Alpha Magnetic Spectrometer (AMS-02) Cryocooler

Preliminary Design Review

September 10, 2002
Contents

• AMS Science/Technical Objective
• Bracket Interfaces and Requirements
• Program Overview
• Mechanical Design
• Structural Analysis
• Thermal Analysis
• Bracket Design Verification, Test Flow, Test Plans
• Other
Program Objective

• Design and analyze a flight qualified cryocooler bracket for the Alpha Magnetic Spectrometer-02 project. The analysis should include structural analysis, flight loads analysis and thermal analysis.
  – Cryocooler structural support with mechanical isolation to allow balancer to reduce cooler vibration
    » Accommodate launch loads with appropriate factors of safety
    » Provide fundamental frequency between 35 and 50 Hz
  – Provide thermal isolation between cooler heat rejection and vacuum case
  – Assist and accommodate cooler heat rejection by loop heat pipe provided
  – Maintain vacuum case seal using provided dual o-ring design

• Deliverables
  – Bracket design drawings
  – Analysis reports
Design Description

LHP Transport Lines (coiled to allow compliance)
Loop Heat Pipe (LHP) Evaporators (Qty 2)
Vacuum Case
Passive Balancer
Cryocooler Support Assembly
Cryocooler
Ring Flexure
Support Housing
Bellows Assembly
Evaporator / Heat Rejection Collar
Structural Interface with the Vacuum Case
Blade Flexure
Interface Requirements

- GSFC Alpha Magnetic Spectrometer-02 (AMS-02) Cryocooler Mechanical Interface Requirements (AMS-552-SPEC-003)
- Swales cryocooler ICD
- Sunpower revised cryocooler ICD
- Caged balancer ICD (defined in AMS-552-SPEC-003)
- Evaporator block ICD (defined in AMS-552-SPEC-003)
Design Introduction

• Geometry overview

• Mechanical interfaces & requirements
  – AMS-02 interface & keep-in zone
  – Vendor ICD

• Design layout
  – Compliance with interface requirements
  – Assembly overview
  – Assembly procedure
  – Electrical/thermal accommodations

• Mass properties/materials list

• Drawing status

• Risk assessment of machining & assembly
AMS-02 Cryocooler Assembly In Vacuum Case

AMS-02 Vacuum Case

Cryocooler Assembly

Passive Balance Mass (removed for shipping)
Interface Requirements (1)

- Accommodate mating interfaces
  - Vacuum Case
    » Eight #10-32 threaded inserts on 5.5” bolt circle for attachment of Cryocooler Assembly
    » 4” opening pass-through for Cryocooler Assembly
    » Double o-ring design required with test port
  - Passive Balance Mass
    » Six #8-32 bolts on 3.910” bolt circle
  - Evaporator Block
    » 14 M4 bolts for both blocks
  - Cryocooler
    » Mating hardware shall conform to geometric features
    » Six M5 helicoils on 2.704” bolt circle
    » Three M6 helicoils
    » Four M3 studs on 1.850” bolt circle
    » Double o-ring design required at Cryocooler shaft (no test port required)
    » Fill tube stay-out zone

- Cryocooler assembly must fit within keep-in zone
Interface Requirements (2)

- Incorporate 400 series CRES in Boot for magnetic shielding of Cryocooler (Lockheed spec calls out for Aluminum - CRES ok per waiver)

- Provide access and support for Loop Heat Pipe routing
  - Allow for compliance during pump-down, launch and on-orbit performance

- Surface roughness of 63 micro inches or better for all structural interfaces

- Mounting surfaces **shall not** be painted (Boot Flange at Vacuum Case shall be primed with Super Koropon to prevent corrosion)

- All vacuum surfaces shall be cleaned, polished and protected with vacuum grease (thin layer)

- Brackets
  - Power lead connector support
  - Temperature sensor lead connector support
  - LHP transport line support (to be defined)
  - Provide mounting locations for additional brackets
Cryocooler Interface

Using different flange design

Using different mounting hardware
Keep-in zone (defined by plane) requires that Balance Mass be removed for transport.

