Cryogenics and Fluids Branch

Cryogenics and Fluids at NASA-Goddard Space Flight Center

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Cryogenics & Fluids Branch (Code 552)

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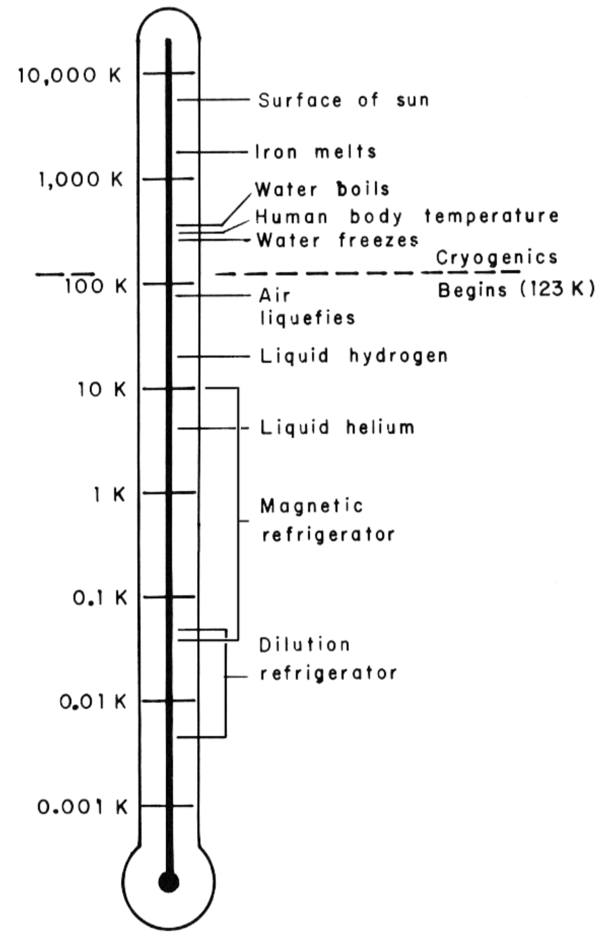
What is Cryogenics?

- "Cryogenics" ≠ "Cryonics"
- Cryogenic Temperatures: ≤123 K (-150° C)
- Cryogenics is needed in space for:
  - ➢ Thermal noise reduction when measuring photon energy for a variety of wavelengths
  - ➢ When the spacecraft is designed to be cold (operating on a cold planet)
  - ➢ When cryogenic liquids must be kept cold
- Relevant boiling points (at 1 atm):

^3He	3.2 K	-	(Can "pump down" to 0.3 K)
^4He	4.2 K	-	(Can "pump down" to 0.8 K)
H_2	20.4 K		
Ne	27.1 K		
N_2	77.3 K		
O_2	90.2 K		
CH_4	111.6 K		
C_2H_6	184.7 K		

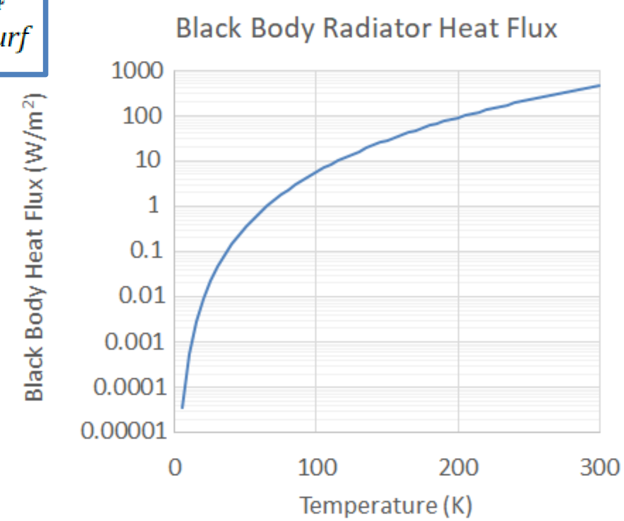


Note: Liquid helium changes to a superfluid phase below about 2 K

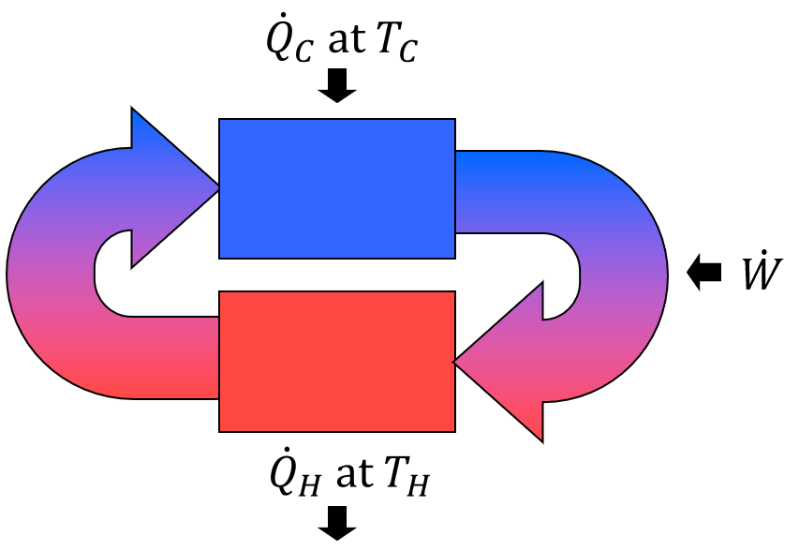
- ➢ Very low viscosity (10^{-7} Pa·s for bulk flow and 10^{-12} Pa·s for microchannel flow)
- ➢ Very high thermal conductivity (86,500 W/m·K) - (no bubbles during boiling)

Even though space is "cold", cooling is still a challenge – why?

- Radiative heat transfer scales with ~ T^4 : $\dot{Q}_{out} = \varepsilon A_{surf} \sigma T^4_{surf}$
  - ➢ Radiation is typically the only way to dump heat off the spacecraft



- Refrigerators are inherently logarithmic as temperature approaches zero
  - ➢ Refrigerators are thermodynamically limited by the ratio of T_C and T_H:



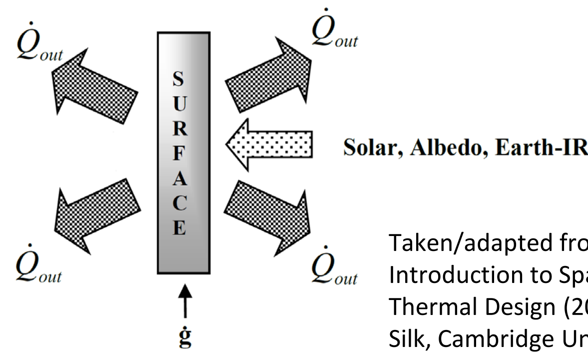
For Carnot:

$$\dot{Q}_C = \dot{Q}_H \frac{T_C}{T_H}$$

$$\dot{W} = \dot{Q}_C \left(\frac{T_H - T_C}{T_C} \right)$$

Spacecraft Thermal Environment (Uncontrolled)

- Uncontrolled spacecraft temperature determined by:
  - ➢ Radiation heat balance
  - ➢ Distance from the sun

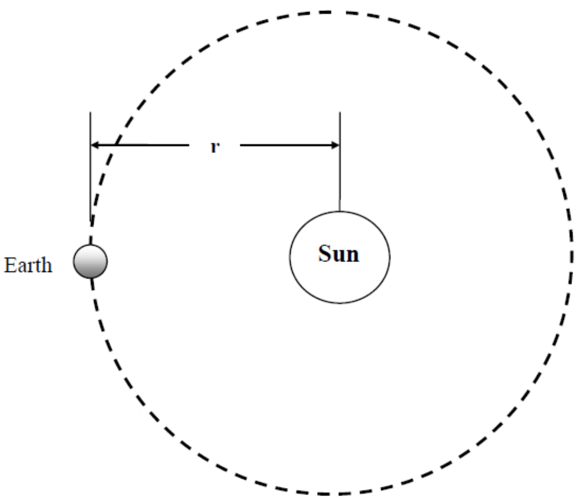


Taken/adapted from Introduction to Spacecraft Thermal Design (2020) by E.A. Silk, Cambridge University Press

$$\dot{Q}_{in} = \dot{Q}_{out}$$

$$\dot{Q}_{in} = \dot{g} + \dot{Q}_{Solar} + \dot{Q}_{Albedo} + \dot{Q}_{Earth\text{-}IR}$$

$$\dot{Q}_{out} = \varepsilon A_{surf} \sigma T_{surf}^{4}$$



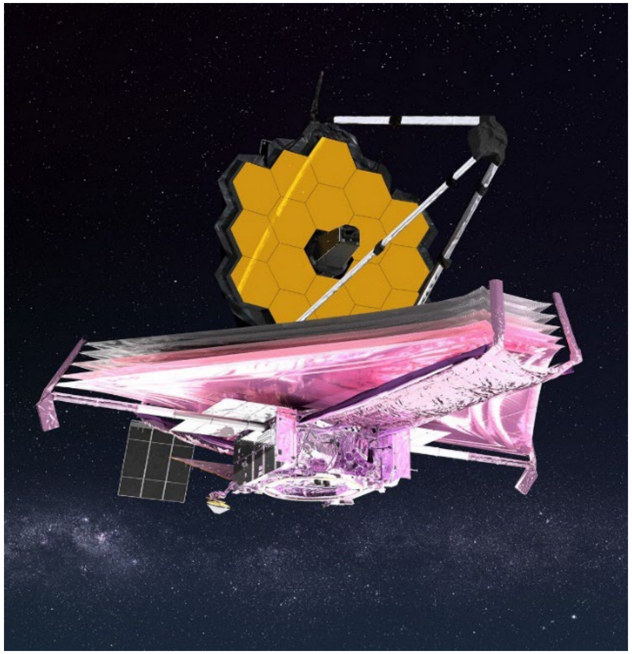
$$I_{jupiter} = I_{earth} \frac{\overline{r}_{earth}^{2}}{\overline{r}_{jupiter}^{2}}$$

Taken/adapted from Introduction to Spacecraft Thermal Design (2020) by E.A. Silk, Cambridge University Press

Planet	Distance from the sun in AU (150,000,000 km)	Solar Intensity Factor (relative to Earth)	Uncontrolled Spacecraft Temperature (K)	Planet Temperature (K)
Mercury	0.39	6.6	447	440
Venus	0.72	1.9	329	737
Earth	**1**	**1**	**279**	**288**
Mars	1.52	0.43	226	208
Jupiter	5.2	0.037	122	163
Saturn	9.5	0.011	91	133
Uranus	19	0.0027	64	78
Neptune	30	0.0011	51	72
Pluto	39	0.00066	45	47
Deep Space	infinite	0	2.7	-

