Cryocoolers for Space Applications #3

R.G. Ross, Jr.

Jet Propulsion Laboratory
California Institute of Technology

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

- Cryocooler Technical Performance Data Requirements
  - Operating needs of typical space detectors
  - Space cryocooler technology and reliability challenges
- Thermal Performance Measurements
  - Example performance & parameter dependencies
  - Spatial distribution of power dissipation
- Effect of Pulse Tube Gravity Orientation on Performance
- Generated Vibration and Vibration Suppression Techniques
- Launch Survivability
- Electrical Interface Compatibility
  - Magnetic and electric fields
  - Inrush and reflected ripple current

References

- Ross, R.G., Jr., "Chapter 11: Cryocooler Performance Characterization," *Spacecraft Thermal Control Handbook, Vol. II: Cryogenics*, The Aerospace Press, El Segundo, CA, (2003) pp. 217-261. (23 references).
- Ross, R.G., Jr. and Johnson, D.L., "Effect of Heat Rejection Conditions on Cryocooler Operational Stability," *Advances in Cryogenic Engineering*, Vol. 43B (1998), pp. 1745-1752.
- Ross, R.G., Jr., Johnson, D.L. and Rodriguez, "Effect of Gravity Orientation on the Thermal Performance of Stirling-type Pulse Tube Cryocoolers," *Cryogenics*, Vol. 44, Issue: 6-8, June - August, 2004, pp. 403-408.
- Ross, R.G., Jr., "Vibration Suppression of Advanced Space Cryocoolers — An Overview," *Proceedings of the International Society of Optical Engineering (SPIE) Conference*, San Diego, CA, March 2-6, 2003.

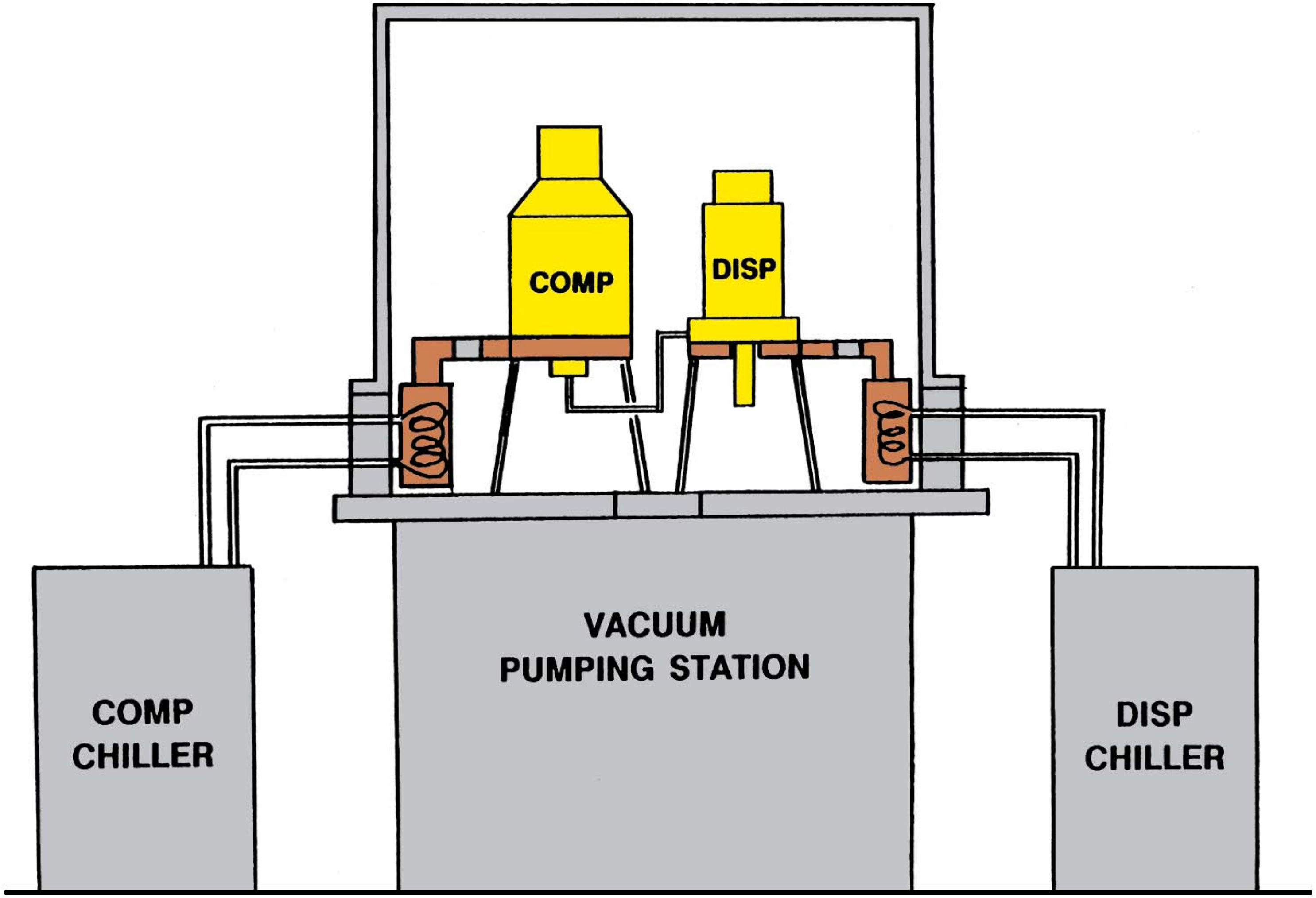
References (Con't)

- Johnson, D.L., Collins, S.A. and Ross, R.G., Jr., "EMI Performance of the AIRS Cooler and Electronics," *Cryocoolers 10*, Plenum Publishing Corp., New York, 1999, pp. 771-780.
- Ross, R.G., Jr., "Chapter 6: Refrigeration Systems for Achieving Cryogenic Temperatures," *Low Temperature Materials and Mechanisms*, Y. Bar-Cohen (Ed.), CRC Press, Boca Raton, FL (Scheduled to be published in Nov. 2015). (79 references)
- Ross, R.G., Jr., "Appendix A: Constructing a Cryocooler Multiparameter Plot," *Spacecraft Thermal Control Handbook, Vol. II: Cryogenics*, The Aerospace Press, El Segundo, CA, (2003) pp. 605-608.
- http://www2.jpl.nasa.gov/adv_tech/ JPL website with 103 JPL cryocooler references as PDFs (R. Ross, webmaster)

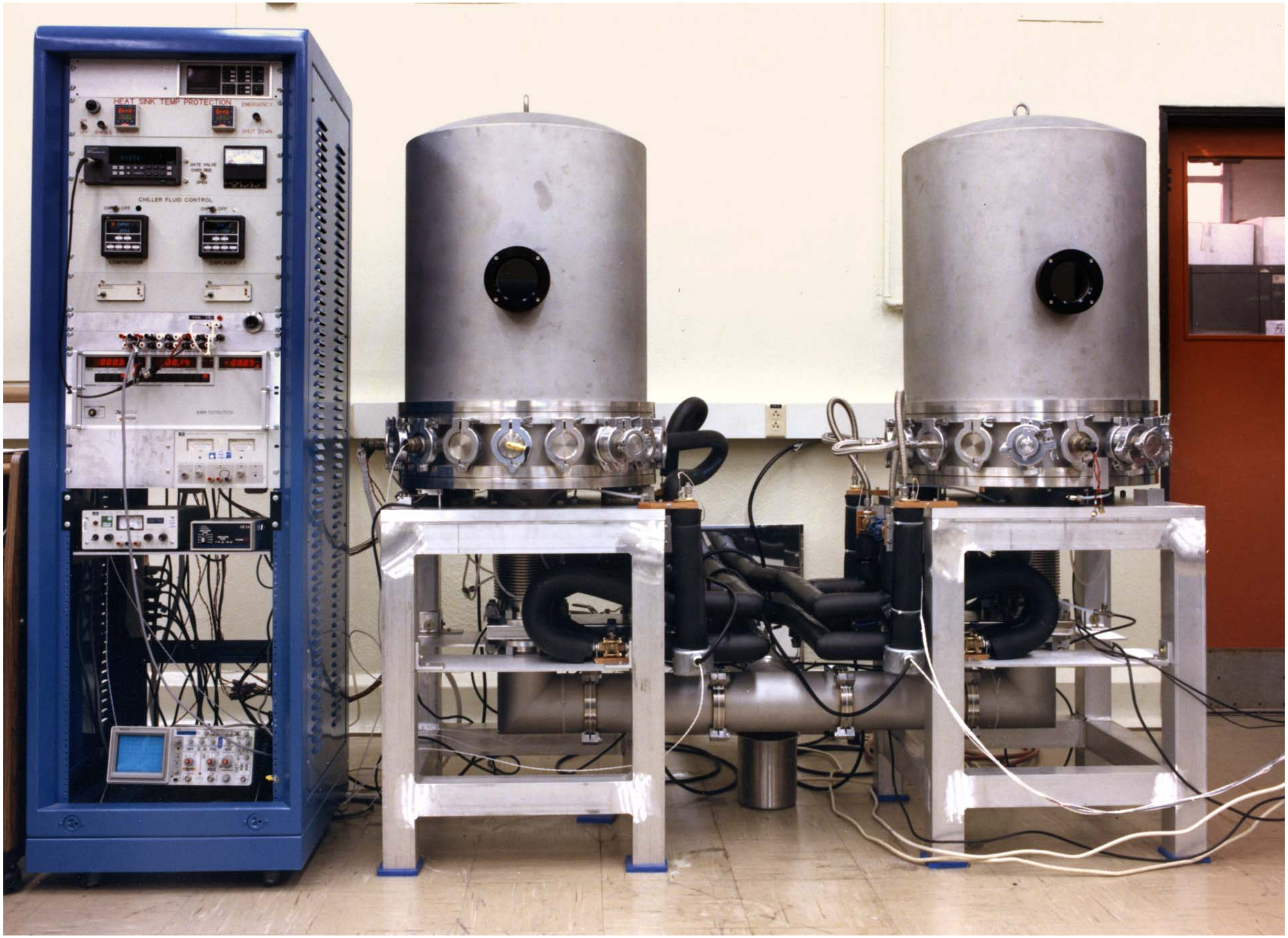
Typical Cryocooler Performance Data Requirements

- **THERMAL PERFORMANCE**
  - Complete parametric thermal performance map including compressor stroke, expander stroke, coldtip temperature, input power, coldtip load, and compressor and expander reject temperature
  - Compressor and expander heat dissipation fractions and thermal resistances from source to heat sink
  - Cooler electronics input power vs compressor input power
- **ALLOWABLE HEATSINK TEMPERATURE RANGE**
- **EMI PERFORMANCE**
  - Mil Std 461 AC and DC magnetic and electric fields
  - Reflected ripple current
- **GENERATED VIBRATION (vs axis and suppression system mode)**
- **LAUNCH VIBRATION SURVIVABILITY (with interface mass on cold finger; with piston motion suppression?)**

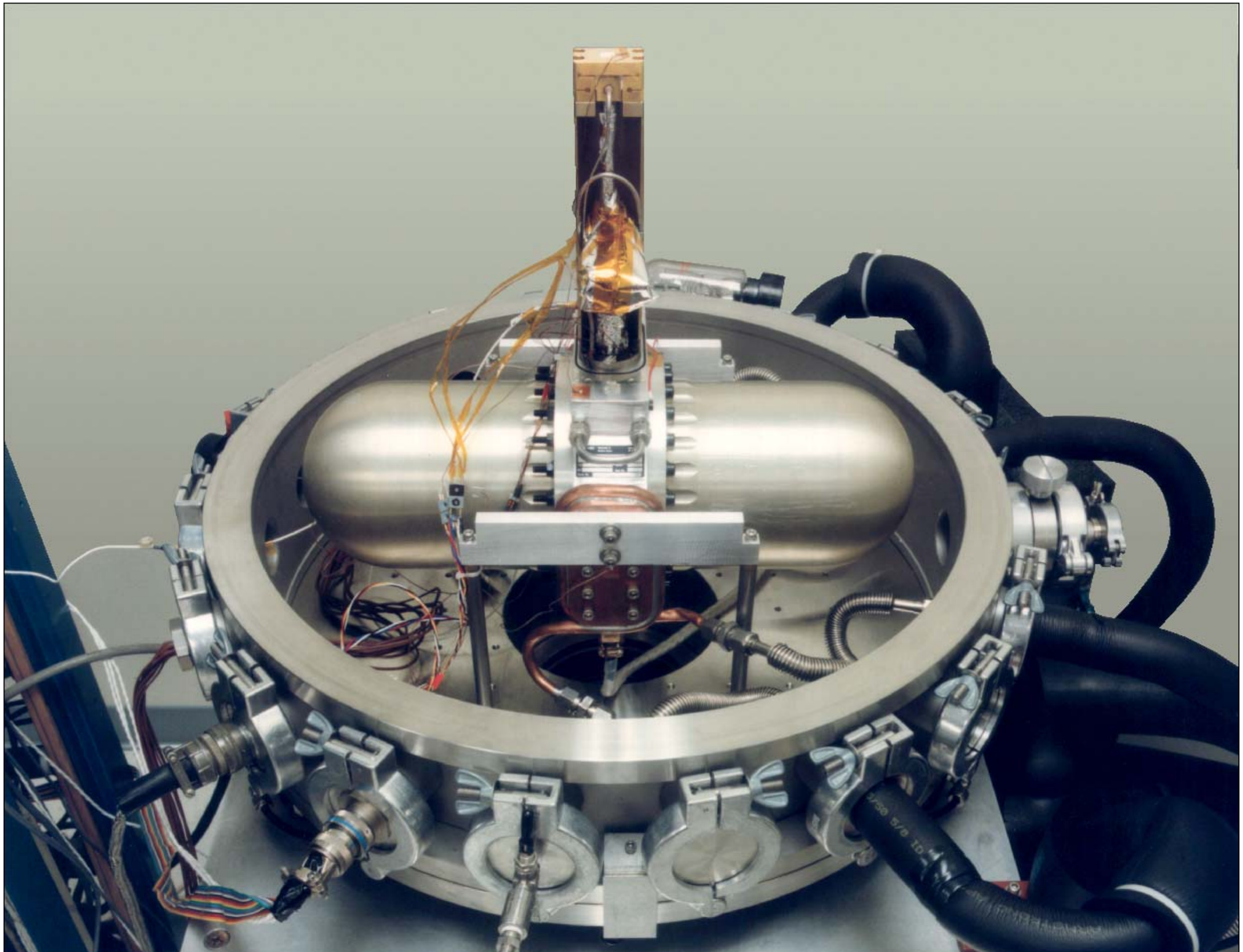
Functional Schematic



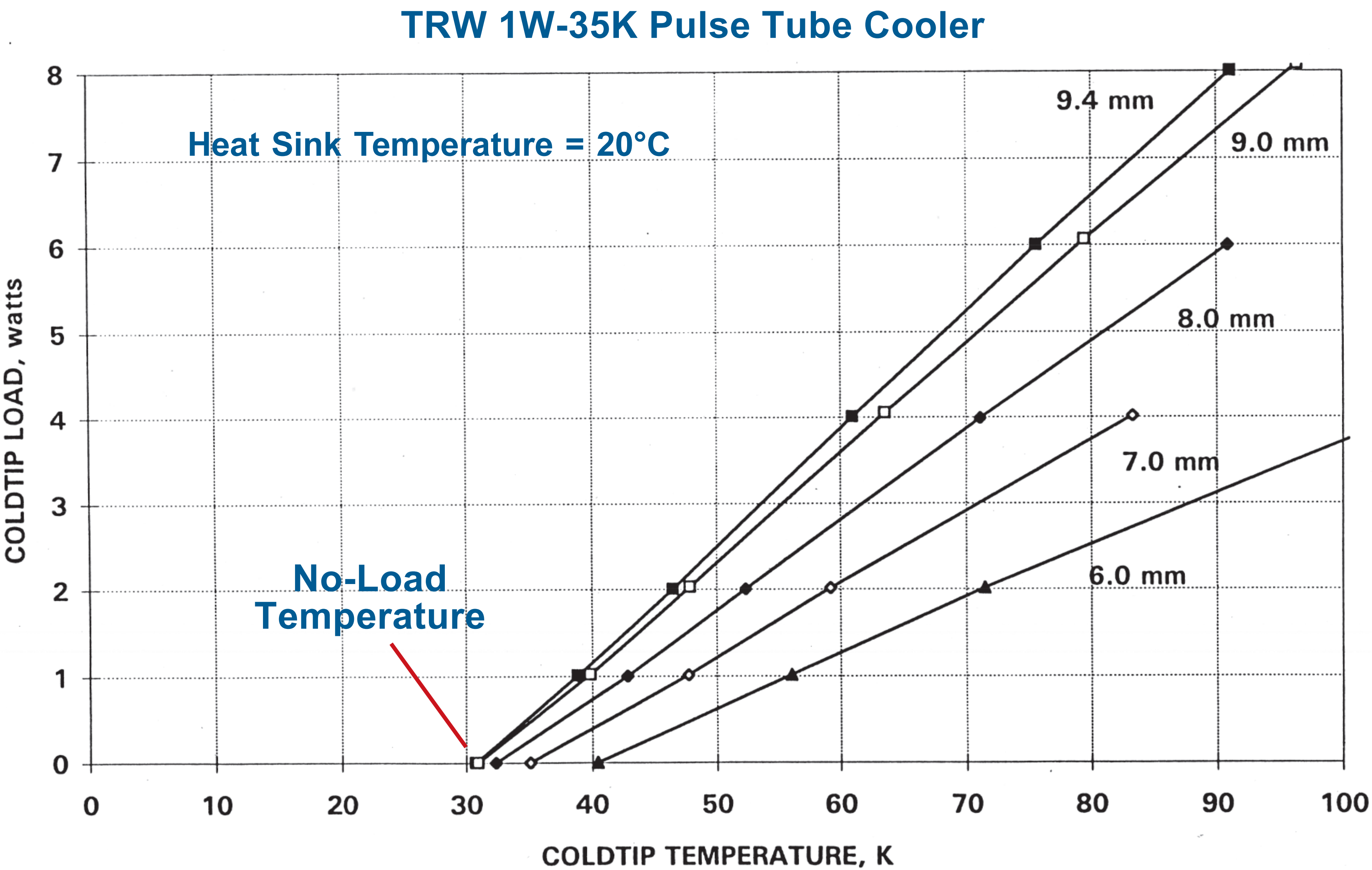
JPL Cryocooler Thermal-Vacuum Characterization and Lifetest Chambers



