ACTIVE REFRIGERATION FOR SPACE ASTROPHYSICS MISSIONS

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ABSTRACT

The use of cryogen dewars limits mission lifetime, increases sensor mass, and increases program engineering and launch costs on spacebased low-background, precision-pointing, instruments, telescopes and interferometers. The recent development of long-life mechanical and sorption coolers capable of refrigeration to temperatures below 2.5 Kelvin, combined with the innovative use of cryogenic radiators and thermally advantageous orbits, is enabling long duration (>5 years) missions that can perform high resolution infrared and sub-mm wave astronomical observations, Several of the available long-life cooling techniques are summarized. This discussion includes: the use of radiators to temperatures as low as 30 K; and the combination of cryogenic radiators with mechanical coolers through a heat interceptor to substantially improve the cooler's efficiency and reduce the required refrigeration. The design of a brassboard 10 K cooler, which will be completed in 1995, for cooling an IR camera is also outlined, A cooler based on this design can be constructed for flight missions which provides 10 mW of continuous refrigeration with an input power of less than 10 watts and a mass of six kg.

As an example of the potential benefits of this proposed thermal design strategy, the potential benefits to two missions, FIRST and WIRE, are described. The low mass and input power requirements associated with several of these long-life cooling techniques could lead to the development of a new class of small, inexpensive space observatories.

INTRODUCTION

in the past using a liquid or solid cryogen filled dewar was the only practical method for achieving <60K temperatures on-orbit (e.g. IRAS, COBE, ISO, etc.). The system mass, complexity and life penalties caused by utilizing a dewar are substantial. In addition, the dewar imposed life limitations often forced mission designers to compromise between sky coverage and image resolution, thereby sacrificing instrument performance. As a result of these impacts, efforts have continued to develop better cryogenic thermal control strategies.[1]

Most of the cryogenic thermal control solutions being examined start with the selection of a thermally advantageous orbit such as the L2 halo orbit. The L2 halo orbit is a halo orbit about the second Lagrangian point of the sun-Earth system located 1.5 x10^6 km from the earth. With such an orbit, earth and solar shielding is much more easily achieved, and cryogenic radiators can be operated to 60 K for most missions and to 30 K on a well designed instrument. The low temperature shielding provided by these radiators reduces heat loads at the focal plane assembly to a point that recently developed long-life cryocoolers can be used to provide the final instrument and focal plane assembly (FPA) refrigeration. The resulting system offers substantial maw, and life advantages over cryogen dewars and substantial mass, power and vibration advantages over systems cooled with active refrigerators from a 300 K ambient. In addition to improving large and moderate missions (e.g. ESA cornerstone and, M3 missions), a whole new class of micromissions (e.g. NASA small and mid-sized explorers) can be enabled or substantially enhanced through application of these thermal control strategies.

There is a strong correlation between the requirements of many planned astrophysics missions: low mass, low power, desire for as large an aperture as possible, desire for very low instrument temperatures, etc., This commonality of desires stems from the common requirement to make observations of faint astronomical objects. Obtaining useful observations of faint objects requires a large, cold aperture focused on a large cold(er) focal plane. Furthermore, many of the missions currently in development are planning to use similar, thermally favorable orbits, and are intending to fly on similar launch vehicles, which imposes the primary mass and dimensional constraints.

Another reason for the commonality of thermal requirements is that there are a limited number of detector materials. In the past, differing detector arrays were typically operated at a single temperature (e.g. IRAS). This is done to simplify the mechanical, and optical design of the sensor despite the fact that the performance of several of these detector types can actually be diminished by operating at too low a temperature (e.g. InSb carrier densities decrease substantially at low temperature). This 'good neighbor' approach to designing the focal plane assembly (FPA) results in a large cooling requirement being placed on the helium cryostat, which could be met at a warmer temperature by an alternate technology without sacrificing any performance.

A summary of the temperatures that must be achieved for astronomical observations is presented in "Table 1. These cooling needs include thermal shields to reduce parasitics, optics and optical enclosure cooling to eliminate thermally emitted photons which add noise to the detector measurements and detector/FPA cooling. In addition, Table 1 notes the available cooling, techniques for meeting these requirements.

Table 2 compares the 1993 projected[2] SIRTF thermal cooling requirements with those of FIRST. While the thermal requirements of both missions are evolving and have changed considerably from what is cited in this table, they are still representative of the likely final set of thermal control requirements. The temperatures and the magnitude of the cooling required for these missions are very similar. This demonstrates that a strong synergism exists between the cooling technologies required for different infrared and sub-mm sensors and missions. Only the sub 1 K loads required by the very long IR and sub-mm wave missions dictate the use of a different cooling technology (either a sorption pumped He^3 bath to 0.3 K, a dilution refrigerator, or an adiabatic demagnetization refrigerator (ADR)).

