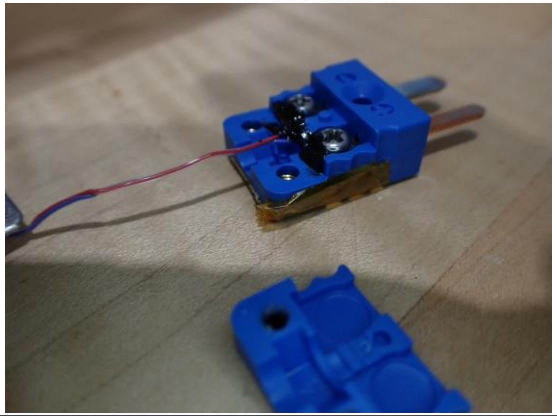
- Implement instrumentation plates for consistent sensor routing
- Route wiring with troubleshooting in mind
- Group instrumentation into organized bundles to minimize tangling
- Design for easier chamber closeout and assembly
- Standardize connector locations and labeling
- Reduce setup time between test campaigns

Problem:
Cryocoolers are rigidly mounted to test frame and vibrate, causing noise and loss of instrumentation.



Data before potting all TCs and diodes with epoxy

Data after potting all TCs and diodes with epoxy



Solution:
Potting inside sensor plug to prevent backing out of internal screws

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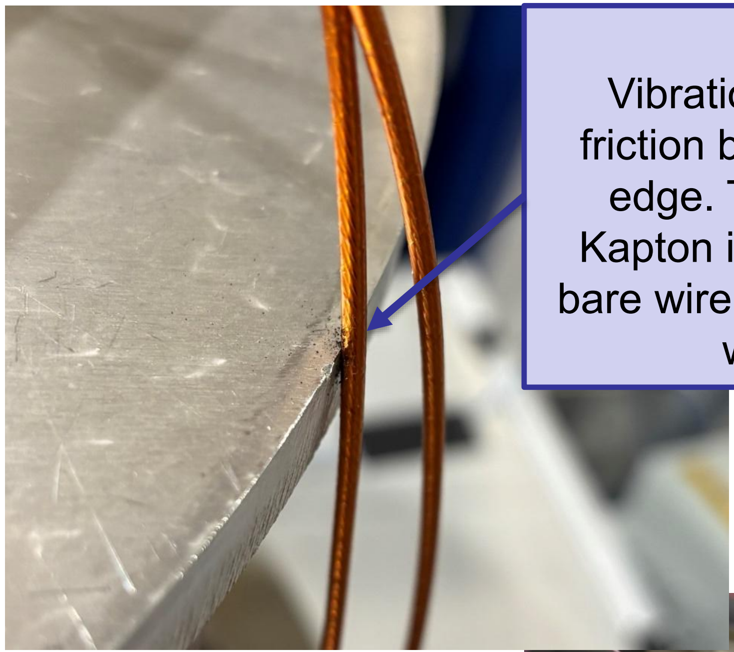
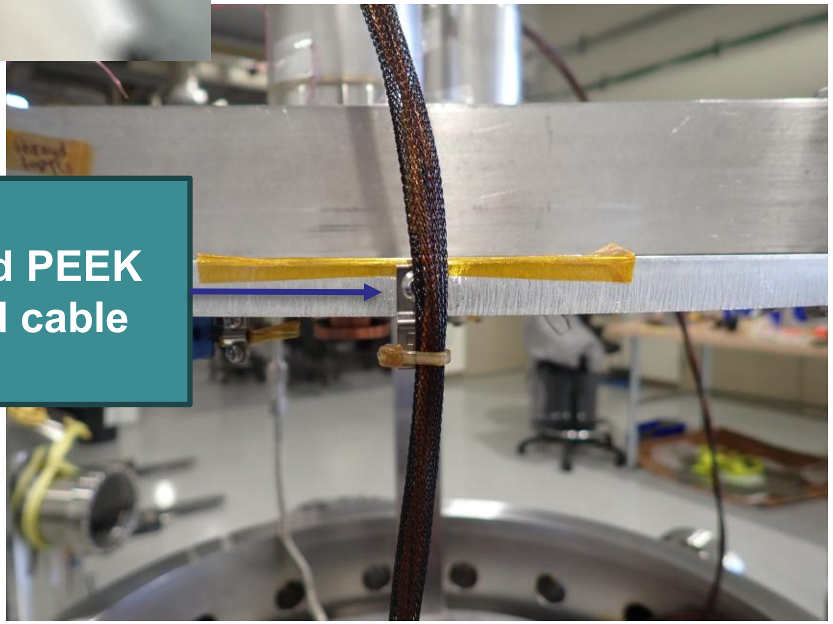


Problem:
Vibration from cryocoolers introduced friction between Kapton wires and frame edge. This caused degradation of the Kapton insulation on wires, exposing the bare wire and resulting in electrical contact with the aluminum frame.



