THERMAL & FLUIDS
ANALYSIS WORKSHOP
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Some General Principles in Cryogenic Design, Implementation, and Testing

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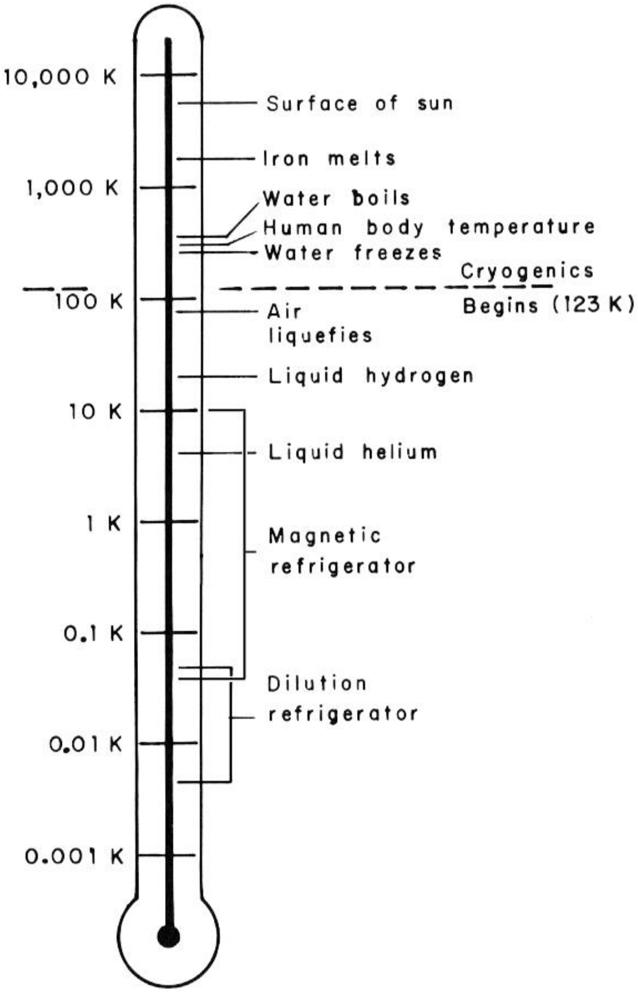
Outline

- Opening remarks
- The role of thermodynamics
- General design principles
- Properties of materials
- Producing “cold”
- Cryo-cooling in space
- Instrumentation
- Heat switches
- Superconductivity
- Sub-Kelvin cooling

What is "Cryogenic"

- For the purposes of this talk, T < 100 K is cryogenic
  - Air liquefies
  - Certain metals and ceramics become suprconducting
  - Is out of the realm of our normal experience (arctic conditions are not cryogenic)
  - Heat capacities decrease from the Dulong & Petit (3/2 R) value
  - In general the physics becomes different from room temperature

The Logarithmic Temperature Scale



- Note use of absolute scale
- Each decade corresponds to different physics and different solutions to design problems
  - – [example]
- Note that properties are not “constant” any more, so concepts like “average” temperature must take this into account
  - – [example]

Thermomdynamics is a Serious Subject!

Robert Boyle
1627-1691

Benjamin Thompson Count
Rumford 1753-1814

Nicolas Léonard
Sadi Carnot 1796-1832

J. Willard Gibbs
1839-1903

Heike Kamerlingh Onnes
1853-1926

Max Planck
1858-1947

James P. Joule
1818-1889

Rudolf Clausius
1822-1888

Gustav Robert
Kirchhoff 1824-1887

Walther Nernst
1864-1941

Constantin Carathéodory
1873-1950

Albert Einstein
1879-1955

William Thomson
Lord Kelvin 1824-1907

Clerk Maxwell
1831-1879

Peter Debye
1884-1966

F. E. Simon
1893-1956

The Laws of Thermodynamics

- First Law of Thermodynamics (Conservation of Energy)
  - Energy in = Work out
  - you can’t get something for nothing