TRW 1W-35K Pulse Tube Cryocooler during Thermal Testing at JPL

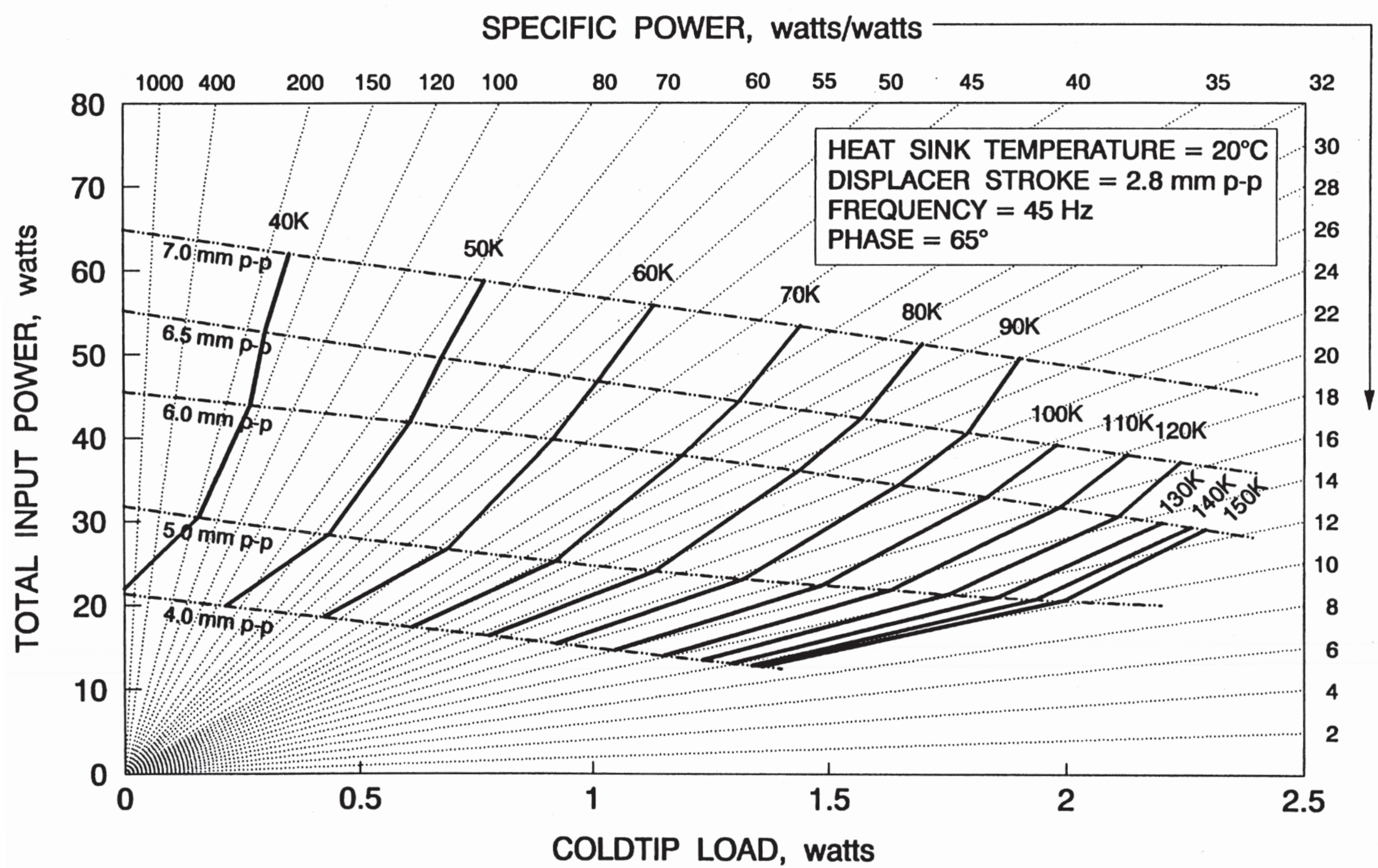


Sensitivity of Thermal Performance to Compressor Stroke



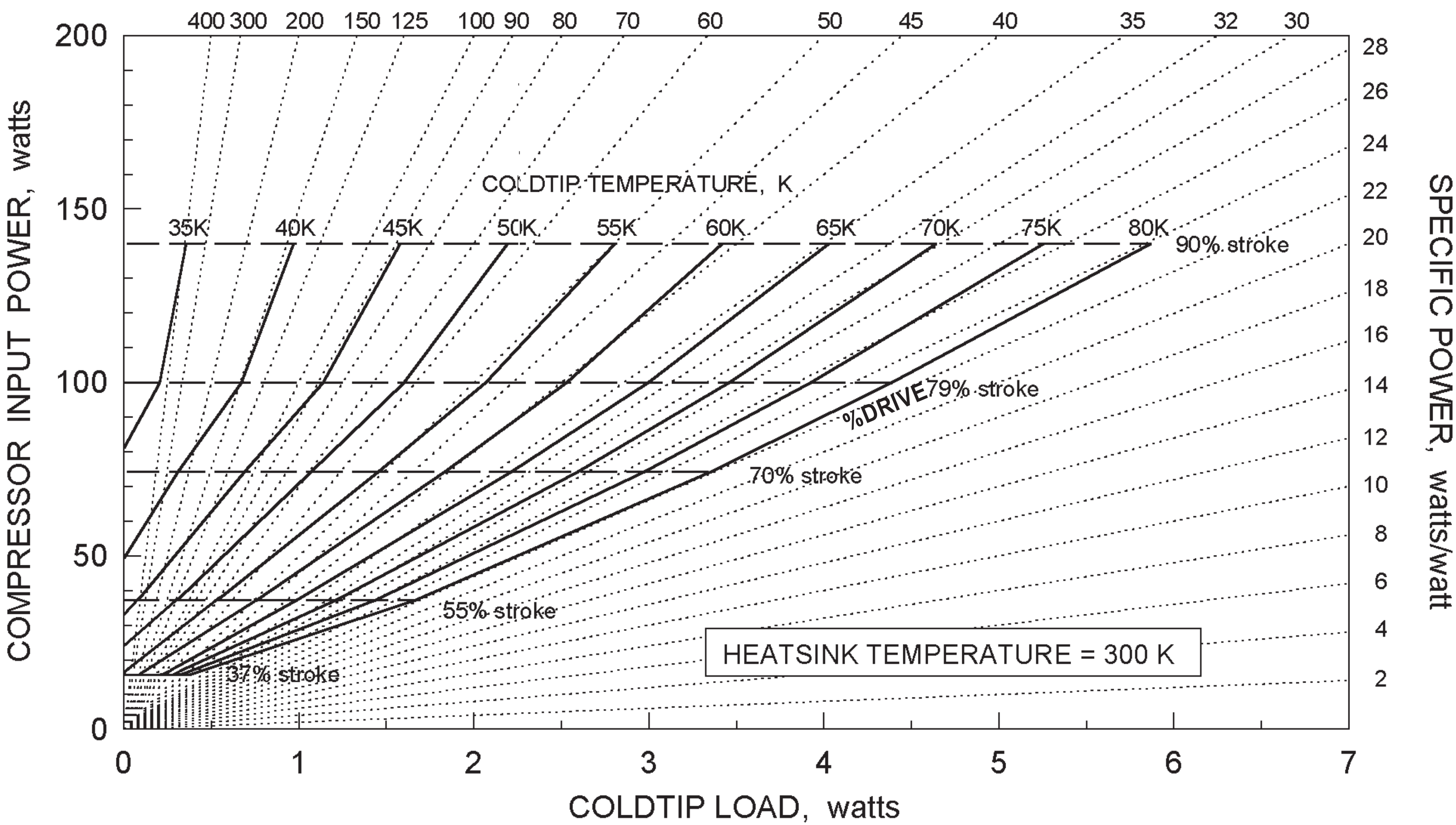
Sensitivity of Thermal Performance to Compressor Stroke

BAe 50 to 80 K Stirling Cryocooler



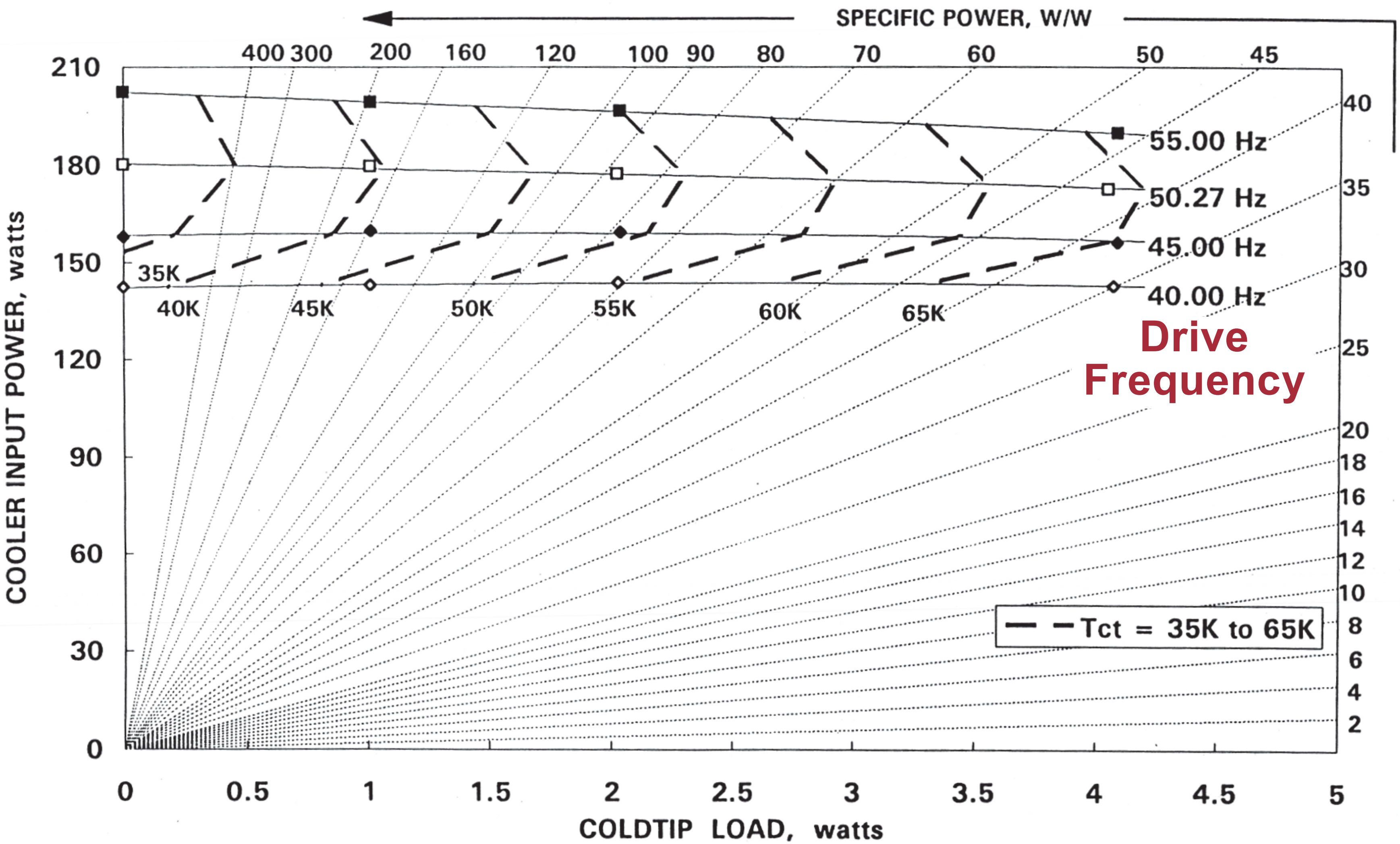
Sensitivity of Thermal Performance to Compressor Stroke

AIRS 55K Pulse Tube Cryocooler



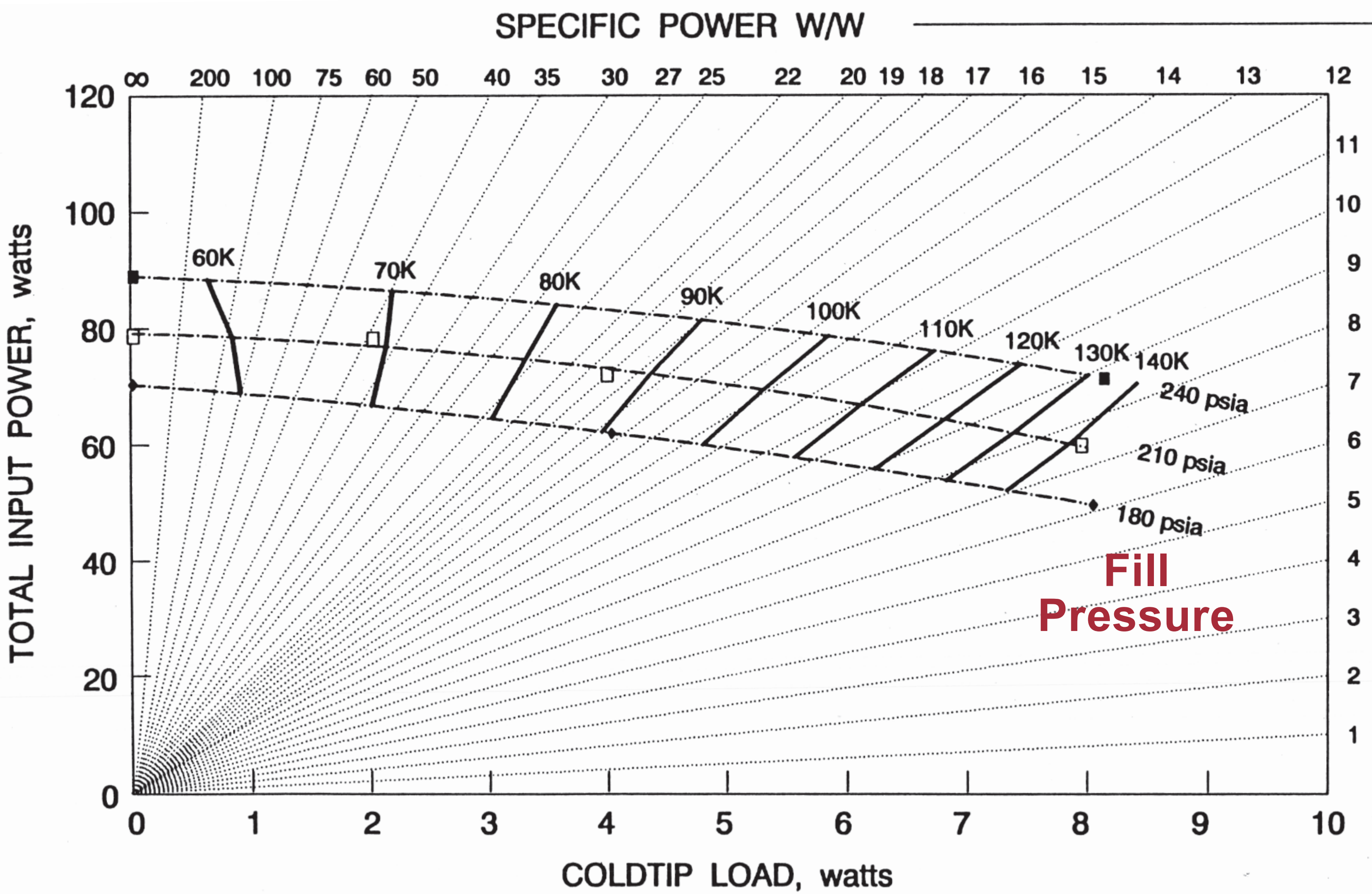
Sensitivity of Thermal Performance to Drive Frequency

TRW 1W-35K Pulse Tube Cooler



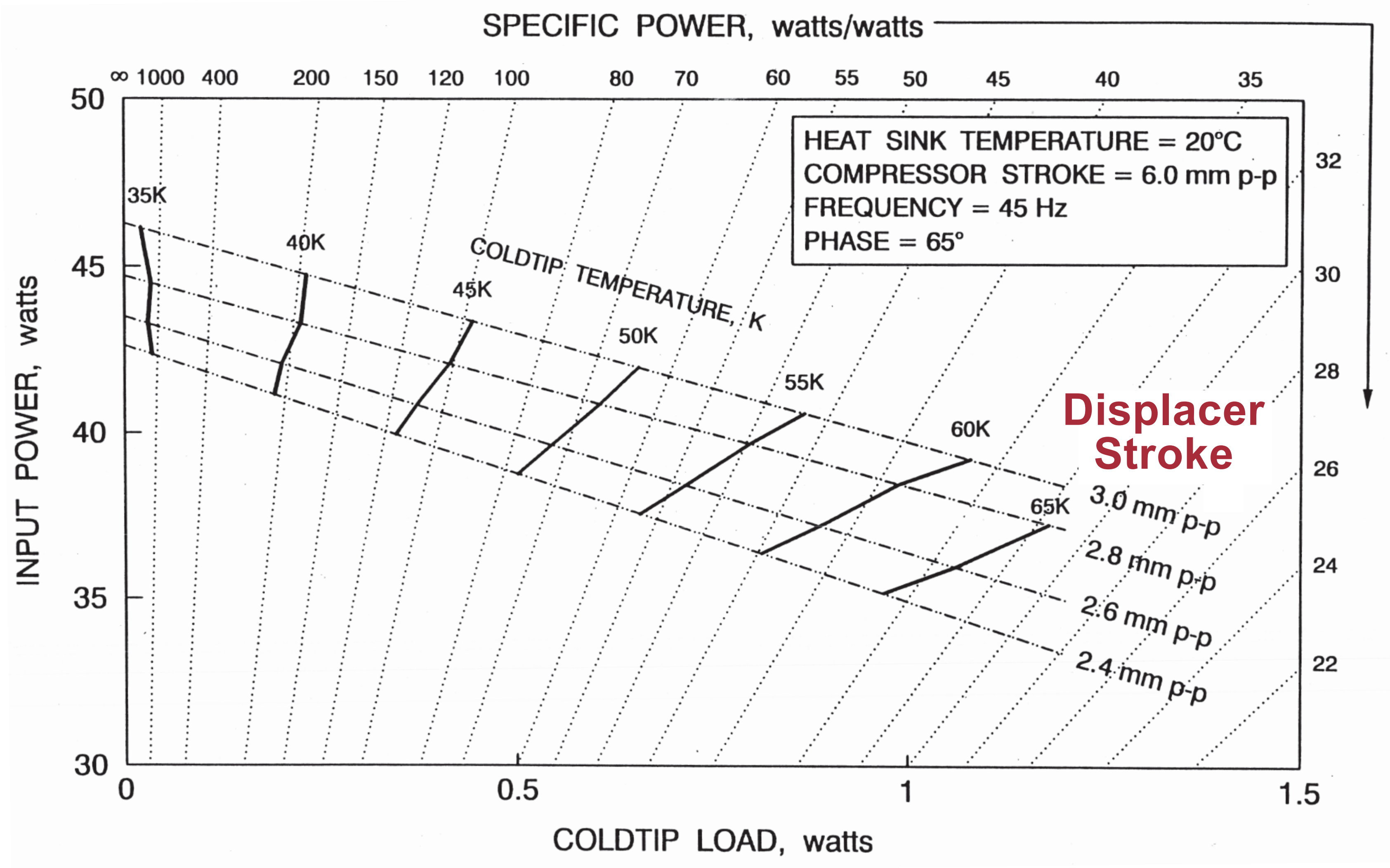
Sensitivity of Thermal Performance to Fill Pressure

Stirling Technology 80K Stirling Cooler



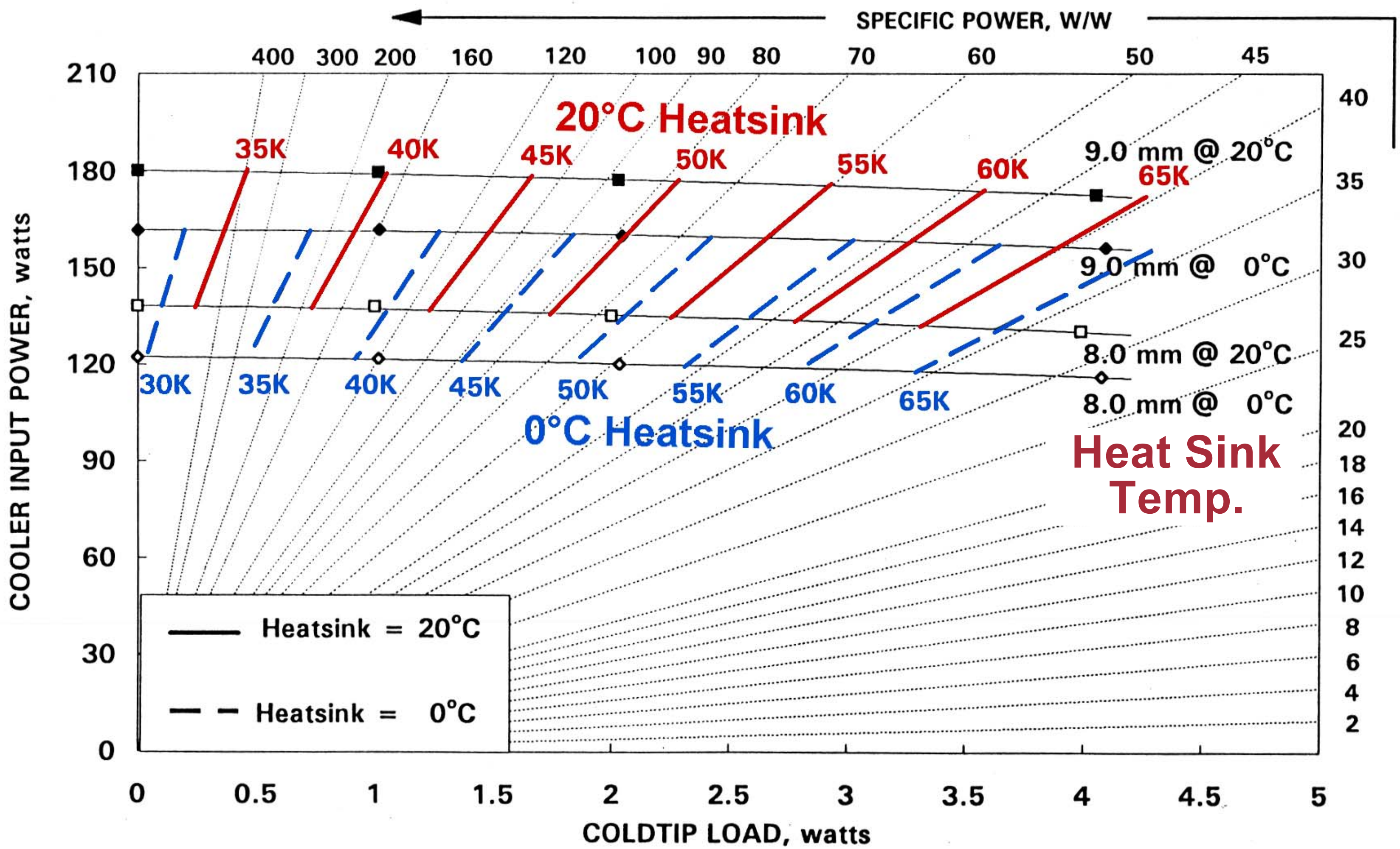
Sensitivity of Thermal Performance to Displacer Stroke

BAe 50 to 80 K Stirling Cryocooler



Sensitivity of Thermal Performance to Heat Sink Temperature

TRW 1W-35K Pulse Tube Cooler



Algorithm for Predicting Effect of Heatsink Temperature Change

Based on the empirically derived findings, one can derive the cooling power $P(T_A, \Theta_A)$ at heatsink temperature T_A and coldend temperature Θ_A and as equal to the cooling power $P(T_0, \Theta_B)$ at the baseline heatsink temperature T_0 and coldend temperature Θ_B , i.e.

