Integration of Oxford Class Cryocoolers with Thermal Detectors,“

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INTEGRATION OF OXFORD CLASS CRYOCOOLERS WITH THERMAL DETECTORS

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ABSTRACT

Mechanical cryocoolers are generally preferable to stored cryogen dewar systems for space applications because they are more than an order of magnitude smaller in size and lighter in weight. Successful flight qualification, endurance testing, and on orbit performance of mechanical cryocoolers over the past ten years have made the use of cryocoolers viable from a lifetime and system reliability perspective. However, the size and weight advantage is partially offset by the introduction of operational vibrations, the possibility of temperature fluctuations at the cooler mounting interface and cold tip, and power draw on the spacecraft bus. The first two can directly affect detector performance. These inherent technical challenges are met through the combination of cryocooler-level and system-level design features and accommodation. For example, adaptive feed forward (AFF) active vibration control provided by the cryocooler control electronics significantly reduces vibration output at the cold tip. Using a flexible thermal strap to connect the detector to the cold tip further attenuates vibrations transmitted from cold tip to detector. Unfortunately, thermal strap efficiency and mechanical strap compliance react in opposite directions with respect to strap cross-sectional area, so a system-level design optimum must be found. Lower cryocooler vibration output and/or higher cryocooler efficiency facilitate the identification of an optimum strap design that meets the detector thermal and jitter requirements. The pages that follow discuss these and other examples of system-level issues that arise in the integration of Stirling-cycle, Oxford-class cryocoolers, and more importantly, how those challenges can be overcome.

INTRODUCTION

The common design objectives of virtually any space cryocooler include long life, high reliability, and high efficiency. Long life and high reliability are essential because, in general, on-orbit service and replacement of deployed systems is not possible. Efficiency is important because cryocooler power consumption adversely impacts multiple spacecraft subsystems. First, the requirements on the spacecraft power system (batteries and solar panels) increase as cryocooler efficiency decreases. Second, all of the input power to the cryocooler must eventually be rejected from the spacecraft radiatively to space. Thus the spacecraft radiator size and weight increase as cryocooler input power increases.

The so-called "Oxford class" cryocooler has emerged as a widely applicable solution to these lifetime, reliability, and efficiency requirements[1]. The Oxford class cryocooler is characterized by the following:

- Separate expander and compressor modules;
- Linear drive motors;
- Flexure suspended pistons;
- Non-contacting clearance seals;
- Hermetically sealed housings.

Later improvements to the basic Oxford class cryocooler have been incorporated to minimize the vibration output of the machines[2]:

- Piston position control systems;
- Drive axis vibration control systems.

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Though the original Oxford cryocooler was a Stirling, the term “Oxford-class” is nowadays commonly taken to include both Stirling and pulse tube cryocoolers that utilize the flexure suspended, non-contacting pistons for the moving mechanisms, which in the case of the pulse tube includes only the compressor.

The stated design objectives of high reliability and long life have been demonstrated through life testing by the space cryocooler industry in collaboration with various government agencies. A brief summary of Raytheon Oxford-class cryocooler life test results/status is provided in Table 1. Life test results such as these at Raytheon and elsewhere have largely convinced the customer community that space cryocooler technology is sufficiently mature to baseline for real on-orbit systems. The inherently smaller size and lower mass of the active cryocoolers provide distinct advantages over the incumbent dewar and cryoradiator passive cooling technology, but the mechanical cryocoolers introduce new system integration challenges that must be met. This paper describes those challenges and how they are overcome both through the design of the cryocooler and at the system integration level.

Table 1. Life test history of Raytheon Oxford-class cryocoolers; >120,000 hours without failure.

Cryocooler	Date	Location	TTL Hours	Operating Point	Status
SBIRS Low FDS #1	1997 -	Raytheon	>37000	3.4W @ 58K	Ongoing; no failures or anomalies
Protoflight Spacecraft Cryocooler	1999 -	AFRL-Kirtland	>27000	2.0W @ 60K	Ongoing; no failures or anomalies
Standard Spacecraft Cryocooler	1998 -	AFRL-Kirtland	>27000	1.3W @ 60K	Ongoing; no failures or anomalies
Improved SSC #1	1994-1997	Raytheon	>23600	0.8W @ 60K	Completed; no failures*
Improved SSC #2	1994-1997	Raytheon	>23900	0.6W @ 60K	Completed; no failures or anomalies

