ADR Design and Optimization for Low Temperature Applications

Peter Shirron

Cryogenics and Fluids Group, Code 552

ADR

IS NOT

ALTERNATIVE DISPUTE RESOLUTION!

ADR

IS

ADIABATIC DEMAGNETIZATION REFRIGERATOR

Safety Week Special:

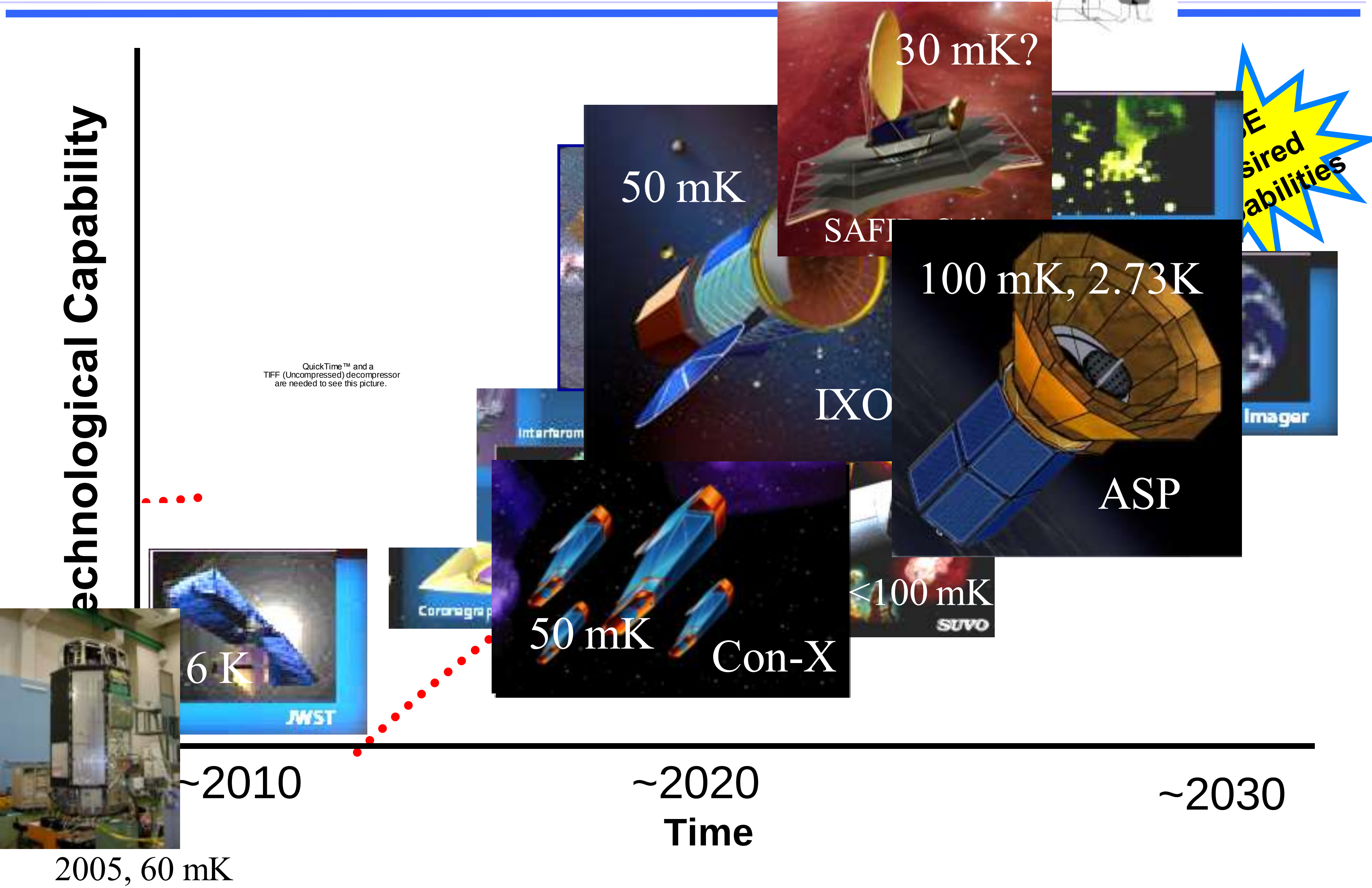
What NOT to do in a Cryogenics Laboratory

Topics

- Science drivers for low temperature cooling
- What is an ADR?
- ADR architectures and cooling capabilities
  - Single-stage ADR
  - Two-stage ADR
  - Continuous ADR
- System optimization
  - Cryogenic systems
  - Safety aspects and impacts
- Future of ADR technology

Science Mission Vision

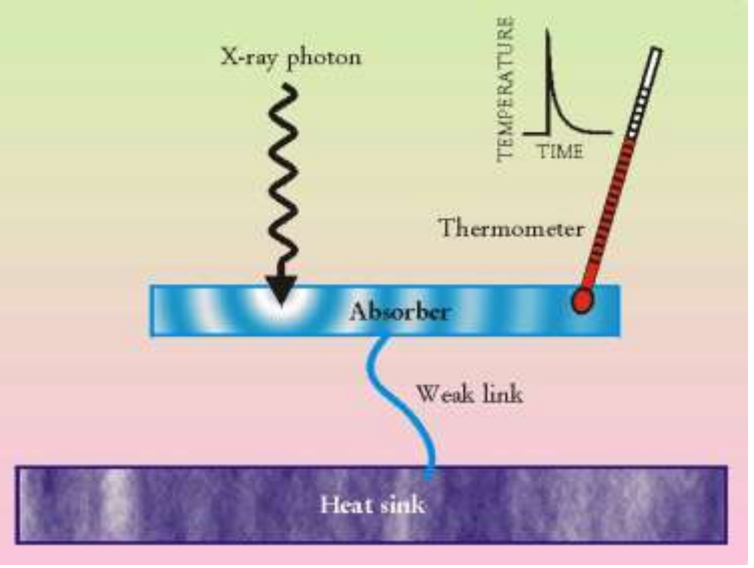
Cryogenics and Fluids Branch



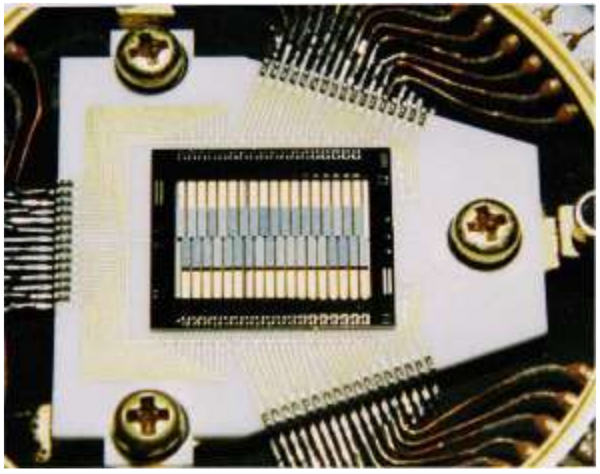
Microcalorimeter Arrays

X-ray microcalorimeter: Thermal detection of individual x-ray photons.

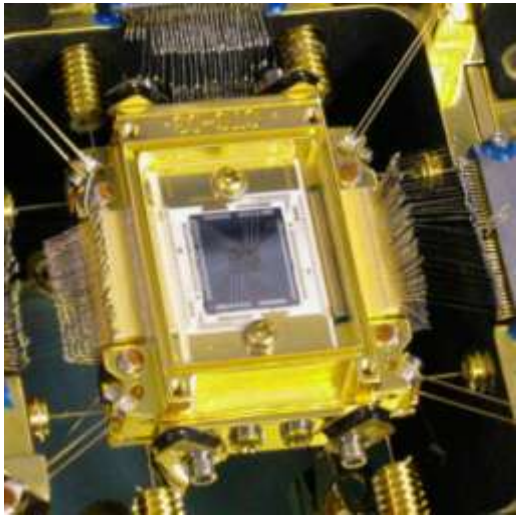
- High Spectral Resolution
- High Intrinsic quantum efficiency
- Non-dispersive - spectral resolution non affected by source angular size



Arrays have been developed for sounding rocket payload and orbiting observatory:



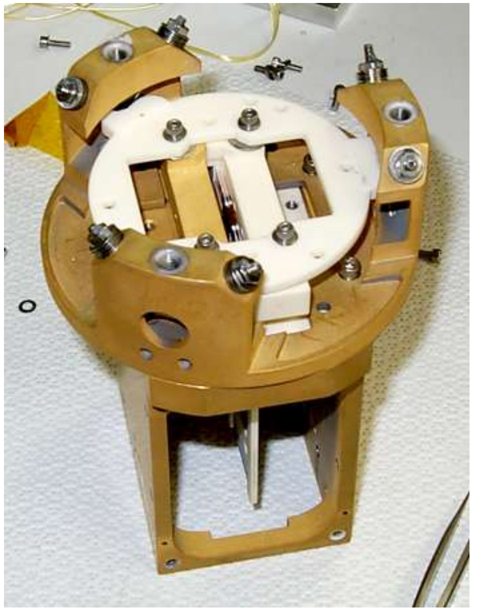
XQC

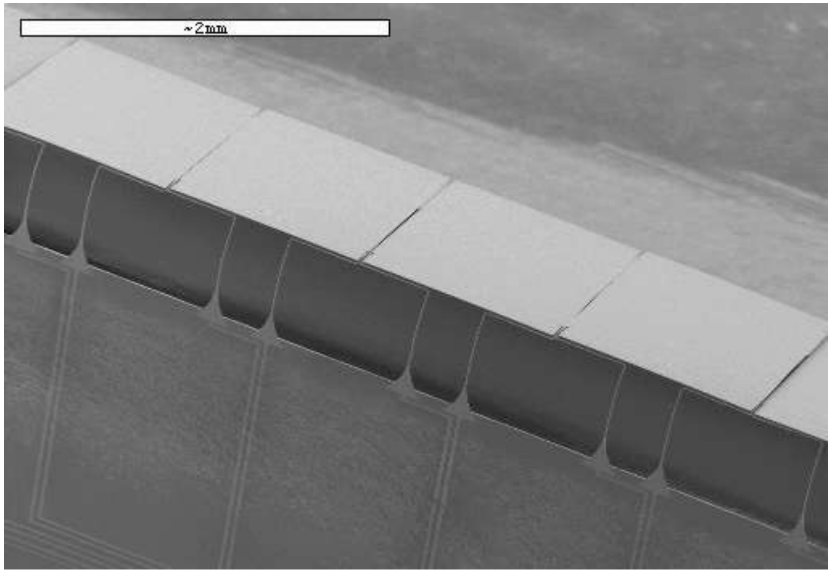


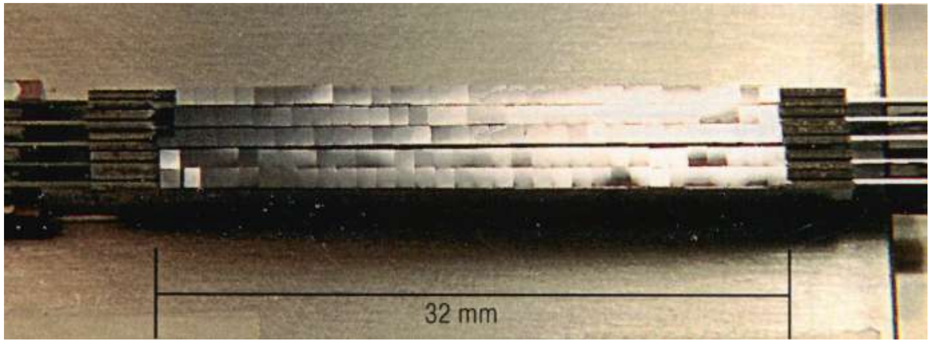
Astro-E2/XRS

Bolometer Arrays

- Low temperature detectors for far-IR missions
  - Large format detector arrays (32x32)
  - Growing number of sensor types
    - Semiconducting, Superconducting, Magnetic
  - Background-limited detection: NEP $<10^{-19}$ W/√Hz
    - Achievable only with cooling to ~20-30 mK
    - Cooling power of ~1 μW at 30 mK







