USAF Thermal Management System Needs

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ABSTRACT

The Air Force Research Laboratory (AFRL) Space Vehicles Directorate pursues cryogenic refrigeration system and system integration technology research in support of the research needs of the Air Force (USAF), Missile Defense Agency (MDA), and Department of Defense (DoD). This effort derives requirements from multiple programs and develops general solutions to the cryogenic needs for general space missions as well as specific solutions for individual mission applications. The general thermal management needs of missions supporting Air Force space operations are supported by modeling payload interactions with their cryogenic components. Specific strengths and weaknesses of the current state of technology are also compared to these needs.

INTRODUCTION

What this country needs is a really good five-cent cigar.
Vice President Thomas Riley Marshall to John Crockett, Chief Clerk of the US Senate

Cryogenic and thermal management needs have often been described in terms of discrete capabilities of the constituent components [1-3] or in terms of how such distinct components might affect payload operations [4-5]. These approaches however are inadequate to applications posed by the Department of Defense as they ignore the transcending fact that any service does not procure or sustain the operations of such low level components. Instead, it procures and sustains the operations of entire systems (e.g. satellite constellations) in which the interactions of the low level components are complex and varying over time. Compounding the problem of system complexity is the fact that during the procurement process many of these interactions are unknown and difficult to measure or predict. This makes any simple prescription (like Thomas Marshall's above) for component capabilities require heavy caveats which often make those prescriptions offered on an a priori basis irrelevant once actual space systems are being designed. This is not to say that distinct capabilities, such as the ability to efficiently cool electro-optical sensors to 10 K are irrelevant. Rather, we should recognize that for non scientific systems there might be several ways that any application's needs can be met. Scientific systems, which many NASA programs might exemplify, conversely require very specific technical capabilities in order to support specific phenomenological measurements, and therefore fall somewhat outside of the scope of this discussion.

In order to support efficient system design and procurement the Department of Defense implements the concept of *development planning (DP)*, which as Carlson [6] points out is critical to proper technology development and systems procurement.

Early DP lays the foundation for identifying materiel solutions for acquiring weapon systems by investigating future threats; recognizing capability gaps and requirements; capturing needed system-performance characteristics; and understanding technology gaps, risks, and needs.

Note that USAF leadership concerns lie not with these capabilities by themselves, but rather with the interaction between capability gaps and the requirements implied by the overall environment and the risk profile to be assumed in operating in that environment. This makes Vice President Marshall's quote more relevant than might initially be expected, presuming that there was a national need for good cigars a century ago, as Marshall was positing a *capability gap,* just as we are today concerned with space thermal management system capability gaps.

PAYLOAD THERMAL MANAGEMENT PLANNING

Current Status in Overall Thermal Management

Donabedian[7, 8] began his review of sensor system thermal uncertainty margins with reference to MIL-STD-1540B [9], since updated to version D [10] and supplemented by MIL-HDBK-340A [11]. Welch [12] reviewed the payload thermal design margins prescribed in these standards and concluded that less rigorous design margins were not justified by the current state of the art in thermal modeling and component and payload performance measurements. A summary review of these standards therefore is the starting point from which any developmental planning for space thermal systems must begin. MIL-HDBK-340A is most cogent in its specifications to:

a. Provide 17 K margins for passively controlled payload systems whose operation has not been characterized by a validated analytical thermal model. With such a model an 11 K margin is specified. These margins are reduced below 203 K on a sliding scale.
b. Provide 25% load margins or duty cycle margins for systems which are actively controlled by heaters or active refrigerators. This is augmented in earlier program phases; 50% during the conceptual technology development phase, 45% during preliminary design, 35% for the critical design review, and 30% for component qualification.
c. Payload components are to be designed to survive vibration, acoustic, and shock environments with testing margins based on statistically expected spectral levels.
d. Other environmental effects (e.g. thermal cycling) must be considered in the design, and testing will demonstrate that adequate ruggedness exists in the design and in its implementation. This either requires simulation of the actual operational environment or testing with greater margins in range to account for shorter durations or less cycles.
e. Payload electronic units thermal mapping for known boundary conditions should be performed in vacuum to verify the internal unit thermal analysis and for thermal mathematical model validation. The validated thermal model is used to demonstrate that critical part temperature limits, consistent with reliability requirements and performance, are not exceeded. Tolerances on model vs. test correlation are +/- 3 K. Note that this testing and simulation sequence uses the 11 K thermal limits in "a", above, unless active thermal controls governed by "b" are used.

