

National Aeronautics and Space Administration

Liquid Hydrogen and other Cryogenic Instrumentation Experience at NASA Glenn

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Outline

- Temperature:
  - Sensor types
  - Installation
  - Calibration and uncertainty
  - Response curves
  - Use cases
- Pressure
- Fill Level
- Flow

Temperature Sensors Introduction

- Sensor types for discussion:
  - Thermocouples
  - Silicone Diodes
  - Cernox
  - RTDs
- Some considerations for sensor selection:
  - Allowable sensor uncertainty
  - Lifecycle of measurement device:
    - Reusability
    - Durability
    - Handleability
    - Replaceability
  - Difficulty in measuring what you are trying to measure
  - What environment in which you are trying to make the measurement (i.e. radiation, vacuum)?
  - Are you measuring a liquid, a gas, or a solid?
  - How are you going to attach the sensor?
  - Available budget
- Best source for detailed information on temperature sensors:
  - Lake Shore Cryotronics Webpage (www.lakeshore.com)
- Other cryogenic temperature sensor providers (beyond thermocouples):
  - Scientific Instruments (https://www.scientificinstruments.com/)
  - Cryotechnics (https://www.cryotechnicsus.com/)
- All vendors generally carry somewhat equivalent sensors

Thermocouple Basics

- Bi-metallic joint of specific known materials
  - Differential voltage created; Peltier effect
- Multiple different types (J, K, T, E, etc)
  - Each type has an ideal temperature performance range
- NIST standard tables for differential voltage vs. temp
  - “Cold Junction” reference temperature
    - Usually, room temperature or ice water
  - Order of magnitude: mV
  - Measure induced voltage change
  - Interpolate b/w table





ANSI Code	ANSI MC 96.1 Color Coding: Thermocouple Grade	ANSI MC 96.1 Color Coding: Extension Grade	Alloy Combination: + Lead	Alloy Combination: – Lead	Comments Environment Bare Wire	Maximum T/C Grade Temp Range	EMF (mV) Over Max Temp Range	IEC 584-3 Color Coding: Thermocouple Grade	IEC 584-3 Color Coding: Intrinsically Safe	IEC Code
J			IRON Fe (magnetic)	CONSTANTAN COPPER-NICKEL Cu-Ni	Reducing, Vacuum, Inert. Limited Use in Oxidizing at High Temperatures. Not Recommended for Low Temperatures.	–210 to 1200°C –346 to 2193°F	–8.095 to 69.553			J
K			CHROMEGA® NICKEL-CHROMIUM Ni-Cr	ALOMEGA® NICKEL-ALUMINUM Ni-Al (magnetic)	Clean Oxidizing and Inert. Limited Use in Vacuum or Reducing. Wide Temperature Range, Most Popular Calibration	–270 to 1372°C –454 to 2501°F	–6.458 to 54.886			K
T			COPPER Cu	CONSTANTAN COPPER-NICKEL Cu-Ni	Mild Oxidizing, Reducing Vacuum or Inert. Good Where Moisture Is Present. Low Temperature & Cryogenic Applications	–270 to 400°C –454 to 752°F	–6.258 to 20.872			T
E			CHROMEGA® NICKEL-CHROMIUM Ni-Cr	CONSTANTAN COPPER-NICKEL Cu-Ni	Oxidizing or Inert. Limited Use in Vacuum or Reducing. Highest EMF Change Per Degree	–270 to 1000°C –454 to 1832°F	–9.835 to 76.373			E
N			OMEGA-P® NICROSIL Ni-Cr-Si	OMEGA-N® NISIL Ni-Si-Mg	Alternative to Type K. More Stable at High Temps	–270 to 1300°C –450 to 2372°F	–4.345 to 47.513			N
R	NONE ESTABLISHED		PLATINUM-13% RHODIUM Pt-13% Rh	PLATINUM Pt	Oxidizing or Inert. Do Not Insert in Metal Tubes. Beware of Contamination. High Temperature	–50 to 1768°C –58 to 3214°F	–0.226 to 21.101			R
S	NONE ESTABLISHED		PLATINUM-10% RHODIUM Pt-10% Rh	PLATINUM Pt	Oxidizing or Inert. Do Not Insert in Metal Tubes. Beware of Contamination. High Temperature	–50 to 1768°C –58 to 3214°F	–0.236 to 18.693			S
U	NONE ESTABLISHED		COPPER Cu	COPPER-LOW NICKEL Cu-Ni	Extension Grade Connecting Wire for R & S Thermocouples, Also Known as RX & SX Extension Wire.					U
B	NONE ESTABLISHED		PLATINUM-30% RHODIUM Pt-30% Rh	PLATINUM-6% RHODIUM Pt-6% Rh	Oxidizing or Inert. Do Not Insert in Metal Tubes. Beware of Contamination. High Temp. Common Use in Glass Industry	0 to 1820°C 32 to 3308°F	0 to 13.820			B

Thermocouples

- NASA has extensive experience using thermocouples in cryogenic systems:
  - Best used for systems above 70 – 80 K.
  - Can perform end to end system calibration for temperatures below 70 K.
  - Best if used with some length of wire along sensor as close to isothermal as possible.
  - Generally, Type E is most common used – has best sensitivity at temperatures below ~ 100 K.
    - Type T and Type K can also work.
  - Published uncertainty ~ +/- 1.6 K + electronics. In practice, we get better than that all the time.
- Typically potted on using Stycast 2850 FT or attached via taping.
- Commonly available NIST standard curves make T/Cs cheap and easy to use.
  - Can buy 500 ft spool and spot welder to make yourself as opposed to buying premade thermocouples.

What is a Diode?

A diode only allows one-way current flow:

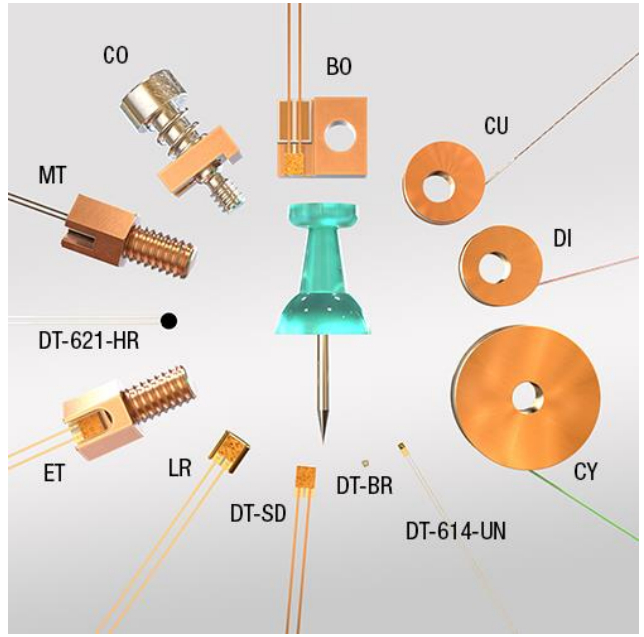
- Silicon type diodes:
  - N-type (negative charge) and P-type (positive charge) silicon.
    - Created by doping silicon with various elements.
  - Joined together so free electrons from N-type flow into P-type to allow current flow if battery oriented correctly.
    - If battery oriented incorrectly, free electrons attracted the wrong way and no signal.
- The voltage of the diode with constant current is a function of it's temperature.
- Requires excitation current (~ 10 μA).
- Costs several hundreds of dollars per sensor or greater.
  - Costs vary based on quantity ordered.

