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# Raytheon dual-use long life cryocooler

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## ABSTRACT

Raytheon has manufactured closed-cycle cryocoolers for both tactical military and space applications for over thirty years. Tactical and space cryocooler technologies have historically been treated as distinct both at Raytheon and throughout the industry. Differing technical requirements, operating lifetimes, and order quantities have driven these types of coolers to dramatically different design approaches and cost levels. For example, a typical space cryocooler system today costs approximately $2M as compared to roughly $10,000 for a tactical cryocooler. However, stimuli from both the tactical and space cooler user communities are driving the markets together. Tactical cryocooler requirements are starting to push towards operating lifetime requirements more characteristic of the space coolers (e.g., 20,000+ hours). Space cryocooler users, in particular Missile Defense Agency, are pushing for substantial cost reduction. In response, Raytheon is developing a low cost space cryocooler with an intended dual-use capability to also serve the tactical marketplace. This cooler leverages proven flexure-suspension technology to achieve long life, and a low cost concentric pulse tube cold head design has been developed that can be packaged into the existing Standard Advanced Dewar Assembly, Type One (SADA-I). The cooler meets or exceeds the SADA-I operational requirements (capacity, efficiency, etc.) as well. For the space-version of the cooler, the electronics cost has been reduced by an estimated 80% versus current designs, largely by approaching the vibration cancellation requirement from a dramatically different perspective. Fabrication of the brassboard expander is nearly complete, and the prototype design is well underway. The design approach, development progress, and proposed applications are presented.

Keywords: cryocooler, pulse tube, SADA, dual use

## 1. INTRODUCTION

Cryocoolers are used by the military for a variety of applications, primarily associated with cooling focal plane arrays in infrared sensors. Military cryocooler technology has traditionally been divided into two categories, space and tactical. Tactical cryocoolers have been in widespread use for fixed wing, rotary wing, infantry, and missile infrared sensor applications for over twenty (20) years. Space cryocooler technology has been around for about thirty (30) years with the first closed cycle cryocooler being deployed in space in 1970 by Hughes Aircraft Company. However, it is only within the last ten years or so that the technology was considered satisfactorily reliable for operational system deployment. NASA has led the charge in that regard, deploying cryocoolers on the Atmospheric Infrared Sounder Instrument (AIRS) and Hubble Space Telescope (HST) in 2002.[1]

With basic operational and reliability objectives now being met, the evolution of space cryocooler technology has now naturally led to the point where matters of cost reduction can be seriously addressed. Cryocooler cost is particularly a concern for small satellite applications where the current nominally $2M cryocooler system cost may represent an unacceptably large percentage of the total payload cost. Meanwhile, on the tactical side of the marketplace, the military is pushing for longer and longer operational lifetime. Typical tactical cryocoolers today have a Mean Time Before Failure (MTBF) of 5000 to 10,000 hours, but there is a push from Joint Strike Fighter (JSF), the Navy's DD(X) programs, and other next generation systems to achieve a MTBF of greater than 20,000, even up to 50,000 hours. Thus the tactical marketplace is pushing for longer lifetimes more typical of a space cryocooler, while on the space side of the business, efforts are underway to achieve substantial cost reduction without commensurately substantial reduction in capability.

Raytheon is unique in that we are a provider of both tactical and space cryocoolers. As such, we were early to recognize these forces pushing the technologies together. In a previous paper we discussed and compared the tactical and space

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cryocooler cost drivers.[2] An early concept of a low cost space / long life tactical (i.e., dual-use) cryocooler was therein described. We collaborated with NIST after that early paper to develop a thermodynamic design for the expander. A key finding was that a concentric pulse tube cold finger can indeed be packaged into the 1.5 W SADA-I dewar and meet all of the SADA operational requirements. The results of that design study were described at the 2003 MCALC-IV meeting in San Diego.[3]

Progress on the development of the dual-use cryocooler has advanced significantly since 2003, and the approach to achieving a first reduction to practice has been established. The development is moving forward on three separate Phase II Small Business Innovative Research (SBIR) Programs from the Missile Defense Agency (MDA), with each program led by a different small business partner. Technology Applications, Inc. (TAI), South Bay Science and Technology Corporation (SBS), and TechnoSoft, Inc. (TSI) are our collaborative partners in the effort. Their respective roles are described herein.