Instrument Trends

XRS2 on Astro-E2 — 32-pixel array at 60 mK

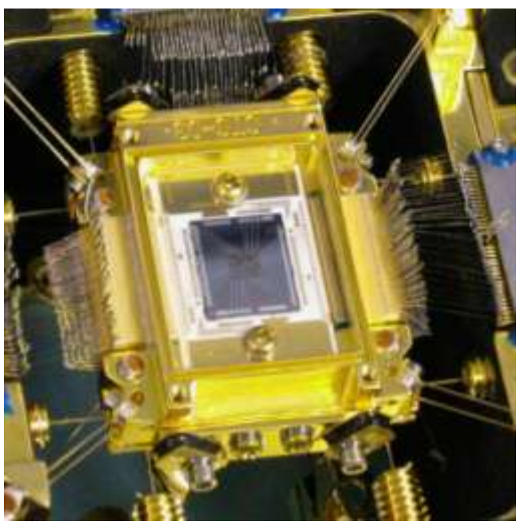
Launched July 2005 — 0.3 μW load

SXS on Astro-H — 64->32-pixel array at 50 mK

Launch in 2013 — 0.7 μW load

Con-X/IXO — 1000-pixel array at 50 mK

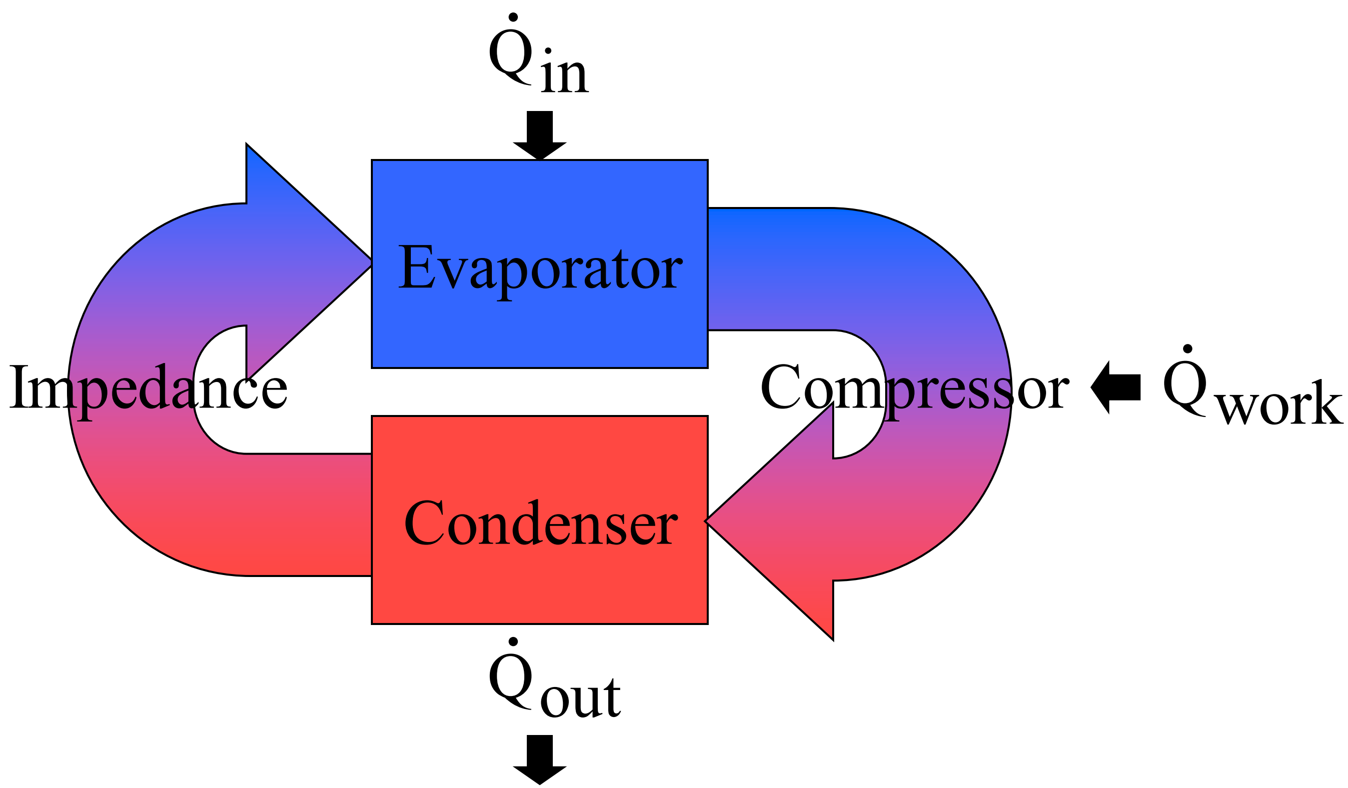
2-5 μW load



Increasing need for more capable cooling systems

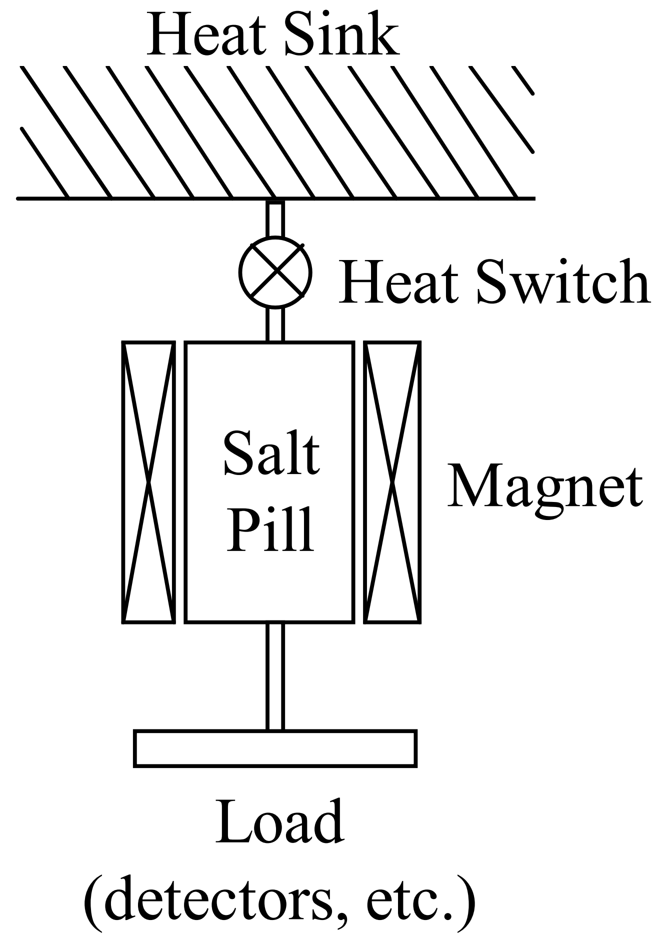
Refrigeration

- Refrigerant must accomplish 4 processes
  - Cool down
  - Absorb heat at lower T
  - Warm up
  - Give off heat at upper T

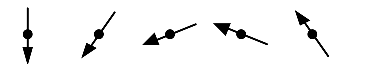


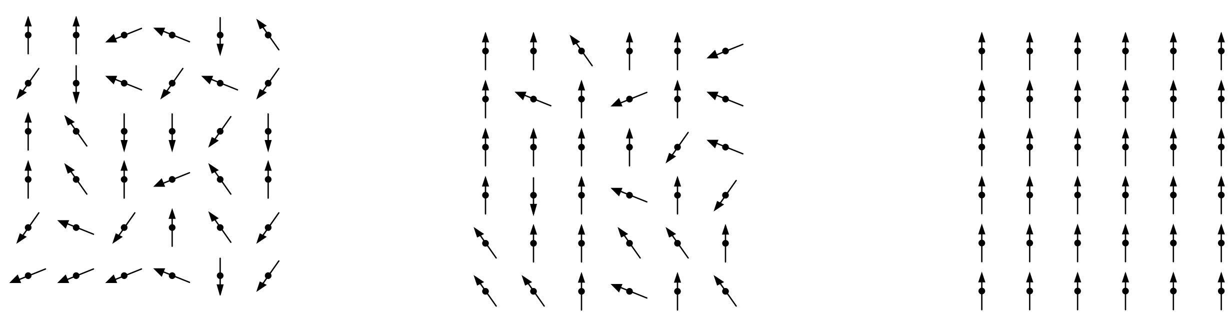
What is an ADR?

- Solid-state cooler
  - Paramagnetic material
    - Called a "salt pill"
  - Magnet
  - Heat switch
  - Suspension
- Based on the "magnetocaloric effect"
  - Increasing magnetic field generates heat
  - Decreasing magnetic field generates cooling



What is an ADR?

- Array of magnetic spins is used to store and release heat
  - Ferric Ammonium Alum (FAA): $\mathbf{Fe^{3+}(NH_4)(SO_4)_2 \cdot 12H_2O}$
  - J=5/2; 6 spin states -5/2, -3/2, -1/2, 1/2, 3/2, 5/2 
  - Population of each state depends on temperature and applied field



high T, low B	intermediate T, B	low T, high B
S/R= ln6	0<S/R<ln 6	S/R=0

- Maximum entropy change is R•ln6 ~ 15 J/mol•K
  - 1 mol (500 grams, 280cm^3) of FAA can store 1 J at 0.06 K

Entropy

- Entropy is proportional to heat flow

$$\Delta S = \Delta Q / T$$

- Entropy of *non-interacting* spins can be calculated exactly

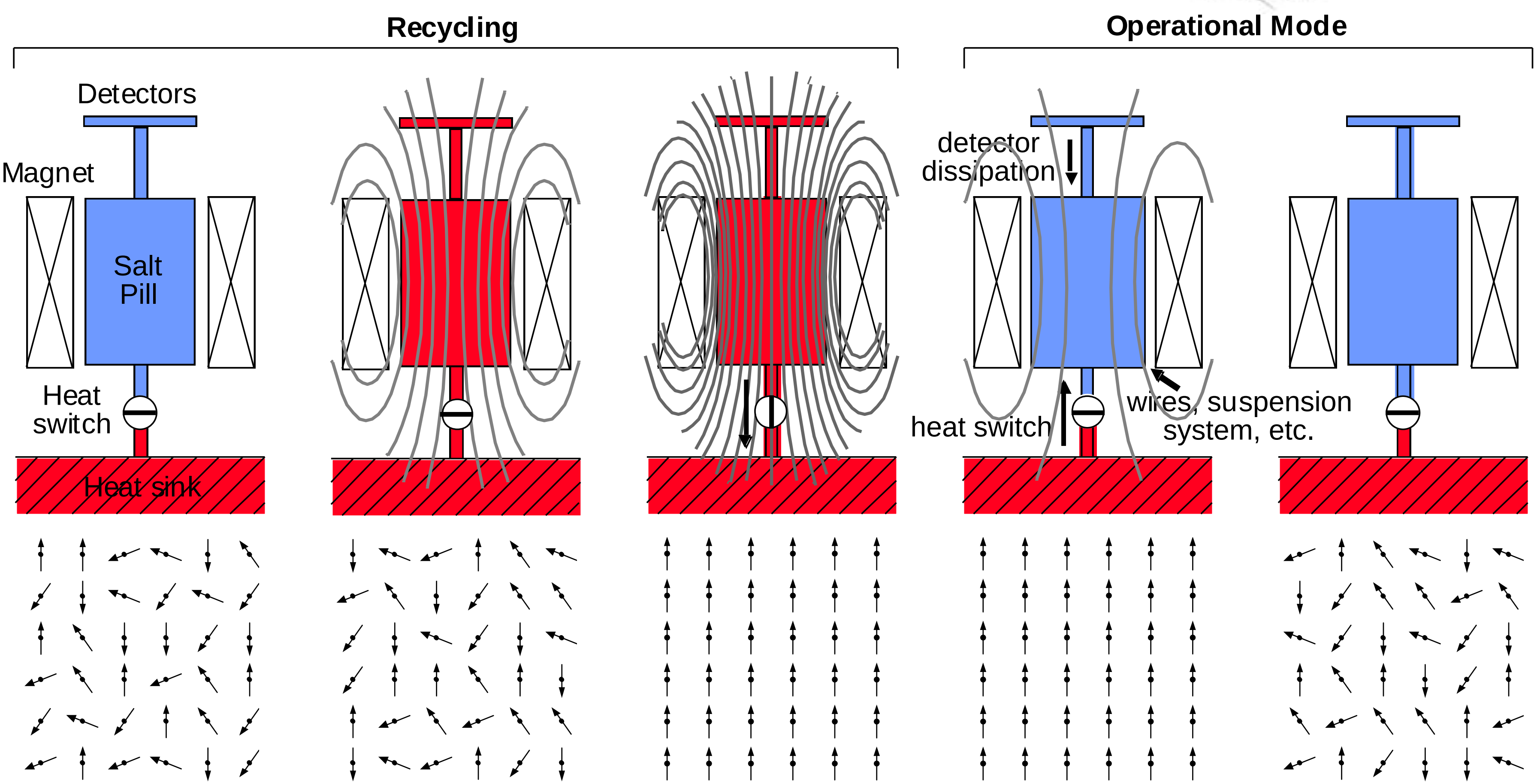
$$S(x)/R = x\coth(x) - (2J+1)x\coth\left((2J+1)x\right) + \ln\left(\frac{\sinh\left((2J+1)x\right)}{\sinh(x)}\right)$$

$$x = \mu_B g B / 2k_B T = (0.336\ \text{K/T})\ g\ B/T$$

  - Under adiabatic conditions, a change in magnetic field produces a proportional change in temperature
  - In presence of a heat load, magnetic field can be decreased to maintain constant temperature

Single-Shot ADR Cycle

Cryogenics and Fluids Branch



- B=0
- T_{salt}=?

