Air Force Research Laboratory Space Cryogenic Technology Research Initiatives

F. Roush and T. Roberts
Air Force Research Laboratory AFRL/VSSS
Kirtland AFB, NM 87117

ABSTRACT

The Air Force Research Laboratory (AFRL) Space Vehicles Directorate actively pursues cryogenic refrigeration system and system integration technology research to support the research needs of the Air Force, Missile Defense Agency, and Department of Defense. This effort takes place using a technology development strategy emphasizing definition of current requirements to support these customers, procurement of the needed technology, and evaluation of the delivered hardware and software so that the future customer requirements can be anticipated and technically satisfied. The balance between research into refrigeration performance, refrigeration capability envelope enhancement, and integration facilitation methods critically affects the short and immediate term results of this long-term strategy. Incorporation of supplier suggestions on nascent technology development opportunities into long-term development planning completes this technology management process. This process is shown in its historical context and extrapolated into the future by projecting current trends and near-term customer projected needs.

INTRODUCTION

The development of the Cryogenic Technology Group within the Space Vehicles Directorate during the past decade was initially motivated by a commitment to support the technology development and validation needs of the Department of Defense in the area of ballistic missile defense. Preliminary program requirements developed by the Strategic Defense Initiative Organization indicated that a midcourse detection capability was required beyond the capabilities of the Defense Support Program's missile launch detection abilities. This mission was pursued along two avenues: active ground-based radars and passive space-based infrared sensors requiring cryogenic refrigeration. The preliminary requirements for infrared detectors were tied to the development of reliable, efficient cooling from 150 K down to 10 K, which support long mission durations of up to 10 years. In general, this requirement space is still relevant today, though the meanings of reliable and efficient have changed along with the mission set supported.

THE SPECTRUM OF SUPPORTED MISSIONS

Infrared Detectors

The detection of targets of military interest is a diverse subject, even for the subset of targets of interest to space-based sensor payloads such as those supported by the Cryogenics Technology Group. In general, the combination of significant radial speeds relative to the sensor and great

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distances poses a challenge that cannot be met by sensors that rely on either close proximity, large amounts of target illumination, or long exposure times. The design of space-based military sensing systems is highly concerned with the reduction of the noise-to-target signal ratio. Given that thermal effects create much of the noise inherent within most detectors, and also create obscuration effects in uncooled optical benches, the use of cryogenic refrigeration systems both allows for the operation of these sensors as well as optimization of the overall sensing system.

Given this general effect, the infrared spectrum can be divided up into sub-spectra named the near infrared (NIR), short wave infrared (SWIR), mid-wave infrared (MWIR), long-wave infrared (LWIR), and very-long-wave infrared (VLWIR), whose sensors have to be cooled to lower temperatures. For instance, while SWIR sensors are often cooled only to 150-200 K, VLWIR sensors require 10 K or lower. This is partially due to the sensor noise as outlined above, but is also a function of the emissive radiation output function described by the Stephan-Boltzman equation.

Superconducting Electronics and Communication Transmission Apparatus

The advent of superconducting microelectronic circuitry has enabled designs to operate at both high temperature (up to 80 K) and low temperatures (up to 20 K). An example of this mission area is the effort to develop high-speed (tens of gigahertz) analog-to-digital converters for the Joint Tactical Radio System (JTRS). Given the limited frequency availability, and the command and control functions exponentially increasing bandwidth requirements, a Niobium superconducting converter was designed to operate at 4 K. Fortunately, given superconducting operations, the 80 mW at 4 K load is small relative to the shielding requirements at 12 K, 25 K, and 80 K.

Similar issues affect the operation of radio frequency antenna systems in space and in certain supersonic avionic environments. Here, the high data rate requires a low noise antenna, which implies that dimensional stability must be assured. This is done by both reducing antenna resistive impedance and by stabilizing the temperature of the antenna using active cooling. A comparable issue arises in lasers used for communication: various types of semiconductor lasers require cryogenic operating temperatures and their output frequency is very dependent on temperature stability.