The immediate focus, per the MDA sponsor of the program, is addressing the needs of small infrared sensor payloads, namely low cost and lightweight. In this paper we describe the baseline technology, the development approach, the status of the underlying programs, and potential applications for this dual-use cryocooler.

## 2. TECHNOLOGY

### 2.1 Requirements

The design and performance objectives for the dual use cryocooler were derived from a combination of the SADA-I cryocooler specifications and our experience regarding what will be required for this cryocooler to have applicability to a wide range of space-borne missions. The objective performance parameters are provided in Table 1. The cold tip temperature, refrigeration capacity, input power, temperature stability, environmental temperature, and weight all come from SADA-I. The remaining requirements (vibration output, lifetime, and total lifetime ionizing dose) are driven by the applicable space-borne missions. This cryocooler is at present not being developed for any specific mission; rather it is a proof of concept that indeed such a cryocooler can be built. Specific missions, once identified, may require tailoring the design. The most likely such tailoring involves the design of the electronics. Other potential modifications include optimizing for capacity and cold tip temperature for space-borne missions, where thermodynamic efficiency is at a premium.

| 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 |

Table 1: Summary of dual-use cryocooler performance requirements.

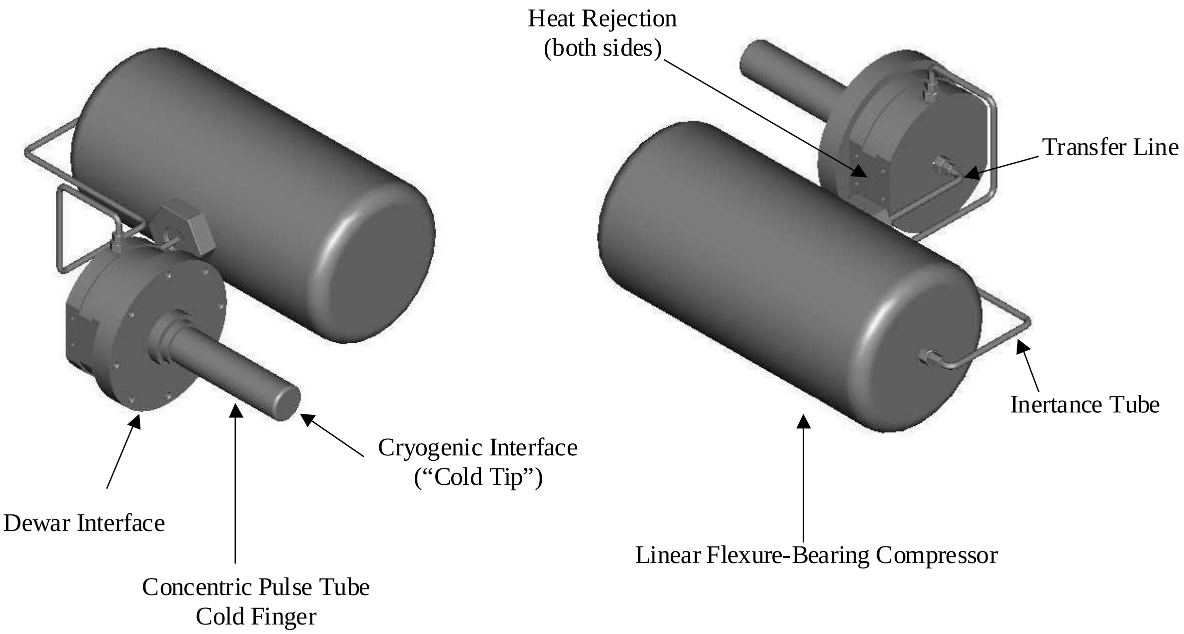

Figure 1: Conceptual design for dual-use cryocooler. Compressor plenum used for surge volume in this design. An alternate configuration utilizing a small, integral volume at the warm end of the expander is also being considered.