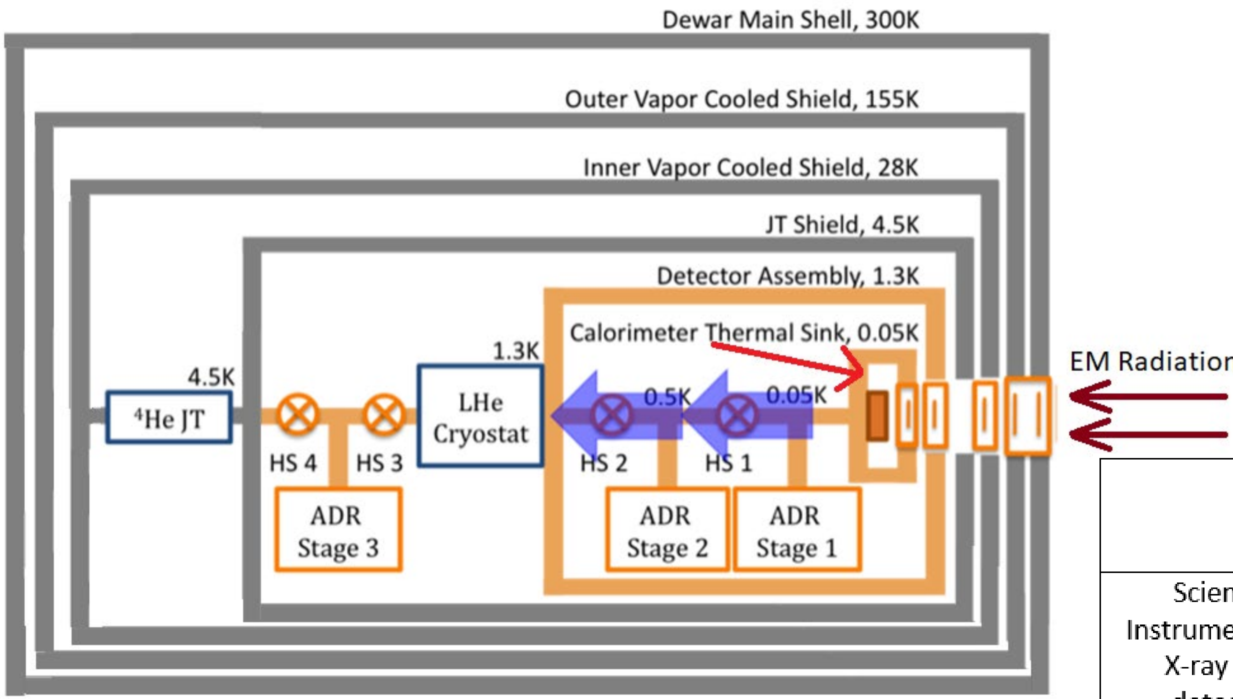
Three Types of Heat Transfer

- Radiation: Rate in = Rate out: **mitigation by layers**: each layer has high heat flux input on one side, but high heat flux output on both sides
  - ➢ JWST Example (pictured to the right)
  - ➢ Multi-Layer Insulation (MLI)
  - ➢ Heat shields



- Convection: Usually not present or minimal – Some planetary missions can be an exception
- Conduction: Distributes heat throughout the spacecraft
  - ➢ *Good Conduction:* Useful for dumping heat onto radiators
  - ➢ *Bad Conduction:* Heat leakage source when one part of the spacecraft needs to be kept cold… minimize ratio of cross-sectional area to length

Astrophysics - Typical Thermal Architecture

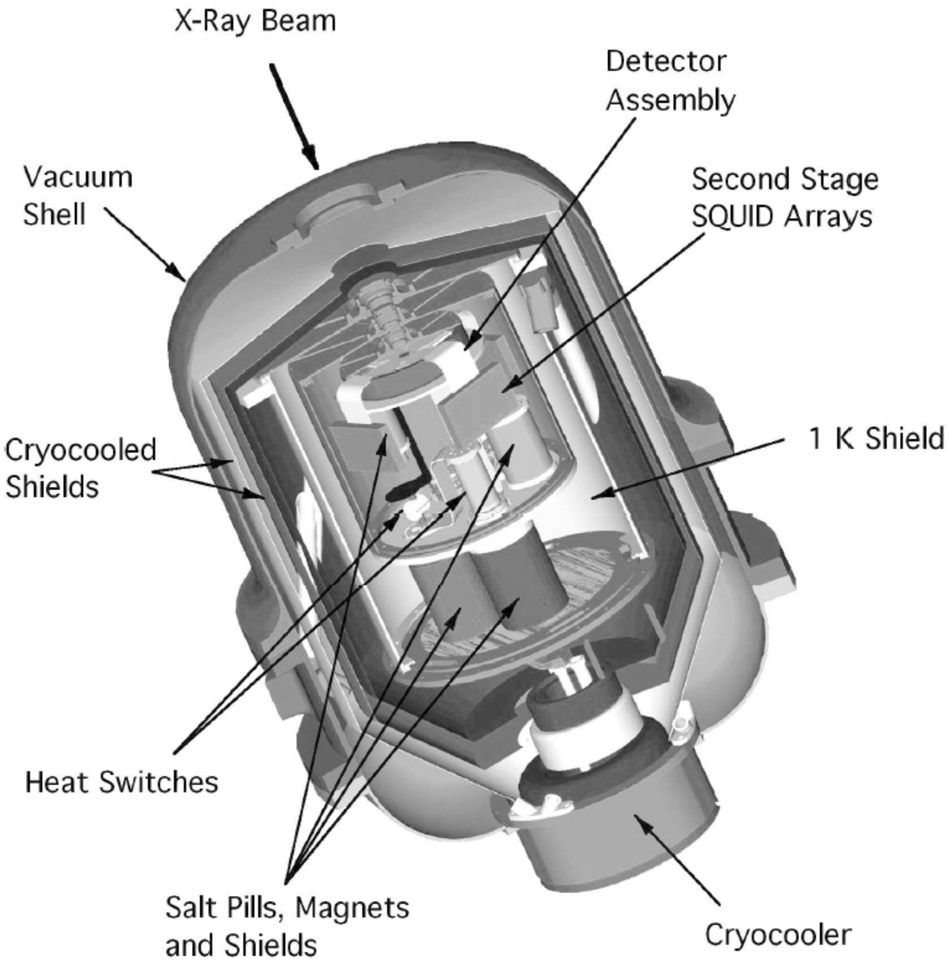


Simplified version of the Astro-H Thermal Architecture

	Example Temperature Range	Operating Principle
Scientific Instrument (e.g., X-ray or IR detector)	< 70 mK	Heat input from photons
Adiabatic Demagnetization Refrigerator (ADR)	**50 mK -> 4 K**	**Magnetocaloric Effect**
Stored Cryogen	1.2 K	Latent Heat
Cryocooler	**4 K –> 300 K**	**Mechanical Refrigeration Cycle**
Radiators	300 K	Thermal Radiation

Note: notional temperatures

Astrophysics - Typical Thermal Architecture



<u>Continuous ADR for the Constellation-X Mission</u>

	Example Temperature Range	Operating Principle
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~~Stored Cryogen~~	~~1.2 K~~	~~Latent Heat~~
Cryocooler	**4 K –> 300 K**	**Mechanical Refrigeration Cycle**
Radiators	300 K	Thermal Radiation

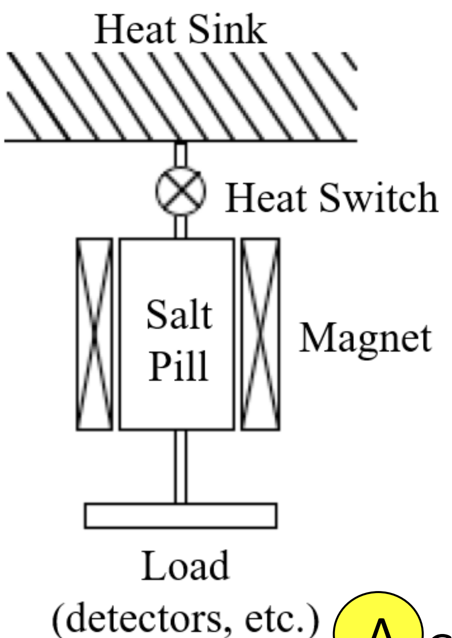
Cryogenics and Fluids Branch

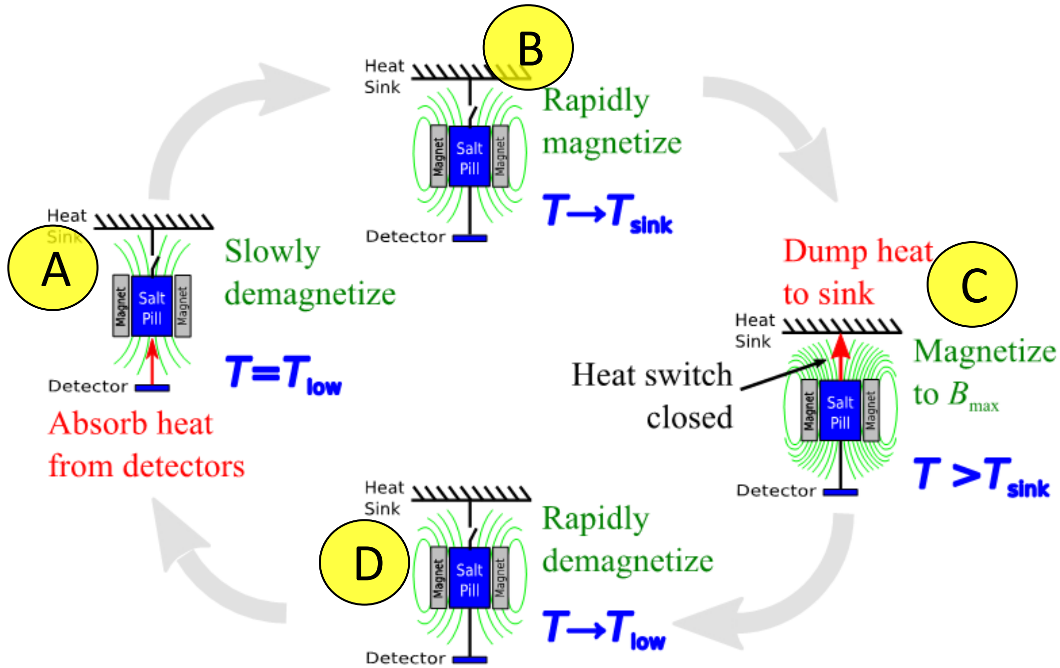
Adiabatic Demagnetization Refrigerators (ADRs)

ADR Principle of Operation

- ADR lifts heat from around 50 mK to 4 K or greater
- Uses the magnetocaloric effect: Heat can be “traded” for entropy:

$$\Delta S = \frac{\Delta Q}{T}$$





A Gradual isothermal demagnetization: Slow heat removal – cooling detectors

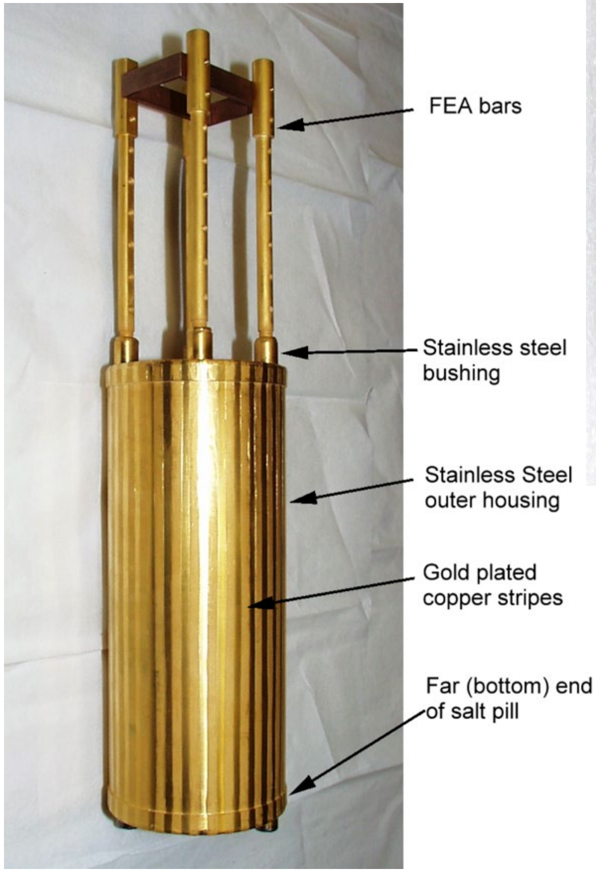
B Rapid magnetization: restore magnetic field to max value and heat up above heat sink temperature

C Close thermal switch: dump heat into heat sink

D Open heat switch, demagnetize slightly to cool to T_{low} and restart cycle

ADR Components

- 6 key ADR components:
  - **Paramagnetic material (grown on a thermal bus)**
  - **Superconducting magnet**
  - Heat switches
  - Thermally isolating support structure
  - Thermal Straps
  - HTS Leads