Solution:
Filed sharp edges, added PEEK braided wire sleeve, and cable mounts

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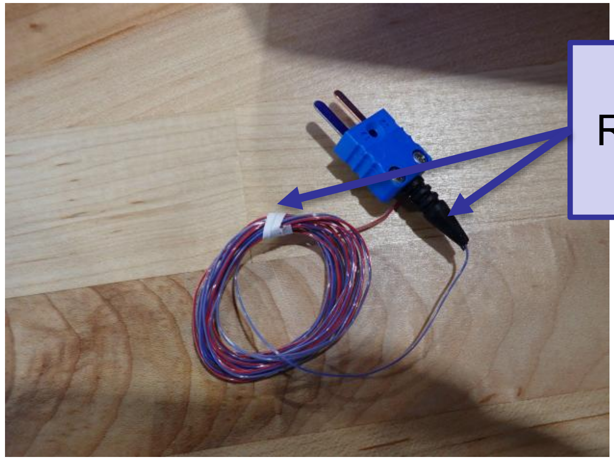
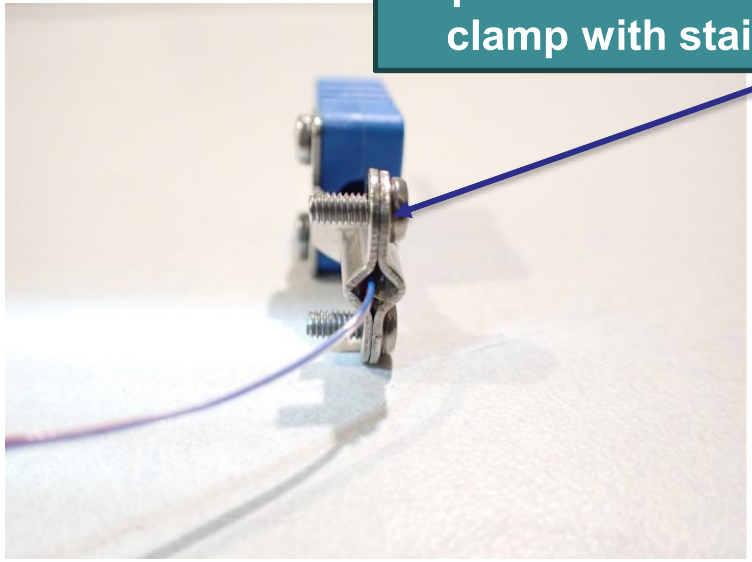
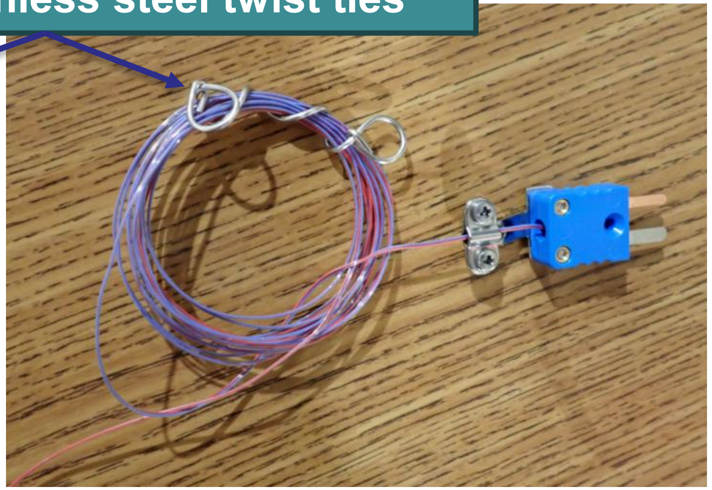


