US Space Cryocoolers for 4 to 6 Kelvin

Cryocoolers for Space

Mid and Far Infrared Astronomy for Future Space Missions

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US Cryocoolers for 4 to 6 Kelvin

- Turbo-Brayton
  - Under development at Creare
- Two-stage Sorption Joule-Thomson (J-T)
  - Under development at JPL
- Stirling/J-T Hybrid
  - Under development at Ball
- Two-stage J-T with Rotary Vane Compressor
  - Under development at Ball
- Stored Cryogen
  - Solid hydrogen plus liquid helium
  - Multi-stage radiators plus liquid helium
**Turbo Brayton Cryocooler - Features**

**System Elements**
- DC/AC conversion for motor drive
- Turbomachines for compression and expansion
- High performance recuperative heat exchangers
- Heat, \( Q_{\text{rej}} \), conveyed to radiator(s) by conduction and gas (fluid loop)

**Features**
- Hermetic, single gas, closed loop
- Low mass, high speed turbomachines produce essentially no vibration
  - No linear motion mass
  - Continuous, steady gas flow
- Self acting gas bearings support shaft
- All metal - no contaminants
- Component based system
  - Fluid tubes between components
  - Readily adaptable to multiple loads
  - Simple cold plate thermal interfaces
- Simple electronics and controls
  - Cooling controlled by compressor speed
  - No vibration compensation required
- Space qualified 70 Kelvin cryocooler
  - HST Orbital System Test on STS-95, October, 1998
HST/NICMOS 75 Kelvin Cryocooler

- Single stage TurboBrayton Cryocooler with cryogenic circulator

- Flight cryocooler components during initial mechanical spin tests
Turbo-Brayton Cryocooler - NGST Design

- Turbo-Brayton cryocooler design presented herein is based on the GSFC Yardstick NGST design
- Nominally 100 W input power
- Mid-IR detector cooling at 6.5 Kelvin
- Heat rejection by radiators
  - 1.7 m² split radiator for NGST Yardstick design presented here
- Essentially no vibration tolerance
Turbo-Brayton Cooler - NGST System Schematic

- Two compressors in series
  - 50 W each, rejected at 220 K
  - 1 m² radiator at about 220 K
  - Will use existing gas-bearing centrifugal design

- Intermediate-stage radiator
  - Approximately 0.5 W, 60 Kelvin radiator

- Two recuperators in series
  - Warm recuperator parasitic heat load rejected at 60 K
  - Baseline existing slotted plate design for both recuperators

- Single expansion turbine
  - Produces refrigeration at 6 to 8 Kelvin
  - Up to 100 mW at 6 Kelvin capacity
Turbo-Brayton Cooler - Technology Status

- Flight heritage from HOST (STS-95)
- Compressor
  - Design approach, materials, and assembly methods established during HST/NICMOS Cryocooler qualification
  - Operating temperature and power levels have been demonstrated
- Turbine
  - Performance optimization required for NGST flow rate
- Recuperator
  - Bearings demonstrated at 12 Kelvin
  - Demonstration for 6 K operation in year 2000
  - Slotted plate (NICMOS) design is baseline
  - New recuperator developments aimed at improved efficiency and packaging of recuperators
Turbo-Brayton Cooler - Development Plan

- Proof of Principle System Demonstration in 2000
  - Component designs tested
    - Low power compressor modified for helium (approximately 50 W)
    - Turboalternator modified for helium gas and 6 Kelvin operation
    - HST/NICMOS slotted plate recuperative heat exchanger
  - Establish component performance characteristics
    - Compressor efficiency
    - Heat exchanger effectiveness down to 6 Kelvin
    - Turboalternator efficiency

- Integrate improvements into breadboard by 2002
  - Refine turbine design to improve cycle efficiency
    - Reduced rotor size
    - Hybrid bearing support
  - Higher performance recuperators
Turbo-Brayton Cooler - Summary

- **Turbo-Brayton Technology for NGST**
  - 100 W input power, 40 kg mass, approximately 100 mW at 6 K
  - Radiator size of 1.7 m²

- **Development Schedule**
  - Proof of Principle demonstration in 2000
  - Breadboard cooler demonstration and begin life test in 2002
  - Flight qualification of cooler in 2004

- **Interfacing and integration issues should be addressed as part of payload design since components can be integrated separately**
  - Components are connected by stainless steel tubing over large distances
    - Bellows can be added to allow flexibility between components
Two-stage Sorption J-T Cryocooler

- NASA/Jet Propulsion Laboratory (JPL) has designed a two-stage J-T cryocooler
  - Hydrogen first-stage based on sorption J-T cryocooler for Planck
    - Pre-cooling of hydrogen provided by radiator
  - Helium second-stage provides 10 mW of cooling at 6 Kelvin
    - Second-stage uses carbon adsorption compressor cooled to 18 Kelvin by the first-stage
Planck Will Make The Definitive Measurement of The Cosmic Microwave Background

- Planck Is the European Space Agency’s Third Mid-Sized Mission (M3)
  - Planck Will Launch With FIRST In 2007

- Two Instruments Image Full Sky Between 30 and 857 GHz In Nine Spectral Bands
  - High Frequency Instrument (HFI) Bolometric Array at 0.1 K
  - Low Frequency Instrument (LFI) HEMT Radiometer at 20 K

- Complete Cooling Chain Includes
  - Passive Cooling To less than 50 K Using V-Groove Radiators
  - Sorption Coolers (Two For Full Redundancy) To 20 K and 18 K
  - RAL Mechanical J-T Cooler To 4.5 K
  - Benoit-Style Open-Cycle Dilution Cooler to 1.6 K and 0.1 K
Two Vibration-Free Sorption Coolers Will Fly on the Planck Mission

