Low Cost, Lightweight Space Cryocoolers

C. S. Kirkconnell[1], G. R. Pruitt[1], K. D. Price[1], B. A. Ross, Jr.[2], and W. R. Derossett[2]

[1]Raytheon Electronic Systems
El Segundo, California 90245
[2]Raytheon Infrared Systems
Goleta, California 93117

ABSTRACT

Raytheon has developed a concept for compact, lightweight space cryocoolers that merges the existing company expertise in tactical cryocoolers and space cryocoolers. The compressor is an upgrade to the existing Raytheon 705X tactical compressor product line in which the rubbing seals are eliminated through the incorporation of a non-contacting, flexure bearing piston support system characteristic of that used presently on the space cryocooler product line. To minimize cost and weight, the expander is a single-stage pulse tube. A concentric pulse tube configuration is used to simplify system integration by providing a distinct cold tip and radially symmetric structural stiffness. The cryocooler electronics module is essentially a radiation-hardened version of the existing tactical high reliability electronics design.

The novel aspect of the proposed concept is the merging of the previously distinct tactical and space cryocooler technologies. The underlying technologies are essentially proven. Over 5,000 linear compressors of similar basic construction (motors, housing, etc.) have been built and fielded by Raytheon over the past ten years. Flexure bearing piston support systems have been employed on many past Raytheon space cryocooler designs (SSC, ISSC, PSC, SBIRS Low) as well as throughout the industry. Similarly, single-stage concentric pulse tubes have been built at Raytheon and elsewhere. More than 100 high reliability cryocooler electronics boxes have been fabricated and delivered to the customer community.

The merging of these proven technologies yields a space cryocooler with recurring costs approximately a factor of ten lower than the present industry average of $2M. The projected weight for the combined cryocooler and electronics module is about 3 kg.

INTRODUCTION

Space cryocoolers and tactical cryocoolers have to date been viewed as distinct technologies because of design and cost differences driven by the much more stringent space requirements. The price tags clearly substantiate this delineation. Tactical coolers typically have recurring costs in the $3000 to $15,000 range, while present generation space cryocoolers cost over $1.0M for the thermo-mechanical unit (TMU) alone and another approximately $1.0M for the control and drive electronics, costs based upon the typical industry order quantity of 2 to 3 units. Table 1, which is a comparison of the specifications for typical Raytheon space and tactical cryocoolers, contains the key re-

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Table 1. Comparison of Typical Tactical and Space Cryocooler Requirements.

Requirement	Space	Tactical
Coldtip Temperature	35 to 120 K	67 to 93 K
Capacity	up to 10 W	< 1.5 W
Residual vibration	< 200 mN	< 2000 mN
Lifetime	>88000 hrs	5000-10000 hrs
Cold Tip Temp. Stability	+/- 0.2 K	+/- 0.5 K
Ionizing Total Dose	100 kRad	N/A

Table 2. Mass Comparison of Tactical and Space Cryocooler Modules.

Module	Space	Tactical
Compressor	8.1 kg (RS1 Compressor; 2.5 cc)	1.8 kg (7080 Compressor; 2.5 cc)
Expander	5.0 kg (RS1 Expander; 5W @ 77K)	0.16 kg (514 Expander; 3W @ 77K)
Electronics	6.1 kg (RCCE - Flight Design)	1.0 kg (M/N 416301; High Reliability)
Total (kg)	19.2	2.96

quirements that drive the cost difference. These are primarily the lifetime, residual vibration, and radiation hardness requirements.

The same factors that drive cost also drive the dramatic size and mass differences between present-generation space and tactical cryocoolers of similar capacity. Table 2 illustrates this fact by comparing the mass of tactical and space cryocooler modules of similar function and capacity. Therefore, the development of a low cost, lightweight cryocooler arose naturally from the dual long-standing goals of continually reducing cost and weight in the space cryocooler product line. The key features of Raytheon's low cost, lightweight space cryocooler design are provided in the pages that follow.