Problem:
Rubber strain relief + plastic twist ties outgas in chamber

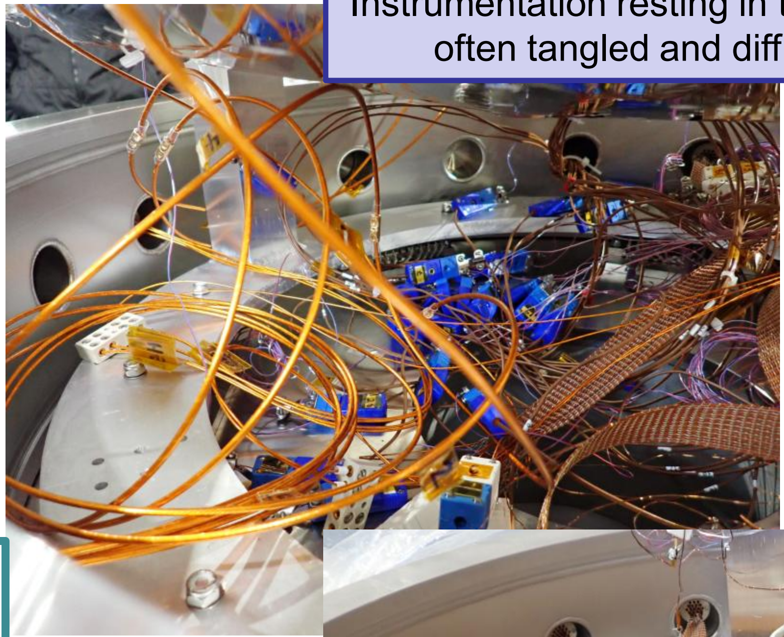
Solution:
Implemented stainless steel strain relief clamp with stainless steel twist ties

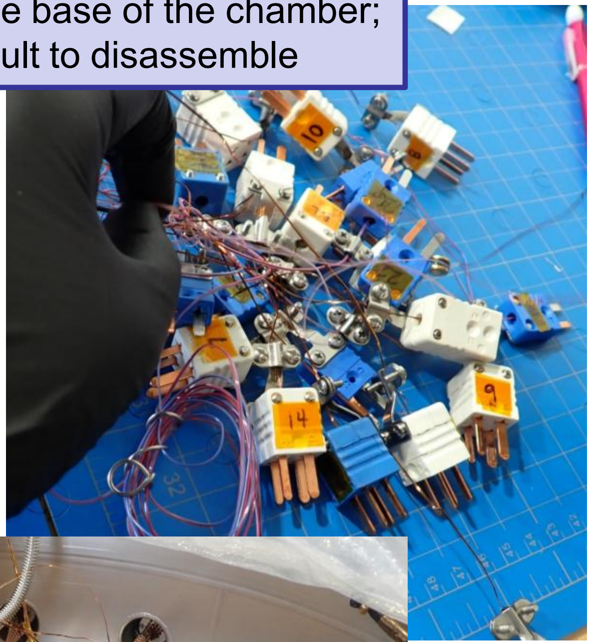


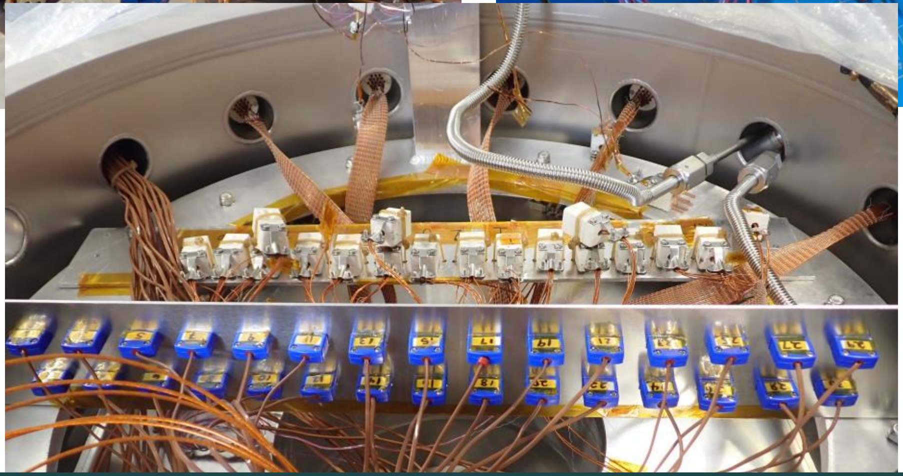


Instrumentation Improvements and Lessons Learned

Problem:
Instrumentation resting in the base of the chamber; often tangled and difficult to disassemble