### 2.2 Mechanical Cryocooler

The dual use cryocooler is a split module design consisting of a single-stage pulse tube expander and a linear compressor connected by a gas transfer line. A solid model depiction of the cooler is shown in Figure 1. Though the current Raytheon production cryocoolers for both tactical and space are Stirling cryocoolers, a pulse tube approach has been selected for this project for the following reasons. Tactical Stirling expanders are of the pneumatic drive type. The requisite phase shift between the expander piston motion and the pressure wave is created passively through the proper design of the resonant spring-damper assembly at the warm end of the expander. These designs are compact and lightweight, but they have no vibration cancellation capability. The space Stirling expanders feature an actively driven piston and an active balance mass assembly to provide both high efficiency expansion and active vibration cancellation, respectively. However, these mechanisms drive up the cost and the mass of the expander. The pulse tube is thus a logical choice for this cryocooler. The absence of moving parts enables an expander design that is long life, low cost and low in vibration output, even without the added mass and complexity of an active balancer.

With proper contamination control measures, the pulse tube expander is essentially infinite life, thus the compressor is the life-limiting element of this cryocooler. To provide the requisite lifetime, the compressor design is based upon a modification of the proven flexure-suspension space cooler technology. Dual opposed pistons are supported by flexures to provide the required axial compliance with high radial stiffness, which minimizes rubbing contact with the cylinder walls during operation. This basic design approach is in widespread use by most if not all space cryocooler manufacturers, including Raytheon.[4] The flexures are designed for infinite fatigue life at the maximum stroke. At Raytheon alone, over 150,000 hours of space cryocooler operation have been accumulated without failure, and an endurance life test on a particular flexure design is approaching nine (9) failure free years (see Figure 2). The dual-use cryocooler compressor suspension is a modified, lower cost version of these previous designs. The present focus is on the tolerance and alignment schemes to determine lower cost methods by which the objective lifetime and high reliability can still be achieved.

Figure 2: Nine-finger spiral flexure endurance test setup. Over 1.1 trillion cycles (>8 years) accumulated without failure. Flexures of this design have been used for several Raytheon cryocooler programs. (Counter shown rolls over every 26 days, so actual accumulated run time is tracked with the log book.)

Referring again to Figure 1, the expander and compressor module are connected with two gas lines, a transfer line and an inertance tube. The transfer line connects the compression chamber with the expander inlet, and the inertance tube connects the expander outlet with a surge volume, or pressure ballast. The inertance tube and surge volume provide the required thermodynamic phase shift in the pulse tube. The inertance tube creates both flow resistance and inductance. The inductance causes the mass flow rate at the warm end of the pulse tube to lead the pressure wave in the expander, which enables the designer to maximize the pressure-volume expansion work that occurs at the cold end of the pulse tube through setting the proper geometric specifications (pulse tube and inertance tube dimensions, primarily). For details on inertance tube theory, the reader is referred to the literature where the subject has been discussed by many, including recently by NIST.[5] The figure shows the compressor plenum space being used as the surge volume. Alternatively, the surge volume can be a separate volume attached to any convenient location. Because of the inherent flexibility afforded by the split module approach and the orientation insensitivity of the cryocooler during operation, the modules can be oriented relative to each other as required by the integration requirements of the system. The primary restriction is that the transfer line length is ideally kept short (<15”) to reduce pressure drop and void volume losses.

### 2.3 Cryocooler Electronics

The mechanical cryocooler will be very similar regardless of whether it is used for a terrestrial or space mission. The electronics, however, are expected to be different. Vibration cancellation is not typically a concern for tactical missions, which is not surprising when one considers the inherent vibration in the typical fixed wing, rotary wing, missile, and ground combat vehicle platform. (One exception may be hand-held infrared cameras and gun sights, where the stealthiness of the warfighter can benefit from a quieter cryocooler.) High reliability is a requirement for tactical military applications, but radiation hardness typically is not. In contrast, radiation hardness is almost always a requirement for space, at least to some modest level (>30 krad total ionizing dose (TID) typical). Low vibration output is also typically required for cooling space infrared sensor payloads; other potential applications, like cooling high temperature superconducting (HTSC) electronic circuits, may not have a vibration output requirement.

Given the above, the dual-use cryocooler electronics for tactical missions are expected to be very similar to the current tactical cryocooler electronics, an example of which is depicted in Figure 3. These low cost electronics provide the basic required functionality: motor drive, temperature control, and system interface. The current technology satisfies the needs of the dual-use cryocooler for tactical missions.

