Cryogenic Technology for CMB-Pol: Mechanical Cryocoolers for the 4K to 200K Temperature Range

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Topics

- Introduction
- Cooler flight heritage
- Current cooler development status
- Advantages/disadvantages of cooler types
- Recommendations for cooler selection
- Summary

Introduction

- Long-life flight coolers to date have been either Stirling, Pulse Tube or Reverse Turbo-Brayton
  - Oxford-style flexure bearing cryocoolers built for multiyear space application have been flying since the 1991 launches of ISAMS and ATSR
  - Three of the flight coolers have more than 10 years of continuous operation
  - With more than 30 coolers in operation, only one cooler failed
  - Most coolers designed for 50K-80K cooling loads
- No long term operation of a J-T cooler has been demonstrated to date (space shuttle demos only)
- Coolers for the 4K -10K range are in development now for ESA, JAXA, NASA and the DoD for future missions
- There has been some Phase I SBIR efforts for a 10W @ 20K zero boil-off cooler
- Each mission has its own unique cooling requirements; there is no standard cooler model that fits all mission's requirements for operating temperatures and cooling loads
  - CMB Pol will undoubtedly have its own unique temperatures/loads requirements, necessitating further cooler development

CMB Polarization Workshop

Heritage Mechanical Coolers

(data as of 08/2008)

Cooler/Mission	Running (yrs)	Comments
Ball Aerospace HIRDLS 60K Stirling	4.0	Turn on: 8/04; ongoing, no degradation
Creare NICMOS Reverse Turbo Brayton	6.3	Turn on: 3/02; ongoing, no degradation
Fujitsu and Mitsubishi		
ASTER (Stirling (2 units))	8.5	Turn on: 3/00; ongoing, no degradation
NGST (TRW)		
CX (Mini PT (2 units))	10.4	Turn on: 2/98; ongoing, no degradation
HTSSE-2 (80K mini Stirling)	2.7	3/99 thru 3/02; mission end, no degradation
MTI (6020 10CC PT)	8.5	Turn on: 3/00; ongoing, no degradation
Hyperion (mini PT)	7.7	Turn on: 12/00; ongoing, no degradation
SABER (mini PT)	6.7	Turn on: 1/02; ongoing, no degradation
AIRS (10cc PT (2 units))	6.2	Turn on: 6/02; ongoing, no degradation
TES (10cc PT (2 units))	4.0	Turn on: 8/04; ongoing, no degradation
JAMI (6cc HEC PT)	3.4	Turn on: 4/05; ongoing, no degradation
Oxford/BAe/MMS/Astrium Stirling		
ISAMS (80K Oxford)	1.8	Turn on: 10/91; mission end, no degradation
HTSSE-2 (80K BAe)	2.7	3/99 thru 3/02; mission end, no degradation
MOPITT (50-80K BAe (2 units))	6.4	Turn on: 3/00; one displacer failed at 10,300 hrs; other still running
ODIN (50-80K Astrium (2 units)	7.5	Turn on: 3/01; ongoing, no degradation
AATSR (50-80K Astrium (2))	6.3	Turn on: 4/02; ongoing, no degradation
MIPAS (50-80K Astrium (2))	6.3	Turn on: 4/02; ongoing, no degradation
INTEGRAL (50-80K Astrium (4))	5.8	Turn on: 11/02; ongoing, no degradation
Rutherford Appleton Laboratory		
ATSR 1 (80K Integral Stirling)	5.0	7/91 thru 6/96; mission end, no degradation
ATSR 2 (80K Integral Stirling)	13.3	Turn on: 5/95; ongoing, no degradation
Sumitomo AKARI (20K Stirling (2 units))	2.5	Turn on 2/06; ongoing, no degradation






4K Cryocoolers under Development

Cooler	Type	Cold Stage	Upper stages	Input Power (W) Compressor	System	Mass (Kg)	TRL
JEM/SMILES	JT/ST	.030W @ 4.5K	200mW @ 20K, 1W @ 100K	140		65 TMU	8
JAXA/SPICA	^{4}HeJT/ST	.050W@4.5K	N/A	145			5
JAXA/SPICA	^{3}He JT/ST	.016W@1.7K	N/A	166			4
U of Twente DARWIN	He/H_2 sorption	.005W at 4.5K	N/A	4 (at 50K)		8.3	4
LM Hypres	4-stage PT	.035W @ 4.5K	50mW@10K, 160mW@25K, 5.2W@66K	725		21 TMU	5
MIRI	JT/ PT	.070W@6K	70mW@18K	320	400	79 TMU + elec	6