Cryogenic Propellant and Liquid Storage

The general needs for cryogen storage in space take two forms: 1) storage of cryogens that are used as refrigerants in open cycle dewars, and 2) storage of cryogenic fuels. In both cases, the use of active refrigeration to prolong the mission life of the payload is the same: refrigeration is used to reduce the boil off of these substances given a staccato usage profile. For fuel storage, a serendipitous benefit is that refrigeration can reduce the need for high pressure storage vessels and, in some cases, ameliorate the chemical reactivity of the stored fuels. An example of the latter is the storage of deuterium/hydrogen fluoride fuels for chemical lasers. The sizes of the respective cooling loads are dependent on the volume of the stored cryogens and can range upwards from 5 W at 20 K plus shielding loads on the order of 10 W at 100 K and higher. Generally, such missions are not small, and, in that sense, refrigerator mass minimization is not itself a high priority. Rather, the large effect that the thermodynamic efficiency has on the overall mass must be considered as a first priority.

ACTIVE REFRIGERATION PROGRAM INITIATIVES AND GOALS

Specific requirements for cryogenic refrigeration were summarized by Donabedian[1], whose graphical depiction of cooling methods versus temperature and capacity can be seen in Figure 1. It should be noted that while Donabedian's chart has only marginally changed in the applications served by active refrigeration, the practical usefulness of active refrigeration has increased significantly due to its dramatically increased efficiency over the past decade. Figure 2 shows the general efficiency trend depicted by cryogenic refrigeration systems based on single-stage efficiency equivalents. This reduction of multistage efficiency to a single stage equivalent is accomplished by summing the exergetic cooling load equivalents of all stages based on the following equation:

$$Q_{c,equiv} = \sum_i Q_i \left(\frac{T_{rej}}{T_{cooling}} - 1 \right) \quad ; \quad Specific\ Power = \frac{P_{input}}{Q_{c,equiv}} \qquad (1)$$

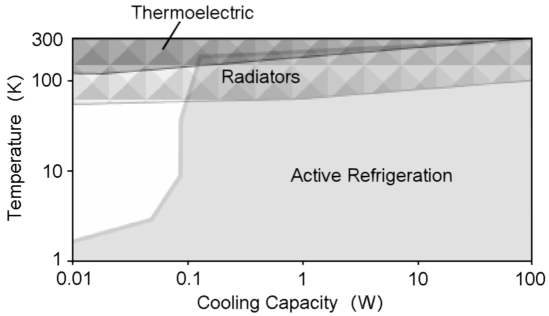

Figure 1. Cryogenic cooling methods, updated.

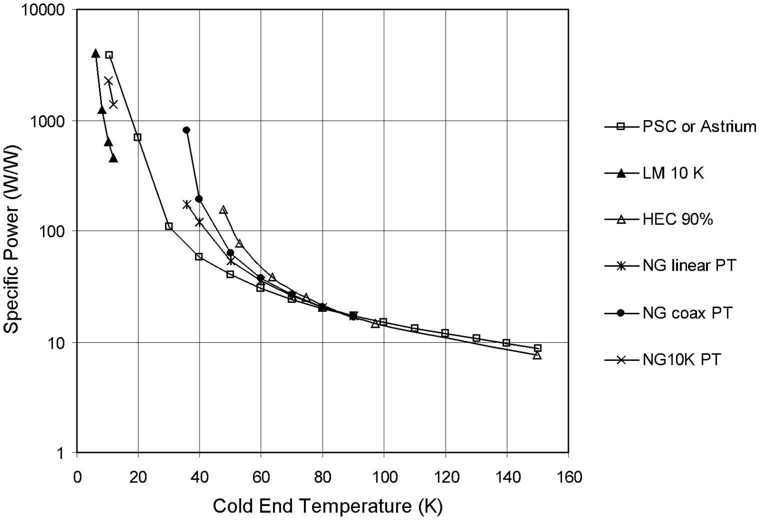

Figure 2. Current trend for cryogenic cooling efficiencies.