- Magnetize salt until $T_{salt} \geq T_{sink}$
- Turn on heat switch

- Magnetize to full field
- Turn off heat switch

- Demagnetize to operating temperature
- Slow demag to maintain T

- B=0

ADR Operation

- Advantages
  - Only type of cooler capable of 50 mK in space
  - Solid-state, no moving parts
  - High efficiency
  - High reliability
  - Dissipation-less temperature control

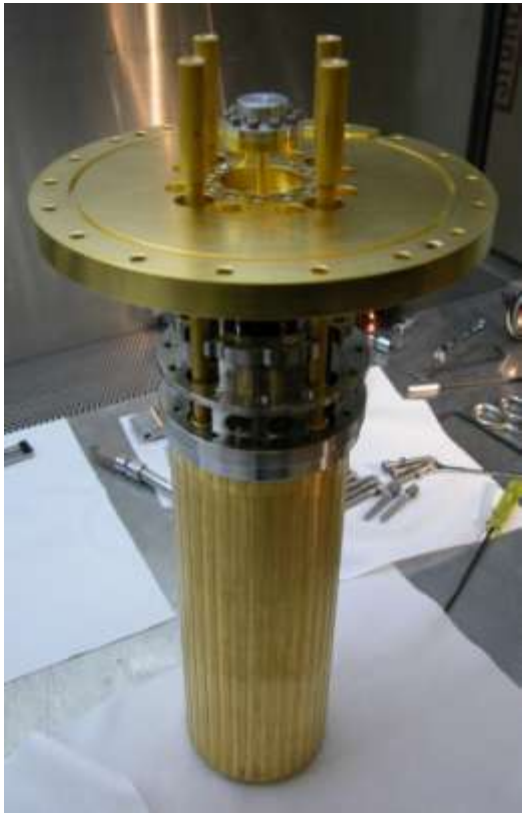
Refrigerants

- Ideal material has high density, high magnetic moment
- Real materials have interacting spins
  - Interaction energy depends on
    - Magnetic moment of each spin
    - Density of spins
- Gives rise to magnetic ordering at low T

Material	*J*	*Ion Density* (/cm^3)	T_C (K)
Cerium Magnesium Nitrate, CMN	1/2	9.10×10^{20}	.0015
Chromic Potassium Alum, CPA	3/2	2.14×10^{21}	.009
			.01
			.026
			~.2
			~.38

- Choose refrigerant based on lowest desired temperature
  - Low T refrigerants have LOW cooling capacity
  - **ADR stores heat during hold time: long hold time <=> low cooling power**

Basic (XRS) ADR



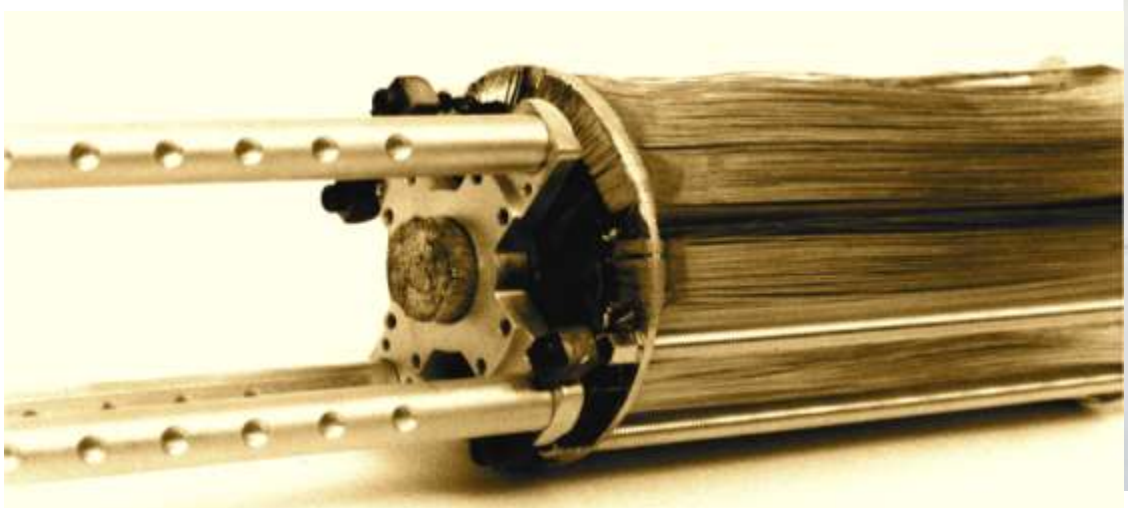
Salt pill, heat switch,
Suspension, baseplate

Magnet (immersed
In liquid helium)

Total mass: 15 kg

Salt Pill

- Refrigerant (hydrated salt) is grown on a "thermal bus"
  - Efficient heat transfer from external interface
- Salt growth can take days (FAA) to weeks (CPA)
  - XRS used 930 g FAA

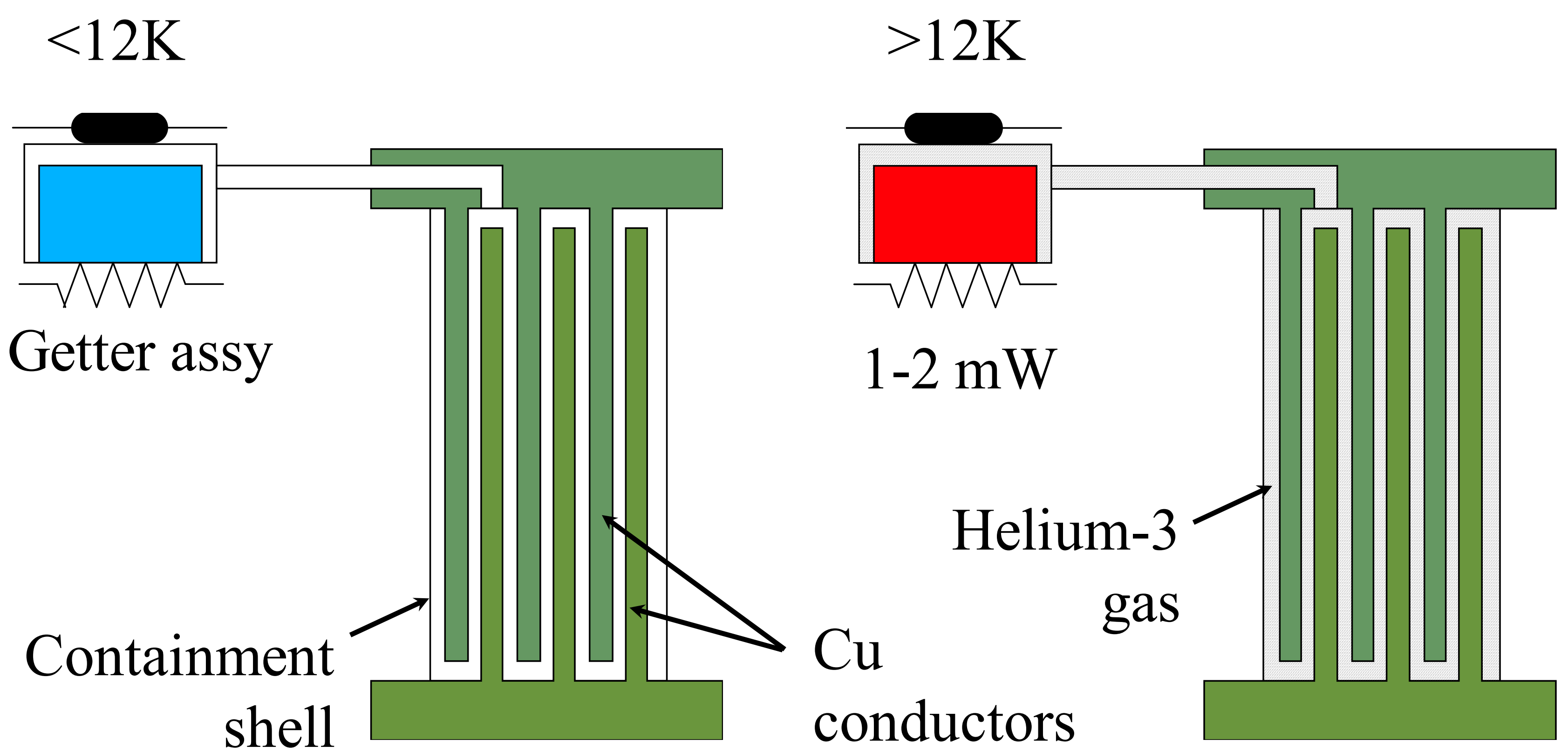


Heat Switch

- Two roles
  - Conducts heat to the heat sink during recycling
  - Thermally isolates the salt during operation
- Goals
  - No moving parts
  - Very high "on" conductance
  - Very low "off" conductance
    - Heat switch can easily dominate the parasitic heat flow to the salt
  - Small, low power

Gas-gap heat switch

Active GGHS


<12K
Getter assy
Containment
shell
>12K
1-2 mW
Helium-3
gas
Cu
conductors

Magnet

- Superconducting NbTi magnet
  - Made by Cryomagnetics, Inc.
- 2.08 T central field at 2 A current
  - 1000 henries
  - 2000 J stored energy at full field
- Bore: 3 inch diameter, 6 inch length

Practical Limits

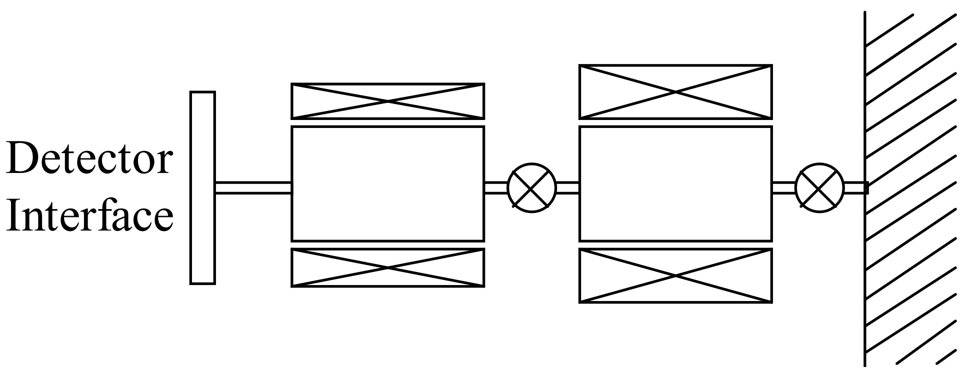
- Single-stage ADR must cool from heat sink to low T
- Typical values
  - Net cooling power: ~0.5 μW
  - Heat sink: 1.3 K
  - Magnetic field: 2 T (2 amps)
  - Refrigerant mass: 1-2 moles
  - Operating T: 50-60 mK
  - Hold time: 24 hours
  - Recycle time: 1 hour

20:1

- Trends
  - Higher heat sink T: higher magnetic field
  - Lower operating T: higher magnetic field
  - Higher cooling power/longer hold time: higher magnetic field, more refrigerant, lower parasitics
- Magnet mass grows very rapidly with increased bore volume and increased magnetic field: >>2 T is unpractical
- Bottom line: improved performance → multi-stage ADRs

