Cryocoolers for Space Applications #4

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Topics

- Space Cryocooler Historical Overview and Applications
- Space Cryogenic Cooling System Design and Sizing
- Space Cryocooler Performance and How It's Measured
- Cryocooler-Specific Application and Integration Example: The AIRS Instrument

Topics

- Overview of AIRS Instrument
  - Example Application Ground Rules and Requirements
  - AIRS Cryosystem Conceptual Design
  - Cryosystem layout and cryo loads estimation
  - Important heatsinking considerations
- Sizing the Cryocooler for the Complete Mission Life Cycle
  - BOL/EOL performance margin analysis
- Temperature Stability Requirements and Control
- Cryocooler Structural Integration Considerations
- Electrical Interface Considerations
  - Meeting magnetic field requirements with shields
  - Meeting Inrush and reflected ripple current requirements

References

- Ross, R.G., Jr. and Green K., "AIRS Cryocooler System Design and Development," *Cryocoolers 9*, Plenum Publishing Corp., New York, 1997, pp. 885-894.
- Ross, R.G., Jr., Johnson, D.L., Collins, S.A., Green K. and Wickman, H. "AIRS PFM Pulse Tube Cooler System-level Performance," *Cryocoolers 10*, Plenum, New York, 1999, pp. 119-128.
- Ross, R.G., Jr., "AIRS Pulse Tube Cooler System Level Performance and In-Space Performance Comparison," *Cryocoolers 12*, Kluwer Academic/Plenum Publishers, New York, 2003, pp. 747-754.
- Ross, R.G., Jr., "Cryocooler Load Increase due to External Contamination of Low-ϵ Cryogenic Surfaces," *Cryocoolers 12*, Kluwer Academic/Plenum Publishers, New York , 2003, pp. 727-736.

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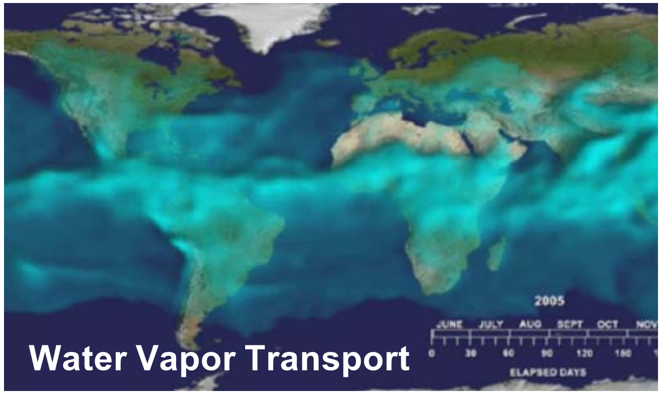
- Ross, R.G., Jr. and Rodriguez, J.I., “Performance of the AIRS Pulse Tube Coolers and Instrument—A first Year in Space,” *Adv. in Cryogenic Engin.*, Vol 49B, Amer. Inst. of Physics, New York, 2004, pp. 1293-1300.
- Ross, R.G., Jr., “Active Versus Standby Redundancy for Improved Cryocooler Reliability in Space,” *Cryocoolers 13*, Springer Science & Business Media, New York, 2005, pp. 609-618.
- Ross, R.G., Jr., et al., “AIRS Pulse Tube Coolers Performance Update – Twelve Years in Space,” *Cryocoolers 18*, ICC Press, Boulder, CO, 2014, pp. 87-95.
- See the AIRS instrument web site for up-to-date descriptions of the science returns from the AIRS instrument and its science team members: http://www-airs.jpl.nasa.gov/
- http://www2.jpl.nasa.gov/adv_tech/ JPL website with 103 JPL cryocooler references as PDFs (R. Ross, webmaster)

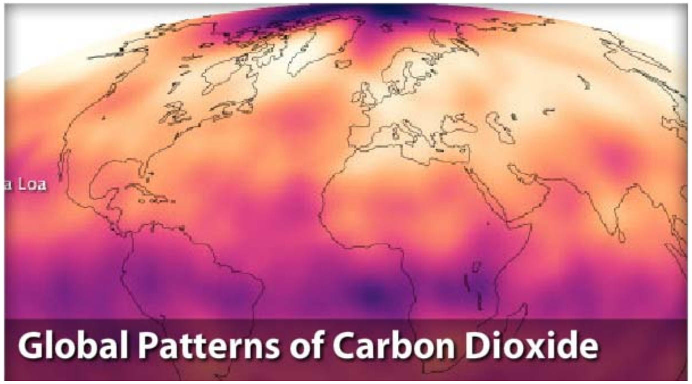
AIRS (Atmospheric Infrared Sounder) is a NASA Earth Science Instrument

- **AIRS is an Atmospheric Infrared Sounder**
  - **Design:** Highly stable IR spectrometer spanning visible to 15.4 µm bands with Focal Plane cooled to 58 K
  - **Launched:** May 2002
    - Still in orbit gathering data
  - **Science Output:**
    - Air Temperature Distributions
    - Atm Gas Concentrations (CO, CO_2, CH_4, H_2O) over Planet

Launched on NASA Aqua Spacecraft in May 2002

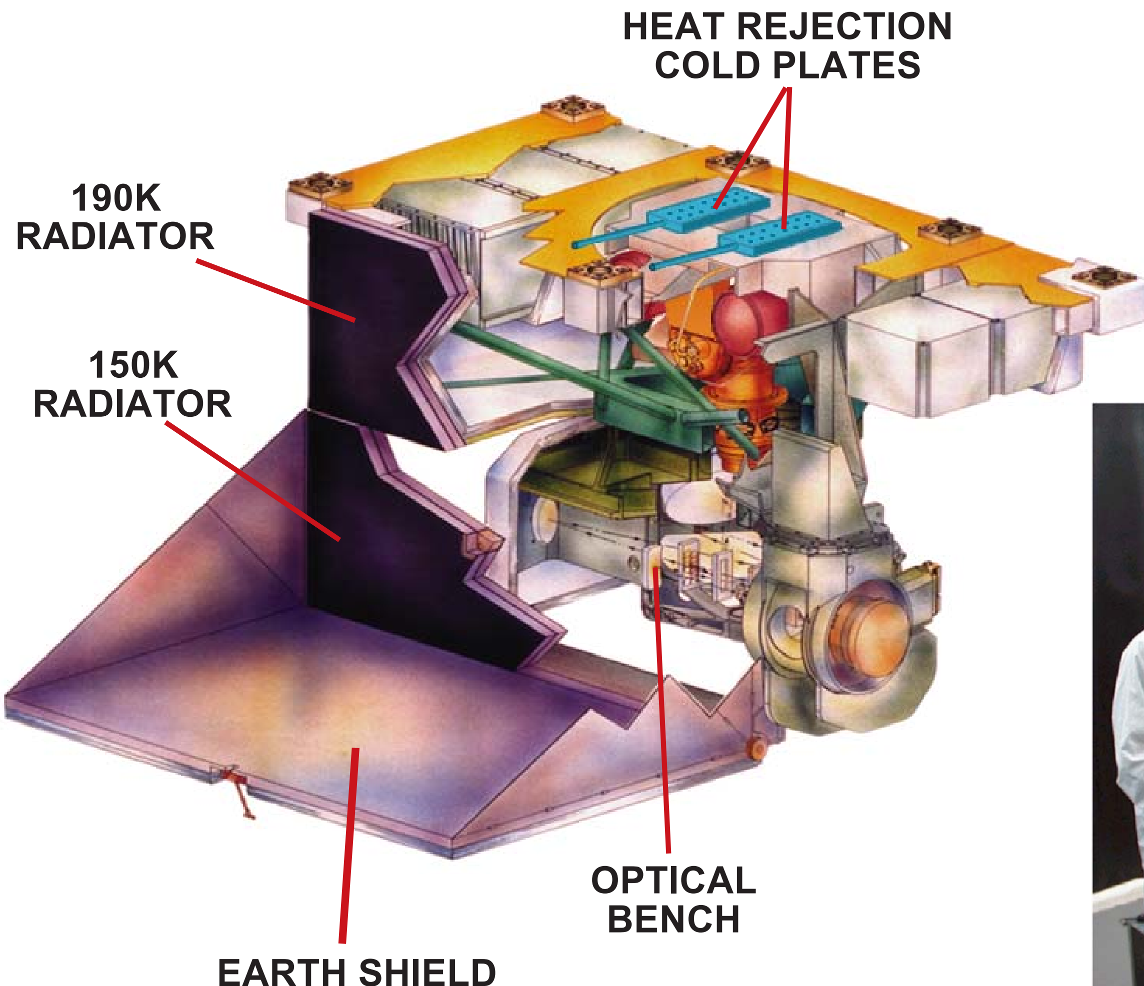


Water Vapor Transport



Global Patterns of Carbon Dioxide

Atmospheric Infrared Sounder (AIRS) Instrument



The AIRS instrument was designed and built under JPL contract by BAE Systems, Lexington, MA

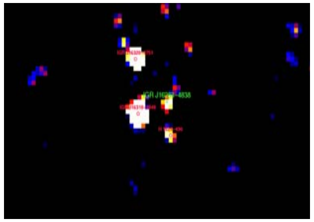
AIRS Flight Instrument

AIRS Cryosystem Ground Rules and Requirements

- Totally redundant cryocoolers—for enhanced reliability
- No heat switches—to avoid increased complexity, cost and unreliability
- Ambient heat rejection to spacecraft-supplied cold plates operating between 10 and 25°C
- Cooler drive fixed at 44.625 Hz, synchronized to the instrument electronics
- Cold-end load (focalplane) mechanically mounted and aligned to the 150 K optical bench with a maximum vibration jitter on the order of 1 μm
- Focalplane calibration (for temperature, motion, etc.) every 2.67 sec (every Earth scan)
- Cooler input power goal of 100 watts (22 to 35 volts dc), and mass goal of 35 kg
- Cooler drive electronics fully isolated (dc-dc) from input power bus; EMI consistent with MIL STD 461.

Detector Technologies and Temperatures

Radiation Type	Wavelength (microns)	Blackbody Temp. (K)	Detector Technology	Detector Oper. Temp. (K)
γ-rays	10^{-5}	3×10^{8} K	Ge Diodes	80 K
γ-rays	10^{-4}	3×10^{7} K	Ge Diodes	80 K
x-rays	10^{-3}	3×10^{6} K	micro calorimeters	0.050 K
x-rays	10^{-2}	3×10^{5} K		0.050 K
UV	0.1	30,000 K	CCD/CMOS	200-300 K
visible	1	3000 K	CCD/CMOS	200-300 K
IR	2	1500 K	HgCdTe	55-130 K
IR	5	600 K	HgCdTe	55-120 K
LWIR	10	300 K	HgCdTe	35-80 K
LWIR	15	200 K	HgCdTe	35-60 K
LWIR	20	150 K	Si:As	6 -10 K
LWIR	50	60 K	Ge:Ga	2.0 K
LWIR/μwaves	100	30 K	Ge:Ga	1.5 K
microwaves	200	15 K	Bolometers	0.100 K
microwaves	500	6 K	Bolometers	0.100 K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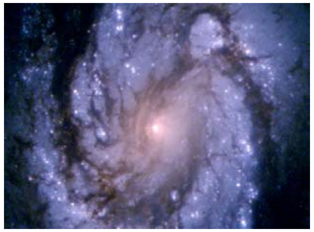
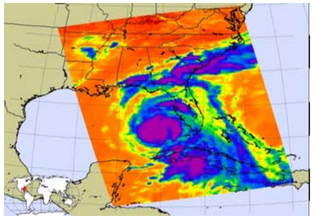
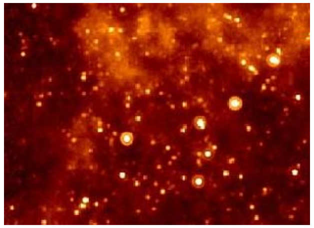