Some requirements are appropriate here concerning imparted vibration or jitter control of mechanical refrigeration systems. There is no general a priori method of saying that a specific payload's jitter level must be below a certain force or acceleration level. For any mission, the spatial motion of an FPA that can be allowed is related to the size and intensity of the target of interest, the background clutter, the payload structure and other vibration sources, and finally the characteristics of the optical bench. For some geosynchronous sensing missions a 1-2 micron displacement amplitude is the operational constraint. Low Earth orbit missions are generally much closer to their targets and hence would be constrained at higher vibration levels than geosynchronous or high Earth orbits, but that is only true as a trend.

10 K and Below Multistage

Two accomplishments during the past year have nearly brought to practical availability the option of using active refrigeration in support of VLWIR Si:As sensors. These were the fabrication at Northrop Grumman of a 10 K engineering model pulse tube cooler[2], and testing at Lockheed Martin of their 10 K and 6 K advanced pulse tube designs.[3,4] Both the Northrop Grumman and Lockheed Martin 10 K pulse tube coolers have three stages as shown in Figure 3 for Lockheed.

In addition to these pulse tube coolers, two other cooler options have been discussed with other manufacturers. A 10 K reverse Brayton design has been funded on the component design and testing level at Creare, and Ball Aerospace has indicated interest in producing and testing a hybrid 10 K Joule-Thomson/Stirling cooler based on their successful 6 K ACTDP cooler development for

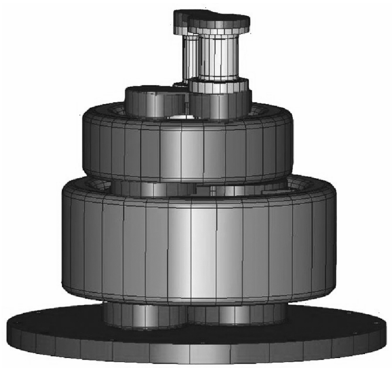

Figure 3. Lockheed Martin 10 K pulse tube cold end design.

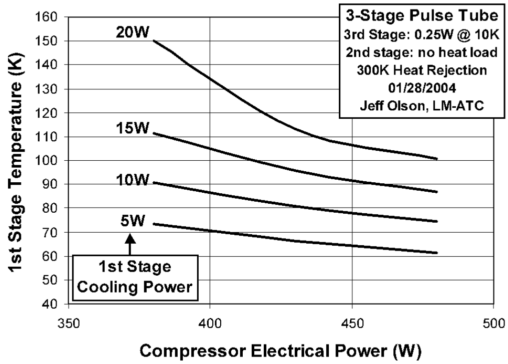

Figure 4. Lockheed Martin 10 K pulse tube cooler performance estimates.

NASA.[5] The investigation of this system's potential for 10 K applications is impeded only by funding constraints. Within the very near term future, the ability to validate the long term stability of these systems will be a high priority for the AFRL Cryogenics Laboratory. If significant program interest in these systems is expressed by specific future payload systems, then demonstration of both lifetime reliability and performance will need to be funded.

AFRL has technically supported the Joint Tactical Radio System's requirements for a 4 K refrigeration system, shown conceptually in Figure 5. This program recently had a critical design review

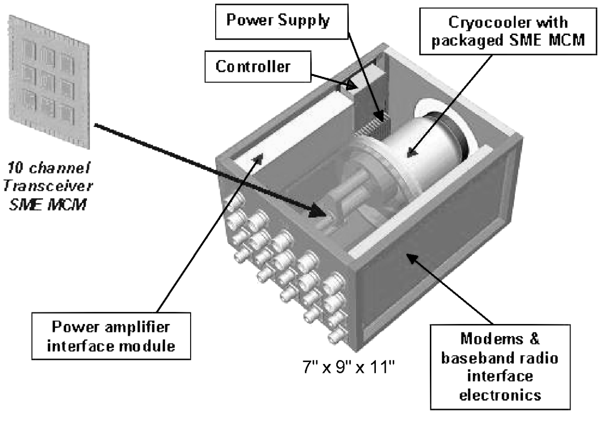

Figure 5. Joint Tactical Radio System's cryogenic cabinet.

at Lockheed Martin in which their NASA-funded four-stage ACTDP pulse tube cooler was described.[4] This cooler uses ^{3}He and has achieved a no-load temperatures of 3.86 K.