What is an RTD

- RTD = Resistance Temperature Detector:
  - Very simple: measure the electrical resistance of a metallic element which has well characterized changes as a function of temperature.
- Two types: positive temperature coefficient and negative temperature coefficient (slope of temperature response line).
  - Positive Temperature Coefficient:
    - Typically made using platinum.
    - Available in resistances between 1 Ohm and 1000 Ohms (usually not less than 100 Ohms).
    - Can be very cheap (< $10 per sensor).
  - Negative Temperature Coefficent:
    - Germanium & Cernox
    - No standard curve, each sensor requires calibration.
    - More accurate, especially below 77 K.
    - Several hundred dollars per sensor.

Calibration

- Silicon diodes available with and without calibration
  - Uncalibrated uncertainty larger (+/- 0.25 K to +/- 1 K) depending on temperature and quality of sensor (can specify), use standard curve
  - Calibrated diode (sensor specific curve) as good as +/- 20 mK
- Cernox®
  - Requires sensor specific calibration (Chebechev)
- Platinum RTD
  - Generally, two test points: LN2 and room temperature (+/- 0.25 K)
    - Sensitivity of 0.00385 deg/K
  - Sensor specific calibration (< +/- 0.1 K)



Lake Shore diode packages

Image credit: Lake Shore Cryotronics

Typical Cal Info from Lakeshore

Polynomial Type: Chebychev
Useful Range of Fit:

1.40 K	to	12.2 K
1.646 Volts	to	1.333 Volts

Lower and Upper limits of Voltage used in computing Chebychev coefficients:
ZL = 1.292547475 ZU = 1.64810718

Order	Coefficient	Std. Deviation of Coefficient	Ratio (Coeff./Std Dev.)
0	7.597167	2.5750E-03	2950.32
1	-6.074082	3.7480E-03	-1620.61
2	0.222141	3.8252E-03	58.07
3	-0.371218	3.5729E-03	-103.90
4	-0.075427	3.3955E-03	-22.21
5	-0.028545	3.3200E-03	-8.60
6	-0.012686	3.2823E-03	-3.86
7	-0.009819	3.2925E-03	-2.98
8	-0.008379	3.3844E-03	-2.48
9	-0.008257	3.5889E-03	-2.30
10	-0.012423	3.5888E-03	-3.46

