Requirements for long-life mechanical cryocoolers for space application

R.G. Ross, Jr

Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109, USA

The growing demand for long wavelength infrared and submillimetre imaging instruments for space observational applications, together with the emergence of the multi-year life Oxford University Stirling cycle cooler, has led to a rapidly expanding near term commitment to mechanical cryocoolers throughout the subkelvin to 150 K temperature range for long-life space missions. To satisfy this growing commitment, emerging cryocoolers must successfully address not only the input power, cooling power and mass constraints of the spacecraft and instruments, but also the broad array of complex interface requirements that critically affect successful integration to the sensitive instrument detectors. Vibration, electromagnetic interference and temperature instability (thermophonics) are particularly important parameters. Historically, the most difficult requirement to meet has been that of operational lifetime with very high reliability. After reviewing the cryogenic temperature ranges receiving the most emphasis within the instrument community, generic requirements are presented for each of these cryocooler requirement areas, which are then contrasted with the projected capabilities of emerging space cryocoolers. The degree of match is used to highlight both the strengths of existing technologies and the areas in need of increased development.

Keywords: space cryogenics; cryocoolers; space instruments; qualification testing

In recent years a growing number of space instrument developers have proposed using long wavelength infrared (IR) and submillimetre imaging detectors to perform systematic mapping of Earth and astrophysical subjects. The demand for low background noise requires that these detectors, and often portions of the electronics and optical subsystems, be cooled to cryogenic temperatures ranging from the subkelvin to 150 K. The expense of these instruments – often in the range of US$100M – together with science objectives of monitoring subject changes over multi-year time spans, demands cryogenic cooling systems with lives of five to 10 years, with reliabilities of the order of 0.95.

Figure 1 highlights the challenge for future space cryocoolers in meeting the temperature and lifetime demands of popular detector types actively being considered by JPL scientists for future low Earth orbit viewing instruments. In the low Earth orbit thermal environment, radiators and thermoelectric coolers lack the capacity to reach the 80 K and below temperatures required by these detectors. Similarly, time proven stored-cryogen systems, such as used on IRAS and numerous military satellites, have inherently short lives as driven by the fixed relationship between detector cooling energy demands and the required mass of the stored cryogen. With continuous cooling demands of the order of 1.0 W at 80 K, stored cryogen systems generally exceed even the most generous mass and volume allocations for low Earth orbit instruments.

The one technology that offers the promise of meeting the cooling needs of future long-life cryogenic instruments is mechanical coolers such as the emerging class of Stirling cycle coolers developed at Oxford University[1,2] and sorption coolers[3]. For these coolers to be successful it is necessary that they not only provide the required cooling over multi-year lives, but also that they successfully address a broad variety of important interface and operational constraints associated with compatibility with instrument system designs.

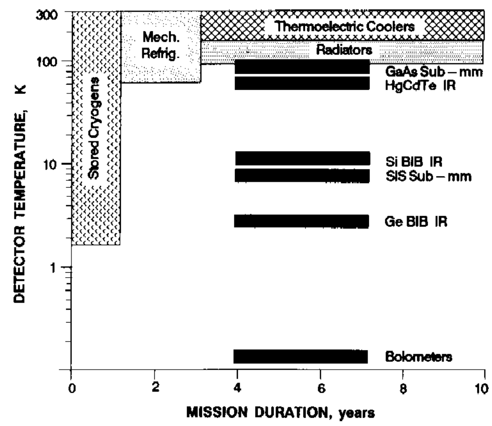

Figure 1 Present cryocooler capability *versus* representative space instrument detector cooling temperature and mission life requirements

Instrument/vehicle mass – power constraints

A fundamental constraint on space cryocoolers is the allowable mass and input power available to the cooler

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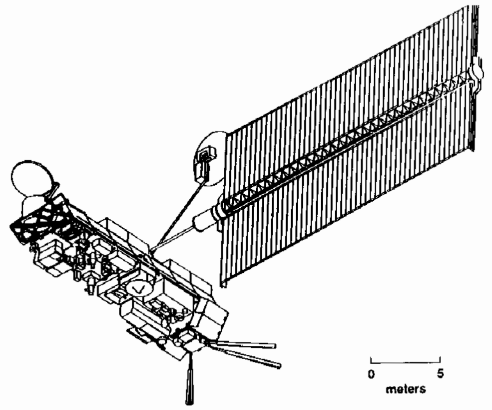