- Second Law of Thermodynamics (Entropy)
  - ∂Entropy ≥ (∂Energy/Temperature)
  - you can’t break even

- Third Law of Thermodynamics (Absolute Zero)
  - Entropy -> 0 as Absolute Temperature -> 0
  - there’s no use trying

Thermodynamics

- Thermodynamics is key to understanding cryogenic processes
- Refrigeration
  - 1st and 2nd laws of thermodynamics
- Approach to Absolute Zero
  - 3rd law of thermodynamics

Staging

- Intercepting heat in stages to reject heat at the highest possible temperature
- In general heat rejection goes as T^2

Design: The "KISS" Principle

- Start with a design that can be calculated using "back of the envelope" methods
  - Make all components easy to analyze
  - The fewer items that are crucial in a design the better
    - Simpler analysis
    - Simpler construction
    - Simpler validation

Example

- GSE motor driven photogrammetry cameras for JWST
  - Original concept: camera housing to cool passively through incidental contact in motor and gears
    - Very difficult to model and verify performance
    - Lead to an extra potential heat source that had to be tracked
  - Solution: make system “deterministic” by using thermal straps

Estimating Suspension System

- [Ron Ross Correlation]

Producing Cold: Cryogens and Cryocoolers

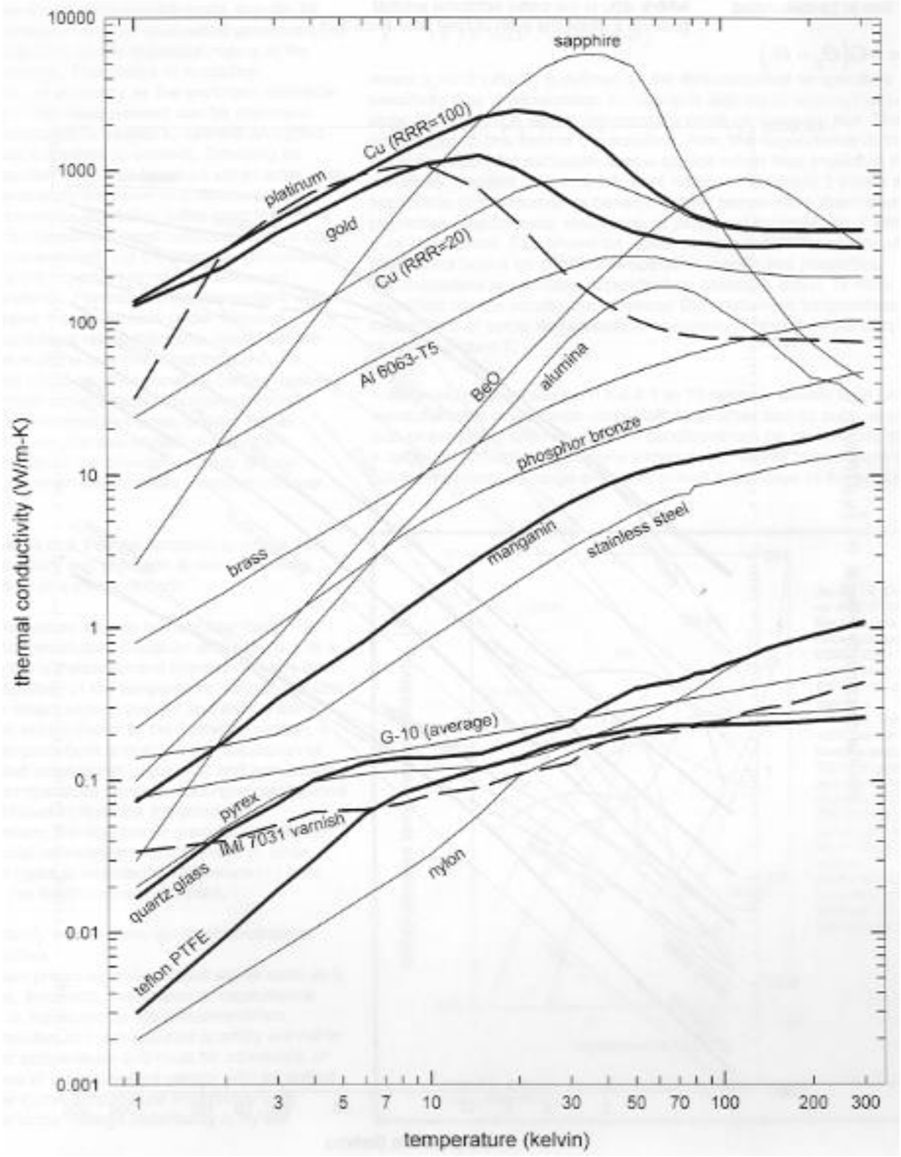
- Cryocoolers
- LN2, LHe, etc.