Will get 4-5 different temp ranges

Can end up with many coefficients per sensor

Credit: Lake Shore Cryotronics

Typical Si Diode Response

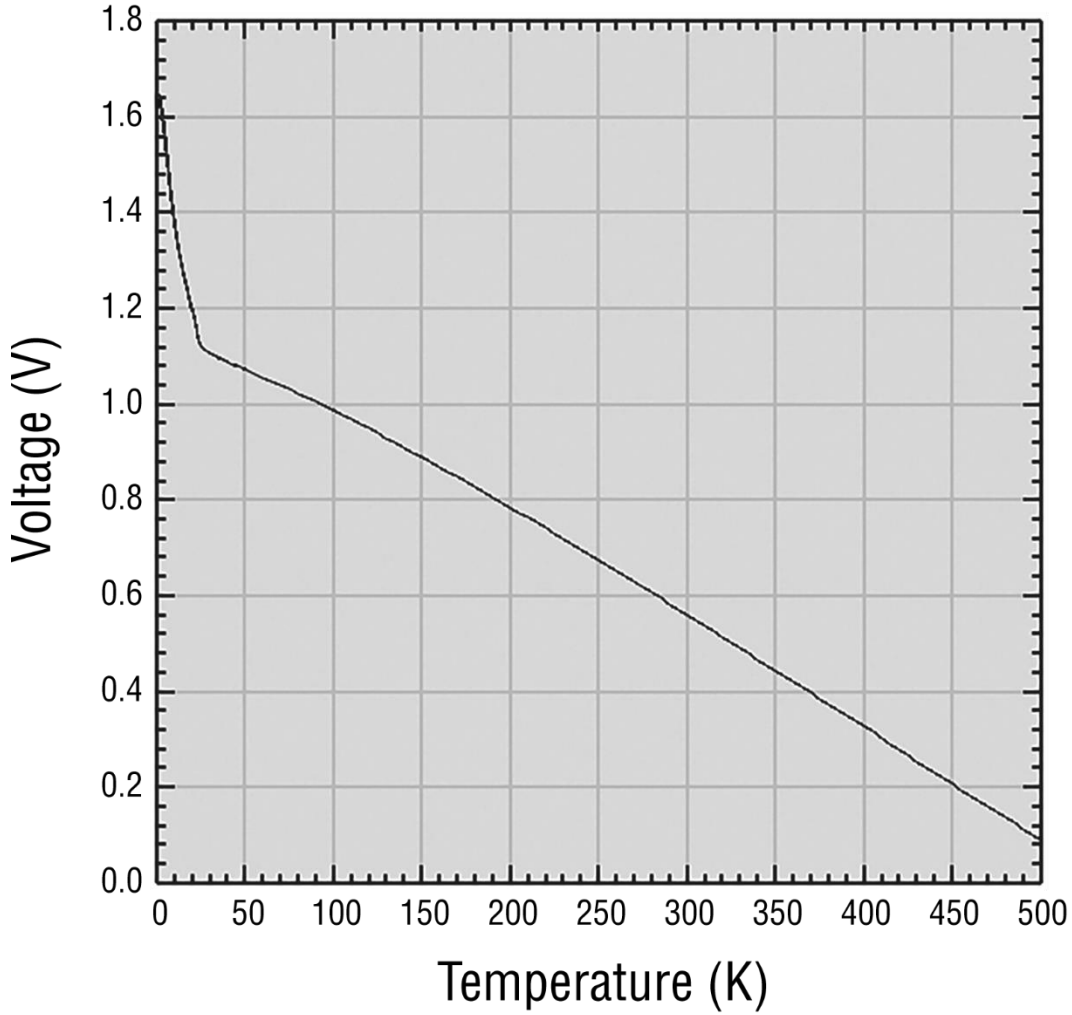


Image credit: Lake Shore Cryotronics

Typical Cernox Response

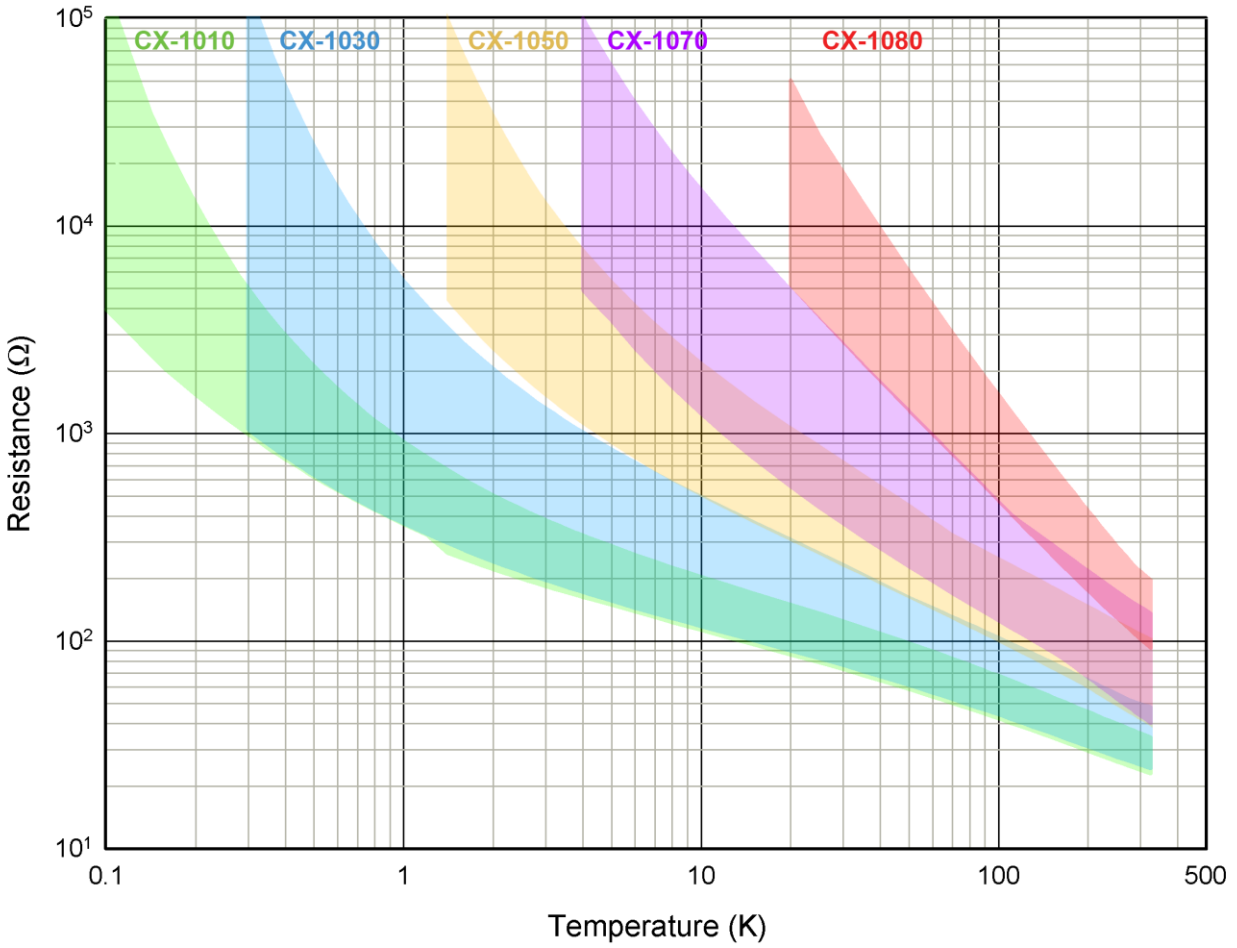


Image credit: Lake Shore Cryotronics

Typical Platinum RTD Response

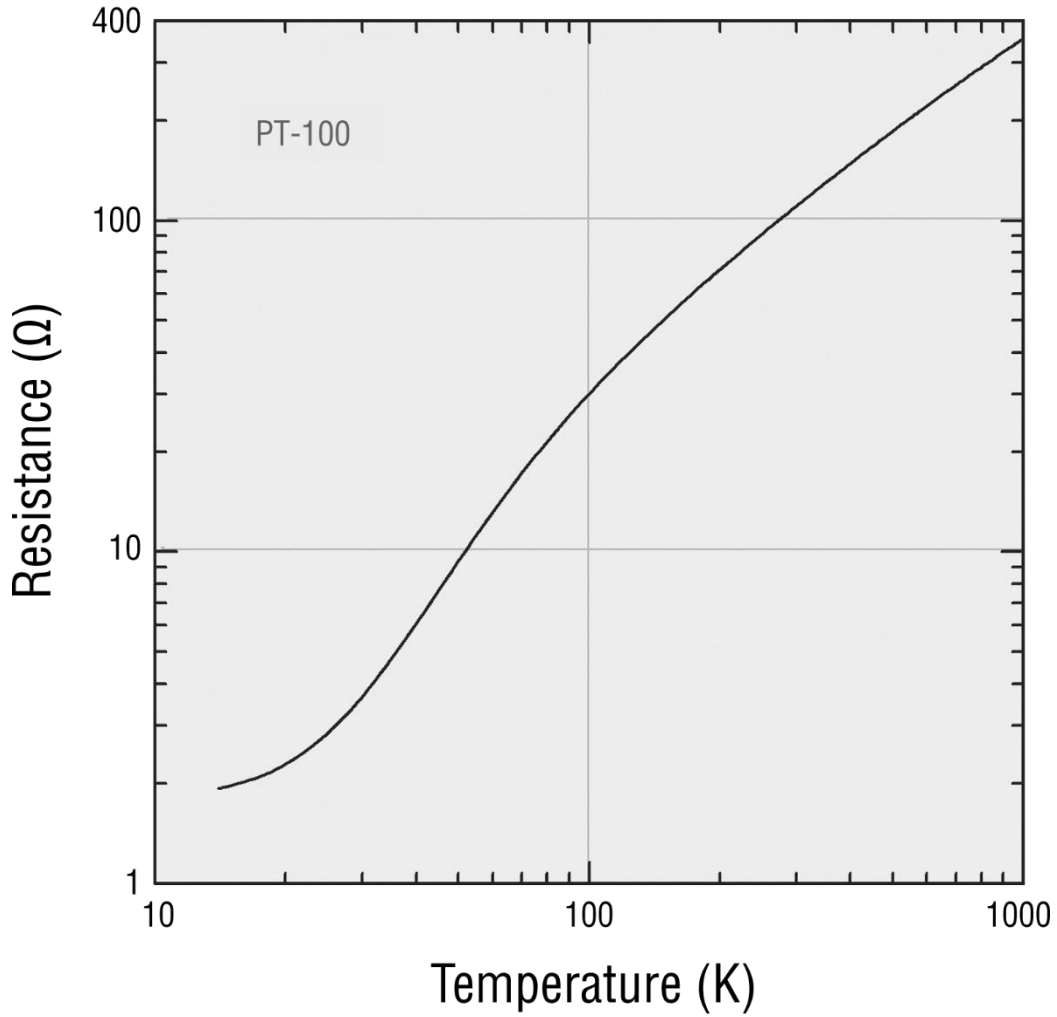


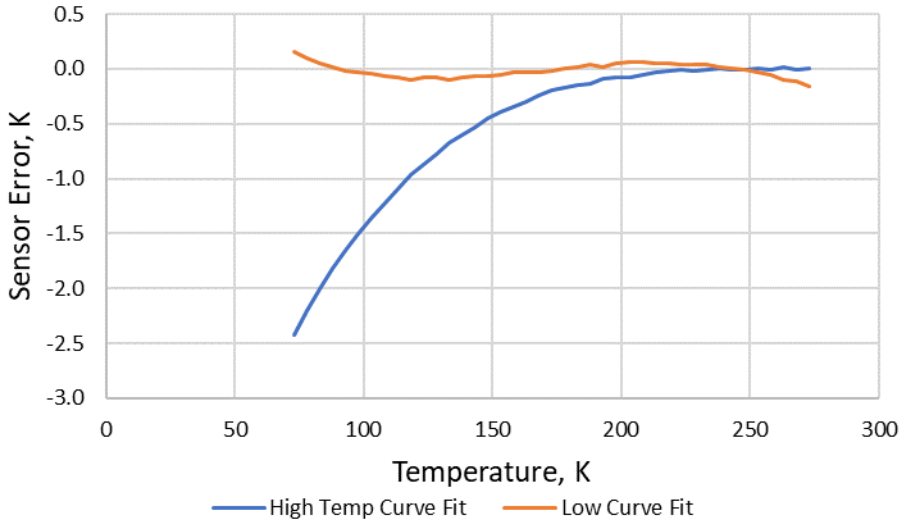
Image credit: Lake Shore Cryotronics

RTD Calibration

RTDs are often calibrated via 2-point temperature measurement (ice bath and LN2) and then linear in between.

Can use IEC 60751 platinum curves if desired.

- Make sure to use curve for -200˚C to 0˚C.
- Not analytically reversable with extra C term.
- Solve for Rt/Ro from a measured voltage.
- Then develop equation to reverse solve for temperature based on Rt/Ro ratio.
- Used successfully during CryoFILL testing.



-200°C to 0°C
$Rt = Ro\,[1+At+Bt^2+c\,(t-100°C)t^3]$
0°C to 850°C
$Rt = Ro\,(1+At+Bt^2)$