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Solution: Implemented instrumentation plates and routed wires through PEEK bundles for cleaner assembly/disassembly

Lessons Learned

We encountered challenges every step of the way…

- Planning
- Materials and Interfaces
- Contamination control
- Instrumentation
- Vacuum operations
- Cryogenic testing
- Troubleshooting
- Scheduling

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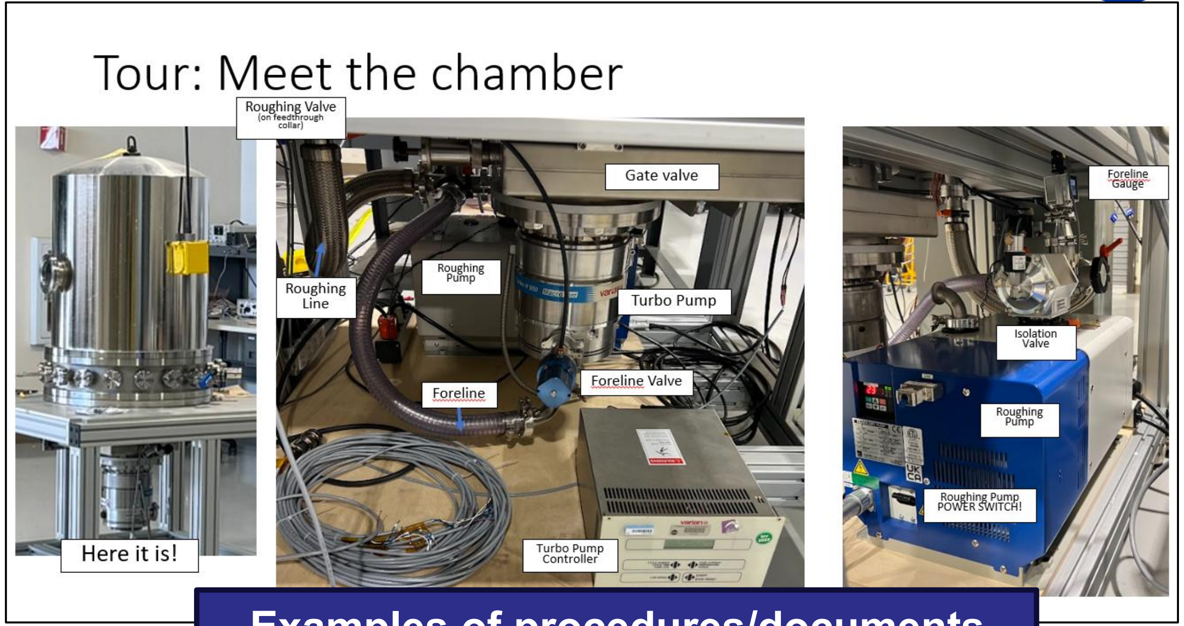
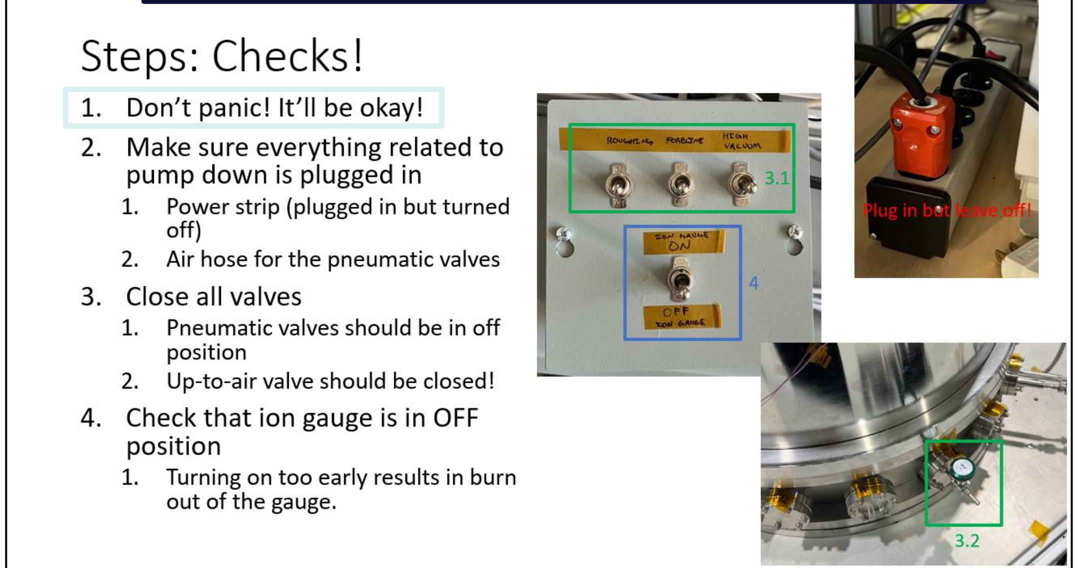
Vacuum Operations