HST


AIRS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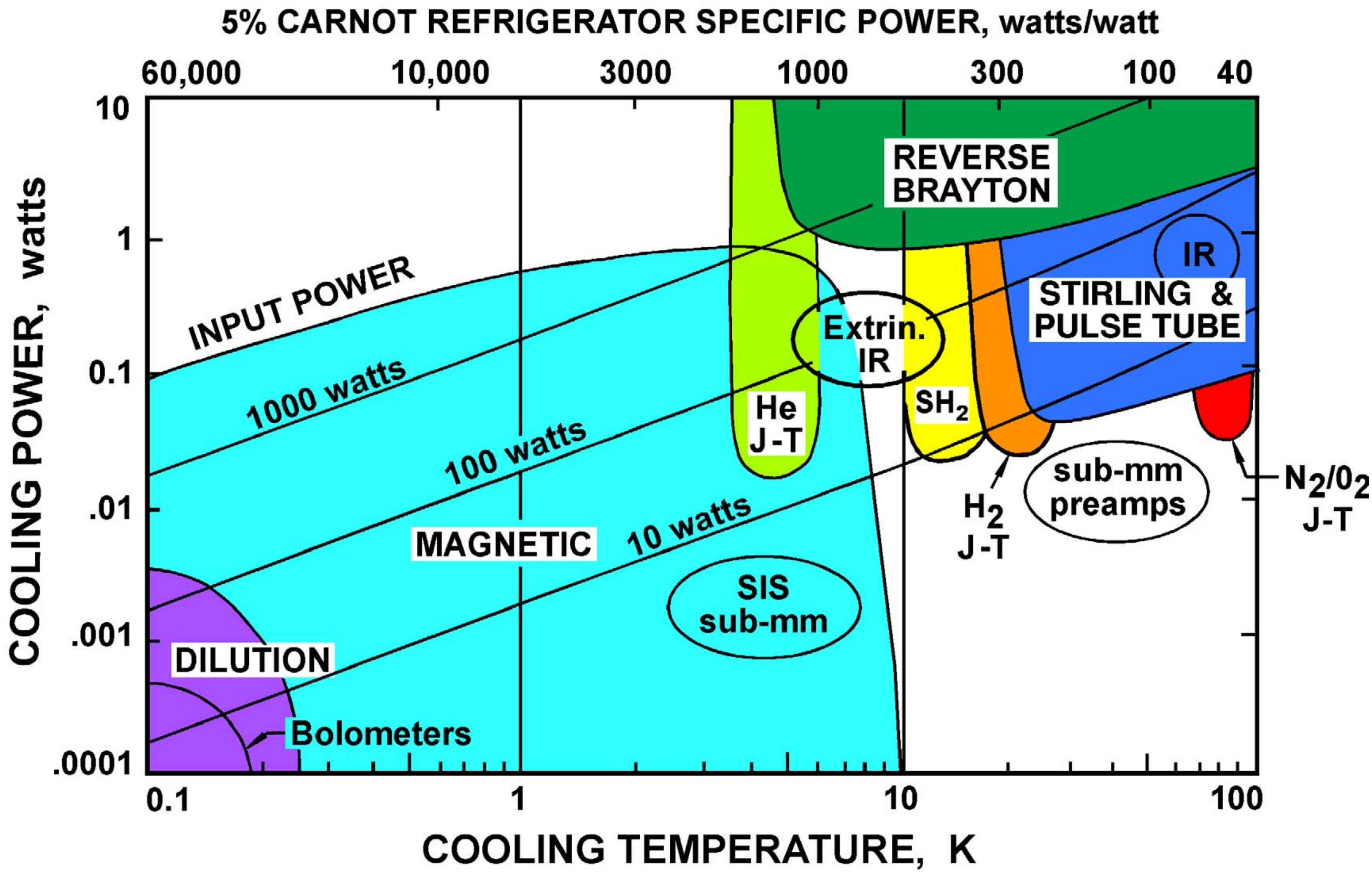
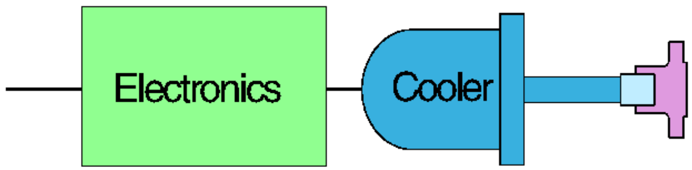
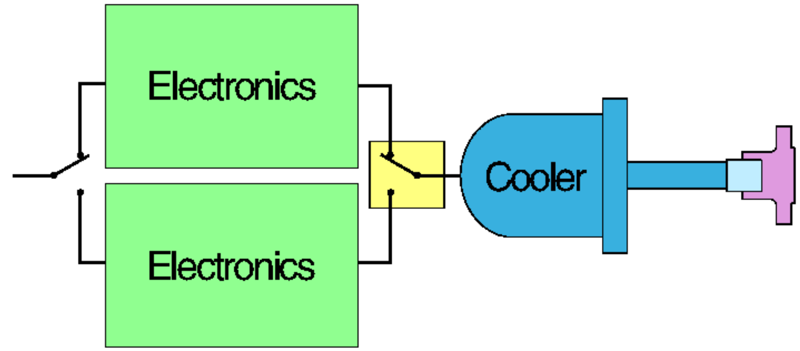
Operating Regions of Cryocoolers vs Detector Cooling Requirements



Candidate Stirling Cryocooler Redundancy Approaches

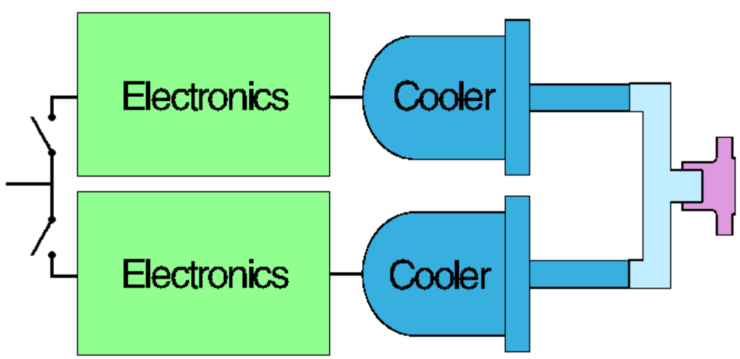


Single Cooler and Electronics
No Redundancy

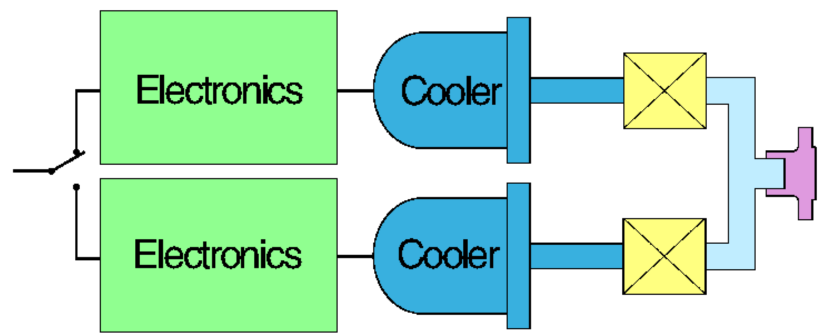


Single Cooler and Dual Electronics
with Electrical Switch

AIRS

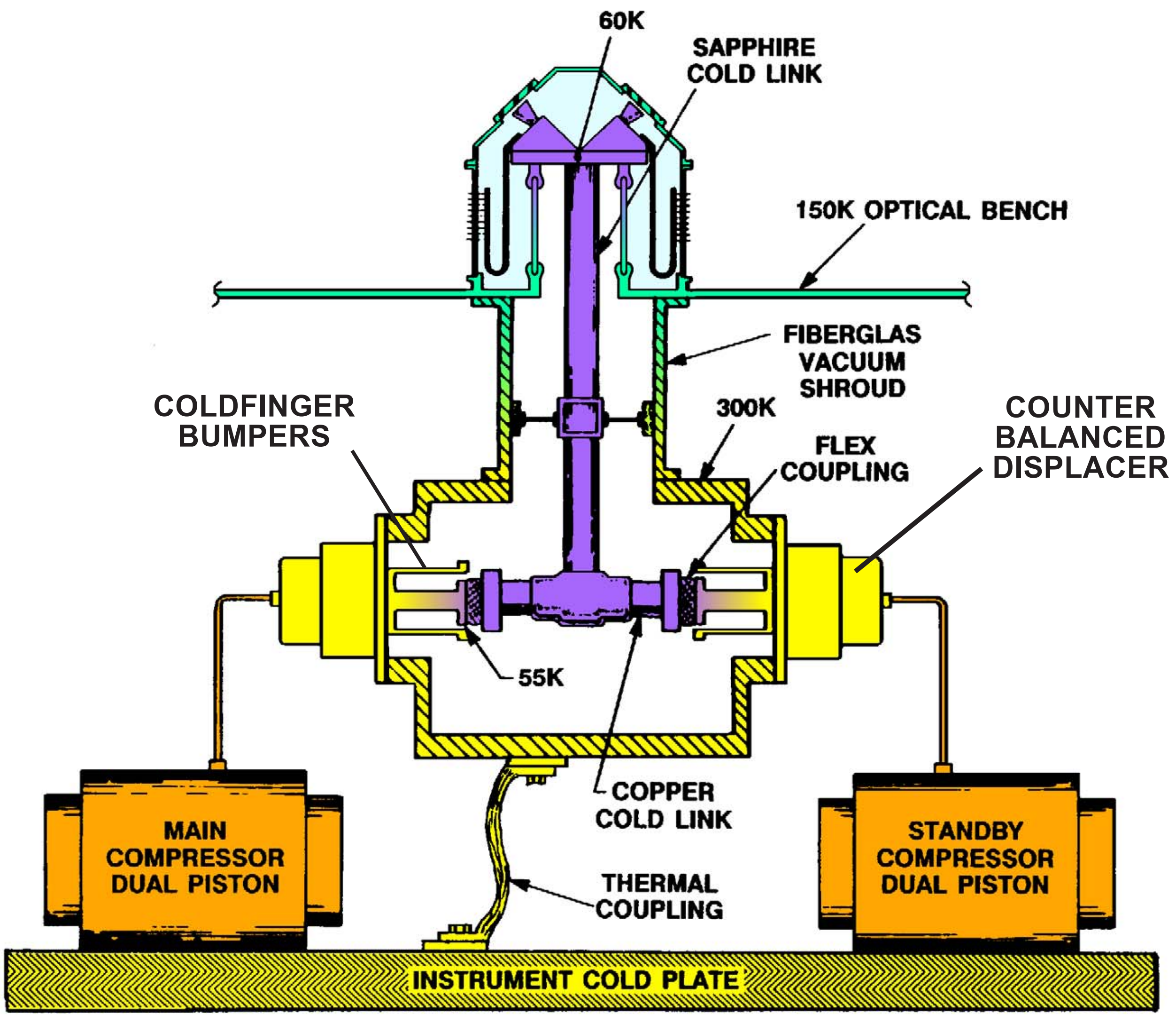


Dual Coolers and Dual Electronics
No Heat Switches



Dual Coolers and Dual Electronics
with Heat Switches

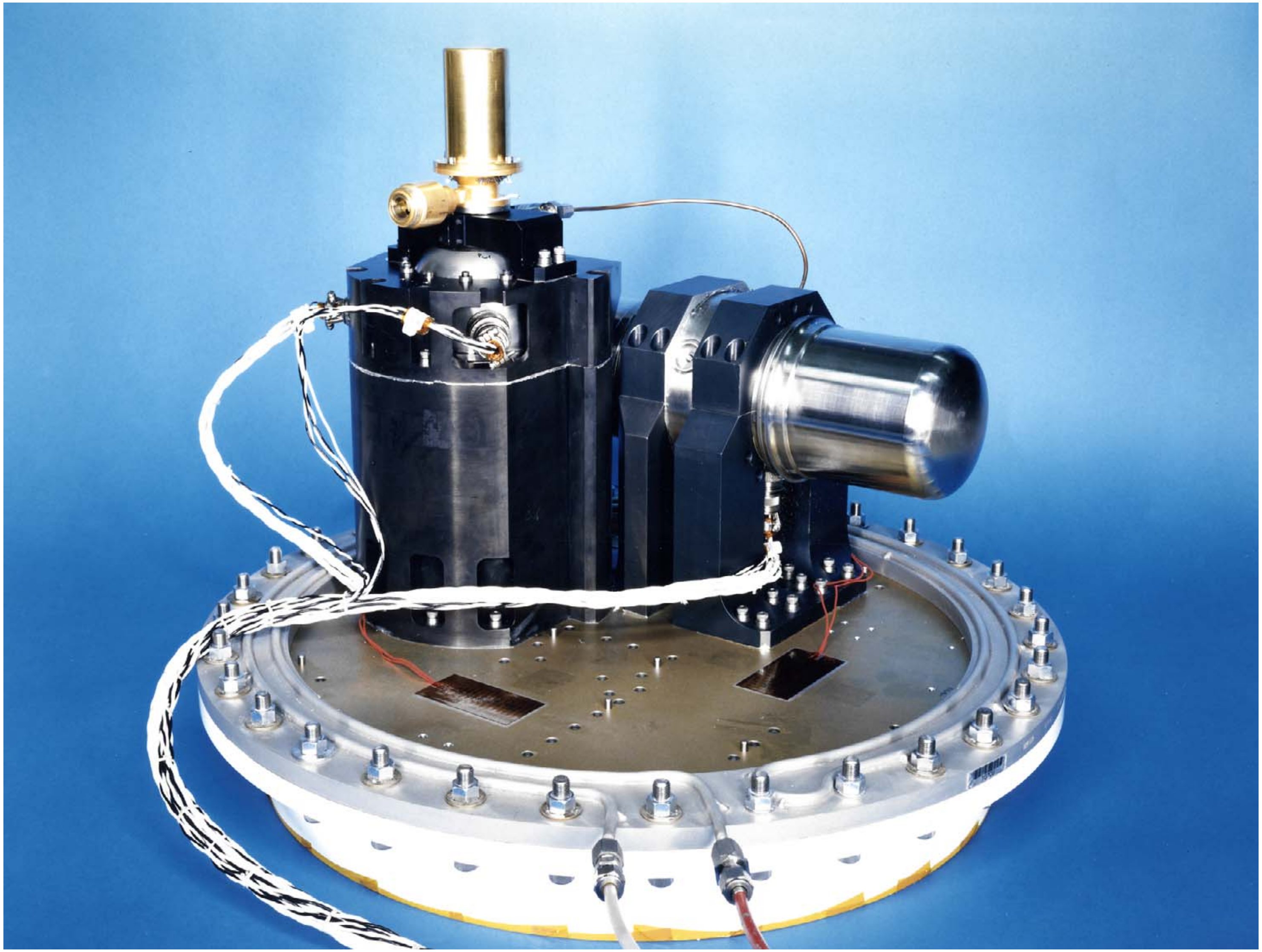
AIRS Cryosystem Initial Conceptual Design with Stirling Cryocoolers