Rt = Resistance at temperature t
Ro = Resistance at t=0°C
$A = 3.9083 \times 10^{-3}\ °C^{-1}$
$B = -5.775 \times 10^{-7}\ °C^{-2}$
$C = -4.183 \times 10^{-12}\ °C^{-4}$

Sensors in External Environments

- Imposed magnetic fields can offset the diode response:
  - Typically Cernox/RTDs more stable.
- Radiation can alter the output of diodes and RTDs:
  - Typically Cernox more stable.
- Duration can also cause a slow drift in output:
  - Typically takes years to see.

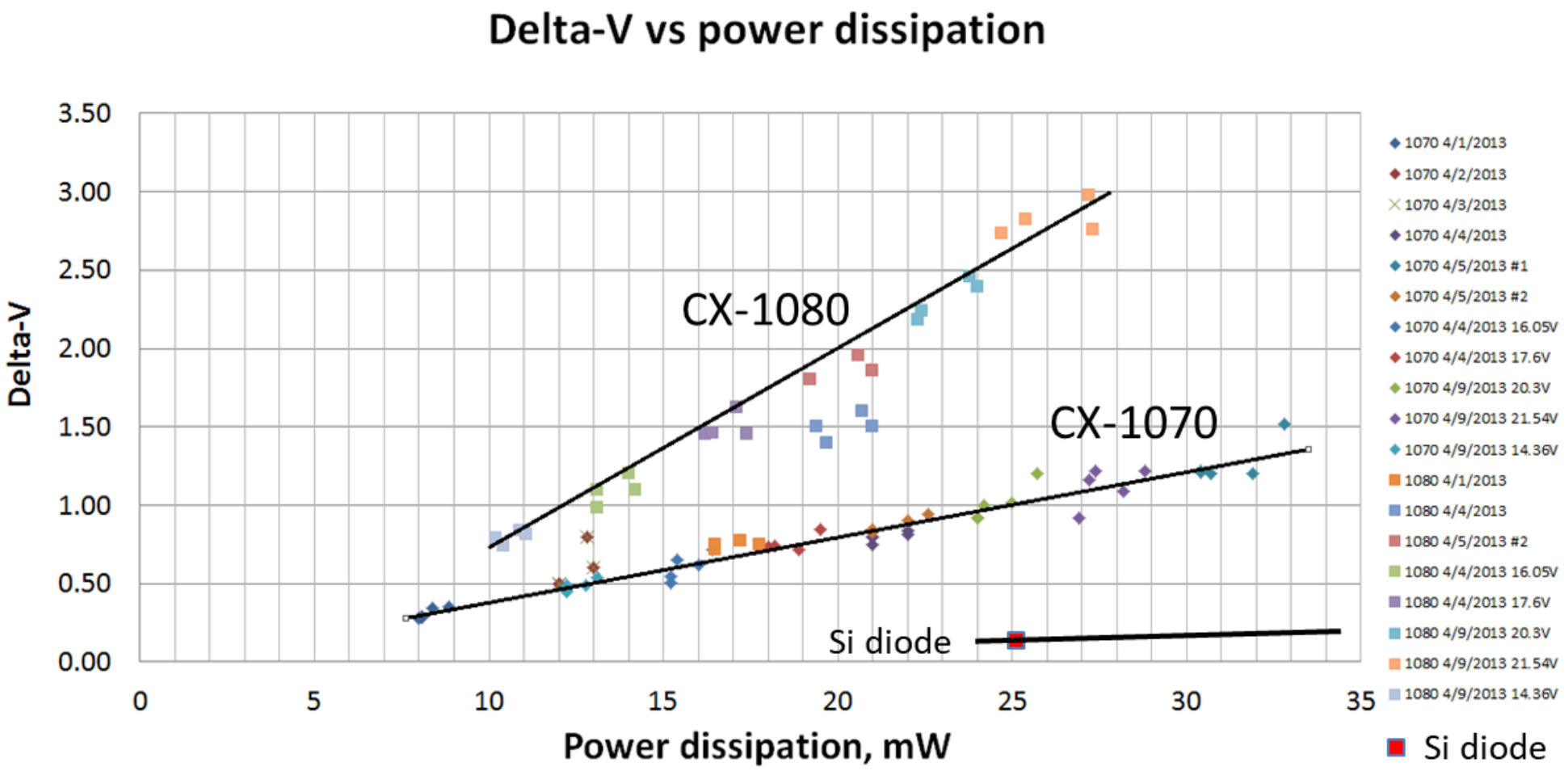
RTD, Silicon Diodes, and Cernox®

- NASA has extensive experience using silicon diodes from Scientific Instruments and Lakeshore as well as Cernox® sensors from Lakeshore.
  - Used as both temperature sensors and wet/dry sensors in cryogenic fluids.
  - Mounted externally to fluid tubes and internally with several different configurations
- Multiple different wiring schemes
  - 2 wire
  - 3 wire
  - 4 wire
- Require current excitation and measure:
  - Voltage for silicon diodes.
  - Resistance for Cernox®

