DESIGN AND DEVELOPMENT OF A HIGH POWER STIRLING COOLER

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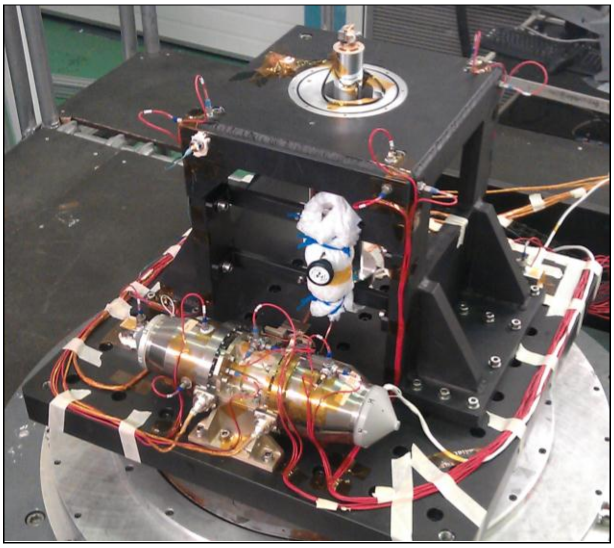

Figure 1. The High Power Stirling Cooler under vibration test

ABSTRACT

Astrium has been producing Cryocoolers for space flight since the 1980s, with more than 210 years accumulated in orbit operation [1], including >125 years for the 50-80°K Cooler.

To meet the requirements of a number of upcoming European Earth Observation missions, Astrium, in response to a European Space Agency requirement, have developed a new higher power Stirling Cycle Cryocooler, based largely upon the highly successful 50-80K Cooler.

This paper looks at the general design of Astrium Cryocoolers and focuses specifically on developments made to increase the available cooling power.

1. THE NEED FOR CRYOCOOLERS ON SPACE MISSIONS

The effective sensitivity of thermal sensors is significantly improved if they, and surrounding equipment, are cooled to cryogenic temperatures. This increases the signal to noise ratio, allowing much more accurate data to be obtained. Such thermal sensors can be used to detect distant energy sources for deep-space astronomy and astrophysics or to measure planetary surface temperatures. There are also applications for military observation satellites.

The target temperature required is dictated by the mission profile. Deep space observatories will commonly operate with instruments in the millikelvin range (< 1K), while for Earth Observation 50 – 80K is typical.

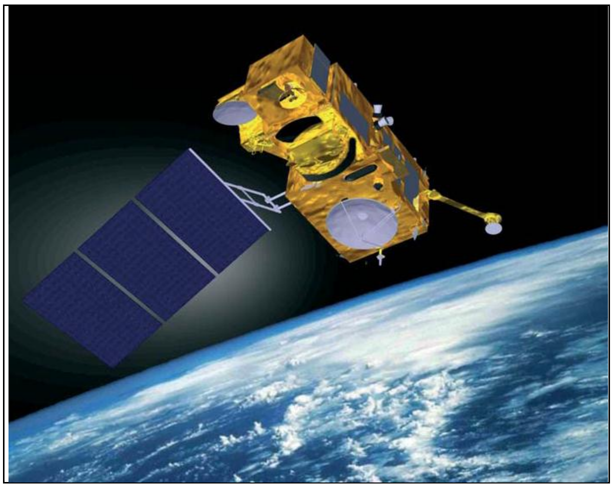

Figure 2. The GMES Sentinel 3, which will carry two Astrium 50-80K Coolers. © ESA

There are three main methods currently employed to achieve this:

- Passive sun shield, as used on Gaia
- Helium cryostat, as used on Planck
- Active closed cycle Cryocooler, as used on Sentinel 3

For Earth Observation missions, where the orbit does not permit use of a sun shield and a limited capacity cryostat will not meet mission lengths of in excess of 10 years, an active closed cycle Cryocooler is required.

To meet projected future mission needs, Astrium have developed the High Power Stirling Cooler, HPSC. This product is designed to lift 2000mW of thermal energy from a target at 50K, more than double that of its predecessor.

2. THE STIRLING CYCLE

Astrium Cryocoolers operate on the Stirling Cycle principle. Originally developed in the 1800s as a means of extracting mechanical work from heat, the

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thermodynamic process can be run in reverse to generate a refrigeration effect.