Donabedian considered only items "a" and "b" and Welch exclusively considered "a". The other items however bring up several payload interactions which are not usually covered in thermal management or cryogenic refrigeration technology development planning. Payload components do not include just cryocoolers or other thermal management devices, so payload interactions must be considered in *all manners.*

For instance, the acoustic environment of an electro-optical sensor can be significantly affected by the acoustic vibrations from the active refrigerator. Insufficient consideration has been shown in how payload design requirements in this area must be incorporated into the technology development and testing of their active elements, such as cryocoolers. A comparison of how launch vibration statistical expectations are incorporated into design and testing, or how thermal loads and limits are similarly incorporated, with the case of payload acoustic designs and testing is indicative of benign negligence in the latter area. Programs in the conceptual and preliminary design phases are left adrift and either tend to over specify or under specify component acoustic spectral output. It is probable that the 3-6 dB margins cited for launch acoustic testing are inappropriate for testing operational payload interactions, or for providing a design margin goal for technology development.

Thermal cycling should be considered both in light of operational and non operational temperature limits within which all payload components will survive and operate, but also with respect to the implications of variations in operating conditions (e.g. orbital variations in rejection interface temperature or cooling loads) on component and system performance. With passive radiators being subject to the 11 K/17 K design margin specification, design envelopes of the active refrigerators using them as rejection devices should be expanded as well (with respect to their reject envelope). Similarly, the effect of cold end instabilities of cryocoolers on sensor focal planes, for example, should be used to establish technology development and testing goals of these refrigerators. Such environmental simulations for various payload components should seek to discover component incompatibilities within the payload. An example would be ensuring that radiator operating temperature limits and cryocooler rejection temperature limits are compatible, both in performance models and in testing.

"Payload electronic units" include both low level microelectronics in printed circuit boards (PCB) and higher level assemblies, such as electro-optical sensors. Prior electronics packaging technology development and testing has been very concerned with the low level issues involved in thermal rejection of waste heat from PCBs and their rack mounts. This ignores how higher level assemblies as a whole are affected by "known boundary conditions", which in the case of electro-optical sensors include focal plane temperature, optics temperature, and constituent PCB assembly rejection temperature. Thermal modeling in its validation for such higher level assemblies must therefore be directly linked to the cryocooler's specifications and testing program. What is not uniformly recognized is that the specifications of HDBK-340A imply a heightened reliance on overall modeling and simulation in predicting payload performance, and both payload and component testing play key roles in validating these models and reducing overall program risk.

Current Status in Cryogenic Refrigeration

Kirkconnell [5] discussed the parameters by which cryogenic refrigerators operating above 20 K might be selected. His discussion of the low level component interactions in actual refrigerator performance is commendable and shows the variety of technically feasible solutions to a variety of applications that are currently possible. Roberts [6] extended that parametric analysis in considering how payload effects (e.g. total payload mass) are more critical to overall payload performance than component performance figures of merit. Both of these approaches are somewhat incompatible with the explicit uncertainty margins expressed in HDBK-340A and recommended by Donabedian. They are even less compatible with the reality of ill defined operational payload acoustic spectral requirements or overall reliability estimates. What is clear from the results of current Department of Defense cryocooler technology development efforts is that the point designs developed to date only serendipitously support wider application regimes, and such modifications as are needed in follow on programs are either left to those programs to fund later or to corporate internal research and development [13-15]. This in turn poses issues for programs with relatively poor payload thermal design definition or short concept-launch timelines. In the former case, payload designers are forced to choose between point designs which are likely not optimal, and may be in hindsight poor choices, in their actual application. In the latter case a lack of available schedule margin forces the payload designer to simply choose from cryogenic refrigerator designs, and often trade thermal margins in order to preserve schedule.

Over the past decade great progress has been made in our technical ability to provide cryogenic refrigeration in wide ranges of operating conditions. But the ability to flexibly support varying applications in a timely manner has progressed much less rapidly. Some of this latter issue is due to payload design requirement vagueness, similar to the prevalent failures cited in the aviation technology sector by Carlson [6], or in major weapons systems by the GAO [16, 17]. But a significant source of this deficit in manufacturing readiness level is due to specific lack of investment into cryocooler manufacturing capabilities. One might compare this situation with the entirely different, rapid rate of progress in passive heat rejection radiators and the thermal linkages to increasingly complex communications satellites, whose technical base was also initially funded by Air Force and NASA research in past decades. The fact that several commercial communications satellites are launched annually, while USAF has yet to launch a long life cryocooler in space, indicates the relative levels of investment in manufacturing for these two technology areas. Inevitably divergence in investment levels leads to disparate manufacturing capacity levels.