SPACE CRYOCOOLER COST DRIVERS

Marketplace

The space cryocooler marketplace is characterized by small quantity orders and unique interface and environmental requirements. The inconsistency in requirements between different customers and payload applications necessitates the tailoring of existing designs for virtually every new program. This is in stark contract to the tactical marketplace's Standard Army Dewar Assembly (SADA) Cryocooler specifications that, through the thorough qualification of a given design to a well-defined requirements set, allow the incorporation of a single cryocooler design into multiple systems. Regarding the order quantities, tactical cryocooler orders typically involved hundreds, perhaps thousands of units, which naturally enables cost savings in materials, reduced process time through incorporation of specialized subassembly stations, batch unit performance screening, etc. The low production quantities for space cryocoolers preclude many of these opportunities for savings, completing a vicious cycle in which high cost reduces demand for these units.

Thermo Mechanical Unit (TMU)

The requirements for long-life and high reliability have motivated the leading space cryocooler suppliers to adopt what has come to be called the "Oxford class" cryocooler design, that is, flexure bearing suspended pistons utilizing non-contacting clearance seals to separate the working volume from the plenum volume. These suspension systems necessitate precise mating structures to maintain alignment within approximately one hundred micro inches to preclude piston-cylinder contact. In contrast, the tactical cryocooler compressor pistons are supported by much less expensive machined springs and utilize contacting seals that wear over time, but in a generally predictable manner. The long life requirement necessitates stringent gas contamination control, which limits the types of epoxies and other volatiles that can be used. Raytheon has addressed this concern in past designs with hermetic motor enclosures that are effective, but add cost.[1]

The other significant cost driver for the TMU is the low residual, or operationally generated vibration requirement. This requirement is traditionally met with a closed-loop dynamic control system that requires knowledge and control of piston position; typically this requires a position sensor, such as a linear variable differential transducer (LVDT) for each piston. Vibration level feedback is provided by load cells or accelerometers. In the case of a Stirling expander or a single-piston compressor design, an additional actively-driven balance mass assembly (mass, piston, motor, position sensor, etc.) must be added to offset the dynamics of the working pistons. The addition of these components adds significant cost and weight to the present state-of-the-art space cryocoolers. Tactical cryocoolers, with the less demanding vibration requirements, do not require piston position sensors and load cells, and Stirling expander vibrations can be sufficiently damped using comparatively small, passive pneumatic or spring-mass balancers.

Electronics

The requirement for low residual vibration drives cost on the electronics module as well as on the TMU. Additional circuits are required to process the signals from the load cells or accelerometers and the piston position sensors, and hundreds of lines of code are required to implement the selected vibration control algorithm, such as the adaptive feed forward method used for Raytheon's PSC.[2] The complication of the vibration feedback control, as well as the more stringent temperature stability requirement, requires the use of an expensive microprocessor in the space cooler electronics that is not needed in the tactical electronics. Naturally, increased parts count relates directly to increased weight. The lifetime/reliability requirement results in the mandatory selection of more expensive high reliability components. On the tactical cryocooler line, Raytheon's high reliability electronics module cost more than ten times the otherwise-similar Low Cost Cryocooler Electronics ($10K vs. <$1K), which provides an indication of how influential this requirement is on the much more complicated space cryocooler electronics modules. Finally, the requirement for radiation hard electronics, typically not requisite for tactical electronics, further increases component cost, and can also increase mechanical design complexity, cost, and weight if the housing is to be relied on for additional radiation shielding. In summary, the low vibration, high reliability, and radiation hardness requirements all contribute to the higher costs and larger size of space cryocooler electronics versus the tactical cryocooler counterpart.