* minor, reversible gas contamination detected in ISSC #1

CRYOCOOLER INTEGRATION CHALLENGES

Passive Cryogenic Cooling Systems

One alternative to a mechanical cryocooler for an on-orbit cryogenically cooled system is a passive radiator. Radiators are a standard component of most spacecraft to reject waste heat. Cryogenic radiators, or cryoradiators, are unique in many ways. Their uniqueness arises primarily from the fourth order dependence of radiated energy to source temperature that makes the radiative rejection of heat at low temperatures an enormous challenge. High performance cryoradiators typically employ multiple cooling stages, elaborate multi-layer insulation (MLI) designs, and shields to prevent Earth view for low orbits. Additionally, there are typically operational requirements that the spacecraft be steered to preclude direct solar loading. The former three increase cost and complexity of the radiator, and the latter constrains the mission and increases cost and complexity of the spacecraft attitude control system. Cryoradiators also tend to be fairly large because the low emissive power density has to be compensated for with increased surface area. However, once deployed the radiator is reliable and imparts no vibrations to the system. There are no active components, so there is no electromagnetic interference (EMI) signature.

Stored cryogen systems are another alternative to mechanical cryocoolers. The two types of stored cryogen systems are those in which cryogenic liquid or solid is stored on the spacecraft in highly insulated containers (dewar systems) and those which expand stored high pressure gas through a Joule-Thomson orifice to create refrigeration.[3] The lifetime of these systems is limited by the amount of stored cryogen or high-pressure gas. Therefore, the major drawback of the stored cryogen approach is the large size and mass of the system that arise from long-life and/or appreciable heat load requirements. The advantages are simplicity, reliability, no EMI, and vibration output limited to only that produced by moving fluid and/or boil off, which is small.

Oxford Class Mechanical Cryocoolers

The system-integration strengths and weaknesses of the mechanical cryocoolers are largely the converse of the characteristics of the passive systems. The primary advantages of the mechanical coolers are that they are compact and lightweight. Some of disadvantages arise from the necessity of utilizing moving parts to achieve these size and weight reductions. The presence of moving parts potentially limits life due to mechanical wear and imparts vibrations to the cryocooler mounting structure and cooled device.

The electromagnetic motors in the cryocooler and the electronics are potential sources of EMI. The mechanical coolers require power from the spacecraft bus, and that input power must be rejected from the cryocooler system as heat. These interactions are illustrated in Figure 1 and described more fully below.

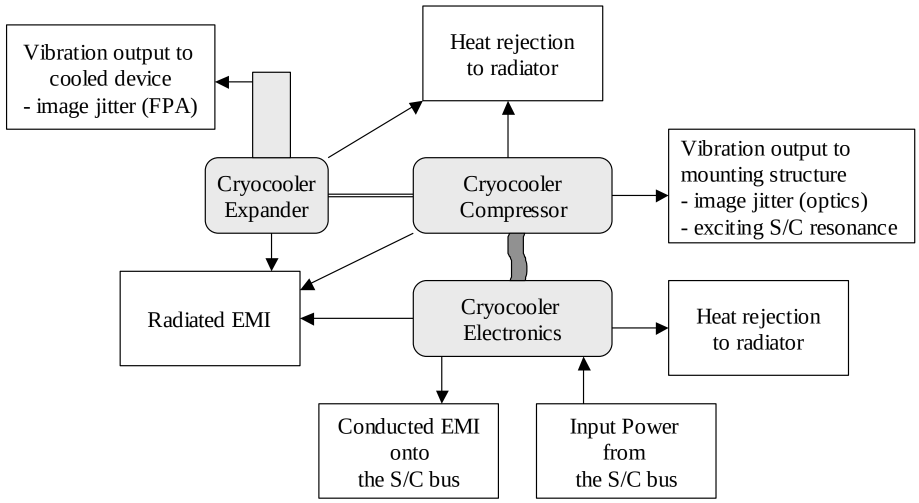

Figure 1. *Cryocooler payload integration system engineering challenges*

Mechanical / Thermal Interfaces: Active cryocoolers must connect to both the cryogenic temperature reservoir (cooled device) and the ambient temperature reservoir (heat rejection system). The interfaces must provide satisfactory thermal conductance and protect the thin-walled cold finger from excessively large dynamic loading during launch.

Line of Sight / Jitter Control: Active cryocoolers impart vibrations at the physical mount points. This typically necessitates the use of a highly compliant, thermally conductive cold strap at the cold end and control of the vibration output at the ambient hard mounts using a closed-loop, active vibration control system composed of measurement devices (e.g., load cells), piston position control, software, and dedicated electronic circuits.

System Reliability: Table 1 illustrates the success to date with the current generation Oxford-class cryocoolers. Nevertheless, when combined with the electronics, typical cryocooler system reliability at 10 years is calculated to be in the range of 0.95. Payload reliability requirements may necessitate the use of a second, redundant cryocooler system. This increases the load on the operational cryocooler due to parasitic load from the off cooler, and may necessitate the additional complexity of a thermal switch.

