Cryocoolers for Space Applications #3

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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

- 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


• 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?)
TRW 1W-35K Pulse Tube Cryocooler during Thermal Testing at JPL
Sensitivity of Thermal Performance to Compressor Stroke

TRW 1W-35K Pulse Tube Cooler

Heat Sink Temperature = 20°C

COLDTIP LOAD, watts

COLDTIP TEMPERATURE, K

No-Load Temperature
Sensitivity of Thermal Performance to Compressor Stroke

BAe 50 to 80 K Stirling Cryocooler

SPECIFIC POWER, watts/watts

HEAT SINK TEMPERATURE = 20°C
DISPLACER STROKE = 2.8 mm p-p
FREQUENCY = 45 Hz
PHASE = 65°
Sensitivity of Thermal Performance to Compressor Stroke

AIRS 55K Pulse Tube Cryocooler

HEATSINK TEMPERATURE = 300 K
Sensitivity of Thermal Performance to Drive Frequency

TRW 1W-35K Pulse Tube Cooler

Drive Frequency

COOLER INPUT POWER, watts

COOLTIP LOAD, watts

SPECIFIC POWER, W/W
Sensitivity of Thermal Performance to Fill Pressure

Stirling Technology 80K Stirling Cooler

Fill Pressure
Sensitivity of Thermal Performance to Displacer Stroke

BAe 50 to 80 K Stirling Cryocooler

Specific Power, watts/watts

Heat Sink Temperature = 20°C
Compressor Stroke = 6.0 mm p-p
Frequency = 45 Hz
Phase = 65°

Displacer Stroke
Sensitivity of Thermal Performance to Heat Sink Temperature

TRW 1W-35K Pulse Tube Cooler

Heat Sink Temp.

Heat Sink Temperature

- 20°C Heatsink
- 0°C Heatsink

COOLER INPUT POWER, watts

COLDTIP LOAD, watts

Heatsink = 20°C

Heatsink = 0°C

SPECIFIC POWER, W/W
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 $\Theta_A$ and as equal to the cooling power $P(T_0, \Theta_B)$ at the baseline heatsink temperature $T_0$ and coldend temperature $\Theta_B$, i.e.

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

where

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

Thermal Performance Plot for Direct Mount to Radiator

COOLER HEAT DISSIPATION, watts

COLD TIP TEMPERATURE, K

REGION OF THERMAL RUNAWAY

SPECIFIC POWER, watts/watt

RADIATOR HEATSINK (T^4 \propto P)

37% stroke

55% stroke

70% stroke

79% stroke

90% stroke
The Carnot Refrigeration Cycle and its Efficiency

**COP**

\[ \text{COP}_{\text{Cooler}} = \frac{\text{cooling power}}{\text{input power}} \]

\[ \text{COP}_{\text{Cooler}} = \frac{\text{heat absorb}}{(\text{heat reject} - \text{heat absorb})} \]

\[ \text{COP}_{\text{Carnot}} = \frac{T_{\text{cold}}}{T_{\text{hot}} - T_{\text{cold}}} \]
Sensitivity of %Carnot COP to Compressor Stroke

TRW 1W-35K Pulse Tube Cooler

%Carnot COP = 100 × \( \frac{\text{COP}_{\text{Cooler}}}{\text{COP}_{\text{Carnot}}} \)

= 100 × \( \frac{\text{Input electrical power} \times (T_{\text{cold}})}{(\text{cooling power @ } T_{\text{cold}}) \times (T_{\text{hot}} - T_{\text{cold}})} \)
JPL Cryocooler Calorimetric Thermal-Vacuum Test Facility

BAe 80 K Stirling Cryocooler
BAe 80 K Stirling Cryocooler

~ 0.5 W at 65 K

7 W heat

1 W

24 W heat

30 W

9 W heat

40 W input
Effect of Heatsink Temperatures on Heat Rejection Location

BAe 80 K Stirling Cryocooler

Power (watts)

Coldtip Temperature (K)

- Comp 320, Disp 280
- Comp 300, Disp 300
- Comp 280, Disp 320

Total

Compressor

Displacer
Effect of Gravity Orientation on Pulse Tube Thermal Performance
Pulse Tube Temperature Regions vs Construction Method

- Cold Tip
- Pulse Tube
- Warm End

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

24 watts/watt at 80K

For 0° Orientation
IMAS 55 K Pulse Tube
Performance vs Power and Load

For 0° Orientation

- 22 watts/watt at 80K
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
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**

**Graphs showing force and moment spectra for frequencies 45 to 495 Hz.**

**Fx, Fy, Fz, Mz**
Vibration Spectrum for Integral Dual-Piston Cooler

COLD BLOCK TEMPERATURE: 35 K
DRIVE FREQUENCY: 46.1 Hz

COMPRESSOR STROKE

<table>
<thead>
<tr>
<th>Stroke Size</th>
<th>Symbol</th>
</tr>
</thead>
<tbody>
<tr>
<td>9 mm</td>
<td>Light</td>
</tr>
<tr>
<td>11 mm</td>
<td>Medium</td>
</tr>
<tr>
<td>10 mm</td>
<td>Medium</td>
</tr>
<tr>
<td>12 mm</td>
<td>Dark</td>
</tr>
</tbody>
</table>

**Force, N**

**F_x**

**F_y**

**F_z**

**M_z**

**Frequency, Hz**

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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

COLD TIP TEMPERATURE: 35 K
COMPRESSOR STROKE: 9.1 mm p-p
DRIVE FREQUENCY: 50.27 Hz
COMPRESSOR OFFSET: 0.0 mm

DEGREE OF HARMONIC NULLING

Fz HARMONICS #1-5 NULLED
Fz HARMONICS #1-9 NULLED

Fx

Fy

Fz

FORCE, N

FORCE, N

FORCE, N

FREQUENCY, Hz

FREQUENCY, Hz

FREQUENCY, Hz

Hz
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 at 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

Fragile Cold Finger

Unconstrained Pistons

Diagram of a cryogenic system with labeled components:
- Pulse Tube
- Cold Block
- Regenerator
- Capacitor Position Sensor
- Flexure Bearings
- Heat Rejection Cold Plate
- Linear Motor Coil
- Piston
- Motor Magnet Assembly
● 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)
• 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

80K

CRYOCOOLER COLDTIP

BUMPER GAP

COLDFINGER

DISPLACER BODY

FIBERGLASS SUPPORT TUBE

(300K)
Example Cryocooler Coldfinger
Particle Damper

Cryocooler Coldtip

Lead or Tungsten Shot

Displacer Body

Factor of 4 Vibration Reduction Achieved with Particle Damper

RELATIVE ACCELERATION

FREQUENCY, Hz

No Damper
w/ Shot Damper
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

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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

Note typical exceedances
High-Frequency AC Electric Field Test Setup with TRW PT Cooler
Early Cryocooler Electronics
AC Electric Field Emissions

Note typical exceedances
AIRS Cryocooler Electronics
Conducted Ripple Current

- **S/N 301**
- **S/N 302**

**Graphs:**
- **Current vs. Time (msec):**
  - Y-axis: Current (A)
  - X-axis: Time (msec)
- **Ripple Current vs. Cooler System Input Power (watts):**
  - S/N 301
  - S/N 302
  - PEAK
  - AVE.

**June 2015**
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.