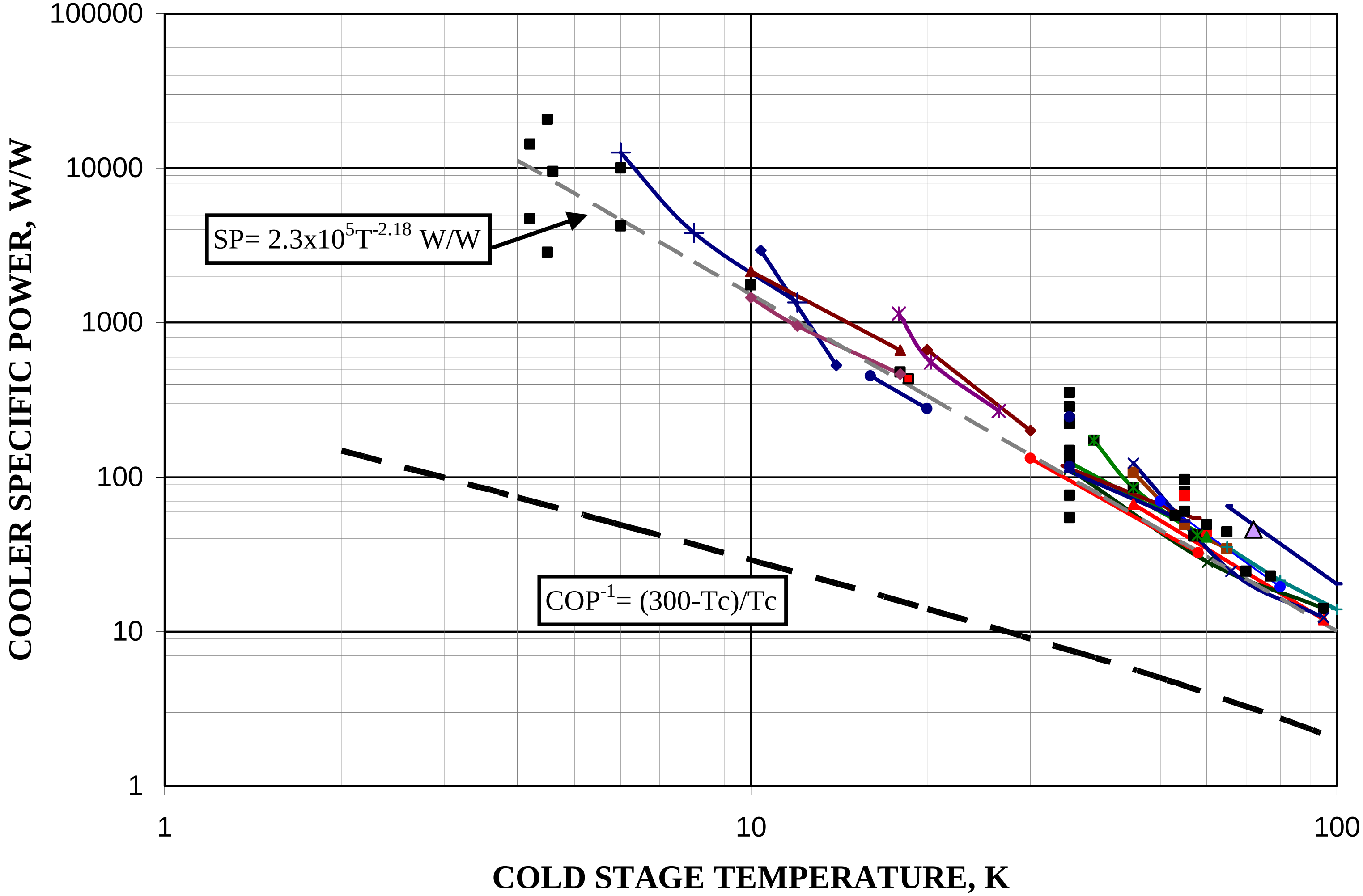
- Cooler can provide single-phase or 2-phase fluid flow to device being cooled
- 4K cooler requires 4-stage pulse tube cooler or hybrid J-T/Stirling (or pulse tube) cooler
  - ^{3}He in J-T loop can extend cooling down to 1.7K
- Passive cooling may be an option to improve performance

