

Aerospace Cryocooler Selection for Optimum Payload Performance

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ABSTRACT

As evidenced by the wide variety of aerospace cryocooler designs presently deployed in space and in development for future deployment, widely variable payload requirements drive the need for a broad selection of cryocooler types and sizes. Reverse Brayton, Stirling, pulse tube, and Joule-Thomson are the most common types, along with hybrid combinations of these, such as the Raytheon Stirling / Pulse Tube Two-Stage (RSP2) line of cryocoolers. Each of these types embodies its own unique advantages, the relevance and importance of which are strongly payload-dependent functions. Operating temperatures, heat loads, number of refrigeration stages, payload physical configuration, and maximum allowable emitted vibration are examples of key payload requirements that drive the selection of the optimum cryocooler type and size. Another critical factor is procurement cost, particularly for the emerging class of “responsive space” infrared sensors requiring cryogenic refrigeration. This paper discusses the strengths and weaknesses of the various cryocooler types and how these characteristics can be aligned for the user’s greatest advantage with the payload requirements.

INTRODUCTION

The NICMOS Cryocooler System, which cools the focal plane assembly (FPA) on the Hubble Space Telescope, is a Creare-built reverse turbo Brayton (RTB) cryocooler [1]. The Creare RTB was selected primarily due to its extremely low vibration, which proved to be the primary driver in cryocooler selection for this highly-sensitive optical instrument [2]. Raytheon selected a Northrop-Grumman Space Technology (NGST) High Efficiency Cryocooler (HEC) for our Japanese Advanced Meteorological Imager (JAMI) payload, primarily because of the compact size and mass, but also because of the maturity of the design relative to comparable machines at the time of selection [3,4]. The Raytheon-built Space Tracking and Surveillance System Block 06 sensor payload uses two NGST pulse tubes on the fore optics, again because of the compact size and low mass, and a Raytheon Improved Standard Spacecraft Cryocooler (ISSC) in the imager to cool the FPA because of the excellent thermodynamic performance at the requisite 35 K cold tip temperature [5]. A plethora of additional examples are provided elsewhere in the literature [6].

For each of these payloads, all of which are space-based infrared sensors, the payload engineers selected different cryocoolers. Exported vibration, thermodynamic efficiency, design

maturity, and mass are all important requirements, but the relative importance of these requirements to each other varies widely between applications. Spacecraft, mission, and orbit all play strongly into the cryocooler selection process. This paper explores how different sets of driving requirements determine different outcomes in the cryocooler selection process.

The cryocooler selection process is intimately linked to, and more accurately a sub-process of, the determination of an optimum cryogenic subsystem design. A 1997 paper by The Aerospace Corporation addressed this issue within the context of the available cryocooler technology at the time [7]. This paper extends on the earlier work by directly comparing and contrasting state of the art cryocooler technologies and discussing how these differences drive payload cryocooler selection. The abovementioned Aerospace paper focused on single-stage cryocoolers and the use of thermal intercept straps to enhance single-stage cryocooler performance at low temperature. Space cryocooler development since 1997 has largely focused on multistage cryocoolers. The resulting availability of multistage cryocoolers has introduced a new dimension to the trade space, namely the choice between multiple single stage cryocoolers versus one multistage cryocooler to satisfy multistage cryogenic subsystem refrigeration needs. This paper introduces some of the issues associated with this new dimension to the trade space.

Operational cryogenic temperatures of 20 K and higher are considered. Thus adiabatic demagnetization refrigerators, hybrid cycles with Joule-Thomson lower stages, and other approaches for achieving very low temperatures are not discussed.

COMPARISON OF COOLER TYPES

Many and varied types of cryogenic refrigerators have been proposed and built over the years, reflecting the breadth of creativity of the cryogenic engineers engaged in this worthy pursuit. Without passing judgment on the present or future merit of the approaches not covered in detail herein, the most prominent types of aerospace cryocoolers at present are the driven-piston Stirling, pulse tube (a Stirling variant), and the RTB. Each particular manufacturer and specific design has its strengths and weaknesses; the discussion that follows is intended to instead focus on the general characteristics of each of these types of cryocoolers.