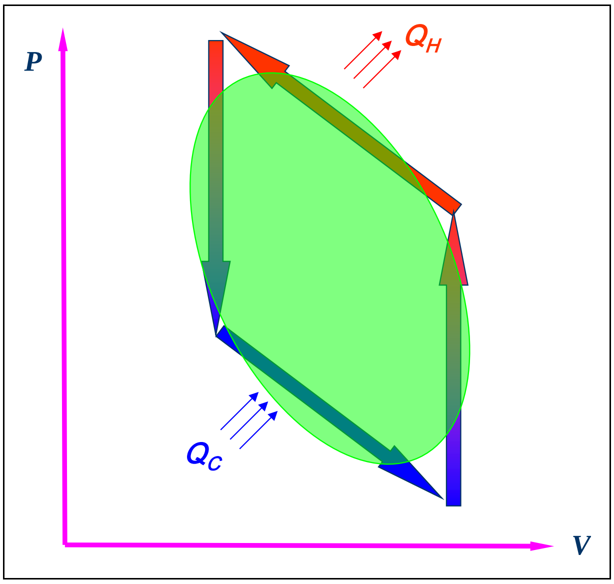

Figure 3. Pressure – Volume diagram of the Stirling Cycle.

The cycle employs two devices: a compressor and a displacer. The compressor powers the cycle and will consume the vast majority of the electrical power. The displacer is where gas expansion occurs, generating the cooling effect. Its mechanism is used to control the compressor – displacer phase difference and not to compress the working fluid. Consequently, it uses <5% of the total electrical power.

The preferred architecture for space use is known as a split cycle configuration. This separates the Cryocooler into two separate assemblies which can be mounted independently. This allows the electrically and mechanically noisy compressor to be mounted away from the instrument, which only needs be mounted directly to the displacer, usually via a flexible Thermal Link Assembly, TLA.

3. HPSC ARCHITECTURE

As discussed above, the HPSC is split into two distinct assemblies: the compressor and the displacer. These are linked by a pipe, which transfers the working fluid between them. All assemblies make use of linear electric motors and together form a pressurised vessel filled with helium at 15bar.

3.1. Compressor Assembly Design

The 50-80K Stirling Cooler features a single compressor mechanism, however to increase the available gas work to the displacer the HPSC incorporates two identical compressor mechanisms. The mechanisms are mounted back-to-back on a central bracket. This design means any vibration generated by a mechanism's operation is inherently cancelled by its opposed partner.

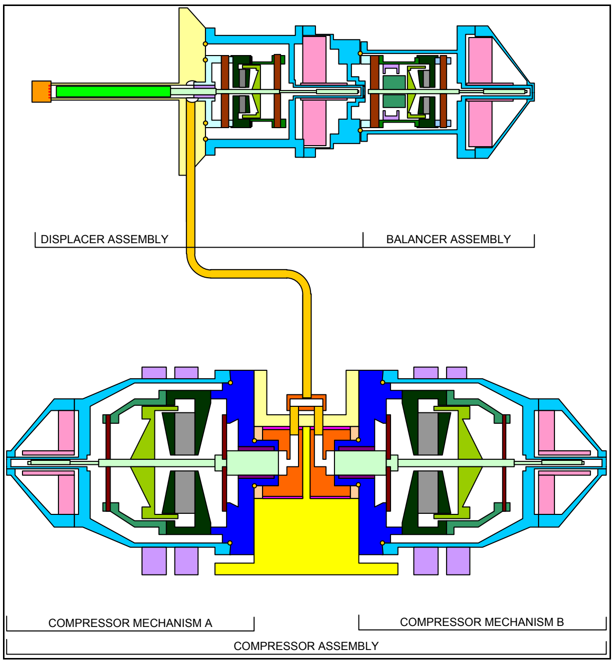

Figure 4. HPSC Schematic.

As well as providing a mechanical mounting for the mechanisms, the central bracket also thermally couples the unit to the Spacecraft, S/C, removing heat from the motor coil resistance and the more significant heat of compression.

3.2. Compressor Mechanism Design

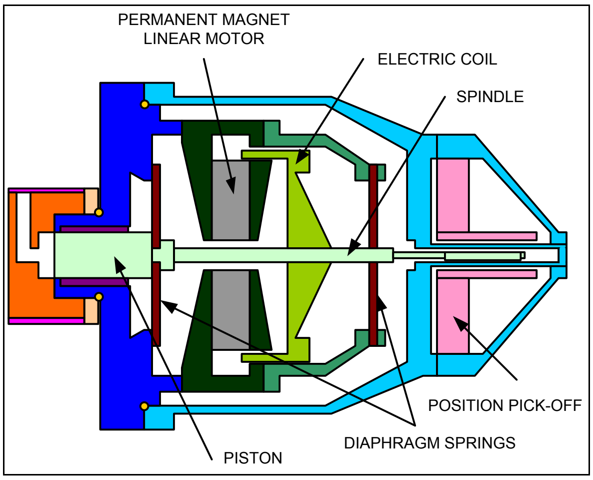

Figure 5. HPSC compressor mechanism.