Vacuum Case
Compliance with Keep-in Zone

- Shipping Stay-out Zone
- Passive Balance Mass Removed for Shipping

Dimensions:
- 7.430" (188.7 mm)
- .927” (23.5 mm)
- 3.896" (99.0 mm)
- 17.812°
• Attach Pull Ring and Evaporator Collar (with pads) to Cryocooler
• Attach Cryocooler Assembly to Assembly Fixture
Assembly – Step 1b

• Nominal gap of 0.100” between Pull Ring and Collar
  – Allows for loose Cryocooler tolerances
  – Close gap to 0.010” max with peelable Pull Ring Shims

• Collar includes 0.005” gap on internal surfaces for Nusil
- Weld Bellows to Boot Flange and to Boot Interface Plate
- Attach Bellows Assembly to Cryocooler studs at four places
Assembly – Step 2b

- Bellows assembly welded off-line

- Two o-ring groves on Boot Flange to allow for vacuum seal to Cryocooler shaft
  - No test port required
  - Chamfer on Cryocooler required (not on ICD)

- Boot Flange and Boot Interface Plate are CRES 410 for magnetic shielding
  - Sized to match off-the-shelf Bellows part

- Bellows
  - Vendor identified: Senior Metal Bellows, division of Senior Flexonics
  - Welded design is less stiff, has longer life
  - Off-the-shelf material is CRES 347
  - Available in CRES 410 with increased expense
  - Rated for 50 psi minimum pressure load

- Weldability of CRES 410 to itself and to CRES 347 is low risk
Assembly – Step 3a

- Attach Boot Housing to Assembly Fixture
- Weld Boot Housing to Boot Interface Plate
Assembly – Step 3b

- Boot Interface Plate and Boot Housing
  - Designed to accommodate three cut-offs and re-weldings (allows access to items internal to Boot Housing)

- Cryocooler cold tip is pneumatically sealed within vacuum case for ground testing pressure differential

- Boot Housing includes test port to test inner o-ring seal
  - Test fitting replaced with plug prior to launch
  - Port, fitting and plug are standard design in accordance with MS33649 (straight pipe thread)

- Use threaded inserts to attach Boot Housing to Assembly Fixture to avoid scratching Boot Housing vacuum seal surface
Assembly – Step 4a

- Attach two Blade Flexures to Evaporator Collar with shear pins and bolts
Assembly – Step 4b

- Blade Flexure
  - Allows for motion only in Cryocooler thrust axis (Z)
  - Pinned to avoid misalignment at assembly and shifting during launch
  - Titanium provides excellent strength while minimizing the thermal path
Assembly – Step 5

• Attach two Flexure Brackets to Blade Flexures to Boot Housing
• Close tolerance bolts minimize flexure shifting during launch
• Use nylon washers on back side of Boot Housing to avoid scratching vacuum seal surface
• Attach Support Housing to two Flexure Brackets
Assembly – Step 6b

- Support Housing
  - Fabricated from Torlon (30% glass-filled thermoplastic) to reduce thermal path
  - Shell wall thickness 0.06” to reduce thermal path
  - Torlon vendor identified: Boedecker Plastics, Inc.
    » Properties defined for compression molded part
    » Stock sizes large enough to manufacture part
• Attach Ring Flexure to Support Housing
Assembly – Step 7b

- Ring Flexure
  - Allows for motion only in Cryocooler thrust axis (Z)
  - Primary load path for Z-axis launch loads
  - Titanium provides excellent strength with minimal thermal path
  - Geometry optimized to meet frequency requirements and reduce stresses
    » Minimum thickness is 0.016”
  - Clears the Cryocooler fill tube
Assembly – Step 8

- Attach Balance Mount to Cryocooler and Ring Flexure (trapped)
- Balance Mount clears the Cryocooler fill tube
• Attach Passive Balance Mass to the Balance Mount

#8-32 Nut (6X) on back-side of Balance Mount

#8-32 Bolt (6X)
Assembly – Step 10

- Remove Cryocooler Assembly from the Assembly Fixture
- Attach Support Brackets between Boot Housing and Support Housing
Assembly – Step 11

- Install Cryocooler Assembly into Vacuum Case
• Attach Evaporator Blocks to the Cryocooler Assembly (requires removal of Support Brackets)
Power/Sensor Connector Brackets
## Electrical Terminations

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<th>Device</th>
<th>Cable</th>
<th>Connector</th>
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<td>Collar Temp Sensor</td>
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<td>3 strands 24 AWG</td>
<td>Airborn 15 pin, MM-222-015-261-22WD</td>
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</table>
Mass Properties Summary

- Items not included:
  - Connector Brackets for thermal sensors and power leads
  - Wiring
  - Blanketing
  - LHP transport lines and brackets