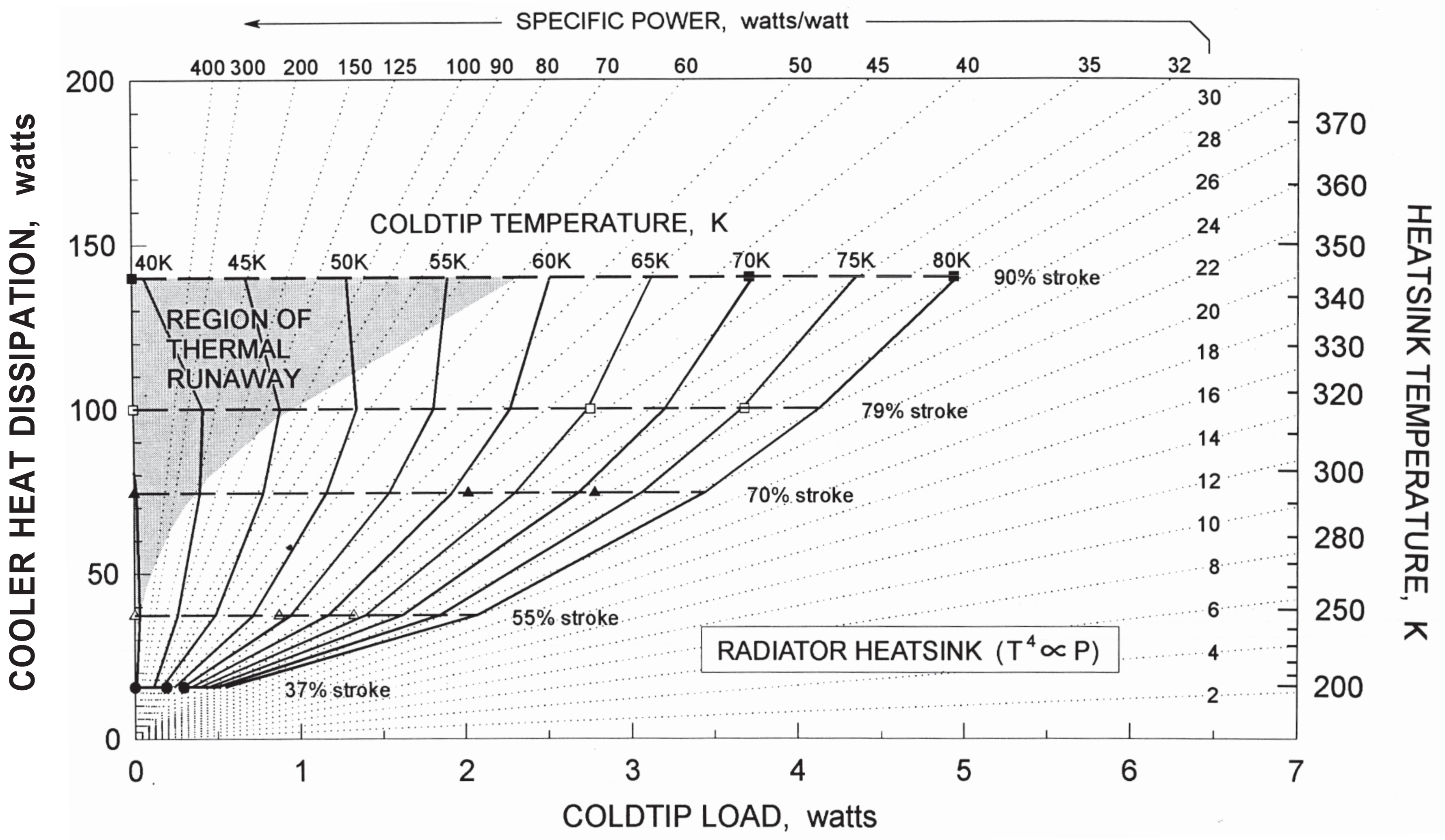
$$P(T_A, \Theta_A) = P(T_0, \Theta_B); \quad \text{where } \Theta_B = \Theta_A - (T_A - T_0)/\Re$$

where

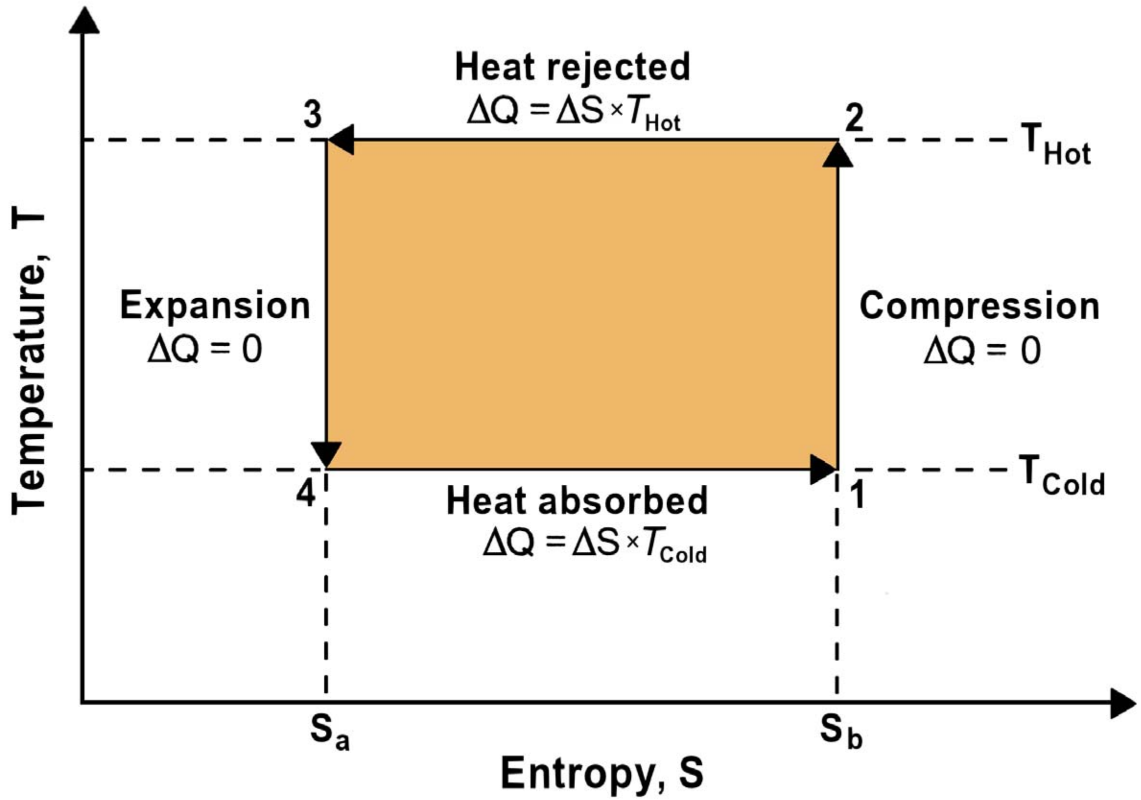
- T_A = Operating heatsink temperature (°C)
- Θ_A = Operating Coldtip temperature (K)
- T_0 = Reference heatsink temperature (°C)
- Θ_B = Effective Coldtip temperature (K) at Ref heatsink temp (T_0)
- $\Re$ = Measured change in heatsink temperature required to shift the coldend performance by 1 K. $\Re \approx 5$ to 7 for many coolers

Ref: Ross, R.G., Jr. and Johnson, D.L., "Effect of Heat Rejection Conditions on Cryocooler Operational Stability," *Advances in Cryogenic Engineering*, Vol. 43B (1998), pp. 1745-1752.

Thermal Performance Plot for Direct Mount to Radiator



The Carnot Refrigeration Cycle and its Efficiency



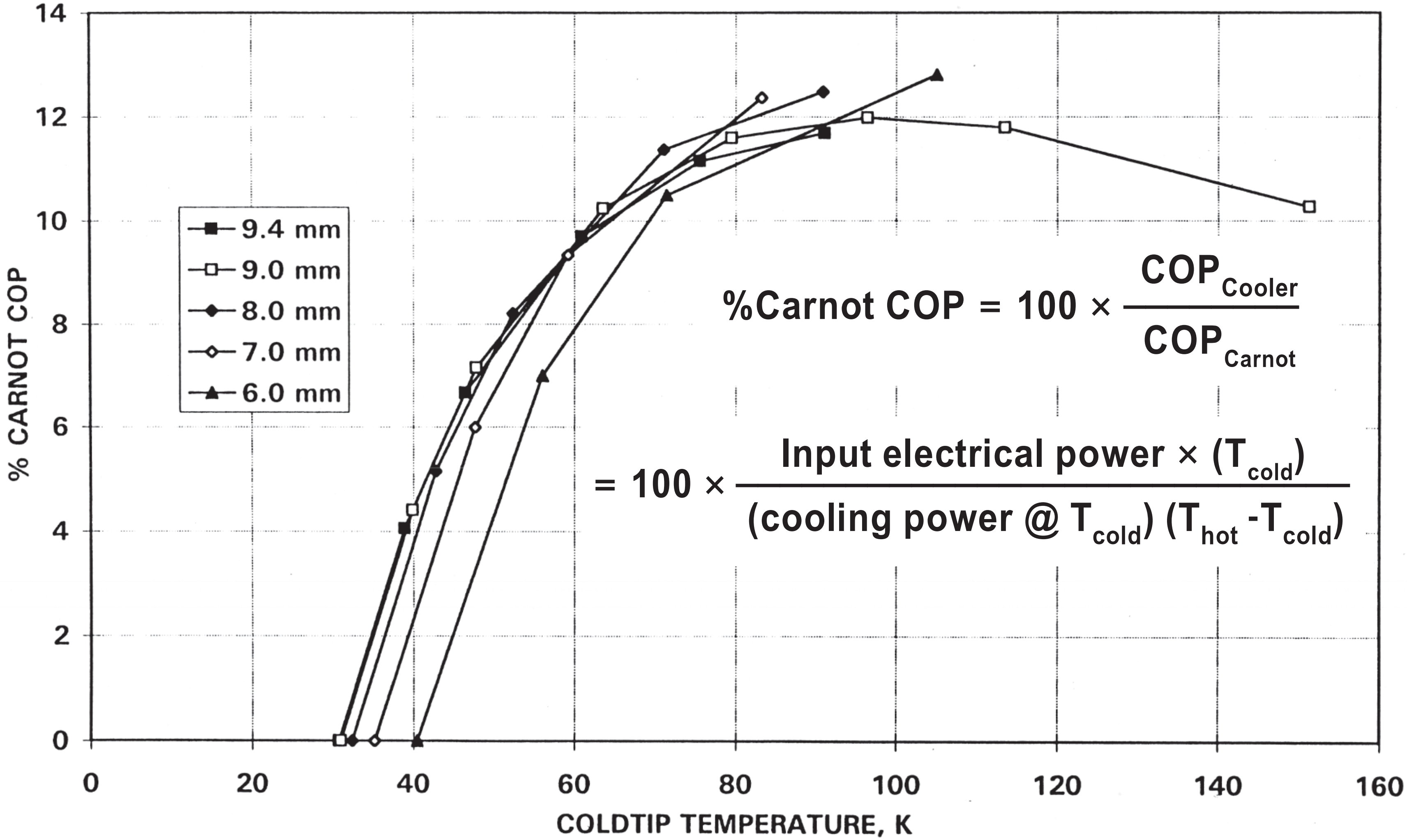
COP_{Cooler} = cooling power / input power

COP_{Cooler} = heat absorb / (heat reject - heat absorb)

$$COP_{Carnot} = T_{cold} / (T_{hot} - T_{cold})$$

Sensitivity of %Carnot COP to Compressor Stroke

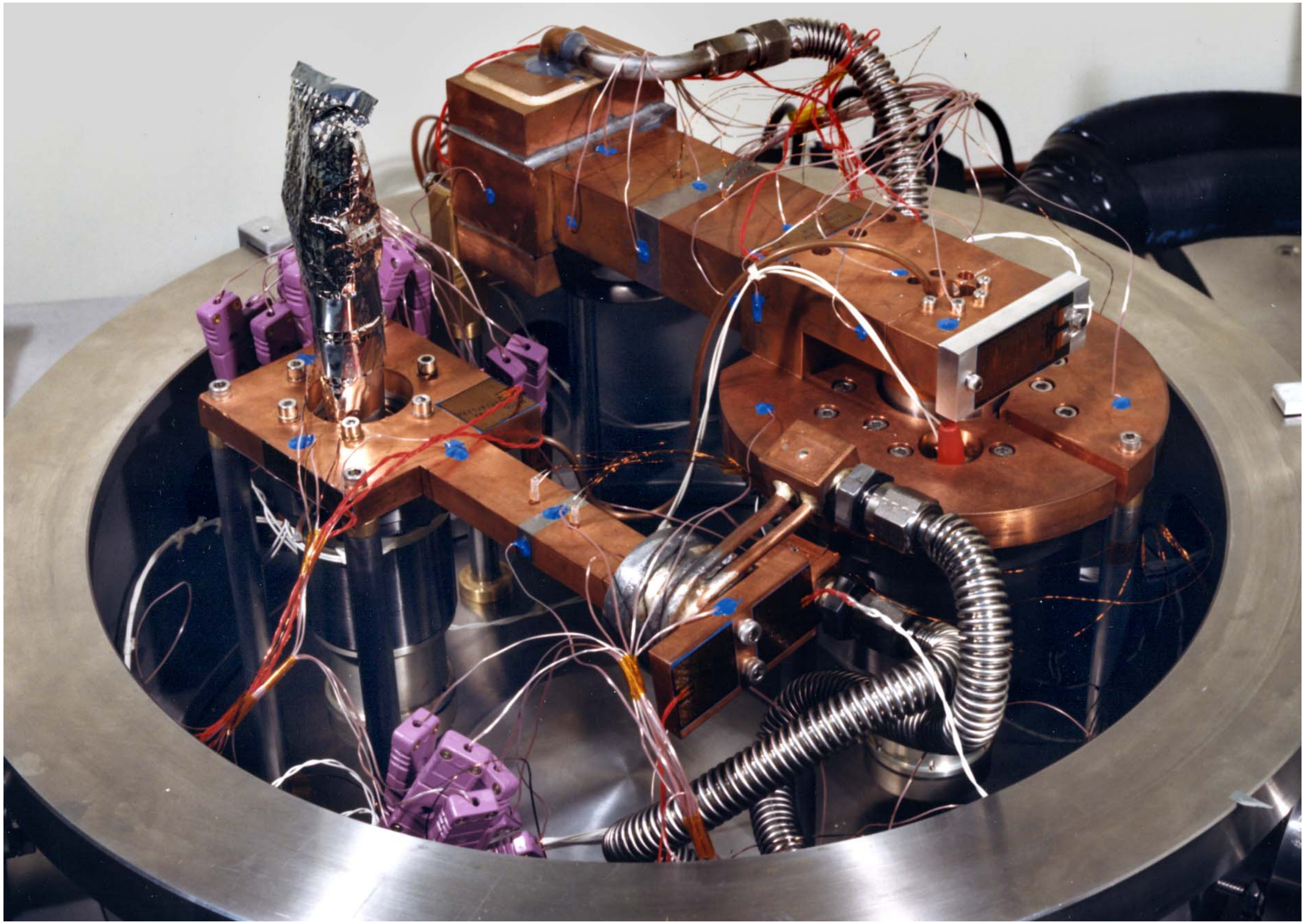
TRW 1W-35K Pulse Tube Cooler



$$\%\text{Carnot COP} = 100 \times \frac{COP_{Cooler}}{COP_{Carnot}}$$

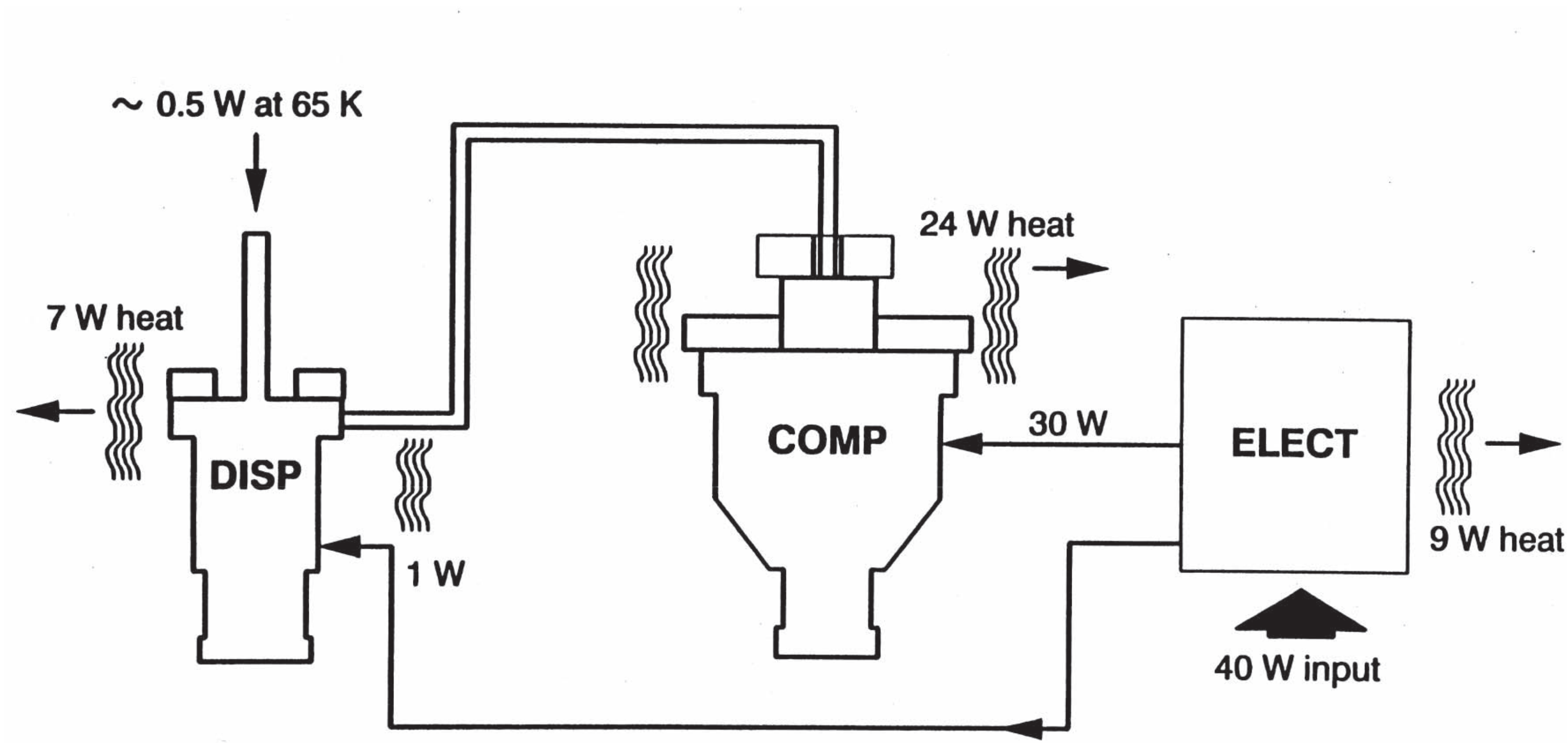
$$= 100 \times \frac{\text{Input electrical power} \times (T_{cold})}{(\text{cooling power @ } T_{cold})\,(T_{hot} - T_{cold})}$$