The HPSC compressor mechanism is directly based upon that of the 50-80K Cooler. To increase the amount of work the unit is capable of without increasing the stroke, the piston bore is 10% larger. This is the only change in the unit, meaning the vast majority of parts are common with the 50-80K Cooler.

The mechanism is built around a central spindle, on which is mounted an electric coil, a piston and a soft iron core. This assembly is suspended between two packs of diaphragm springs, with the piston and soft iron core extending at either end.

The coil oscillates axially inside the stationary bore of the close fitting permanent magnet. It is electrically connected to the Cooler Drive Electronics, CDE, via flexible lead-in wires. An electric current is then driven through the coil, and the field generated causes the spindle to move linearly, driving the piston in and out of the cylinder head.

The soft iron core is used for position sensing of the mechanism. This is done by means of a linear variable differential transformer, LVDT, mounted in the mechanism cover.

The oscillation approximates a sine wave and is tuned to match the mechanisms natural frequency of approximately 40Hz. The maximum rated stroke is 9.0mm peak-to-peak, PkPk, at which the compressor will draw approximately 70W electrical power.

3.3. Displacer and Momentum Balancer Design

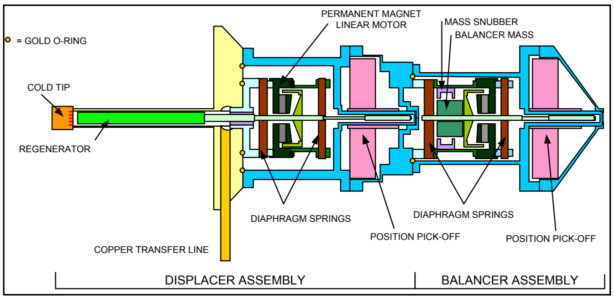

Figure 6. HPSC displacer assembly.

The HPSC displacer comprises of two mechanisms mounted inline: the actual displacer mechanism and a momentum balancer to provide vibration cancelation.

The displacer and momentum balancer mechanisms' design are fundamentally the same as the compressor mechanism, but reduced in size to reflect their lower stroke and electrical power draw: 4.6mm PkPk and 5W electrical respectively.

To improve thermodynamic efficiency, the piston is replaced by a regenerator. This acts a thermal capacitor, storing heat from the hot compressed gas as it is transferred to cold displacer and restoring it on the return journey.

As with the compressor mechanisms, the majority of components in the displacer and momentum balancer are common to the 50-80K Cooler.

4. MECHANISM OPERATING ENVIRONMENT

All mechanisms are completely enclosed within the Cryocooler pressure vessel. Prior to sealing, the pressure vessel is vacuum baked-out to remove any contaminants. The unit is then filled with the working fluid, high purity helium gas. Any contamination present in the Cryocooler would accumulate at the cold tip, where it would freeze. This reduces heat transfer, can block gas flow and even jam the precision mechanisms.

5. DESIGN FOR INFINITE LIFE

The HPSC is required to provide 8 years (12 goal) continuous operation. Several 50-80K Stirling Coolers have achieved over 12 years' service in orbit. With an operating frequency of 40Hz, this equates to >12 x 10^9 cycles. Therefore, the Cryocooler is designed for "infinite life," with all components theoretically capable of endless operation.

5.1. Compressor Mechanism Design

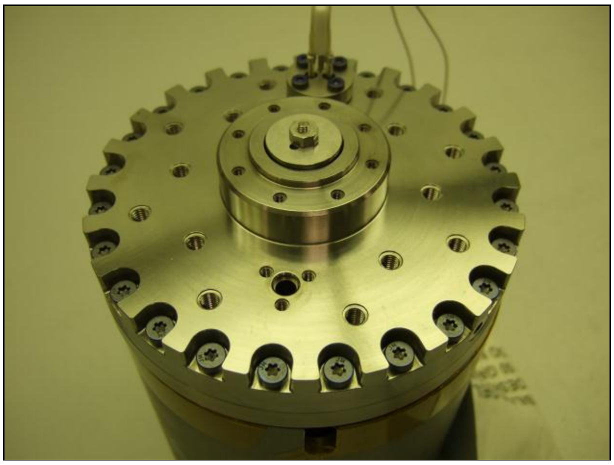

Figure 7. Compressor assembly showing piston in clearance seal.