Possible Issues

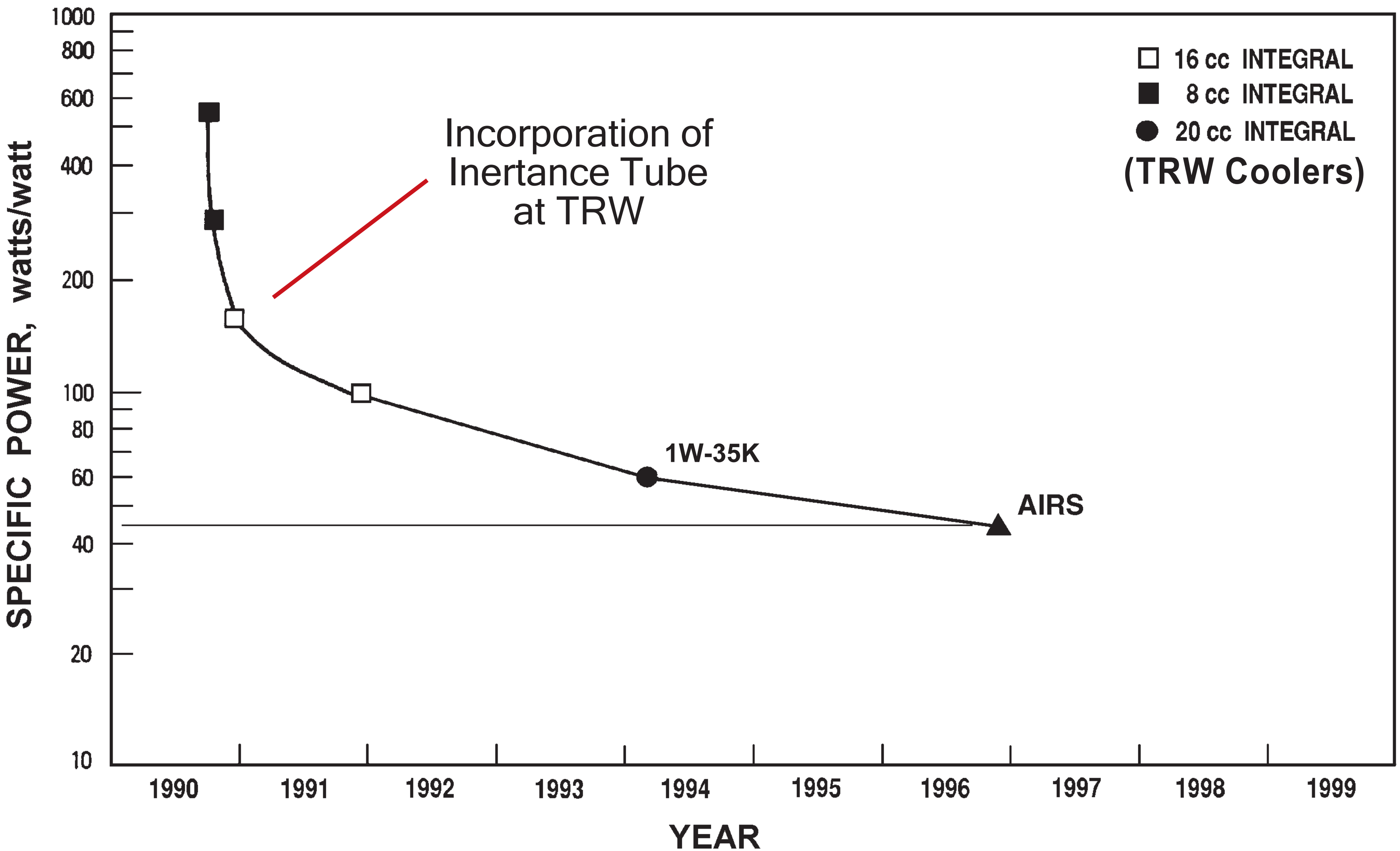
- Displacer heatsinking
- Displacer vibration
- Displacer reliability

Hughes CSE Cryocooler Mounted in Heat Sink Assemblies

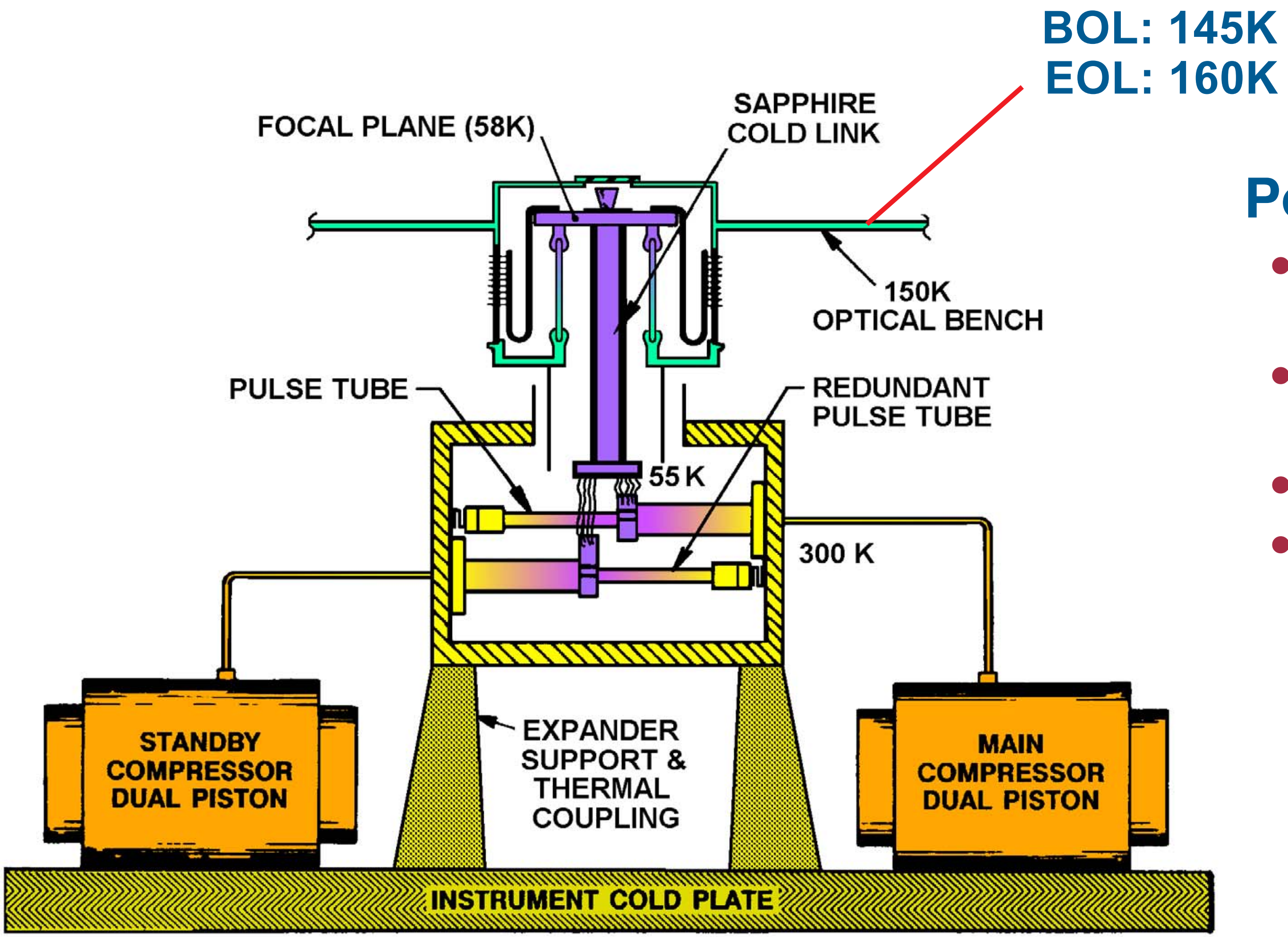


Rapid Development of the Pulse Tube Occurred Just in Time for AIRS

Specific Power at 58 K



AIRS Cryosystem Conceptual Design with Pulse Tube Coolers



Possible Issues

- Optics Contamination
- Pulse Tube Contamination
- Horizontal PTs
- PT/OB relative motion

Vacuum Level Considerations for Space Cryogenic Applications

Three Vacuum Level Issues: Gaseous Conduction, Cryopumping loads, Increased Emittance from contaminant films

Typical Vacuum Levels Achieved:

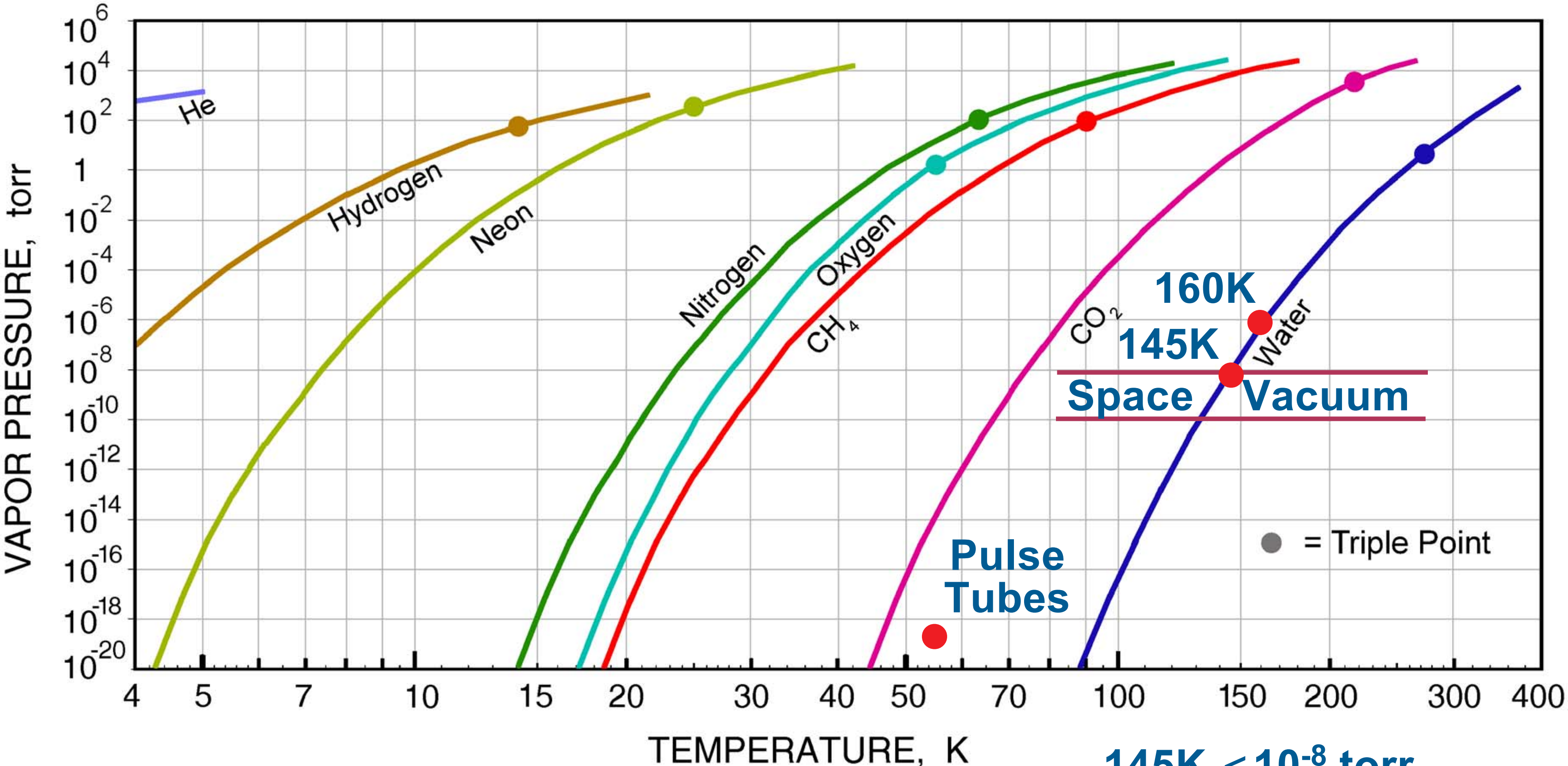
- 10^{-8} torr: Exterior to spacecraft sunlit surfaces (short term)
- 10^{-9} torr: Exterior to spacecraft sunlit surfaces (long term)
- 10^{-10} torr: Exterior to spacecraft shaded-side surfaces (long term)

Contamination Implications:

Vacuum Level	Time for 1 μm H_2O	H_2O Cryopumping Heat Transfer
10^{-6} torr	1.7 hours	340 mW/m^2
10^{-8} torr	7 days	3.4 mW/m^2
10^{-9} torr	70 days	0.34 mW/m^2
10^{-10} torr	2 years	0.034 mW/m^2