After reviewing the thermal control requirements for several proposed missions (including COBRAS/SAMBA, FIRST, WIRE, SIRTF, SMIM, PSI) it was apparent that system mass could be substantially reduced and system life substantially increased by synergistically combining the choice of a good thermal environment (orbit), utilizing radiators at as low a temperature as possible for thermal shielding and instrument cooling, and employing the newly developed active coolers which incorporate radiatively cooled heat interceptors[3] in the mechanical cooler interface design. The benefits due to reduced mass arc fairly clear: reduced cost due to small launch vehicle requirements and fabrication. The benefits of long life arc somewhat more subtle. Having a 5 to 10 year mission life provides the spacecraft designer with much more flexibility in terms of data rates and mission operations, in addition to permitting the instrument to gather data longer. The ability to gather data longer also permits tbc instrument to be designed to achieve it's maximum resolution. Often, as in tbc case with WIRE, the instrument resolution is sacrificed in order to achieve a large enough fleld-of-view (FOV) to provide significant sky coverage during a missions short life. Having an essentially unlimited life permits the designer to optimize a system for resolution. The small FOV achieved when observing at maximum instrument resolution is still sufficient to provide complete sky coverage. Also, recent progress in image reconstruction techniques can bc applied to achieve resolution that exceeds an instrument's diffraction limited performance if enough detectors per diffraction disk (the central diffraction disk in the image of a point source) arc available (and given a sufficient signal to noise ratio). "Ibis still further reduces the FOV available for a given detector array size. Longer life therefore translates not only to more data, but to higher resolution.

Table 1. Summary of cooling technologies appropriate at required temperatures.

Temperature Range	Cooled Device or Component	Cooling, Technology
>45 K	< 5 micron optics, and thermal shields	radiative cooling and/or vent gas cooling and stored cryogen
≤30 K	InSb FPA, HEMT FPA, <28 micron optics and thermal shields	radiative cooling or two-stage Ball or BAe 30K Stirling coolers or single-stage sorption cooler or vent gas cooling and stored cryogen
≤10 K	< 20( ) micron optics	two-stage sorption cooler or three-stage Stirling/J-T cooler or He vent gas cooling and stored cryogen or stored H_2 cryogen
≤8 K	Si:As BIB FPA	two-stage sorption cooler or three-stage Stirling/J-T cooler or He vent gas cooling, and stored He cryogen or stored H_2 cryogen
2 to 4 K	Si:Sb BIB FPA and SIS heterodyne receivers	three-stage sorption cooler or three stage BAe Stirling/J-T cooler or hybrid sorption/BAe J-T cooler or stored He cryogen or adiabatic demagnetization refrigerator
1.5 to 3 K	Ge FPA (all types)	three to four stage sorption cooler or three to four stage Stirling/J-T cooler or hybrid sorption/BAe J-T cooler or stored superfluid He cryogen or adiabatic demagnetization refrigerator
≤0.3 K	Bolometers	dilution cooler, sorption pumped He^3 cooler or adiabatic demagnetization refrigerator

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LONG-LIFE COOLING TECHNIQUES SUMMARY

Cryogenic Radiators

in low Earth orbits, temperatures of 200 K are very readily achieved radiatively for sizable cooling loads. For very small loads, and with careful design, temperatures as low as 80 K can be achieved radiatively (e.g. Thematic Mapper and MODIS). With the selection of a thermally favorable orbit such as a solar orbit, L2 halo orbit and a Highly Eccentric Orbit (HEO), cryogenic radiators can achieve far lower temperatures. As an example the SIRTF thermal model predicts that the SIRTF optics and FPA will stabilize at 40 to 45 K after cryogen depletion if in HEO[4]. Similar predictions are made for other missions (e.g. Edison[5]). The latest SIRTF design has incorporated these concepts[6]. It now will be in an L2 halo orbit, has a substantial earth/solar shield and launches warm, relying on radiative cooling to achieve approximately 60 K. The entire telescope structure will also be maintained during operation at 60 K through radiative cooling. These design changes permitted the cryogen required to be reduced from 1000 l to approximately 450 l.

Telescope cooling to <60 K temperatures can and often should be achieved radiatively. This includes cooling thermal shields and instrument enclosures to these temperatures. Inflatable shields have the potential to reduce the mass of the radiatively cooled shields. For missions like the proposed Edison project, the shield masses are relatively small already as they are designed solely to meet the thermal requirement and have no need to contain cryogen or support the cryogen mass through launch.