Properties of Materials

- Thermal Conductivity
- Thermal Absorptivity and Emissivity
- Strength and Brittleness Properties
- Electrical Conductivity
- Specific Heat
- Gases and Liquids

Conductivity Graph

- Thermal conductivity varies greatly between room T and low T



High Purity Metals

- At low temperature electrons have fewer phonons to scatter from, so the thermal conductivity goes up until defects and impurities dominate

Wiedemann-Franz

- Electrons carry the heat in metals
- W-F is a relation between electrical and thermal conductivity

  Rho = $L_0 T/K$

  Where rho = resistivity, T = absolute temperature, K = thermal conductivity, and L_0 = Lorentz constant = $2.44 \times 10^{-8}\ V^2/K^2$
- Not applicable to superconductors

Emissivity and Absorptivity: Temp. and Wavelength Dependence

- The emissivity of most materials is temperature and wavelength dependent
  - Requires wavelength dependent analysis for radiation which is usually accomplished by creating a few wavelength bands in the analysis software

Properties of MLI

- The Lockheed Equation
- Degradation of MLI at lower T
  - Basically dominated by thru-layer conduction at low T
- Structural MLI
- Lateral conduction

DAK Emissivity vs. T

- Metals follow the Hagen-Ruebens relation to first order:

Suitable Materials for Cryo

- Austenitic stainless steels: 304, 304L, 316, 321, A286
- Aluminum alloys: 6061, 6063, 5083, 2219, 1100
- Copper: OFHC, ETP and phosphorous deoxidized
- Brass
- Fiber reinforced plastics: G –10 and G –11, CFRP
- Niobium & Titanium (frequently used in superconducting RF systems)
- Invar (Ni /Fe alloy)
- Indium (used as an O ring material)
- Kapton and Mylar (used in Multilayer Insulation and as electrical insulation
- Teflon (does not become brittle, but creeps)
- Quartz (used in windows)

Unsuitable Materials for Cryo

- Martensitic stainless steels - Undergoes ductile to brittle transition when cooled down.
- Cast Iron – also becomes brittle
- Carbon steels – also becomes brittle. Sometimes used in 300 K vacuum vessels but care must be taken that breaks in cryogenic lines do not cause the vacuum vessels to cool down and fail
- Rubber and most plastics
  - Plastic insulated wires are frequently OK as long as the wire is not repeatedly flexed which could lead to cracking of the insulation (check outgassing first)

Gas Conduction

- Molecular Heat Transfer
- Conduction
- Transition Region
- JWST example
- ASTRO-H example

Gifford McMahon Cycle

- Gifford-McMahon Refrigeration Cycle
    - Regenerator stores heat in compression phase, and releases heat in expansion phase
    - Compress while most of the gas is at warm end, and expand while most of the gas is at the cold end
    - Reverse the phase, and you have an expensive heater!