The space version of the electronics will require an upgrade to the tactical electronics with respect to radiation hardness, at a minimum. If active vibration cancellation is required, that represents additional complexity. However, much simpler implementations of active vibration cancellation (relative to the present space cryocooler technology) are being developed for this project. As with the mechanical cryocooler, the electronics is being developed mindful of achieving a careful balance between capability and cost. One of the objectives of the development is to determine how close we can get to the <100 mN output levels presently achieved with our line of space of cryocoolers while still achieving the objective order of magnitude reduction in production cost. The answer to that question is unknown at present; the goal is shown in Table 1.

Figure 3: Example of tactical cryocooler electronics. Raytheon Low Cost Cryocooler Electronics (LCCE) module shown as representative of dual-use cryocooler electronics.

## 3. DEVELOPMENT PLAN AND PROGRESS

### 3.1 Early Work

The initial step in the development was to identify a basic requirements set that satisfies the needs of a sufficiently broad cross section of space and tactical applications. As discussed in our early work on the subject,[1] the SADA-I specification was selected as a starting point. The SADA-I is in broad use across a range of tactical programs, so it is evidently relevant to many tactical military applications. With respect to the space applications, a cooler of this approximate size will more ideally satisfy infrared sensor cooling requirements for which the present space cryocooler technology is oversized. This point is made clear by comparing the capacity versus temperature curve for the dual-use cryocooler to that of the current Raytheon Stirling One-Stage (RS1) production space cryocooler (Figure 4).

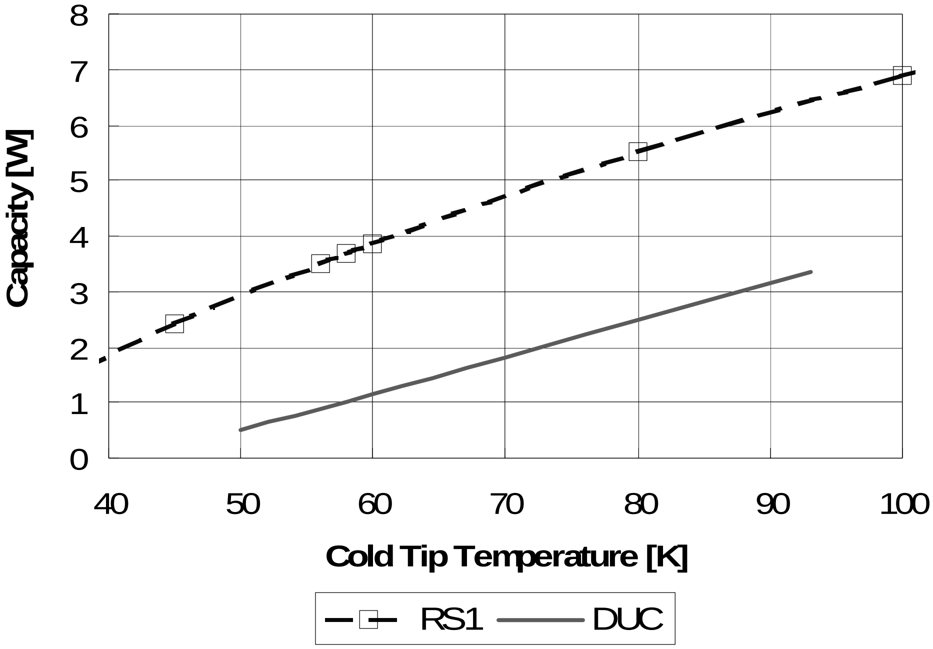

Figure 4: Comparison of load curves for RS1 and Dual-use cryocooler (DUC). RS1 data shown measured using a flight-design unit off the production line. DUC performance projected from thermodynamic model. RS1 weighs 13 kg versus <3 kg for DUC.