Stirling cryocoolers are designed upon the premise of achieving the Stirling thermodynamic cycle through a straightforward mechanical implementation with pistons. The pressure-volume (PV) compression is provided by an actively driven piston, or dual opposed pistons for improved mechanical balance. The PV expansion space is similarly produced with an actively driven piston. (Tactical Stirling cryocoolers typically utilize some sort of passive resonant drive mechanism, either purely mechanical or pneumatic, to move the displacer. This approach has generally proved ill-suited for space due to low thermodynamic efficiency and large exported vibration.) An active balancer acting along the drive axis is required to cancel the vibrations produced by the moving piston [8]. The presence of a controllable expander piston is what distinguishes a Stirling from a pulse tube. Stirling cryocoolers tend to be high in thermodynamic efficiency, particularly below 50K, because the expansion phase angle is actively controlled [8]. Also because of the controlled expander piston, they are operationally adjustable (phase angle, stroke amplitude, and to a lesser extent frequency) to optimally meet varying combinations of cold tip temperature, heat load, and rejection temperature. However, as is illustrated later in this section, the moving mechanisms in the expander add considerable mass.

Pulse tube cryocoolers are a variant of the Stirling in which the PV expansion is produced passively through the proper geometric design of an impedance flow network in the expander. There are many variations on how to achieve the requisite expansion phase shift in a pulse tube, the most prevalent at present being the use of an inertance tube [9]. The elimination of moving parts in the expander theoretically contributes to improved producibility and higher reliability, though these benefits have not yet manifested themselves in the marketplace as noticeably lower prices and longer lifetimes. However, the mass of a pulse tube expander is considerably less than that of a comparable capacity Stirling expander because of the elimination of the displacer

piston and balancer assemblies [10, 11]. The inability to actively control the expansion process means that pulse tube coolers are less capable of achieving efficient operation over a wide range of conditions, particularly once the inertance tube design is locked down.

Whereas the first two types of cryocoolers are reciprocating devices, the RTB is a recirculating cryocooler. The prevailing approach, which is best exemplified by the Creare NICMOS Cryocooler System (NCS), is to use small-scale turbomachines to sequentially compress (ambient) and expand (cryogenic) the gas. The ambient and cryogenic temperature regimes are bridged by a counter flow recuperative heat exchanger. More details on the Creare NCS are available elsewhere [1]. The primary advantage of the RTB from Raytheon's perspective is its very low exported vibration (<10 mN versus typically ~200 mN for Stirling and pulse tube cryocoolers) [12]. The components (compressor, heat exchangers, and expander) can be separated by considerable distances from each other because the RTB is a recirculating, not reciprocating, device. This affords certain integration advantages in payloads where it is necessary to have remote cooling. Based upon the generation of flight coolers discussed herein, the disadvantages of the RTB are the larger size, higher mass, and generally lower efficiency relative to the Stirling and pulse tube competitors.

REQUIREMENTS DRIVERS

In addition to the obvious design drivers of refrigeration capacity, power efficiency, and mass, previous papers have identified several additional line items as key considerations for cryocooler integration:

- Mechanical and thermal interface design and accessibility;
- Exported vibration;
- System reliability (as it relates to redundancy);
- Orientation sensitivity for ground testing [7, 13].

Each of these possible design drivers is discussed below in the context of how they tend to motivate the selection of one cryocooler technology over another. The challenge in developing this narrative stems from the fact that each space cryocooler is typically designed to a unique requirements set. Furthermore, there are limitations as to the data that appears in the open literature which arise from competitive concerns and export control laws. These are the same hurdles faced by the system engineer responsible for cryocooler selection, thus this section only attempts to accurately generalize the trade space. A focused investigation and consideration of current technologies for each specific cryocooler application is strongly recommended.