10K-35K Cryocoolers under Development

Cooler	Type	Cold Stage	Upper stages	Input Power (W) Compressor	System	Mass (Kg)	TRL
LM 10K	3-stage PT	.260W@10K	10.4W@85K	600		16 TMU	4
NGST 10K	3-stage PT	.250W@10K, or .525W@15K	1W@51K	370		18.7 TMU	5
JPL Planck Sorption	JT/ H2 sorption	.963W@18K	Heat rejected to radiator <60K	426			8
JAXA AKARI	2-stage ST	.200W@20K	N/A	90			9
LM SBIRS Low	2-stage PT	1.7W@35K	17W@85K	610		23.8 TMU	5
Creare	1-stage RTB	3W @ 35K		350		10 TMU	4
Creare HCC	2-stage RTB	2W @ 35K	20 W @ 85K	490		18 TMU	4
Ball 35K HCC	2-stage ST	1.5W@35K	8.5W@85K	200		14.4 TMU	4
NGST 35K HCC	2-stage PT	2.25W@35K	17.4W@85K	500		14.3 TMU	5
Raytheon RSP2	2-stage ST/PT	2.6W @ 35K	16.2W @ 85K	513		20 TMU	4

- Can opt for 2- or 3-stage Stirling or Pulse Tube cooler for temperatures between 20K and 35K
  - Attach J-T or RTB cooler to base of precooler to use as circulator to transport heat from HEMTs
  - Use Neon as working fluid in J-T loop if 2-phase flow desired
  - Passive cooling may be an option to improve performance
- Planck 20K sorption cooler refrigeration capacity can double if use passive cooling below 40K

Specific Power



- Specific power determined here uses total compressor input power but considers only the cold stage heat lift
- Cooler Efficiency=COP^{-1}/SP ~1% at 4.5K