The Cryogenic Technology Group has also considered other alternative technologies for obtaining reliable 10 K refrigeration for space missions. The use of thermoelectric coolers has been practically limited by poor thermoelectric figure-of-merit (ZT) factors below 150 K and by issues inherent with the traditional cascaded design of these systems when cooling from ambient. Recent proposals to investigate new classes of materials that possibly might be applicable in the 10-40 K range are being considered for coupling with 40 K active refrigerators to eliminate all but one or two cascaded cooling steps (along with the need to fund research into what materials might bridge the gap between 40 K and 150 K).[6]

35 K Multistage Supporting LWIR Sensors

Two related efforts have received funding during the past year: 1) the Raytheon RSP2 refrigeration system and control electronics[7], and 2) the Northrop Grumman HCC refrigeration system and control electronics.[8] Both of these programs have upper stages supporting large optics-bench loads (15-20 W at 85 K) and 2 W loads at the focal plane. Their control electronics are required to demonstrate 300 krad total dose hardening, closed loop thermal control to 0.1 K, and closed loop exported vibration control.

The Ball SB235 cryocooler was also evaluated; it is roughly a quarter of the size and power input as the Northrop and Lockheed coolers. Given that the power input levels of these systems is above 500 W, future efforts in this area will concentrate on raising thermodynamic efficiency and reducing payload mass penalties.

In this area, the hydrogen sorption bed compressors with Joule-Thomson expanders have been reviewed with respect to their ability to support cooling requirements and their potential for reducing the number of moving parts. Significant progress has been made in hydride bed stability,[9] though the practical demonstration of the actual lifetime has only been done on the order of a year at practical continuous-duty-cycle levels. This review has been motivated by interest within the USAF and the Missile Defense Agency in compressors utilizing few or no moving parts. A potential alternative to the sorption concept is the use of nanoparticle reinforced proton-conducting materials that can generate either a direct or oscillating flow of hydrogen.[10]

Above 60 K Multistage

Before 2006, this area was a relatively low priority for the Cryogenic Technology Group, but due to reassessment of the follow-on system to the Defense Support Program series of payloads, and a concurrent lack of large-scale high-temperature MWIR focal plane arrays available within the next few years, the refrigeration in the 70-110 K range at very significant loads has become a very high priority. Complicating this situation are the particular issues relevant to the missile launch detection problem, especially:

1. The use of variable frame rates in tracking algorithms. If a 4 megapixel array generates a load of 0.2 W at 10 Hz, close to 1.25 W at 30 Hz, and 4 W or more at 75 Hz. Such alterations in cooling load might occur over a period of several seconds and even might be local to certain subsets of pixels in the focal plane, but not to the whole array.

2. By historical standards, the use of very large arrays. In order to stare at the whole Earth from geosynchronous orbit at a resolution of 3 km or less, it is necessary to use total array sizes of four thousand pixels square. At a 20 micron pixel dimension, that implies focal plane dimensions exceeding 8 cm by 8 cm. Traditional focal plane calibration and linearization methods require isothermality within 0.1 K of the design temperature.

These two considerations impose radically new requirements on the cryogenic refrigeration systems and, in particular, their control systems. It is probable that traditional feedback PID loops will be insufficient for maintaining both average temperature stability as well as spatial isothermality at the focal plane.

Given the programmatic requirement in the missile launch detection context for demonstrable risk reduction prior to eventual system launch, the Cryogenic Technology Group has been tasked to provide technical support to various preliminary flight experiments and ground testing of their cryogenic components in both stand-alone component life testing as well as integrated-payload testing.

Responsive Space and Microscale Cooling

The size of any optics bench and focal plane refrigeration system is a function of the nature of the mission supported. Large field-of-view staring optics operating at high frame rates will intrinsically have higher cooling loads than small field scanning systems that are used to track distinct targets initially acquired by other means. In turn, sensors for close inspection of space objects might be smaller again by one or more orders of magnitude. There is a current disparity between the size spectrum of these applications and the capacity to downsize cryogenic refrigeration systems beyond approximately one tenth of a watt. Part of the issue here is the nonlinear scaling rules for working fluid dynamics, but the other general phenomena that causes traditional thermodynamic cycles to have decreasing efficiencies as size is reduced is a general tendency towards smaller and smaller Biot numbers as spatial dimensions are reduced. Eventually, thermal conductivity predominates in the system and thermodynamic refrigeration recedes into the background as a second-order effect.