Effective gas sealing is required for practical operation of the compressor and displacer mechanisms. All dynamic seals are of the clearance type.

Clearance seals rely on tight clearances between moving components to generate the sealing effect. Experimentation and trial has shown the target radial clearance needed to be ≈ 10µm. Larger than this and large quantities of gas can flow past the piston, damaging efficiency.

These tight clearances mean that it is inevitable the moving surfaces will at some point come into contact, such as during vibration or shock testing. To mitigate for this and prevent damage occurring, a low friction interface is employed. A combination of the TA11 titanium piston and molybdenum disulphide loaded Vespel SP3 bore provides the required material pairing.

While this solution is effective, the dissimilar coefficients of thermal expansion, CTEs, mean that careful design and assembly must be employed to prevent jamming at temperature extremes.

5.2. Diaphragm Springs

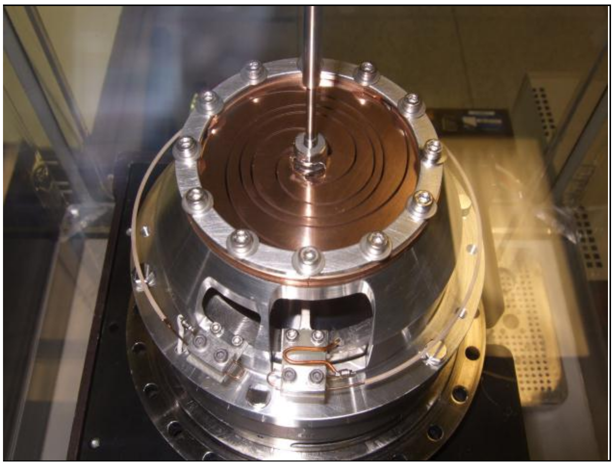

Figure 8. Compressor assembly showing the outer diaphragm spring and lead in wire.

As previously stated, the mechanism spindles are supported between two packs of diaphragm springs, or flexure bearings as they are also known. These allow the linear movement required while providing the high radial stiffness necessary for maintaining the clearance seal gap.

The springs were originally developed by Oxford University in the 1980s for use on a pressure modulator mechanism [1]. They have since been used in linear Cryocooler mechanisms around the world, indeed compressors such as those employed in the HPSC are colloquially known to be of the "Oxford Design."

The springs have been designed so that at maximum operating stroke the springs are below their fatigue limit. To aid this fatigue resistance, the springs are photo-chemically etched from sheet beryllium copper, placing no machining stresses on the heat-treated material. Each spring is individually polished to ensure no surface deformations act as stress concentrations, while springs in a stack are spaced apart to prevent any contact wear occurring. There are six springs in each pack.

5.3. Electrical Lead-ins

It is necessary to carry electrical current to the motor coils across their travel. These lead-ins must be able to survive the same number of oscillations as the diaphragm spring and are single point failures in the mechanism, as a single broken item would halt all power from reaching the motor.

Again beryllium copper is used, due to its high fatigue limit. As with the diaphragm springs, the wires are prepared by hand for use, undergoing heat-treatment and surface polishing. Additional checks are made during assembly to ensure the Cryocooler operating frequency is not any mode of the individual installed wires.

5.4. Gold O-Ring Sealing

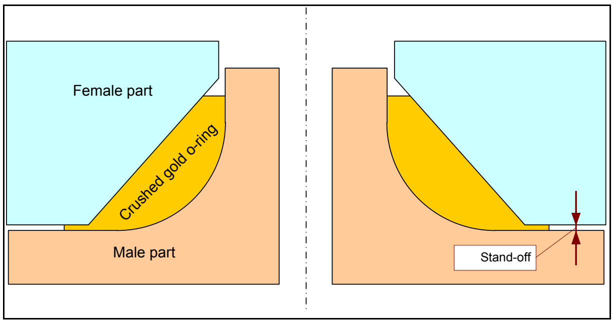

Figure 9. A typical gold o-ring seal geometry.

As previously stated, the Cryocooler is pressurised with high purity helium gas which drives the thermodynamic cycle. Cooling performance is approximately directly proportional to the fill pressure. Therefore in order to ensure Cryocooler performance over life, the unit must be sealed to a high standard.

All permanent seals are achieved through electron beam welding and brazing. However, this is not possible for joints which may need to be disassembled. These joints are sealed through the use of gold o-rings. Rings are formed from gold wire and then plastically crushed between the sealing surfaces.

This technique allows total Cooler leak rates < 10^{-7} mbar.l/s to be achieved, equating to a pressure drop over the required life time of <0.5%.