Two-Stage ADR

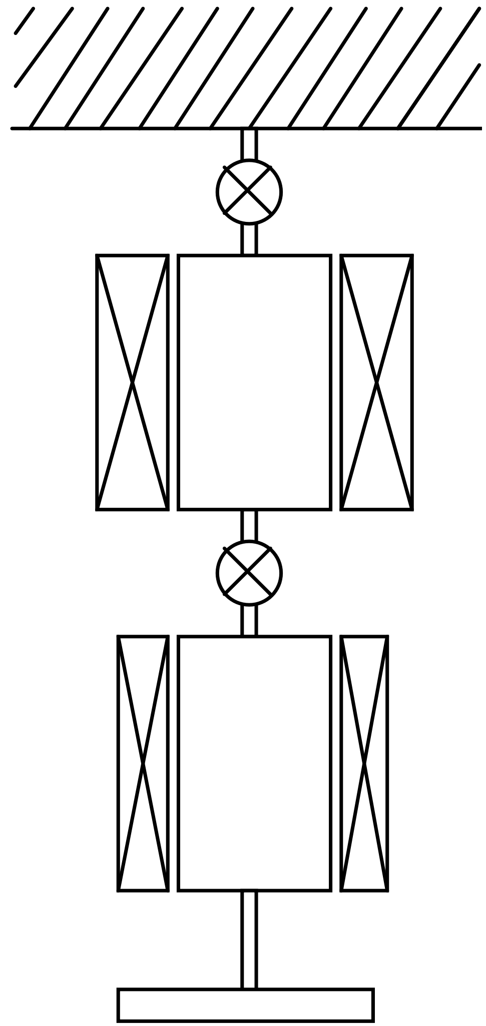
- Two configurations: parallel and series
- Parallel
  - ADR stages are operated in synch (both cool from T_{sink})
  - Warmer stage intercepts parasitic heat loads
- Series
  - Upper stage pre-cools lower stage and reduces parasitic heat loads

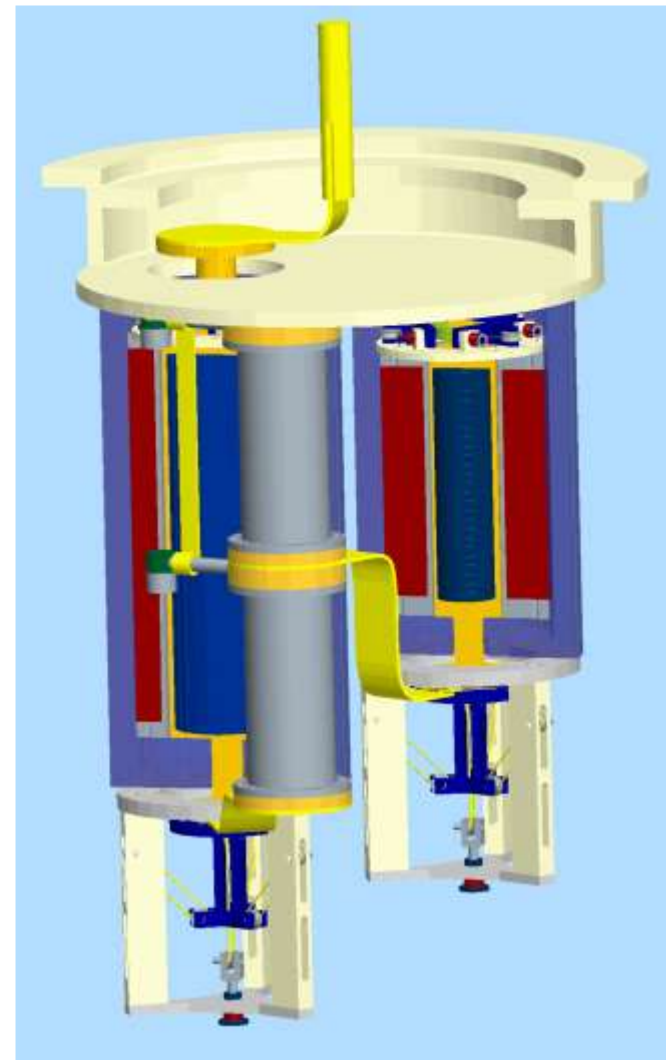


Astro-H ADR

- Upper stage
  - 150 g GLF
  - T_{high}=2 K
  - T_{low}=0.5 K
  - 3 T magnet (2A)
- Lower stage
  - 240 g CPA
  - T_{high}=0.8 K
  - T_{low}=50 mK
  - 2 T magnet (2A)

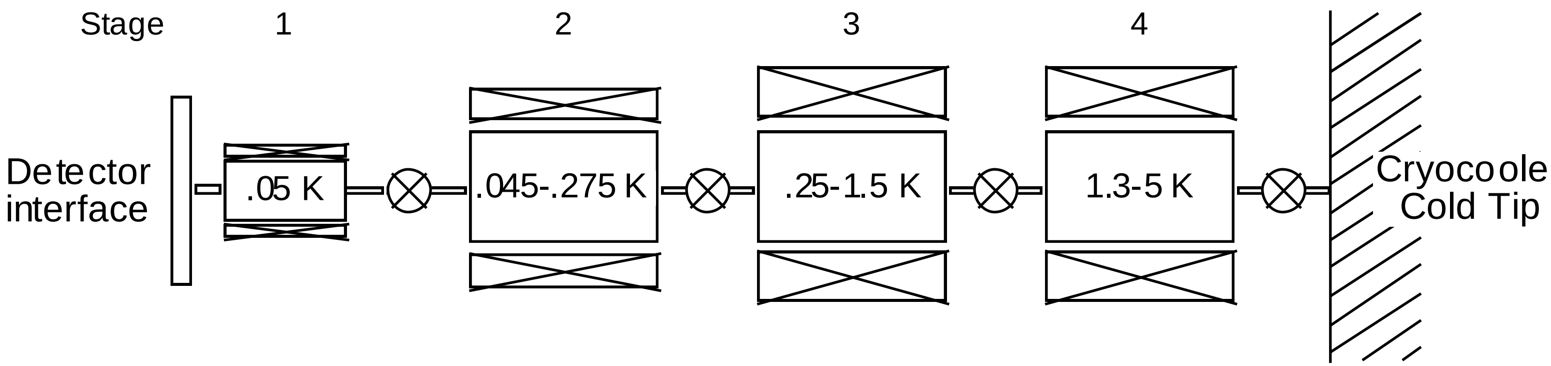
- Provides up to 1.5 μW detector cooling (24 hour hold time)





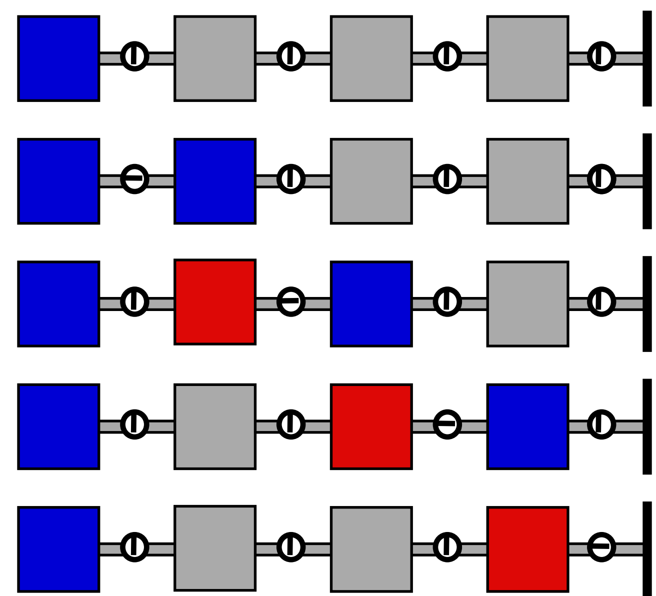
Total mass: 10 kg

Continuous ADR

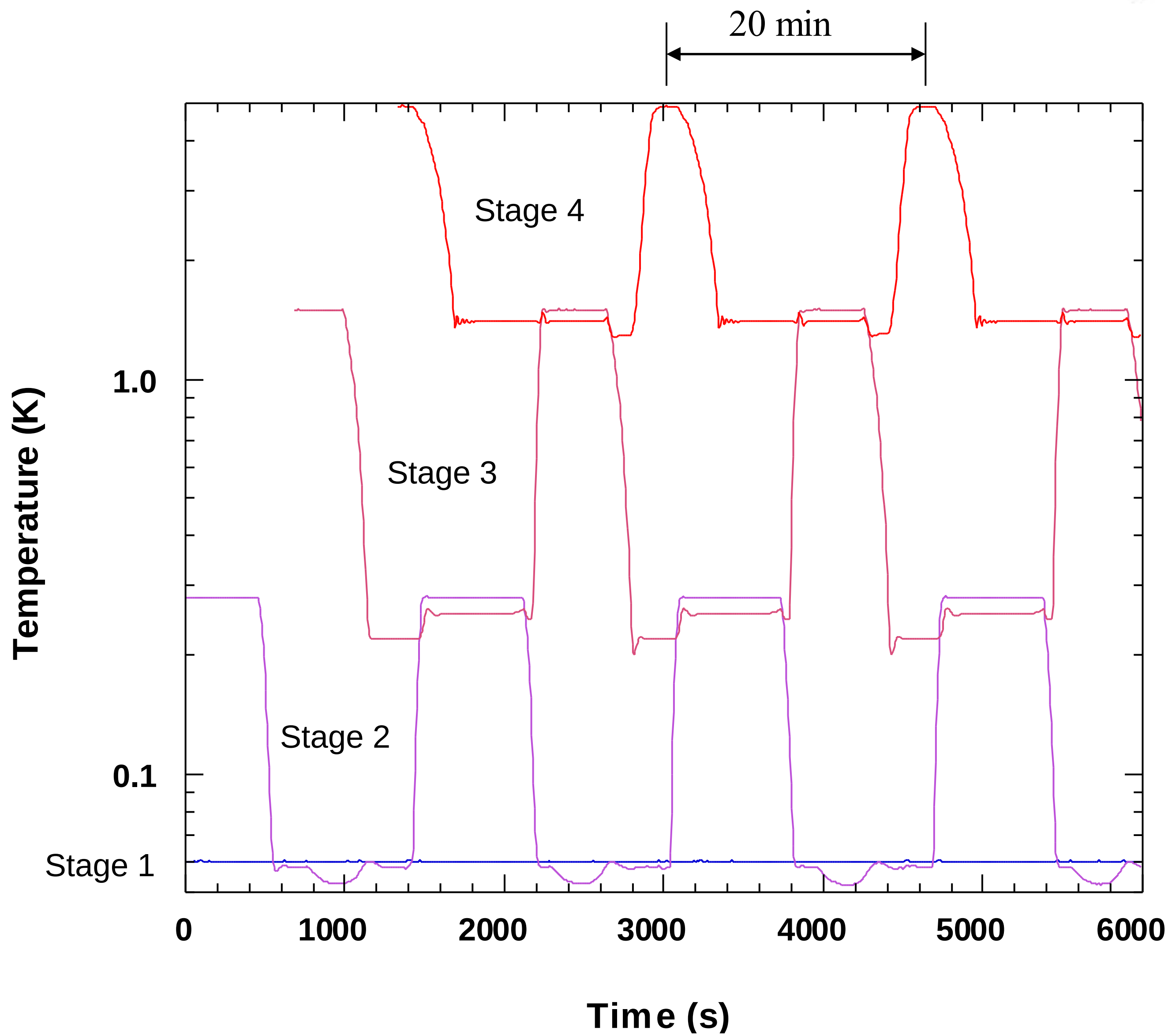


- Load is cooled by a "continuous" stage
- Other stages work to cascade heat up to the heat sink
  - Number of stages depends on temperature range and heat switch properties
- Cycle time can be short, 20-30 minutes
  - Much shorter heat storage time
  - Order of magnitude less refrigerant needed
- Can add stages to achieve lower T_{det} or higher T_{sink}