As posed in the previous section, Stirling cryocoolers excel relative to pulse tube and RTB cryocoolers with respect to efficiency, particularly in the 20 K to 50 K regime. Figure 1 compares the published specific power ($SP = \text{input compressor power} / \text{net refrigeration}$) at 45 K for several single-stage cryocoolers of comparable capacity and design maturity to illustrate this point. Note that the two Stirling cryocoolers (RS1 and SB160) are the most efficient. However, for the current generation of production cryocoolers, the efficiency advantage of Stirlings largely disappears at higher refrigeration temperatures (see Figure 2). This is likely due to a number of factors. The RS1 and SB160 Stirling cryocoolers on the list have design points of nominally 60 K; NCS and HEC have higher design point temperatures (70 K and 95 K, respectively). Thus the 95 K data in Figure 2 represents an optimized operating point for the HEC, but not for the other cryocoolers. Theoretically, a Stirling cryocooler optimized for a given operating point should be more efficient than either a RTB or pulse tube optimized for the same condition because the Stirling refrigeration cycle is the only one of three that is an ideal cycle (i.e., theoretical efficiency equal to Carnot). In reality, differences in the design approach and engineering details between cryocoolers are more important discriminators, particularly if one is constrained to using an already existing design. This point is clearly evident in Figure 2.

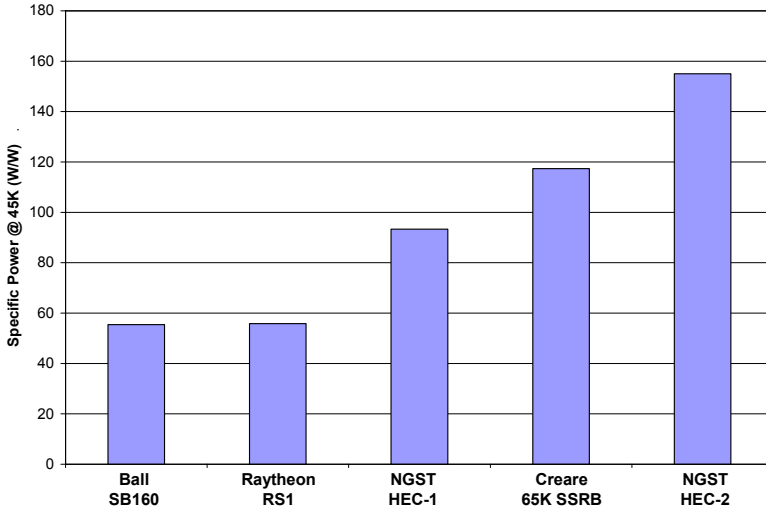


Figure 1. Comparison of specific power at 45 K for selected cryocoolers. Rejection temperature = 300 K. SB160 data [14]. RS1 data [15]. HEC-1 (NASA data) [16]. SSRB [14]. HEC-2 (AFRL data) [17]. SSRB shown as characteristic of NCS for which 45K could not be found in the open literature.

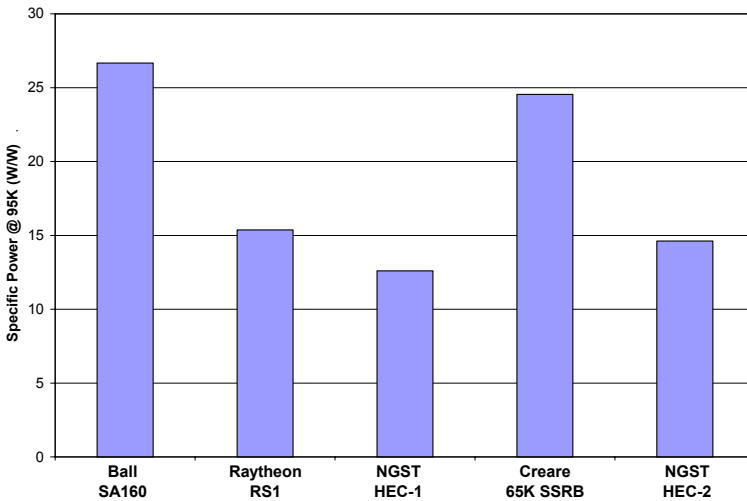


Figure 2. Comparison of specific power at 95 K for selected cryocoolers. Rejection temperature = 300 K. SA160 [14] shown as characteristic of SB160 for which 95K could not be found in the open literature. Other references same as Figure 1.