6. THERMAL DESIGN ISSUES

As would be expected with a heat engine, successful resolution of thermal design issues is vital to achieving product performance.

6.1. Geometric Design

Prior to detailed mechanical design, a number of optimisation models were run to generate the required geometry of the compressor pistons and the displacer gas expansion volume. These were performed using SAGE Stirling Cycle analysis software and Matlab.

Both computational models were validated through production of a breadboard before the start of engineering model, EM, manufacture.

6.2. Cold finger design

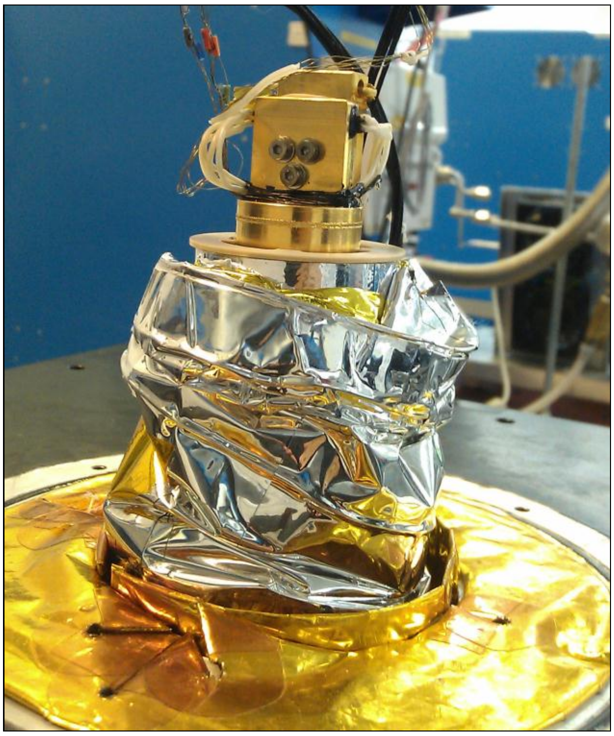

Figure 10. The cold finger fitted with instrumentation and multi-layer insulation

The Cryocooler cold finger is approximately 100mm in length, but crosses a thermal gradient of over 200°C, between the S/C at ambient, ≈20°C, and the cryogenic instrument, ≈50K. Any thermal energy in the form of heat, leaking up the cold finger structure from hot to cold, is a parasitic load on the Cryocooler, reducing the net available cooling power to the user.

To achieve a high thermal resistance, the cold finger is machined out of TA11 titanium alloy, a material with a thermal conductivity of 7W/m.K. Cross sectional area is kept to a minimum by having a wall thickness of 0.1mm.

Inside the cold finger tube runs the regenerator, a polymer sleeve filled with densely packed metal gauze discs. As previously discussed, this relies on clearance seals for efficient operation. The regenerator is of the same length as the cold finger, making tight geometric controls during manufacturing necessary. A custom process had to be developed involving several heat-treatment stages and different machining operations.

This tube is part of the pressure vessel, filled to 15bar. This is sufficient to balloon the thin walls, increasing clearance to the displacer and leading to unacceptable leakage. Consequently, stiffening rings have been added at four locations to reduce this effect.

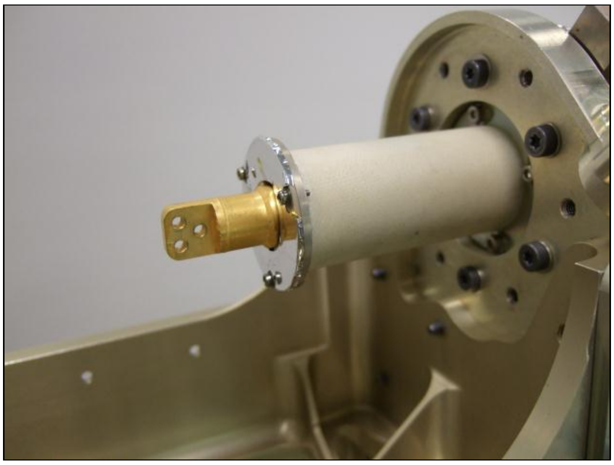

Figure 11. The cold finger snubber of a 50-80K Cooler.

For mechanical vibration, the cold finger is protected by a snubber structure. This is preset with clearance, to prevent any conductive parasitic loads.