To ameliorate the effects of this trend, two avenues for future efforts must be pursued:

1. Investment must be made into component technologies that themselves can be flexibly downscaled. MEMS and 'cryogenic' in the same statement should not designate an implicit oxymoron.
2. Overall designs will have to be more complex at the macroscale. Any of the refrigeration systems supporting large cooling loads are conceptually simple, despite the fact that their internal options might be complex; one uses one refrigerator that operates between one heat sink at low temperature and one heat sink at high temperature. Microscale refrigerators, forced to operate between closer heat sink temperatures, will probably be used in series, with one element cooling another element's high temperature heat sink in an overall design that might approach biological complexity.

The benefit for the payload designer attempting to rapidly respond to a short warning mission would be that such microscale refrigerators could be standardized and would be used in massively parallel or sequential structures. This is completely different from the current situation where individual systems designed for particular applications cannot be flexibly reused in off-nominal design-point missions. The Missile Defense Agency has tasked the Cryogenic Technology Group to compose and manage two SBIR and STTR topics in this general area in 2007, and it is anticipated that this area of research will increase dramatically in overall funding in the next years.

THERMAL MANAGEMENT OF PAYLOADS AND REFRIGERATION INTEGRATION METHODS

Two payload features motivated funding interest in the area of cryogenic integration methods in 2006: 1) on-gimbal infrared sensors, and 2) distributed cooling requirements. Implicit with on-gimbal sensors is the need to minimize gimbal mass and its attendant position-wheel systems. Past programs have demonstrated that removing the waste heat from an on-gimbal refrigeration system to an off-gimbal radiator is feasible; the present initiative seeks to remove a 35 K multistage refrigerator from the gimbal entirely. Distributed cooling load requirements at various temperatures is akin to the on-gimbal sensor issue, although without the dynamic swiveling context of the gimbal. Consequently, a possible answer to these similar issues was funded through and Missile Defense Agency SBIR award to Creare, Inc. for the cryogenic transport loop whose pump is depicted in Figure 6. The Creare proposal features a helium working fluid pumped by a cryogenic circulator with direct heritage from the NASA NICMOS repair system inserted on the Hubble Space Telescope in 2002.[11] An ancillary benefit of such a cryogenic integration scheme would be the removal of the refrigerator's source of exported vibration from the neighborhood of the focal plane.

An associated area of interest is cryogenic passive radiators as a supplement, or complement to active refrigeration in many high-temperature cryogenic applications. As Donabedian noted[1], the

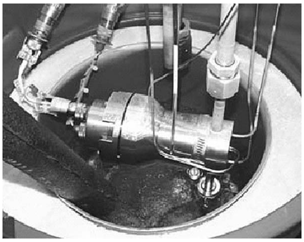

Figure 6. Creare NCS circulator proposed for a cross gimbal cryogenic transport loop.

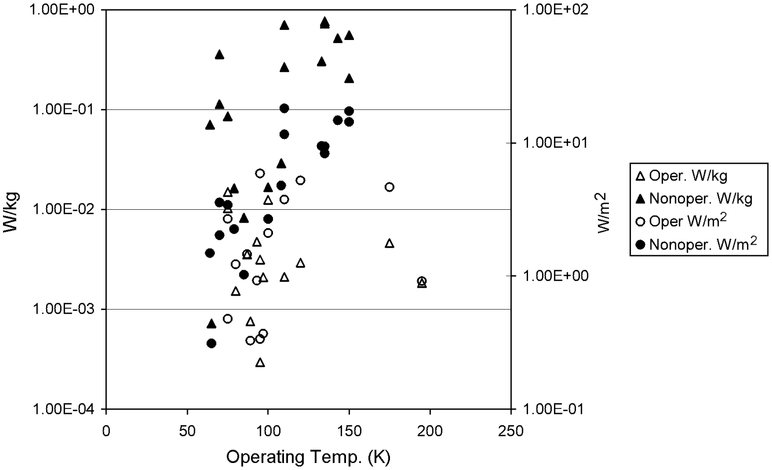

Figure 7. Selected cryogenic radiator performance as a function of temperature.[1]