Pulse tube cryocoolers tend to be lower in mass for a given refrigeration capacity than either Stirling or RTB cryocoolers. Table 1 contains the mass and nominal input power of the same group of cryocoolers we have been considering, and indicates that the pulse tube cryocooler is by far the least massive. Figures 3 and 4 display the specific mass (SM) at 45 K and 95 K, with lower values of both factors and hence the product being desirable. The approach followed here is similar to that used in the earlier Aerospace paper, including the use of a total system penalty

factor of 0.375 kg/W [7]. However, instead of using the individual refrigeration capacity of each cryocooler to make the calculations, the same refrigeration load was assumed for all cryocoolers at a given refrigeration temperature (1 W for 45 K, 5 W for 95 K). Thus the curves are more representative of the typical user's perspective in which there is a particular load to cool and they seek the most efficient means by which to accomplish the task.

$$SM = (M_{\text{cooler}} + (Q_{\text{load}} * SP * 0.375)) / Q_{\text{load}} \quad (1)$$

M_{cooler} is the cryocooler mass, excluding electronics, and Q_{load} is the refrigeration load on the cryocooler. (The total system penalty factor is intended to account for the power system, thermal management system, mounting structure, and other such system impacts the cryocooler has on the payload [7].) Figures 3 and 4 reveal several important factors. First, from a total payload mass impact perspective, the Stirling cryocoolers continue to excel at 45 K. The pulse tube cryocooler is the best choice from a total payload mass perspective at 95 K.

The consideration of mechanical and thermal integration issues is essential in cryocooler selection, though the optimum selection in this regard is clearly payload dependent. For example, the relatively large size of RTB components can create obvious packaging challenges (for example, the NCS recuperator is 660-mm long by 90-mm diameter). However, these integration challenges can be offset in some applications, particularly those sensitive to emitted disturbances, by virtue of the RTB's extremely low exported vibration. Given the system requirements, it may be possible to bolt a RTB compressor directly to a heat pipe interface, for example, whereas a Stirling or pulse tube may have to be connected via a flexible thermal strap to attenuate vibrations. This would tend to increase the temperature as seen by the Stirling or pulse tube compressor for a given heat pipe interface temperature, which would decrease the thermodynamic efficiency. Thus the efficiency and integration issues are tightly coupled. The cold head configuration is also important. For example, folded or concentric pulse tubes present cold tips like a Stirling; these are in general easier to integrate than linear pulse tubes in which the cold block resides between ambient structure [11]. There are many such other considerations not presented here for the sake of brevity. Suffice it to say that the best approach to determine the optimum cryocooler with respect to mechanical and thermal interfaces is to develop integrated payload models that include the candidate cryocoolers of interest, establish first order thermal and structural models, and then proceed from that properly informed perspective.

As discussed previously, low exported vibration is a strength of the RTB. Published data on Stirling and pulse tube cryocoolers indicates generally comparable exported vibration, and those levels are about an order of magnitude higher than the RTB [14]. The method by which the exported vibration levels are established during flight qualification compared to the method by which low vibration operation is achieved on orbit is another important point. Raytheon has made it a priority to qualify exported vibration levels on the ground with the same instrumentation and methods as used to control vibrations on orbit. Figure 5 is provided to show our preferred approach by which the load washers used in ground qualification of the cryocooler are part of the deliverable flight system, thus the ground data is fully representative of on orbit performance.

Table 1. Comparison of cryocooler mass

Vendor/Model	Mass (kg)
Ball SB160	10.5
Raytheon RS1	13.1
NGST HEC	4.3
Creare NCS	18.5