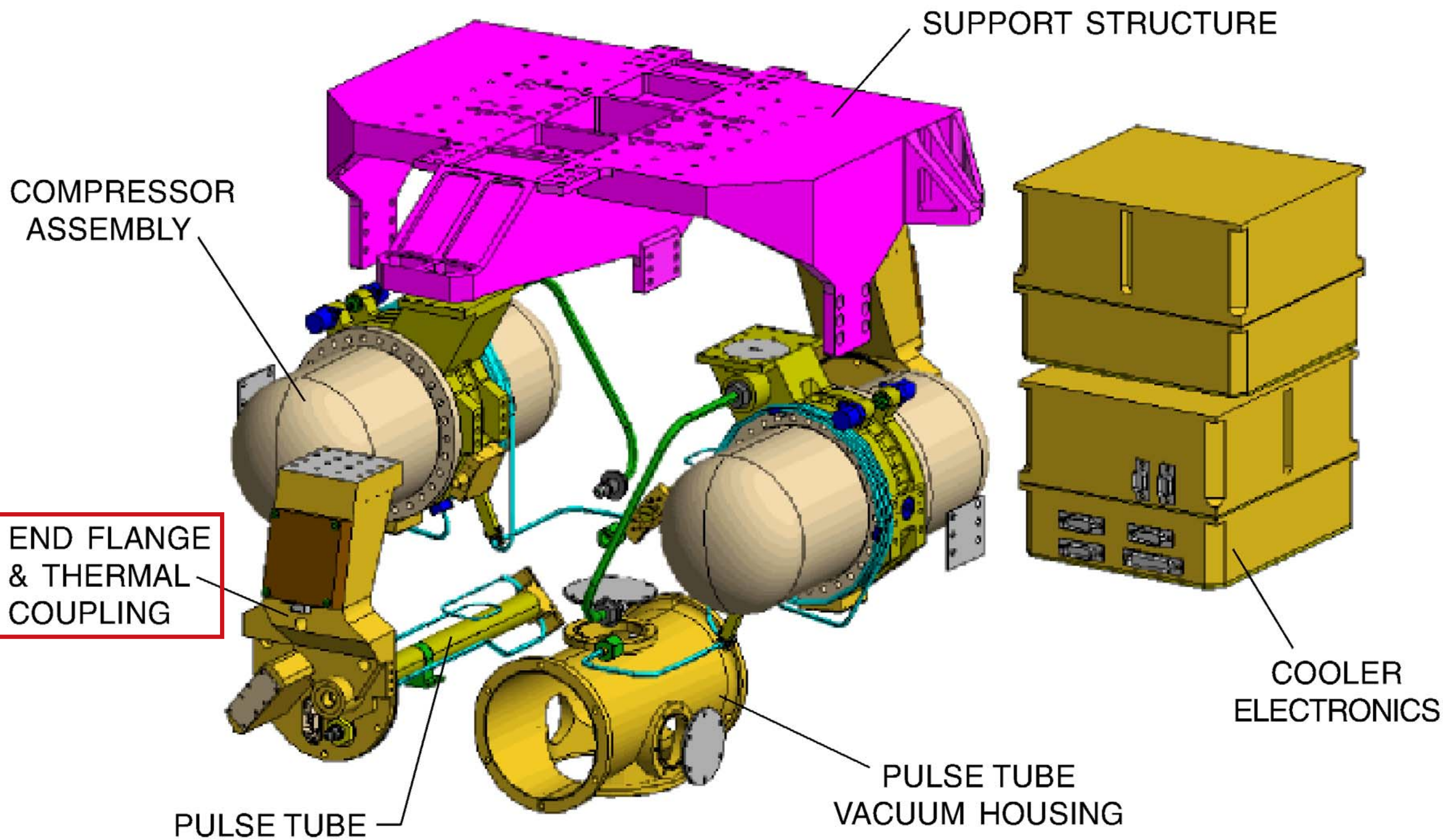
AIRS Optical Bench Contamination Risk Assessment

Optical Bench BOL Design: 145 K ($10^{-8.5}$ torr): Contamination Likely
Optical Bench EOL Design: 160 K (10^{-6} torr): Looks Good
Pulse Tube Design: 55 K (10^{-50} torr): Contamination Very Likely