- The fully redundant cooler design will provide approximately 230 MW cooling at 18 K for HFI and approximately 1.45 W cooling at 20 K for LFI
- Mission life requirement is 18 months on orbit
  - 2.5 years minimum with ground testing
- Input power of less than 550 W including electronics
  - Heat rejected at 270 K radiator on spacecraft bus
- Each cooler will mass less than 50 kg including electronics and support structures
- Cooler now in development at NASA’s Jet Propulsion Laboratory
  - Flight electronics and software will be developed by ISN in Grenoble, France
  - Qualification Model Cooler delivered January 2003 will fly as redundant spare
  - Flight Model Cooler delivered March 2004
Stirling/J-T Cryocooler - Introduction

- Stirling/J-T hybrid system under development to provide 250 mW cooling at 10 K
  - Can be scaled to provide 10 mW at 6.5 Kelvin for NGST
- Three-stage Stirling cryocooler based on existing 35/60 Kelvin three-stage cooler
  - New cold finger will provide 15 Kelvin pre-cooling for J-T stage
- Currently developing rotary vane compressor for helium J-T loop
Ball Development of J-T Cryocoolers

- Initial development focused on three-stage J-T systems
- COOLLAR program began in 1985 - developed:
  - compressors
  - non-plugging J-T Valves
  - heat exchangers
  - contamination control systems
- COOLLAR cryocooler flight demonstrated
  - flew on STS-85 in August 1997
  - demonstrated performance of oil-lubricated compressor, non-plugging J-T valves, heat exchangers, and contamination control system
  - all mission objectives met - 300 hours of continuous operation
Stirling/J-T Cryocooler - Status

- Began development of rotary vane compressor in 1996
  - Based on highly reliable commercial compressor
  - Small, lightweight, no valves
  - Vane wear rate testing shows 10 year life in dry helium

- Currently developing helium J-T loop
  - Stirling/J-T hybrid system to provide 250 mW cooling at 10 K
  - Fabrication of J-T loop underway
Ball Two-Stage J-T Cooler - Introduction

- Two-stage hydrogen & helium Joule-Thomson Cryocooler
- Long life rotary vane compressor for each stage
  - Reduced vibration from Stirling cycle linear cooler
- Flight proven J-T cold head technologies
  - Compact, simple tube in tube heat exchanger design, demonstrated on COOLLAR
  - J-T Valves with in line filter - clog resistant, etched "button" valves from COOLLAR
- Electronics
  - Simple brushless DC motor controller
- Low input power system design with use of mid-stage radiator
Hydrogen/Helium Two-Stage J-T Cryocooler

Spacecraft Radiator

- 19 W at 220 K or 21 W at 270 K

ISIM Radiator

- 114 mW at 33 K

Detector Cold Stop

- 18 K

Focal Plane

- 10 mW at 6 K

Hydrogen Loop

Helium Loop

Compressors

Heat Exchangers

Heat Exchangers

Heat Exchangers

H$_2$ to He HXN

J-T Valve
# H\textsubscript{2}/He J-T Cryocooler - Characteristics

<table>
<thead>
<tr>
<th>Feature</th>
<th>Benefit</th>
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<tbody>
<tr>
<td>Rotary vane compressors</td>
<td>Simple, valve-less design with long life, no linear motion</td>
</tr>
<tr>
<td>Compressors, warm radiator located at/near S/C bus</td>
<td>Minimizes jitter impact, allows optimum NGST passive thermal performance</td>
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<tr>
<td>No moving parts in cold head</td>
<td>No vibration source at detector interface</td>
</tr>
<tr>
<td>High efficiency</td>
<td>Minimizes input power, radiator size</td>
</tr>
<tr>
<td>Design based on heritage at Ball</td>
<td>Minimizes risk</td>
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# H$_2$/He J-T Cryocooler - Performance

<table>
<thead>
<tr>
<th>Item</th>
<th>NGST Requirement (Goals)</th>
<th>Performance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Focal Plane Temperature</td>
<td>6-8 K</td>
<td>6.5 K w/$^4$He</td>
</tr>
<tr>
<td></td>
<td></td>
<td>6 K w/$^3$He</td>
</tr>
<tr>
<td>Focal Plane Load</td>
<td>10 mW</td>
<td>10 mW</td>
</tr>
<tr>
<td>Cold Shield Temperature</td>
<td>15-20 K</td>
<td>18 K</td>
</tr>
<tr>
<td>Vibration Induced Jitter</td>
<td>&lt; 15 nrads LOS disturbance</td>
<td>&lt; 6 nrads if passively isolated, 19 nrads if hard-mounted</td>
</tr>
<tr>
<td>NGST ISIM Radiator Sink</td>
<td>&lt;200 mW at 33 K</td>
<td>114 mW at 33 K</td>
</tr>
<tr>
<td>Input Power</td>
<td>&lt;100 W at 220 K goal</td>
<td>19 W at 220 K, or 21 W at 270 K</td>
</tr>
<tr>
<td>Mass (including Electronics)</td>
<td>Minimize as a goal</td>
<td>12 kg</td>
</tr>
</tbody>
</table>
H₂/He J-T Cryocooler - Summary

- Highly Leveraged, Low Risk Design
  - AFRL 10 K development of long life rotary vane helium compressor
    - Easy scaling (80% of 10 K) to low pressure hydrogen
      - COOLLAR development of cold head technologies
  - Inherently High Efficiency
    - Very low input power < 20 W with electronics
- Inherently High Reliability
- Minimal System Impacts
  - Minimal power usage at either 220 K or 270 K
  - Flexible location of compressor
  - No moving parts in cold head
  - Very low induced vibration