Silicon Diodes and Cernox® as Wet/Dry Sensors

- NASA GRC discovered the ability to use diodes as a wet/dry sensor.
  - Dempsey and Fabik, “Using Silicon Diodes for Detecting the Liquid-Vapor Interface in Hydrogen”, NASA TM-105541.
  - Metzger and Zimmerli (NASA GRC) determined that Cernox® had a 6 – 15 x larger response than the silicon diodes (lower values for CX-1080 with LN2).
  - Normally chip sensors are used for this implementation.
- Normally, a diode (or Cernox ®) receives an excitation current or voltage:
  - Silicon Diodes: 10 μA
  - Cernox ®: <10 mV
- By increasing the voltage or current across the sensor, it causes the sensor to self-heat more.
  - In a liquid that self heating is easily removed through convection, the measured response does not change.
  - In a vapor the self heating causes the diode to respond as if the fluid is warmer and the voltage response changes.
  - Based on the response to self heating, logic can be applied to the DAQ to determine if the sensor is wet or dry.
  - This also requires thermal isolation from the temperature rake or any other thermal mass.
- On SHIIVER, cylinder (“can”) style SI diodes were used and this did not work for a few reasons.
  - The “can” had more thermal mass than the normally used chip configurations and took longer to “overheat”
  - The sensors were more closely coupled to the perforated board (tied down with wire) to prevent damage during installation and filling of the tank.

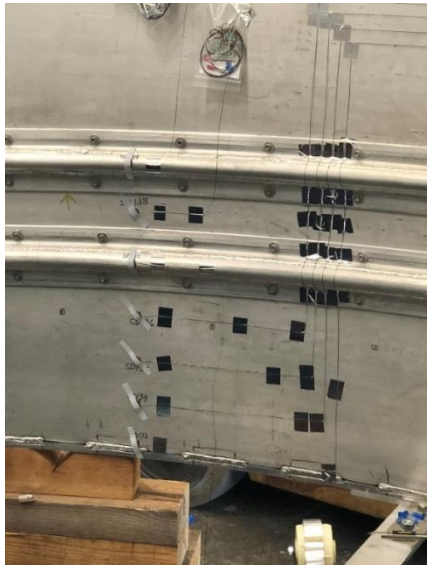
Overpowering data with LH_2

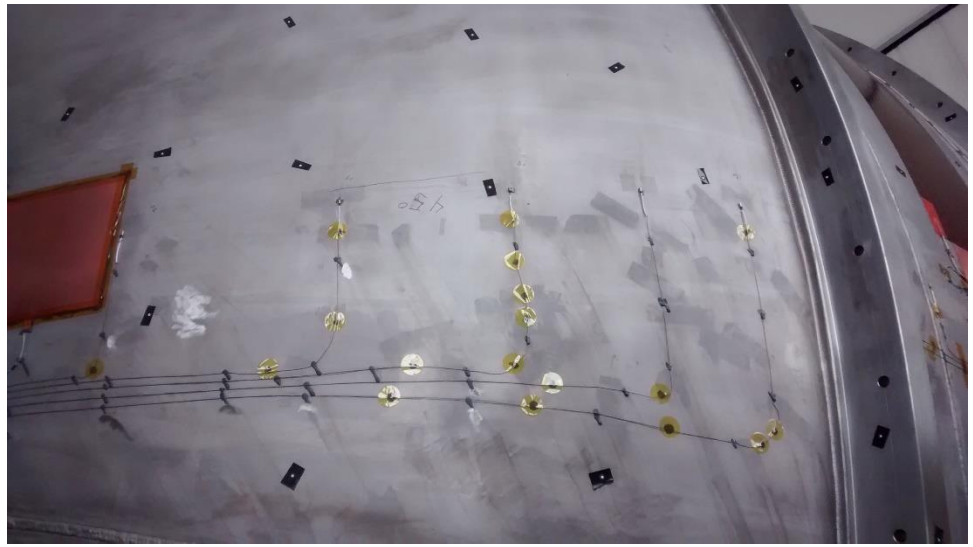


Credit Metzger and Zimmerli, NASA GRC

Epoxy/Varnish/Attachments

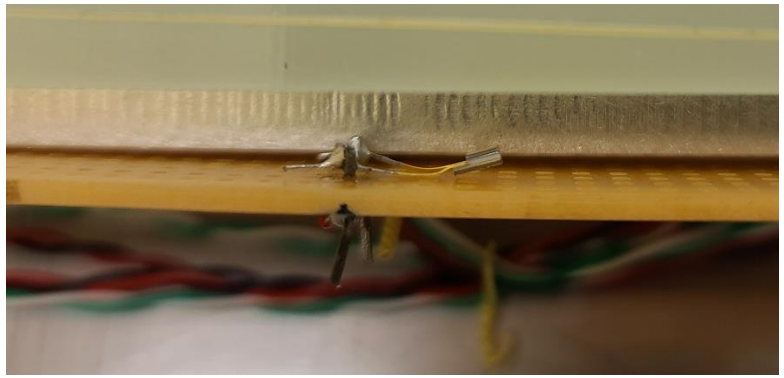
- SMiRF uses Stycast 2850 FT for epoxying sensors in place.
  - The Stycast is thermally conductive, but not electrically conductive.
- Often use “band-aids” to hold sensor in place while epoxy is drying.
- ARC and GRC use GE varnish (now IMI 7031™) if sensors are to be “resusable” or relocatable.