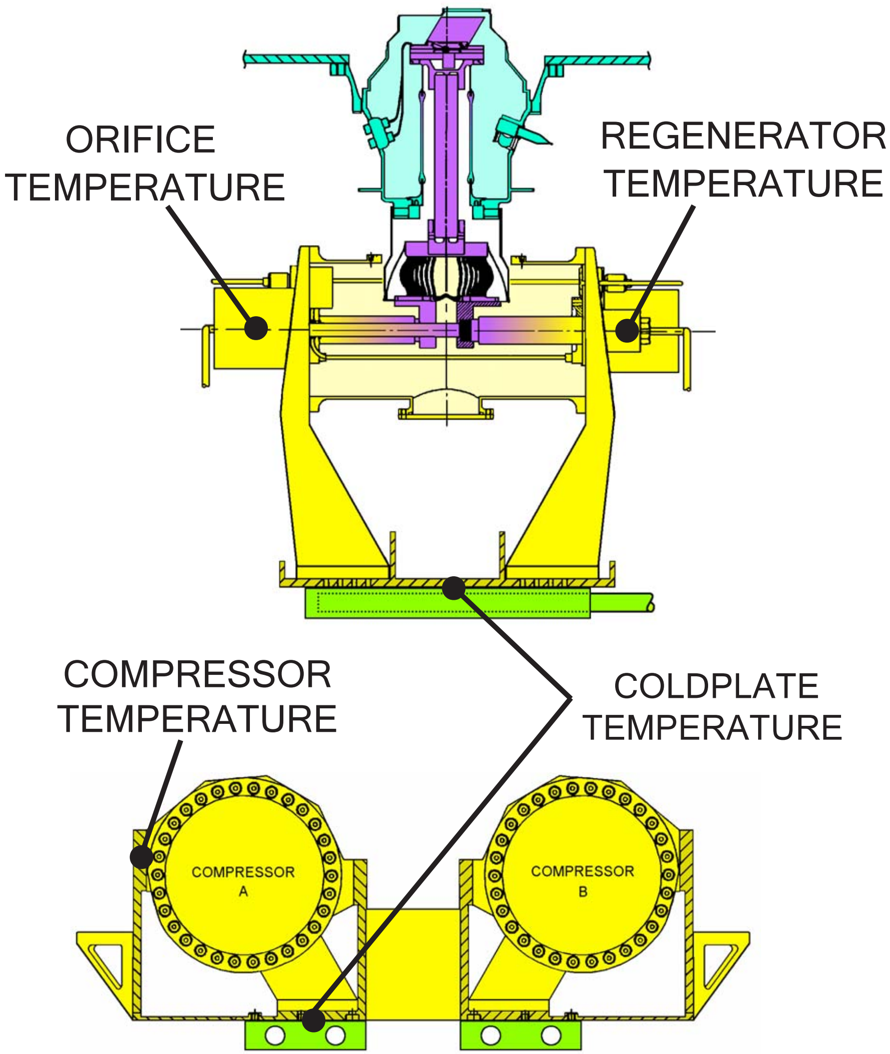


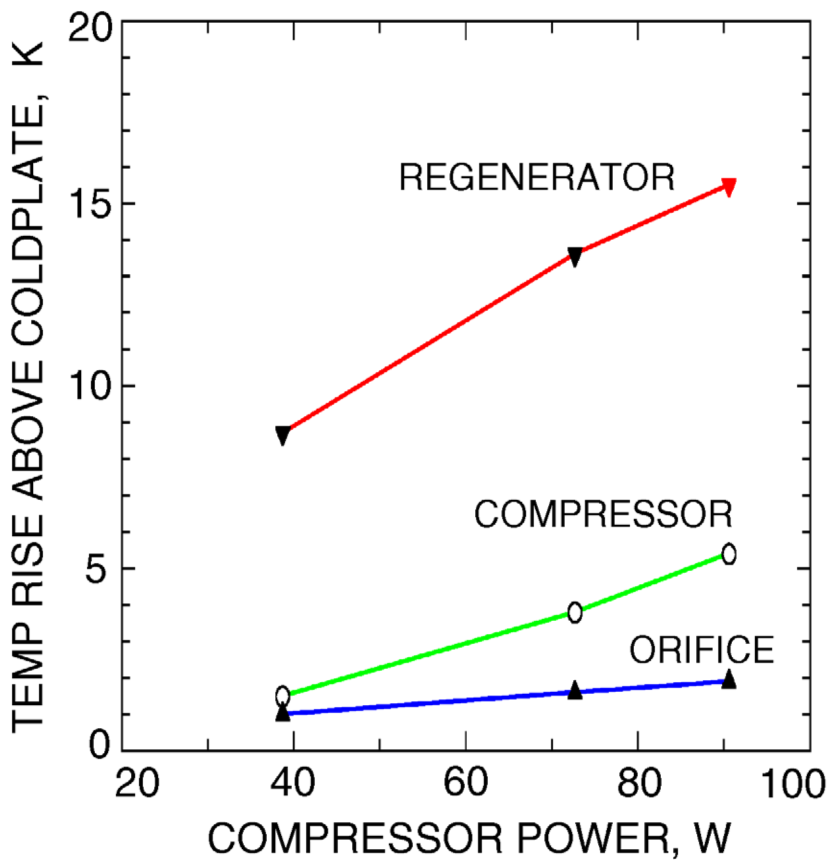
145K < 10^{-8} torr

Massive Heat Sinks Added to AIRS Pulse Tubes

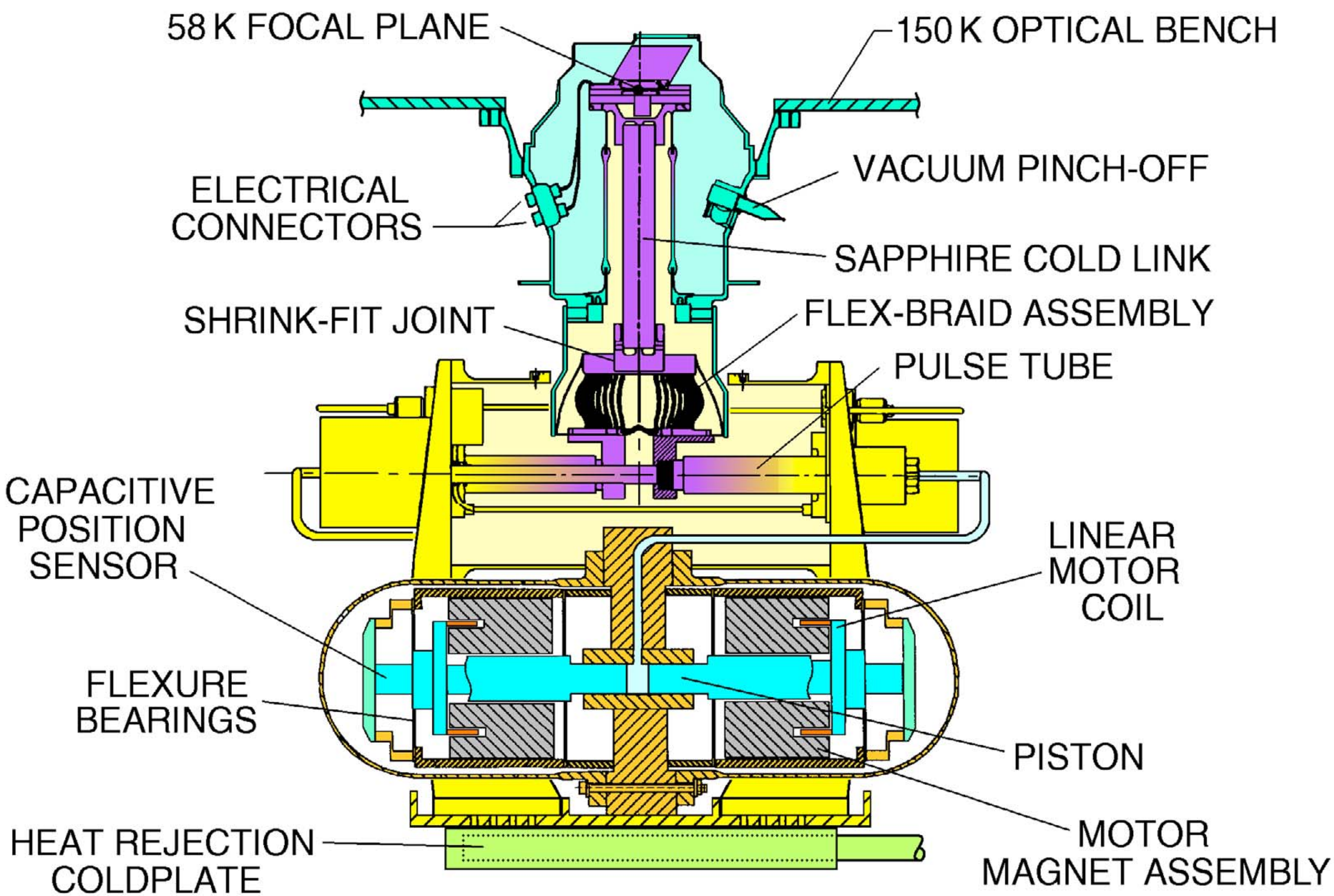


Summary of AIRS Cooler System Thermal Gradients

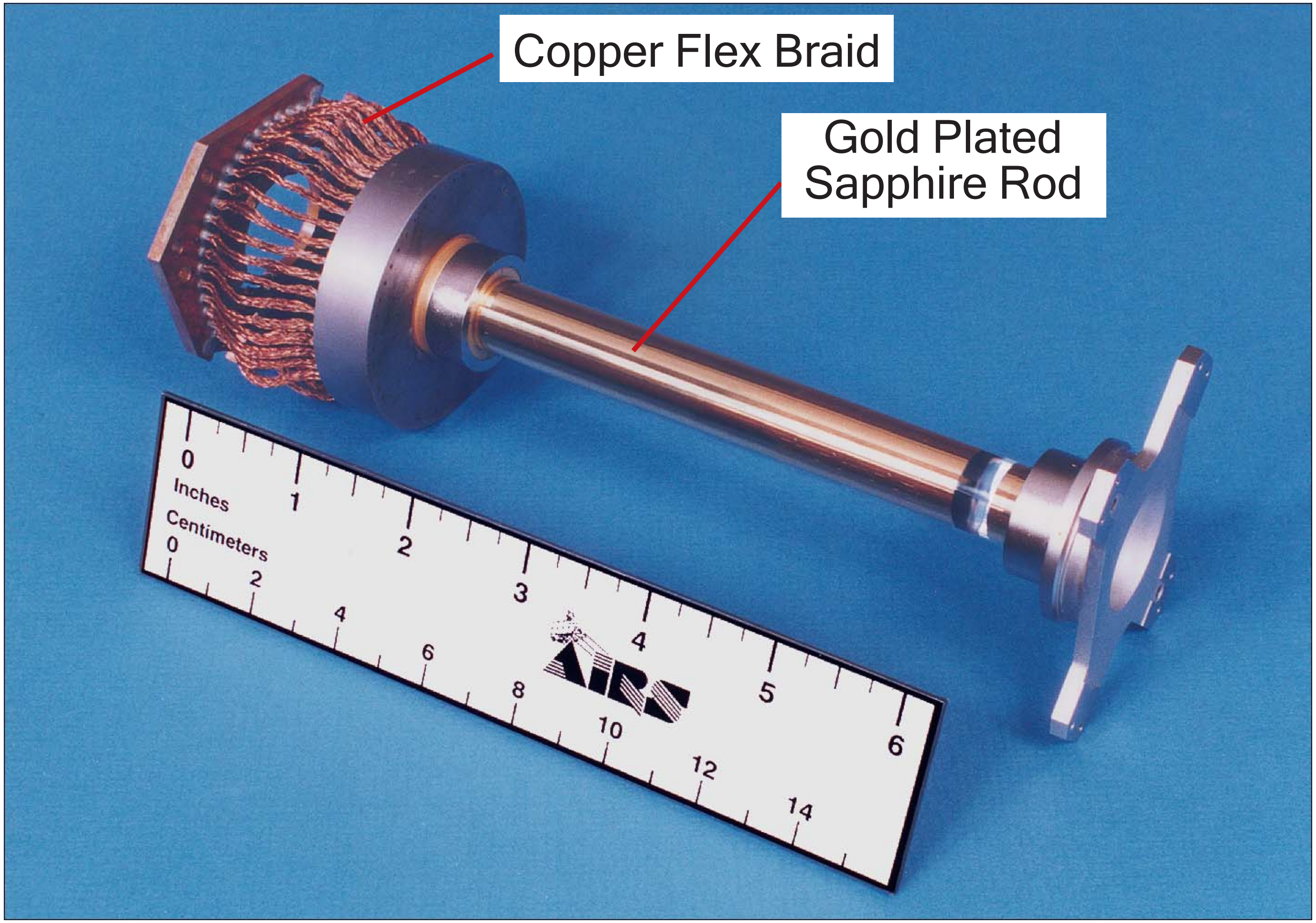




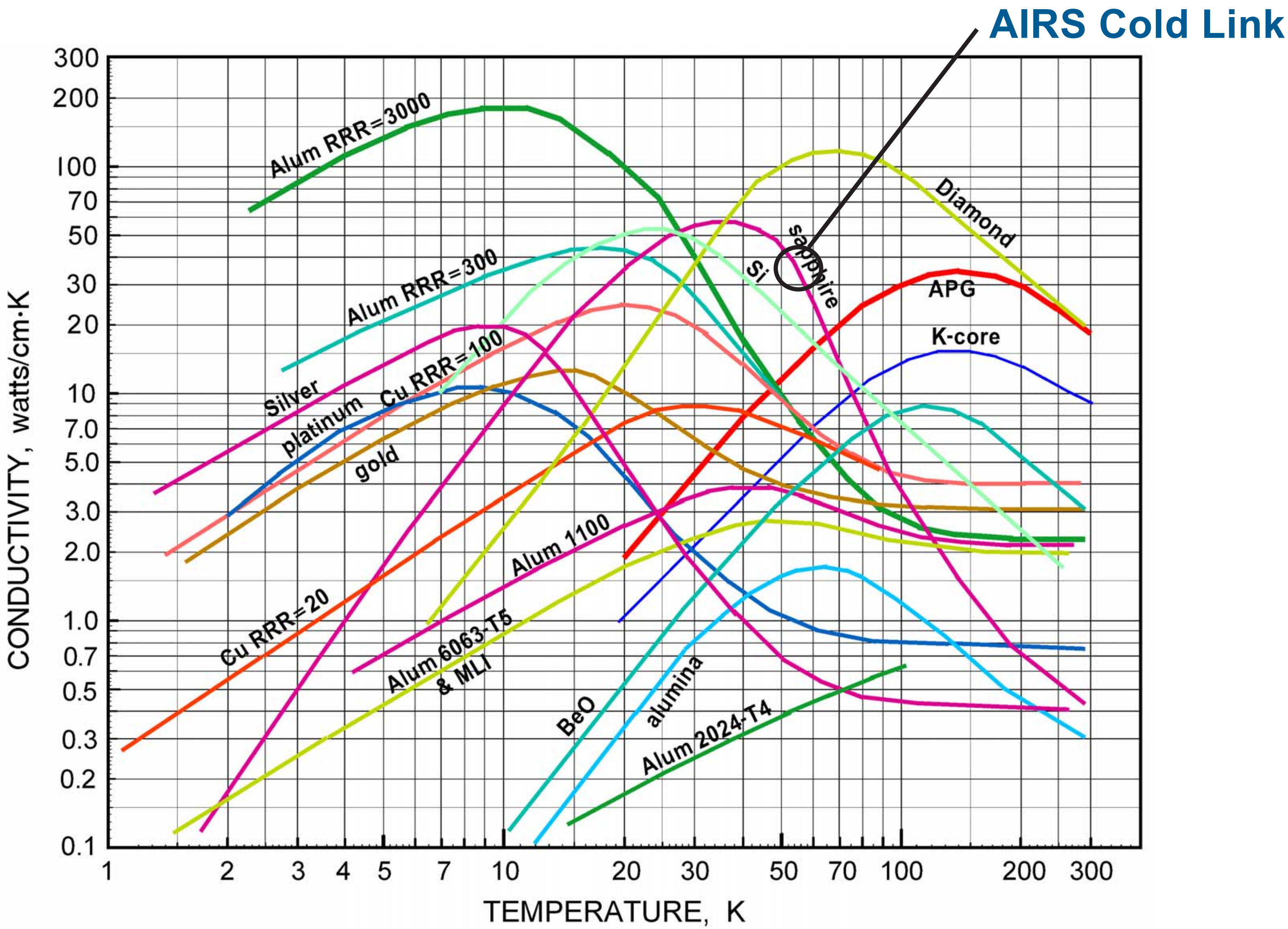
AIRS Cryosystem Cold Link Design with Pulse Tube Coolers



AIRS Cold Link Assembly



Cryogenic Conductivity of High Conductivity Materials



Breakdown of AIRS Coldlink Assembly Thermal Resistances

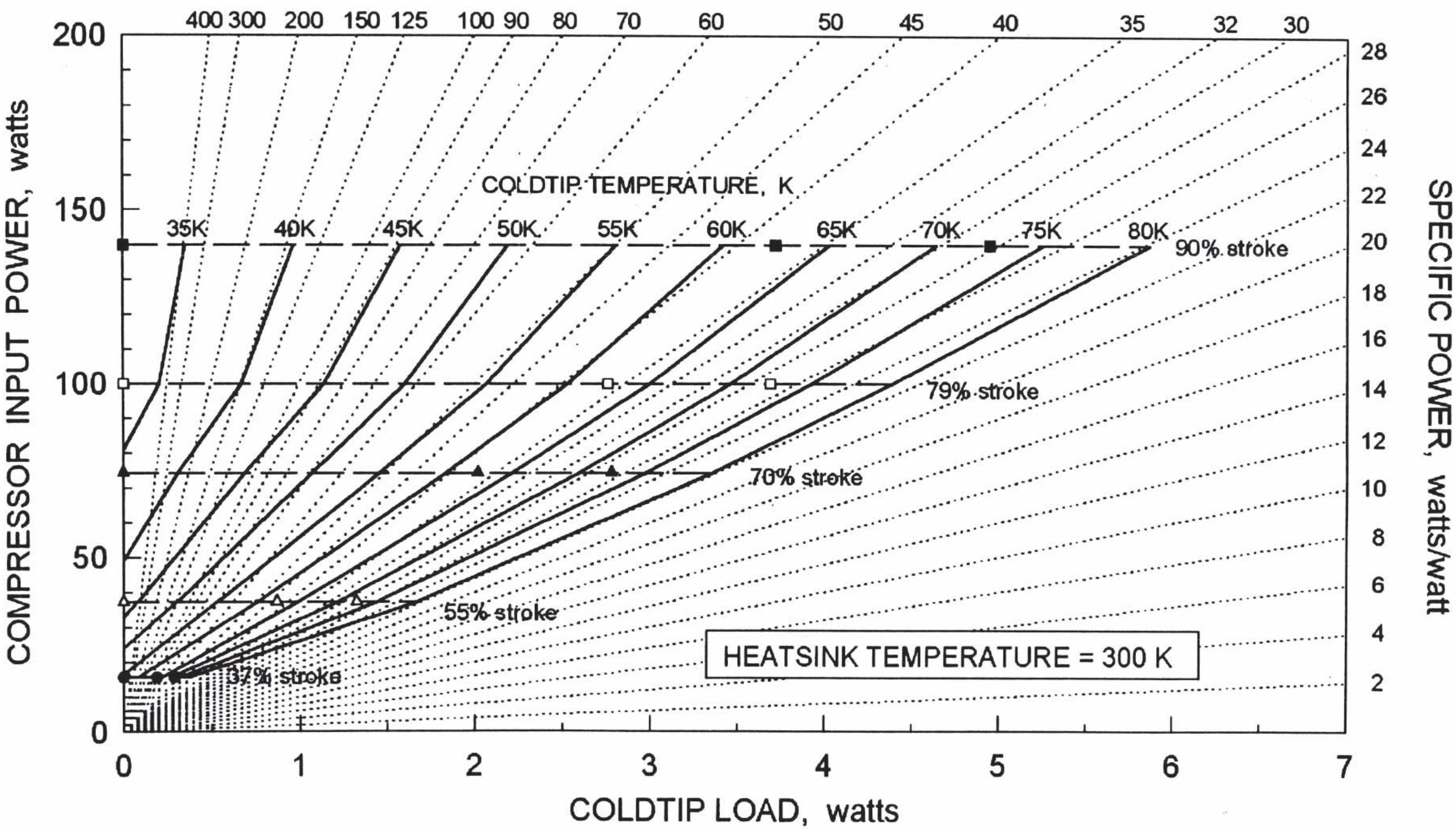
ITEM	Resistance (K/W)
Focal plane to Sapphire rod	1.57
Conduction down Sapphire rod	0.16
Sapphire rod to moly coupling	0.34
Resistance across shrink-fit joint	0.40
Resistance across flex braid	1.35
Coldblock contact resistance	0.30
Total focal plane/pulse tube thermal resistance	4.12 K/W

Summary of AIRS Instrument Cryocooler Loads

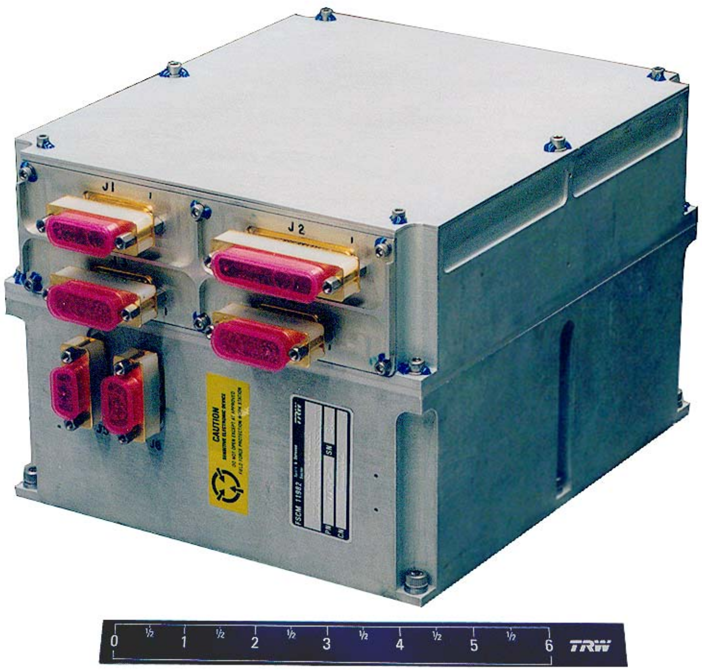
FOCAL PLANE: 58 K, OPTICAL BENCH: 145 K BOL, 160 K EOL