It should be noted that a number of papers that have been published (e.g. Reference 1) on radiative cooling of astronomical instruments have concluded that cooling to 20 K, or lower, is possible radiatively. The analyses presented are based on idealized beginning-of-life devices. A real device, designed to withstand launch loads, and after degradation due to condensation of contaminates, space environment, etc., is unlikely to prove capable of achieving these temperatures. However there is little doubt that several of the proposed shielding concepts will out-perform conventional designs while weighing less.

Table 2. Infrared (SIRTF) and sub-mm (FIRST) sensor thermal requirements compared

Temperature (respectively)	SIRTF (1993) cooling requirement	FIRST cooling requirement
21 K / 23.5 K	76 mW	210 mW
4.5 K / 4 K	14 mW	10 mW
1.4 K / 1.6 K	22 mW	0.6 mW
0.5 K	0	3 uW
0.15 K	0	100 nW

Stifling and Pulse Tube Coolers

Stirling and pulse tube coolers capable of providing useful refrigeration at temperatures as low as 30 K are being successfully developed by ESA, BMDO, and NASA for space applications as described elsewhere in this conference. It is clear that a rapid maturation of these technologies is underway with system integration issues and techniques being the dominate concern. In addition, it appears that 2+ year life times and reasonable cooler efficiencies are currently available from most of the major manufacturers of these coolers,

Cryocooler Coldfinger Heat Interceptor

The cryocooler coldfinger heat interceptor, developed at JPL[3], couples a cryogenic radiator through a thermal strap to the cold finger of a mechanical refrigerator such as a pulse tube or Stirling cooler. Laboratory demonstrations of the technology indicated a factor of two performance improvement with the BAe cryocoolers operating with a 55 K cooling load when intercepting heat with a 1 SO K cold sink. Figure 1 shows the measured performance sensitivity of the BAe 80 K cooler at several heat interceptor temperatures.

While the demonstrated performance improvement is substantial, of equal import is the reduction in required cooling, available through utilization of the 150 to 190 K thermal sink to provide thermal shielding. Achieving instrument lifetimes of 5 years requires at least one redundant cooler be attached to the FPA. It was found[3] that the coldtip thermal conduction was reduced from 250 mW to less than 1 SO mW with the heat interceptor attached. in addition, the 150 K heat sink to cool a thermal shield, thereby significantly reducing FPA radiative and conductive parasitic.

The combination of improving cooler efficiency, reducing redundant cooler parasitics, arid providing FPA radiation shielding, and thermal sinking of conductive structure and launch supports can reduce, by a factor of 3 to 4, the required cooler input power. This dramatic reduction of cooler input power enables the use of active refrigerators for km~-life missions even when the spacecraft's available power is severely limited.

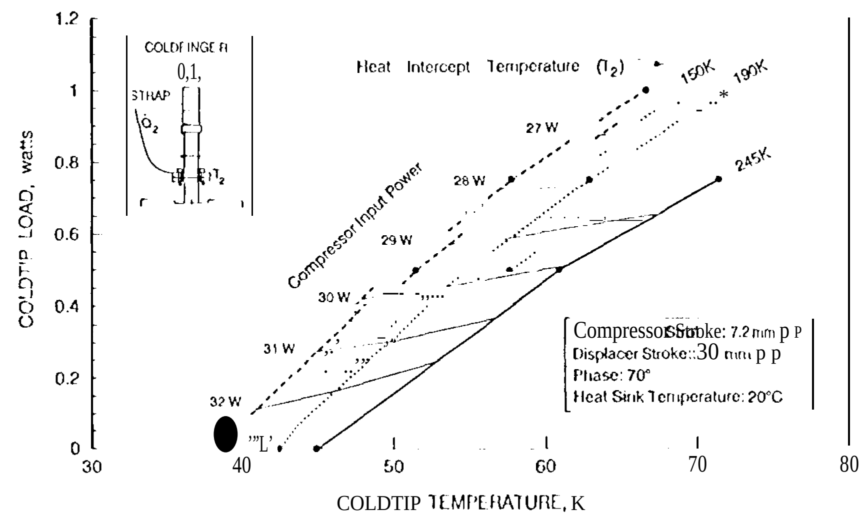

Figure 1. BAe 80 K cooler, with heat intercept strap, sensitivity of thermal performance to heat intercept temperature.[3]

10 '1'030 K Sorption Cooks

A sorption cooler is a sorption compressor which typically is combined with a J-T expander. In this combination the compressed gas is expanded through the J-T orifice or capillary tube, producing a ?.-phasc gas/liquid refi igerant mixture without the use of any moving parts, The liquid refrigerant is subsequently separated and retained in a wick material at the cold-tip where it absorbs the detector heat load and is thereby evaporated. A pre-cooling stage is inserted before the J-']' expansion to improve cooler efficiency.