Current Status in USAF Payload Development Planning

The current Air Force programs designed to use extensive cryogenic cooling systems are Program A's (a missile warning and launch detection constellation) GEO and HEO payloads, Program B (a midcourse missile tracking constellation), and the Program C (a missile warning and launch detection constellation).

a. Program A's cryogenic systems are fully defined (passive radiators) and in payload ground test per the requirements cited above [10, 11] or in space (the HEO payload launched). No changes to this cryogenic design are being contemplated, with additional purchases in that acquisition program being considered on a "build to print" basis only [18].

b. Program B has funded extensive technology development programs in cryogenic engineering and to a more limited extent in thermal management since a predecessor program of the 1980's, however, there is at present no notional payload design around which any of these efforts should coordinate technical goals. Program B has used HgCdTe focal planes operating at 40 K as a baseline sensor system to support, and indicates that the required loads to support the contemplated payload designs will be in the area of 2 W at 35 K and 15-20 W at 85 K. Electronic systems should be hardened to a 300 krad, total dose level over a 10 year mission life. Interactive payload relationships, particularly acoustic spectral output levels and EMI/EMC requirements are undefined. Overall, the likelihood that this requirement set will change is high.

c. Program C is actively pursuing the payload design development as a precursor to cryogenic system development. This missile warning and launch detection mission has baselined large format HgCdTe focal planes operating in the 110-120 K range with optics cooled to various temperatures, depending on payload design. Raytheon SAS and SAIC have active prototype payload fabrication programs preparing for ground testing and performance evaluations prior to acquisition milestone "B" [19]. The cryogenic refrigeration systems to be used in these payloads will be acquired within those prototype fabrication efforts, as will be the case for the Program C objective system payloads. Current load estimates for focal plane cooling loads are in the 10-15 W at 105-110 K range, while optics cooling estimates vary greatly depending on radiometric performance considerations of the sensor design; at the high end there are estimated active cooling needs on the order of 48 W at 170 K, while at the low end other designs intend on radiating 10-30 W at 205-240 K. Vibration output level requirements are a matter of substantial debate, partly reflecting the conceptual development stage Program C is currently in, and partly reflecting a lack of clarity in camera-cooler interaction models. At present, the Program C sensors are expected to require vibration control on the order of 100-200 mN rms total output. This might dramatically change if finer ground separation distances require a reduction in this vibration output by a factor of 4 to 16 with possibly more stringent restrictions in specific spectral bands. Radiation hardening is expected to the 50 krad total dose level over a 10 year period for the GEO mission, while being undefined for the HEO mission. Finally, the possible effect of InSb focal plane detectors is being studied, which would require similar cooling loads to HgCdTe, but at 65-70 K, thereby roughly doubling input power requirements.

In addition to the formal programs, above, the Air Force also launches various flight experiments which often require cryogenic cooling. The Near Field InfraRed Experiment (NFIRE) experiment is typical in its use of a SADA II tactical cryocooler to support a low duty cycle experimental schedule. Other flight experiments expect to increase their use of cryogenic sensors as low cost options arise.

FUTURE TECHNOLOGY DEVELOPMENT PLANNING AND NEEDS

The principal deficit confronting the development of improved cryogenic refrigerators to support USAF missions are poor capabilities in modeling of cryocooler performance and payload interactions. A close second is the poor ability to perform rapid fabrication of design prototypes and derivative flight items. As the technology development center for USAF, the Air Force Research Laboratory (AFRL) is actively funding research in both of these areas. The complex relationships between this centrally funded set of efforts at AFRL and with the separate acquisition programs' Program Office efforts requires more detailed explanation.

AFRL Direct Efforts. On site research is currently being conducted into cryogenic refrigeration thermodynamic cycles and performance on a system and component basis [e.g. 20, 21]. An extensive payload thermal modeling effort is also being established to support the following goals:

a. Obtain a better understanding of payload thermal interactions during practical operating conditions.
b. Estimate orbital cooling loads for future payload refrigeration applications.
c. Estimate how satellite thermal balances contribute to resident space object (RSO, i.e. foreign satellites and unknown objects) characterization and identification.

Figures 1 and 2 show temporal and spatial temperature distributions for a Program C payload solar exclusion baffle and optical train/electronics exterior. In turn, the model is used to link these external elements' thermal balances to the insulated electronics and optical train and their heat generation and cooling loads. The temperature of the optical train is further linked to the focal plane dewar and its cooling load and to the cryocooler and radiator performance models. (These latter details concern proprietary information and cannot be publically released, hence the surface-only temperature plots shown.)