Figure 2 NASA Earth Observing System (Eos-A) space platform with representative complement of instruments

Table 1 Mass and power available for cryogenic cooling on typical NASA space instruments based on 50% of total instrument mass and power allocated to the cooler

Space vehicle	Cooler allocation	
	Mass (kg)	Power (W)
Hubble Space Telescope	150	70
Eos Space Platform	80–150	50–100

from the space vehicle. Except for a minority of specialized single-purpose space vehicles, most cryogenic space instruments are targeted for integration onto multi-instrument space platforms such as the Hubble Space Telescope (HST) and the series of currently planned Earth Observing System (Eos) platforms[4], illustrated in *Figure 2*. Although these vehicles have the flexibility to accommodate a variety of instrument sizes, the total mass and power available to any given instrument is generally constrained to values similar to those in *Table 1*. In this table, the cooler allocation represents 50% of the total instrument allocation – a representative fraction for many instruments. The key conclusion to be drawn is that mechanical coolers, to be compatible with typical space platform applications, must be able to provide their cooling function while drawing no more than 100 W of total input power and weighing no more than 100–150 kg.

In interpreting the 100 W constraint, it is important to recognize that the spacecraft power bus is often unconditioned (has large variations in voltage) and almost always has tight constraints on the level of electromagnetic interference (EMI) and current ripple that can be fed back onto it. Meeting these power quality constraints generally requires a significant power conditioning function internal to or in series with the cooler, and detracts considerably from the ideal efficiency and mass of the cooler.

Instrument/detector cooling power requirements

In competition with the constraints on available input power is the cooling power needed to maintain the science detectors and optics (the refrigeration load) at their required cryogenic temperatures. *Table 2* presents representative operating temperature requirements for a variety of state of the art detector types. Unfortunately, the cooling load is a strong function of the nature and design of the instrument; parameters such as the size of the detector array, the nature of the read-out electronics and whether the instrument is Earth or space viewing can affect the required cooling power by two orders of magnitude.

Table 2 Cooling temperature requirements for typical space instrument detectors requiring cryogenic cooling

Operating temperature (K)	Detector type
65–80	HgCdTe IR detectors/preamps GaAs Schottky submillimetre detectors Gamma ray detectors
20–65	Submillimetre preamps
8–10	Silicon BIB IR detectors/preamps
4–8	NbN SIS submillimetre detectors
2–4	Ge BIB IR detectors/preamps Pb and Nb SIS submillimetre detectors
Subkelvin (0.1)	Bolometers

The 65–80 K temperature region is the one of most importance for space instruments and is dominated by mercury–cadmium–telluride (HgCdTe) infrared array detectors for spectral imaging in the wavelength range from 1 to 15 μm. These detector arrays often have several thousand pixels and require integral multiplexers/preamplifiers to reduce the number of electrical signal and power leads to a manageable number. A broad variety of Earth viewing IR instruments require cooling powers of $\approx$0.5 W at 65 K per focal plane, and may have two or more focal planes. Another class of IR detector is the extrinsic doped BIB detector that is useful in the far IR (from 30 to 200 μm); these devices have power requirements similar to those for HgCdTe, but require cooling to temperatures below 10 K. However, some deep-space pointing instruments propose using large BIB arrays with cryogenic power dissipations as low as 10 mW.

In the submillimetre wavelength range, present day instruments emphasize the use of gallium arsenide (GaAs) Schottky mixers and HEMT amplifiers, which require cooling similar to that of the IR arrays. For future submillimetre applications, superconductor–insulator–superconductor (SIS) devices are actively under development; these devices, based on NbN, Nb and Pb, require temperatures in the 2–8 K range to achieve a useful superconducting state.

At the bottom of the temperature scale are bolometers and bolometer arrays used for the extreme far IR out to 700 μm. Although bolometers require temperatures of the order of 0.1 K to reduce background noise to negligible levels, they have the advantage of very small power dissipation levels, typically below 1.0 mW and often below 10 μW.