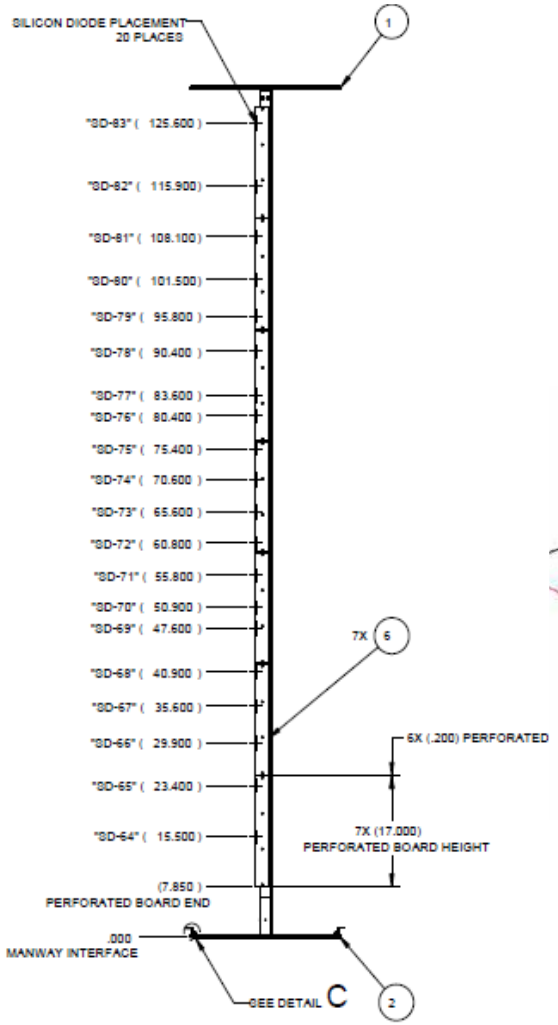


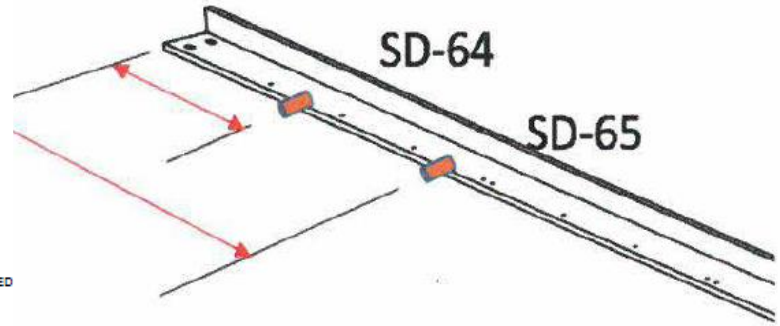
Temperature Sensors in Tank

- GRC often uses temperature sensors in the tank, exposed to liquid hydrogen.
  - Mounted on epoxy perforated board that allows sensor to “hang out” into the liquid that surrounds it.
  - Image below shows Si diode (SD style) mounted on perf-board.
  - Wires run through board and then out through 20 K certified connector (CeramTec or equivalent).
- Sensors used to measure stratification within the liquid of a tank and not the metal they are mounted on.

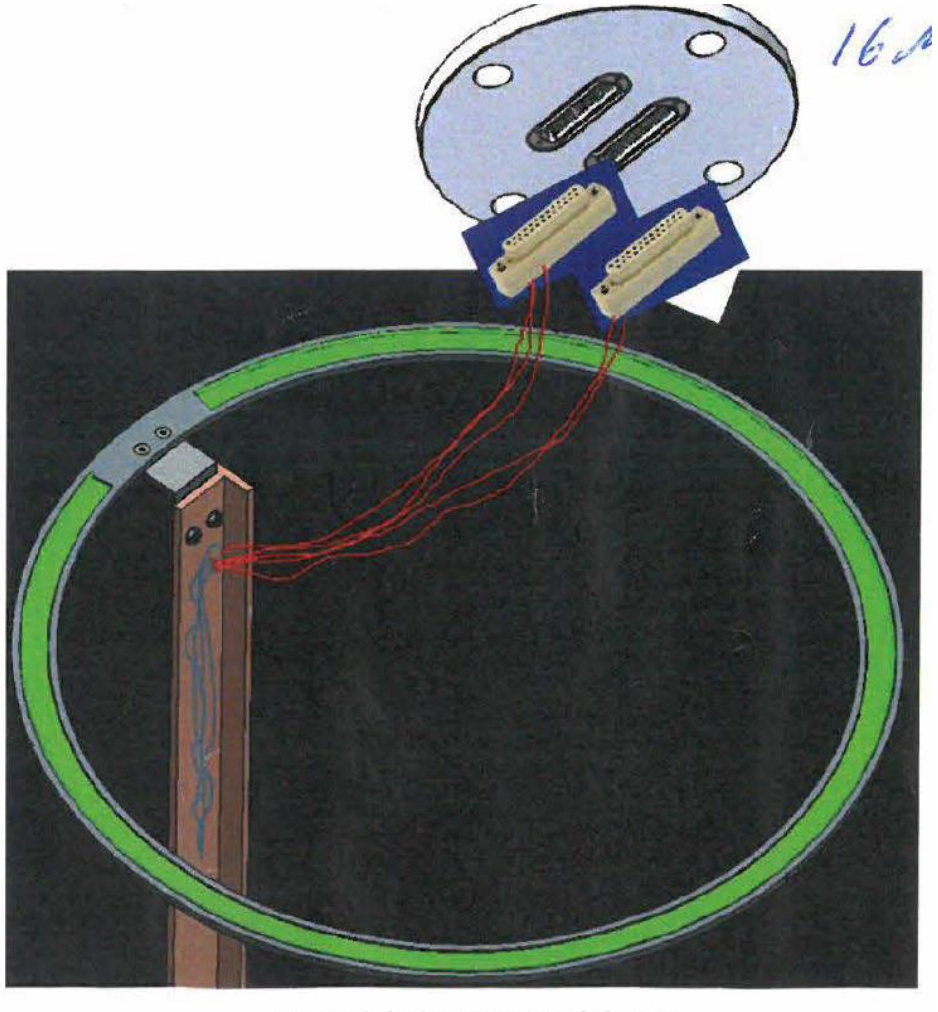


Show images of SHIIVER that were released





FR-4 Epoxy-Glass Perforated Board



Silicon Diodes in Flow

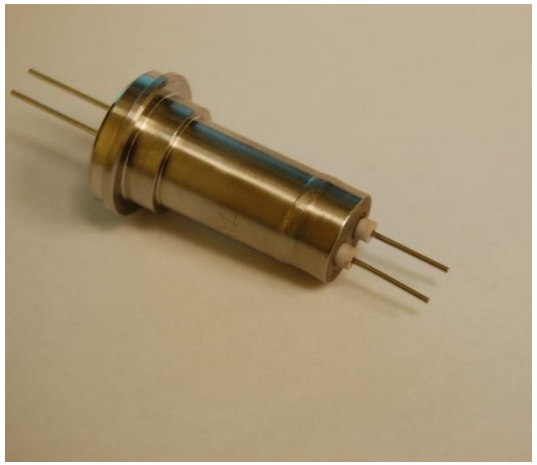
- There are multiple different ways to get a temperature sensor into an internal flow:
  - Probes available from Lakeshore (or made in house).
  - GRC SMiRF internal diode transition.
  - GRC SHIIVER internal diode mounting.
- These mounting techniques would work with Cernox® or RTDs as well as Silicon Diodes.