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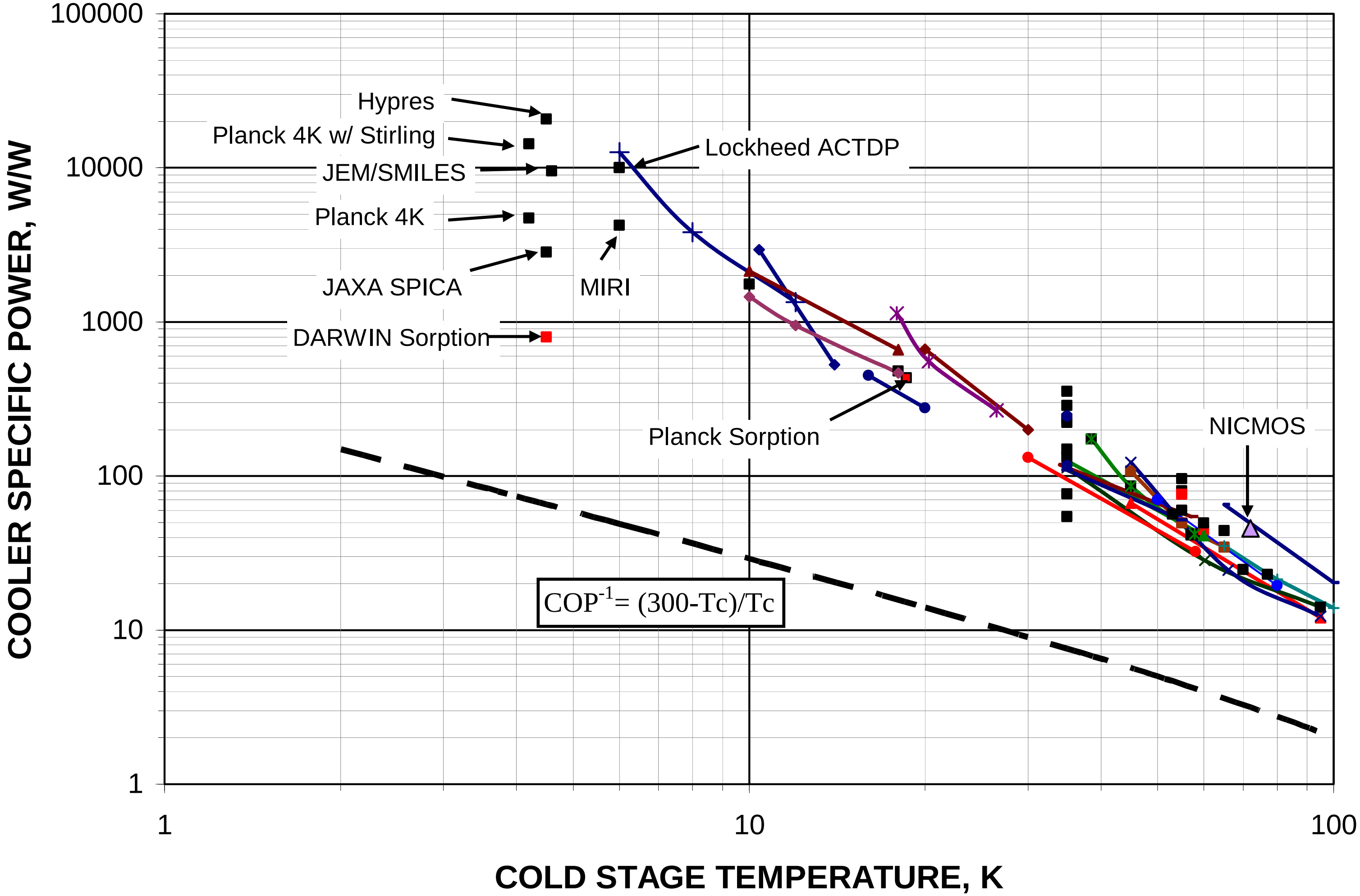