6.3. Displacer head design

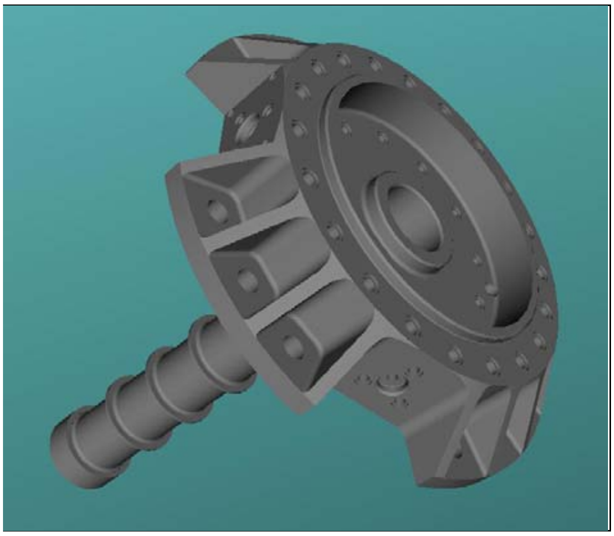

Figure 12. The cold head, showing cold finger stiffening rings and heat transfer ribs at the base

The cold finger joins to the displacer head, which in turn connects the assembly to the S/C both thermally and mechanically.

The displacer mounting interface conducts most of the heat generated by the displacer and momentum balancer linear motors, as well as a small proportion of that generated through the thermodynamic cycle, away from the Cryocooler. It also supports the significant weight of the displacer and cantilevered momentum balancer, along with associated loads during vibration.

AMS348 grade 2 titanium was selected for this component. This grade of titanium has a relatively high thermal conductivity, ≈17W/m.K, while still strong enough for the required mechanical loads. The grade also has a low oxygen content, allowing electron beam welding to the low conductivity Ti cold finger.

6.4. Compressor Central Bracket Design

The vast majority of heat generated by the thermodynamic cycle is removed from the gas at the copper compressor heads and transferred through the aluminium central bracket. This has been optimised through both thermal and stress finite element analysis to minimise the final mass.

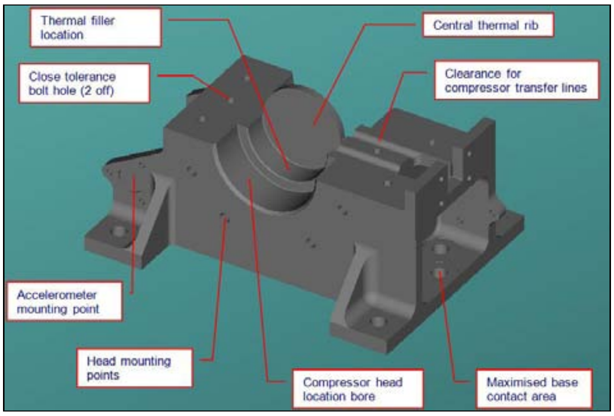

Figure 13. The compressor assembly central bracket lower section with design details shown

As the bracket is not part of the pressure vessel, 6082 aluminium alloy is used.

7. COOLER ASSEMBLY ISSUES

The Cryocooler build process is typical for a precision space mechanism. Cleanliness is a priority, not just to prevent debris damaging the unit's clearance seals, but also at a molecular level as a Cryocooler will normally directly interface with the optical instrument. Therefore, the HPSC was assembled in a laminar flow cabinet rated better than class 10'000.

The most significant challenge is achieving the required alignment for the reciprocating clearance seals. This is done by loosely assembling a mechanism and heating it until relative thermal expansions cause the unit to seize. At this point the assembly is assumed to have been perfectly centralised and all fixings are tightened. This process is repeated several times during build.

Vespel, used in all clearance seals, is a highly hydrophilic material and can experience volume changes of >5% from the dry state. Therefore, the material must be dried under vacuum prior to machining and stored appropriately. Consequently, part built mechanisms are stored in a vacuum oven and alignment checks performed soon after removal.

7.1. Mechanism level build checks

In addition to standard mechanical build checks, each mechanism also undergoes flow and stiction testing. For both of these, the unit is thoroughly dried held at ambient temperature.

For flow testing, the mechanism pressure vessel is filled with helium and sealed so the only exit for the gas is past the clearance seal. A flow meter is then used to monitor the gas flow required from the supply to maintain a set pressure gradient across the seal. Experience has generated a family of data against which results can be compared:

- Too low a flow indicates there is insufficient clearance for the Cooler to avoid sticking at high temperatures. Typically, the piston will be removed and polished.
- Too high a flow indicates the seal is too loose or poorly aligned. If a partial rebuild does not improve results a new piston or bush is needed.

The other test performed during assembly is 'stiction' testing. This involves running the mechanism at very low speed, taking several minutes to complete one cycle. A plot of drive current against stroke is then made.