Critical to have good understanding of vacuum procedures to ensure safety of lab personnel, pumps, and test hardware

- Engineers operate our chambers, so understanding chamber operation and pumps is essential
- Developed written procedures to ensure operating consistency



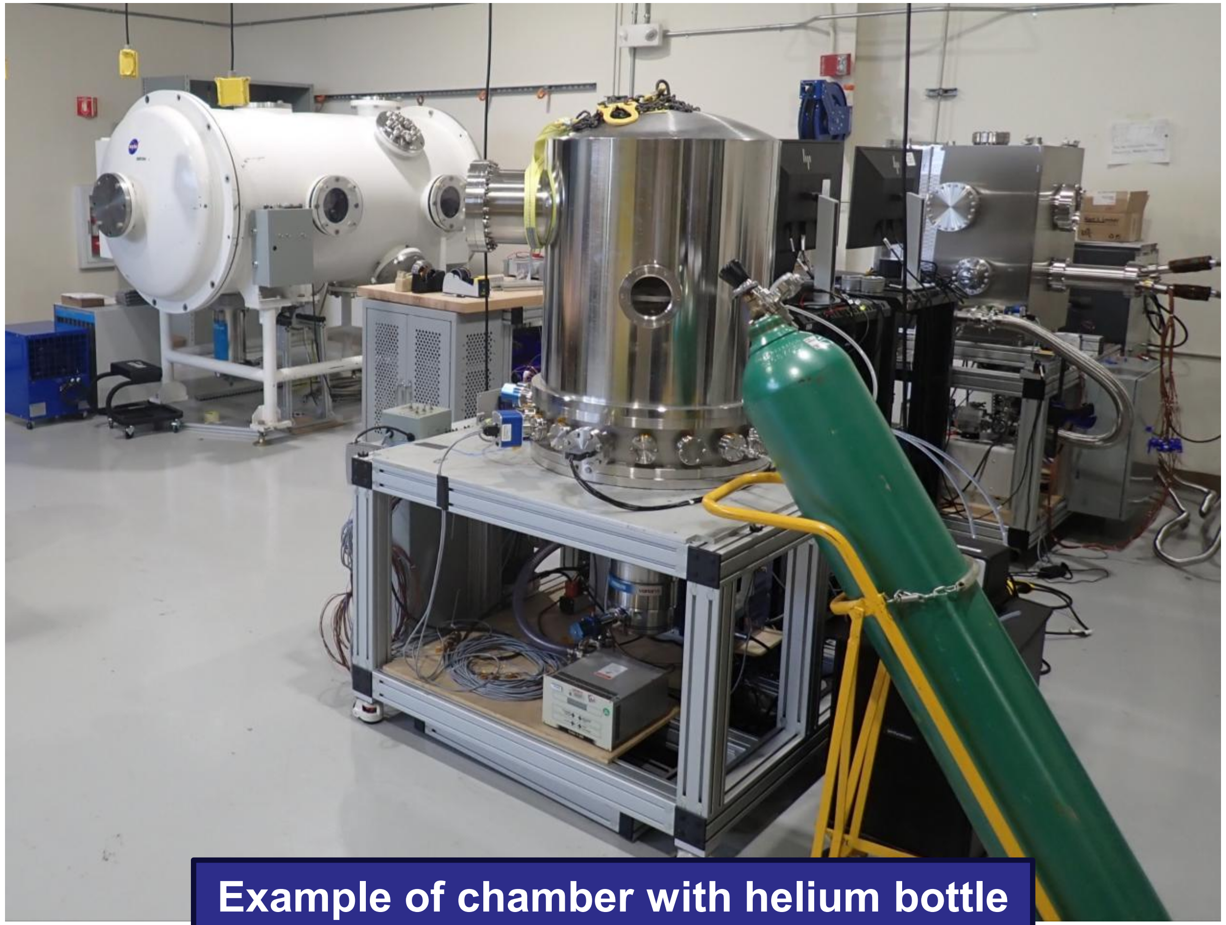
Examples of procedures/documents from our lab