Once a nominal requirements set was defined, the next step was to determine if a mechanical design concept could be identified to satisfy those requirements for both space and tactical missions. For the reasons cited above, it was predetermined to pursue a single-stage pulse tube design with some form of a flexure-bearing compressor. Fundamental to the success of this approach was developing a cold head packaging scheme that meets the SADA-I integration requirements. The SADA-I dewar cavity into which the cooler integrated presumes that the expander presents a cylindrical cold finger, like a Stirling. The only viable pulse tube was therefore a concentric pulse tube, that is, a pulse tube expander in which an annular regenerator surrounds a cylindrical pulse tube. This arrangement is shown schematically in Figure 5. As was discussed at the MCALC-IV Conference,[3] a design study was conducted by Kirkconnell, Ross, and Drs. Radebaugh and Bradley at the National Institute of Standards and Technology (NIST) in Boulder, CO to investigate the feasibility of using a concentric pulse tube cooler for SADA. It was determined that indeed the SADA-I performance and packaging specifications could be met with a concentric pulse tube. The preliminary performance predictions arising from that study are shown in Figure 4, and the thermodynamic design developed during the Raytheon-NIST project is the basis for the present efforts described below.

### 3.2 Brassboard Expander

The next step in the development is the design, fabrication, and test of a brassboard expander. The objective of the brassboard is to correlate the thermodynamic model to guide future improved designs. The thermodynamic design, e.g., the regenerator cross section and length, pulse tube diameter and length, and heat exchangers, is very close to the design determined from the Raytheon/NIST project. The diameters and cross sections are the same; the lengths of the regenerator and pulse tube were adjusted slightly based upon refined system modeling performed at Raytheon. Of note is that the brassboard expander is of a "U-tube" configuration with the pulse tube and regenerator arranged as parallel cylinders. A solid model of the cold head design showing this component arrangement is provided in Figure 6. This approach was selected to facilitate model correlation because the U-tube contains one less thermodynamic loss mechanism, radial heat transfer between the regenerator and the pulse tube. The regenerator axial temperature profile tends to be nearly linear in most cryocoolers, particularly those operating at temperatures above 50K. The pulse tube temperature profile, however, is not linear.[6] This results in a radial temperature gradient in the concentric pulse tube that drives radial heat transfer, which is an obvious source of entropy generation. Eliminating this loss from the system