- Parts associated with moving mass are highlighted
  - Total moving mass = 13.5 lbs (6.1 kg)
## Drawing Status Summary

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<th>Quantity</th>
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Alpha Magnetic Spectrometer
(AMS-02) Cryocooler
Structural Analysis

Perry Wagner – Structural Analysis Group
Phone Number: 301-902-4527
Email: pwagner@swales.com
Structural Analysis Introduction

- Structural requirements/load cases
  - Loads/testing levels defined

- Material allowables

- Finite element model

- Analysis results
  - Normal modes
  - Maximum deflections
  - Random vibration spec

- Margin of safety summary table

- Fracture classification

- Summary
Structural Requirements (1)

• Fundamental Frequency
  – Above 35 Hz (Shuttle requirement)
  – Below 50 Hz in Cryocooler thrust axis (vibration isolation)

• Quasi-static Loads
  – \(X=\pm 14.4G, \ Y=\pm 3.6G, \ Z=\pm 3.6G\)
  – \(X=\pm 3.6G, \ Y=\pm 14.4G, \ Z=\pm 3.6G\)
  – \(X=\pm 3.6G, \ Y=\pm 3.6G, \ Z=\pm 14.4G\)

• GEVS Workmanship Random Vibration Input
  – Peak PSD = .04 G^2/Hz
  – Overall \(G_{\text{RMS}} = 6.8\)
  – 60 seconds per axis

• 1 atmosphere pressure differential (ground test)
Structural Requirements (2)

- Factors of Safety
  - Yield = 1.25
  - Ultimate = 2.0

- Fracture classification of all parts required
  - 3 launch/landings
  - 3 operational years plus 2 contingency years on ISS

- Miscellaneous
  - No kick-load requirement
  - Limit Cryocooler travel during launch to ±0.12”
Owners' manual (1)

• Lockheed-Martin analysis/test approach (email dated 12/21/01):
  – Analyze to reduced quasi-static loads 14.4/3.6/3.6 (reduced from 40/10/10)
  – Analyze to trunnion random vibration levels $(3.2 \text{ G}_{\text{RMS}})$
    » No load amplification and some damping due to AMS-02
    » No acoustic loads on Cryocooler assembly
  – Test to GEVS workmanship random vibration levels
    » Use this test as a qualification test
  – Use yield and ultimate factors of safety of 1.25/2.0 (reduced from “no-test” factors of 2.0/2.6)
  – NASA/JSC has provided preliminary approval of above approach

• Higher loads require stops to limit deflections
  – Non-linear random analysis shows high impact loads at stops, Support Housing and Brackets
Loads/Test Definition (2)

• Updated structural requirements:
  – Use reduced quasi-static loads (14.4/3.6/3.6)
  – Adopt lower factors of safety (1.25/2.0)
  – Analyze to GEVS workmanship random vibration levels (6.8 $G_{\text{RMS}}$)
  – Test to GEVS workmanship random vibration levels
  – Recommendation: Perform sine burst to 18.0G’s (1.25 * 14.4) for qualification in all three axes
Material Allowables

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<tr>
<th>Material</th>
<th>Specification</th>
<th>Modulus (Msi)</th>
<th>Density (lbs/in^3)</th>
<th>Ftu (ksi)</th>
<th>Fty (ksi)</th>
<th>Fsu (ksi)</th>
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<td>28</td>
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Stress corrosion cracking not considered to be an issue
- Aluminum 6061-T6 and Ti-6Al-4V are in accordance with MSFC-STD-3029, Table I.
- CRES 410 is classified as Table II
  - Stresses are low
  - Requires MUA waiver
- Torlon is a glass-filled composite
- Oxygen-free copper is not classified in MSFC-STD-3029
- Cryocooler, Evaporator Collar, Pull Ring and Boot Flange modeled as lumped mass
- Total moving mass is 13.5 lbs
Normal Modes Results

First mode is 43 Hz – Cryocooler mass translating in Z-axis

- Higher order modes are well above 60 Hz Cryocooler driving mode
Deflection Results

• Maximum predicted deflection of the Cryocooler in the Z-axis due to:
  – 1 atmosphere pressure differential (ground test) is 0.016”
  – Quasi-static loads (3.6/3.6/14.4) is 0.078”
  – Random vibration spec is 0.087”
  – Sine burst testing is 0.098”

• Max Cryocooler deflection is below 0.12” allowable
Random Vibration Analysis

Miles Equation:

\[ g = 3 \left[ \left( \frac{\pi}{2} \right) (PSD)(f_n)(Q) \right]^{0.5} \]