Vacuum Operations

Improvements to pump down procedures:

- Start heaters during rough pump down to off-gas contaminants and improve vacuum level reached
  - Slowly increasing temperature of heaters improves off-gassing during pump down
- Implement helium purges to free contaminants from surfaces
  - Helium is more energetic particle, so it knocks contaminants off surfaces



Example of chamber with helium bottle prepared for helium purges

Lessons Learned

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Cryogenic Testing – HI-TTeMP Experience

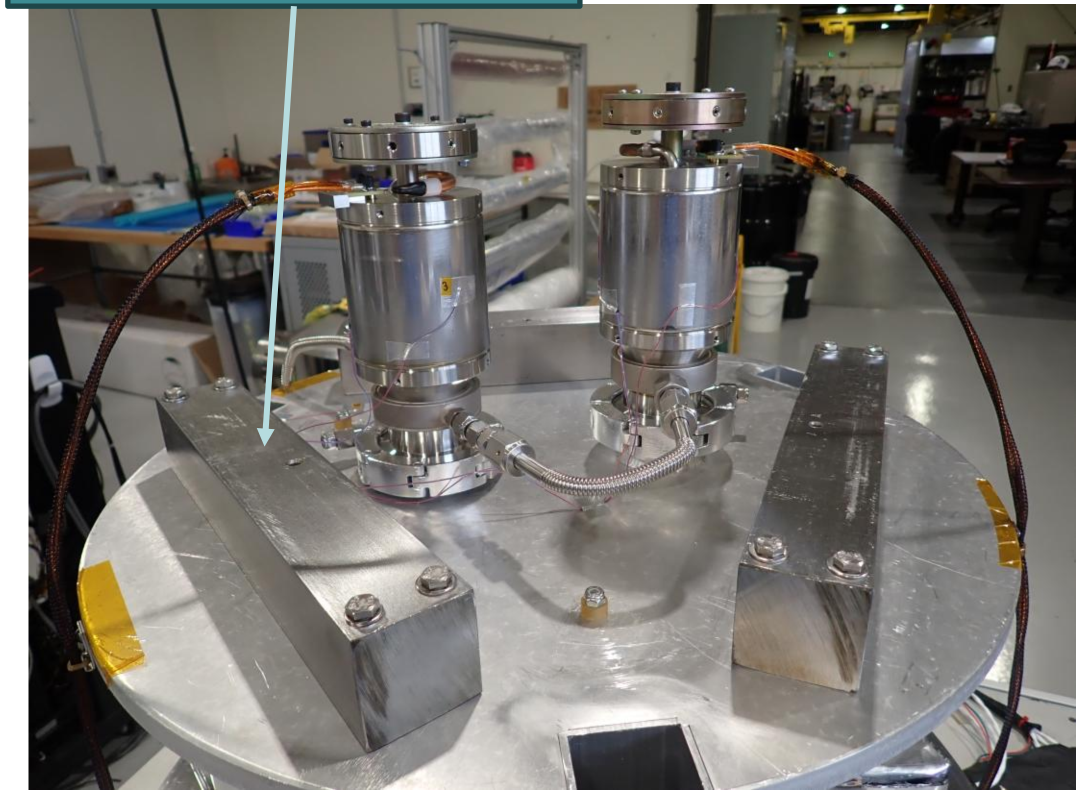
- Cryocoolers (Sunpower, Stirling Cycle) used in the HI-TTeMP lab for this example test
  - Provide cryogenic cooling capability without need for propellants
  - One cryocooler cools a custom shroud to provide uniform boundary conditions surrounding the test article
  - One cryocooler cools a cold plate attached to the test article
- Used different mounting methods and number of cryocoolers
  - Have used one cryocooler on other test stands, have also used two cryocoolers on same test stand
    - Two cryocoolers mounted rigidly to stand using KF flange (shown to right)
    - Two cryocoolers mounted using bolt holes on side of pressure vessel and custom 3D printed brackets
    - A single cryocooler mounted using bolt holes on side of pressure vessel and custom 3D printed brackets