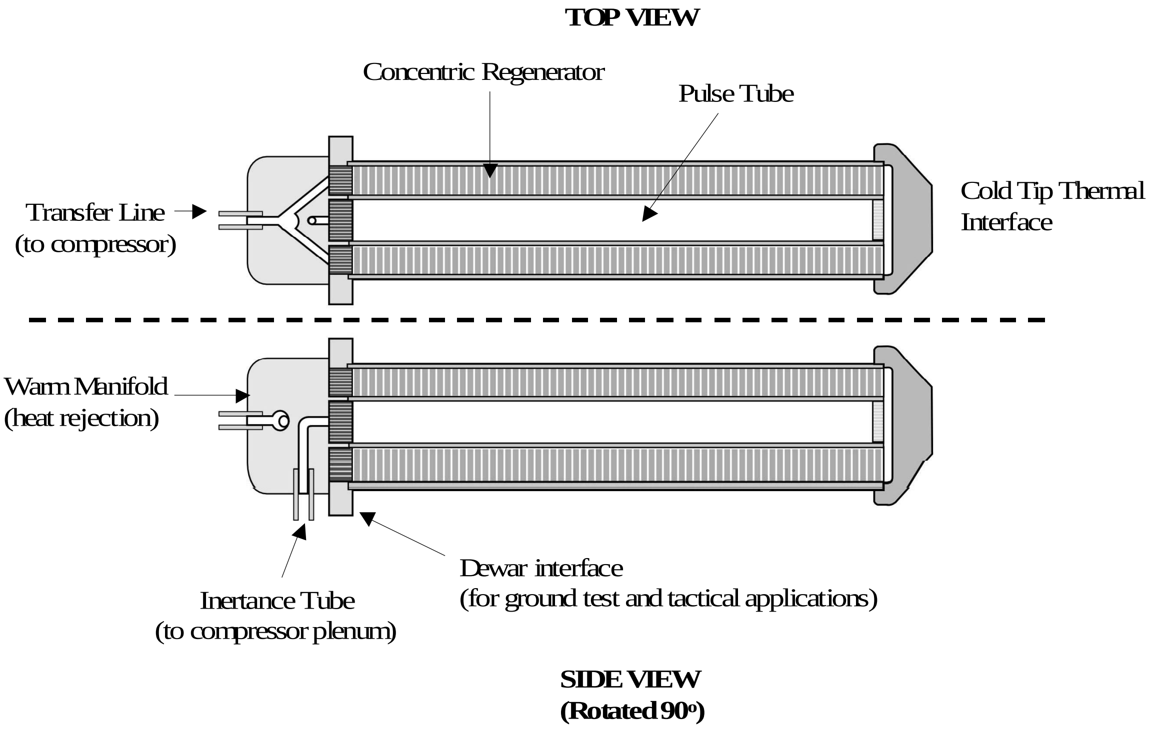

Figure 5: Schematic of a concentric pulse tube cold finger. Two views provided to illustrate all key features.

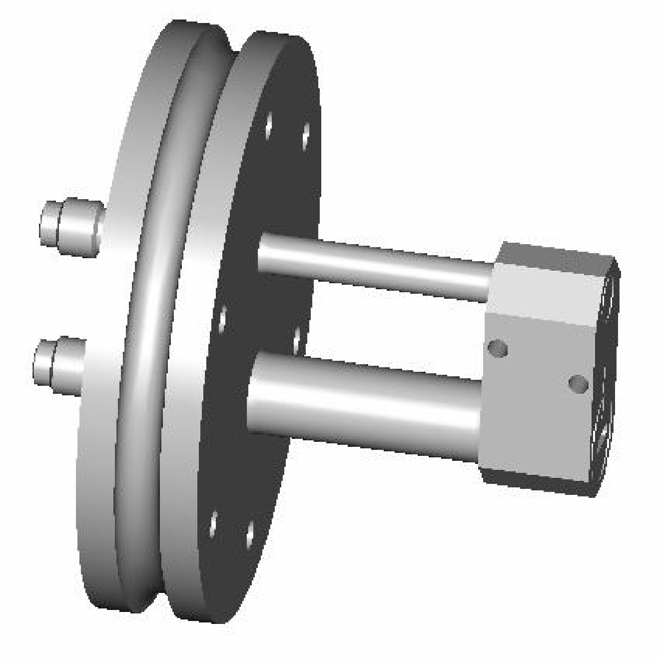

Figure 6. Solid model of brassboard “U-Tube” expander. Large warm end flange provided to accommodate laboratory dewar for convenient, low cost testing. Groove in perimeter of warm end flange for water coolant loop, also to accommodate laboratory testing.

facilitates model correlation. If the model can be successfully correlated with the U-tube expander, then the only remaining significant uncertainty in correlating the model to the subsequent concentric design is this one loss mechanism, thus its contribution has been isolated.

The brassboard expander design is complete and in fabrication. The only component yet to be delivered to Raytheon is the regenerator matrix, which is expected in May ’05. The expander will begin test in June ’05, driven by a Raytheon 7049 tactical compressor. Though this cryocooler will be directly supporting the dual-use cryocooler development program model correlation needs, its primary intended purpose is to serve as a test bed for advanced flow controller technology being developed by TAI. Should TAI’s flow controller project prove successful, the efficiency of the cryocooler will be better than that shown in Figure 4.

### 3.3 Prototype Cryocooler

South Bay Science and Raytheon are collaborating on an MDA-sponsored, AFRL-managed project to develop a prototype low cost, lightweight space cryocooler. The technical approach is as described previously. The expander is a concentric pulse tube. The compressor is of the linear type with dual-opposed, flexure-suspended pistons. This first prototype is clearly focused on the space applications, but the thermodynamic design is the same SADA-compatible design as the brassboard. Following this approach, adapting this cryocooler for tactical applications is expected to be straightforward. Furthermore, by utilizing the same thermodynamic design as the brassboard expander, the maximum benefit of the U-tube model correlation is realized in correlating the concentric model.

The prototype cryocooler design is well underway. The primary focus at present is to identify lower cost designs and manufacturing techniques that do not compromise the cryocooler’s ability to satisfy the high reliability, high efficiency requirements that are present for every space cryocooler application. The design challenge for the compressor primarily relates to the packaging and tolerancing scheme for the flexure-piston subassembly. For the expander, we are seeking to minimize process steps and hands on operations, preferring instead a design and manufacturing sequence that can be largely automated for quantity production. The prototype cryocooler is expected to be in test by early 2006.