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Producing Low Temperatures in Space

- Radiation can only work so far practically
- [graph from earlier presentation]

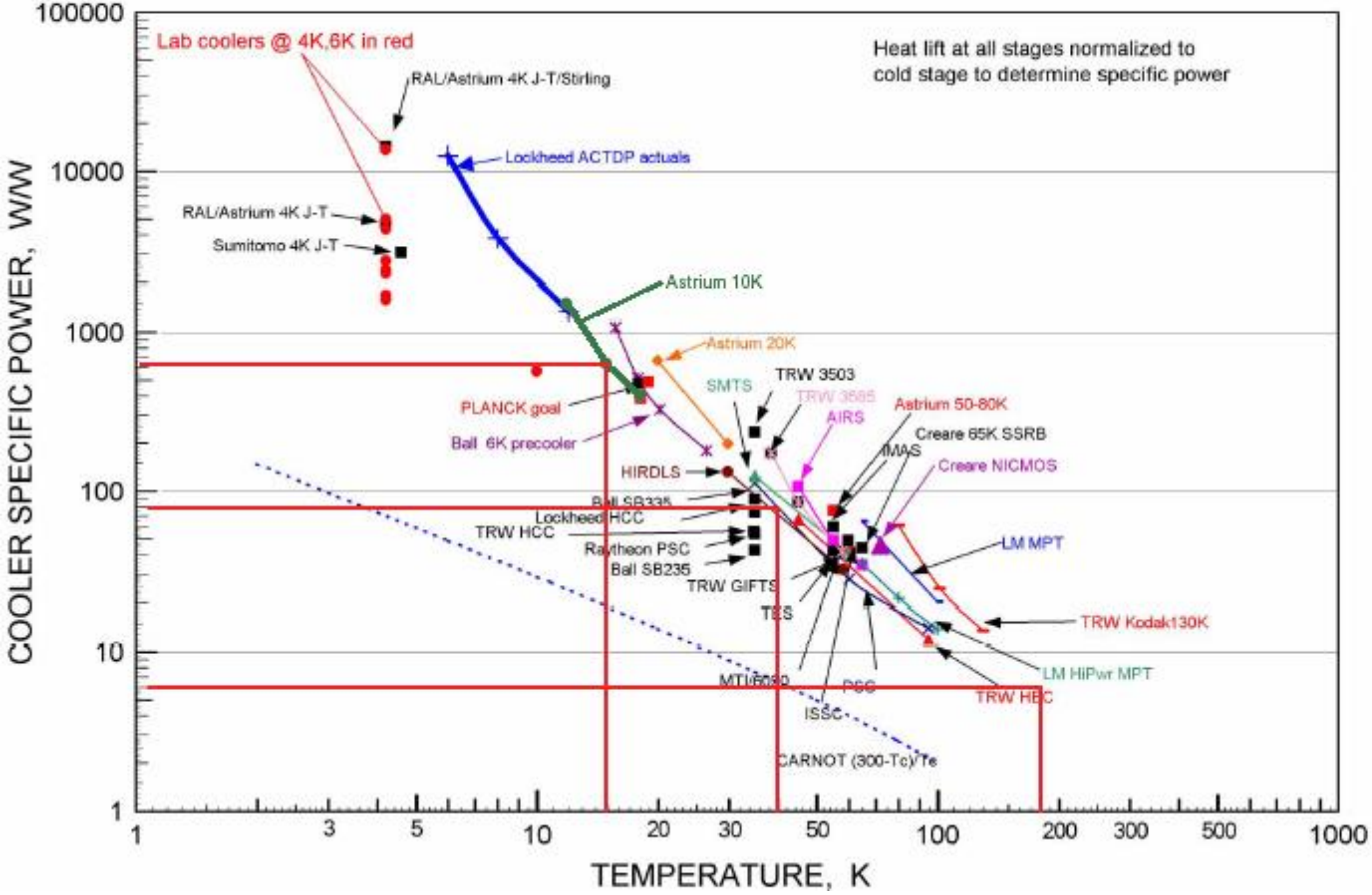
Radiators in Space

- Some flight heritage at cryogenic temperatures (COBE, Landsat, Cassini/CIRS, MAP, Spitzer)
  - JWST will use radiative cooling
  - Successful test of Subscale Cryo-optical Thermal Testbed in support of ST-9 Large Space Telescope proposal
- Operate from room temperature (and above) to as low as 30 K
  - Depends strongly on mission design
- Passive heat rejection
  - Sunshade/earthshade provides shielding from incoming radiation
  - Radiator with a view of deep space connects to heat source (instrument, optics, part of spacecraft bus) by means of a thermal distribution system
    - Metal conductors
    - Loop heat pipes
  - Requires heaters/thermostats to regulate temperature
- Require stringent controls to meeting thermal budgets