BAe 80 K Stirling Cryocooler



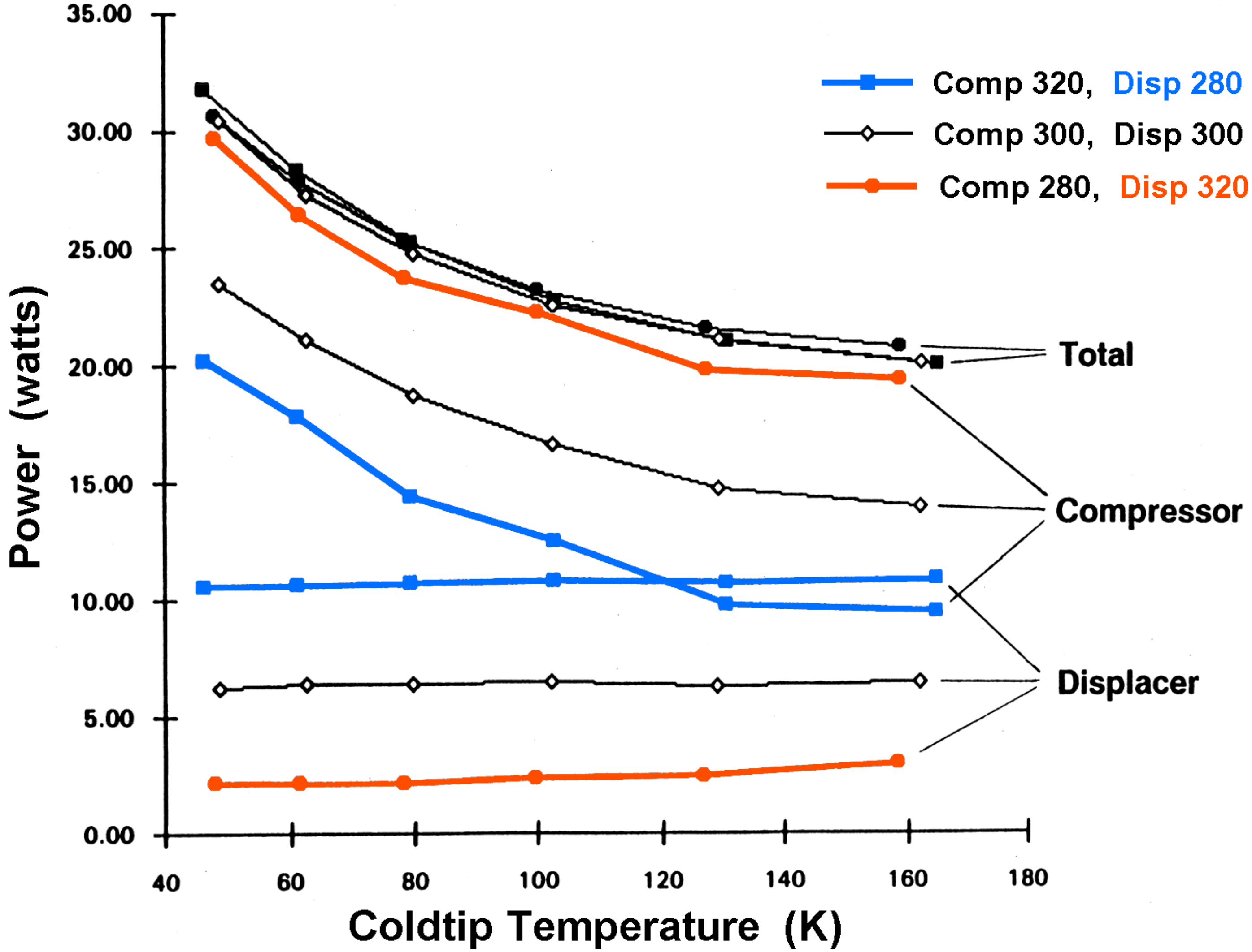
Stirling Cooler Input Power and Thermal Dissipation Characteristics