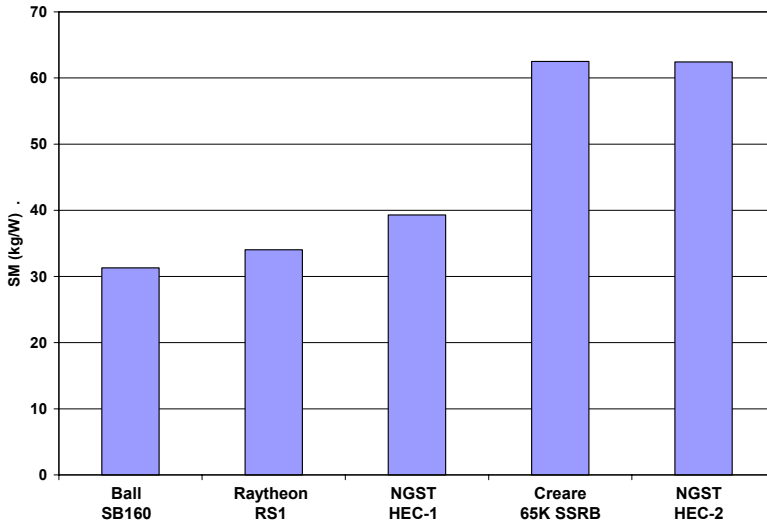


Figure 3. Comparison of specific mass at 45 K for selected aerospace cryocoolers. Same references and comments as Figure 1. $Q_{load} = 1$ W for all cases. Cryocooler electronics mass not included.

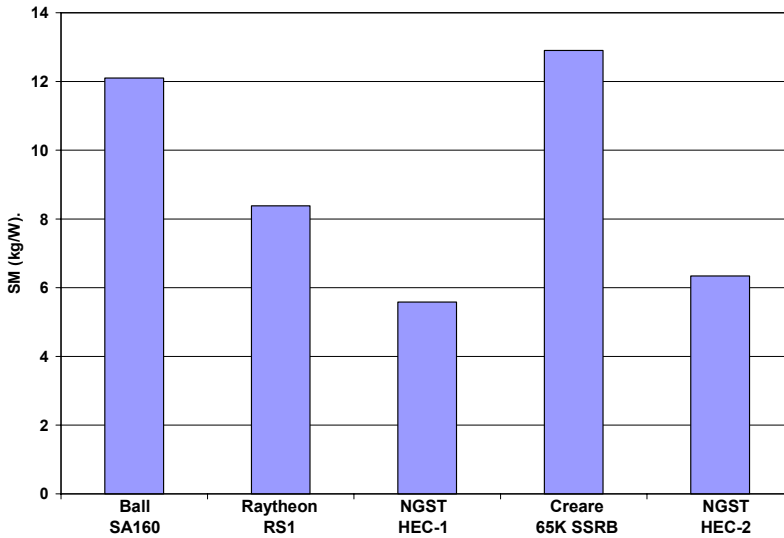


Figure 4. Comparison of specific mass at 95 K for selected aerospace cryocoolers. Same references and comments as Figure 2. $Q_{load} = 5$ W for all cases. Cryocooler electronics mass not included.

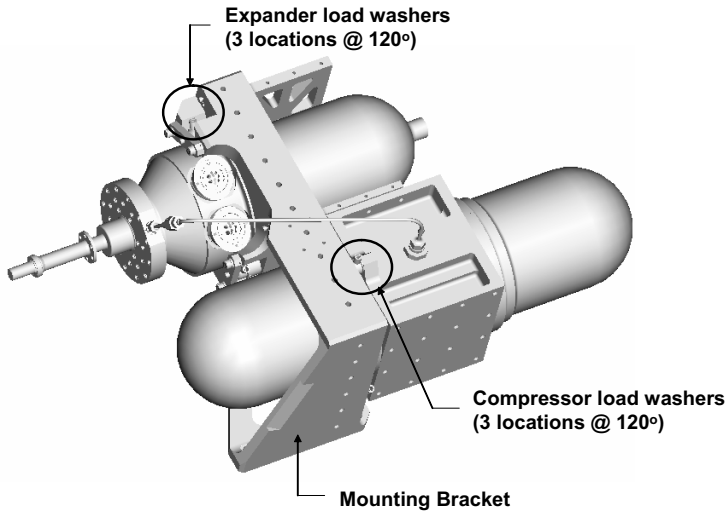


Figure 5. Typical mounting scheme for RS1 Cryocooler. Each cryocooler module mounts to the bracket across three (3) load washers. Active vibration cancellation is performed by cryocooler electronics (not shown) for each module individually. Mounting bracket is bolted directly to payload interface, thus on orbit vibration cancellation instrumentation is the same as the ground instrumentation.