Cryocoolers for Space Use

- Stirling Cycle
- Pulse Tubes
- Reverse Brayton Cycle
- Joule/Thomson Coolers

Space Cryocooler Performance



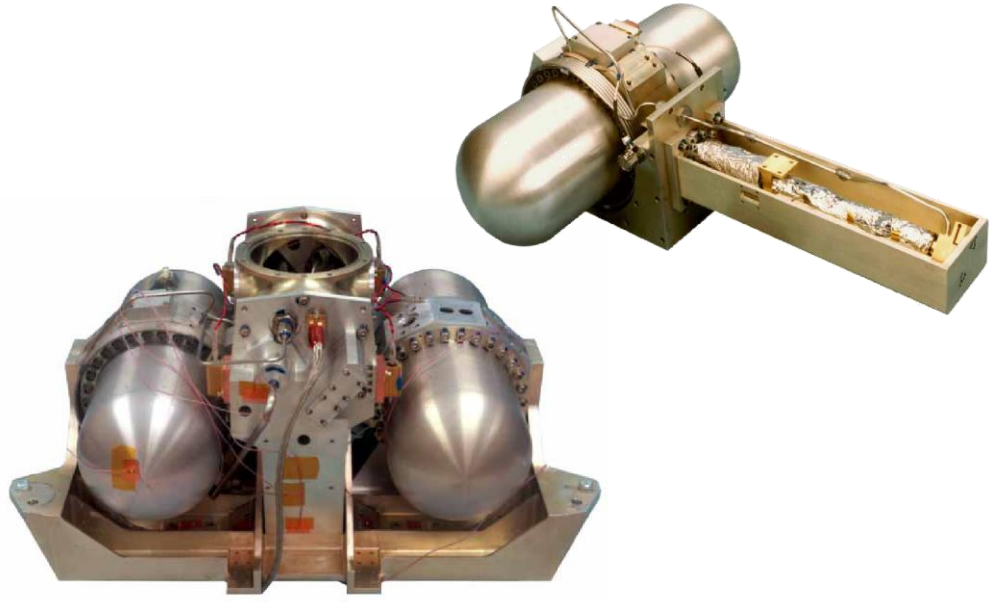
- Roughly T^{-2} dependence on input power to cooling power ratio

Stirling Cycle

- Similar to GM cycle
  - Identical function of regenerator in coldfinger
  - Pressure cycle driven by oscillator rather than tanks, valves and a compressor
  - Phase angle controlled electrically, mechanically, or pneumatically
- Easier to miniaturize than GM

