Some General Principles in Cryogenic Design, Implementation, and Testing

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(with material from Rob Boyle)

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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 superconducting
  - 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]
Thermodynamics is a Serious Subject!

Robert Boyle 1627-1691
Benjamin Thompson Count Rumford 1753-1814
Nicolas Leonard 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)
  – $\partial$Entropy $\geq (\partial$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
  - 1\textsuperscript{st} and 2\textsuperscript{nd} laws of thermodynamics
- Approach to Absolute Zero
  - 3\textsuperscript{rd} 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
• Thermal conductivity varies greatly between room T and low T
• At low temperature electrons have fewer phonons to scatter from, so the thermal conductivity goes up until defects and impurities dominate
• Electrons carry the heat in metals
• W-F is a relation between electrical and thermal conductivity
  \[ \rho = L_0 \frac{T}{K} \]
  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
• 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
• 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
• 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.
• Content
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 = $10^{-9} T^2$
• Cernox – best < 70K
• Pt – best for > 70 K
• Si diodes good over wide range
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, $T_c \sim 39$ 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
• Sorption Coolers use a getter to pump the vapor from a liquid reservoir
  – Getter 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]