"Hidden" Program Costs

Easily overlooked but nevertheless significant contributors to the unit cost of a space cryocooler are the documentation and reporting requirements imposed by the customer. These include conformance to allowable parts and materials lists, which often drive expensive component and process replacement, piece part traceability and planning sheets for each unit, multiple design reviews, and numerous "consent to" meetings preceding key events like the start of manufacture, test, and delivery of each unit. A high level of unit-to-unit oversight is certainly warranted in the space cooler business because of the unit cost, the criticality of the cryocooler to the system performance, and the enormous expense or outright impossibility of fixing repairs or replacing units on orbit. However, these documentation and reporting expenses can easily account for more than 25% of the

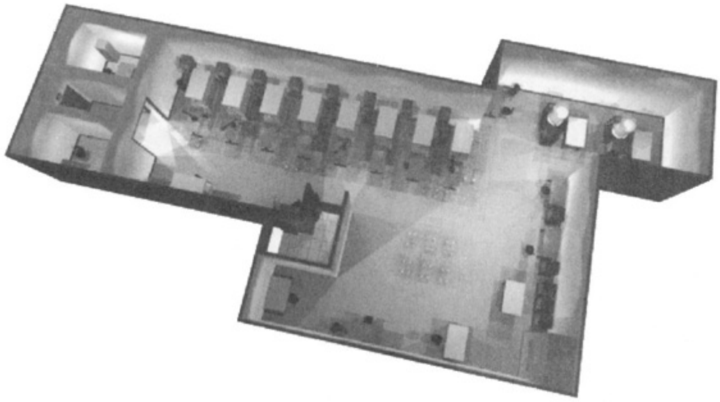

Figure 1. Raytheon Space Cryocooler Manufacturing Facility – Artist's Concept. Production capacity of four coolers/month; collocated test and assembly (2200 ft²). Scheduled for completion in August 2002.

unit cost in a typical space cryocooler program. The hope and expectation is that as the space cryocooler technology and marketplace mature together, a more equitable balance between program management requirements and imposed expense will evolve.

PROGRESS TO DATE ON CONTROLLING SPACE CRYOCOOLER COSTS

The most direct method by which to reduce recurring cost is to make design changes that selectively target the expensive features of the preceding design. For example, the next generation Raytheon Stirling/Pulse Tube Two-Stage (RSP2) Cryocooler incorporates many cost saving features such as non-hermetically sealed motors and LVDT coils and an improved design that reduces parts count and simplifies piston alignment. The novel RSP2 was developed in the course of the recent 95K High Efficiency Cryocooler Program and is discussed elsewhere in more detail.[3,4] More aggressive design changes to further drive down cost are proposed in the next section. However, significant progress has been made already in reducing the recurring cost for the present build of a single-stage Stirling cryocooler called the RS1, very similar in design to the PSC cryocooler with respect to piston suspension, contamination control, total parts count, and total assembly and process steps.[1] Raytheon is presently building fifteen (15) of these flight-qualified cryocoolers for an internal laboratory program, and this production quantity has made cost effective the implementation of a manufacturing facility based upon cost saving low rate initial production (LRIP) techniques such as batch processing, parts kitting, subassembly stations, and in process staging. The space cryocooler manufacturing facility that will be used for the present build, scheduled for completion by August '02, is depicted in Figure 1. Cost savings have been realized due to reduced costs at the component level by virtue of the higher order quantities of each piece part. Well before the end of the production build, the combined recurring cost of the TMU and the flight-design electronics module is projected to be less than $1.0M compared to the approximately $2.0M industry average for small lot (< 4 units) orders. The accomplishment of this cost target is particularly noteworthy because the design of the RS1 does not incorporate many of the cost saving features of newer designs. Application of these manufacturing techniques and utilization of this state-of-the art space cryocooler manufacturing facility will enable even larger savings when applied to a low cost design such as that described in the next section.