Power implications for cooler designs

To better understand the implications of the 100 W input power limit and the typical detector cooling loads, it is useful to contrast these general requirements against realistic estimates of the achievable performance of state of the art mechanical refrigerators. The thermodynamic efficiency of such refrigerators is a strong function of the

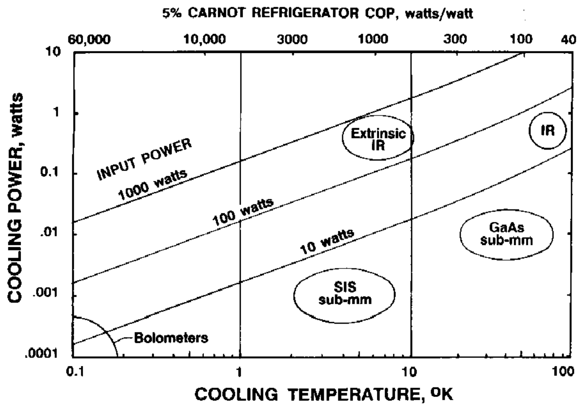

Figure 3 Available cooling power of present day cryocoolers (5% Carnot efficiency rejecting to 300 K heat sink) contrasted with cooling requirements of typical space instrument detectors

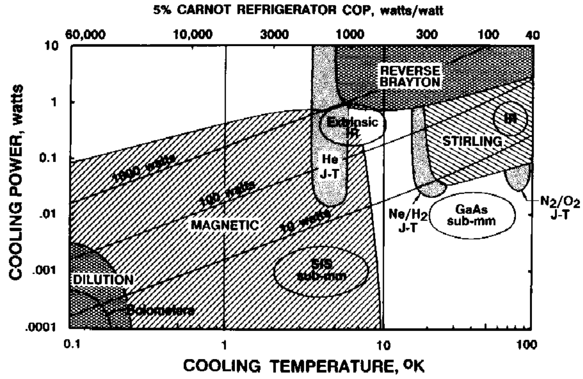

Figure 4 Useful operating regions of common refrigerator types contrasted with cooling requirements of typical space instrument detectors

cooling temperature required, and is bounded by the efficiency of the ideal Carnot cycle refrigerator. The coefficient of performance (COP), i.e. watts of input power required for each watt of cooling, of the ideal Carnot refrigerator is given by

$$\mathrm{COP} = \frac{T_H - T_C}{T_C} \tag{1}$$

where T_C = cooling temperature (in K) and T_H = heat rejection temperature (e.g. 300 K). State of the art refrigerators rarely approach this ideal Carnot efficiency; in fact most, such as the Oxford Stirling cycle cooler, have efficiencies ≈2−5% of Carnot, i.e. the COP is 20−50 times that of the ideal Carnot cycle.

If the 5% figure is adopted as being realistic, parametric curves of cooling power achievable for various input powers can be plotted as a function of cooling temperature. *Figure 3* overlays such curves on a summary of the detector cooling requirements noted above, and highlights the challenge associated with achieving the cooling demands of each of the detector types. Notice that all of the detector types are consistent with the 100 W input power limitation, except for high power applications of the extrinsic BIB IR detectors. The important conclusion is that the thermodynamic efficiency of typical state of the art cryocoolers is entirely consistent with the demands of most near term space instruments. At the same time, the fact that present cryocoolers are achieving only 2−5% of the ultimate efficiency achievable, implies that there is also fertile opportunity for efficiency improvement in the future. For example, some carefully optimized present day refrigerators, such as the miniature Inframetrics 80 K Stirling cycle cooler, have achieved efficiencies of greater than 10% of the ideal Carnot cycle[5].

As a next step in this analysis, it is useful to overlay onto *Figure 3* the efficient operating regions of the common refrigerator types. This is done in *Figure 4*. From this figure it is apparent why nitrogen Joule−Thomson (J−T) and Stirling cycle coolers have substantial popularity for IR detector cooling, and why large magnetic, reverse Brayton and helium (J−T) refrigerators are targeted for potential high power extrinsic IR applications.

A major weakness in available technologies is low power (small scale) long-life refrigerators for milliwatt level cooling applications in the 4−10 K temperature range. The development of magnetic refrigeration for this temperature/power range has been slow in coming, and is still a considerable distance from realization. Although attempts to achieve small closed cycle compressor driven helium J−T refrigerators for this range are also in progress[6], this technology is also at too early a stage to prove feasibility, particularly with respect to reliability.

Cooler reliability: critical challenge for space applications

Although cooler input power and cooling load have to fall within certain limits for successful space application, lifetime and reliability are the critical issues currently limiting the use of mechanical cryogenic refrigerators in space. To this author's knowledge there have been no mechanical coolers that have been flown in space that have lasted in excess of a few months; most have lasted only a few weeks. This is in sharp contrast to the common requirement of present day instruments for a five to 10 year lifetime with 0.95 reliability. The shortfall in reliability is of the order of one to two orders of magnitude.