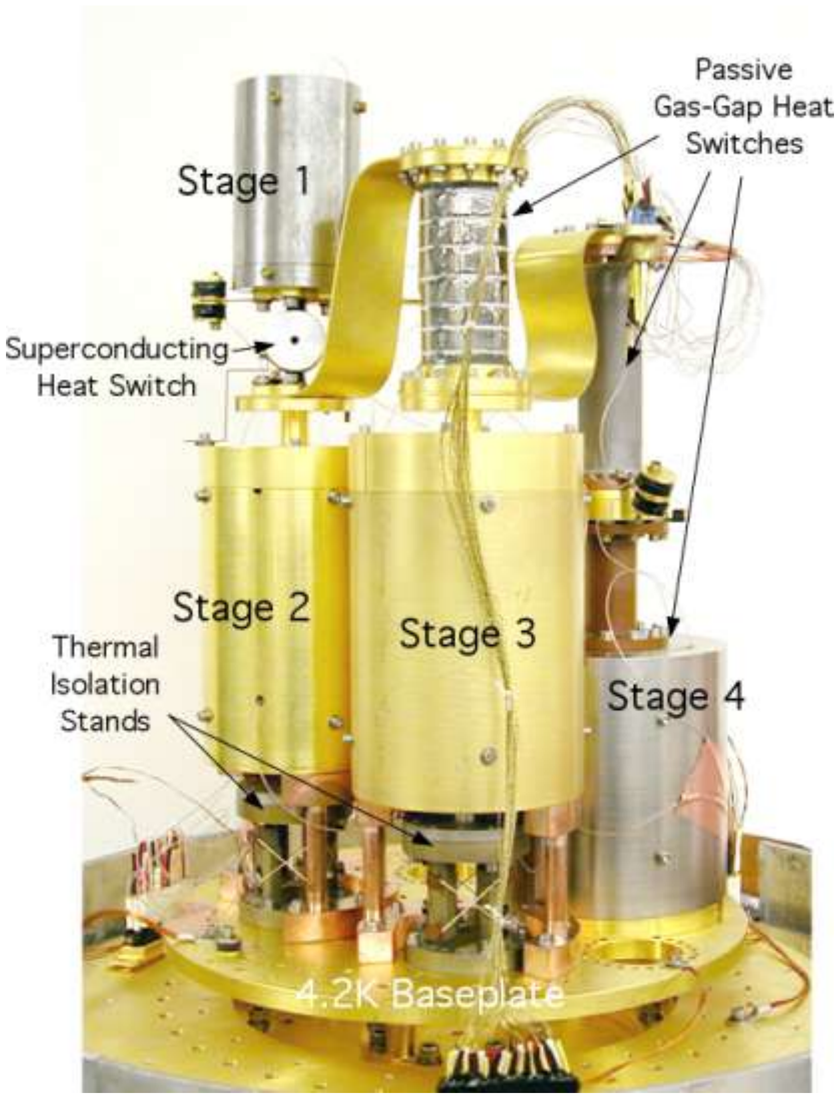
Recycling Sequence



4-Stage Cycling

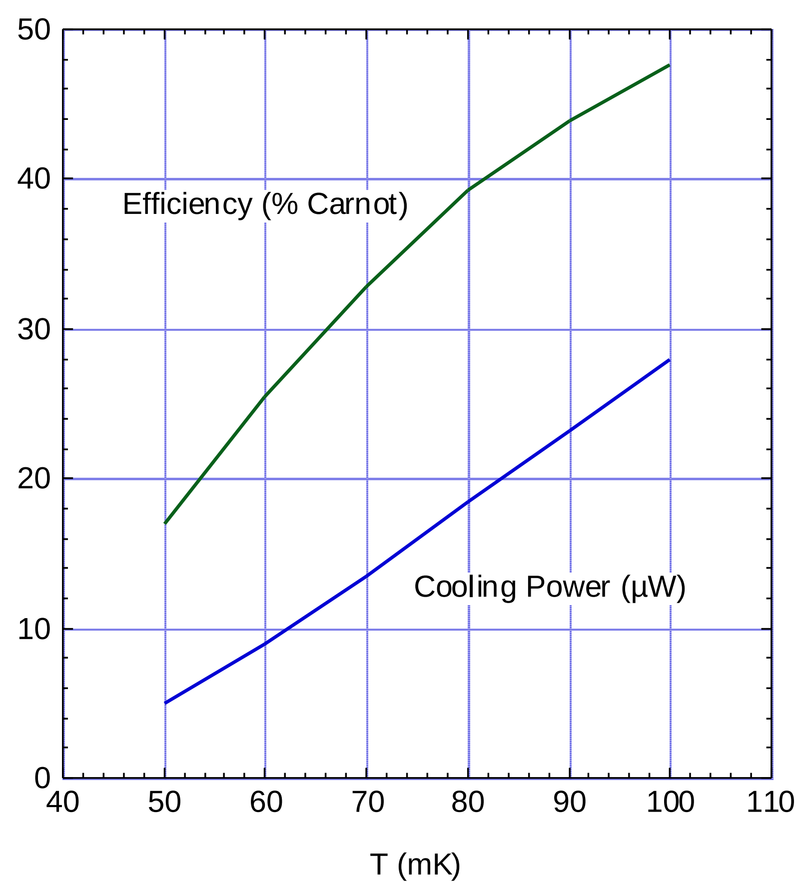


4-Stage CADR



Complete in-house GSFC build

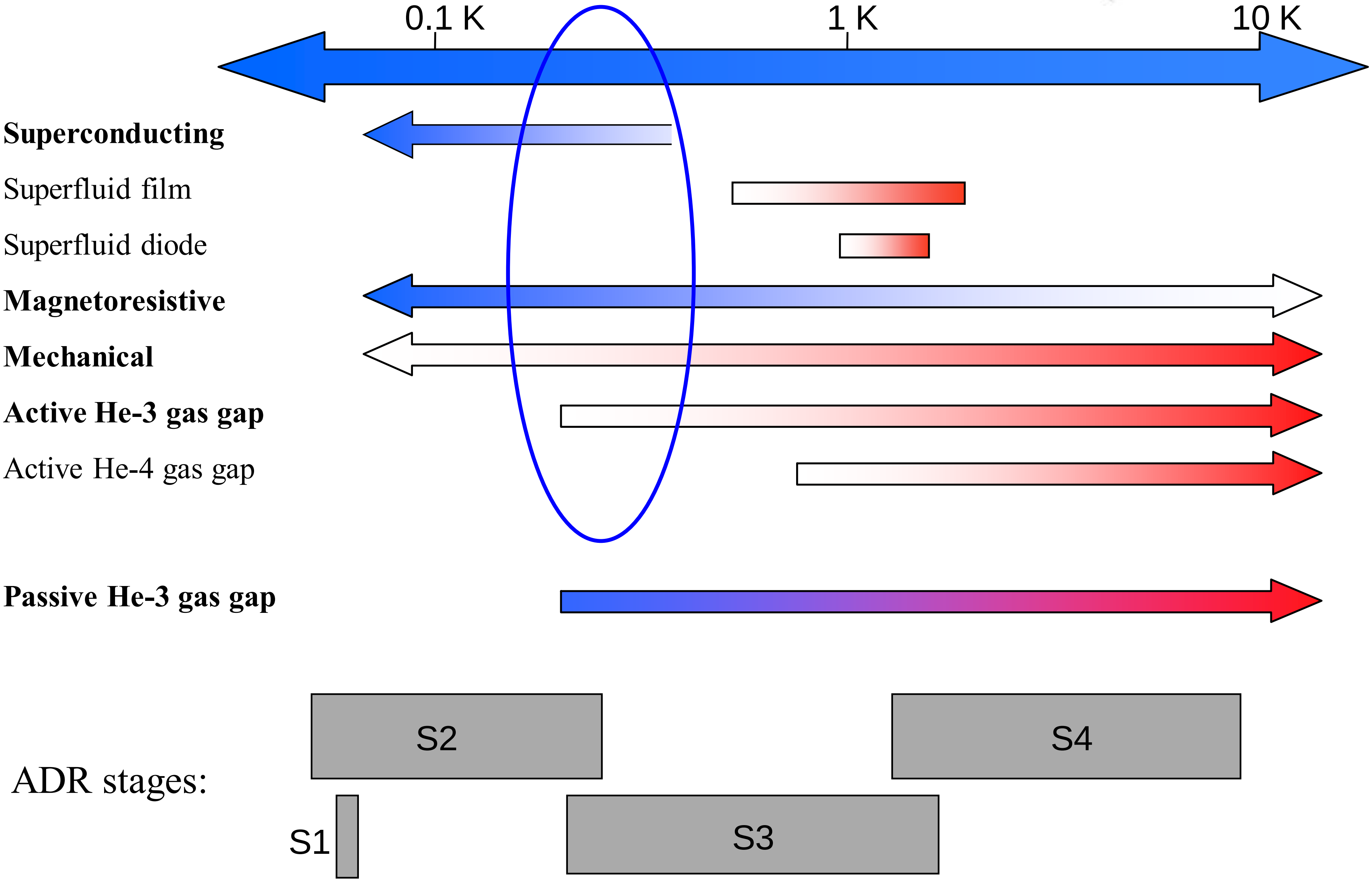
- Uses 4.2 K helium bath
- Total mass of 7.7 kg
- Magnets are fully shielded
- Fully automated operation



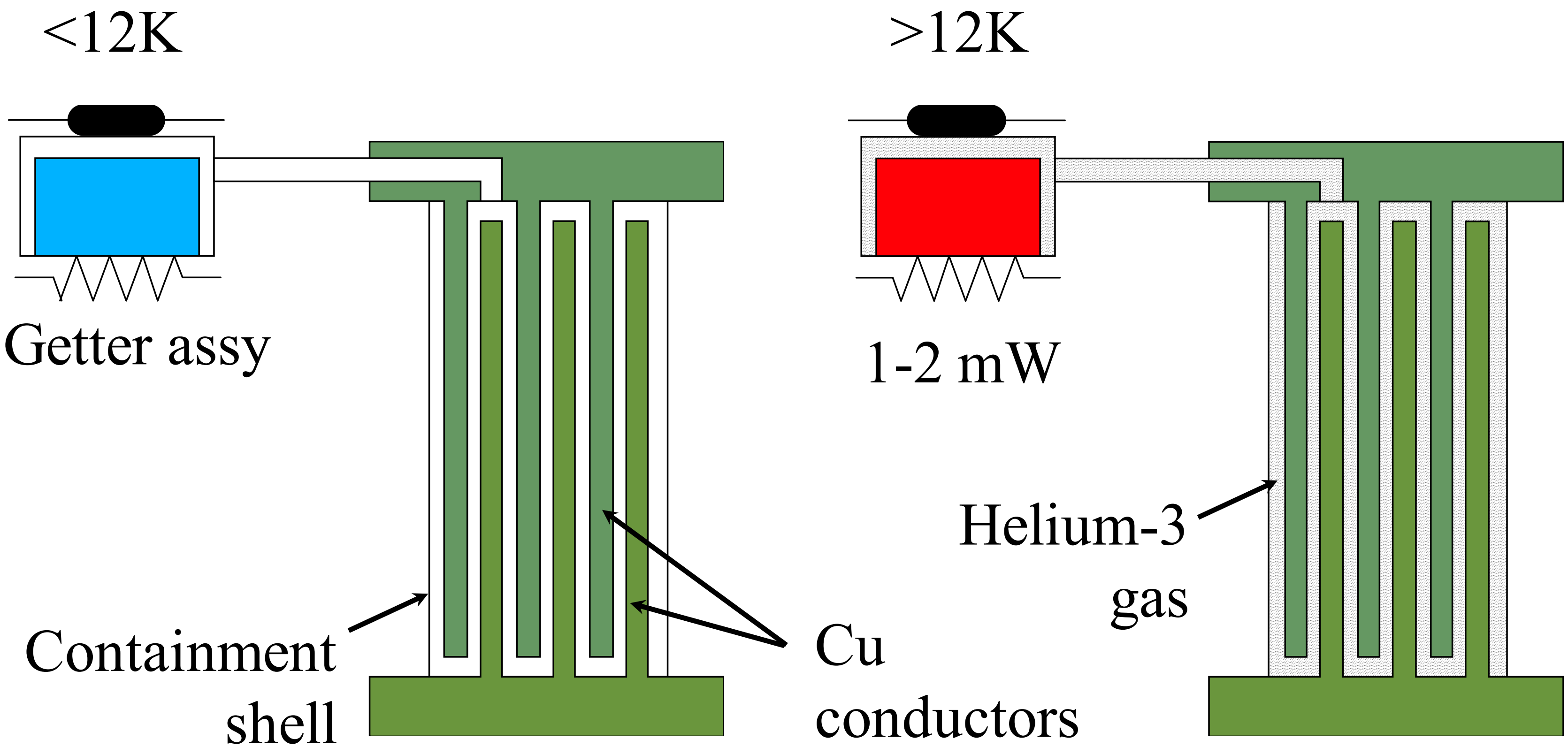
Technology Needs

- Heat switches
  - Needed new heat switches that could operate over a wide range of temperature
- Salt pills
  - Small salt pills capable of high heat flux
- Magnets
  - Smaller, simpler magnets with modest field capability
- Control electronics