- PSD (at \( f_n = 43 \) Hz) = 0.021 g²/Hz
- Assume \( Q = 20 \)

Equivalent 16.0G static load
### Margin of Safety Summary Table

<table>
<thead>
<tr>
<th>Component Description</th>
<th>Material</th>
<th>Failure Mode</th>
<th>Critical Load Case</th>
<th>Allowable (ksi)</th>
<th>Minimum Margin of Safety</th>
<th>Associated Stress (psi)</th>
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<tbody>
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<td>Pull Ring</td>
<td>6061-T651</td>
<td>Flange Bending</td>
<td>Assembly Pre-load</td>
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<td>+4.93  +3.37</td>
<td>4,803</td>
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<tr>
<td>Balance Mount</td>
<td>6061-T651</td>
<td>Bending</td>
<td>Launch (14.4 / 3.6 / 3.6)</td>
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<td>+HIGH  +HIGH</td>
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<tr>
<td>Ring Flexure</td>
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<td>52,085</td>
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<tr>
<td>Support Housing</td>
<td>Torlon 5530</td>
<td>Flange Bending</td>
<td>Launch (3.6 / 3.6 / 14.4)</td>
<td>-  - 15</td>
<td>-  -  +4.64</td>
<td>1,329</td>
</tr>
<tr>
<td>Flexure Bracket</td>
<td>6061-T651</td>
<td>Flange Bending</td>
<td>Launch (3.6 / 14.4 / 3.6)</td>
<td>35  42</td>
<td>+2.24  +1.43</td>
<td>8,642</td>
</tr>
<tr>
<td>Support Bracket</td>
<td>6061-T651</td>
<td>Flange Bending</td>
<td>Random Vibration (Y-axis)</td>
<td>35  42</td>
<td>+1.28  +0.71</td>
<td>12,280</td>
</tr>
<tr>
<td>Boot Assembly</td>
<td>CRES 410</td>
<td>Flange Bending</td>
<td>Random Vibration (Y-axis)</td>
<td>40  70</td>
<td>+HIGH  +HIGH</td>
<td>3,540</td>
</tr>
<tr>
<td>Blade Flexure</td>
<td>Ti-6Al-4V</td>
<td>Bending</td>
<td>Random Vibration (Z-axis)</td>
<td>120 130</td>
<td>+1.02  +0.37</td>
<td>47,581</td>
</tr>
</tbody>
</table>

Stresses are low in Evaporator Collar and Connector Brackets
# Fracture Classification Summary Table

<table>
<thead>
<tr>
<th>Component Description</th>
<th>Material</th>
<th>Resistance to Stress Corrosion Cracking</th>
<th>Fracture Control Classification</th>
<th>Fracture Critical?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pull Ring</td>
<td>6061-T651</td>
<td>High</td>
<td>Low Risk Fracture Part</td>
<td>No</td>
</tr>
<tr>
<td>Balance Mount</td>
<td>6061-T651</td>
<td>High</td>
<td>Low Risk Fracture Part</td>
<td>No</td>
</tr>
<tr>
<td>Ring Flexure</td>
<td>Ti-6Al-4V</td>
<td>High</td>
<td>Safe-Life Fracture Part</td>
<td>Yes</td>
</tr>
<tr>
<td>Support Housing</td>
<td>Torlon 5530</td>
<td>High</td>
<td>Low Risk Fracture Part</td>
<td>No</td>
</tr>
<tr>
<td>Flexure Bracket</td>
<td>6061-T651</td>
<td>High</td>
<td>Low Risk Fracture Part</td>
<td>No</td>
</tr>
<tr>
<td>Support Bracket</td>
<td>6061-T651</td>
<td>High</td>
<td>Low Risk Fracture Part</td>
<td>No</td>
</tr>
<tr>
<td>Boot Assembly</td>
<td>CRES 410</td>
<td>Medium</td>
<td>Low Risk Fracture Part</td>
<td>No</td>
</tr>
<tr>
<td>Blade Flexure</td>
<td>Ti-6Al-4V</td>
<td>High</td>
<td>Safe-Life Fracture Part</td>
<td>Yes</td>
</tr>
<tr>
<td>Evaporator Collar</td>
<td>OF Copper C101</td>
<td>High</td>
<td>Low Risk Fracture Part</td>
<td>No</td>
</tr>
</tbody>
</table>
Cryocooler assembly meets all structural requirements