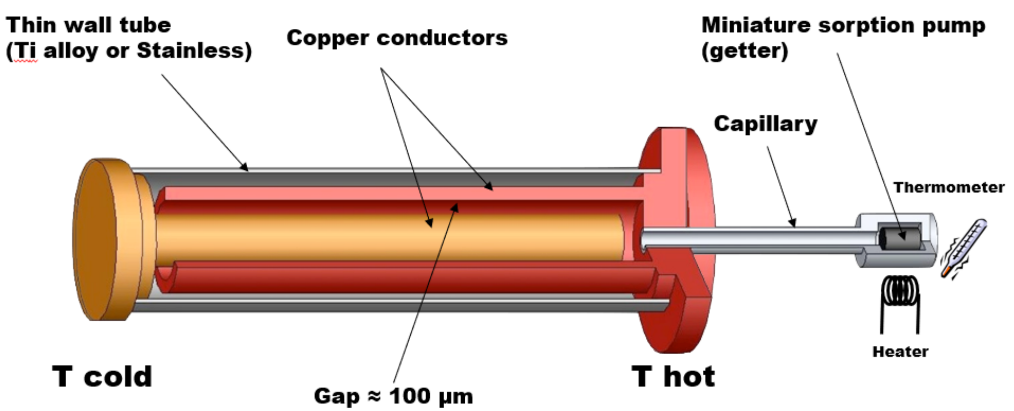


Salt Pill in Thermal Bus

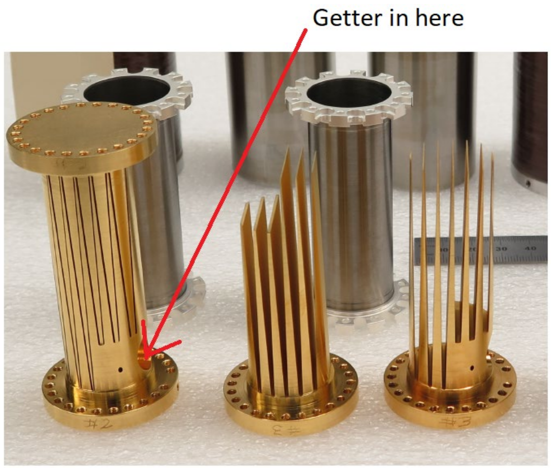
Superconducting Magnet

ADR Components

- 6 key ADR components:
  - ➢ Paramagnetic material (grown on a thermal bus)
  - ➢ Superconducting magnet
  - ➢ **Heat switches**
  - ➢ Thermally isolating support structure
  - ➢ Thermal Straps
  - ➢ HTS Leads
- Heat switch performance quantified as the ratio of on vs. off conductance
- Active vs. Passive Switches:
  - ➢ Active switches can be controlled
  - ➢ Passive switches require no wasted heat and no control electronics
- Lower temperature option (<500 mK): superconducting heat switch



Active Gas Gap Heat Switch - Concept

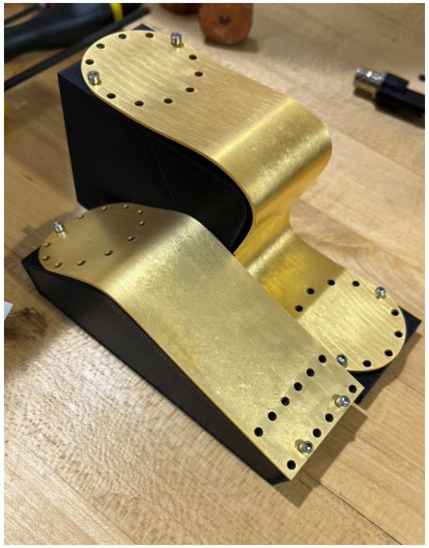


Active Gas Gap Heat Switch – as-built

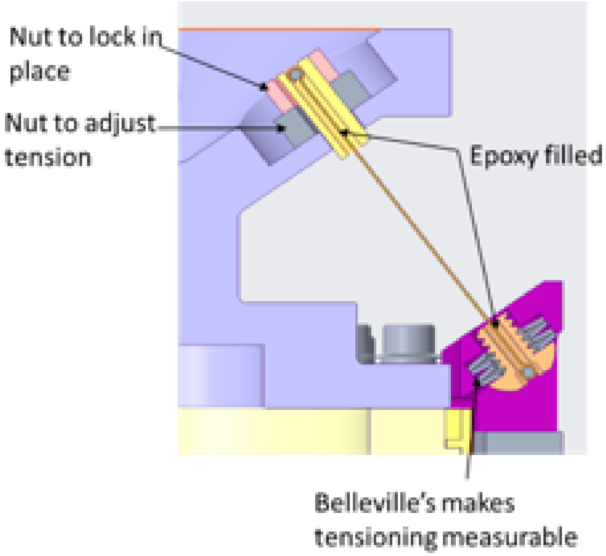
Images from: "Passive Gas-Gap Heat Switches for use in Low-Temperature Cryogenic Systems" (Kimball et al., 2017)

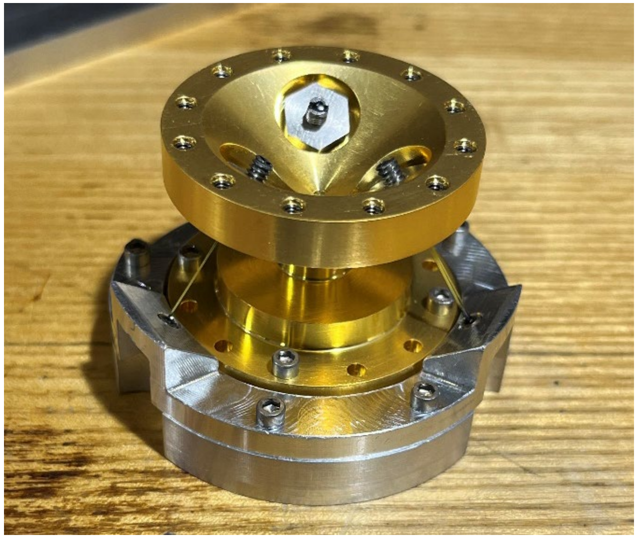
ADR Components

- 6 key ADR components:
  - Paramagnetic material (grown on a thermal bus)
  - Superconducting magnet
  - Heat switches
  - **Thermally isolating support structure**
  - **Thermal Straps**
  - HTS Leads



EXCLAIM thermal straps made from gold-plated 99.999% pure copper

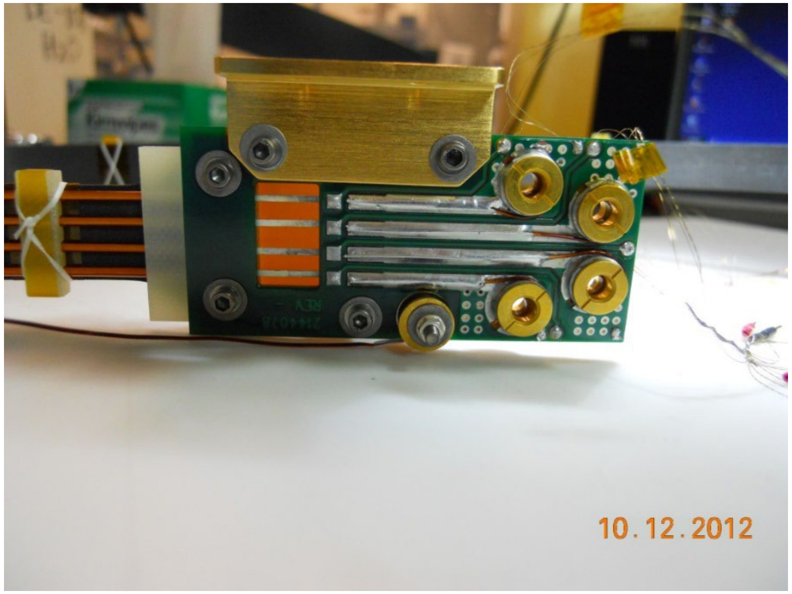


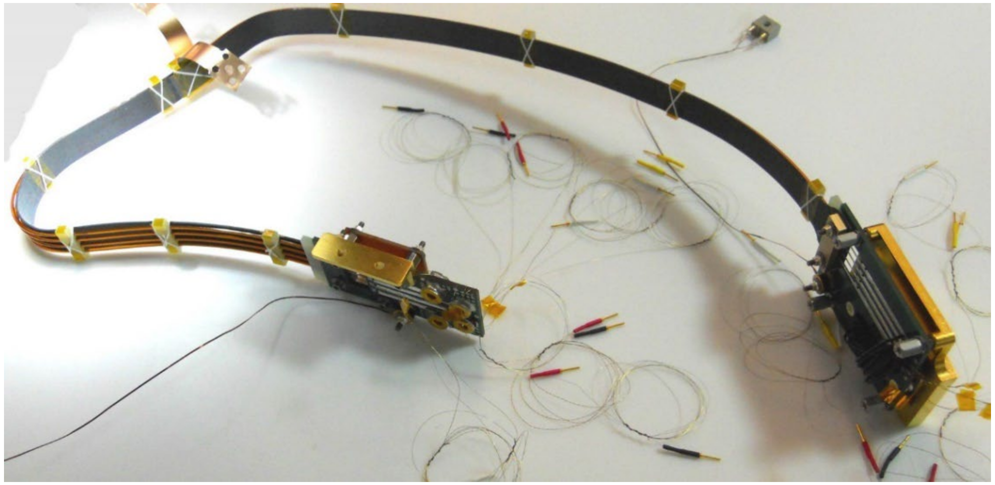


EXCLAIM tensioning system – as-built

ADR Components

- 6 key ADR components:
  - Paramagnetic material (grown on a thermal bus)
  - Superconducting magnet
  - Heat switches
  - Thermally isolating support structure
  - Thermal Straps
  - **HTS Leads**

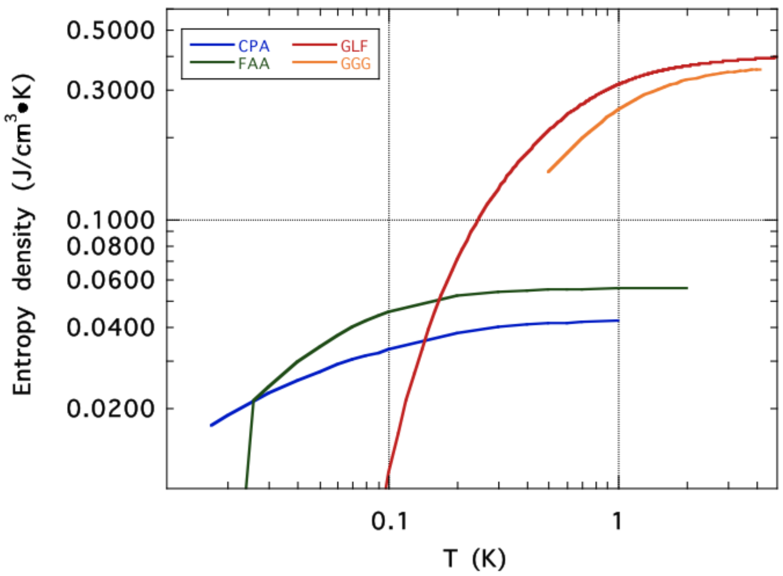


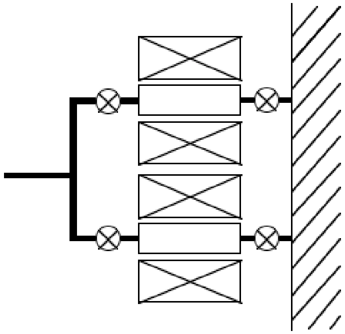


High Temperature Superconducting leads provide current to the ADR system internal to the cryogenic volume without producing Joule heating

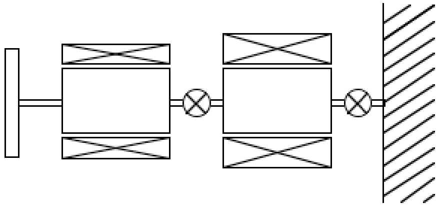
ADR Configurations

- Need multiple stages – the material, number, and configuration of stages depends on mission requirements
  - Entropy density is temperature and material dependent
  - Heat load requirements:
    - Quantity of heat to be lifted
    - Temperature of heat to be lifted
    - Intermediate heat lift?
  - Continuous vs. single-shot capability