Dual cryocoolers mounted rigidly to example test stand with KF Flanges

Cryogenic Testing – Cryocooler Lessons Learned

- Considerations when integrating cryocoolers into test stand
  - Need to consider vibrations regardless of mounting method or number of cryocoolers used
    - Have had interference between cryocoolers when both are rigidly mounted to test stand
      - Success with added mass and wire rope isolators under stand
    - Have also had vibrations impact the rest of the test stand with just one cryocooler being used
  - Need to protect cryocooler power source/cabling
    - Wires have been shorted due to insulation being rubbed off due to vibrations
- Need to decide if running entire cryocooler inside cryostat or just cold finger inside cryostat
  - Determines cabling/feedthroughs, also impacts mounting and vibration concerns
  - Controllers from Sunpower cannot be run inside cryostat, consider when wiring through feedthroughs

Added mass to mitigate vibration impacts



Dual cryocoolers mounted rigidly to example test stand with KF Flanges

Cryogenic Testing – Cryocooler Lessons Learned

- Need to consider operational limits of equipment vs hardware
  - *In this example test with the specific cryocoolers used in the HI-TTeMP lab:*
  - Cryocoolers cannot be operated if cold tip temp is above 87° C
    - For bakeout, must limit temperature of components connected to cold tip
  - Cryocoolers cannot be shut down if cold tip is below 70K
    - Depending on thermal load and test parameters, sometimes cold tip falls below this
    - If cold tip falls below this temperature, the cooler cannot be shut down, or spontaneous self excitation may occur.
  - Must consider the amount of load you're putting into the cooler, as well as fail safes for test shutdown if cooler is below this temp
    - Solutions: adding heaters directly to cold tip, adding additional heat from other heaters
  - Bottom line: an important component of the test/operating procedure must consider the safety of the cryocoolers themselves!

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Troubleshooting

- Make a thorough plan and discuss before jumping in
- Have patience
  - Easier said than done, but taking the time to understand the issue is worth it to find an effective solution
- Try to isolate the problem
  - Ex: with sensors, try to isolate if issue is with sensor bead/head, with plug, feedthrough, DAQ system and so on.
  - Narrowing down and isolating the issue first can save time later down the line
- Document!
  - Blindly trying fixes and hoping something clicks might work sometimes, but it is easy to get lost and compound the problem
  - Creating logs/excel sheets to methodically check every permutation of the problem or checkout helps keep things organized
  - Documenting as many details as possible may take added time but is extremely useful if it is necessary to retrace steps
- Check the expected as well as the **unexpected**
  - Ex: if you expect a circuit to be continuous through certain pins, check those! Also check combinations of the pins with others (even if you’re reasonably confident, they’re not connected) because sometimes shorts or other issues can come up without being obvious.

Lessons Learned

We encountered challenges every step of the way…

- Planning
- Materials and Interfaces
- Contamination control
- Instrumentation
- Vacuum operations
- Cryogenic testing
- Troubleshooting
- Scheduling

Scheduling

- Quality results take time to achieve
- Try to add margin!
  - It is possible to encounter unexpected challenges that will require all hands-on deck to troubleshoot, delaying schedule
- Analysis can be helpful in scheduling and planning stage to have base understanding of when test stages will occur
  - Add margin to the analysis as well – steady state, especially in cryogenic systems can take longer than projected
- <u>Expect the unexpected </u>- even the best laid plans sometimes go awry

Conclusion

- After encountering many issues, troubleshooting, and then implementing many lessons learned, the HI-TTeMP lab team finally completed *one* 30-day TVAC test of the hardware discussed in this presentation
  - From start of the first run to end of the final (successful) run, our efforts totaled about 9 months of work!

The team persevered through many challenges and used everything learned to benefit the test and lab as a whole!