Heat Switches



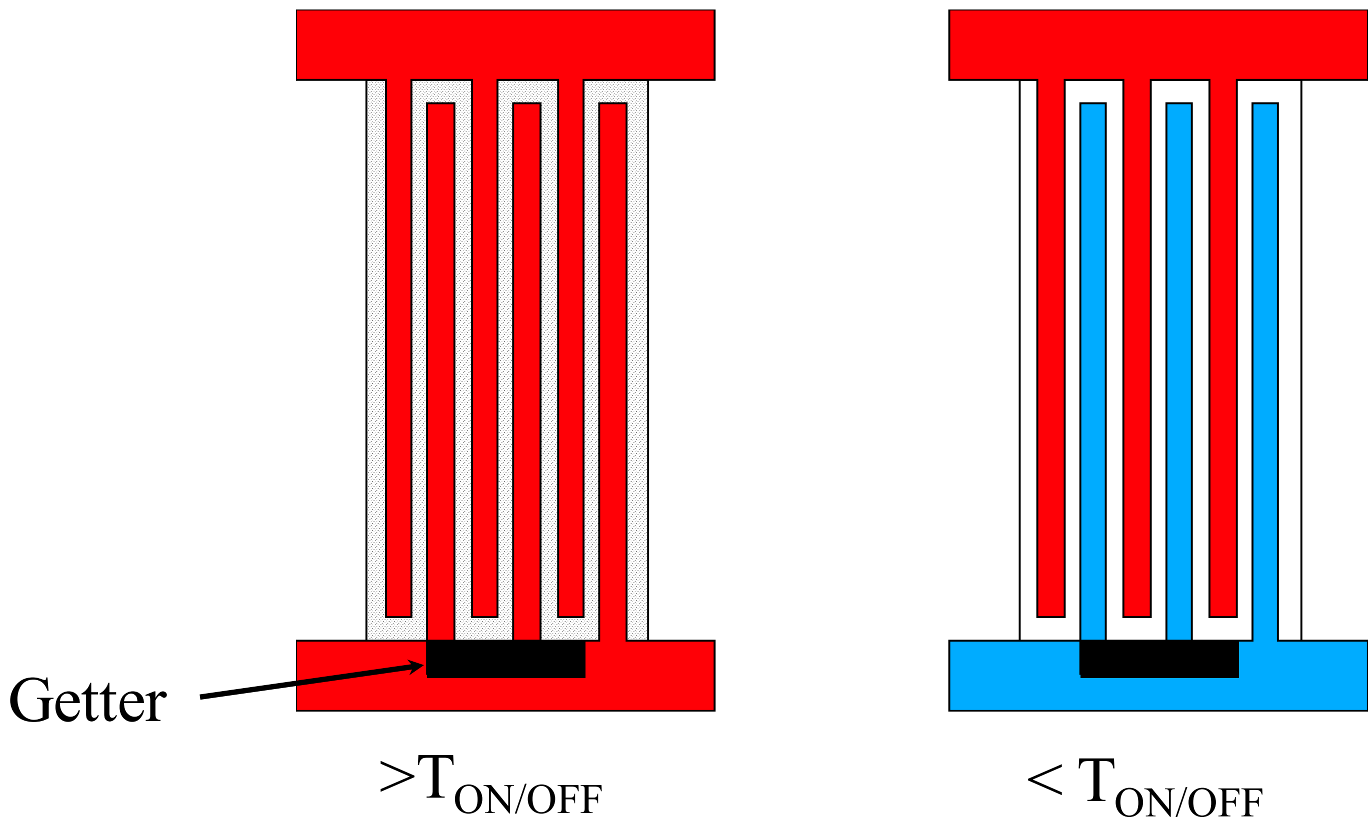
Active GGHS



- Process works extremely well at temperatures above 1 K
- Below ~0.5 K, gas pressures are so low that pumpout times are unacceptably long (hours)

Passive GGHS

- Getter is located **inside** the switch
  - Helium gas adsorbs and desorbs based on ADR temperature
  - $T_{ON/OFF}$ can be any temperature from 0.2 K to >20 K

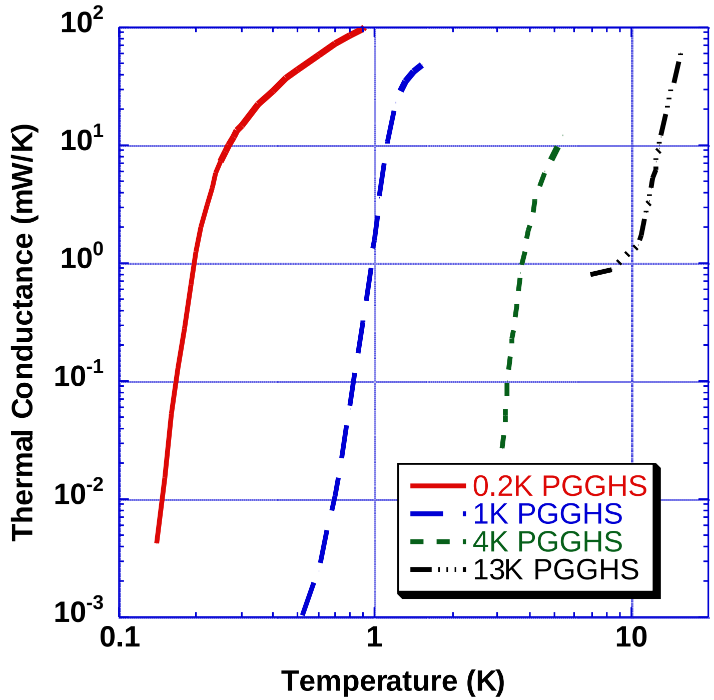


Passive GGHS

- No control electronics
- Instantaneous transition from on <-> off states
- No power dissipation in the refrigerator

Adjustability

- On/off temperature is adjusted by tuning the binding energy of the getter surface
  - Inclusion of gases (hydrogen, neon) that freeze onto the getter
  - Varying helium fill level will smoothly change binging energy, enabling any desired on/off temperature



Salt Pills

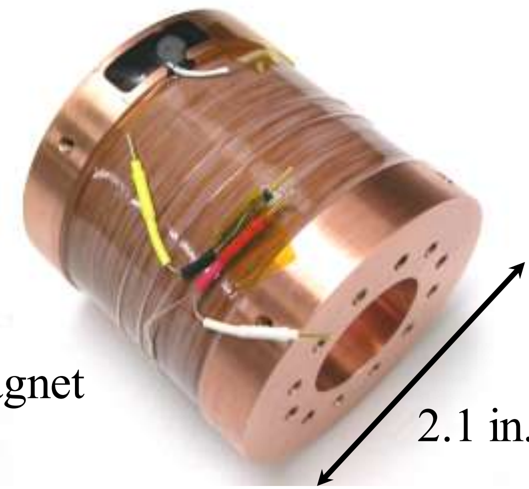
- Large cooling power in a small salt pill requires extensive thermal bus
  - Bus is wire EDM cut from a copper block
  - CPA does not dissolve copper

Continuous Stage Salt Pill
(42 gram CPA)

2nd & 3rd Stage Salt Pill
(100 gram CPA)

Magnets

- Magnets for CADR are multi-filamentary NbTi solenoids (with diode protection)
- Field requirements
  - Stage 1 0.1 T
  - Stage 2 0.5 T
  - Stage 3 1.5 T
  - Stage 4 3.5 T
- Small bore sizes



Stage 4 magnet

2.1 in.

Stages 2,3 magnet

Review

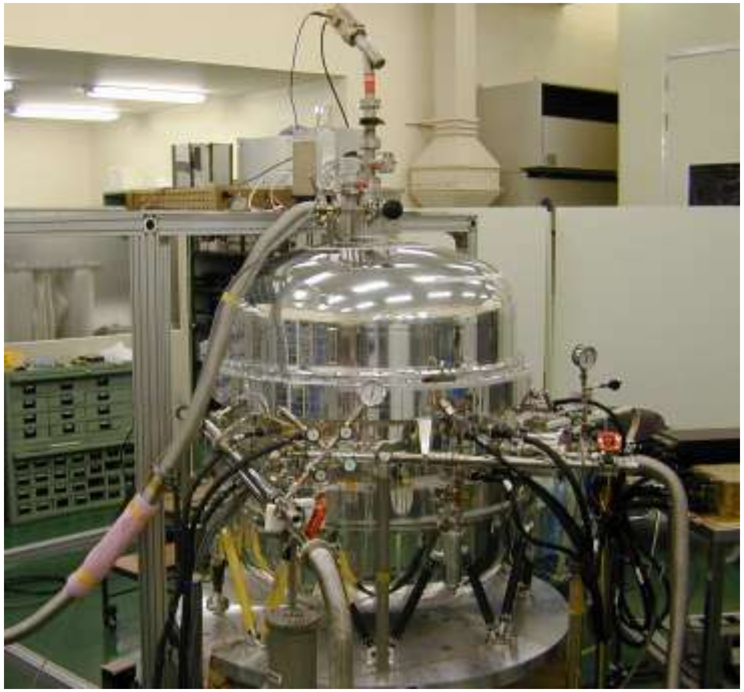
- Single-stage ADR
  - Practical limit of 20:1 ratio for T_{sink}:T_{low}
    - For 50-60 mK, max heat sink ~1.3 K, with max cooling power of 1 μW
    - For space missions: superfluid helium bath
- Two-stage ADR
  - Increases max T_{sink} up to 4 K
  - Decreases mass and improves useful cooling capacity: 1-2 μW
- Continuous ADR
  - No limit to T_{sink} (except for magnet technology)
  - Significant increase in cooling power per mass
    - 6 μW at 50 mK operating from 4.2 K
  - Smoothes out heat flow to heat sink: better match to cryocooler

System Optimization

- ADR pre-cooler
  - Stored cryogens vs cryocooler vs hybrid
  - Heat sink temperature, cooling power
- Detector/telescope cooling requirements
- Efficiency of cryogenic cooling chain
  - Efficiency affects
    - Sizing of cryogenic system
    - Power system
    - Thermal system
    - Electronics
  - ADR configuration can accommodate wide range of pre-coolers
    - Lower temperature heat sink simplifies ADR design
    - But should design for overall system performance