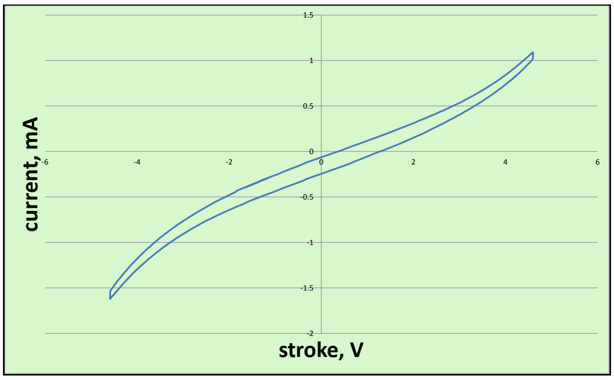

Figure 14. A typical stiction plot

The current drop between changes of direction is an indicator of friction present in the system and strict self-imposed limits are employed. Any additional distortion of the curve can suggest other anomalies in the mechanism. Note that during normal operation contact is not made.

Following testing of the EM HPSC compressor mechanisms, it is clear that while stiction readings are very low, the gas flow is far too high, implying the pistons have too much clearance. This will reduce the mechanisms' efficiency, as much of the work done during compression will be lost through the seal.

Usually, the pistons would be removed and a new pair machined. However, due to project constraints this was not possible and testing was forced to proceed using the compressors as is.

8. COOLER OPTIMISATION

When running a Stirling Cycle Cryocooler, there are several operating parameters which all effect cooling and require careful tuning to achieve optimal performance. Therefore, it is necessary to run through an optimisation programme.

As the HPSC is significantly larger than previous Astrium Coolers, it was necessary to cover a wide range of parameter values to ensure a full survey was taken. Parameters reviewed were:

- Operating frequency: This is tuned to match the compressor mechanisms' natural resonance. This reduces the power required to drive the compressor thus maximising the system efficiency.
- Phase difference between compressor and displacer mechanisms: A poorly set phase can result in heat being transferred to, rather than from, the cold tip
- Displacer stroke: Experimentation showed a larger stroke than predicted gave maximum cooling
- Cooler fill pressure: Due to project constraints this was not investigated.

As all parameters are interrelated, optimisation can be a long process. It is necessary to wait for the Cooler to reach equilibrium before any readings can be taken, and it can take several hours to generate enough data for a single load line.

9. COOLER PERFORMANCE

Cryocooler performance is typically stated in terms of heat lift. This can be defined as the net amount of thermal energy that the unit can remove at the cold tip per unit time. There are three independent factors that most significantly influence this:

- Cold tip temperature
- Compressor electrical power
- Rejection temperature

To take into account the above, Cooler performance is usually displayed as a family of plots of cold tip temperature against heat lift at various system power consumptions.

9.1. HPSC load lines

The shown load lines summarise the EM HPSC performance that was achieved following both vibration and thermal vacuum testing. The compressor rejection (boundary interface) temperature was kept approximately constant throughout at ambient, 22°C.

At the nominal operating point of 150W electrical power and 2000mW heat load, a cold tip temperature of ≈50K was achieved (70W / comp mech plot in Fig15).

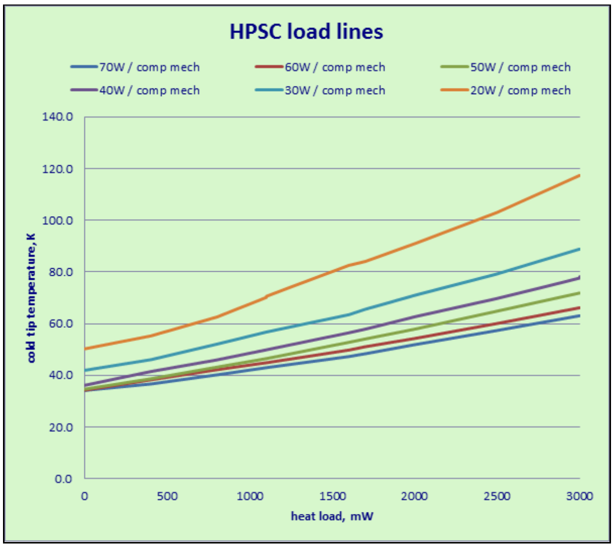

Figure 15. HPSC load lines

A direct comparison of performance can be made to the 50-80K Stirling Cycle Cooler, with which many common parts are shared.