Orientation sensitivity is an issue for cryocooler ground testing, much in the same way that heat pipe orientation can be a concern for payload ground testing. If the payload performs differently on the ground than in orbit, it poses potentially significant challenges for integrated testing, thermal balance testing, etc. Pulse tube cryocoolers tend to be more sensitive to orientation than Stirlings due to the hollow pulse tube component in which convection cells can be established. This has been observed with respect to off-state parasitic load [18] and operationally at low temperatures [19]. Gas bearing supported turbomachinery can be sensitive in 1g to orientation during low speed operation, as is experienced during start / stop cycles [20]. Raytheon Stirling cryocoolers do not exhibit orientation sensitivity down to at least 20 K, which we believe is likely a general characteristic of Stirlings. Though not typically a primary driver in cryocooler selection, ground testability is a consideration, and downstream cost can be averted by properly considering this issue early in a payload development program.

The Raytheon position is that system reliability is more a function of the cryocooler integration scheme rather than the type of cryocooler when the trade space is limited to consideration of fairly mature technologies, such as those discussed herein. The low build quantity of any particular space cryocooler model makes the meaningful determination of a Mean Time To Failure (MTTF) impossible within the traditional interpretation of reliability engineering. Assessment of Technology Readiness Level (TRL) and consideration of legacy life test and operational flight hours of a particular design are the primary means by which reliability concerns are introduced into the cryocooler selection process at Raytheon.

Reliability comes more into play with respect to the cryocooler electronics, and the other integration considerations unfortunately tend to compete with reliability with respect to what is optimum. For example, features such as input current ripple suppression facilitate integration because the cooler can be powered directly off the spacecraft bus, but this adds complexity and components to the electronics, which decreases reliability. As noted in a previous paper, a big driver in electronics complexity is active vibration cancellation [21]. Electronics complexity, hence reliability, is largely driven by active vibration cancellation, thus our advocacy for much simpler electronics for applications in which active vibration is not required.

Cost is becoming a more important factor in aerospace cryocooler selection. This is largely due to two factors. Firstly, as the cost drivers are becoming better understood, developers and users can more intelligently assess the cost/benefit relationship for the incorporation of a particular feature or compatibility. This alone would be insufficient impetus to drive the development of a lower cost space cryocooler because the cost leverage of a \$2M cryocooler system on the traditional \$100M+ payload is minimal from a dollars perspective. Clearly the relationship between efficiency and system mass, and thus efficiency and cost, is clearly a more important overall cost driver for the traditional payload. However, with the emergence of “responsive space” programs with desired recurring IR sensor payload cost in the \$10M (or less) range, cryocooler recurring cost has become a factor. Many science experiments, military and civilian space, also fall into this category. Thus it is the combination of these factors, a better cost model and emerging payload needs, that is driving low cost space cryocooler development at Raytheon [11], and presumably elsewhere.

The relative importance of each of these considerations for a given payload varies widely between applications. Furthermore, there are numerous additional examples of the subtle interplay among these various integration considerations not yet mentioned, and these relationships are also payload dependent. Thus the overriding recommendation embedded herein is to consider all of these issues within the particular context of the application of interest. There is no “one size fits all” when it comes to cryocoolers.

SINGLE VERSUS MULTISTAGE CRYOCOOLER USE

Fueled largely by the mission need to provide simultaneous optics and focal plane cooling, much of the recent development on space cryocoolers has focused on two-stage devices. The logic behind this thrust is sound. The number of cryocoolers for a given system is reduced versus the most operationally equivalent alternate approach, which would be to use two single-stage cryocoolers, one dedicated for each stage. However, there are disadvantages in the multistage cryocooler approach for some payloads, so this aspect of the trade space needs to be as fully considered as the requirements drivers discussed in the previous section.

Figure 6 compares thermal solutions for a two-stage cryogenic system using single-stage coolers versus a single two-stage cooler assuming a Stirling or pulse tube type approach. Cryocooler system mass is reduced considerably by going to multistage coolers because the number of moving mechanism-motor assemblies for a two-stage Stirling or pulse tube is the same as its single-stage counterpart. Thus the number of drive mechanisms is cut in half by going to a two-stage cooler, which not only reduces the total mechanical cryocooler mass, but also provided considerable mass savings in the electronics. Furthermore, reliability is improved by the reduction in moving parts and electronic components. These are generally accurate positions and not typically a subject of debate.