This independent model notably falls short of what might be expected by HDBK-340A as it has not been directly tied to an ongoing payload test program by which it might be validated. Furthermore, if and when such testing results become available through Program C government testing, the

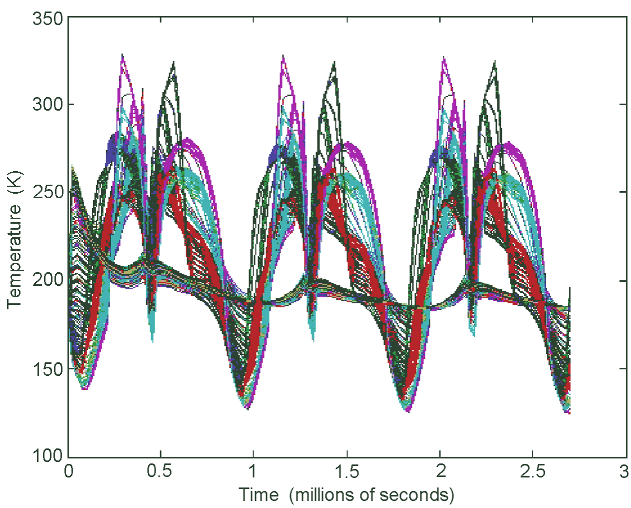

Figure 1. Temperature plot over three orbits in GEO of various components of an 3GIRS payload.

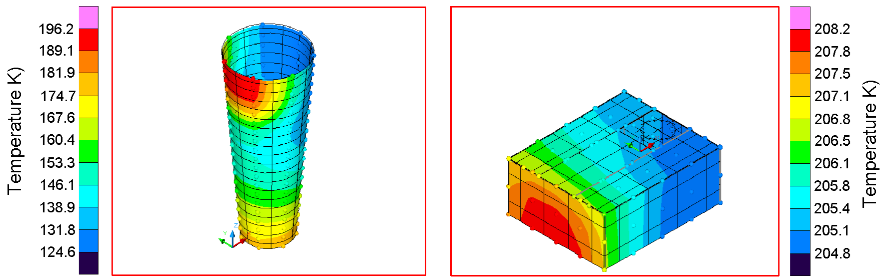

Figure 2. Temperature plot at the last position after three orbits for the baffle and enclosure. Note the solar hotspot on the top of the baffle, left of enclosure.

HDBK-340A mandated correlation standards may or may not be followed, depending on the level of government insight into the actual design of the tested payload and funding. Instead, the purpose of this modeling effort is to project payload cooling and heat rejection requirements on a parametric basis across a wider parametric manifold than might be expected of any contractor short of objective system preliminary design review. As cited above, the 3GIRS program is at least 2 years short of the milestone "B" approval decision to proceed to an objective system source selection, and the results of this modeling effort are needed instead to project technology development planning needs and gaps.

The results of this effort in thermal modeling are correlated with performance models of actual cryocooler systems [e.g. 22] to assess whether current cooler designs are capable of meeting HDBK-340A margin requirements or if technology development programs are necessary. These assessments are then provided to non AFRL studies or technology assessments, as described below.

AFRL executes a variety of space flight experiments which often use cryogenic refrigeration, however the low loads and light duty cycles involved usually allow for low cost cryocoolers to be used. This avenue for space flight verification of technology readiness level (TRL 7, to be precise) is being considered now with respect to cryocoolers developed under corporate internal research and development or developed under other programs' research efforts.

Basic research into novel thermodynamic cycles and design concepts are also conducted or funded. Current efforts include a thermoacoustic replacement for Joule Thompson valves [23] and materials and design research into no-moving-parts compressor systems [24]. Such efforts are implicitly mandated by AFRL's central mission, but cannot be considered "current needs". Instead they represent leading research into concepts and processes by which future requirements might be more effectively met, much as efforts in reverse Brayton turbine research were regarded in the 1980-90's [25].

Space and Missile Systems Center (SMC) Planning Efforts. Program C has contracted for two separate system requirements studies which have as intermediate goals an assessment of whether current cryocooler technology is capable of supporting payload requirements. Both teams indicated on a preliminary basis at their Systems Requirement Reviews that requirements could be met with some minor risks in vibration output control and system mass and reliability. System mass and reliability are linked as low lot production items such as cryocoolers normally are used in redundant pairs to increase payload reliability margins. The Program C program office has furthermore been tasked by SMC and the Air Force Space Command to study the overall requirements and technology maturity situation of any next generation infrared missile warning and launch detection constellation, and the preliminary results again indicated that current technology could generally support these future requirements, with the same caveats concerning vibration interactions with sensor optics and payload reliability expectations. Projected cooling capacity needs for systems launching in the 2025 timeframe however become quite large largely due to increased focal plane mosaic dimensions, as the satellite thermal rejection requirements increase similarly, caused by projected increases in payload data processing.