BAe 80 K Stirling Cryocooler

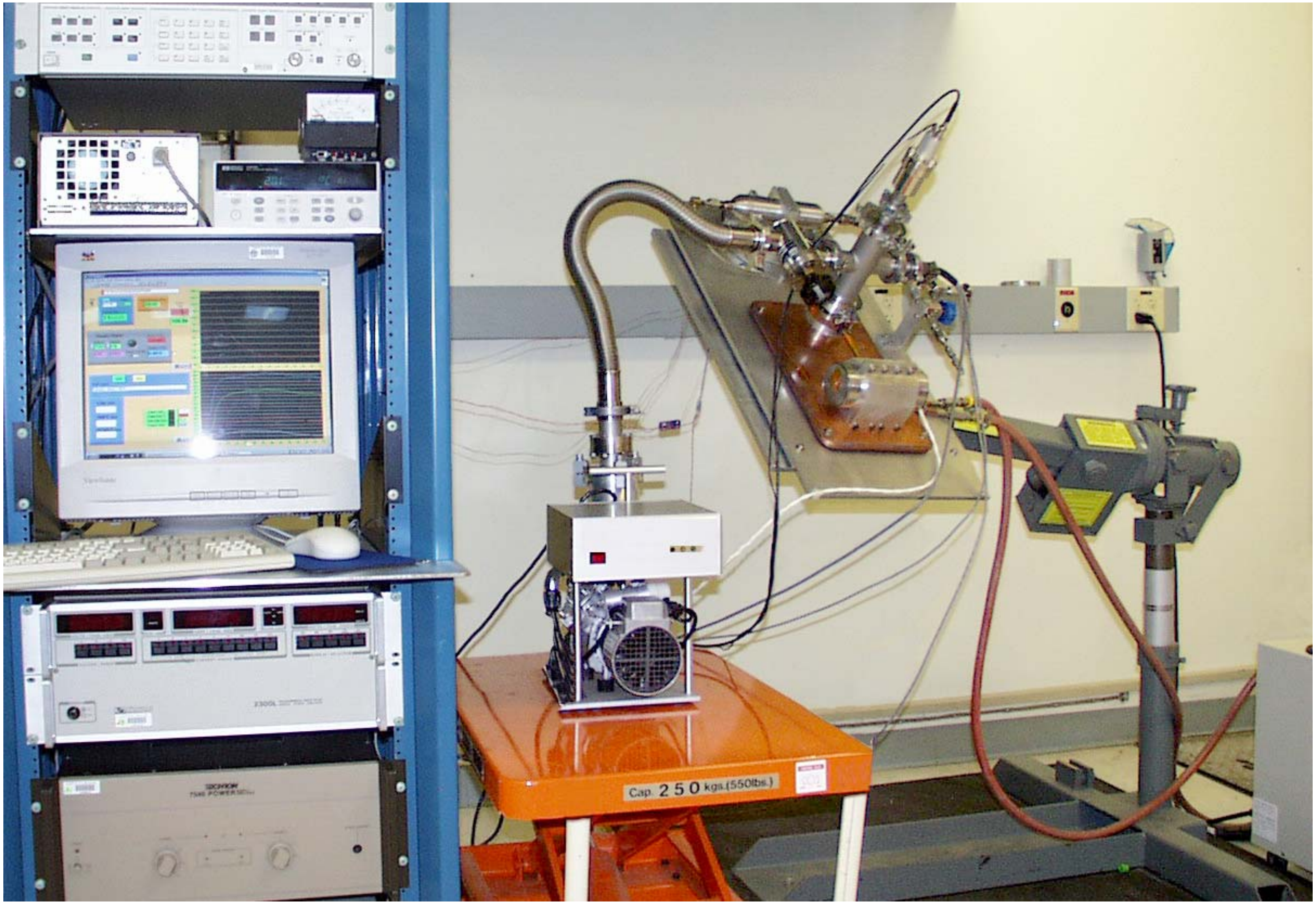


Effect of Heatsink Temperatures on Heat Rejection Location

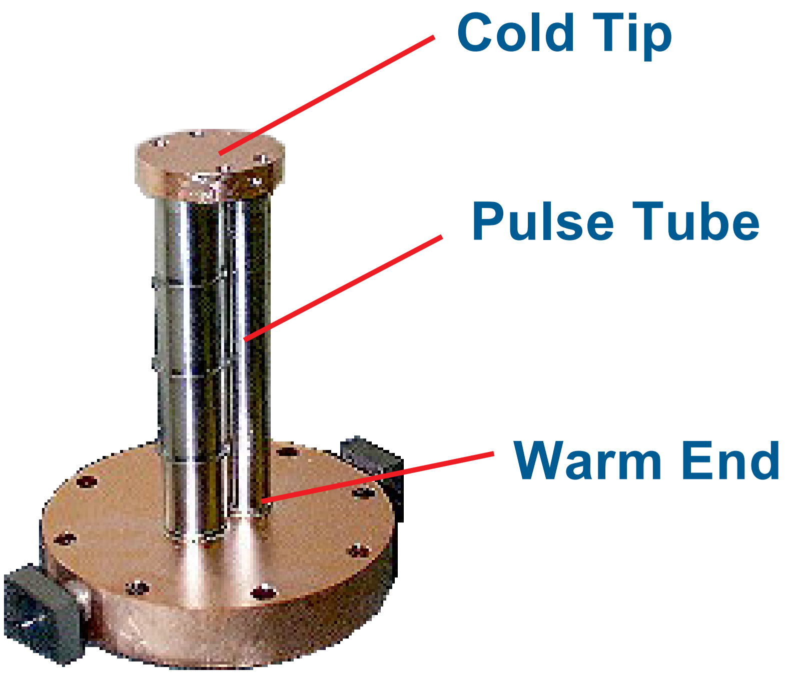
BAe 80 K Stirling Cryocooler

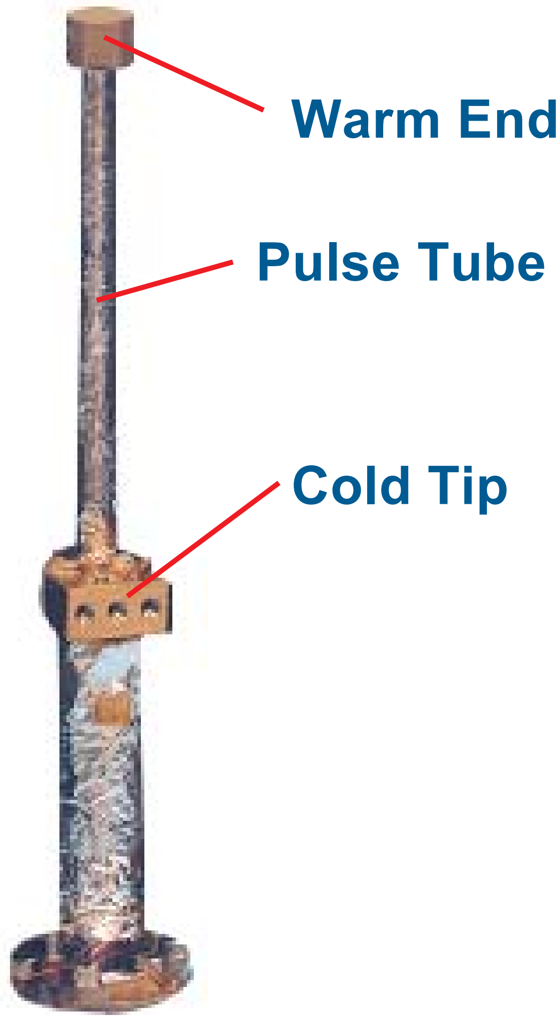


Effect of Gravity Orientation on Pulse Tube Thermal Performance

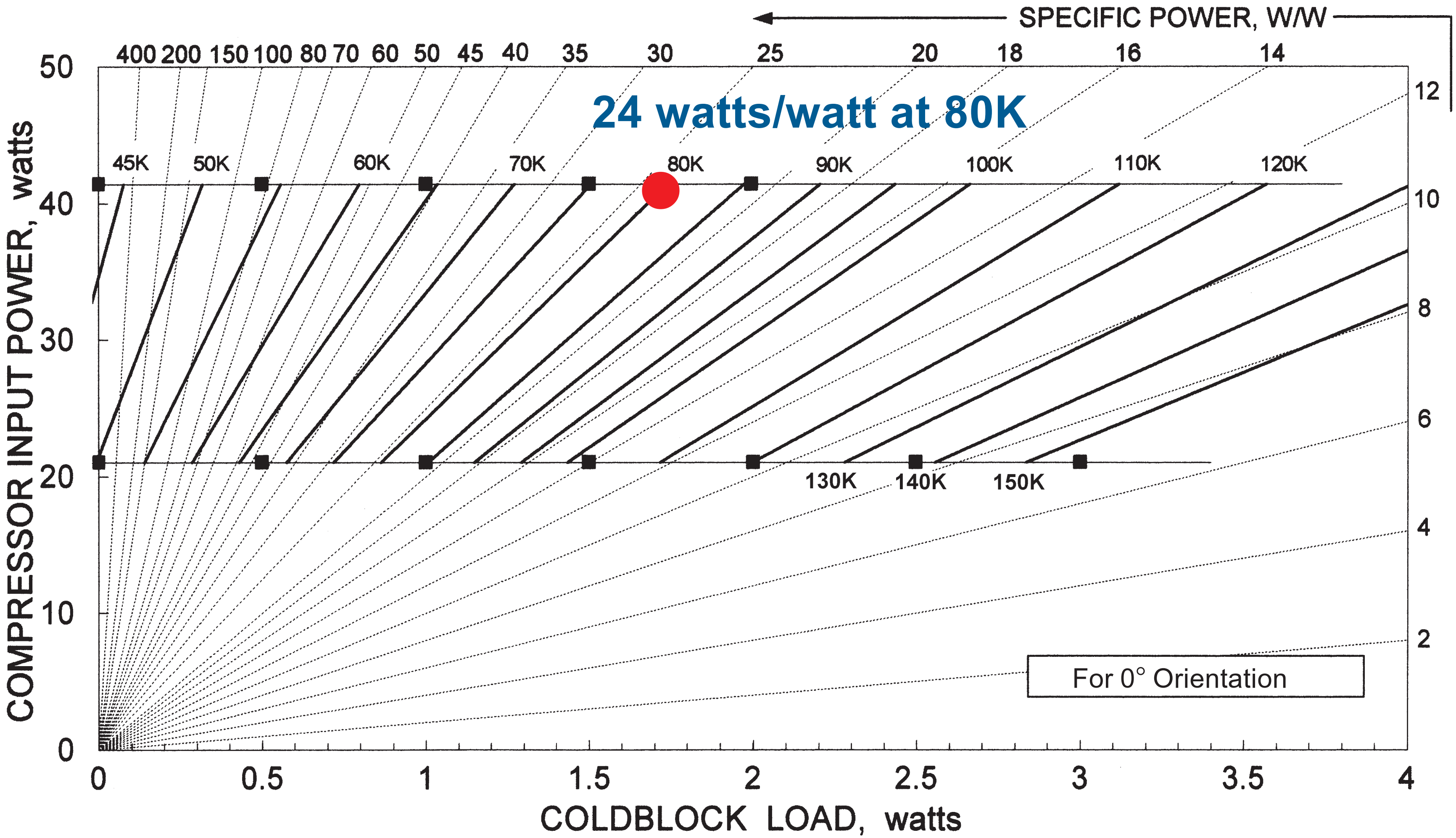


Pulse Tube Temperature Regions vs Construction Method

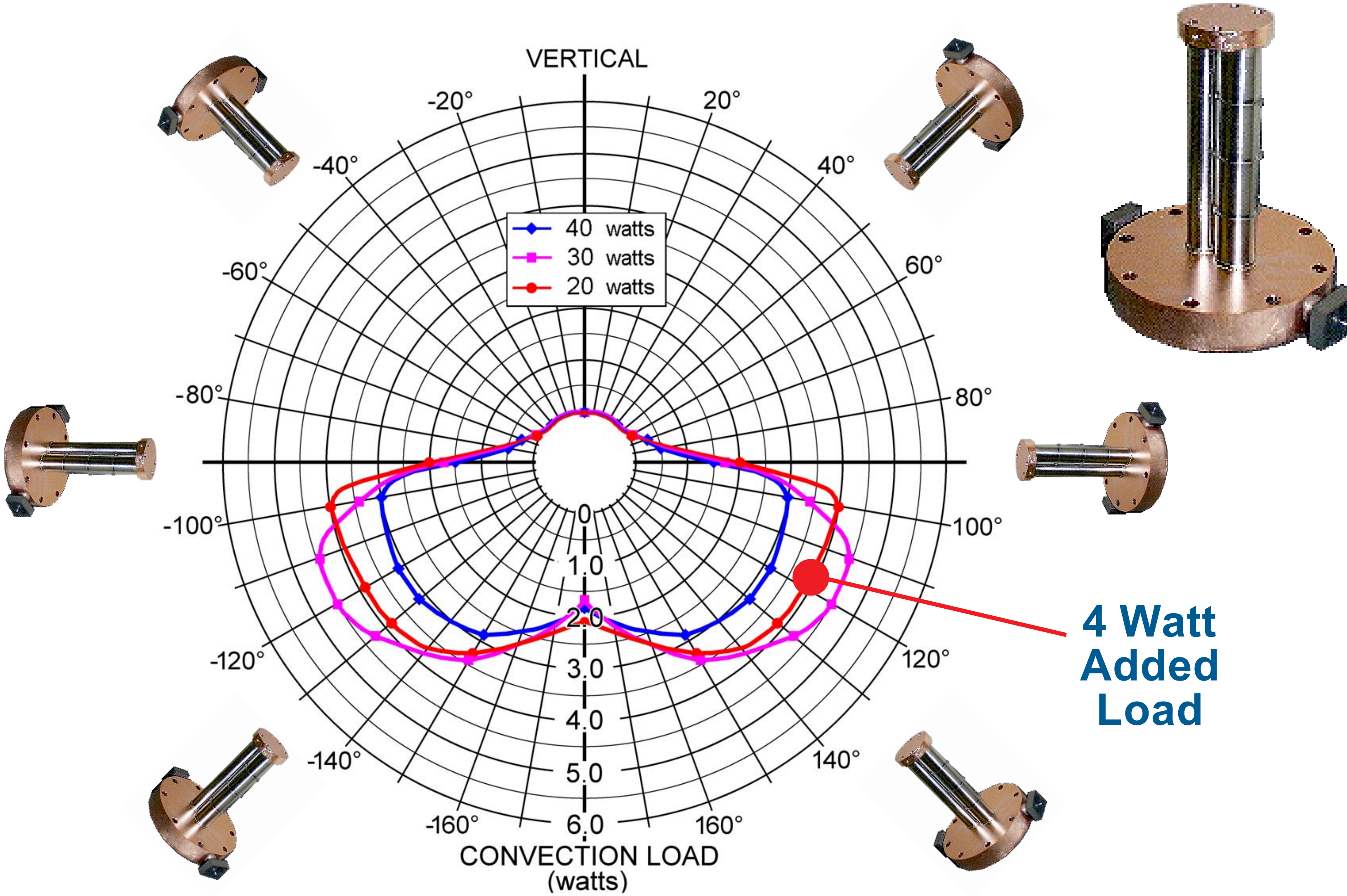




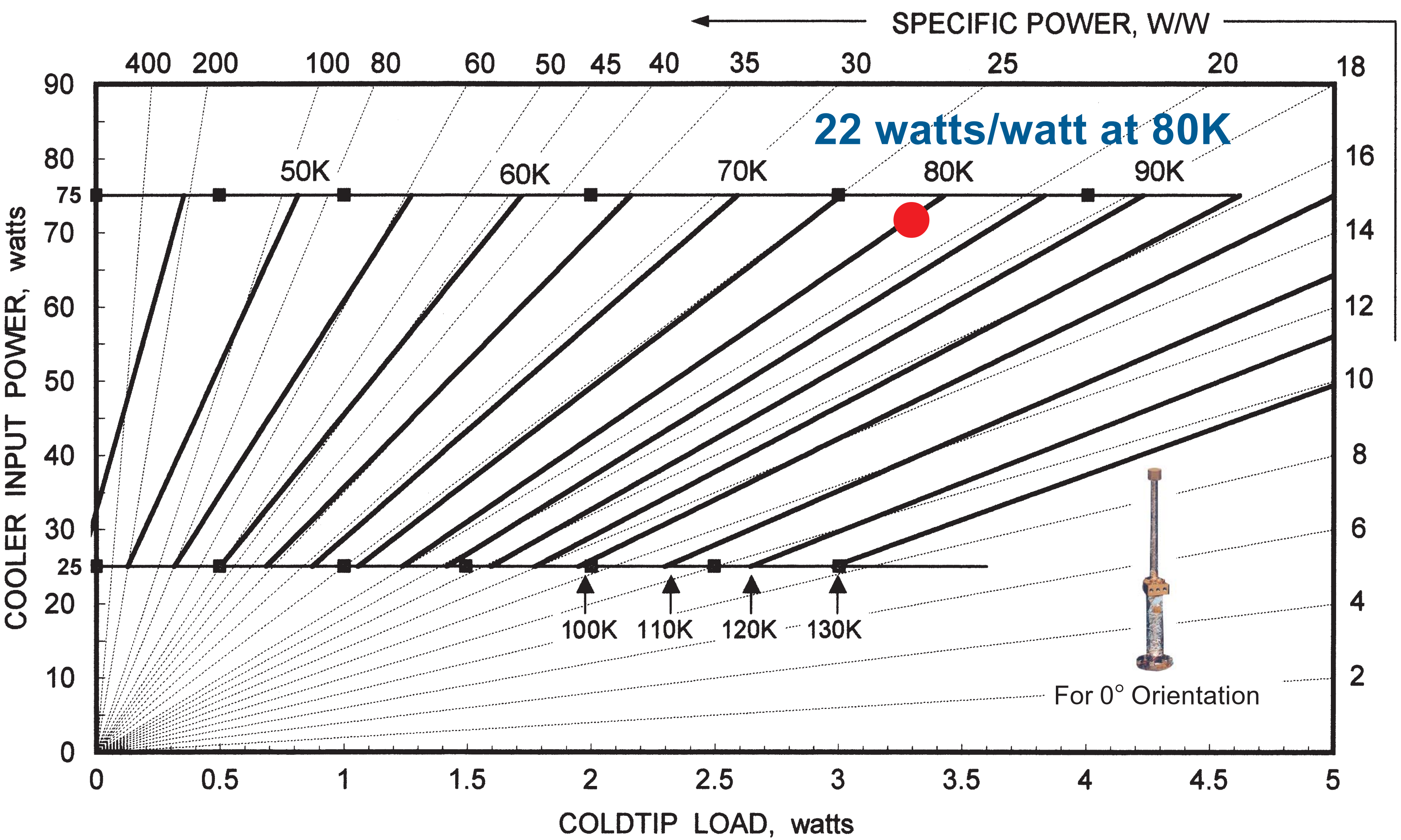
Gamma-Ray 80 K Pulse Tube Performance vs Power and Load



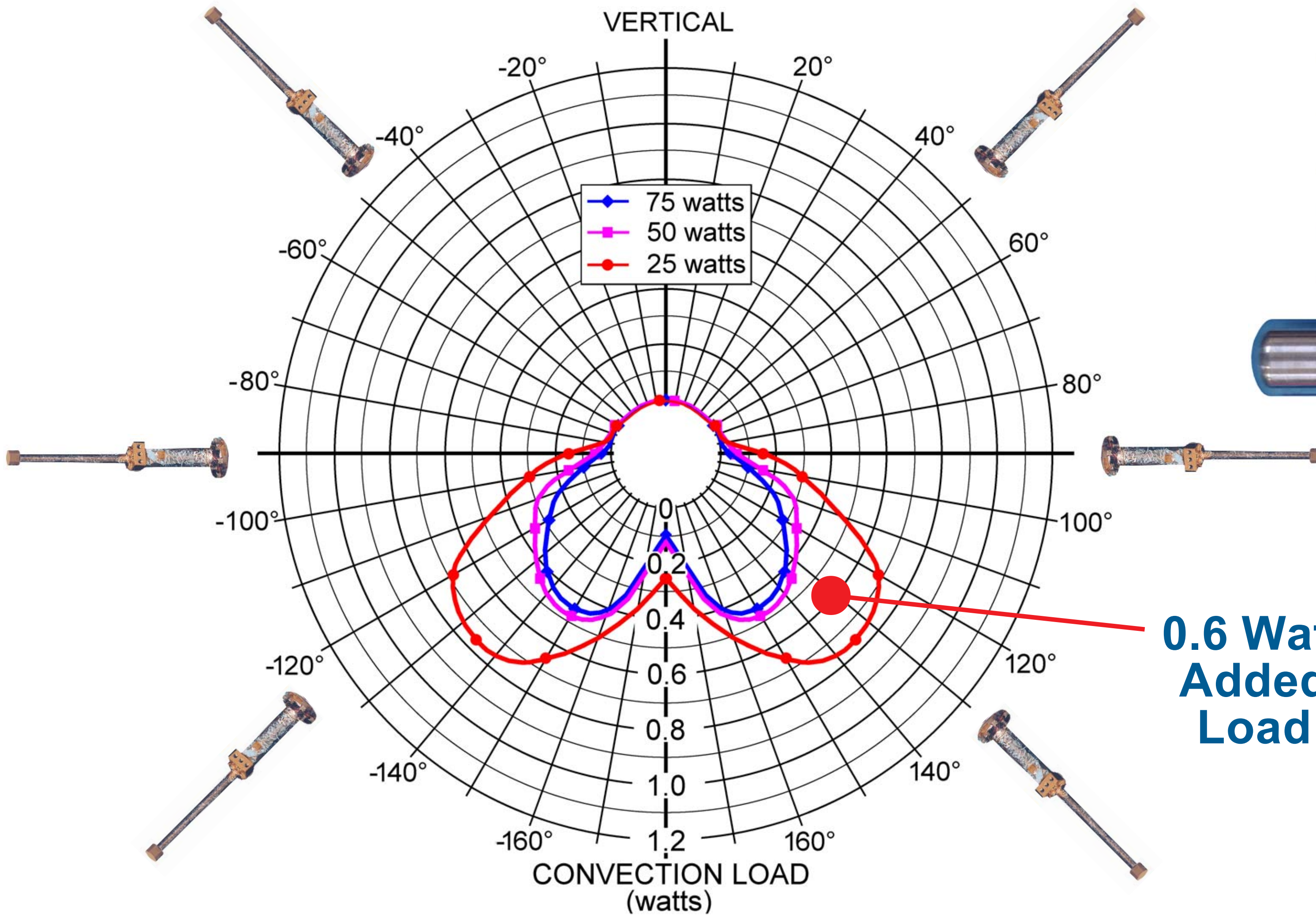
Gamma-Ray 80 K Pulse Tube Convective Load vs Angle



IMAS 55 K Pulse Tube Performance vs Power and Load



IMAS 55 K Pulse Tube Convective Load vs Angle



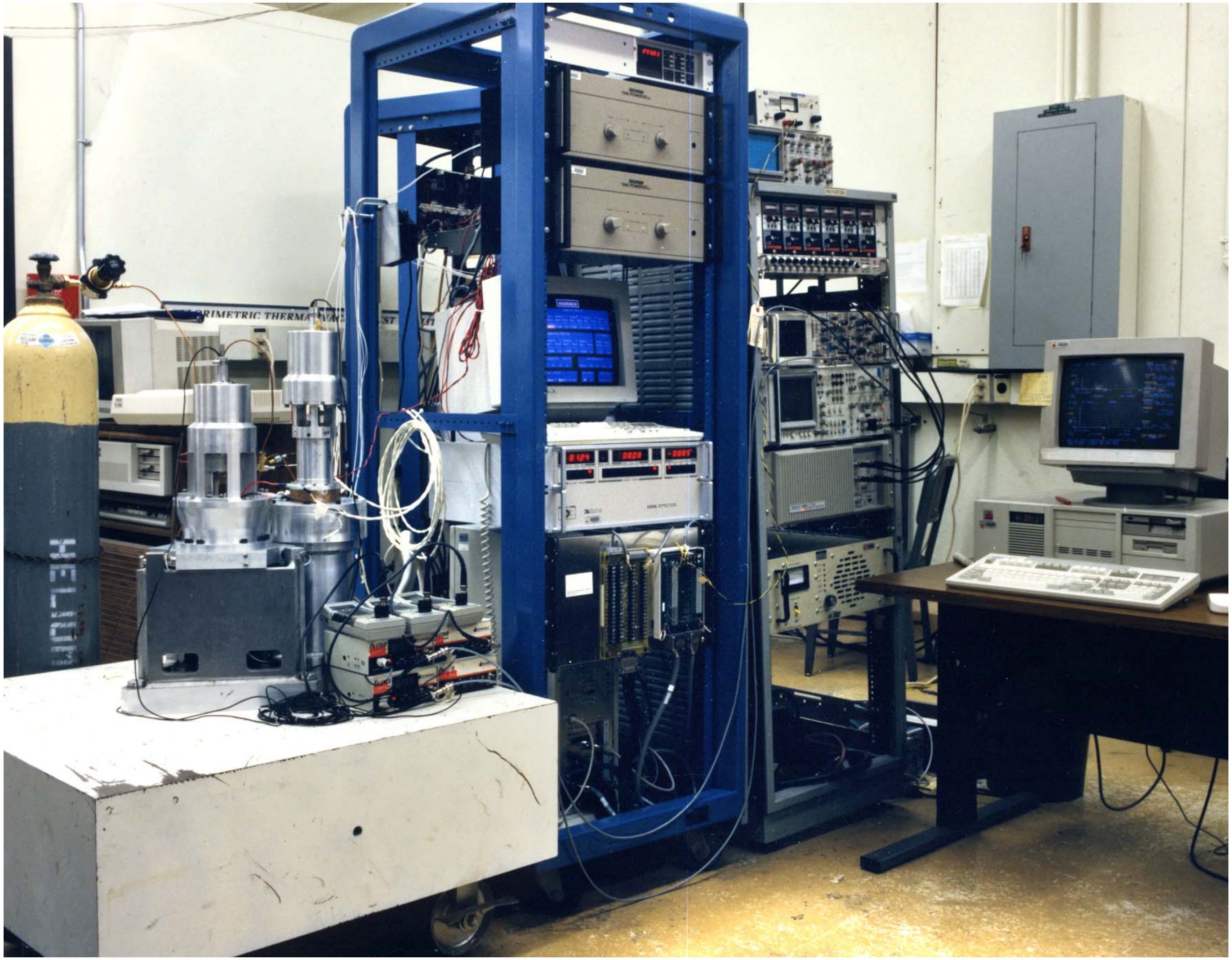
0.6 Watt Added Load

Effect of Gravity Orientation on PT Performance: Conclusions

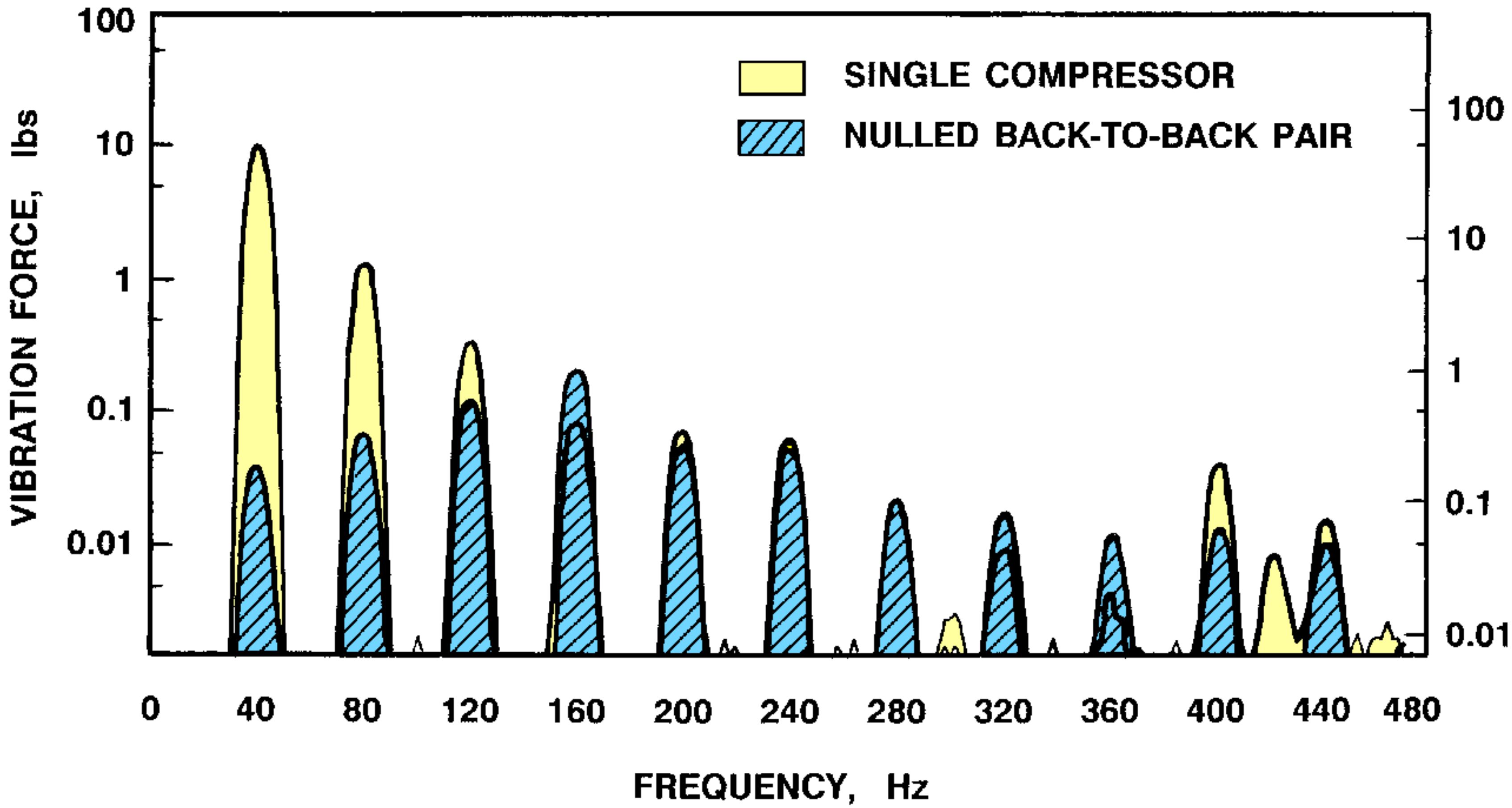
- **Key Conclusions**:
  - When the PT hot end is oriented UP (+/- 80 degrees) the PT performance is normal (reflects the nominal non-convection conductivity of the PT)
  - When the PT is horizontal or the hot end is tilted down the PT performance can be impacted by large convection loads internal to the PT.
  - The level of convection loads has been found to be a strong function of the aspect ratio of the PT geometry. Long-slim PTs have minimal effect, whereas short squat PTs can have very large effects
  - Gravity Orientation can be an important constraint during cryogenic system ground testing

JPL Exported Vibration Characterization Facility

6-DOF Vibration-Force Dynamometer



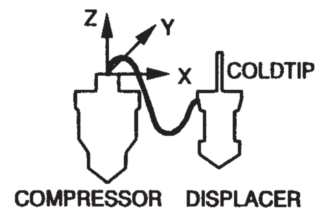
Typical Generated Vibration from Oxford-Style Compressor



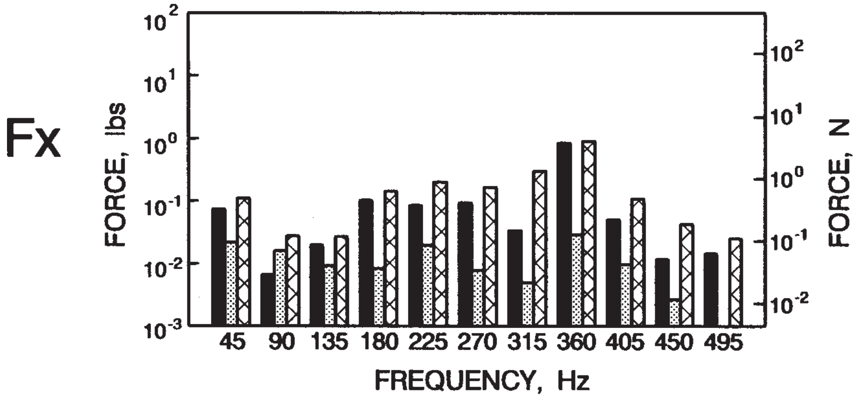
Vibration Force Spectrum for Single Piston Oxford Cooler