RAYTHEON LOW COST, LIGHTWEIGHT CRYOCOOLER

Basic Concept

Raytheon is in the singular position of being an established supplier of both tactical and space cryocoolers. Since 1978 Raytheon has delivered over 50,000 rotary and linear tactical cryocoolers,

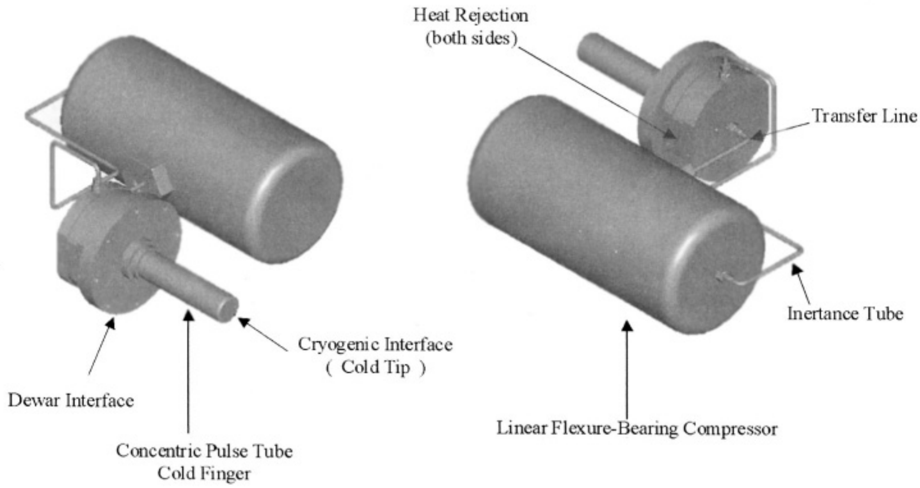

Figure 2. Raytheon Low Cost, Lightweight Space Cryocooler Concept. Flexure-suspended, dual opposed piston compressor derived from tactical design mated to a concentric pulse tube expander.

and that line continues today with production of cryocoolers for AIM-9X, Maverick, and several other programs. The Raytheon space cryocooler experience also stretches back over 30 years, starting with several Vuilleumier cryocoolers built and delivered in the early 1980's to the flight-qualified Stirling cycle PSC and SBIRS Low cryocoolers of the 1990's. As discussed previously, fifteen (15) cryocoolers of the flight-qualified RS1 design are presently in production. The basic concept for the low cost space cryocooler evolved from this dual space and tactical cryocooler legacy. The compressor module is based upon an existing tactical linear compressor with the machined spring suspension system replaced with a flexure bearing suspension system with legacy to the space product line. The expander is a single-stage pulse tube, building upon past experience with several IR&D programs[5-7] and the commercial Low Cost Cryocooler (LCC) program.[8] The integrated compressor-expander assembly (the TMU) is shown in Figure 2. The electronics module is a radiation hardened version of the current high reliability tactical cryocooler electronics package. In short, the low cost space cryocooler approach is to baseline a tactical cryocooler and incorporate only those features from the space cryocooler line that are required to meet the critical mission objectives.

As noted earlier, the space cryocooler marketplace requirements are varied and broad in scope. The more the requirements trend towards the demanding end of the spectrum, particularly with respect to cost driving technical features like residual vibration control, the less amenable the design will be to controlling cost. For the present purposes, it was necessary to establish a baseline requirements set to which the design concept must conform so that the applicability of the concept to the general marketplace was evident. Those top level specifications, which were derived from a combination of various tactical and space cryocooler specification documents, are provided in Table 3. Given the focus of the effort on controlling cost and weight, these baseline requirements are representative of the type of space mission more conducive to this low cost approach, that is, moderately stressing in terms of refrigeration temperature, capacity, and vibration control.

Compressor Module

The compressor is a dual opposed piston linear compressor with direct legacy to the existing tactical cryocooler product line. The primary difference is that the machined springs and rubbing seals are replaced with flexure bearings and clearance seals to provide the required life and reliability. The change to a flexure suspension system necessitated changes in the motor design. Aggressive size and mass requirements were imposed to make the compressor compatible for various long

Table 3. Low Cost Space Cryocooler Baseline Requirements.