There is also the perception that the two-stage approach is inherently more thermodynamically efficient because the first stage of the cryocooler intercepts most of the internal parasitic losses in the cooler, increasing second stage net capacity for a given input power. While it is true that parasitic losses are intercepted, it is not *necessarily* true that the net result is that one two-stage cryocooler will draw less power to achieve a certain cooling requirement than two one-stage cryocoolers. This arises from the fact that the performance of the stages is linked in typical two-stage cryocooler implementations, so the stages cannot be individually optimized. For example, if a single compressor is driving two cold heads, they must operate at the same frequency and mean pressure. In a two-stage, single-piston Stirling, the expansion phase angles of the first and second stages are intimately linked. Thus the expansion processes in each expansion stage cannot in general be independently tuned to the optimum mean pressure, frequency, phase angle, etc. This drawback of the multistage cooler approach is somewhat mitigated in the Stirling / pulse tube hybrid because the first stage expansion is actively controlled (like a Stirling) but is not intimately linked to the second stage expansion (like a pulse tube). This partial decoupling of the stages, which has been discussed extensively

elsewhere, provides the ability to actively shift loads between stages at near constant overall refrigeration efficiency [22]. However, the frequency and mean pressure of the expansion stages must still be identical, so the mitigation of this drawback in the hybrid is only partial.

There are many additional dimensions to this trade space. For example, the single higher power compressor for the two-stage cooler is likely to be more efficient than either of the two smaller compressors because large force constants (Newtons/Amp) can be achieved more readily in a larger motor. If two electronics modules were used to control the two coolers, each would require its own overhead power (“tare”), so that penalty would have to be paid twice rather than once, although the two coolers could be driven by a single box if so designed and thus eliminate this consideration. On the other hand, the two-cooler approach provides significant operational flexibility by decoupling the first and second stage thermal control. The choice of locations for the first and second stage cryogenic interfaces is also decoupled, which may not be the case for the multistage cold head, depending on its particular configuration. The availability and maturity of single stage coolers is also better, at least at present. For these reasons, the trade study between single and multistage coolers for the management of multistage cryogenic subsystems warrants serious consideration in most, if not all, cases.

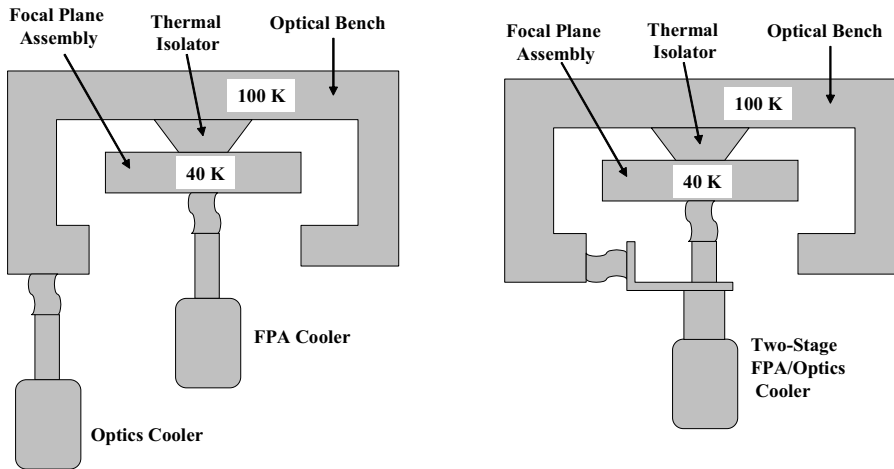


Figure 6. Competing approaches for thermal management of a particular two-stage cryogenic system. (L) Two single-stage cryocoolers. (R) One two-stage cryocooler.

CONCLUSION

There is no “one size fits all” cryocooler choice, nor is there a singularly evident preferred method of achieving multistage refrigeration. That is why Raytheon develops multiple types of cryocoolers and collaborates with outside suppliers, as required, to optimally meet the cryogenic subsystem requirements of each unique payload.

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