The lack of reliability stems directly from the extreme sensitivity of cryocoolers to both gaseous and particulate contamination. Any gaseous contaminant such as water vapour or a hydrocarbon gas is gettered to the cold end of the cooler where it condenses, freezes and inhibits the refrigerator function. With cryocoolers that operate below 10 K, any gas other than helium is a contaminant and a likely problem.

This extreme sensitivity to gaseous contaminants places extremely rigorous constraints on the purity of initial refrigerant gases, on the degassing of internal cooler surfaces, on the use of any potential outgassing materials such as polymers and on any degradation mechanisms that could lead to the generation of contaminant gases.

Directly tied to the problem of contamination is the problem of lubrication, because the lubricity or wear tolerance of most surfaces is strongly tied to the presence of lubricants and surface plasticizers, most of which outgas contaminant gases. The result has been an unwritten rule that a long-life cryocooler must avoid any rubbing surfaces and depend instead on flexure bearings, gas bearings based on the refrigerant gas or magnetic bearings. The Oxford flexure bearing Stirling cycle cooler and various helium gas bearing Brayton cycle coolers are examples.

A key problem that remains is achieving non-rubbing seals for high pressure ratio compressors such as those needed in Stirling cycle compressors, and particularly for closed cycle mechanical J–T compressors. The well known clearance seal is one aproach, but it has an extreme sensitivity to manufacturing and assembly precision, as well as to long term cooler dimensional stability. Consistent long term reliability of piston clearances in the range 3–15 μm remains to be proven. Sorption refrigeration, under development at JPL and Aerojet, is another technique being advanced to achieve high pressure ratios while avoiding the wear and contamination associated with moving pistons[3].

A second problem closely related to the problem of achieving high reliability long-life refrigerators, is measuring their life. This is particularly troublesome because there is no acceptable way to accelerate the degradation mechanisms in a quantitative way and no obvious means of measuring a cooler's reliability other than running it until failure occurs. Compounding the problem is a history of wide unit to unit variations in the lives of seemingly identical coolers. This raises serious questions about the process required to qualify coolers for space application and how to run acceptance tests on any given flight unit.

Instrument/cooler interface considerations

In addition to the fundamental constraints of input power, cooling power and reliability, there are a variety of cooler interface issues that strongly influence the acceptability of mechanical coolers for space instrument applications. One class of these relates to adverse environments created by the cooler that can adversely impact the instrument's operation; another relates to functional attributes that can ease or exacerbate the difficulty of meeting the cooler's requirements for thermal, mechanical and electrical integration.

Cooler generated environments

Vibration. Cooler generated vibration is a particularly troubling environment for precision imaging instruments

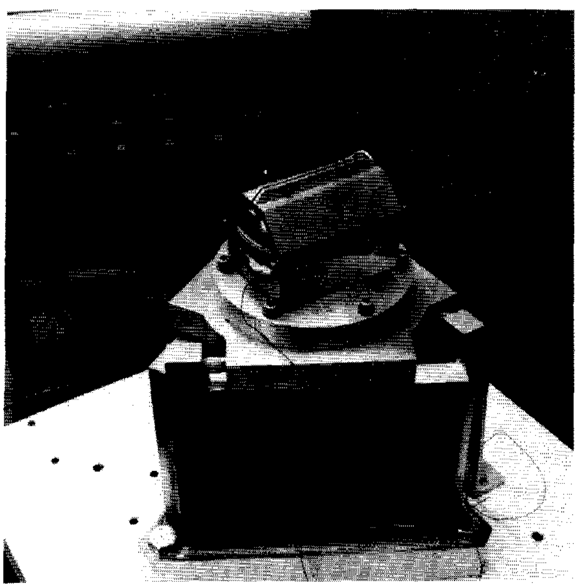

Figure 5 JPL six degrees of freedom force dynamometer with Stirling cycle compressor mounted for testing

In characterizing cooler generated vibration it is this author's preference to speak of the peak vibratory force imparted by the cooler into its supports when rigidly mounted. This force is the reaction force to moving masses within the cooler that undergo peak accelerations during various phases of the cooler's operational cycle. The accelerations can be from controlled motion such as the reciprocating motion of a Stirling cycle piston, or natural vibratory resonances of the cooler's elastic structural elements.