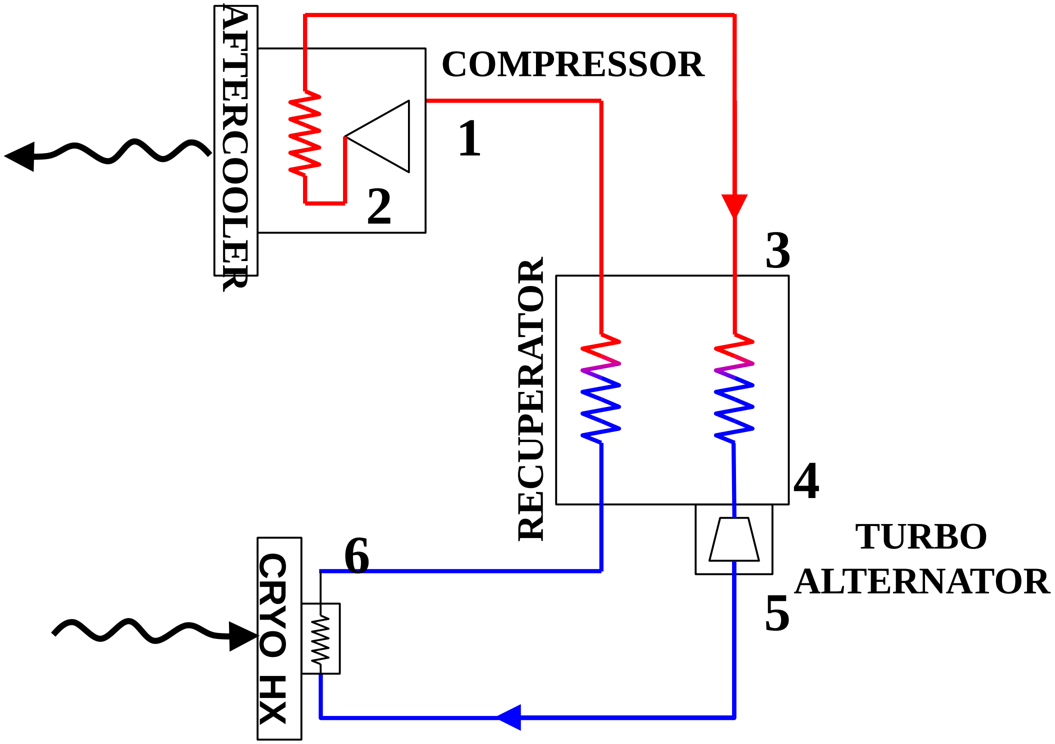
Pulse Tubes

- Similar to Stirling cycle
  - Identical function of regenerator in coldfinger, pressure cycle driven by oscillator
  - Phase angle controlled by resonant gas volume
  - Simpler mechanism than Stirling, but a whole new set of gas-control challenges



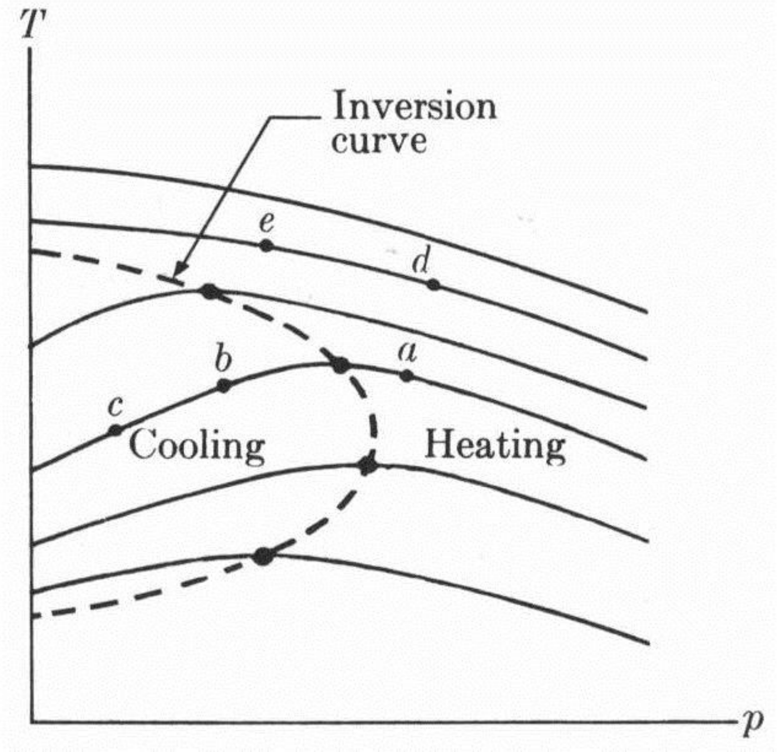
Reverse Brayton Cycle

Turbo alternator removes work from cold stage therefore increasing cooling



Joule Thomson Expansion

- Gas must be precooled and not too high in pressure to produce cooling when expanded isenthalpically