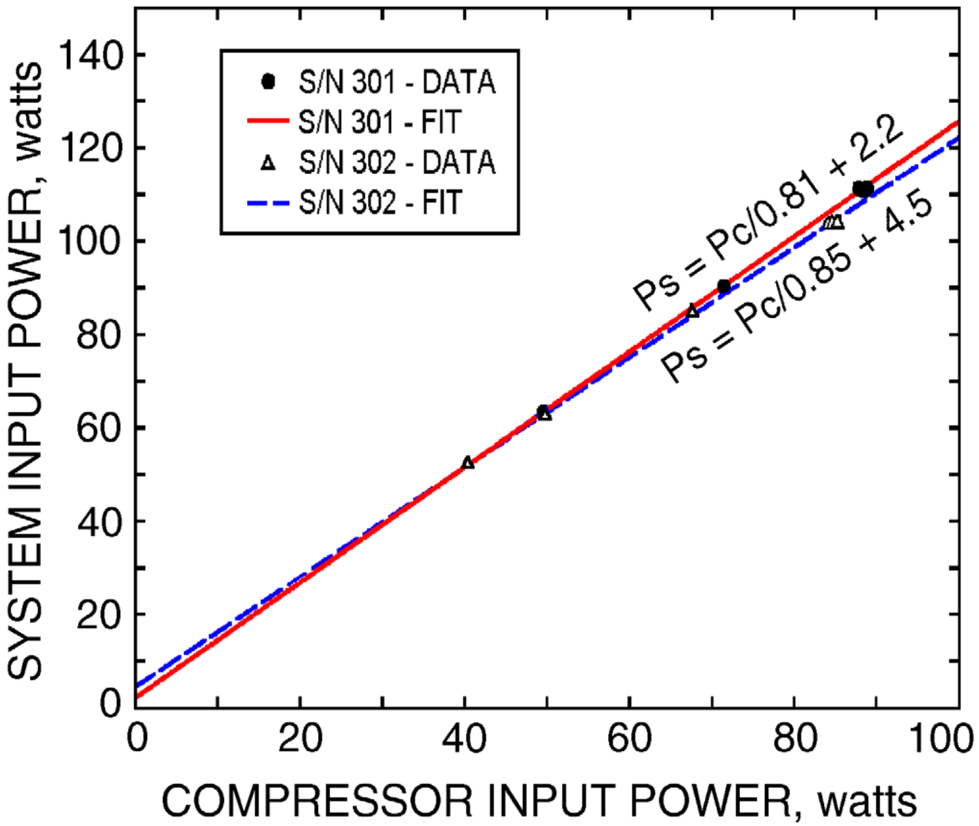
ITEM	Load (mW) BOL	Load (mW) EOL
Focal Plane Radiation Load from OB	73	108
Focal Plane Electrical Dissipation	193	193
Focal plane Lead Wire Conduction	98	118
Focal plane Structural Support Conduction	129	158
Radiation to Coldlink from Optical Bench	17	24
Radiation to Coldlink from Vacuum Housing	177	195
Off-state Conduction of Redundant Cryocooler	486	496
Total Cryocooler Load	1173	1292

AIRS Predicted Cryocooler Thermal Performance



AIRS Cryocooler Electronics Efficiency

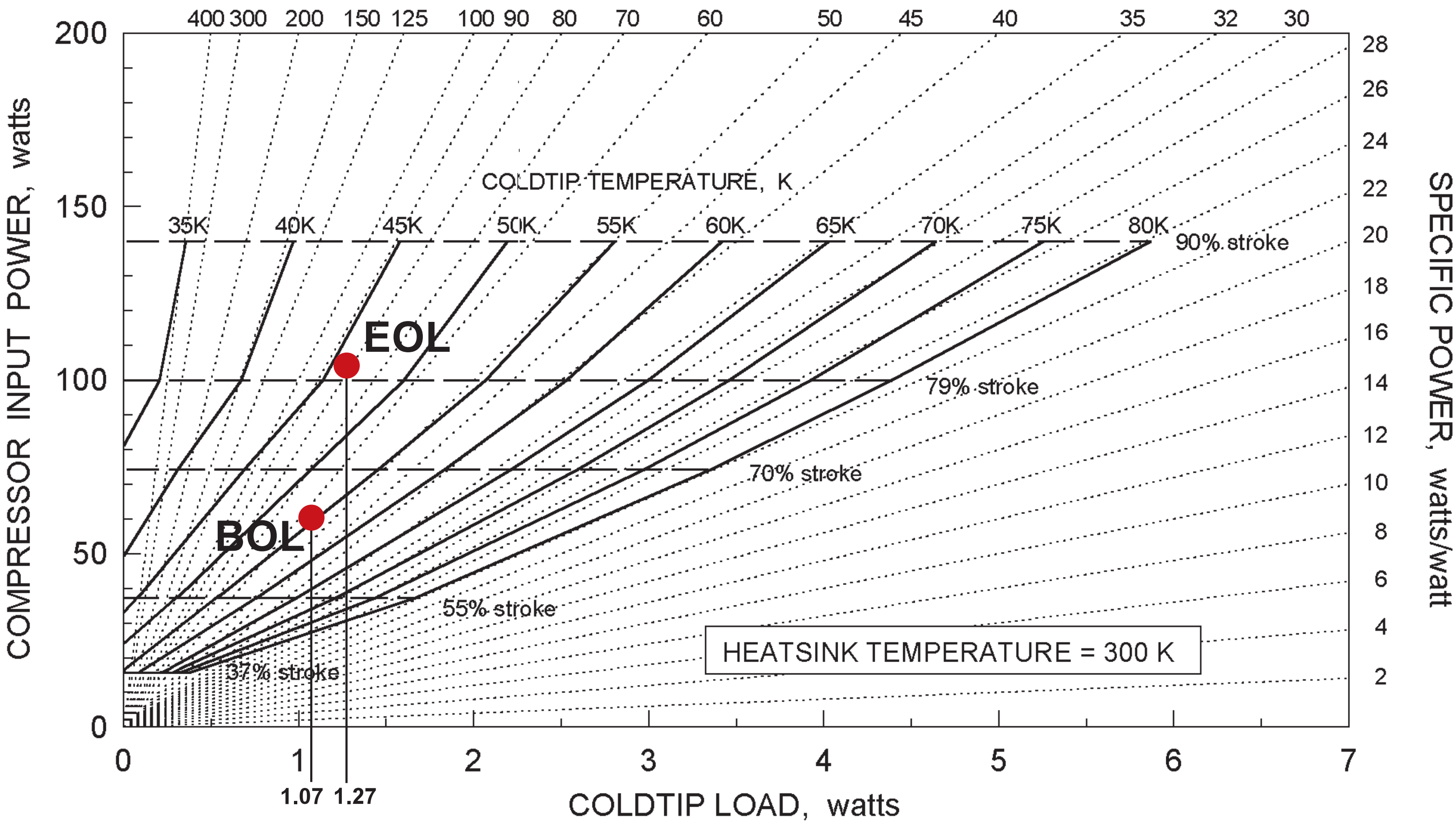




AIRS BOL/EOL Performance Margin Analysis

PARAMETER	Unit	BOL Perfor-mance	200 mW Load Increase	15°C Heatsink Increase	Cooler Wearout Degrad.	EOL Perfor-mance
Focalplane Temperature	K	58	58	58	58	58
Total Cooler Cold-End Load	W	1.07	1.27	1.07	1.07	1.27
Cooler Cold-tip ΔT to FP (3 K/W)	K	3	3.4	3	3	3.4
Cooler Cold-tip Temperature (T_C)	K	55	54.6	55	55	54.6
Heat Rejection Coldplate Temp	K	290	290	305	290	305
Expander to Coldplate ΔT (0.16 K/W)	K	9.8	11.2	10.6	12.0	16.8
Comp. to Coldplate ΔT (0.05 K/W)	K	3.0	3.5	3.3	3.8	5.3
Avg. Cooler Rejection Temp (T_R)	K	296	297	312	298	316
T_C Correction for $T_R \neq$ 300K (0.17 K/K)	K	+0.7	+0.5	-2.0	+0.3	-2.7
T_C Correction for Cooler Wearout	K	0	0	0	-5.0	-5.0
Total Cold-tip Temp Correction	K	+0.7	+0.5	-2.0	-4.7	-7.7
Effective 300K Cold-tip Temp (T_{EC})	K	55.7	55.1	53.0	50.3	46.9
Cooler Specific Power at T_{EC}	W/W	57	55	62	72	83
Cooler Compressor Power (P)	W	57	67	65	75	101
Total Input Power (P/0.9 + 10)	W	73	84	82	93	122
Compressor Stroke	%	64	68	67	70	80

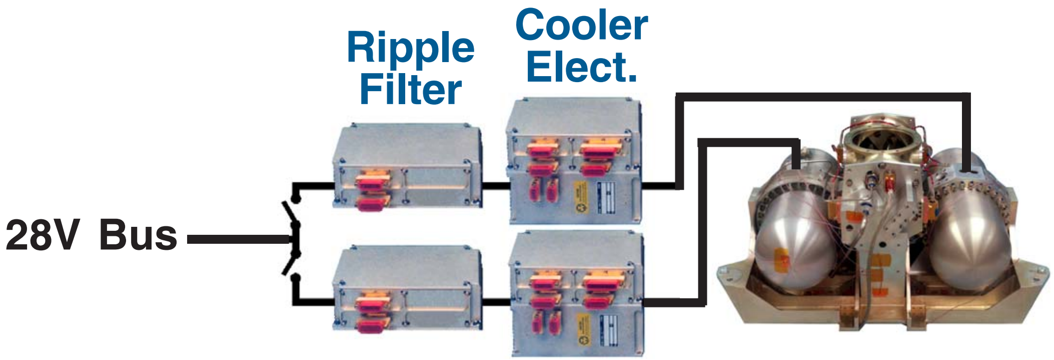
AIRS BOL/EOL Operating State Verification Analysis

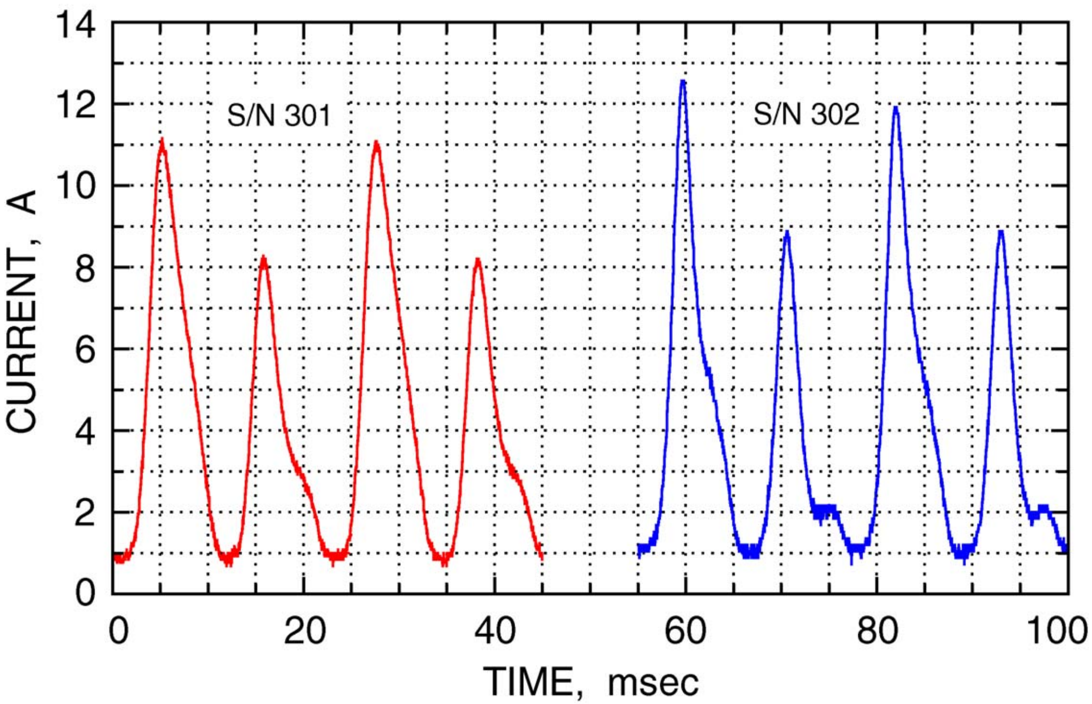


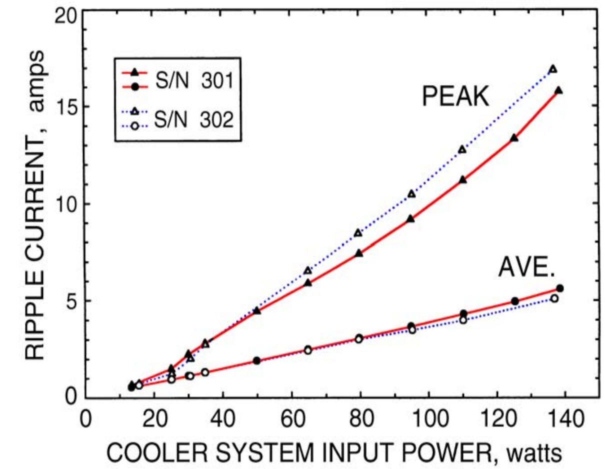
Key Cryocooler Electrical Integration Considerations

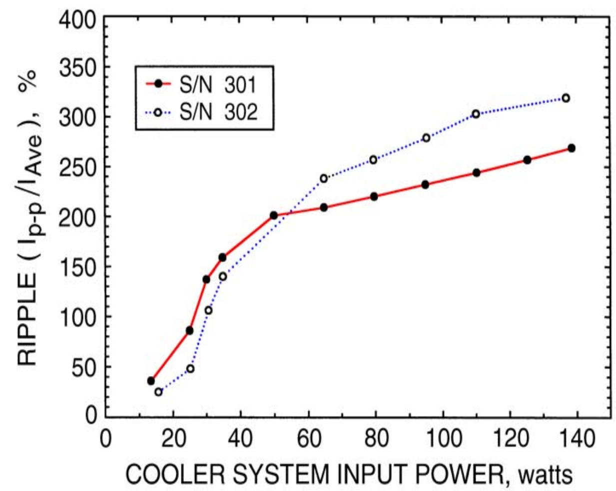
- Meet inrush and reflected ripple current requirements
- Accommodate broad input voltage ranges as compounded by high ripple current of cooler
- Suppress EMI to low levels consistent with MIL-Std 461 and accommodate MIL-Std 461 susceptibility levels
- Provide high isolation from ground loops: case isolated from ground; possible dc-dc isolation from power bus
- Provide digital data interface for communication of commands and transmission of measured parameters & performance data