### 3.4 Electronics Development

The electronics are being developed by Raytheon as a component of another MDA-sponsored program, this one primed by TechnoSoft, Inc. Following the technical approach previously described, the objective is to develop a radiation hard version of the present day tactical cryocooler electronics to meet the needs of the space applications for the dual-use cryocooler. First order vibration cancellation capability will be implemented together with the radiation hardness upgrade. A breadboard version of the electronics is to be built and tested on the TSI program. We expect the electronics to be available in time to support the 2006 testing of the prototype cryocooler.

## 4. APPLICATIONS

### 4.1 Tactical

One application already mentioned is the upgrade of the current family of SADA-I cryocoolers from Stirling type to higher reliability, longer lifetime, lower cost pulse tubes. An important and growing application for tactical infrared systems is missile warning and direction of countermeasures, which is needed for airborne (both rotary and fixed wing), shipboard (DDX) and land-based tactical applications, as well as for civil jet aircraft. The warning system may utilize a single infrared detector, but is more likely to include a group (up to six) of infrared sensors to cover the area of interest, meaning that multiple long-life cryocoolers are required for each application. With well over 10,000 potential applications that each uses multiple cryocoolers, it is easy to envision the need for long-life cryocoolers to exceed 50,000 for defense and civil aircraft alone over the next several years. In addition, there is interest in using a long-life cryocooler to cool a laser that would disable incoming missiles. That would increase the cryocooler count per aircraft by one. The target operating lifetime for missile defense systems in civil aircraft is 50,000 hours, which is within the range of what is achievable with the dual-use cryocooler.

Traditionally, cryogenic cooling of infrared imagers for missile applications has been provided with short duration, open cycle, Joule-Thompson systems. These continue to be used on some missile applications, but other missile programs are switching to closed cycle tactical cryocoolers. With a tactical cooler, the imager on the missile can be cooled to provide valuable imagery to the pilot during the life cycle period prior to missile launch. Cryocooler operating lifetimes on the order of a few thousand hours, which can be achieved with conventional tactical cryocooler technology, are adequate for this application. Application of the dual-use cryocooler for these applications would likely have to be driven by cost advantages derived from replacing the Stirling expander with a lower cost pulse tube, perhaps still utilizing the conventional tactical compressor technology to minimize cost.

### 4.2 Space

The fundamental objective of developing lower cost space cryocooler designs is of general interest to all customers. However, depending upon the program specific requirements, the dual-use cryocooler as described herein may or may not be applicable. Low refrigeration temperatures, say less than 50K, are not achievable in a single-stage pulse tube with an efficiency that is competitive with a Stirling cooler, at least given the present state of the art. Very low allowable vibration output levels (< 100 mN) over a broad bandwidth (e.g., 0 to 500 Hz) will likely still require active vibration cancellation like the adaptive feed forward (AFF) method used on our current production units for space. There is no reason, however, that AFF or a similar approach would be incompatible with the basic dual-use cryocooler design approach, so a combination of this new design with “traditional” cryocooler technologies may be advantageous for some space applications.

The applications being immediately targeted by the dual-use cryocooler are those that demand low cost and light weight, require refrigeration above 60K, are tolerant of vibration output levels in the hundreds of millinewtons, and require operational lifetimes in the 40,000 to 50,000 hour range. Small satellite applications are envisioned, as are space station science experiments. Present day space cryocooler systems cost about $2M each for the typical build quantities of 3 to 5 systems. (A “system” includes the mechanical cryocooler and the electronics.) This is cost prohibitive for many science missions. We are targeting a recurring cost an order of magnitude lower, which we expect to open up opportunities presently not practical with current technology.

## 5. SUMMARY

Raytheon is presently engaged with many partners and supported by MDA and AFRL to develop a dual-use cryocooler with applicability to both space and tactical missions. A prototype version is presently being designed with a focus on the space mission. Testing is planned to commence early in 2006. The breadth of applicability of this cryocooler to the marketplace will be determined by our success in simultaneously satisfying the sometimes contradictory requirements of the space and tactical military applications..

## ACKNOWLEDGMENTS

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