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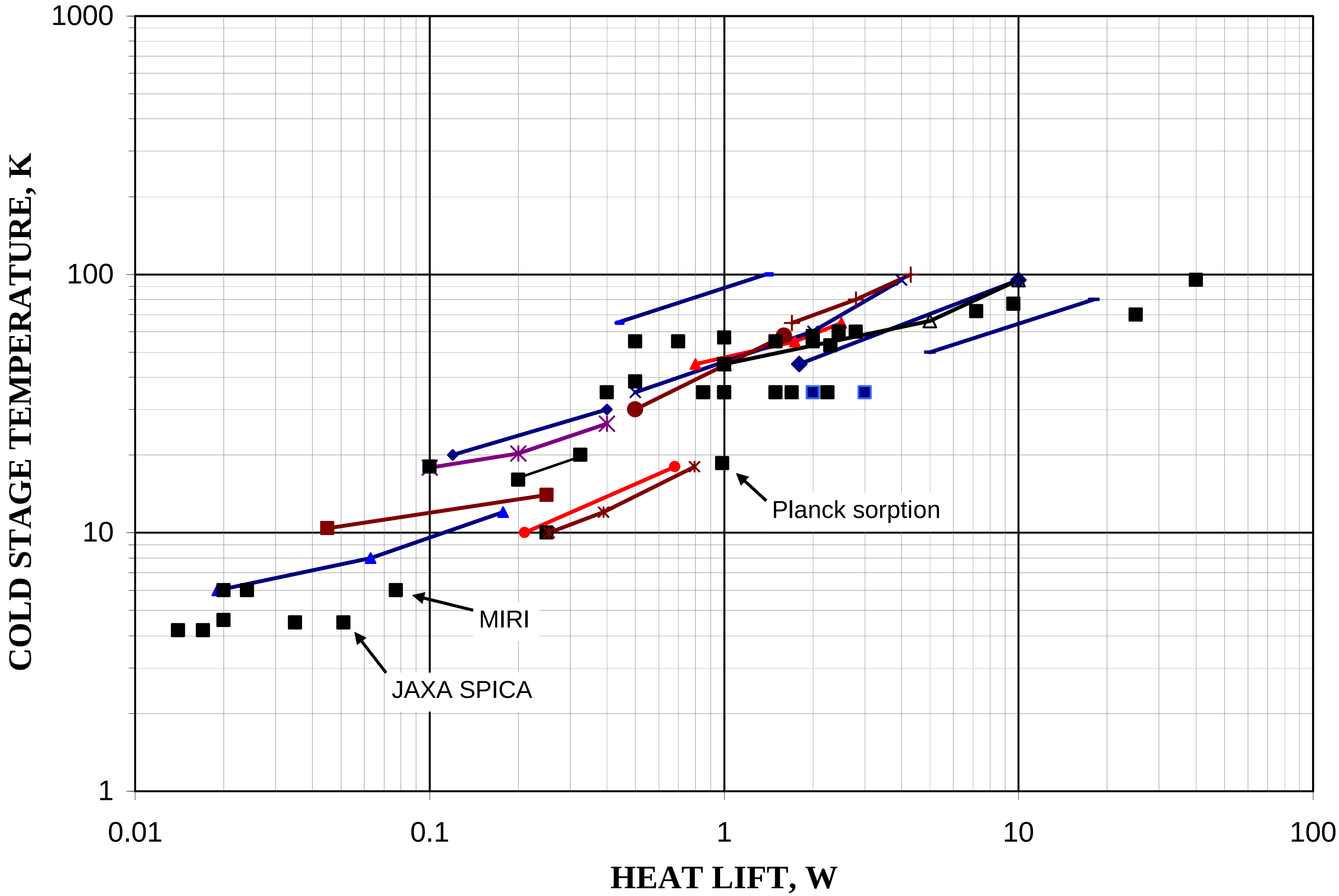