practical results from passive radiator cooling have varied dramatically from either ground-test results or design goals. This is particularly evident in its effects on cryogenic payload mass penalties versus the actual loads supported, as extracted from Donabedian's data in Figure 7. Donabedian's observation about the propensity of actual flight performance to not follow predicted estimates is confirmed by the trend demonstrated in Figure 7. Here, the unflown (non-operational) systems consistently out perform their working brethren. Investigation of how to make this important source of cryogenic cooling more predictable will be a considerable concern in the next years.

CRYOGENIC SYSTEM RELIABILITY AND MISSION DURATION

The ability of cryogenic systems to stably support mission requirements has been a source of concern during the past decades, and not just in the limited context of active refrigerators. While launch costs and schedules have prevented truly responsive space launch and payload operations in the past, the emphasis on nearly infinite lifetimes has been posed as a payload component requirement, often at great cost to the government. This has led to a virtual divorce between the development of terrestrial and avionic cryogenic refrigeration systems, which could be maintained between missions, and space systems, which were distant from any possible source of maintenance support.

The advent of more flexible space-operational concepts, as well as the realization that avionic system downtime represents a significant operational cost factor, has led to a gradual reconciliation of what constitutes system reliability for both avionic and space systems. This initiative has been motivated by research into avionic system Prognostic Heath Monitoring[12,13] as a template for how to evaluate the remaining lifetime for cryogenic refrigeration systems supporting complex avionic weapons platforms. What will be of interest to the Air Force is how this theory can be translated into estimates for space-system remaining mission life, particularly if these payloads contain components (such as active refrigerators) that are designed as standardized components in missions of far less than long-to-infinite lifetimes.

IN HOUSE RESEARCH

Procurement of black boxes is not a wise use of government research and development funding. Therefore, significant efforts are made to understand the functioning and phenomenology demonstrated by actual cryogenic systems. Many of the detailed results of these efforts are and have been presented in the proceedings of the International Cryocooler Conference, but their current status and future intentions are summarized below.

First Order System Modeling

The goal for the effort put into first order system modeling is to provide a code for in-house simulations of various configurations of pulse tube and Stirling cryocoolers. The modeling is focused on quantifying the exergetic losses in the various components of the cryocooler system. The simulations will be verified with the empirical data from some of our in-house coolers to get confidence levels for our simulation code. Due to the large parameter space involved with the various cryocooler components, a code is needed that is fast and can give good approximations when attempting to model new cooling systems. When the physics for modeling components becomes complex, empirical data to enhance the model is used to simulate the complex component. Typical outputs of our system include the various components' pressures, mass flowrates, temperatures, phase shifts, enthalpies, irreversibilities, and exergies. One such output is shown in Figure 8, which shows where the exergy or availability of work is destroyed in various components in this particular pulse tube simulation.

Computational Fluid Dynamics Modeling of Refrigeration Components

With recent advances in computational capabilities, modeling of refrigeration components with computational fluid dynamics (CFD) has become very effective. Recent in-house studies have successfully achieved accurate results of modeled refrigeration components based upon widely available empirical data and first order in-house research. To demonstrate this ability, a plot of the cycled averaged and instantaneous axial temperature profiles throughout the pulse tube are shown in Figure 9. These results provide sufficient evidence for the labs ability to rely upon CFD to accurately model variations in refrigeration component geometry and its affect on refrigeration performance. CFD will provide the lab with greater ease to accurately model refrigeration components in cryocoolers procured from the manufacturer and aid in their ability to improve performance.