Dewar Construction

- Content

Different Geometry - JWST Harness Radiator

Working with Cryogenic Fluids

- In general:
  - Low heat of vaporization
  - Can be pumped or pressurized to change boiling point
  - Can freeze if too cold
  - Low to zero contact angle, i.e., wets all surfaces
  - Represents a large potential energy in a sealed container

Instrumentation and What is Important to Measure

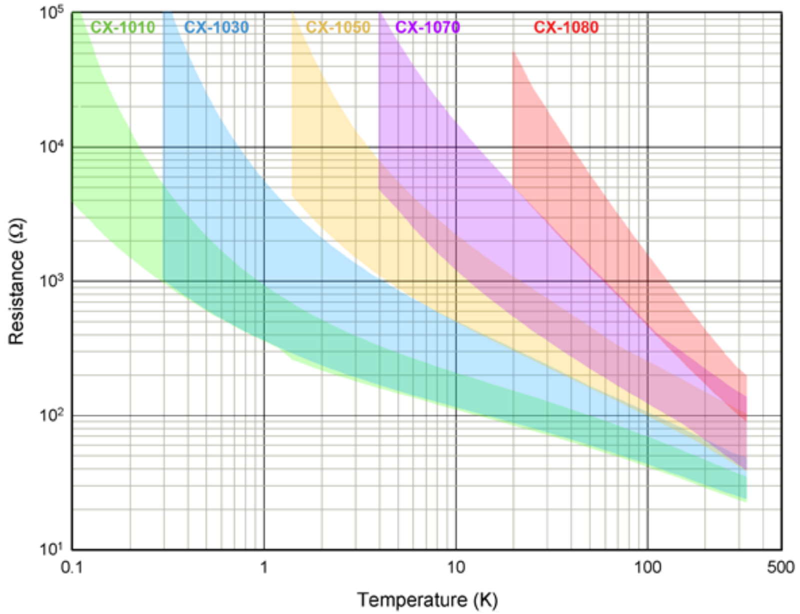
- Thermometry, thermometry, thermometry
- Pressure for fluids
- Pressure for vacuum
  - Pressure reading depends on temperature