Other Programs. The concept of Operationally Responsive Space (ORS) has been identified as a critical need by Congress and the Air Force staff, due in part to historically lengthy design to launch trends, but also due to the nature of the perceived threat environment [26]. This concept is still early in its conceptual development phase, and has yet to express cogent cryogenic cooling or thermal management goals as there is currently a diversity of interpretation of what ORS actually is defined to be. Two (at least) conflicting motivations are at the root of this debate: 1.) creating the ability to rapidly reconstitute US space capabilities (which are dominated by large numbers of communications satellites not using cryogenic systems) in short order if they are "degraded" [e.g. 27], and 2.) reducing the costs and time needed to launch new space capabilities in an adaptive response to changing in-theatre needs. The former can take advantage of common constellation designs, the latter can only attempt design commonality at the hardware component level. How these diverse motivations will be reconciled in the future is difficult to see at present.

CONCLUSIONS

Forward progress in cryogenic designs is therefore highly dependent on concurrent progress in payload definition and simulation, outside of basic science research into new cycles or concepts. Investment into modeling of both payload and system thermal components (e.g. cryocoolers) is therefore a critical necessity before any cryocooler development effort is initiated. This is true for both thermal simulations as well as operational vibration simulations, and the balance between these two dissimilar simulation and testing environments has to be evaluated based on payload acquisition risk assessments.

Given the evolving nature of many USAF sensor payload designs, distinct refrigeration and payload heat rejection loads and interfaces can only be generalized as follows:

1. Missile warning and launch detection programs:
   a. Cooling loads at 105-110 K (if InSb, 65-70 K) of 10-15 W and at 170-230 K of 20-30 W. These loads might quadruple in the 2025 timeframe.
   b. Total vibration spectral output levels of less than 100-200 mN rms. These output levels might be reduced by an order of magnitude in the 2025 timeframe.
   c. Payload heat rejection levels are estimated to be on the order of 1.5-2 kW at 280-290 K. Passive transport devices are baselined currently. These levels might double in the 2025 timeframe, possibly requiring development of active transport devices from loads to radiators, subject to the same vibration output constraints as the cryocooler.
   d. Radiation hardening to 50 krad total dose over 10 years for GEO.
2. Flight experiments and ORS:
   a. Cooling loads at 70-110 K of 1-10 W.
   b. Total vibration spectral output levels of less than 500 mN rms.
   c. Payload heat rejection levels are estimated to be less than 0.5 kW at 280-290 K. Passive transport devices are baselined currently.
   d. Radiation hardening to 50 krad total dose over 10 years for GEO.
3. Missile tracking and interception program:
   a. Cooling loads at 35 K of 2 W and 15-20 W at 85 K.
   b. Total vibration spectral output levels of less than 500 mN rms.
   c. Payload heat rejection levels are estimated to be less than 1 kW at 280-290 K. Passive transport devices are baselined currently.
   d. Issue of across-gimbaled thermal transport is significant. Payload design is negatively affected by mass and power requirements of placing cryocoolers on tracking gimbal [5], so mitigation designs are being actively pursued [e.g. 28].
   e. Radiation hardening to 300 krad total dose over 10 years for GEO.

Asides from general deficits in thermal and dynamic modeling cited above, capability gaps are apparent in considering long term requirements for missile warning and launch detection programs, possibly using InSb focal planes. The size of these thermal management systems implies a distinct need for more efficient (20-30% of Carnot limits) cryocooling and heat rejection devices, as irreversibilities in these systems simply adds to the overall thermal design problems confronting payload designers. Control electronics also constitute a current gap, due partially to persistent underinvestment in this critical technology.

However, this situation in electronics is part and parcel with the previous pattern of research investment in serial point thermomechanical unit designs rather than in responsive overall capabilities. Future USAF space cryogenic needs will best be met by adaptable designs which can be rapidly fabricated using build-to-print design families capable of supporting wide application environments with substantial load margins. As senior USAF leadership as well as Congress has indicated that decades-long space system acquisition programs "initiated with inadequate technology maturity" are unacceptable [6, 19], we should expect to see an accelerated prototyping environment in both payload design simulations and thermal management hardware built for prototype payload testing in the next decades. In these efforts, capability gaps will be reduced and design flaws uncovered, rather than programmatically seeking to obtain perfect results that are technically distant or unobtainable. Or, as Vice President Marshall indicated, he didn't need a *perfect* cigar, just one that was *really good* at a reasonable cost...

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