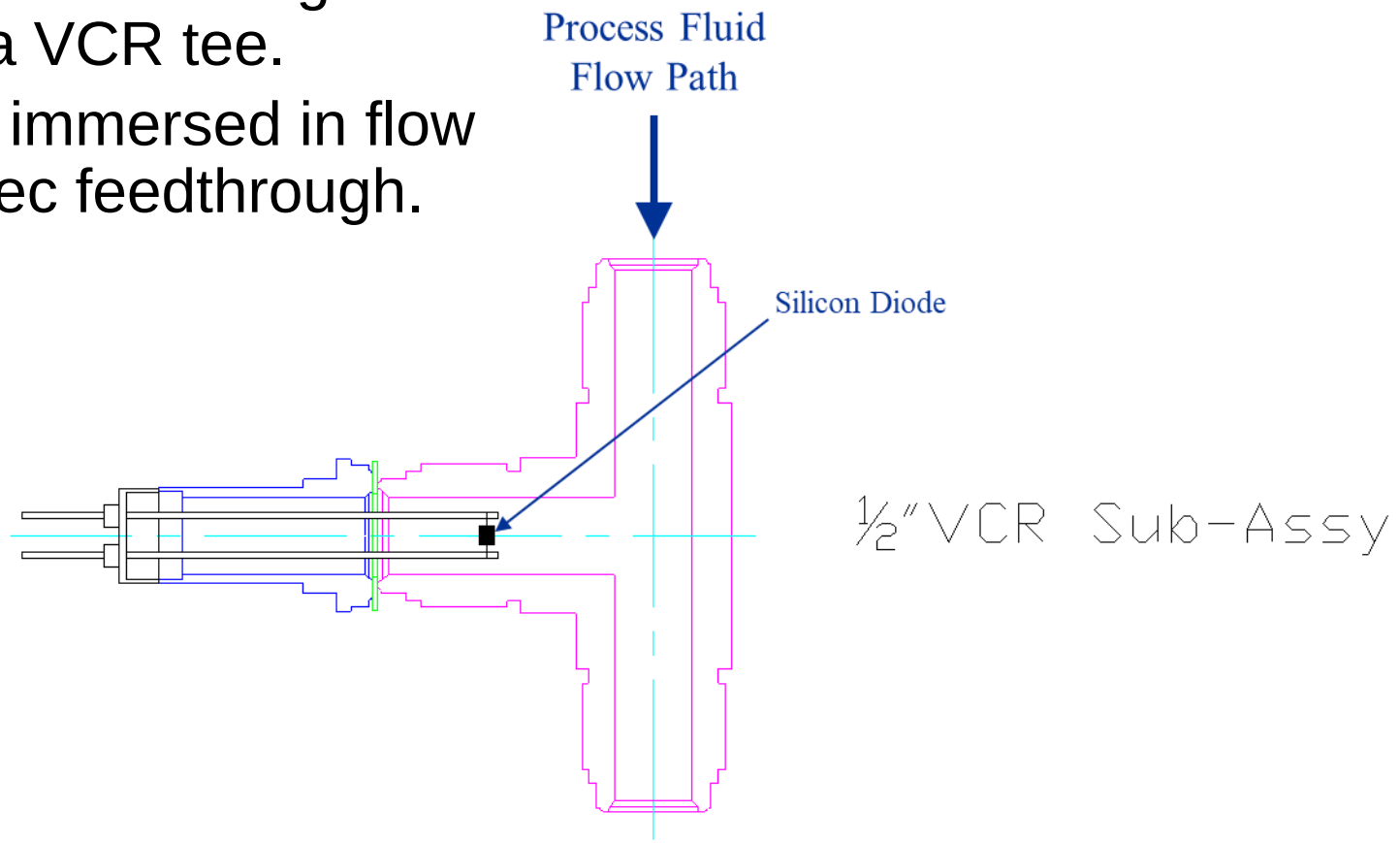
Probes

- Probes can be procured or manufactured to get temperature sensors into a flow stream.
  - Probes typically consist of a tube with one end welded shut.
- The temperature sensor is inserted down the tube with some sort of heat sink at the bottom.
  - Some sort of cryogenic goop/epoxy/grease to bridge any thermal gaps between tube and heat sink.
  - Has been known to break thermal contact in right conditions.
- Appropriate design accounts for conduction down the tube and tube response to flow.
  - Maximize immersion of probe while leaving minimal hot side probe exposure.
  - Use external insulation of probe (loosely fit MLI). Ideally hot side of probe approaches internal fluid temperature.
  - If you need to measure dT, ensure the probe configurations are the same for each Temp measurement. Perhaps consider flow entrance condition similarity (ex: leave X diameters of straight run prior to measurement), much like flow meters.

SMiRF internal transition

- Developed by Helmut Bamberger at SMiRF for various testing activities there.
  - Uses two wire Ceramtec feedthrough and VCR gland to attach in a VCR tee.
  - Sensor may not be fully immersed in flow due to length of Ceramtec feedthrough.





Credit Helmut Bamberger, NASA GRC

SHIIVER Internal Transition

- Developed by Keith Johnson in conjunction with GRC instrumentation shop to support SHIIVER testing.
- Similar to probes, but doesn't weld tip closed.
  - Epoxy used to isolate diodes from tube wall.
    - Tried just sealing tube off at top and bottom with potting compound. Had some leaks over time, eventually filled whole tube.
  - Uses tubing to support diodes against internal flow forces
- Use SI can type diodes
  - Single sensor in 1/8th inch tube
  - Dual sensors in ¼ inch tube
  - Goes into piping via swage fitting





Temperature sensors (2x) in SHIIVER vent line.

SHIIVER TP: NASA TP 20205008233

Different Wire Measurement Options

- A standard diode/RTD/Cernox® requires excitation.
- The excitation wires can be used to measure response in a two wire system:
  - Depending on the wire length (i.e. resistance), this can lead to large offsets in readings.
  - Different types of wire (copper or phosphor bronze) can be used to adjust offsets.
- This is usually corrected for by measuring response with two separate wires, hence the four wire system.
- GRC does have experience wiring up to six diodes in series for excitation.
  - This is the three wire configuration
  - This also minimizes the number of current sources required if current sources are used separately from monitoring response.
  - If one diode is lost, then all diodes on that string are lost (not appropriate for measurement redundancy).
  - There may also be some accuracy losses with this method.