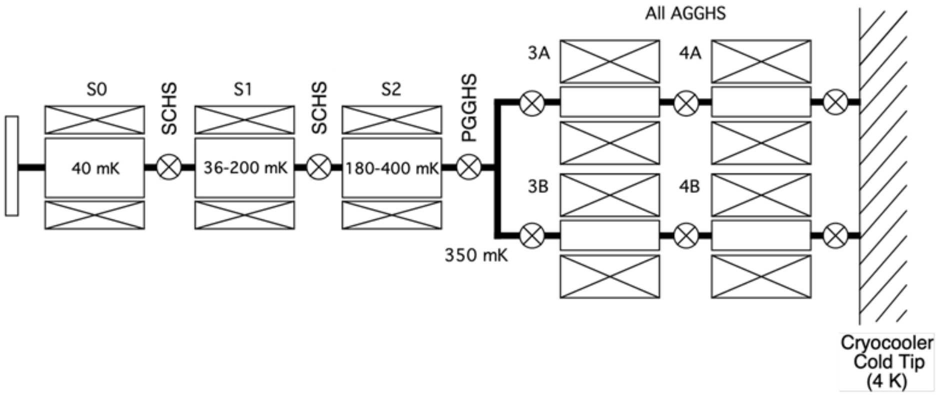




Parallel



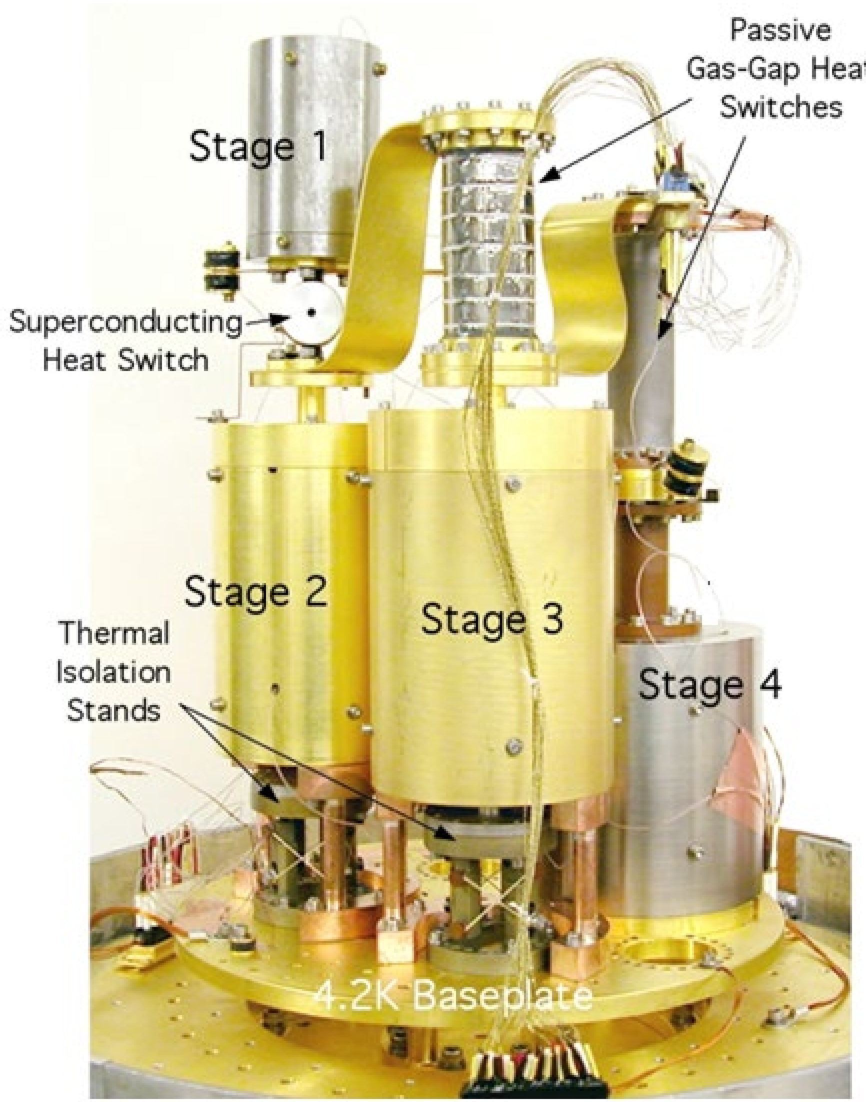
Series



Combination of Series and Parallel

ADR Picture

Heat Flows flows from Stage 1 to Stage 4 to the 4.2 K baseplate to the cryocooler cold tip



Astro-H ADR Installation

Recent ADR Missions

- **Astro-H** used an array of 36 bolometers with absorbers tuned to soft-Xray energies. **Temperature of 50 mK** required to achieve proper detector sensitivity. Mission lost due to Rx-wheel event. Temperature of 50 mK required to achieve proper detector sensitivity. Mission lost due to Rx-wheel event. 6 μW cooling at 50 mK with heat reject of 70 μW at 4K.

- **XRISM** is a rebuild of the Astro-H instrument and Sub-Kelvin cooling system.

- **PIPER** (2016 balloon mission) uses two superconducting transition-edge sensors (TES) detectors developed at NASA/GSFC to measure polarization of the CMB (> 5000 pixels). TES tuned to **work in the 100 mK temperature range**.

- **EXCLAIM** (2024 balloon mission) uses a cryogenic design to cool the telescope optics to approximately 1.7 K which is coupled to six μ-Spec spectrometer modules, featuring microwave kinetic inductance detectors that require cooling in the **100 mK temperature range**.

Planetary Missions – DragonFly Example

DragonFly – Project description

- Johns Hopkins APL-led Mission to Titan (Saturn's Largest Moon – second largest moon in solar system) - soil measurements – prebiotic compounds?
    - ➢ clouds, rain, rivers, lakes and seas of liquid hydrocarbons (e.g., methane and ethane)
    - ➢ Water ice present
    - ➢ Underground water ocean

Image from Johns Hopkins APL

Image from Huygens probe

- Gravitational constant: 1.35 m/s^2 (0.14X Earth)
- Surface pressure: 1.45 atm
- Surface temperature: 94 K
- Air density: 5.3 kg/m^3 (4.3X Earth)
- 95% N_2 & 5% CH_4
- Launch date: 2027?
- Mission sequence:

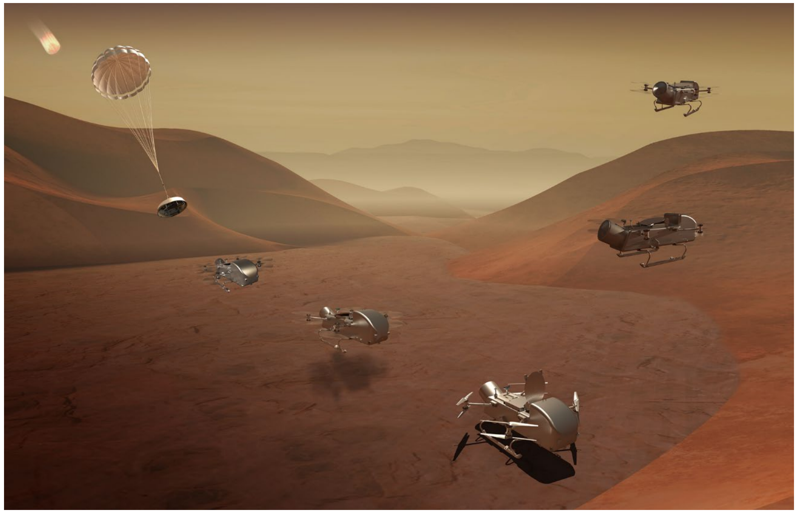


Image from Johns Hopkins APL

- ➢ Launch -> cruise for 7 years (vacuum conditions) -> descent to Titan -> land and perform mass spectroscopy -> re-charge batteries using onboard radioisotope thermoelectric generator (MMRTG) -> fly to next location and perform mass spectroscopy

DragonFly – Operations

- Sample delivered to one of two instruments:
  - ➢ Gas Chromatograph Mode – small molecules
  - ➢ Laser Desorption Mode – large molecules
- MMRTG is the only source of heat to provide power and to maintain required temperatures in the lander
- Samples drilled from one of two drills and airborne particulates -> routed to single-use sample cups -> carousel ring rotates sample to selected mass spectrometer

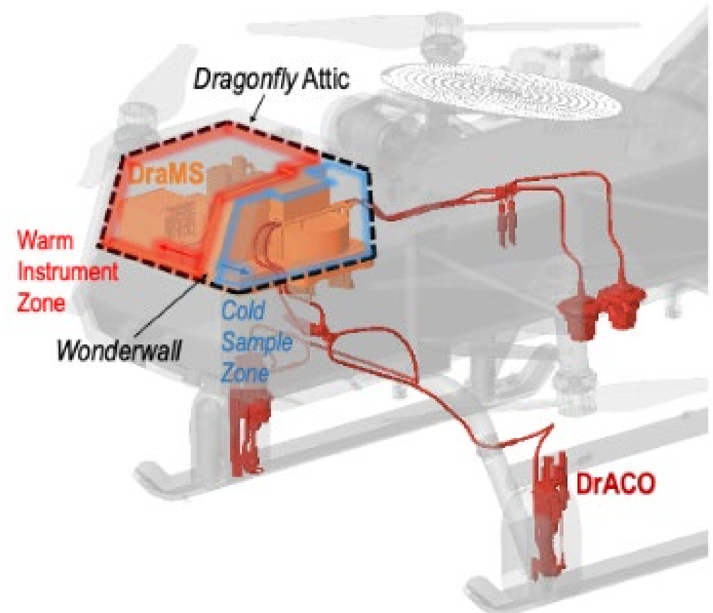


Figure 1. The *Dragonfly* "Attic" Cold Zone and Warm Zone.
Development of the Dragonfly Mass Spectrometer (DraMS) for Titan, M.G. Trainer, et al.

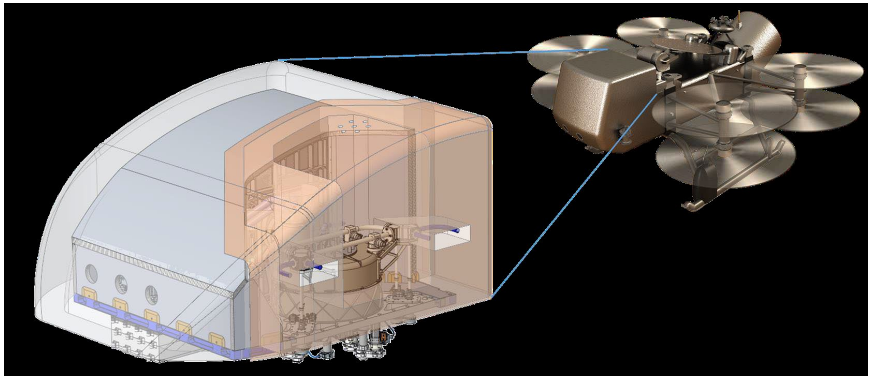


Image from Johns Hopkins APL

DragonFly – Thermal/Fluid Considerations

- Rotors are designed for higher Reynolds numbers (some wind turbine rotor features, e.g., curvature, adopted for rotors)

$$\frac{Re_{Titan}}{Re_{Earth}} = \frac{\left(\frac{\rho UL}{\mu}\right)_{Titan}}{\left(\frac{\rho UL}{\mu}\right)_{Earth}} = \frac{\dfrac{(5.3\,\frac{kg}{m^3})\cancel{U_{tip}}\cancel{L_{rotor}}}{6.59 \times 10^{-6} Pa \cdot s}}{\dfrac{(1.2\,\frac{kg}{m^3})\cancel{U_{tip}}\cancel{L_{rotor}}}{1.83 \times 10^{-5} Pa \cdot s}} = 12.3$$