AIRS Cryocooler Electronics Conducted Ripple Current



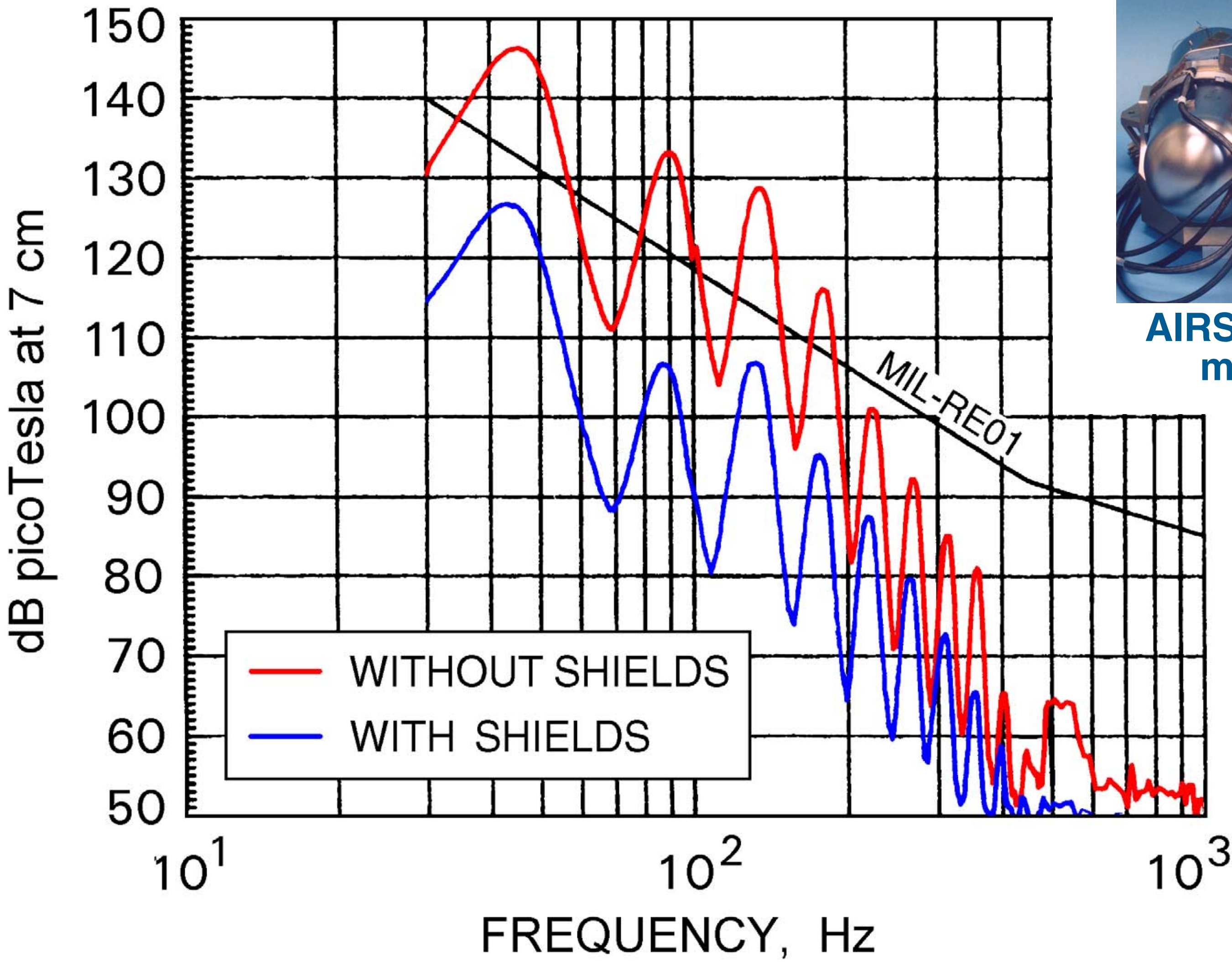


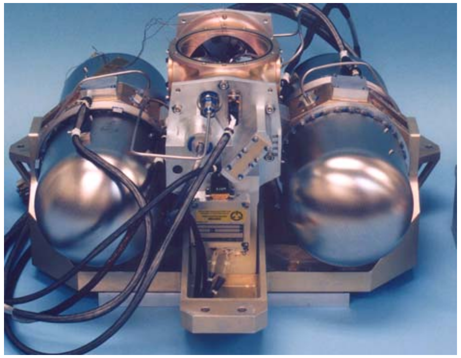




Prototype Magnetic Shields Used in Magnetic Shielding Studies

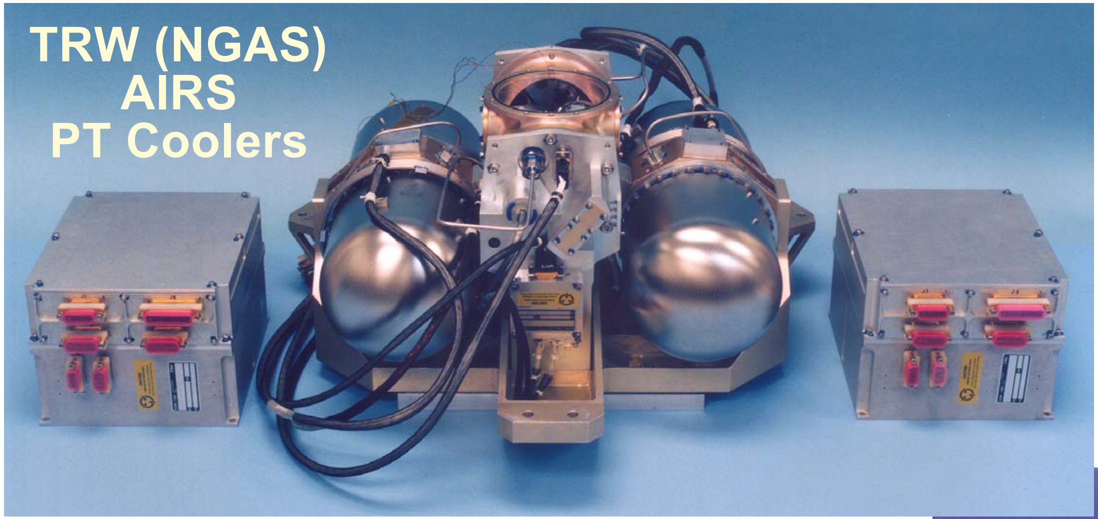
AIRS Compressor AC Magnetic Fields (With and Without Mag Shields)