- Fundamental frequency in Z-axis is 43 Hz
- Positive margin of safety demonstrated for all parts due to quasi-static and random vibration load cases
  - Minimum margin of safety is +0.25 in Ring Flexure
- Maximum expected deflection is less than the allowable gap
- Sine burst test recommended for qualification testing
AMS Thermal Analysis

Topics

- Requirements
- Thermal Design
- Nodal Diagram
- Thermal Properties
- Conductance Values
- Predicted Performance
- Summary/Conclusions
AMS Thermal Analysis

Requirements

- Cooler dissipation: 100 W (95 W at ring, 5 W in body)
- Conductance from cooler to mounting surface: < 0.01 W/K
- Conductance from cooler to evaps. via Cu collar: > 16.66 W/K … ΔT < 6 K
- Heat transfer from cooler body to Cu collar: ~ 5 W transport, ΔT < 2 K
AMS Thermal Analysis

Thermal Design: Basic Approach

- **Mounting Interface**: (double o-ring seal)
- **6Al-4V Ti Flexure**: (thermal isolator, soft flexure)
- **Nusil I/F Material**
- **Foil* I/F Material**: *unspecified

- **Cryocooler Body**
  - ~ 5 W Dissipation

- **6Al-4V Titanium Ring**: (moderately stiff flexure)

- **Evaporator Interface**: (thermal conductor)
  - ~ 95 W Dissipation

- **Torlon Cylinder**: (thermal isolator)

- **OFHC Cu Collar**: (thermal conductor)

- **Stainless Steel Bellows (Welded) Assembly**: (thermal isolator, double o-ring seal to cooler)
AMS Thermal Analysis
Thermal Design: Key Components

- 6Al-4V Titanium Ring
- Stainless Steel Bellows Assembly
- OFHC Cu Collar
- 6Al-4V Titanium Flexure
- Torlon Cylinder
AMS Thermal Analysis

Nodal Diagram

- Nodal Diagram

\[
\begin{array}{c}
\text{G1} & \text{Ti Ring} \\
\text{G2} & \text{Torlon Cylinder} \\
\text{G6} & \text{Ti Flexure} \\
\text{G*} & 95 \text{ W} \\
\text{G**} & 5 \text{ W} \\
\text{G3} & \text{Copper Collar} \\
\text{G4} & \text{Nusil I/F Material} \\
\text{G5} & \text{Nusil I/F Material} \\
\end{array}
\]

- C1 = Cooler bottom
- C2 = Cooler top
- E = Evaporator I/F
- M = Mounting I/F
- G* = Internal cooler coupling
- G** = Coupling of cooler top to Cu collar
AMSA Thermal Analysis
Thermal Properties

• Thermal Properties at 300 K
  - Ti (6Al-4V) \( k = 7.5 \text{ W/m K} \)
  - Stainless Steel \( k = 15 \text{ W/m K} \)
  - Cu (OFHC) \( k = 400 \text{ W/m K} \)
  - Torlon \( k = 0.36 \text{ W/m K} \) (30% glass filled)
  - Nusil (I/F material) \( h = 7.5 \text{ W/in}^2 \text{ K} \)
  - Foil* (I/F Material) \( h = 10 \text{ W/in}^2 \text{ K} \)

*type of foil unspecified
AMS Thermal Analysis

Conductance

• Component Geometry
  – Ti Ring  \textit{thinnest section}: OD = 4.4", ID = 3.8", t = 0.016"
  – Torlon Cylinder \textit{thinnest section}: ID = 4.4", L = 2.238", t = 0.060"
  – Copper Bracket Pro-E --> STEP file --> FEMAP --> direct conductance calc.
  – Cooler I/F \textit{internal surface}: D = 2.5", W = 0.75"
  – Evaporator I/F \textit{single surface}: L = 3.937", W = 1.181", 2 surfaces
  – Ti Flexure \textit{single blade}: L = 1.182", W = 0.25", t = 0.020", 4 blades
  – St. Stl. Bellows \textit{1/2 convolution}: OD = 2.25", ID = 1.5", t = 0.016", 30 half convols.