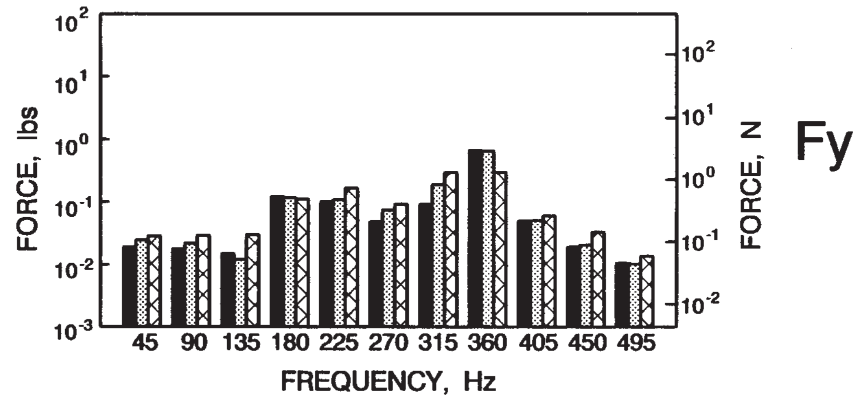
BAe 50-80K Cryocooler

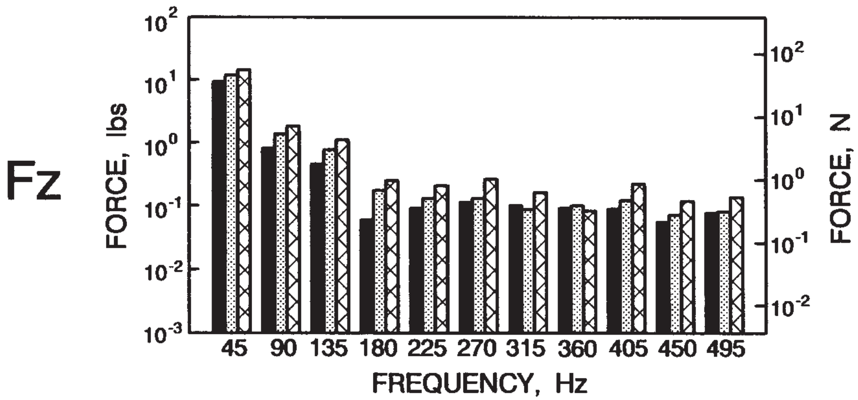
- COMPRESSOR STROKE = 4 mm p-p
- COMPRESSOR STROKE = 5 mm p-p
- COMPRESSOR STROKE = 6 mm p-p

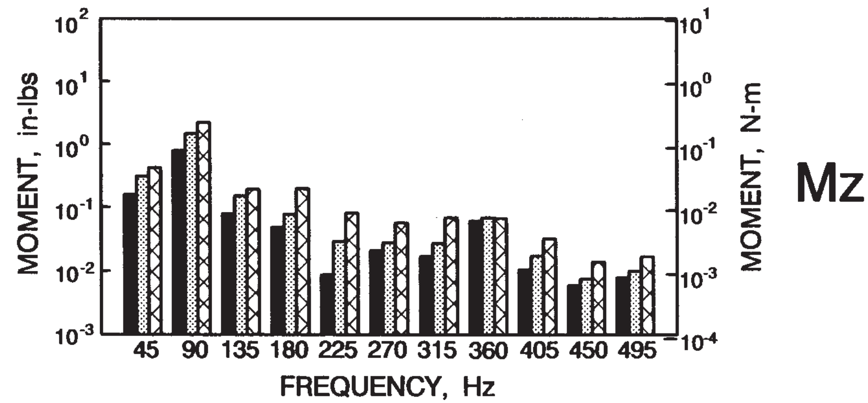


COLDTIP TEMPERATURE = 40K
DISPLACER STROKE: 2.8 mm p-p
FUNDAMENTAL FREQUENCY: 45 Hz

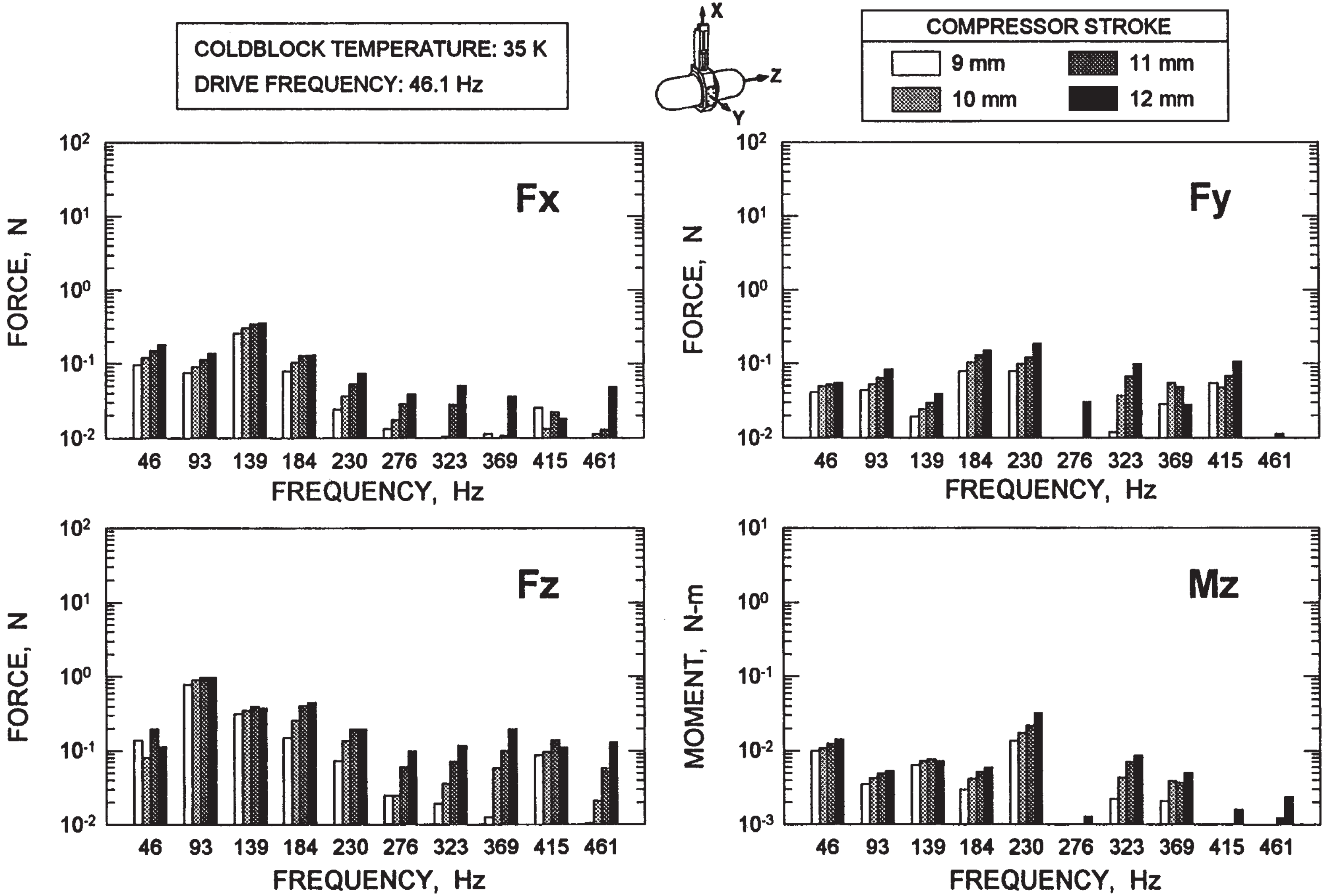




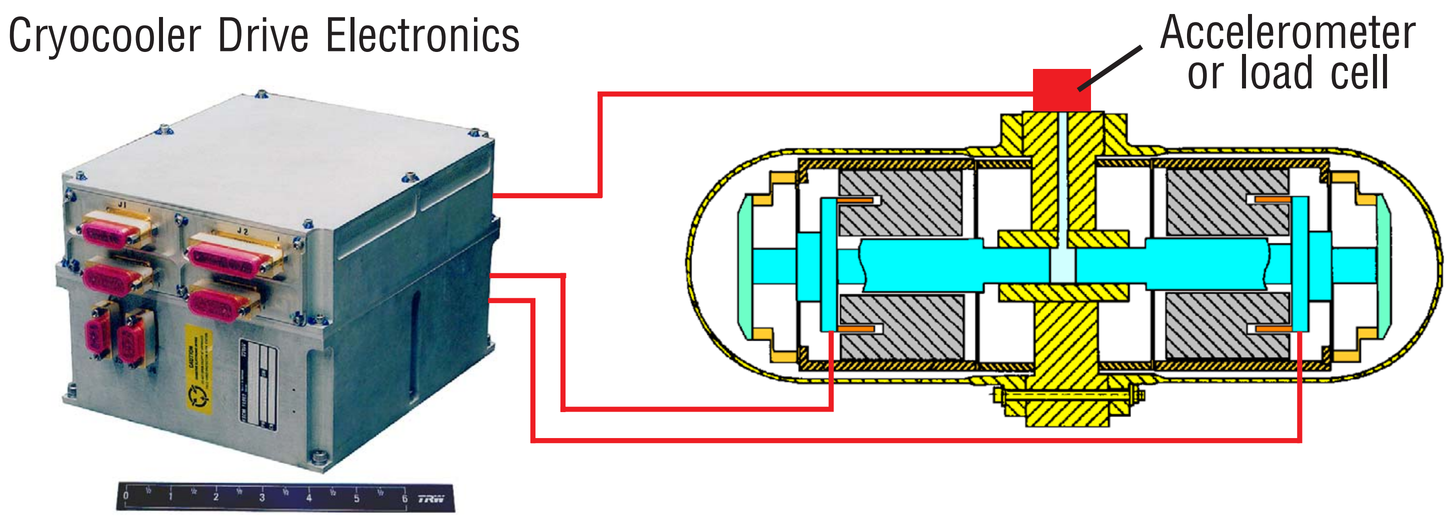




Vibration Spectrum for Integral Dual-Piston Cooler



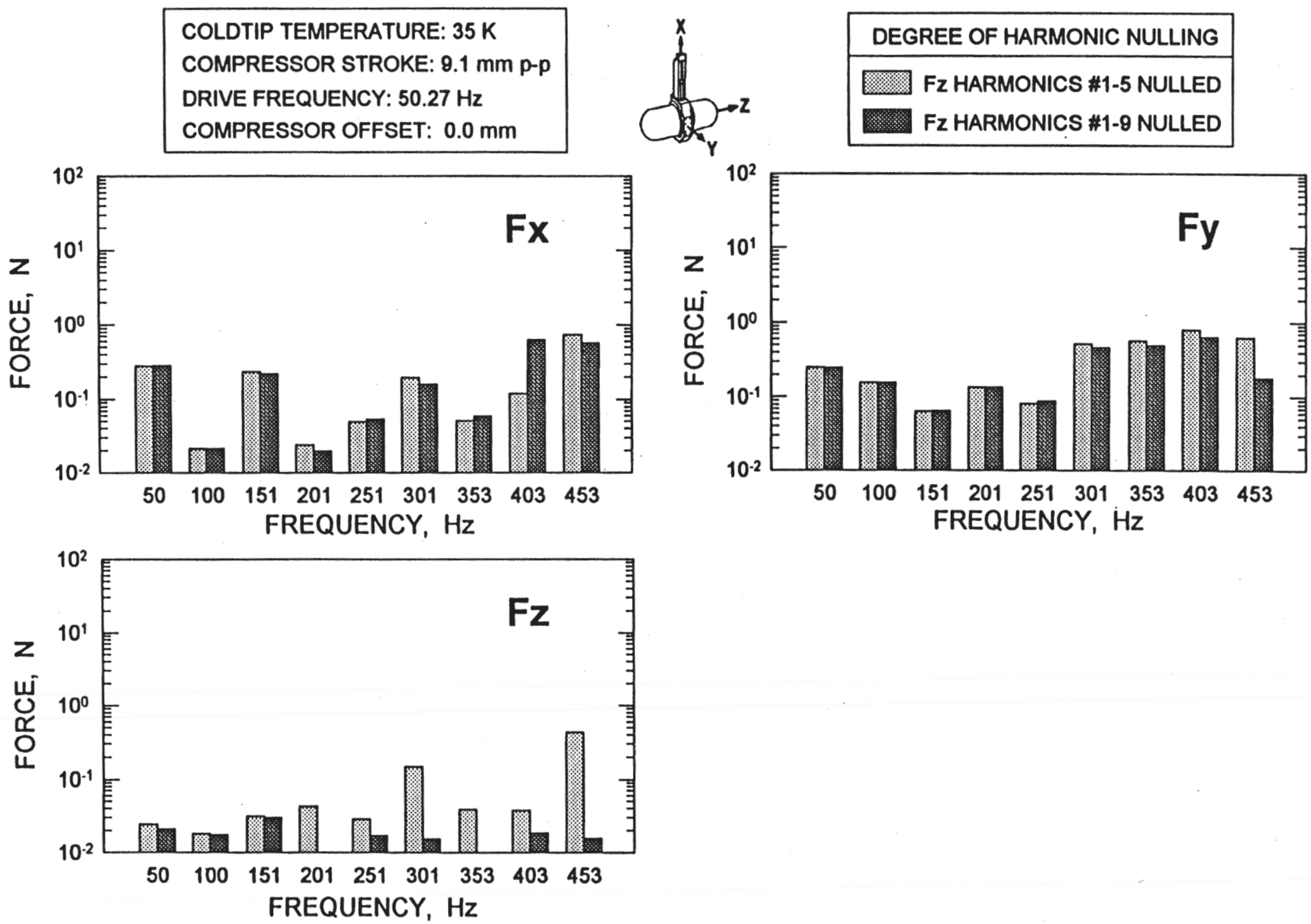
Approach to Cryocooler Active Vibration Suppression



- **Adaptive feed forward algorithms used to null measured acceleration or vibration force by tailoring individual harmonic amplitude and phase on one of the two compressor halves**

- **Generally implemented digitally in cryocooler drive electronics, some nulling as many as 16 harmonics**

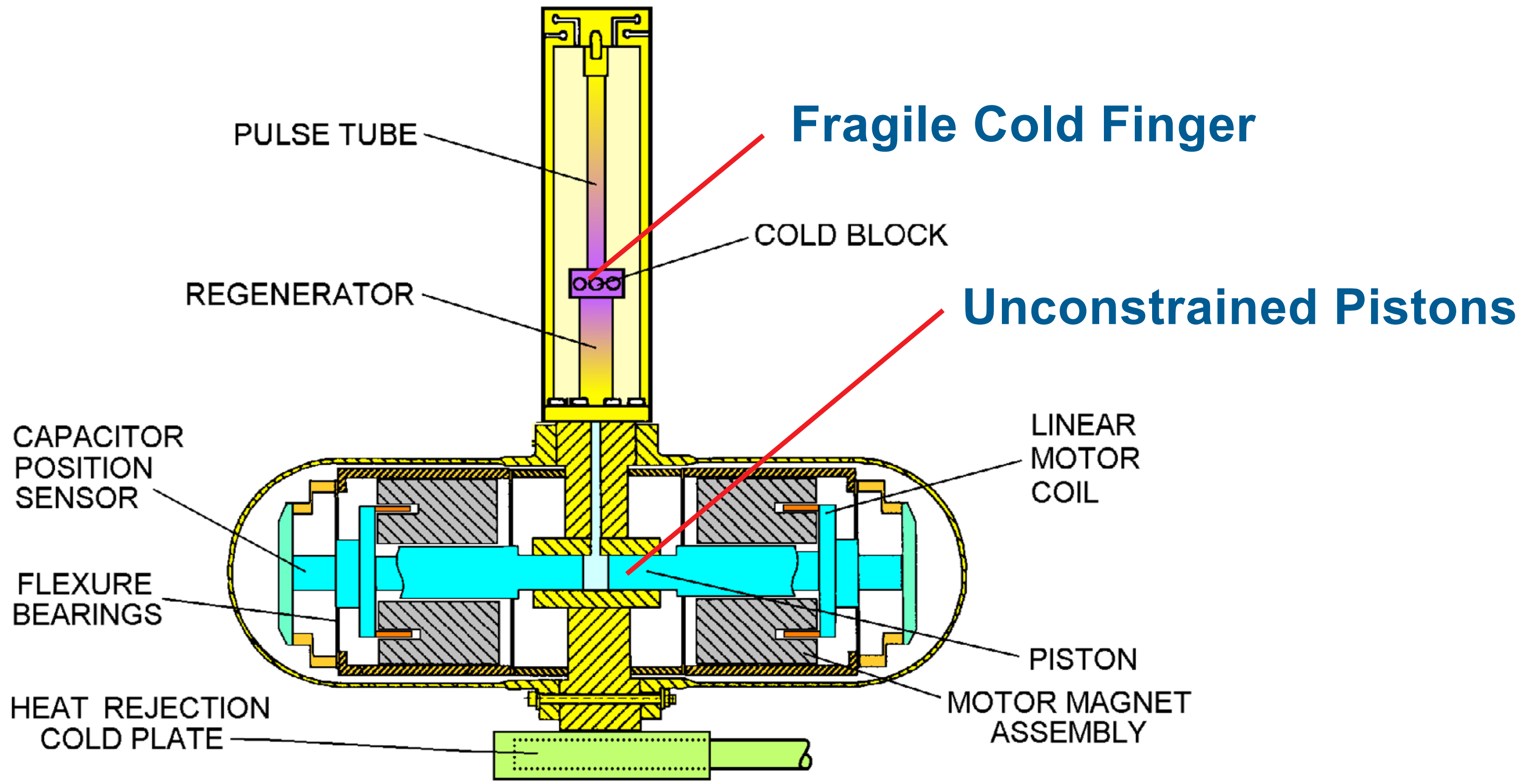
Dual Compressor Vibration Force Spectra with Harmonic Nulling



Cryocooler-Generated Vibration Conclusions

- Large quantities of exported vibration data have been acquired on a broad cross-section of Oxford-style coolers. The data reflect a high degree of similarity between machines
- Key Conclusions:
  - Head-to-head mounting of coolers can do a good job a cancelling the fundamental and 2nd harmonic (100x reduction)
  - Higher harmonics are typically not improved with head-to-head mounting unless active vibration suppression is used
  - With active vibration suppression, cross-axis harmonics generally create the worst case exported vibration levels