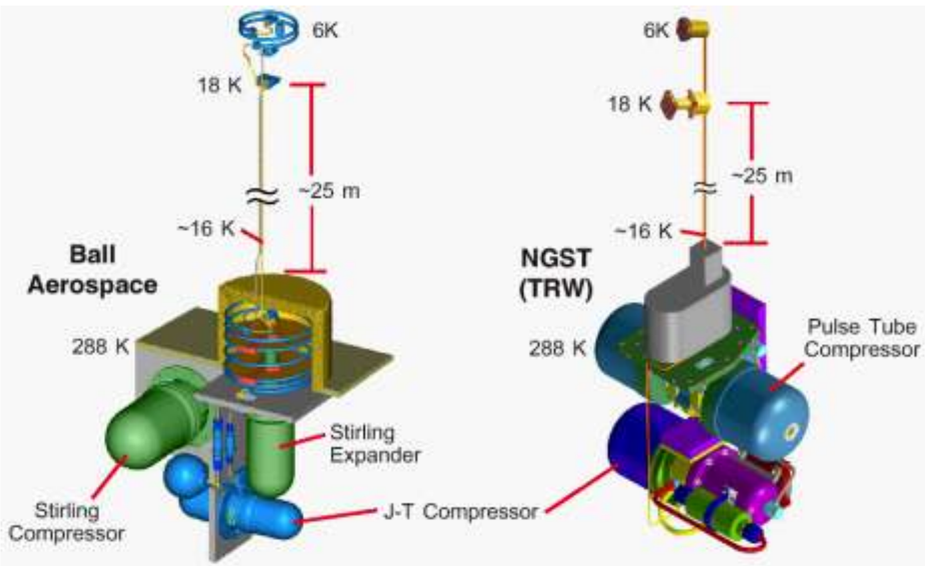
SOA Pre-Coolers

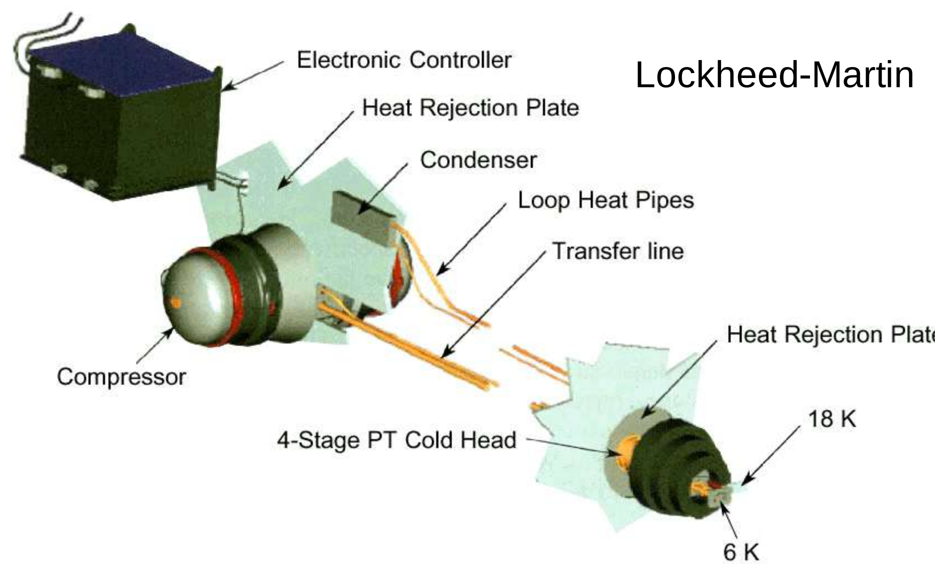
- Stored Cryogens
  - Superfluid helium at ~1.3 K
    - With or without upper cooling, such as 17 K solid neon on XRS/2
- ADR Options
  - 1-stage; 2-stage; 3-stage continuous



SOA Pre-Coolers

- Cryocoolers
  - 6 K cryocoolers developed in US
    - All are capable of operation down to 4-5 K
  - 1.8 K JT/Stirling cryocooler developed in Japan





- ADR options
  - 2-stage; 3-, 4-stage continuous

Relative Merits

- Stored cryogens
  - Low base temperature; simplest ADR
    - More complex ADRs can be used where higher performance is req'd
  - Limited lifetime
  - Flight heritage: "known" technology
  - Complex, require expertise to operate, and RISKS!
- Cryocoolers
  - Less mature technology, but long-life
  - Higher base temperature
  - Limited cooling power (less compatible with single-shot ADRs)
  - Possible vibration issues
  - Reliability (electronics)
  - Efficiency: low compared to ADRs => suggests using ADR to as high T as possible

Stored Cryogen Risks

- Flight dewars are subject to all of the "usual" hazards
  - Extreme cold
  - Oxygen deficiency potential
  - Enclosed volume of liquid/solid with high-pressure potential
- "Natural" state of cryogens in orbit is low pressure
  - Solid state for hydrogen, neon, nitrogen, etc.
  - Superfluid state for helium
- Ground operation must create flight conditions
  - Must operate sub-atmospheric
    - Potential for ice plugs
  - Low-temperature top-off of SHe tanks before launch
    - Sub-cooled liquid transfer and close-out

Cryogen Risks

- Immense stored energy!
  - Liquid helium expands 700x warming from 4.2 K to RT
- Cryogens are cold enough to solidify many gases
  - LN2: readily freezes water vapor
  - LHe: readily freezes everything else!
- Even operation at atmospheric conditions poses risks

Over-Pressure Protection

- All dewars (He, LN2, LOX, Lar, …) should have passive pressure relief devices that protect against excessive internal pressure

Burst disc

Pressure relief
valve

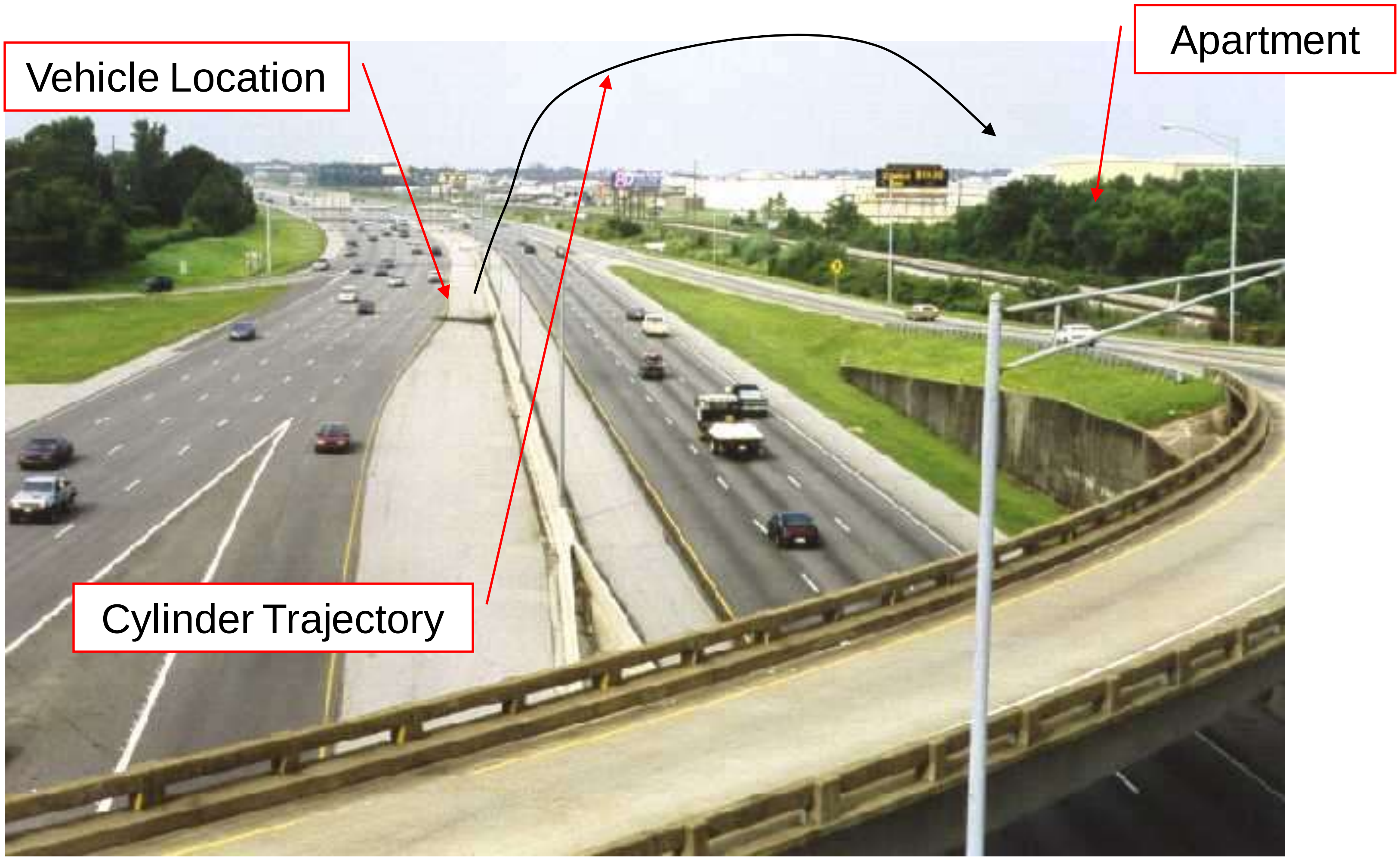
Commercial LN2
Dewar

Commercial LHe Dewar

Dumb and Dumber

- Use scrap LOX storage dewar for their scrap metal cutting business
- Dewar blew down quickly through pressure reliefs on first fill at LOX dealer
- Solution: remove/plug pressure relief devices
- Flat tire disabled truck on I-10 in hot summer heat

Dewar Trajectory



Aftermath

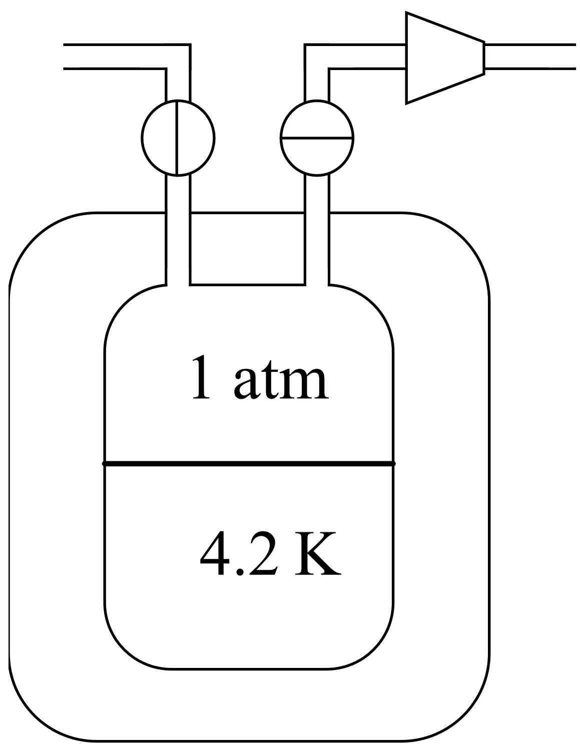
Cryogenics and Fluids Branch

What a Little LOX Will Do

Cryogen Risks

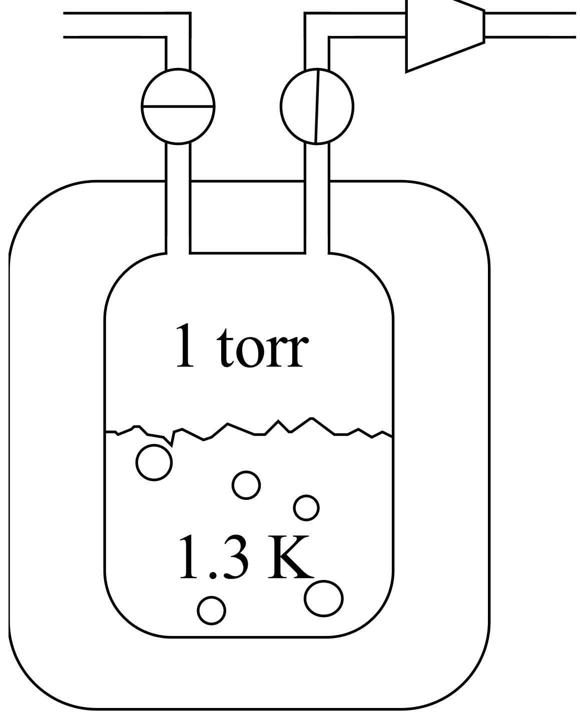
- Sub-atmospheric operation is much riskier
  - Every component containing sub-atm cryogen from the surrounding atmosphere must be leak-tight!
    - Tanks, plumbing, valves
  - Operations must be carefully scripted to avoid accidental venting into sub-atm space
  - Operators must have a full understanding of cryogen and cryogenic system behavior