• Conductance
  – Ti Ring \quad G_1 = 2 \pi k t \ln \left(\frac{\text{OD}}{\text{ID}}\right) = 0.13 \quad \text{W/K}
  – Torlon Cylinder \quad G_2 = k \pi (D + 2t) t / L = 0.0035 \quad \text{W/K}
  – Copper Bracket \quad G_3 = 26.8 \quad \text{W/K}
  – Cooler I/F \quad G_4 = h \pi D W = 44.2 \quad \text{W/K}
  – Evaporator I/F \quad G_5 = 2 h L W = 93.0 \quad \text{W/K}
  – Ti Flexure \quad G_6 = 4 k W t / L = 0.0032 \quad \text{W/K}
  – St. Stl. Bellows \quad G_7 = \left(\frac{1}{30}\right) 2 \pi k t \ln \left(\frac{\text{OD}}{\text{ID}}\right) = 0.0031 \quad \text{W/K}
Predicted Performance

- Conductance from cooler to mounting surface
  - Path 1: \((1/G1 + 1/G2)^{-1}\) = 0.0034 W/K
  - Path 2: \(G6\) = 0.0032 W/K
  - Path 3: \(G7\) = 0.0031 W/K
  - Paths 1-3 in parallel = 0.0097 W/K

- Conductance from cooler to evap. via Cu collar
  - Path 1: \(G4\) = 44.2 W/K
  - Path 2: \(G3\) = 26.8 W/K
  - Path 3: \(G5\) = 93.0 W/K
  - Paths 1-3 in series = 14.1 W/K

- Provide coupling from cooler body to Cu collar to transport 5 W with < 2 K ∆T
  - Two possible heat transfer paths
  - First path is via can that clamps Cu collar to cooler
  - Second path is gap between Cu collar near evaporators and cooler
    - Gap can be filled with Nusil … cross-sectional area several square inches
  - Those two paths will provide the needed coupling (> 3 W/K with Nusil-filled gap)
AMS Thermal Analysis

Summary/Conclusions

• Summary
  – Conductance from cooler to mounting surface 0.0097 W/K vs. < 0.01 W/K reqt.
  – Conductance from cooler to evaporators via Cu collar 14.1 W/K vs. >16.66 W/K reqt.
  – Coupling from cooler body to Cu collar >> 3 W/K

• Conclusions
  – Isolation between cooler and mounting interface is acceptable
  – \( \Delta T \) between cooler and evaporator surface expected to be 95/14.1 = 6.7 K (vs. 6.0 reqt.)
  – \( \Delta T \) can be reduced by
    ▪ Attaching Cu collar to cooler with higher performance I/F material
    ▪ Attaching evaporators to Cu collar with higher performance I/F material
    ▪ Increasing conductance of Cu collar via embedding higher conductance material within collar (perhaps APG) or possibly by embedding miniature heat pipes within collar
    ▪ Above options were not pursued due to their added complexity and higher risk
Alpha Magnetic Spectrometer (AMS-02) Cryocooler

Appendix (Back-up Slides)
AMS-02 Vacuum Case
• Eight #10-32 threaded inserts on 5.5” bolt circle for attachment of Cryocooler to Vacuum Case

• Double O-ring design defined
Evaporator Block Interface
Balance Mount
Load Case: Launch (14.4/3.6/3.6)

Output Set: MSC/NASTRAN Case 5
Contour: Plate Top VonMises Stress, Plate Bot VonMises Stress
FEM Stress Analysis Results (2)

Ring Flexure
Load Case: Random Vibration (Z-axis)

Output Set: MSC/NASTRAN Case 19
Contour: Plate Top VonMises Stress, Plate Bot VonMises Stress
FEM Stress Analysis Results (3)

Support Housing
Load Case: Launch (3.6/3.6/14.4)

Output Set: MSC/NASTRAN Case 14
Contour: Plate Top VonMises Stress, Plate Bot VonMises Stress
Flexure Brackets
Load Case: Launch (3.6/14.4/3.6)

Peak Stress

Output Set: MSC/NASTRAN Case 9
Contour: Plate Top VonMises Stress, Plate Bot VonMises Stress
Support Brackets
Load Case: Random Vibration (Y-axis)

Output Set: MSC/NASTRAN Case 18
Contour: Plate Top VonMises Stress, Plate Bot VonMises Stress
FEM Stress Analysis Results (6)

Boot Assembly
Load Case: Random Vibration (Y-axis)

Output Set: MSC/NASTRAN Case 18
Contour: Plate Top VonMises Stress, Plate Bot VonMises Stress
Blade Flexure
Load Case: Random Vibration (Z-axis)

Output Set: MSC/NASTRAN Case 19
Contour: Plate Top VonMises Stress, Plate Bot VonMises Stress