Sensor Placement for Conduction Heat Loads

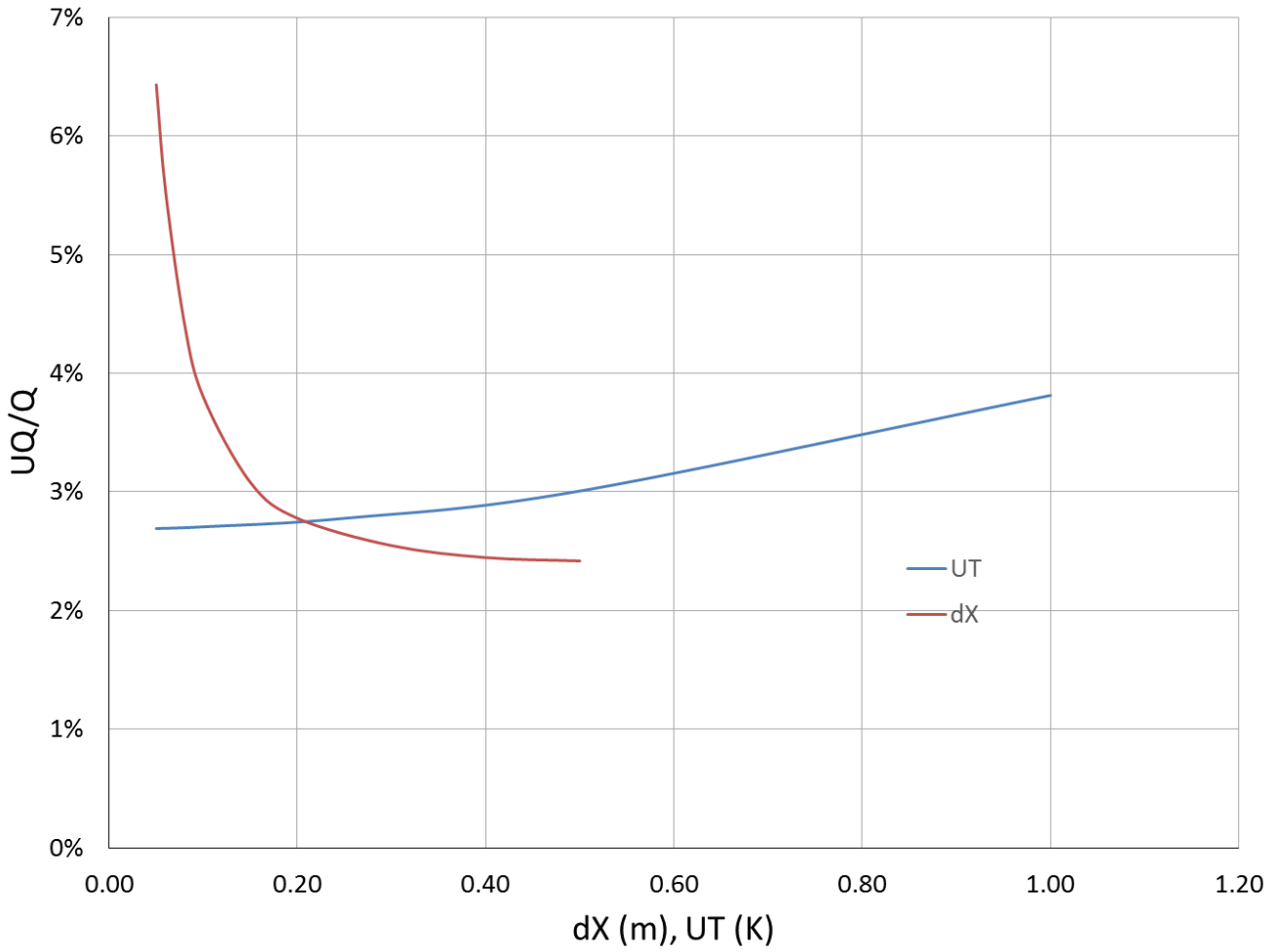
- Based on the uncertainty of sensors and the positioning of the sensors, the uncertainty of a measurement can be estimated and sensitivities used to drive sensor location.
  - Does not take into account radiation between the environment and the structure being measured – will push sensors closer together.

$$\dot{Q} = \frac{-A}{L}\int -k(T)dT = \frac{-k_{eff}A}{L}(T_{warm} - T_{cold})$$

$$U_Q^2 = U_k^2\frac{\delta Q}{\delta k} + U_A^2\frac{\delta Q}{\delta A} + U_L^2\frac{\delta Q}{\delta L} + U_{\Delta T}^2\frac{\delta Q}{\delta \Delta T}$$

$$\frac{U_Q}{Q} = \sqrt{\left(\frac{U_L}{-L}\right)^2 + \left(\frac{U_A}{A}\right)^2 + \left(\frac{U_k}{k}\right)^2 + \left(2\frac{U_T}{\Delta T}\right)^2}$$

Uncertainty Example



Based on the uncertainty in differential temperature (UT) measurement (1% uncertainty in cross-sectional area and 2% uncertainty in thermal conductivity) and differential distance (dx) between the sensors, the conduction heat load can be minimized.

In this case (SHIIVER), the ideal distance was about 0.2 m (8 inches). Placed series of three sensors, each 4 inches apart – required 2 of the 3 sensors to work to enable calculation.

The uncertainty for heat load with actual temperature sensor uncertainty was observed to not decrease much below 2.5%, thus the standard uncertainty of +/- 0.25 K at 20 K and +/- 1 K above 100 K was acceptable.

Pressure Measurements

- For testing, we typically use pressure measurements that are thermally isolated from the experiment:
  - By long sense tube, even outside the vacuum chamber.
  - Need to be wary of Thermo-Acoustic Oscillations.
    - Avoid simplest by plumbing redundant sense lines together.
- There have been some developments in cold pressure transducers.
  - Results still have to be corrected for temperature.
  - Typically, more for spaceflight type applications.

Fill Level Measurements (1/2)

- Load Cells
  - Direct measurement of system weight preferred method of determining fill level.
  - Can be tricky with liquid hydrogen because usually system mass much greater than differential hydrogen mass.
- Temperature Rakes
  - Use in Wet/Dry mode if at all possible (see earlier slides).
  - Trying to determine via temperature response is not very accurate, though can work in a pinch.
- Capacitance Probes
  - Need to recalibrate for different fluids.
  - Make sure you know where top of liquid is when you calibrate.
  - Make sure that tank wet percentage as a function of height is known in the cold, shrunk, pressurized configuration!

Fill Level Measurement (2/2)

- Delta Pressure Transducers:
  - Make sure that tank wet percentage as a function of height is known in the cold, shrunk, pressurized configuration!
  - Use p-traps to prevent liquid ingestion into external lines. This can act as an additional heat source on your tank and mess up the measurement.
  - Avoid thermoacoustic oscillations with a warm sensor.
- Radio Frequency Mass Gauge
  - Developed by Dr. Greg Zimmerli at GRC.
  - Disperses RF signal in tank and measures response looking for modes within tank.
  - Compares measured RF response to predicted model response.

Flow Measurements

- Typically for boil-off measurements, use thermal mass flow meters (based on thermal anemometry).
  - Make sure to calibrate with correct gas or use conversion constant.
- For SHIIVER (and CryoFILL) used Coriolis flow meters
  - Not best for low density gas (such as hydrogen).
  - Used to minimize pressure drop in the flow meter.
  - Requires special care and integration to make work.
  - If using where may see temperature below 100 K make sure to inform vendor so they purge cavity with helium not nitrogen gas.
- Make sure appropriate line lengths before and after flow measurement to enable correct measurement.

Summary

- An array of different temperature sensors can be used effectively in liquid hydrogen systems.
- Can measure hardware or fluid temperatures within a system.
- Experience developed at NASA GRC over the past 60+ years of liquid hydrogen system testing has been shared to help the general audience with their measurement needs.
  - This presentation is a cumulation of the developments and lessons learned over the past 60 years and not solely of the author or presenters.