- Thermal requirements:
  - Keep Titan samples cold prior to mass spectrometry (don't want to lose volatiles): required to keep < 160 K
  - Keep the rest of the lander near room temperature (electronics, etc. were not developed for cryogenic operation)

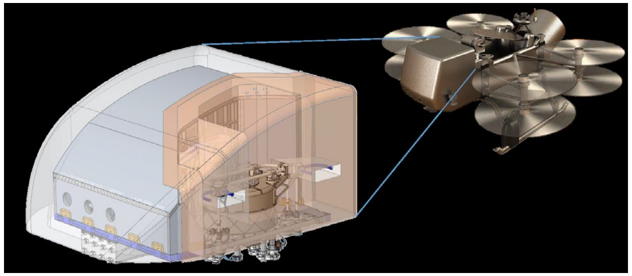


Image from Johns Hopkins APL

DragonFly – Thermal/Fluid Considerations

- Internal lander body temperature maintained by forced circulation (fans) and opening/closing parallel cooling duct
  - **Earth Test Pressure = 1.45 atm** to maintain constant Reynolds number and prototypic heat transfer coefficient (Earth vs. Titan gravity is not relevant – all other test conditions are prototypic)
  - Standard heat transfer coefficient correlations: Dittus-Boelter, etc.
- Natural convection occurring in lander cooling duct and Cryo Zone chimney – can't test in prototypic gravity
  - **Earth Test Pressure ≈ 0.56 atm** (density of 2.0 kg/m^3 at 94 K) to maintain constant Grashoff number
  - Experimentally verified this density scaling approach

$$Gr_{Titan} = Gr_{Earth} = \frac{buoyancy\ stresses}{viscous\ stresses}$$

$$\left[\left(\frac{gL^3\rho^2}{\mu^2}\right)\left(\frac{\Delta\rho}{\rho}\right)\right]_{Titan} = \left[\left(\frac{gL^3\rho^2}{\mu^2}\right)\left(\frac{\Delta\rho}{\rho}\right)\right]_{Earth}$$

$$(g\rho^2)_{Titan} = (g\rho^2)_{Earth}$$

$$\rho_{Earth} = \rho_{Titan}\sqrt{\frac{g_{Titan}}{g_{Earth}}}$$

$$\rho_{Earth} = \left(5.3\,\frac{kg}{m^3}\right)\sqrt{\frac{1.35\ m/s^2}{9.81\ m/s^2}} = 2.0\ kg/m^3$$

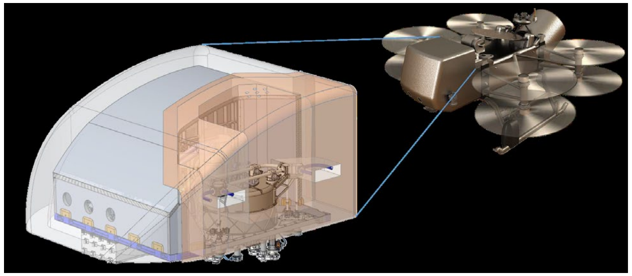


Image from Johns Hopkins APL

DragonFly – Foam Design Constraints

- Temperature requirements / Limited heat from MMRTG – <u>foam insulation required inside and outside of lander</u>
    - Limited outgassing of organics from foam
    - Machinability
    - No foam particles near samples – encapsulate with conformal coating? Thickness of coating?
    - No fracture under CTE mismatch
    - Limited gas leak rate – <u>must provide some sealing</u> (part of the pressure boundary of the warm part of the lander – to limit heat leak)

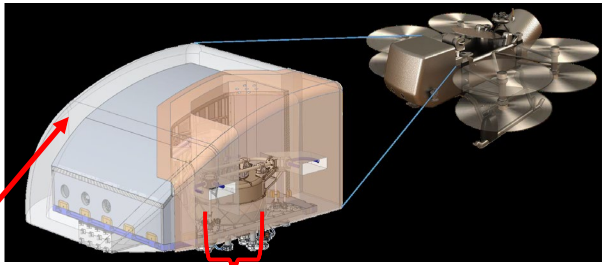


Image adapted from Johns Hopkins APL

External Foam

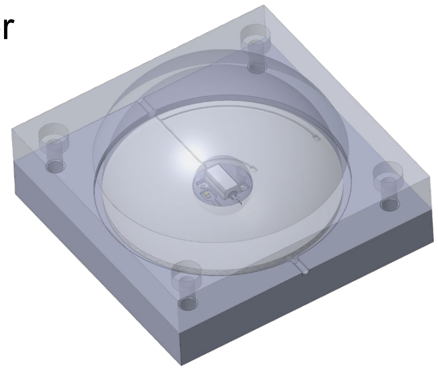
Sample Internal Foam Insulation (~11" diameter)

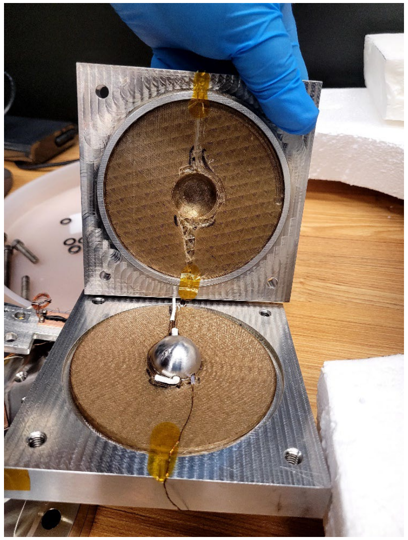
DragonFly – Insulation Thermal Conductivity Testing

- Establish steady-state heat flux by:
  - Heat inner sphere to maintain hot temp (300 K)
  - Controlled cooling via liquid nitrogen bath of outer sphere to maintain boundary condition cold temp (94 K)

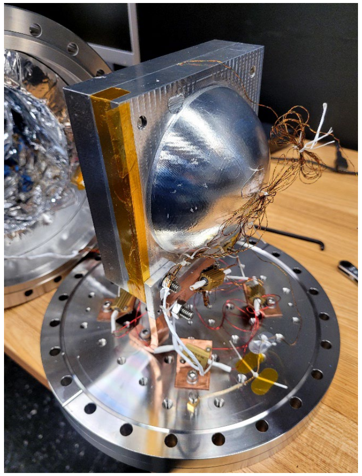
Heat input to inner sphere →

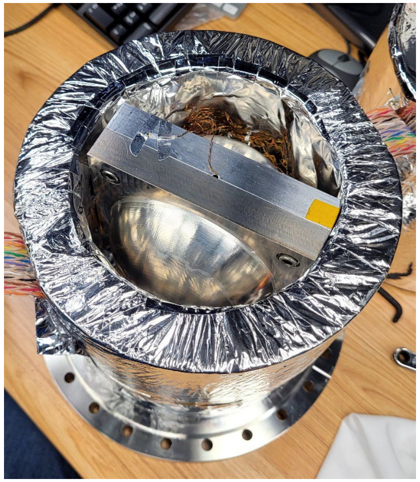
$$\dot{Q} = \frac{4\pi k R_{in}(T_{in} - T_{out})}{1 - \frac{R_{in}}{R_{out}}}$$

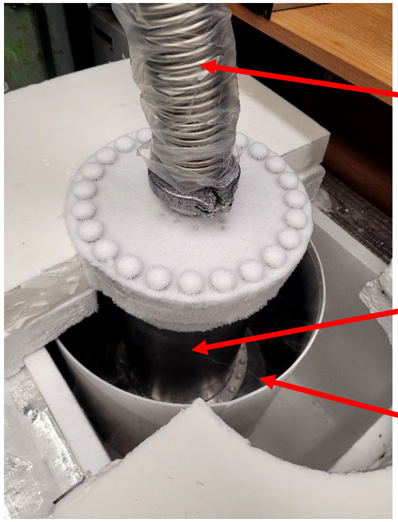




- ΔT can be varied
- Chamber pressure can be varied from vacuum to 1.45 atm (Titan pressure) or higher
  - Conductivity measured includes convection effects







Pressure communication from gaseous nitrogen cylinder and electrical cables

Experimental chamber (sealed)

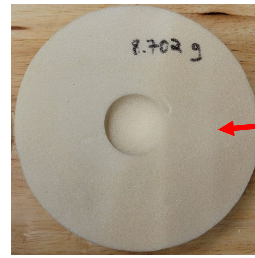
Liquid nitrogen bath (77 K boundary condition)

DragonFly – Insulation Test Results

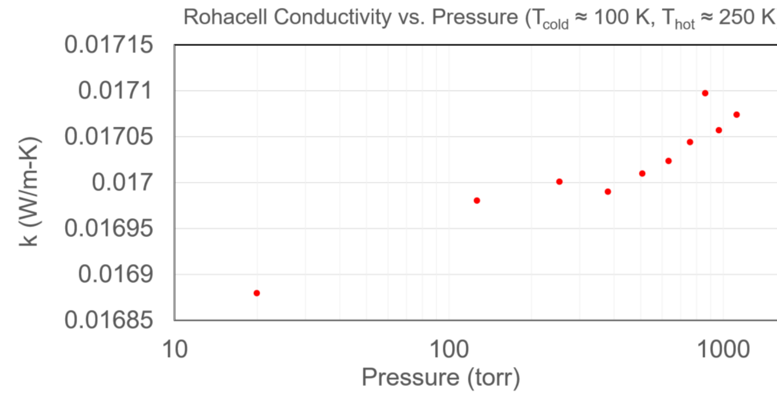
- Closed (or semi-closed) cell foams: Rohacell 31-HF (polymethacrylimide) and Elfoam P200 (polyisocyanurate)
  - ➢ Density about 32 kg/m^3
  - ➢ Closed cell – insensitive to pressure
- PEEK (3D Printed, with cubic cell infill)
  - ➢ Density: 1300 kg/m^3 (bulk, printed density depends on infill) – natural convection
  - ➢ Worse conductivity, but no outgassing and no powder
  - ➢ Much more affected by pressure, extent determined by cell size
  - ➢ Bend in the curve happens at a critical Rayleigh number of about 700 with Ra defined as:

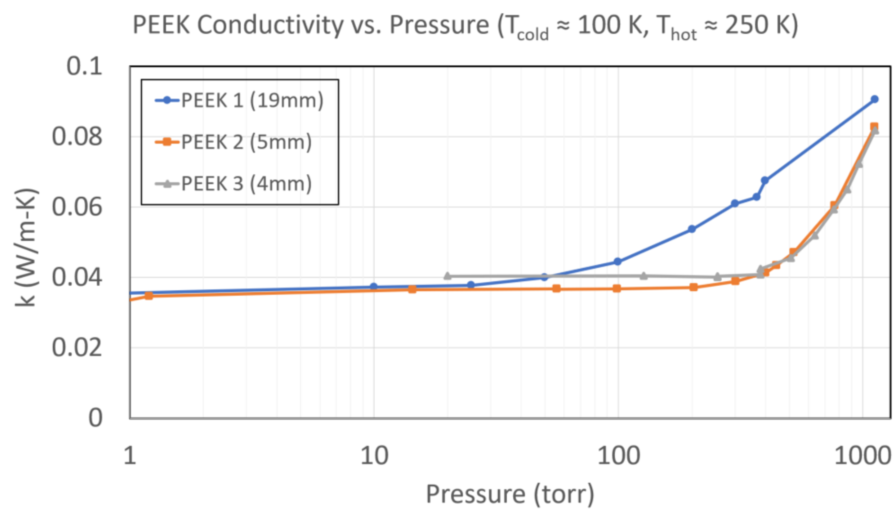
$$Ra = \frac{g\beta L^3 \rho(\delta T)}{\mu\, \alpha} = 700 = \frac{thermal\ diffusion}{natural\ convection}$$

$$\delta T \equiv \Delta T \left(\frac{cell\ width}{full\ radial\ distance}\right)$$



Closed-cell half-sphere (Elfoam P200)





Cryocooler Types (like DC vs. AC electricity)