Another Challenge — Surviving Launch Vibration

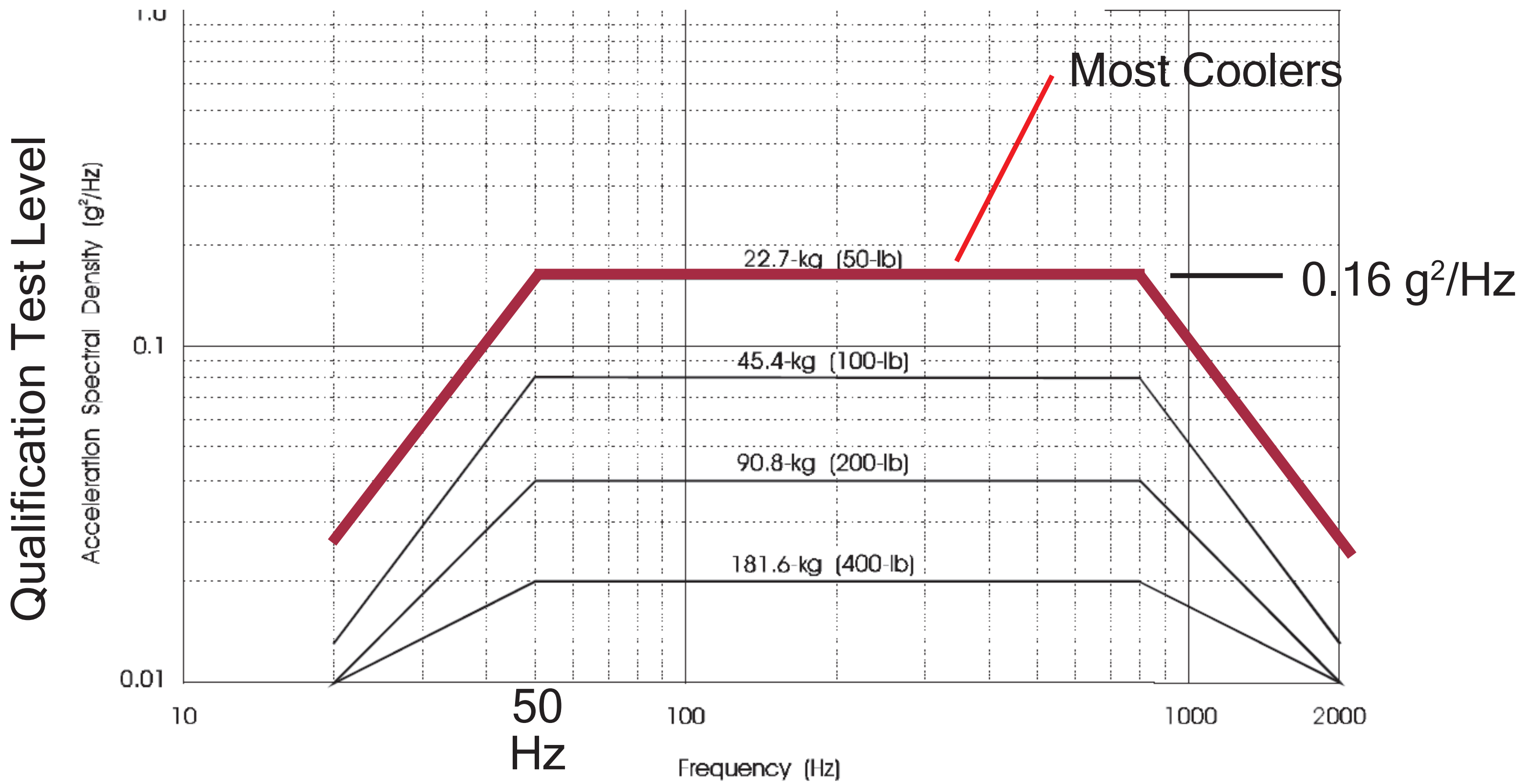


Launch Vibration Requirements, Challenges, and Test Methods

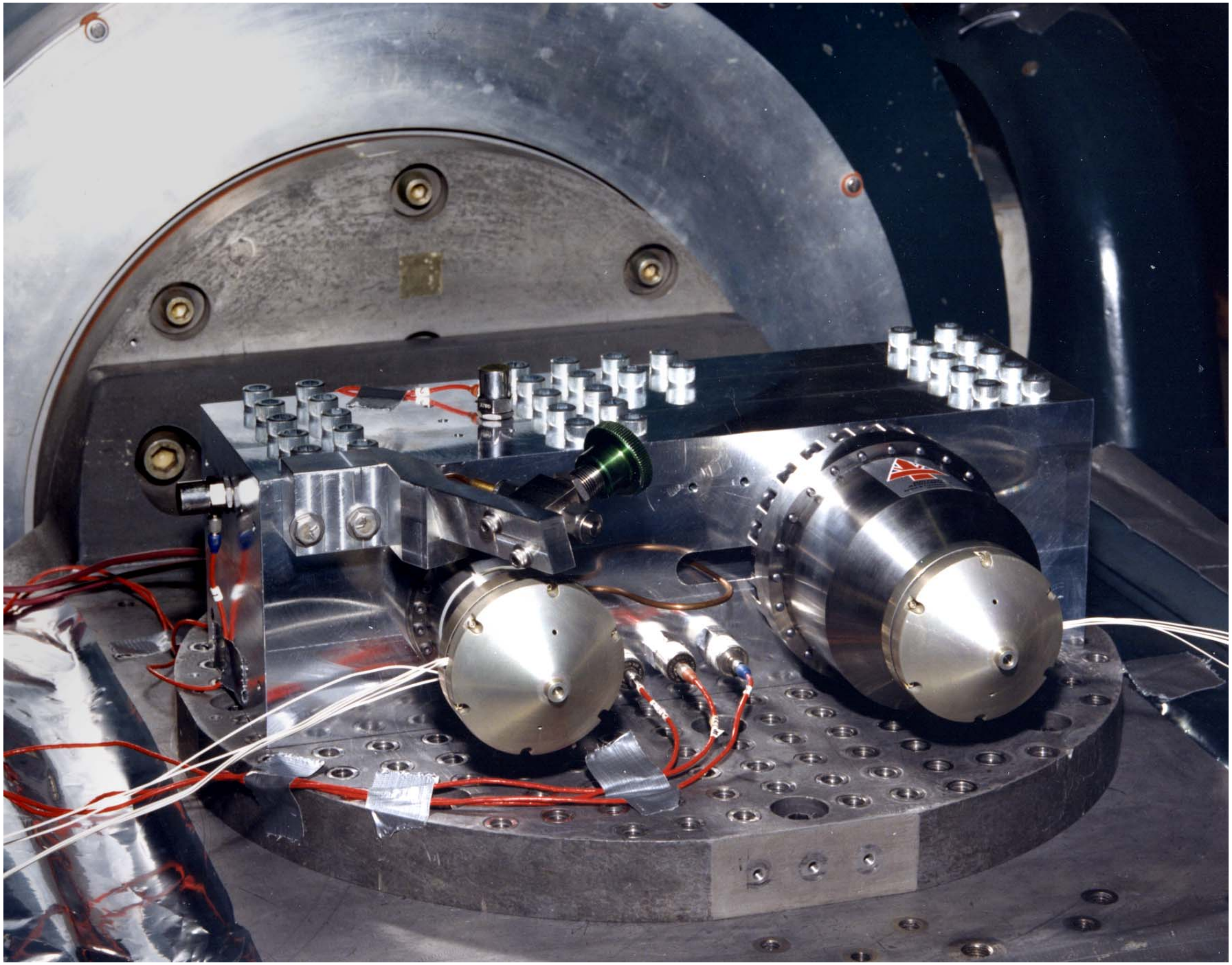
- **REQUIREMENTS**
  - Random Vibration on the order of 0.16 G^2/Hz from 50 to 800 Hz
  - Sinusoidal Vibration from 10 to 100 Hz (3 to 8 G, mission specific)
- **CHALLENGES**
  - Most Oxford-style compressors have little trouble passing the random vibration requirement
  - Stirling and PT coldfingers are quite vulnerable to Random Vibe
  - The low-frequency sinusoidal environment can be troublesome for integral back-to-back Oxford-style compressors because of their very low frequency piston slosh mode
  - The low-frequency sinusoidal environment can also be troublesome for Stirling displacers and counter-balancers
- **TEST METHODS**
  - Typical aerospace vibration test facilities
  - Piston/displacer/balancer stroke measurement during test runs via supplementary electronics

Typical Space Launch Vibration Requirements (from GEVS)

Design Limit Loads = Use Mass Acceleration Curve (MAC)
Flight Acceptance Levels = 1 minute per axis at (Qual Levels/two)
Protoflight Levels = 1 minutes per axis at Qual Levels
Qualification Levels = 2 minutes per axis at Qual Levels
Typically, Lowest Resonant Frequency > 50 Hz (hard for coolers to meet)



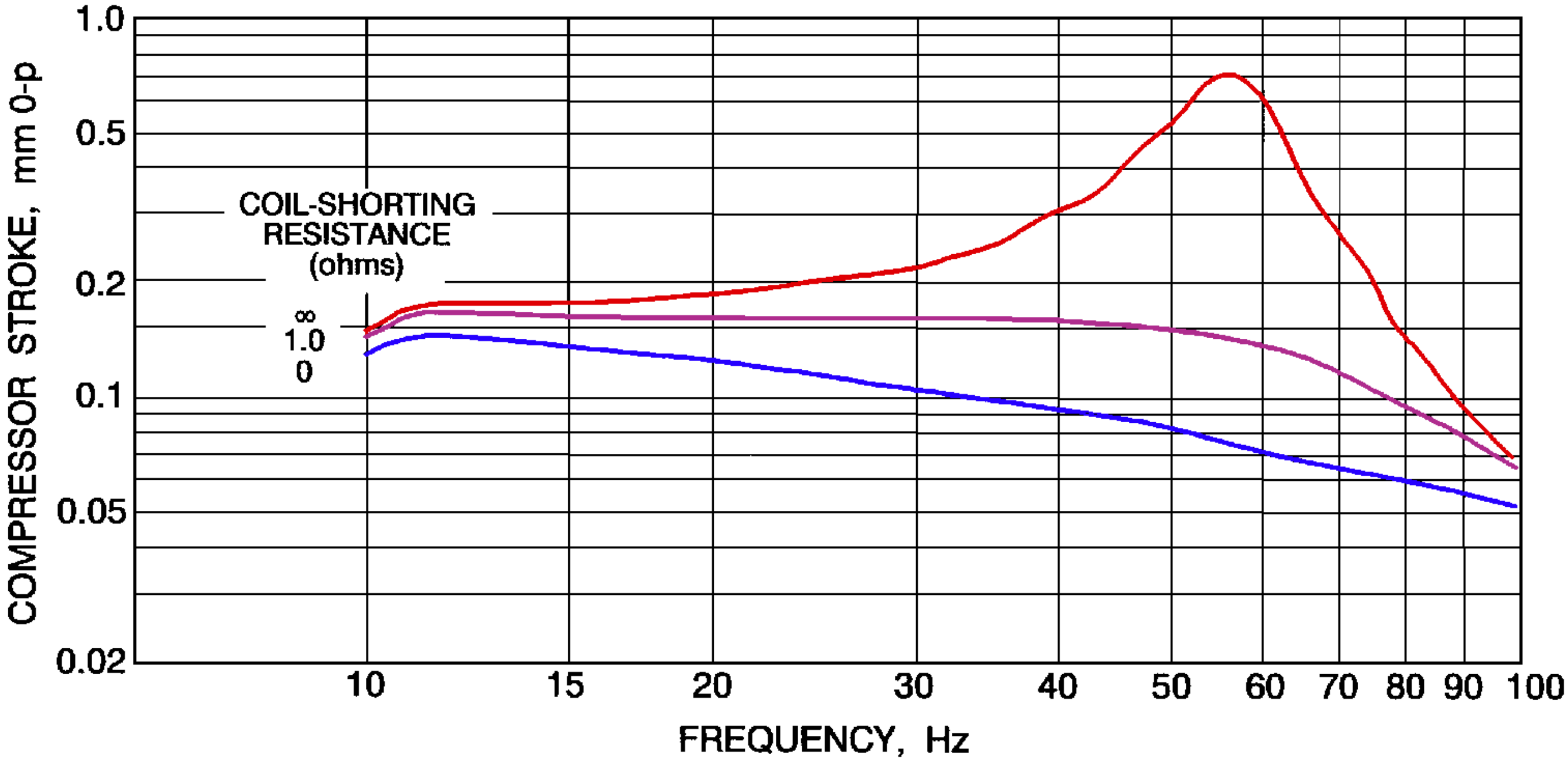
BAe 55 K Cooler Undergoing Launch Vibration Testing at JPL



Compressor Stroke during Sine Vibe Test vs Coil-Shorting Resistance

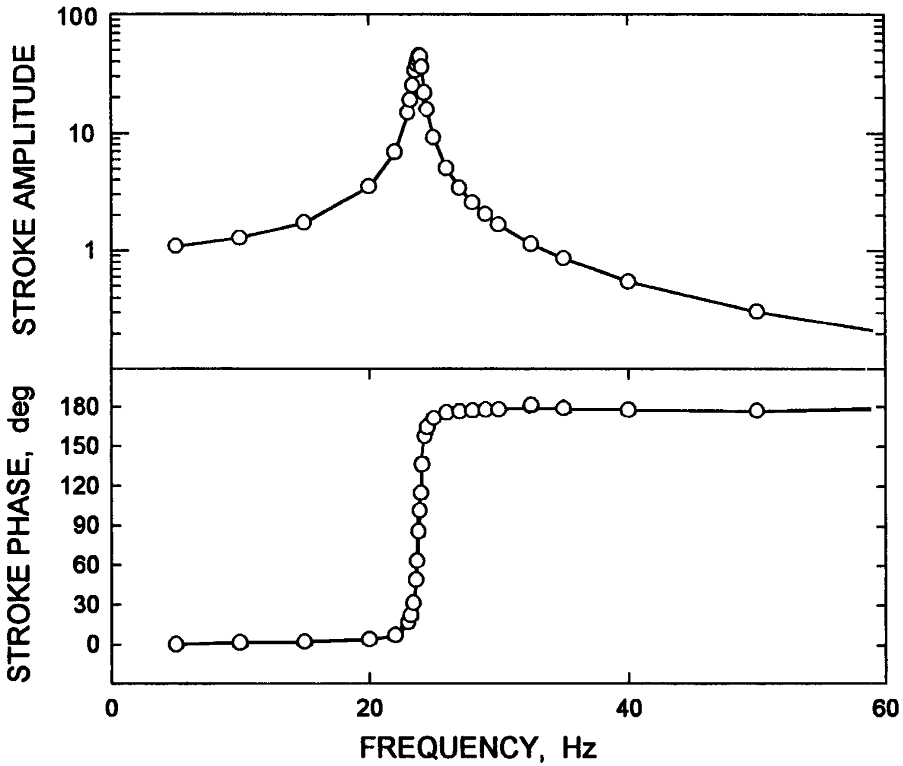
(3-g Sine sweep at 2 Octaves/minute)

Single-Piston Compressor (BAe 50-80K Cryocooler)



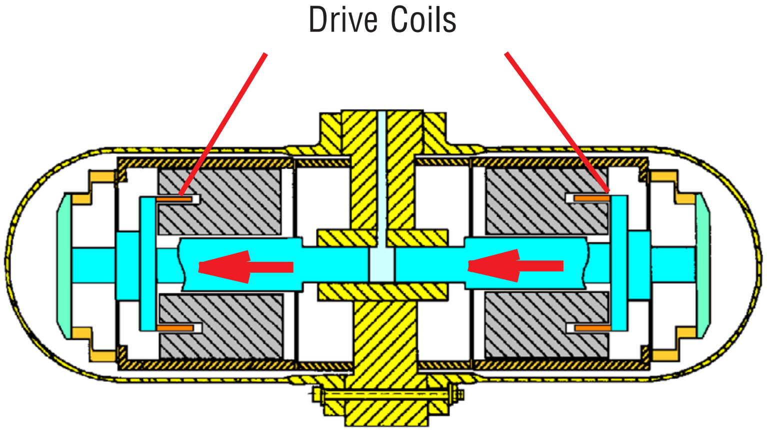
Example Resonant Response of Integral Two-Piston Compressor

TRW 1W-35K Pulse Tube Cryocooler

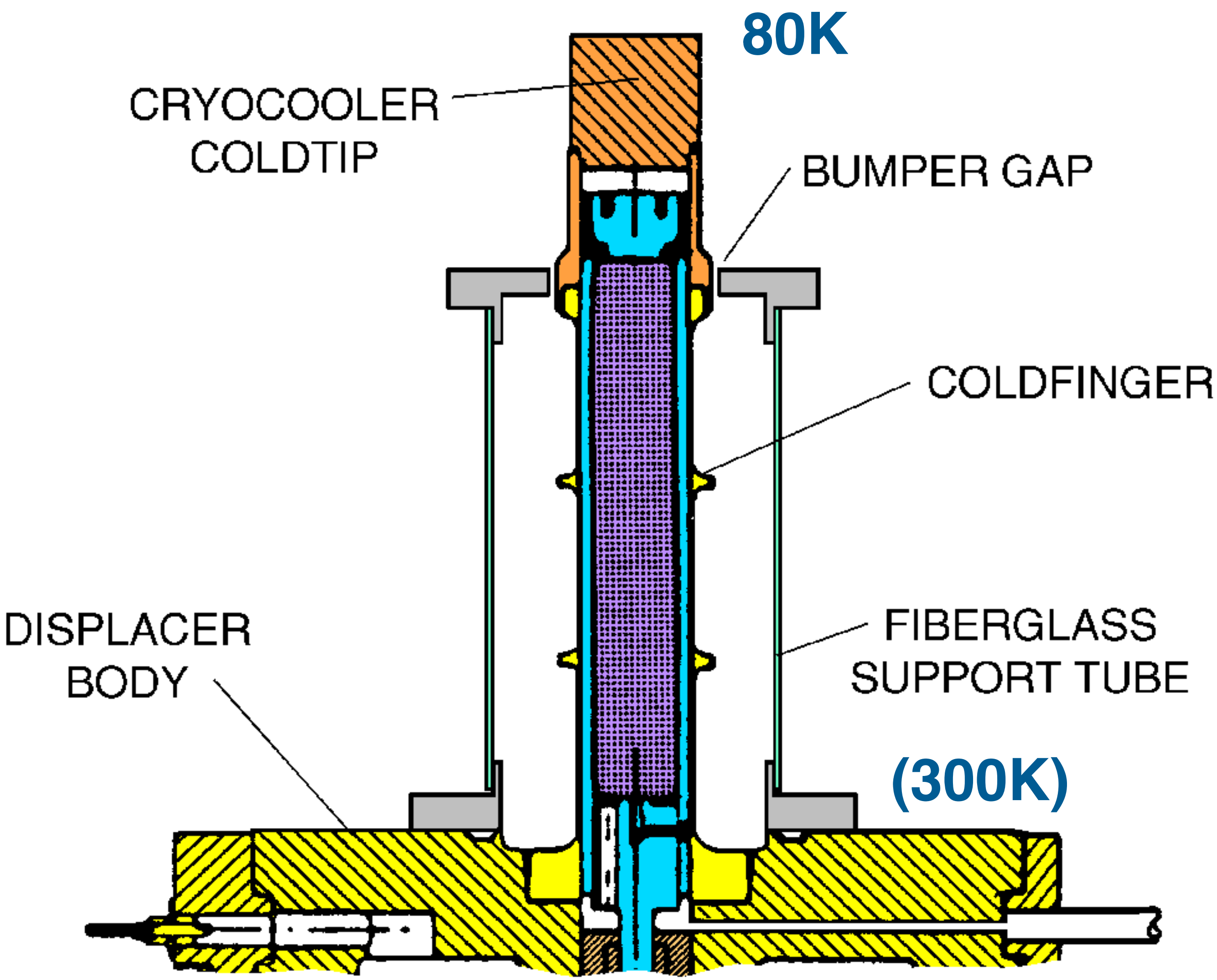


Piston Slosh Mode

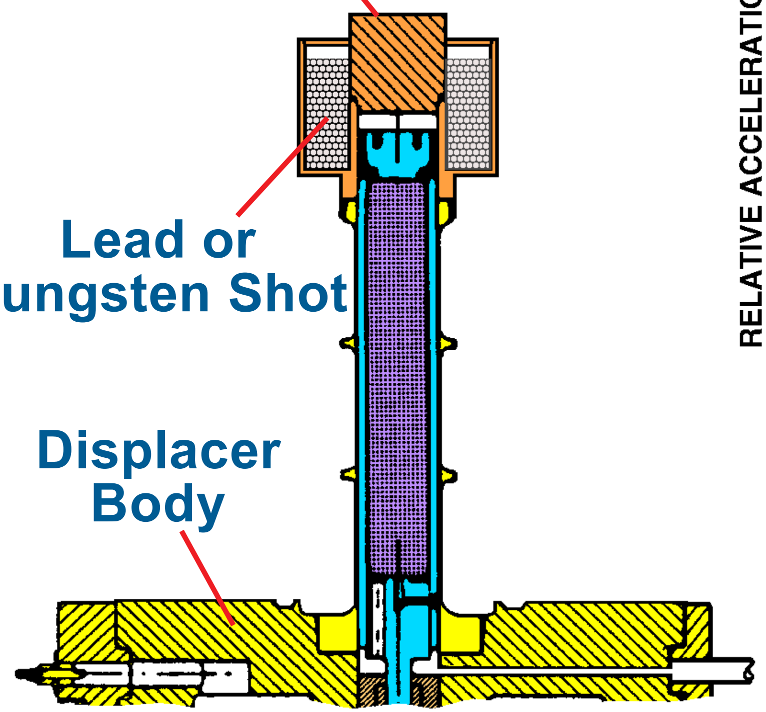
- **Inphase piston response is very high Q and well coupled to launch excitation**
- **Vibration suppression involves shorting the drive coils to provide electrodynamic braking**