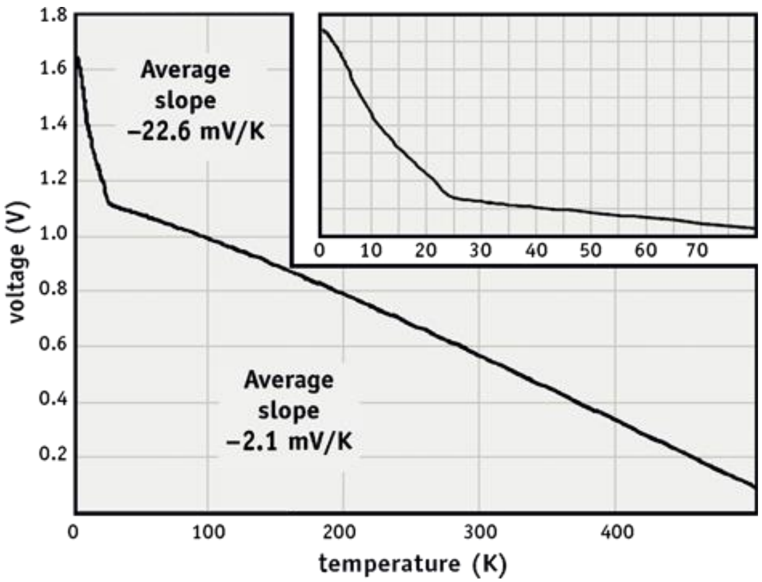
Thermometry

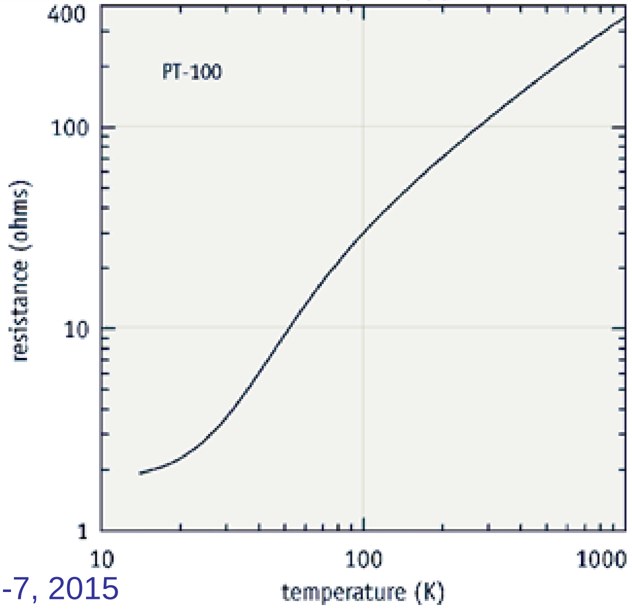
- Select thermometer type based on temperature range
  - Use 4 lead devices where high sensitivity and accuracy are required
    - Remove thermal emfs by reversing current
- Self heating can produce erroneous readings in thermistors
  - Function of power and temperature
    - Readout power applied = $10^{-9}\ T^2$

Thermometry Chart

- Cernox – best < 70K
- Pt – best for > 70 K
- Si diodes good over wide range







Heat Switches-Gas Gap

Heat Switches-Mechanical

- Differential contraction
- Motor driven
- Manual
- Magnetostrictive
- Piezoelectric

Heat Switches - Other

- Superconducting
- Magnetoresistive

Superconductivity

- Quantum mechanical effect where electrons in certain conductors combine to form “Cooper pairs”
  - Transition point affected by temperature, current density, and magnetic field
- Characterized by zero electrical resistance and drop in thermal conductivity
  - Cooper pairs carry current and pass through the material without interacting
- Types of superconductors
  - Type I – Generally pure metals, $T_c < 10$ K
    - Also can be used as a magnetic shield
  - Type II – Alloys, some pure metals, $T_c < 20$ K
  - MgB2 – Magnesium Diboride, T_c ~39 K
  - High Temperature Superconductors (HTS) – Ceramics, $T_c < 110$ K

High Temperature Superconductivity

- Usually a ceramic consisting of RBCO, where R is a rare earth element, for instance YBCO, yttrium barium copper oxide
- Can make large/high field coils
- Joints have small amount of resistance so coil is not "persistent"
- Best performance is for bulk or flat tapes made with a thin film deposition
  - Round wire forms are now being explored

Making Use of Superconductivity

- i^2R-free coils for motors and actuators
- Low thermal conductance high current wiring

Sub Kelvin Temperatures

- Quantum behavior
- ^{3}He and ^{4}He
- Boundary Resistance

Sub Kelvin Refrigeration

- ^{3}He sorption coolers
- Dilution refrigerators
- Adiabatic demagnetization

^{3}He Sorption

- Sorption Coolers use a getter to pump the vapor from a liquid reservoir
  - Geeter is recycled by heating and the gas is recondensed by a higher temperature stage

Dilution Refrigeration

- Diluting the lighter isotope ^{3}He, in liquid ^{4}He increases the entropy of the system and therefore cools
- Makes use of the non-zero solubility of ^{3}He in ^{4}He even at very low temperatures
- Can be made continuous by separating the ^{3}He out of solution at higher temperature and then re-condensing it

Adiabatic Demagnetization

- SdT = MdH takes the place of d(ST) = d(PV) in a cryocooler cycle
- Adiabatic demagnetization refrigeration follows a very Carnot-like cycle of constant S and constant T
  - Produces efficiencies close to Carnot
  - No moving parts for low temperature ADRs using gas-gap heat switches

Continuous ADR

Summary

- [quote about using problems to achieve even lower T]
- [quote of Anthony Leggett at LT-15 in Grenoble]