Problems occur when the vibrating interface forces cause elastic deflections and resonances within the instrument structure and components that either adversely affect its alignment, or generate spurious electrical signals. The latter are generated when electrical current carrying or capacitively coupled components undergo relative motions. Although no formally agreed upon requirements exist for acceptable vibratory force levels, a value of the order of 0.2 N (0.05 lb) is gaining acceptance as a desirable goal.

To help quantify the force levels generated by present cooler designs, JPL has recently developed the new six degrees of freedom force dynamometer shown in *Figure 5*. This dynamometer has a frequency range from 10 to 500 Hz and a force sensitivity from 0.005 N (0.001 lb) to 445 N (100 lb), full scale[7]. It is presently being used to quantify the vibration levels of miniature Stirling cycle coolers of the Oxford type.

Cooler generated electromagnetic interference. Another cooler generated environment that must be maintained at low levels is EMI. EMI resulting from fluctuating currents and magnetic fields within the cooler can be either radiatively coupled, or conducted into the instrument through the cooler's electrical power supply. Although the instrument's sensitive detectors and their associated read-out electronics are particularly vulnerable (and exacerbated by their close proximity to the cooler), EMI tolerance varies widely from instrument to instrument. Often the limiting requirement is the tolerance of an adjacent or nearby instrument such as a magnetometer. Typical magnetometers on JPL spacecraft have sensitivities of the order of 8 pT (seven orders of magnitude less than Earth's magnetic field). For example, the presence of a sensitive magnetometer on the Galileo spacecraft resulted in the following requirement for allowable magnetic fields for Galileo equipment: static field, 10 nT at 1 m; and dynamic field, 0.1 nT at 1 m at 40 Hz, decreasing proportional to 1/frequency for higher frequencies. Such requirements can place stringent demands on cooler magnetic and electrical design.

Thermophonics and temperature fluctuations. Science instrument detectors, because they are repeatedly recalibrated *in situ*, tend to be relatively insensitive to long term changes in operating temperature (plus or minus a degree), but are often strongly sensitive to small temperature fluctuations during the period of a single exposure or read-out. Significant temperature induced read-out noise has been reported with short term temperature fluctuations of 50–100 mK; as a result, detector temperature stability requirements of the order of 1–5 mK are not uncommon.

This demand for high levels of short term temperature stability for the detector places important requirements on the level of temperature ripple, often referred to as thermophonics, that can be accommodated at the refrigerator cold finger. Although this requirement rarely drives the design of the cooler itself, it can bias the selection toward a cooler with extremely low ripple, so as to avoid having to add thermal mass damping to the detector. The addition of thermal mass is generally undesirable because it requires stronger structural supports, which inevitably leads to increased thermal parasitics and adversely affects the cool-down rate.

Cooler/instrument functional integration attributes

In addition to cooler generated environments there are a number of important cooler/instrument functional integration attributes that can significantly affect the suitability of any particular cooler for a given application. These include such issues as:

1 Cooling being available simultaneously at various temperatures to serve multiple loads, such as detectors, shrouds and optics, at different temperatures. This is often a useful attribute of multistage refrigerators.
2 Cooling power being easily throttlable over a broad range; this is useful to achieve rapid cool-down, together with reduced input power and improved reliability during normal operation. It also allows easy switching from normal to standby low power operation.
3 The cold head being able to be located remote from the main body and heat rejection surfaces of the refrigerator. This greatly eases the constraints on the overall instrument design, where often it is difficult to position the cold detectors near external radiator surfaces. It also allows separation of the sensitive detectors from the EMI- and vibration-prone compressors.
4 The refrigerator being easily integratable to spacecraft structures and heat sinks. This includes such features as simplicity of mechanical attachment and tolerance to structural loads applied to the cooler during temperature excursions.
5 The refrigerator being amenable to enhanced reliability through the easy incorporation of redundant cooler elements. This includes such things as the ability to connect redundant compressors into a common remote cold head and having very low parasitic loads from 'off' cold heads, so as to allow redundant cold heads without requiring heat switches.
6 The refrigerator electronics being easily integratable with the instrument and vehicle power supplies. This includes being able to accept a broad range of input voltages and having a high tolerance to EMI on the power bus.

Qualification and ground testing issues

The last, but by no means the least requirement on flight refrigerators is the need to be able to survive launch vibration loads and mission thermal environments.