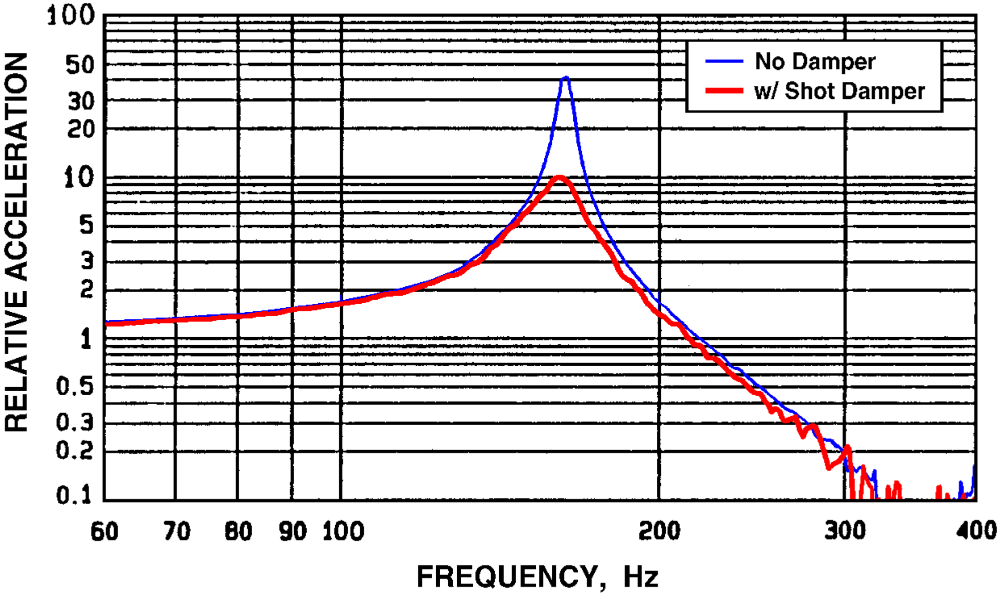
Example Cryocooler Coldfinger Bumper Assembly



Example Cryocooler Coldfinger Particle Damper



Factor of 4 Vibration Reduction Achieved with Particle Damper



Cryocooler Launch Vibration Testing Conclusions

- A significant number of cryocoolers have been tested for robustness with respect to launch vibration tolerance
- Key Conclusions:
  - Most compressors have little difficulty passing typical launch random vibration Qual test levels
  - However, most coldfingers and pulse tubes are marginal at typical launch random vibration Qual test levels. Most require add-on supports (bumper ass'y) or added damping
  - Most compressors have difficulty passing typical low-frequency launch sine vibration Qual test levels (20 to 40 Hz). Most require additional piston restraint such as by shorting motor windings

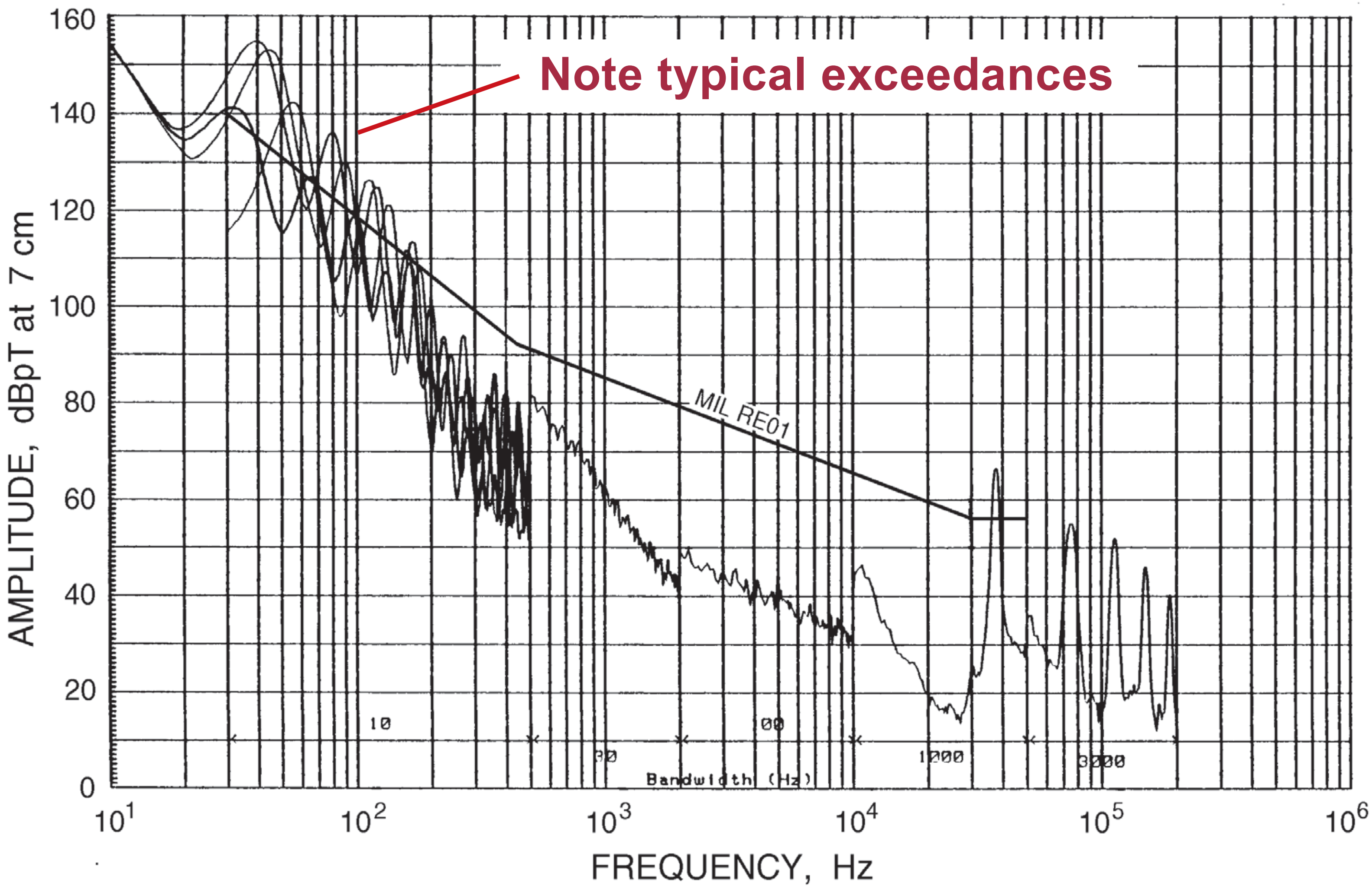
Cryocooler EMI Requirements, Challenges, and Test Methods

- **REQUIREMENTS**
  - Magnetic Fields below Mil Std 461C RE01 & 462 RE04
  - Electric Fields below Mil Std 461C RE02
  - Ripple Currents below Mil Std 461C CE01/03.
  - In-Rush Current Limits
  - Must pass Susceptibility to External EMI
- **CHALLENGES**
  - Most Oxford-style compressors have very high Magnetic Fields at their fundamental operating frequency
  - Most Oxford-style compressors have very high Ripple Currents at twice their fundamental operating frequency
  - Inrush currents and electric fields need to be managed with proper circuit design and shielding
- **TEST METHODS**
  - Mil Std 461 in screen room
  - Need means (vacuum bonnet) to allow cooler to operate outside of vacuum chamber

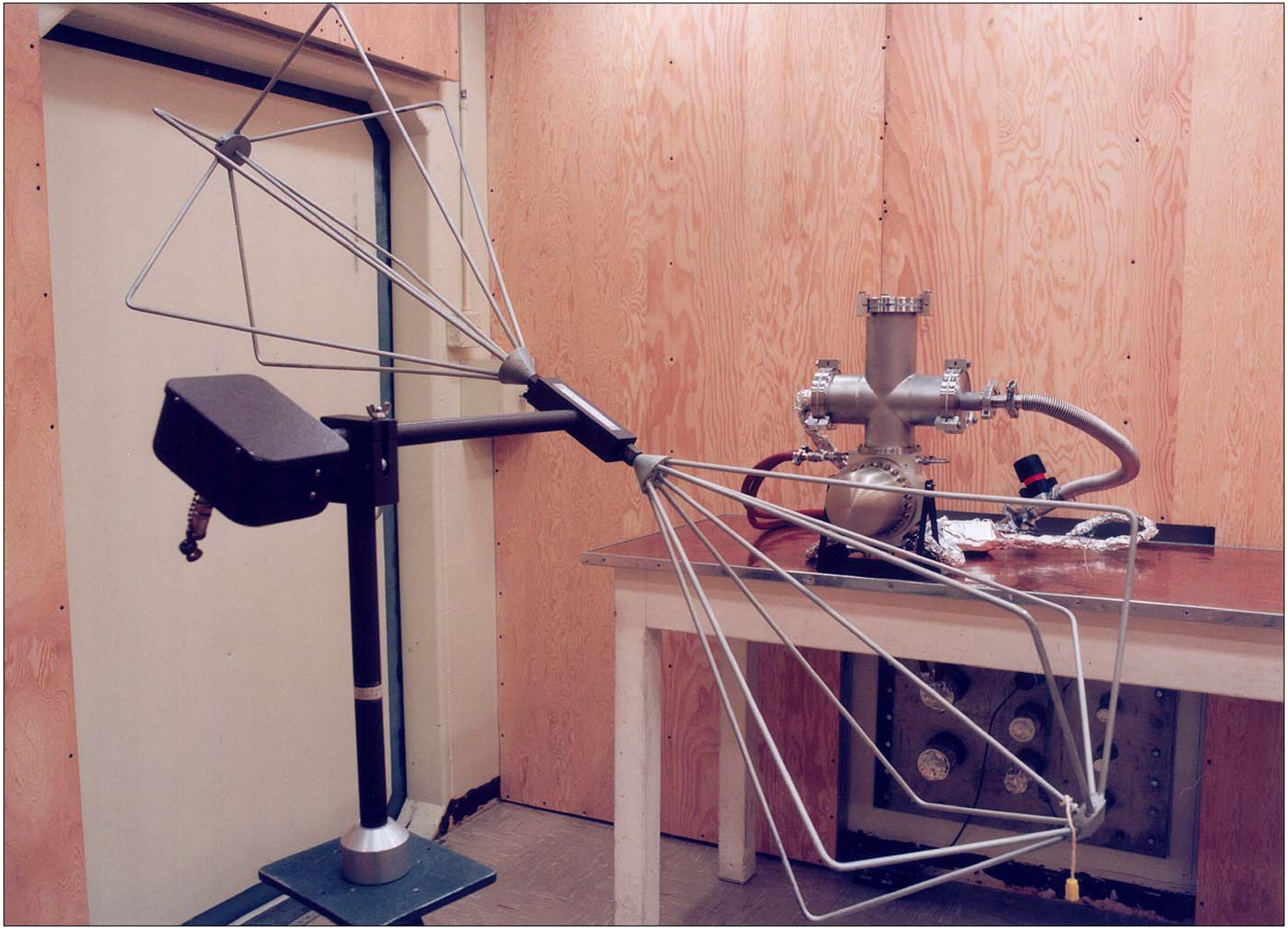
Low-Frequency AC Magnetic Field Test Setup with TRW PT Cooler

Historical Cryocooler Compressor AC Magnetic Field Emissions

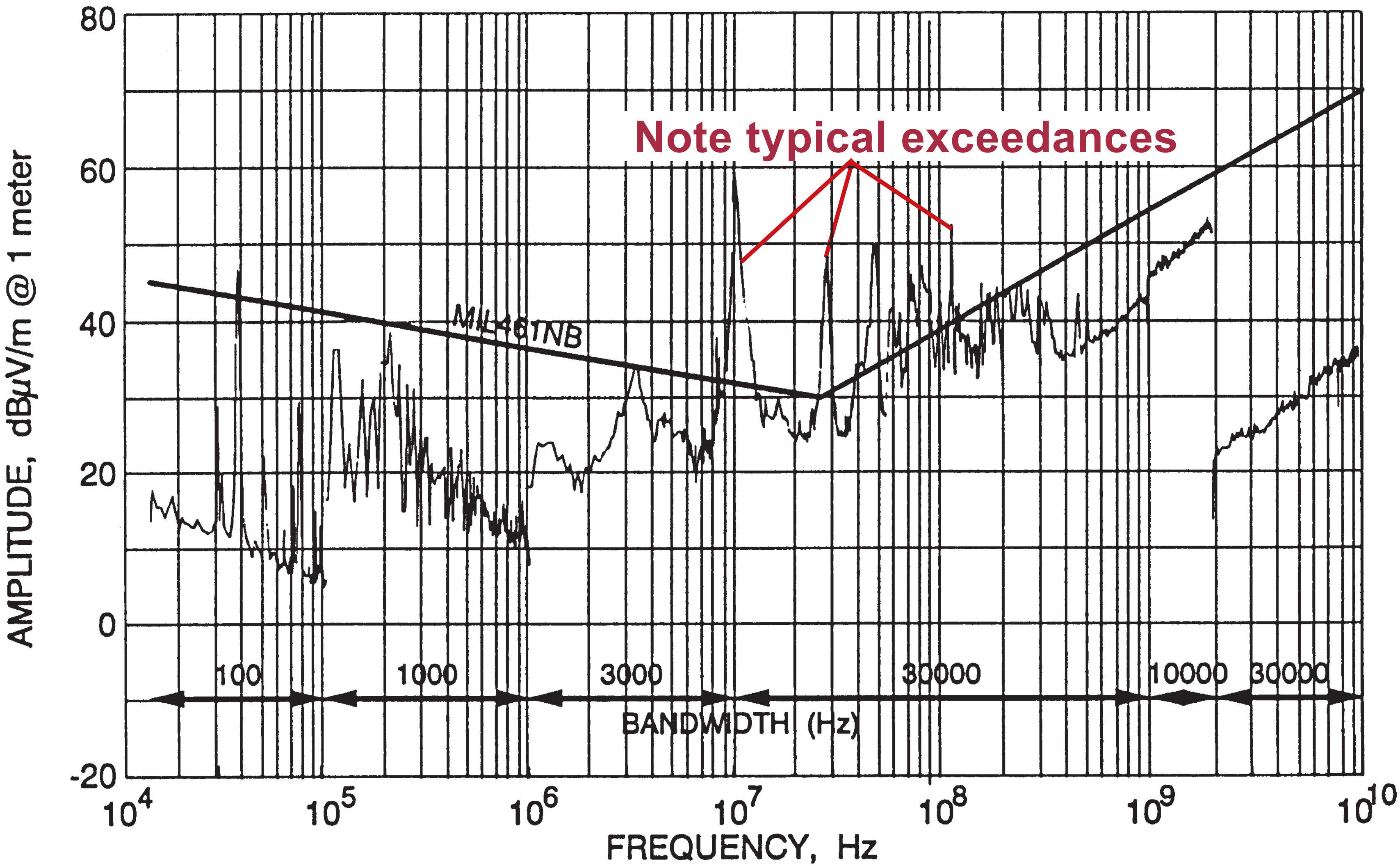
Compared with Mil Std 461 RE01 Requirements



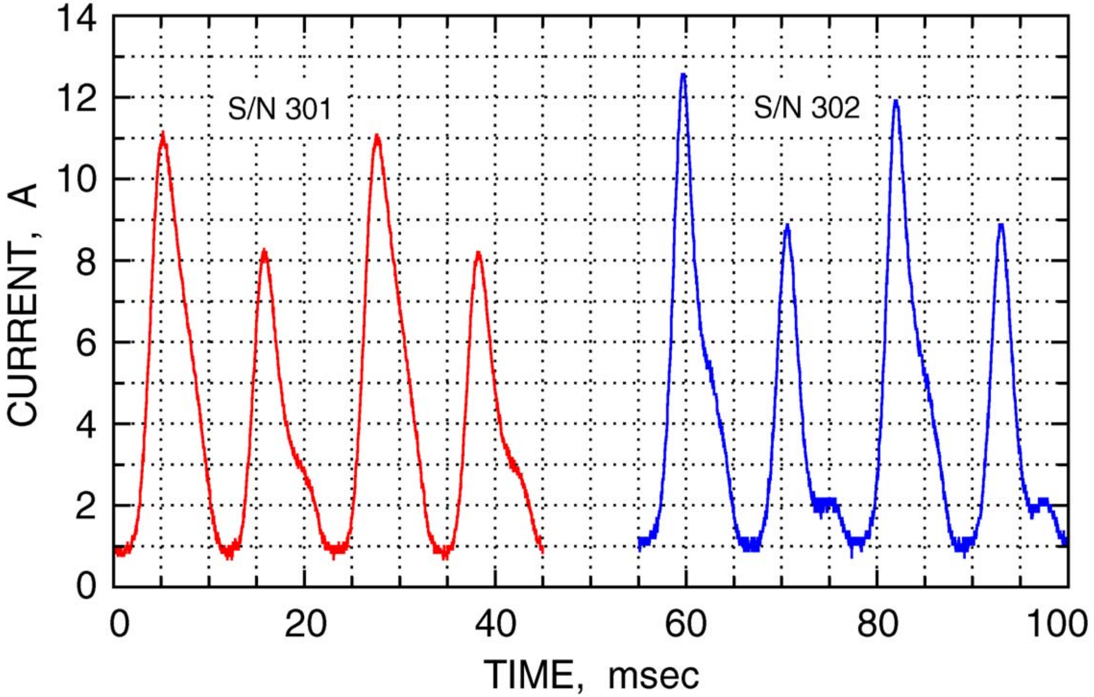
High-Frequency AC Electric Field Test Setup with TRW PT Cooler

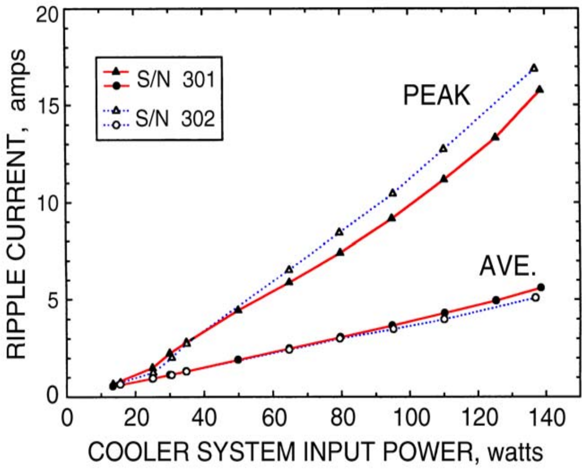


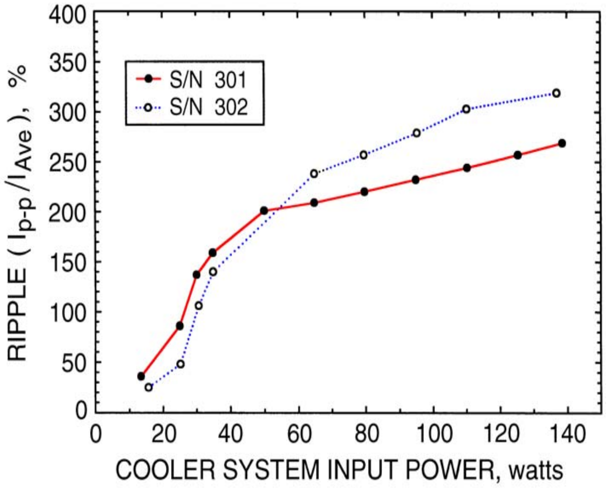
Early Cryocooler Electronics AC Electric Field Emissions



AIRS Cryocooler Electronics Conducted Ripple Current







Cryocooler Measurement Summary

- Measurement and test techniques for space cryocoolers are quite well developed and documented in the literature
  - Thermal performance as a function of drive parameters
  - Heat dissipation quantities and locations
  - Coldhead gravity effects on performance
  - Generated vibration as a function of drive parameters
  - Launch vibration robustness
  - Generated EMI and Susceptibility to External EMI

- Typical test data are also readily available in the literature

- Means of bringing coolers into conformance with typical space requirements are also documented in the literature