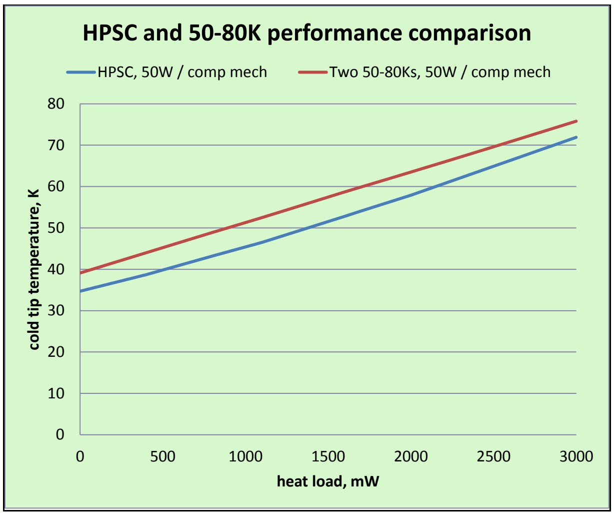

Figure 16. HPSC performance compares to the 50-80K Cooler

As can be seen by the plot, even when not operating at its design point, the HPSC outperforms two 50-80K Coolers drawing equivalent electrical power. A dependability study has shown that the new Cooler also gives greater reliability than its predecessors.

10. CURRENT STATUS

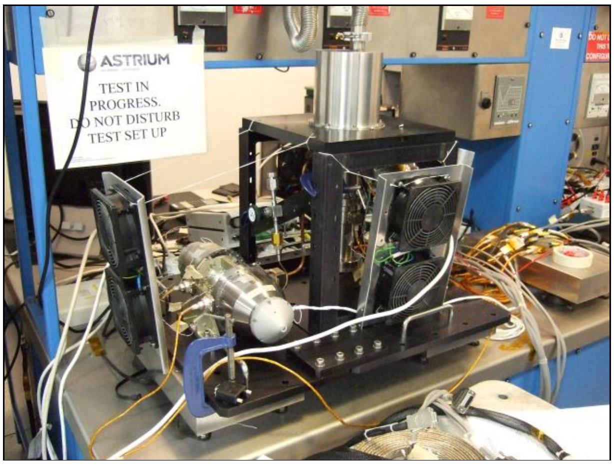

Figure 17. HPSC under life test

Since the completion of formal testing, the Cooler has been intermittently run/ continuously at full power and has currently achieved several thousand hours. Performance is regularly checked, and has been found to be constant throughout this period.

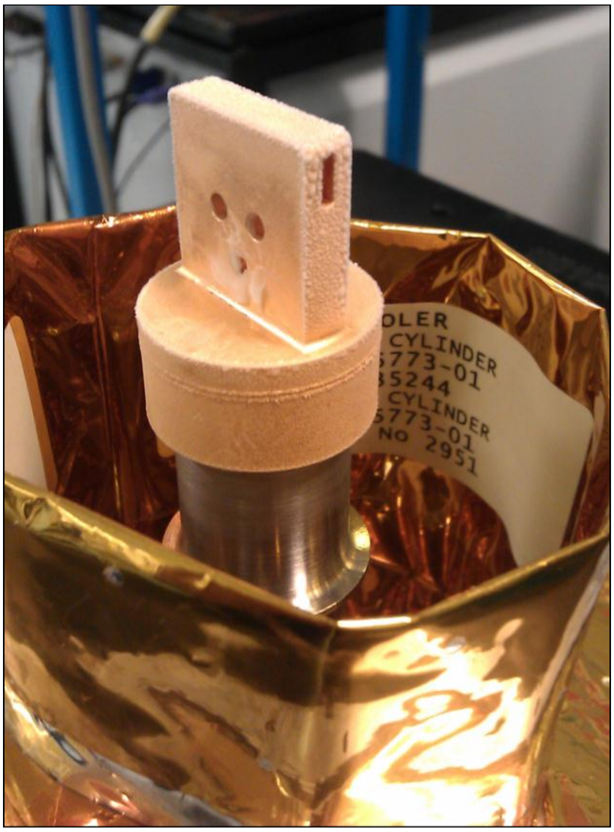

Figure 18. HPSC cold tip showing icing after brief demonstration run in ambient conditions

11. REFERENCES

1. Gibson, A. S.; Reed, J.; Bradshaw, T. W.; Linder, M. (2008). *Heritage Overview: 20 Years of Commercial Production of Cryocoolers for Space*, Transactions of the Cryogenic Engineering Conference - CEC, Vol. 52. AIP Conference Proceedings, Volume 985, pp. 493-505.

2. Linder, M. (2007). *Requirement Specification of the Advanced 50-80K Cooler*, ESA document reference TEC-MCT/2007/3597/ln/ML