The exact operating temperature of a refr igerator incorporating a Joule-Thomson expansion device is determined by controlling the back pressure above the collected refrigerant. As an example, when using hydrogen as the refrigerant the cold tip temperature can be effectively varied between 7.5 K and 32 K. Pressures above 0,4 Ml>a lead to temperatures above 26 K being provided by liquid hydrogen; whereas for pressures below 50 torr, the. hydrogen solidifies, thus providing a sublimating solid cryogen. Very low' pressures, mar 1 torr, lead to temperatures below 10 K.

The primary advantage of this type of cooler, other than the absence of vibration, is the ability to scale to very small cooling loads. It is this ability to scale to loads less than 10 mW that enables the development of very small missions. Many missions currently under consideration have less than 100 Watts of electrical power available. As an example, Pluto Fast Flyby has less than 7 Watts available for the entire science payload.

Sorption coolers for applications requiring quick-cooldown to below 10 K, and periodic-operation arc currently under development by BMDO to support 10 year life missions[7]. A flight project to space qualify such a cooler is currently in final integration and checkout at JPL (BETSCE)[8].

Development of a continuous version of this periodic-operation cooler would result in mass reduction and life extension of the proposed astrophysics missions. This cooler could serve to cool focal planes for observation out to 28 microns, optics cooling for observation out to 200 microns and to pr ovide thermal shielding for colder FPAs. Studies have indicated that, for the 10 mW load requirements typical of low background, precision-pointing IR instruments, telescopes and interferometers, non-regenerative hydride based coolers can be extremely competitive with mechanical refrigerators[9]. A cooler of this type is capable of providing 10 m W of refrigeration at <10 K with a mass of <6 kg and average input power of less than 10 watts. 65 K precooking would be provided by a passive radiator in a flight version.

Figure 2 shows a schematic of such a miniaturized cooler. The proposed cooler consists of two low pressure (ZrNi hydride) sorption compressors coupled to a single high pressure ($LaNi_{4.8}Sn_{0.2}$ hydride) sorbent bed operating on a 12 hour cycle, and J-T expander capable of operating over a temperature <10 K. The low pressure sorbent bed will absorb hydrogen at a pressure below one torr, thereby allowing temperatures below 10 K to be achieved.

The hydrogen storage tank serves to supply the J-1' expander with refrigerant at approximately 11 MPa. Precooling of the hydrogen to below its inversion temperature is provided by liquid nitrogen (during ground test), which simulates the 60-80 K space radiator upper stage. After expansion (and absorbing the detector load) the now low pressure hydrogen is absorbed by the low pressure sorbent bed. A sorbent bed, which is ready for absorption, is selected by activating a solenoid valve. When heated, the low pressure bed will desorb the hydrogen refrigerant at a pressure of 0.1 Ml)a and a temperature of S75 K. The high pressure bed will absorb the hydrogen desorbed by the low pressure bed. Upon heating the high pressure bed will desorb the hydrogen refrigerant at a pressure in excess of 11 Ml's into a hydrogen storage tank. After desorption is complete, the compressors cool by natural convection back to the laboratory ambient temperature (during ground tests) at which time they are ready to begin another absorption cycle. By operating two low pressure sorbent beds 180° out of phase, continuous refrigeration can be achieved. The gas flow during the recharge cycle is directed through passive check valves.

A variant of this concept design which incorporates parallel, two-stage compressors operating 180° out of phase is capable, in a flight configuration, of delivering 100 mW at 20K and 10 mW at <10K with a mass of only 25 kg and an input power of 25 watts.