Table 3 illustrates typical thermal environmental requirements imposed on JPL space instruments and highlights the relationship between design, test and expected flight levels. Notice that mechanisms are often tested to different temperatures than electronics, reflecting the more design-specific thermal environments they are likely to encounter. An additional thermal requirement on electronics is the imposition of a maximum allowable junction temperature (typically 110°C) on each electronic part during the 75°C qualification test; thus the total rise for the junction is limited to 35°C. This practice greatly reduces the degradation rates of materials and semiconductor failure mechanisms that exhibit Arrhenius rate dependence and results in significantly greater flight reliability.

Table 4 presents similar qualification requirements for launch vibration and pyrotechnic shock. Although these levels are considered representative, they vary somewhat depending on the specific launch vehicle. Because they are qualification levels, they include the usual design margin required above the expected flight levels. For static structural loads, design requirements specify a 1.0 factor of safety on yield strength and a 1.4 factor of safety on ultimate strength.

Following 'type approval' of a representative cooler at the qualification test levels, individual flight articles are normally subjected only to lower flight acceptance (FA) test levels to verify workmanship and general fitness for flight. An important element of this process is the need to determine the flight worthiness of a cooler after exposure to the test environment. This is historically a problem with cryogenic refrigeration because the principal failure mechanisms – contamination, leakage and

Table 4 Typical JPL space instrument structural dynamic requirements

	Frequency (Hz)	Acceleration level
Sine vibration	5–24	0.5in double amplitude
	24–50	15g peak
	50–100	10g peak
Random vibration	20–100	+6 dB octave^{-1} PSD
	100–500	0.20g^2 Hz^{-1} PSD
	500–2000	−6 dB octave^{-1} PSD
Pyrotechnic shock	100	10g peak
	1000	700g peak
	5000–10 000	3000g peak

Table 3 Typical space instrument thermal environmental requirements

	Environment temperature range (°C)				
Item	Expected flight	Allowable flight	FA test	Qualification test	Design
Electronics	20–30	5–50	0–55	−20–75	−30–85
Mechanisms					
Example 1	0–25	−10–35	−15–40	−35–60	−45–70
Example 2	−10–10	−20–20	−25–25	−45–45	−55–55
Example 3	0–5	−5–10	−10–15	−30–35	−40–45

wear – are not inspectable; these mechanisms, unless extreme, only show up after a significant period of operation. Another challenge for the qualification process is the tendency for large unit to unit variations to exist among the same manufacturing batch. The poor inspectability and large unit to unit variability of cryocoolers is likely to require reconsideration of the classical 'type approval' test philosophy, along with a higher than normal reliance on non-destructive acceptance testing of each flight unit.

To minimize the risk of failure in the qualification and acceptance process it is necessary that individual refrigerators be highly tolerant to expected variabilities in fabrication and assembly processes and materials. Amenability to rework and having a long shelf-life are also important. Because cryocoolers must be operated during system level testing of the instrument, it is also desirable that they be testable in any position or orientation. This greatly relieves positioning constraints on the instrument and system test design.

Summary

Most near term cryogenic space refrigeration applications have constraints levied by typical space platforms that limit maximum allowable input powers to ≈ 100 W and maximum allowable masses to $100-150$ kg. Space refrigerators under development, with efficiencies $\approx 5\%$ of Carnot, can easily satisfy these constraints and serve the vast majority of space instrument cooling needs. This low efficiency of present day cryocoolers, when combined with isolated examples of up to four times greater efficiency, also suggests that significant efficiency improvements are possible and likely in the not to distant future. This will open up an even greater array of future applications for space cryocoolers and, in particular, will most likely be required to keep pace with the rapidly increasing sophistication of space instruments.

The key obstacle to the use of present day emerging space cryocoolers is their uncertain and generally poor reliability. The poor reliability and short life of past cryogenic refrigerators stems from an extreme sensitivity to contamination and wear, and to manufacturing and assembly precision. Compounding the problem is a lack of inspection and qualification techniques to quantify the reliability of any given refrigerator. Major advancements are needed in this area if space refrigerators are going to be successful; the criticality and US\$100M cost of typical cryogenic instruments demands that refrigerators achieve five to 10 year lives with reliabilities of 0.95 and higher.

In conclusion, better quantitative data and improved insight into the key parameters limiting cooler performance are urgently needed to support the rapidly expanding commitment to space cryocoolers. Assuming that the needed programmes are forthcoming, space cryogenic refrigerators are destined to play an ever-increasing role in space instruments in the years ahead.

Acknowledgement

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