Orientation Sensitivity in 1G: Gravity driven convection forces can affect cryocooler performance during ground testing. This is more pronounced in pulse tube than Stirling coolers because the open volume of the pulse tube promotes buoyancy-driven convection cells.[4] The problem is particularly pronounced in an off state cooler, but can also appear during operation as drive frequency and/or cold tip temperature decrease. Low-temperature, G-M systems (piston and pulse tube) exhibit orientation sensitivity, for example.

Electromagnetic Interference: Active cryocoolers output broadband magnetic and electric fields, static magnetic fields, and reflect AC current ripple onto the power bus. Each of these must be considered in actively cooled sensor design. For example, conducted EMI can be handled at the cryocooler system level through the use of either active and passive filtering circuits, or the spacecraft may dedicate power lines to the cryocooler so that low frequency AC current ripple does not interfere with other spacecraft subsystems.

CRYOCOOLER DESIGN FOR INTEGRATION

Incorporation of an active cryocooler into a payload always requires some degree of accommodation. The decision of whether that level of accommodation is warranted versus that introduced by competing passive cooling approaches is a system level decision based upon temperatures, orbit, mission, heat load, launch vehicle, etc. The best type of cryocooler, be it Stirling, pulse tube, reverse-Brayton, Joule-Thomson, etc., is also a system level decision given the competing strengths and weaknesses of the different types of cryocoolers. The following example is illustrative of how the system integrator's task can be made easier for an Oxford-class cryocooler integration by anticipating the system level challenges in the course of the cryocooler design.

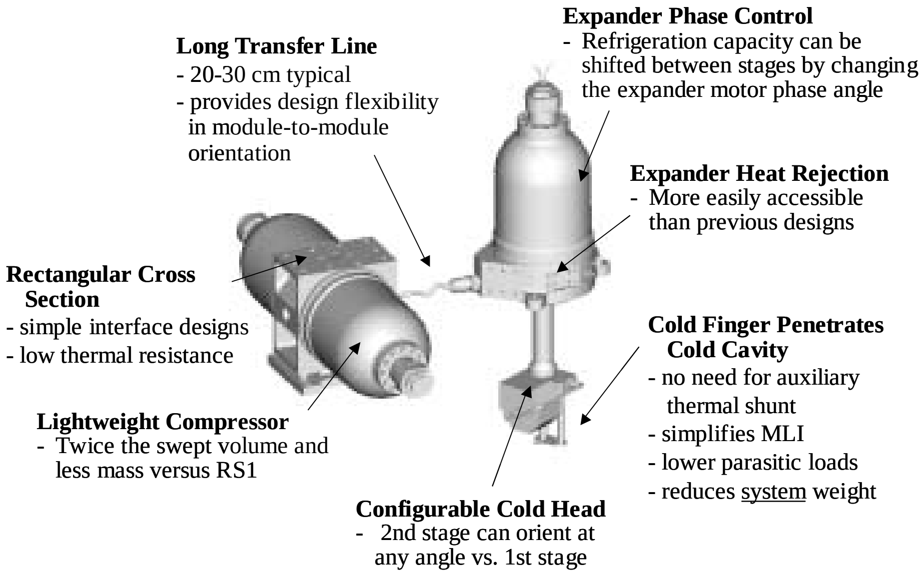

***Figure 2**. Raytheon Stirling Pulse Tube Two-Stage (RSP2) Cryocooler "ease of integration" features.*

The Raytheon Stirling Pulse Tube Two-Stage (RSP2) Cryocooler depicted in Figure 2 embodies system-level design compatibility lessons learned over the past ten years involving the integration of mechanical cryocoolers into space-based infrared sensors. At the most basic level, the two-stage approach provides considerable advantage for applications in which a redundant cooler is required because the majority of the off-cooler parasitic can be carried at the more efficient upper stage temperature of the "on" cooler. The use of a transfer line with separate expander and compressor modules provides design flexibility, and the extension of the cold interfaces as a "finger" from the ambient temperature structure simplifies the design of the cryogenic subsystem and obviates the need for long cryogenic thermal shunts. The RSP2's ability to shift refrigeration between stages allows for on-orbit adjustment, and when combined with a first stage triple-point thermal storage unit, provides an optimal system-level solution for duty-cycled applications. This characteristic and others of the RSP2 are discussed in more detail elsewhere.[5]

CONCLUSION

Mechanical cryocoolers for space applications, and in particular Oxford-class cryocoolers, have reached a sufficient level of maturity that they meet typical lifetime and reliability requirements of the user community. The size and mass advantages of the Oxford class cryocoolers are partially offset by the required system-level accommodation of vibration output, EMI, power draw, and heat rejection. These integration challenges are best met through a combination of features that are built into the cryocooler and proper system-level design.

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