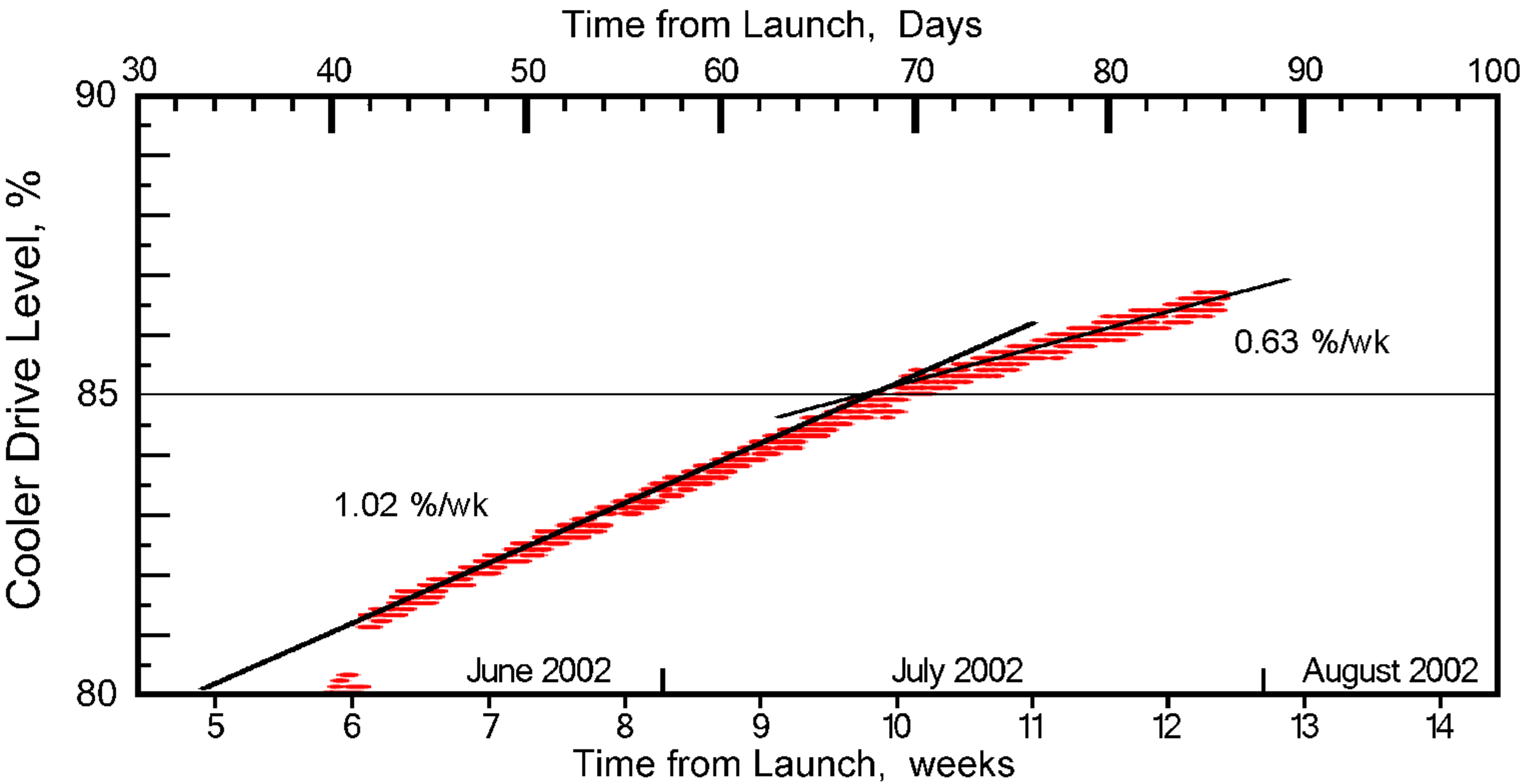
AIRS coolers with mag shields

AIRS Flight Pulse Tube Coolers

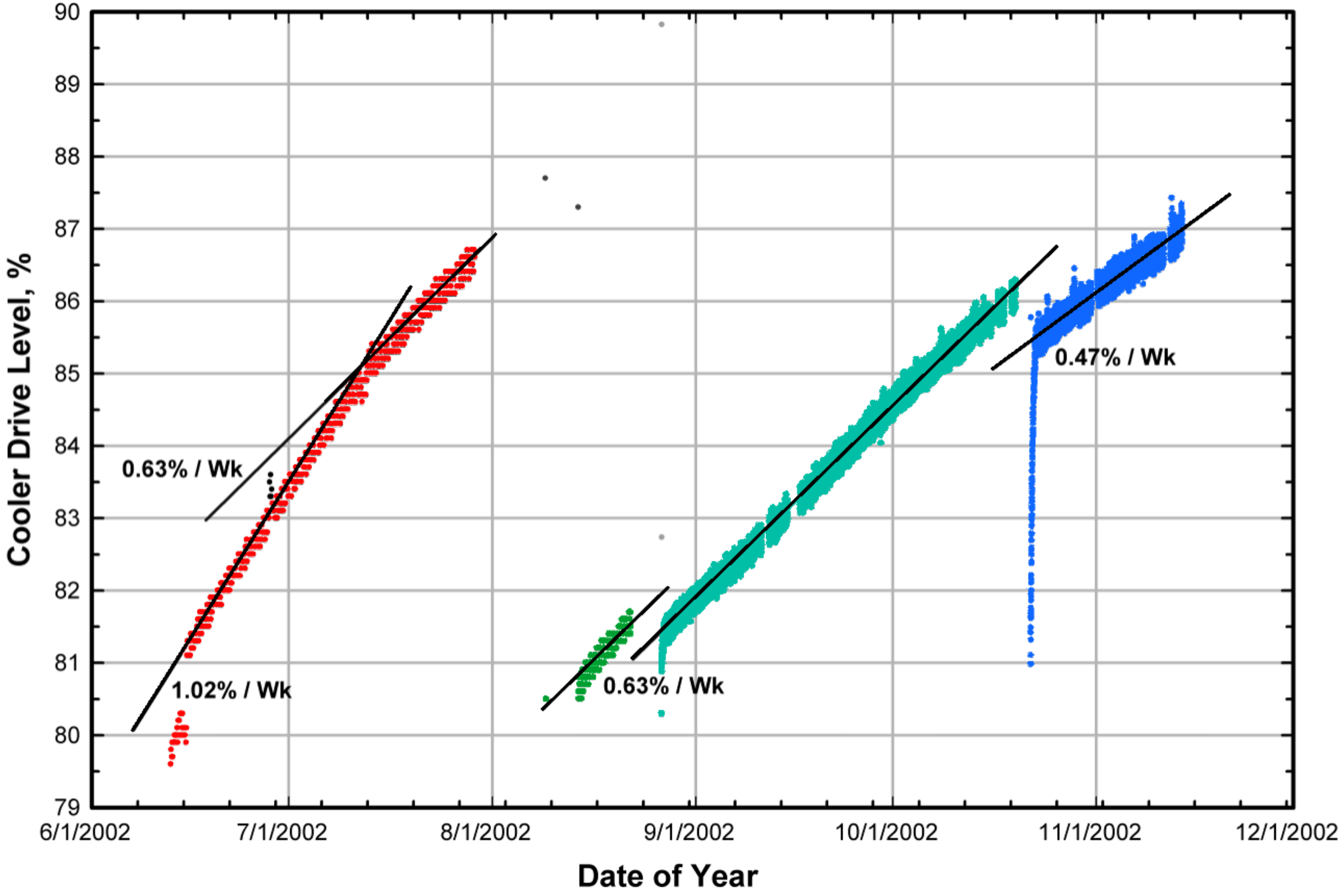


Launched on NASA Aqua Spacecraft in May 2002

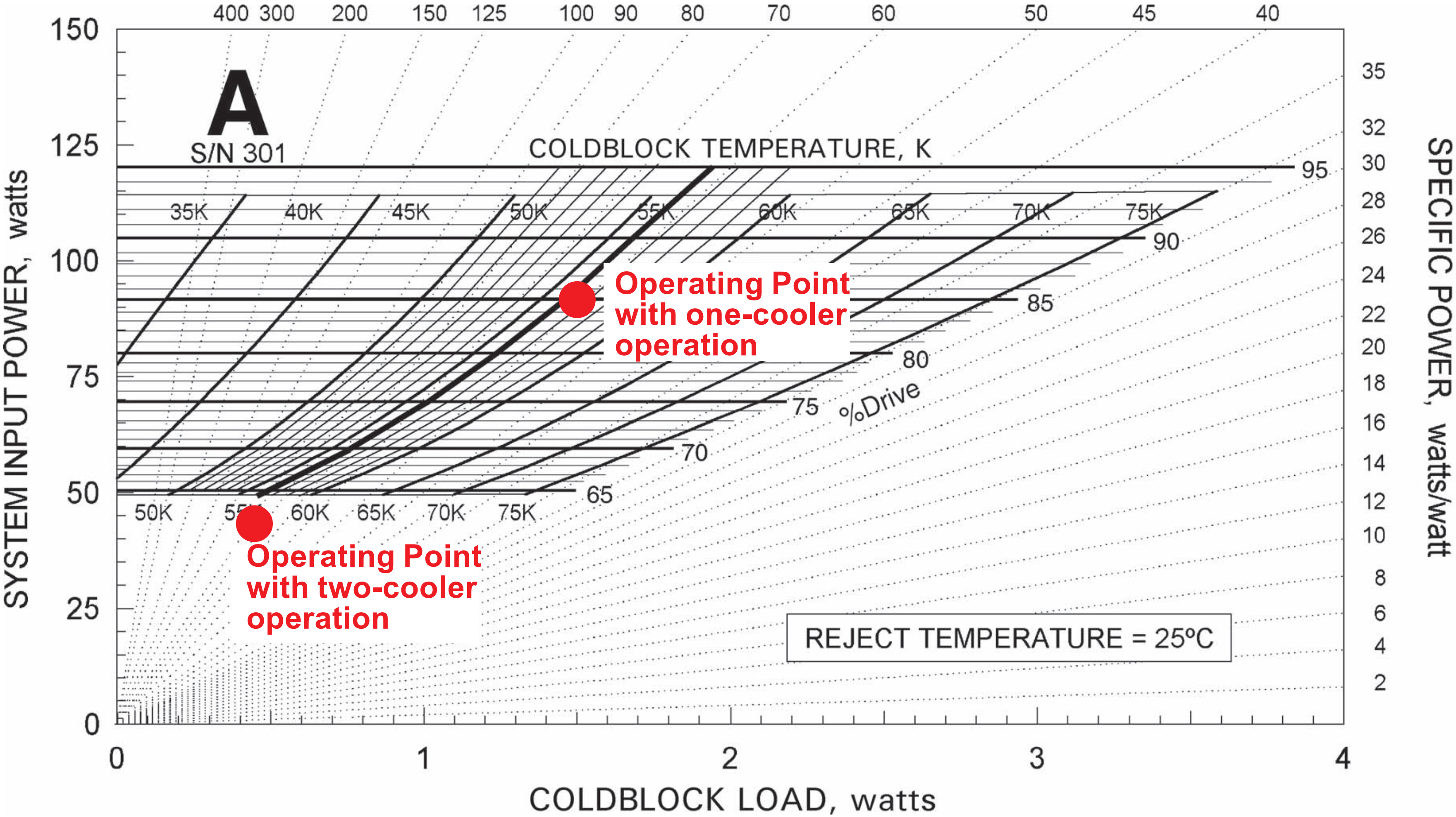
Cooler Drive Level During First 50 Days of Mission



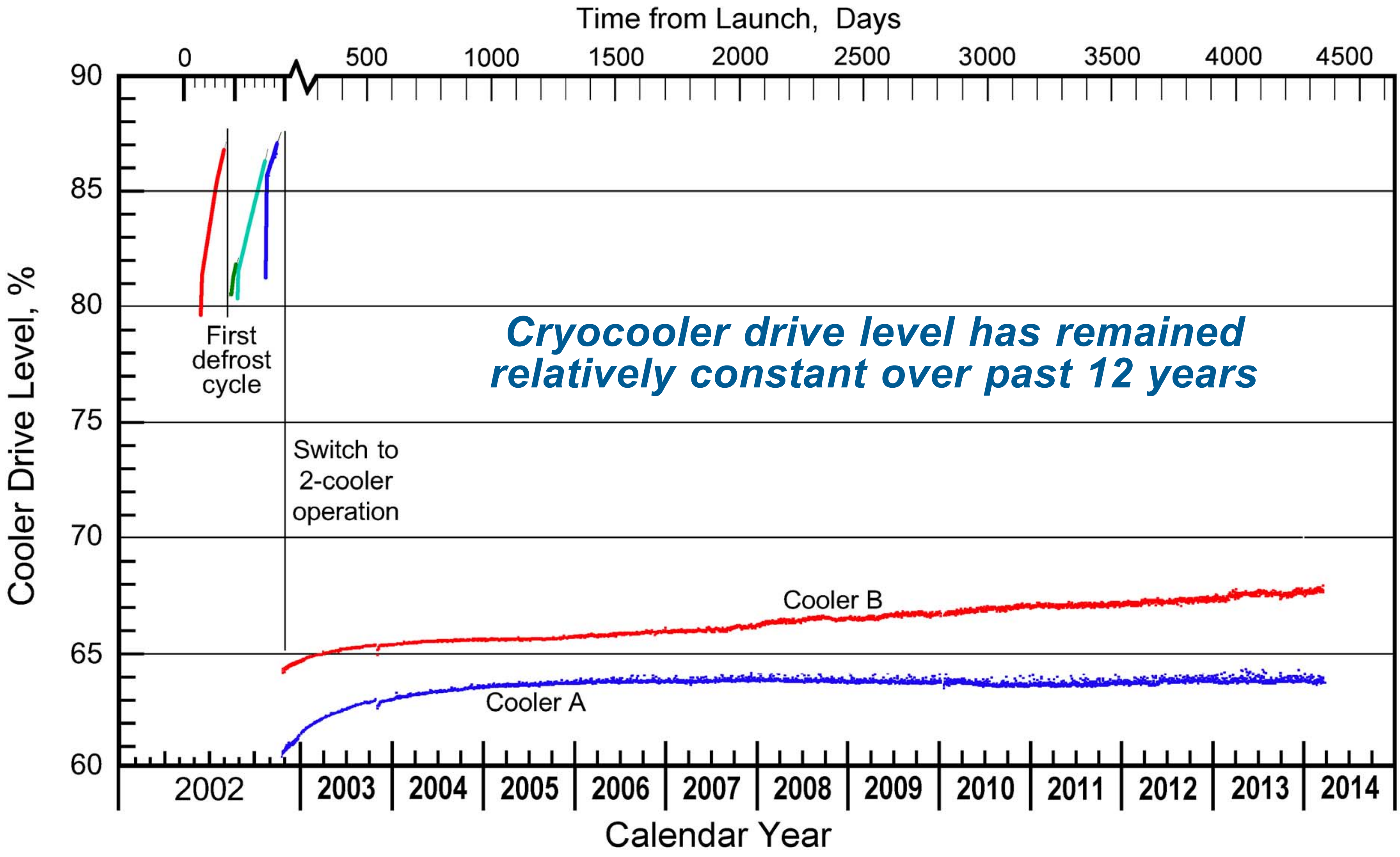
Cooler Drive Level During First 120 Days of Mission



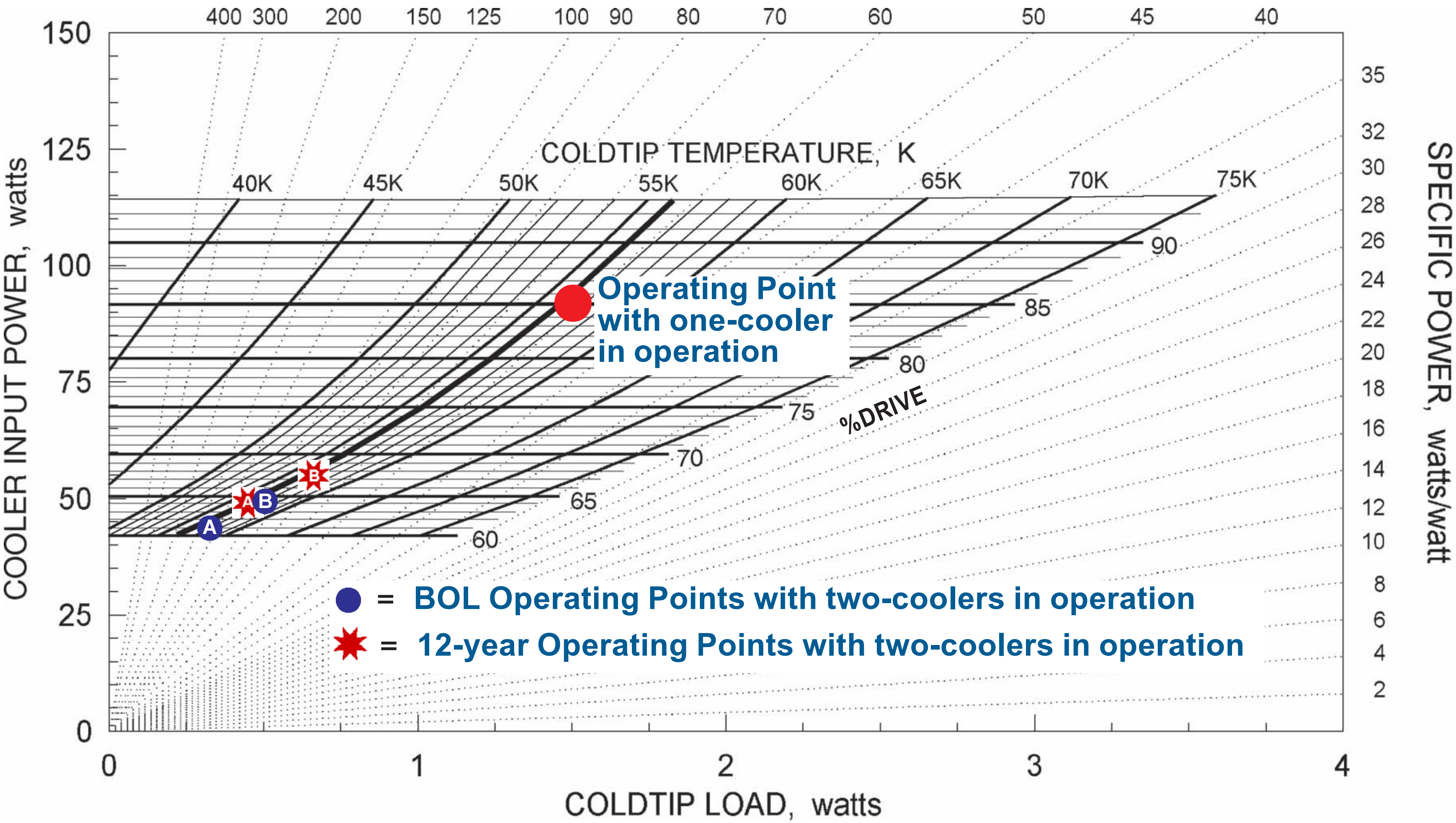
Cooler Load Point for 2-Cooler vs 1+Standby Operation



Cooler Drive Level Summary for 12 Years of Operation



AIRS Cooler Load Point Since Two-Cooler Operation Began



Summary

- **AIRS was the first space instrument to commit to a pulse tube cryocooler and served as a very successful example**
  - **Cooler performance characterization**
  - **Dealing with Heat Rejection and Coldlink design**
  - **Achieving tolerable generated vibration and EMI levels**
- **During the 20 years since the AIRS conceptual design was developed, we've learned a great deal more about a number of integration challenges:**
  - **Two-cooler operational redundancy trade-offs**
  - **Space vacuum levels and contamination sensitivity**
  - **Cryo MLI performance**
  - **Internal ripple current suppression**
  - **Lighter and more efficient 2-stage coolers that can accommodate both the 150K optical bench load and the 58 K focal plane load**
- **Bottom Line: Space cryocoolers continue to evolve and we continue to learn how to improve their system performance**