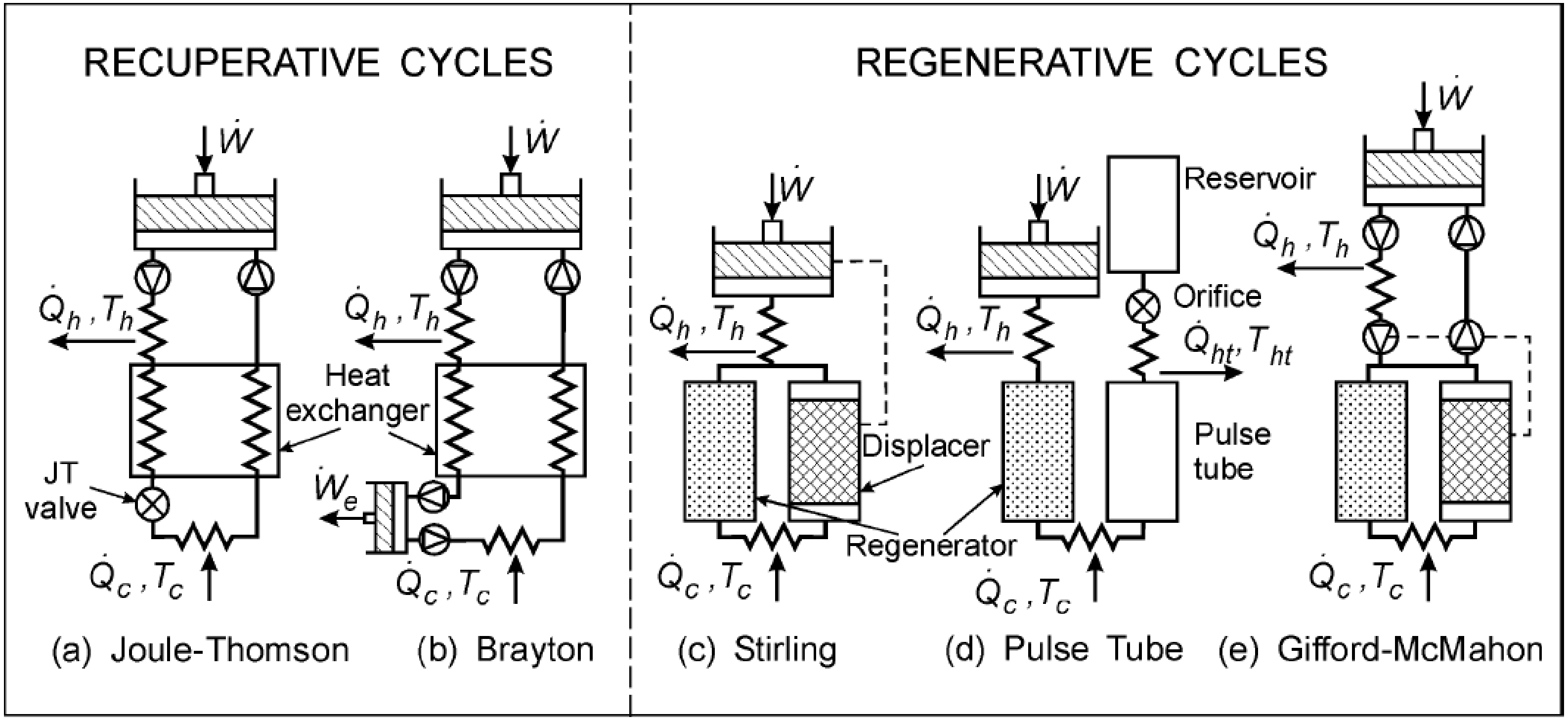


Image from: “Pulse Tube Cryocoolers for Cooling Infrared Sensors”, Proceedings of SPIE, The International Society for Optical Engineering, Infrared Technology and Applications XXVI, Vol. 4130, pp. 363-379 (Radebaugh, 2000)

- Recuperative Cryocoolers: Continuous, loop flow
  - Components: Evaporator (cold head), recuperative heat exchanger, gas compressor, aftercooler (heat sink), J-T valve (isenthalpic expansion) (OR turboexpansion to extract work)

Joule-Thompson Cryocooler

Joule-Thompson coefficient Inversion Curve

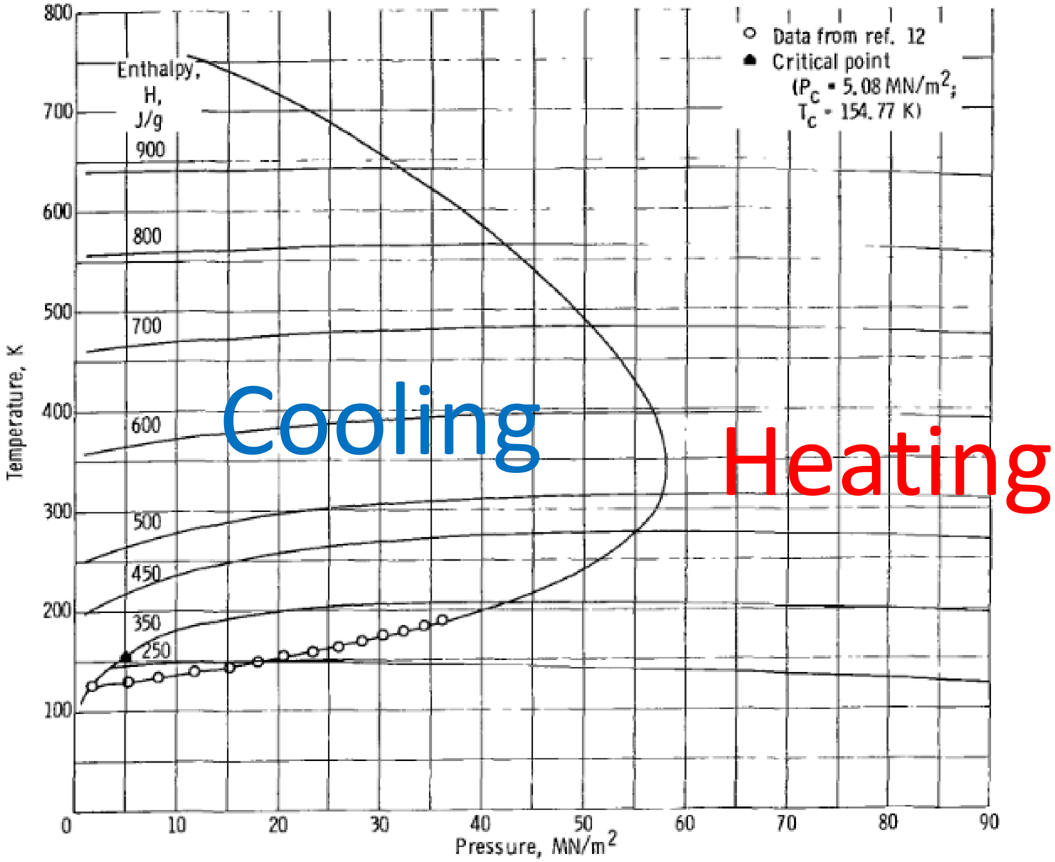


Figure 7. - Joule-Thomson inversion curve for oxygen. Curve and selected isenthalps based on PVT extensions as calculated from reference 15; data from reference 12.

Image from: "Joule-Thomson Inversion Curves and Related Coefficients for Several Simple Fluids" – NASA Technical Note (Hendricks, et al., 1972)

- Cooling relies on behavior of real gases (ideal gases expand isenthalpically)
- Each substance has its own J-T inversion curve (J-T Cryocoolers often use nitrogen or methane)

Open-Cycle Joule-Thompson Cryocooler

Image from: “Pulse Tube Cryocoolers for Cooling Infrared Sensors”, Proceedings of SPIE, The International Society for Optical Engineering, Infrared Technology and Applications XXVI, Vol. 4130, pp. 363-379 (Radebaugh, 2000)

- Uses stored compressed gas
- Can use gas mixtures rather than a pure gas to increase non-ideality and increase the J-T coefficient (Radebaugh, 2018)
  - Can increase J-T coefficient by a factor of 2.5 to 5 by adding methane, ethane, and propane to nitrogen
  - Oil solubility also increased

Cryocooler Types – Regenerative

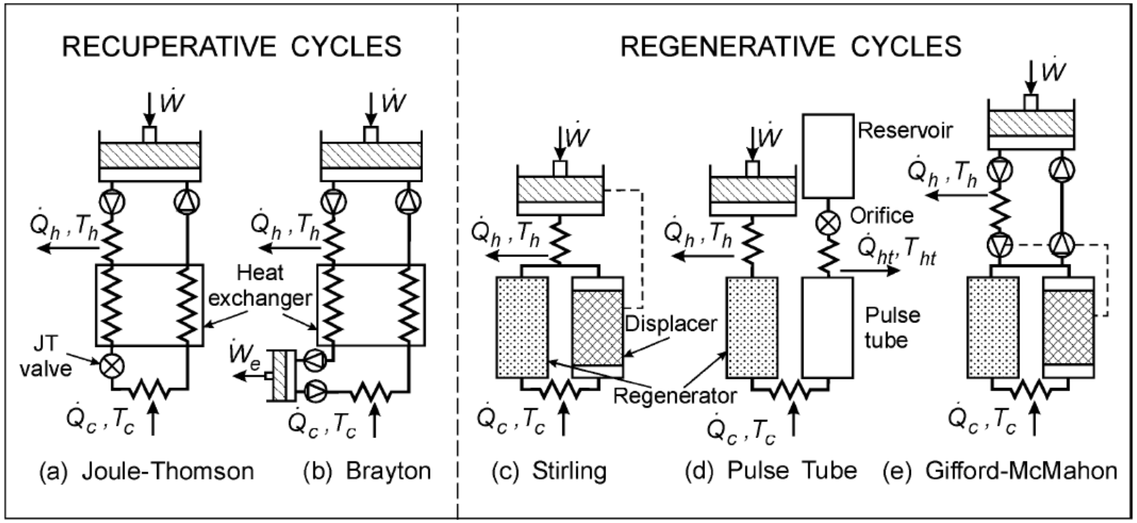
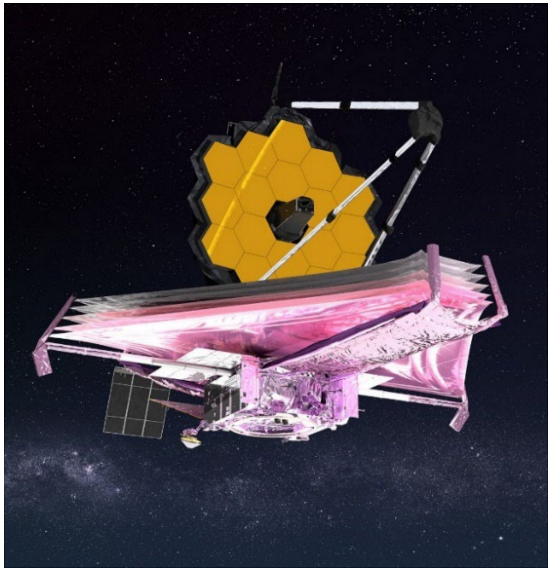
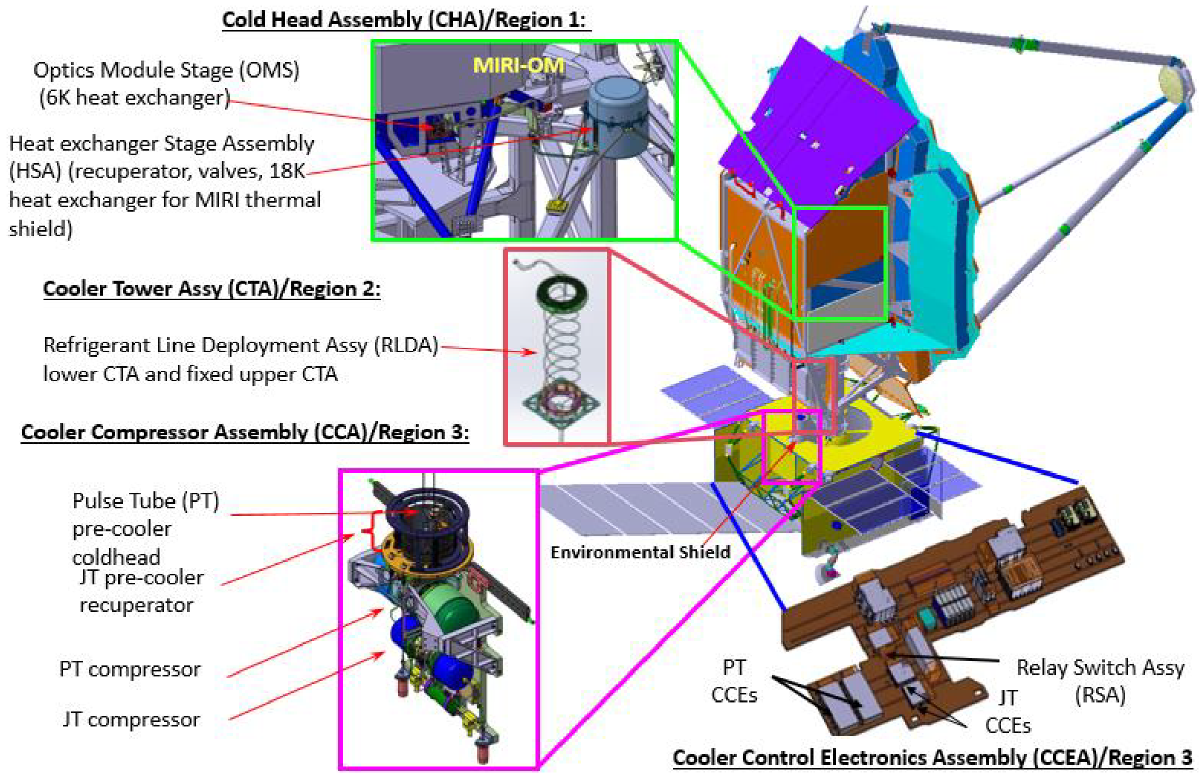