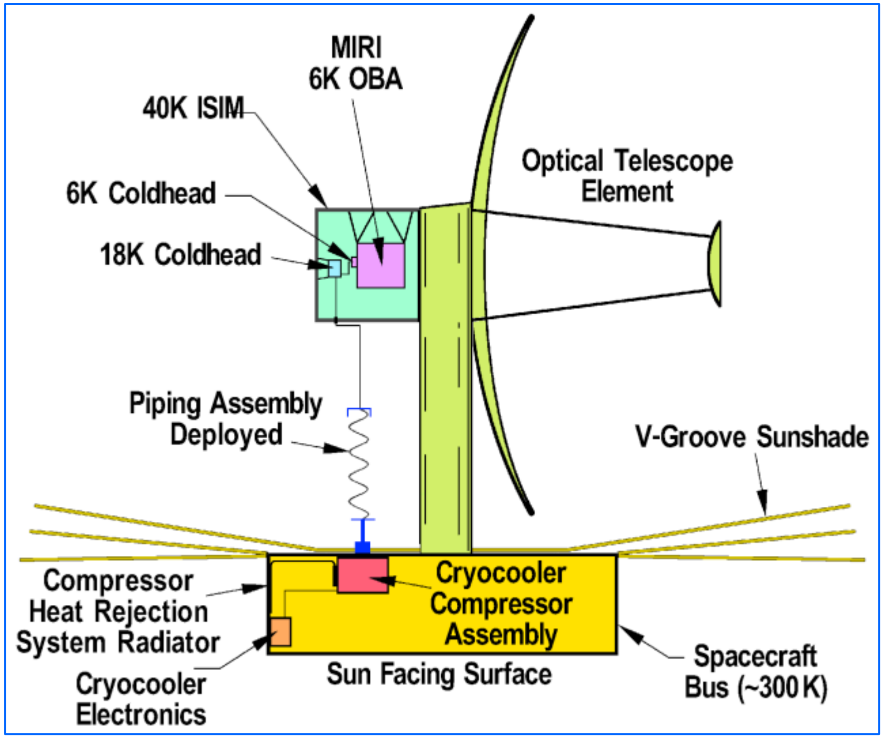
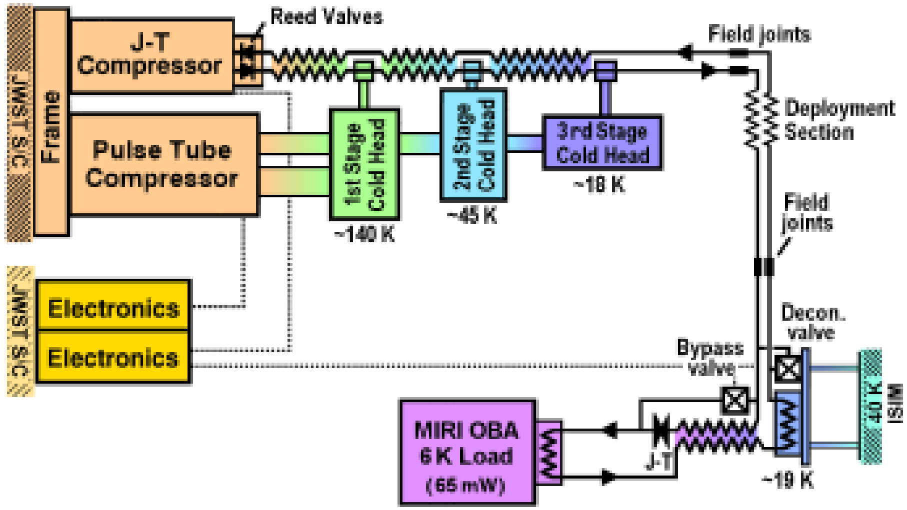
Cold Stage Heat Lift Capacity of Coolers