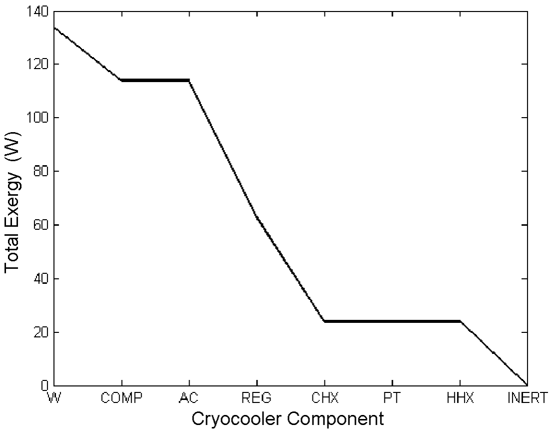

Figure 8. Simulation of an Inertance Tube Pulse Tube Refrigerator (ITPTR) and shows the exergy or availability of work as it is destroyed in the various components of the cooler.

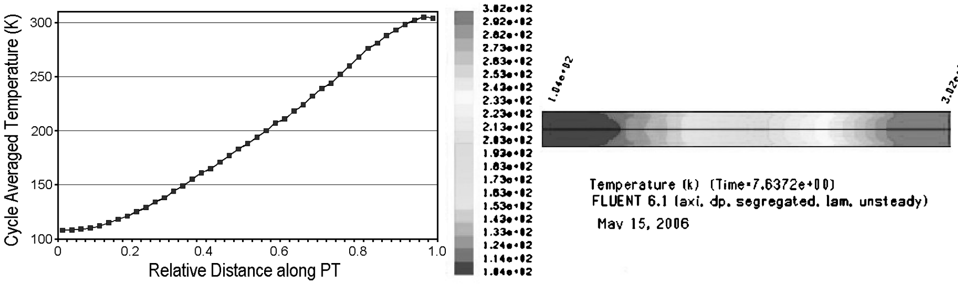

Figure 9. Cycled Averaged and Instantaneous Pulse Tube Temperature.[14]

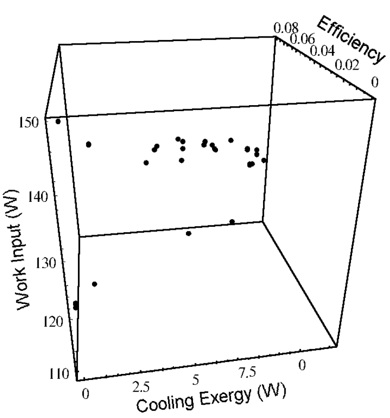

Figure 10. Ball Aerospace SB235 two stage cryocooler cooling exergy path (reject T= 300K, 90% stroke; efficiency as % of 2nd Law limit, cooling loads from 25 K to 225 K).

Empirical Measurements and Modeling

The goals of the Cryogenic Technology Laboratory are to transition technology from low readiness levels to a point at which actual space missions can use that technology to mitigate payload risk for space payload designers, and to understand the basic phenomenology inherent in cryogenic technology relevant to space missions. Most of the physical plant in the lab is designed to gather large empirical data sets on actual system performance across long times and disparate environmental conditions. Correlation of these data sets with the modeling efforts described above is a direct outgrowth of those efforts, and both validate the modeling efforts as well as providing insight into how actual system performance varies. In an example of this sort of correlation effort, empirical proof of discrete cooling exergy paths theoretically predicted for two stage cryogenic refrigeration systems was obtained for the Ball SB235 cooler, as depicted in Figure 10. In this correlation, the definition of exergetic cooling in Eq. (1) for multistage systems was used. Such paths enable the extension of theoretical predictions for multistage refrigeration performance across an entire system's performance envelope, and will provide an essential tool for flexibly using such systems in responsive space or transient-load missions supporting space sensing or superconducting electronics applications.

FUTURE REQUIREMENT PROJECTIONS

The prime goal to be addressed in a general sense is to make active refrigeration available as a flexible and responsive technology asset. For example, cryocoolers should be designed to meet needs rather than focal planes being designed to make up for the lack of a relevant cryocooler. While a commitment to long life reliability will be a major motivation, increased attention will be paid to small-scale and low-cost systems that might not demonstrate long life characters as preliminary prototypes. Bounds on payload effects due to such deficiencies and obtaining an understanding of their causes and possible mitigation methods would be then pursued. In this effort, the most efficient combination of contractor-supplied, academic, and government internal resources will be supported. Particular attention will be paid to the issues of size reduction and efficiency improvement, both motivated by the desire to minimize payload effects posed by cryogenic refrigeration systems.

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