Image from: "Pulse Tube Cryocoolers for Cooling Infrared Sensors", Proceedings of SPIE, The International Society for Optical Engineering, Infrared Technology and Applications XXVI, Vol. 4130, pp. 363-379 (Radebaugh, 2000)

- Regenerative Cryocoolers: Oscillatory, single-path flow
  - Components: Evaporator (cold head), regenerator (high heat capacity, high surface area stacked fine-mesh screen or packed spheres), displacer, aftercooler (heat sink), valveless compressor (though Gifford-McMahon does have valves)
  - Principle of operation for Stirling Cryocooler: Compressor piston expands gas, then displacer pushes gas from cold end to warm end. High heat capacity regenerator warms gas as it travels from cold end to warm end… principle works in reverse during the compression part of the cycle…
  - Pulse Tube is like Stirling, but uses an orifice and a reservoir as an alternative way to create phase lag in the mass flow wave so that cooled or warmed gas is moved in the proper direction after the adiabatic cooling/heating – pulse tube eliminates motion of displacer (wear component, unwanted conduction, vibration, etc.)

Cryocooler Application – James Webb Space Telescope





- Launch date: 12/2/21, Sun-Earth L2 Observatory (arrived 1/24/2022)
- Four Primary Science Instruments on JWST: three instruments detect near-IR photons, while MIRI (mid-infrared) detects longer IR wavelengths – needs cooling to 7 K
- 3-stage pulse-tube cryocooler pre-cools to 18K, and a J-T cryocooler to achieve under 6K
- Cooler built by Northrop Grumman and overseen by JPL and NASA/GSFC – GSFC Cryogenics Roles/Responsibilities:
  - Cryogenic Systems Engineering, Cryogenic I&T Guidance/Support, Lead NASA Org. for MIRI Cryocooler

Cryocooler Type Comparison

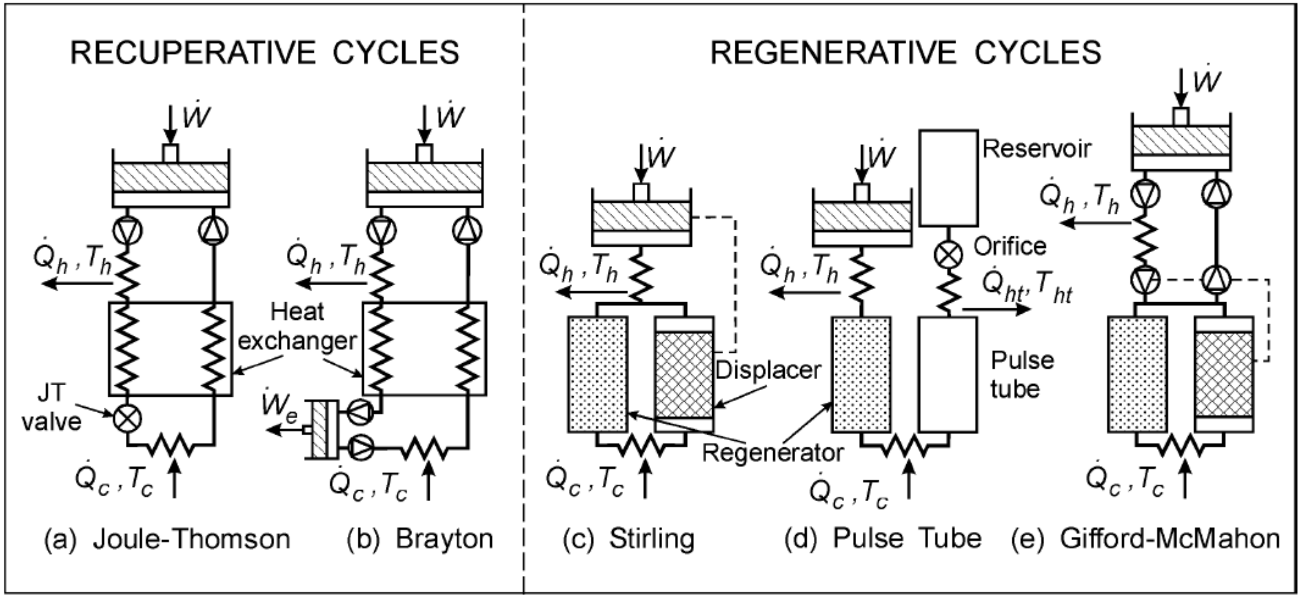


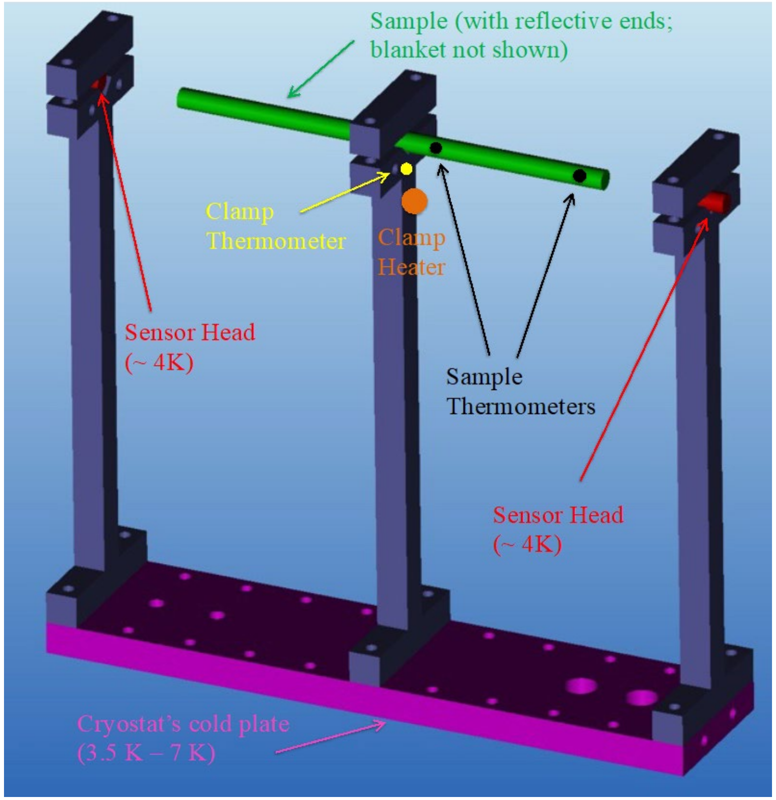
Image from: "Pulse Tube Cryocoolers for Cooling Infrared Sensors", Proceedings of SPIE, The International Society for Optical Engineering, Infrared Technology and Applications XXVI, Vol. 4130, pp. 363-379 (Radebaugh, 2000)

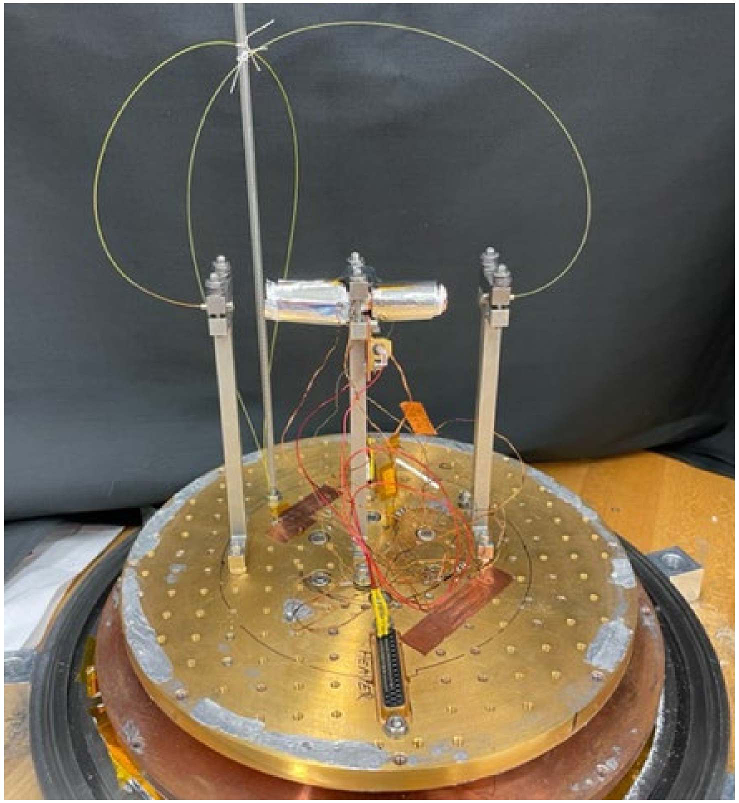
- Pros and Cons of Recuperative vs. Regenerative Cryocoolers
  - Recuperative may be easier to separate cold end (with no moving parts) from compressor – allows compressor vibrations and electromagnetic interference (EMI) to be located far from detectors
  - Rapid cool-down is possible for recuperative
  - Recuperative may be subject to clogging of the orifice from moisture or compressor oil can if it gets into the working fluid and freezes
  - Recuperative cryocoolers require high pressure (>200 bar) – compressors not very efficient at these pressures