“Routine” SHe Use



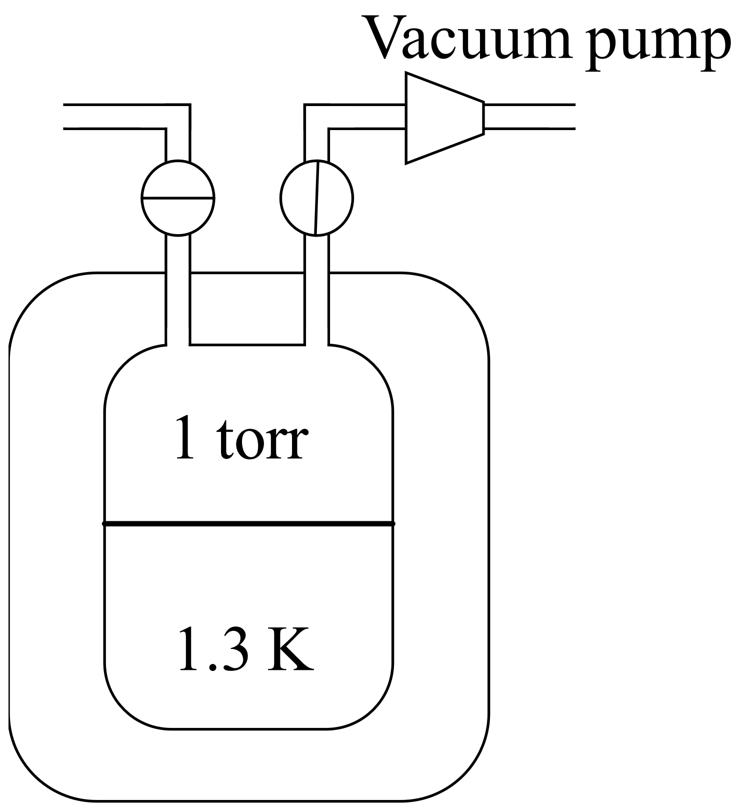
- Begin with liquid helium at NBP venting to atmosphere

"Routine" SHe Operation



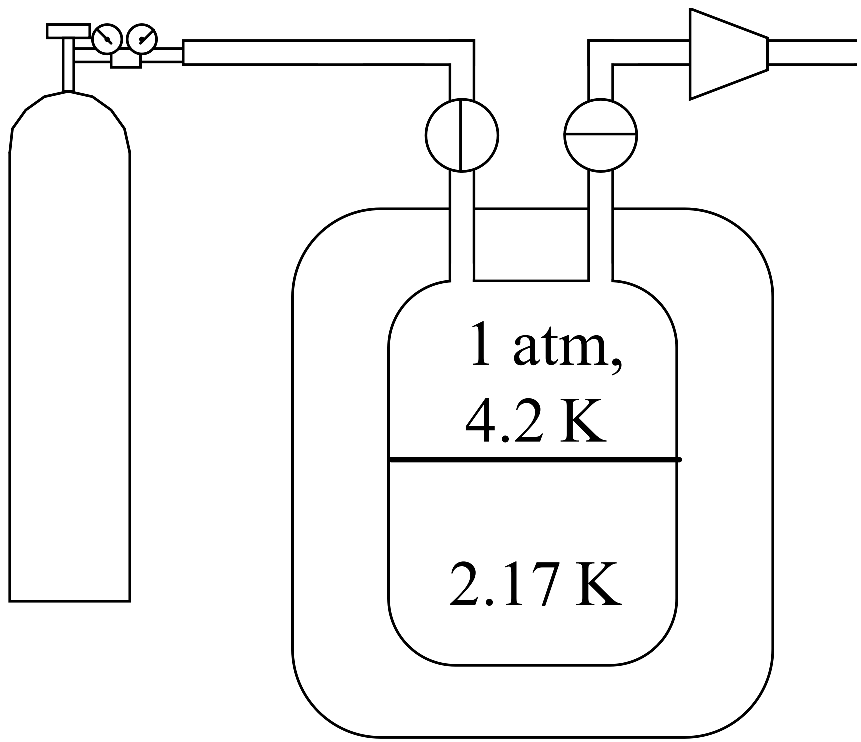
- Pump bath to lower pressure; liquid boils and temperature drops

“Routine” SHe Operation



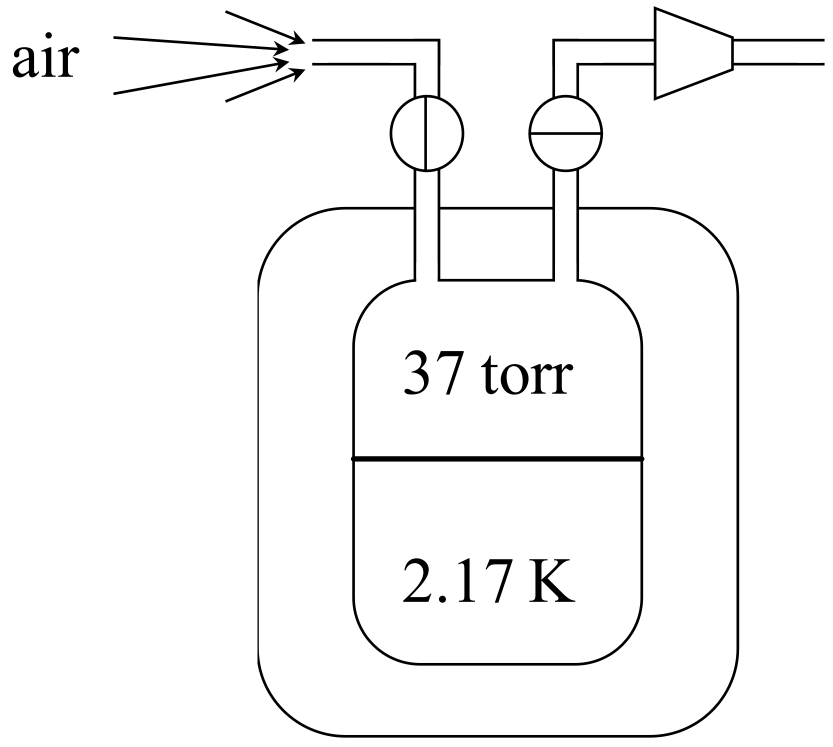
- Conduct experiment

“Routine” SHe Operation



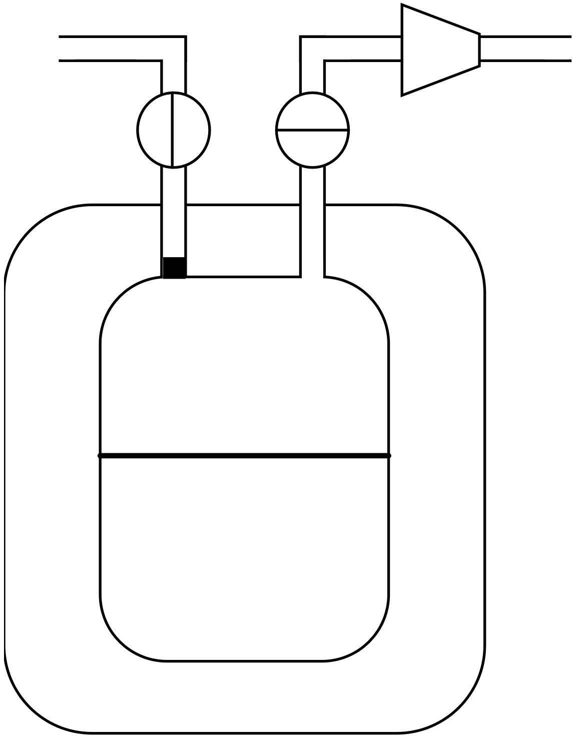
- Backfill dewar with GHe to warm up
- Liquid stratifies

NOT "Routine" SHe Operation



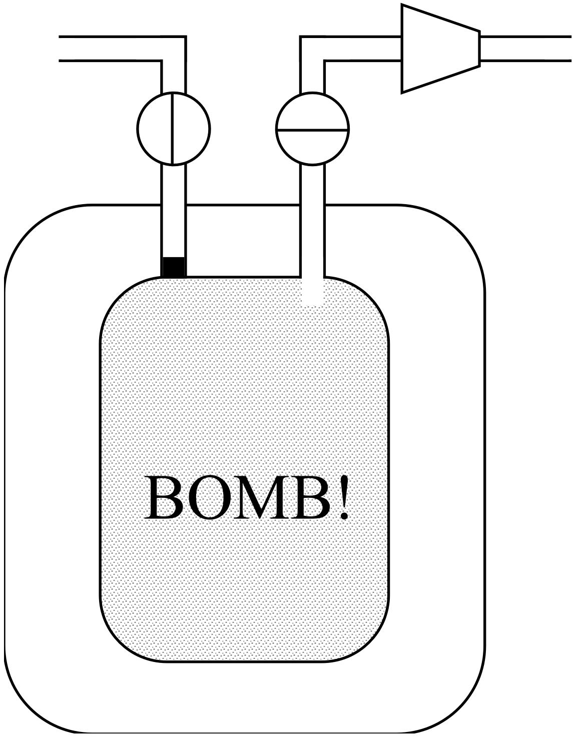
- Dewar is bumped, or surface of liquid cools by conduction: liquid destratifies and pressure drops

NOT "Routine" SHe Operation

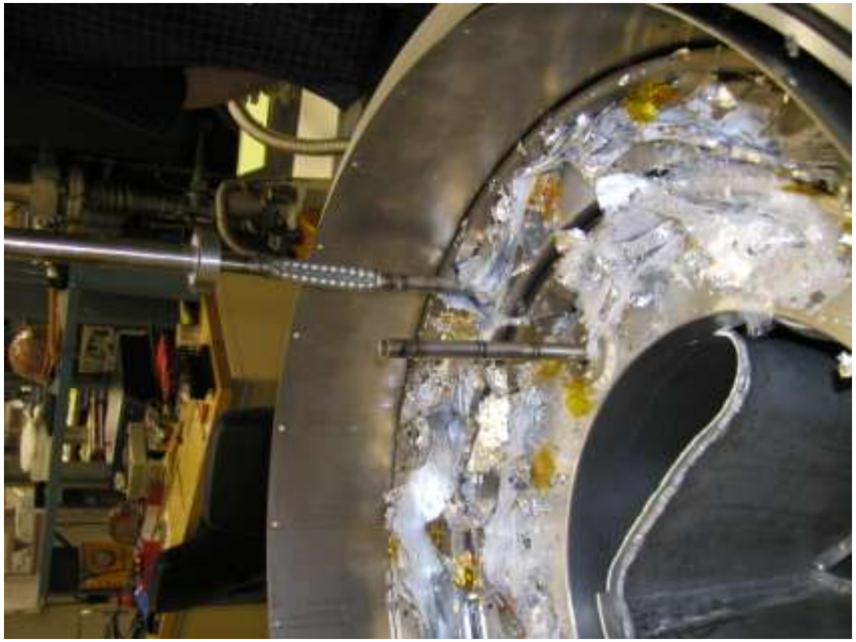


- Ice plug forms

NOT "Routine" SHe Operation



Dewar Failure, Jan 2005



Fortunately, damage was contained within dewar main shell

Stored Cryogen Missions

Mission	Launch	Cooler	Issues	Mission Outcome
IRAS	1983	SHe	Blew burst disc during servicing	Recovered
SpaceLab II	1985	SHe	Overheating of on-board vacuum pump	Recovered
COBE	1989	SHe	None	Outrageous success!
BBXRT	1990	Solid Argon	None	Successful
LPE	1992	SHe	Ice-plug in vent line	Recovered
SHOOT	1993	SHe, 1.1-3 K	Ice plugs in emergency vent line	Successful
IRTS	1994	SHe	None	Successful
ISO	1995	SHe	Leaking valves	Successful
NICMOS	1997	Solid Nitrogen	Distortion of dewar from expansion of SN2	Focus issues; short lifetime; retrofitted w/ cryocooler
WIRE	1999	Solid Hydrogen	Premature ejection of cover	Loss of mission
XRS1/Astro-E1	2000	SHe/Solid Neon	None	Rocket failure
Spitzer (SIRTF)	2003	SHe	Ice plug in vent line	Recovered
GP-B	2004	SHe	Ice plug in He guard tank	Recovered
XRS2/Astro-E2	2005	SHe/Solid Ne/cryocooler	Ice plug and explosion of GSE helium tank; contamination of dewar guard vacuum with He gas on orbit	Successful operation (2 weeks) until catastrophic venting of He

- Increasingly high-performance required of cryogenic coolers is leading to very complex systems and sensitivity to additional failure modes

Future Directions

- Strong trend toward cryocooler-only missions
  - Higher heat sink temperature
- Detector systems
  - Larger arrays => higher cooling power
  - Lower operating temperature
- Instruments
  - Stable control of telescope components
    - e.g. near 2.725 K for CMB studies

- Multi-stage ADRs have the capability to meet these requirements

Credits

- CADR funding
  - DDF, CETDP (Code R), IRAD, IPP (CTD and Seed Funding), Con-X
- LakeShore Cryotronics, Inc.
  - Licensed PGGHS technology
- Detector groups (x-ray and IR)
- Code 552