JWST MIRI 6K Cooler

- JWST cools most of the instruments through passive radiators to ~40K
- Mid-Infrared Instrument (MIRI) needs additional cooling to 6K
  - 6K load located several (~10-15) meters from the compressors
  - Precooler & JT compressor located in spacecraft bus
  - J-T transfer line must be flexible due to deployable telescope

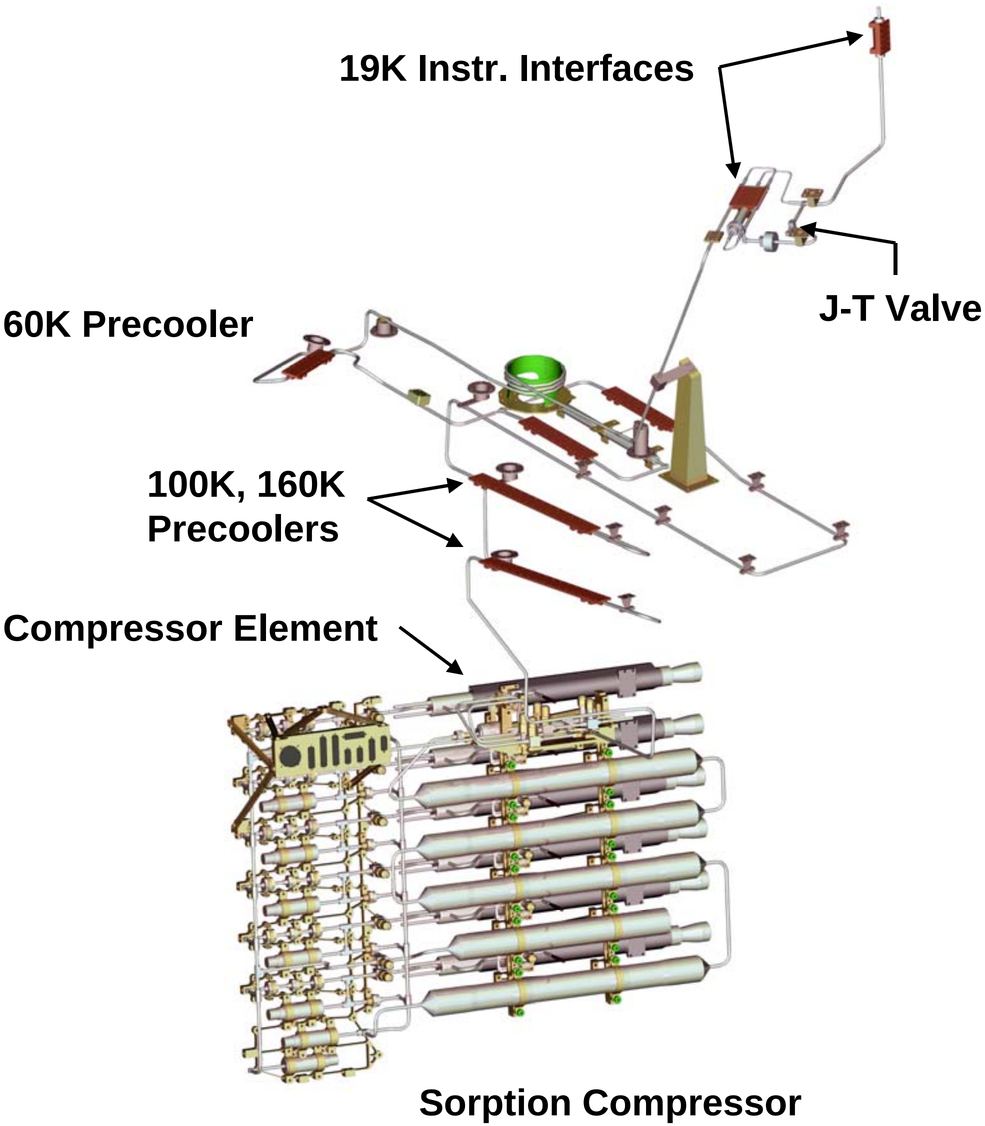




Cooler self-induced vibration:

- Vibration req’t at ISIM is < 80e-9 N^2/Hz below 200Hz
- Vibration req’t at S/C bus is <.65N

Planck 20K Sorption Cooler



Advantages/Disadvantages to Different Coolers

Stirling and Pulse Tube Precoolers

- Pulse tube and Stirling coolers both use back-to-back compressors with flexure bearing drive motors for low vibration operation
- Pulse tube coldhead is passive; it does not have a driven displacer as does the Stirling cooler, and therefore also does not require a momentum balance motor for the coldhead
  - Stirling cooler thus has two additional drive motors and additional drive electronics
  - Stirling cooler requires launch lock of displacer and balancer motors
- Pulse tube coldhead is sensitive to gravitational orientation which must be considered for all phases of ground testing

Joule-Thomson and Reverse Turbo-Brayton Coolers

- Can provide remote, vibration free cooling many meters from precoolers and compressors
- Can attach to cold end of precooler to provide additional stage of refrigeration or function as circulators to transport heat
  - RTB can handle larger single-phase fluid flow rates than J-T cooling stage
  - RTB is less susceptible to gas contamination than J-T since it does not have small orifice as in the J-T expansion valve
  - J-T can provide two-phase flow if desire to use latent heat of fluid
- Are more easily adaptable for interfacing with passive coolers than are mechanical precoolers

Milestones to Improve Cooler TRL for CMB Pol

- Re-sizing cooler coldhead and compressor will require ~2-3 years of development work to get it to TRL 4-5
  - Designing and building scaled-up drive electronics can take a similar amount of time

- Modification of coldhead dimensions to change operating stage temps and refrigeration capacities could take 1-2 years

- Flight builds of complex cryocooler systems can be expected to take an additional 2-3 years

Recommendations

- Understand loads and temperatures so that one can assess applicability of current stable of coolers
  - Minimizing the load on the active cooler is probably the most effective way to reduce cooler mass and power requirements.
  - Detectors generally are only a small fraction of the load--parasitics can dominate, especially in space systems that must survive launch loads
- Select an oversized cooler; thermal loads inevitably increase as the flight program matures through its development phases
  - Cooler should have a performance margin of 50% to 100% at the beginning of the program, and at least 25% at launch
  - Determine the cooling requirement for end-of-life, not for the beginning-of-life when everything is pristine
- Consider Passive Cooling technology as a useful tool for enhancing cooler performance or reducing cooler mass and power requirements

Summary

- Mechanical coolers have demonstrated their long term reliability, with several coolers having logged over 10 years of space flight operation
- There are active coolers currently in development that are applicable for the various CMB Pol configurations, though their heat lift capability and temperature stages will need modification to satisfy CMB Pol needs
- Cooler build cycles are on the order of 3 years, but each new generation cooler leads towards improvements that lower mass or increase efficiency
- The need to oversize the cooler cannot be stressed enough
  - Thermal loads inevitably increase as the flight program matures through its design and development phases
  - The cooler must be designed for the mission end-of life conditions when parasitic loads are highest