A few more things…

CTE Measurements
Heat Pipes
Laboratory Considerations

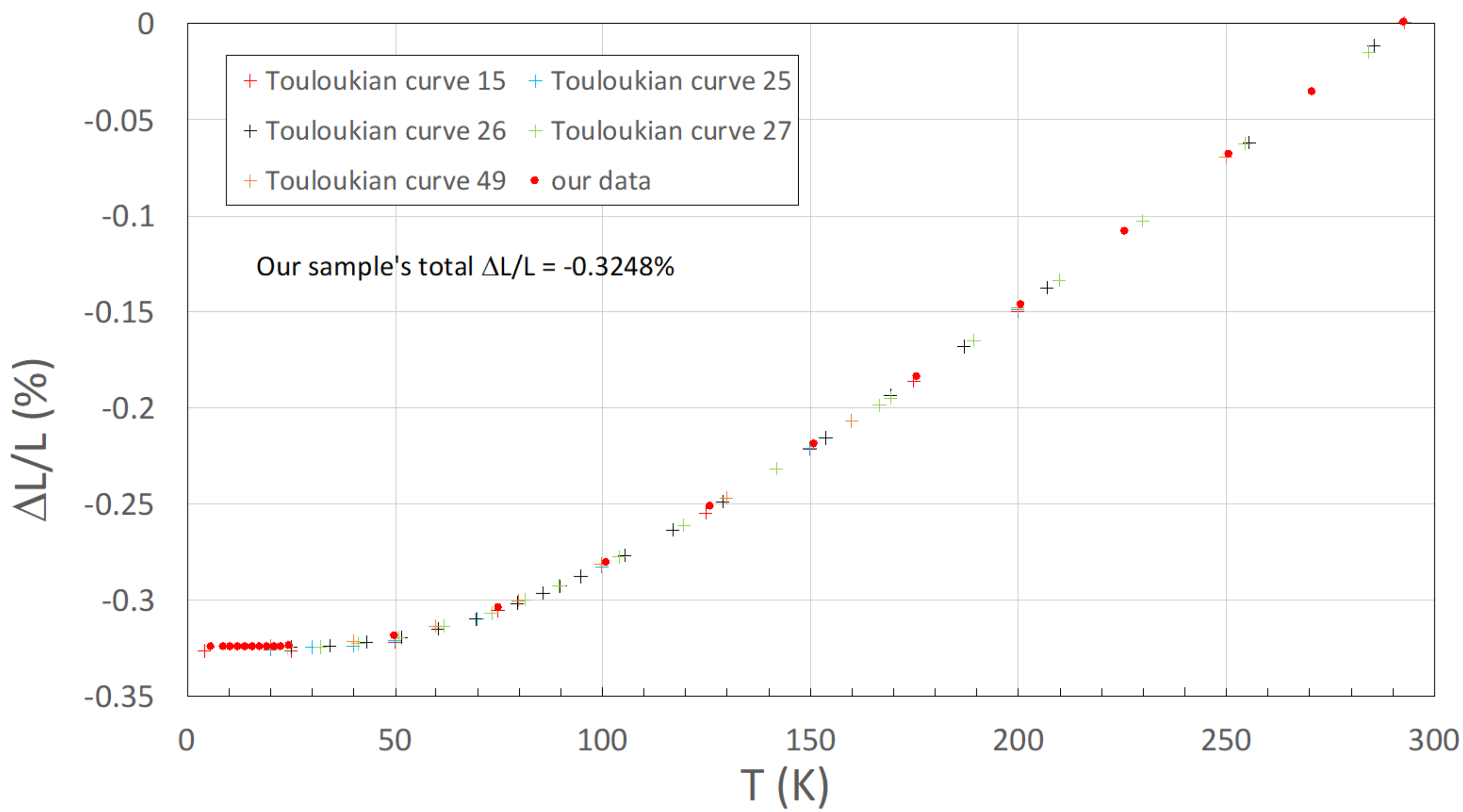
Coefficient of Thermal Expansion Measurement





- Attocube Model IDS3010 position sensor – laser interferometer in a cryostat – distance to sample cylinder ends
- Heat middle post to vary sample temperature – start at 4 K and increment up to 293 K (where cylinder length is known)
  - Note: Sensor posts are kept at 4 K, so the baseplate dimensions don't shift
- Sample ends are polished or polished disks are attached

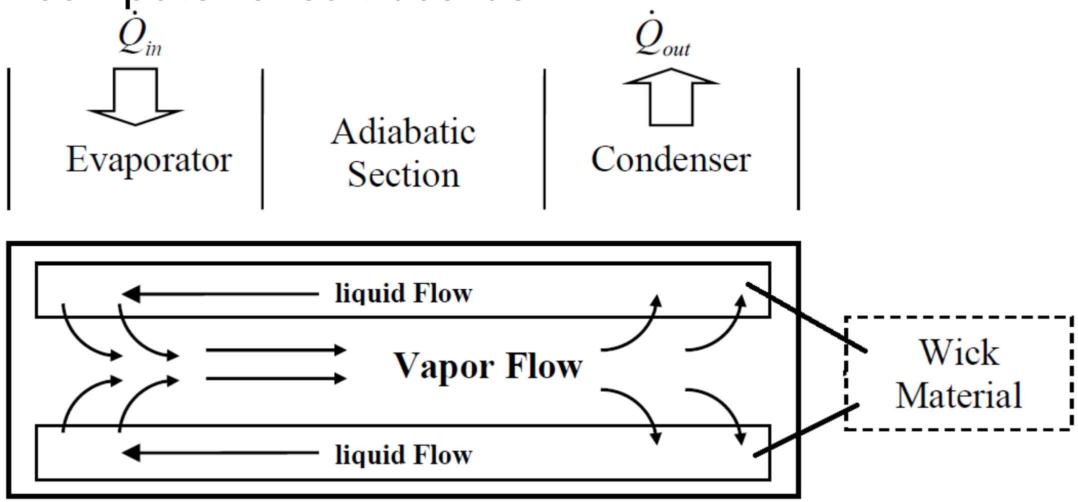
Copper ΔL/L between 393 K and 6 K

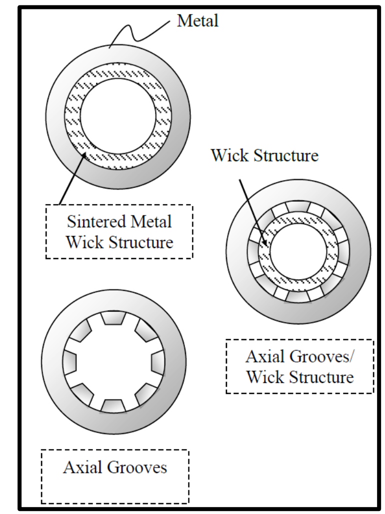


- Our measured ΔL/L from 293 K to 6 K: -0.3248% – good agreement with literature
- Measured alumina and sintered samarium cobalt for project use
- Looking into establishing a collaboration for future applications – e.g., quantifying CTE anisotropy in additively manufactured materials

Heat Pipes

- Heat pipes transport heat along a temperature gradient – also used to cool computer circuit boards

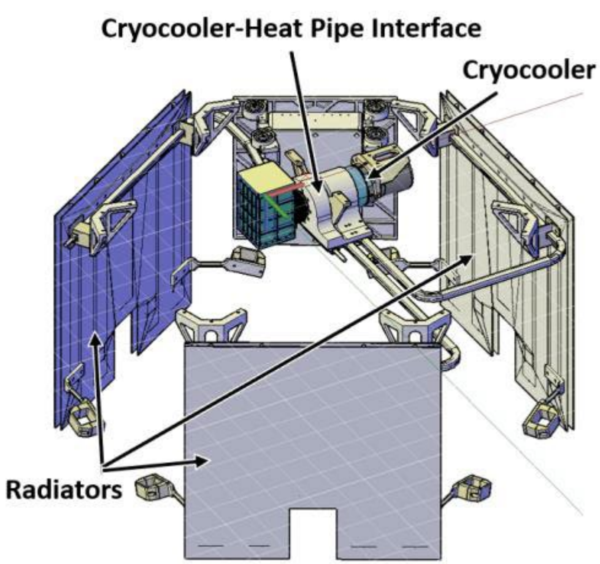


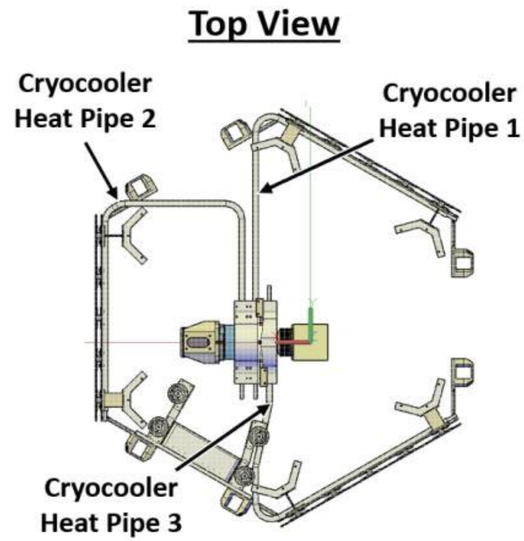


Taken/adapted from Introduction to Spacecraft Thermal Design (2020) by E.A. Silk, Cambridge University Press

- Vapor flow driven by ΔP caused by vapor generation at evaporator, liquid flow driven by surface tension
- Operational limits (for power and temperature) include: critical heat flux, capillary flow limit, entrainment
- Gravity hinders liquid flow, but not in space – complication for integrated spacecraft testing
- Common room temperature working fluids: ammonia, water
- Investigating cryogenic heat pipes using methane and considering neon, etc.

COSI (Compton Spectrometer and Imager)



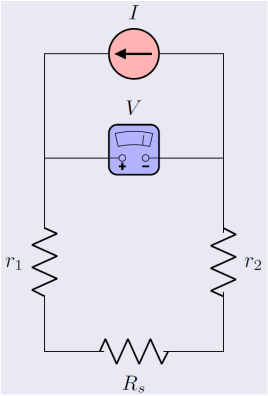


SunPower CryoTel CT-8 Cryocooler

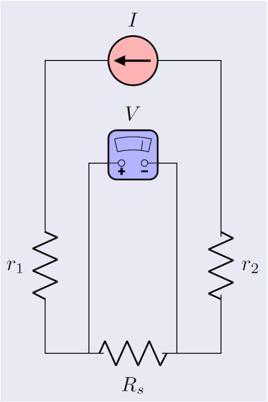
- Class D mission collaboration between University of California Berkley/Northrop Grumman/NASA – launching in 2026?
- Heat flow path: Gamma-ray detector -> cryocooler -> heat pipe -> radiators
- Total of 15 ammonia heat pipes (restricted to 2D orientations to eliminate gravity in testing)

Some Laboratory Considerations

- Cold – wear gloves, goggles, etc.
- Dewars should not be pressurized – relief valve continuously relieving at 22 psig
- Liquid nitrogen is plentiful – a lot of data gets taken at 77 K
- Cryogenic fluid transfer – have to cool the lines first
- Oxygen exclusion (always have oxygen monitoring) – high-ceilinged building for large quantities
- 2-wire vs 4-wire temperature measurement
- Equilibrium times can be long – low heat flows
- Need to use vacuum pumps, fittings, etc.
  - ➢ Electronics need feed-throughs
  - ➢ Helium leak detectors
  - ➢ CTE mismatch – vacuum sealing:
    - ○ Some fitting types work better than others
    - ○ Dissimilar metals: Indium seal or Explosion-welded fitting



2-wire



4-wire

Cryogenics and Fluids Branch

Front Row (Left to Right): **Mike Sampson, Kim Barnstable, Chullhee Cho, Amir Jahromi, Steven Cale, Oriana Tomlin, Hak Seung-Lee, Mike Dipirro, Mark Kimball, Robert Boyle**

Middle Row (Left to Right): **Charles Hebron, Edgar Canavan, Rick Letmate, Jim Tuttle, Howard Tseng, Bryan James, Matt Francom, Richard Ottens, Paul Rueger**

Back Row (Left to Right): **Jacob Nellis, Paul Whitehouse, Brian Comber, Kelly Burch, Eric Silk, Pete Barfknecht**

Not present: ***Sandra Alston, Kim Banks, Stuart Banks, John Francis, Evan Sheehan, Shuvo Mustafi, Peter Shirron***

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Cryogenics and Fluids Branch

Thank you

Questions?

Acronym Table

- ADR – Adiabatic Demagnetization Refrigerator
- EXCLAIM – Experiment for Cryogenic Large-Aperture Intensity Mapping
- XRISM – X-ray Imaging and Spectroscopy Mission
- PIPER – Primordial Inflation Polarization Explorer
- MMRTG – Multi-Mission Radioisotope Thermoelectric Generator
- EMI – Electromagnetic Interference