Requirement	Spec Value
Coldtip Temperature	67 K
Capacity (nominal)	1.5 W
Maximum Input Power	94 W
Residual Vibration	< 250 mN
Lifetime	>50000 hrs
Cold Tip Temp. Stability	+/- 0.5 K
Env Temperature	-40C to +62C
Maximum Mass	2.4 kg
Ionizing Total Dose	100 kRad

life, high reliability tactical missions of interest. The result is a 2.5 cc swept volume compressor with a mass of 1.8 kg, length of 12.5 cm, and a 6.0 cm diameter. For comparison, the present RS1 compressor design with similar thermodynamic capacity is 8.1 kg. Preliminary analysis has been performed to verify that the flexure stress state meets the targeted 20,000 hour tactical life requirement. Additional analysis is planned to identify what modifications will be required to extend the flexure design life to the 50,000 hour low cost space cryocooler target. The impact on the overall unit size and mass is expected to be small. To control vibration to first order, the moving masses flexure stack spring rates of the opposed piston assemblies are matched.

The low cost space cryocooler compressor is essentially a tactical compressor that includes strategically selected upgrades from the space cryocooler line. The flexure design has legacy to the space cryocooler line and the extensive life test data at both the cryocooler level (PSC, >20,000 hours; SBIRS Low, >30,000 hours) and the flexure suspension subsystem level (>8+ years on the SBIRS Low /RS1 compressor flexure suspension system design). Like the existing tactical designs, the motor housings are non-hermetic, but unlike most tactical applications, space cryocoolers tend to operate continuously and are thus more susceptible to long term performance degradation due to freeze out of volatile contaminants. The same material selection and bake out procedures that were established for the non-hermetic motors on RSP2 will therefore be applied to the present effort to minimize volatile evolution. These measures are more extreme than those required on the tactical line. In general, however, tactical cryocooler design practice has been applied wherever possible.

Expander Module

The expander is a single-stage pulse tube to save the added cost of the active-drive Stirling displacer and the additional cost and weight of the active-drive balance mass assembly. (The 250 mN_{rms} requirement cannot be met with the existing tactical passively-balanced Stirling expander design approach.) The pulse tube cold head is a concentric pulse tube, that is, the regenerator is contained in an annular volume around the pulse tube which yields a radially symmetric cold finger. The concept is illustrated in Figure 3. This approach was taken versus the competing linear and U-tube arrangements to provide optimum system integration features for the user. If cost is a concern at the cryocooler level for a program, it will certainly be a concern at the system level, and complex interfaces increase integration costs. The linear pulse tube design, used extensively throughout industry and often preferred because of the efficiency advantages afforded by its characteristic low void volumes and simple flow paths, is notoriously difficult to integrate because of the location of the cryogenic interface midway down the cold finger, sandwiched between ambient structure at

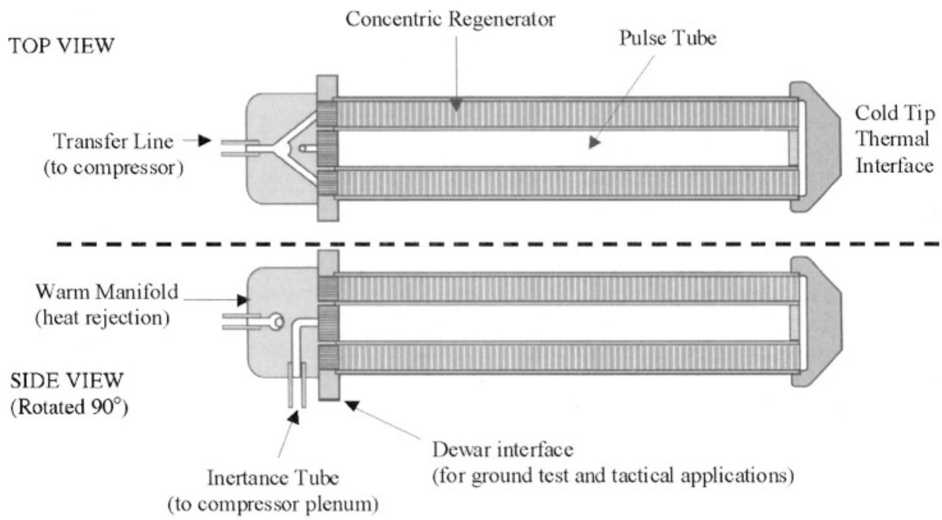

Figure 3. Low Cost, Lightweight Expander. Concentric pulse tube cold head connected to compressor port through transfer line and to compressor plenum by inertance tube.

both ends. The U-tube and the concentric pulse tube are easier to integrate because, like a Stirling, their cryogenic interface is at the end of the cold finger, providing a distinct "cold tip" that can be conveniently accessed, inserted into tight cryogenic spaces, etc. The concentric pulse tube was selected as the baseline because it is slightly more compact than the U-tube, and it has radially symmetric stiffness. In contrast, the U-tube has a soft axis and a stiff axis, and the impact of this asymmetric load bearing capability must be considered at the system integration level. However, a U-tube configuration can be used, if desired, and all of the first order cost and weight advantages of the basic low cost cryocooler design are still realized.

Electronics

The electronics design is a radiation hardened version based on the existing RIO tactical electronics module 416301 and the FPGA controller design of later LCCE and PAWS-II units, which is made up exclusively of high reliability piece parts so the required component upgrade is only with respect to the radiation requirement. Detailed parts selection has not yet occurred, but it is evident from both the legacy RIO 416301 design and the present space cryocooler electronics design that component cost will drive the total module cost. Component-level and box-level shielding will be traded against radiation hard component cost to identify the combination of radiation hard design approaches that optimally balances cost, survivability, and weight. Low cost tactical electronics design, assembly, and test practices will be used to the greatest extent possible, though the performance and reliability screening will obviously have to be more extensive for space applications.

The cost of the electronics is significantly lower than present space cryocooler electronics primarily because the vibration level is controlled to first order through design (dual-opposed non-contacting pistons, pulse tube expander with no moving parts, etc.) and manufacture (matched moving masses, carefully screening motor magnets for field uniformity, etc.). Therefore, the electronics simply provide the fine tuning through unit-specific motor drive parameters that are set when the electronics and the TMU are first integrated. This approach precludes the need for the extensive circuitry and software presently used for space cryocooler electronics to monitor and actively control the vibration level. Preliminary analysis indicates that vibration levels below 350 mN can be readily achieved by this approach; achieving the 250 mN target level over the life of the unit may require some limited capability to adjust the motor drive parameters on orbit.

CONCLUDING REMARKS

Raytheon has developed a concept for a low cost, lightweight space cryocooler that meets the requirements for many present and near term missions. The proposed design combines an upgraded tactical compressor with flexure-suspended pistons to a concentric pulse tube expander. The cryocooler electronics are a radiation hardened version of the present high reliability design. A representative requirements set was defined for the purpose of establishing a baseline. The extent to which these cost cutting, light-weighting measures can be applied for a real system will depend on the comparative values of the key cost driving requirements to those assumed herein. For the baseline requirements set, the estimated recurring costs are $80K for the mechanical cryocooler and $60K for the electronics. Given these module costs and projecting that "hidden" program costs will naturally decline as quantities increase and the technology matures, the integrated and tested complete cryocooler system can be delivered for $200K. The projected weight of 3 kg for the combined cryocooler and electronics module is about 1/3 of the present state of the art for a cryocooler of comparable refrigeration capacity.

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