The brassboard refrigerator being developed for 1995 demonstration will be integrated with a 8 to 30 micron camera (MIRLIN) being developed at JPL for astronomical observations at the Hale Telescope on Mt. Palomar. The resulting Long Life Infrared Observational System consists of a test bed cooler, mid-IR camera within a dewar, and power control and readout electronics. Demonstrating integrated operation through ground-based astronomical imaging will validate the compatibility of the involved technologies and alleviate concerns such as temperature stability, vibration and electromagnetic interference (EMI) for future spaceborne applications

4 K and 2.5 K BAe/RAL J-T COOLER

British Aerospace (BAe)[10] is commercializing a 4 K helium space cryocooler first developed by the Rutherford Appleton Laboratory (RAL). The effort is being jointly funded by ESA through BAe. The cooler is scheduled for completion in 1994 and is baselined for the FIRST mission, The British Aerospace (BAe) 4 K cooler, which uses flexure-bearing two-stage Stirling mechanical coolers to provide 20 K upper stage precooling to a 4 K cooling stage. The 4 K stage is comprised of a J-T expander coupled with a flexure-bearing two-stage mechanical compressor,

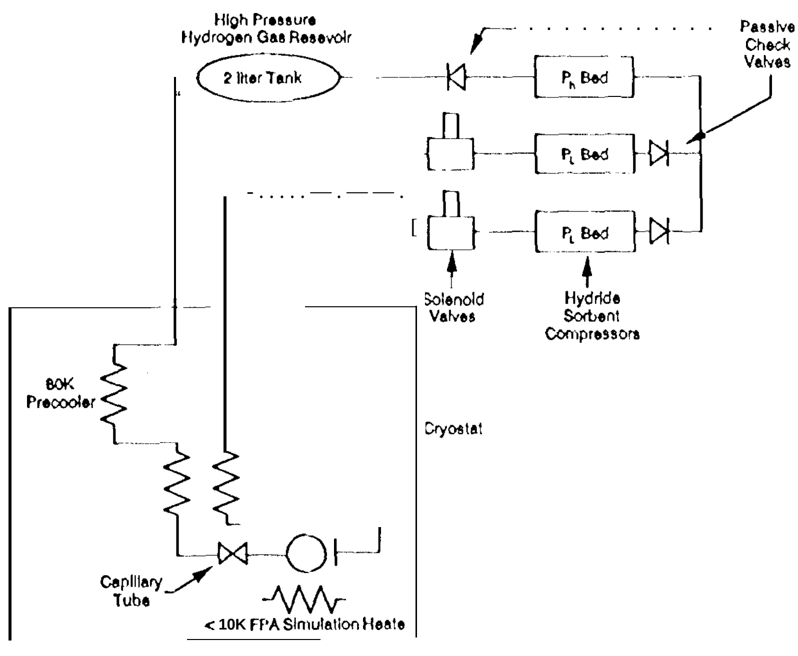

Figure 2. Schematic representation of a continuous 10 mW cooler with two stage compressor.

I{ AI, has also demonstrated a similar cooler[11], which uses He^3 as the refrigerant, which achieved 3.5 mW of cooling at 2.5 K in addition, a second version of the 4 K cooler has been developed at RAL which provides 11 mW of cooling at 4.35 K. These coolers have been baselined for FIRST. As FIRST has been funded, it is probable that these coolers will also be available for future NASA astrophysics missions.

The performance of these RAL hybrid J-T/Stirling coolers is primarily limited by the precooking temperature available from the two-stage Stirling (currently 17 K). It has been proposed by the author to replace the two-stage Stirling precooler with an 8 K sorption cooler. Combining the RAL J-T stage with an 8 K sorption precooler would result in a 3.3 times increase in the cooling power of the cold stage at 4 K while minimizing EMI, and vibration effects on the focal plane.[12] This combination also substantially reduces the cryocooler power requirement. Finally, development of this cooler would provide tbc cooling platform required for successful operation of sub 1 K coolers.

Sub 1K Coolers

Three types of refrigeration techniques arc available for cooling below 1 K: the dilution cooler, the Adiabatic Demagnetization Refrigerator (ADR), and the sorption pumped He^3 cooler. ADRs have been proposed which could cool to below 1 K from a 4 to 8 K heat sink. This type of cooler has particular advantages when cooling very small loads and when cooling below 0.3 K. Work on ADRs is currently underway at Ames Research Center[13]. Hardware demonstration of a brassboard sub 1 K cooler is expected this year. The small loads (i.e. 5 mW at 2.5 K or 1 mW at 1.5 K) typical of a 10 RST type mission would likely permit a substantial mechanical simplification of the current designs.

A dilution refrigerators, baselined for FIRST, is being developed by Benoit and Pujol.[14] In addition, Roach and Gray[15] have demonstrated a dilution refrigerator, which could be used for space applications, using activated charcoal to pump the helium. This cooler operated at temperatures below 20 mK.

Finally, by pumping on He^3 with activated charcoal to provide cooling to 0.3 K has been the preferred laboratory method for cooling to 0.3 K for decades.[16] Duband et al,[17] developed such a He^3 refrigerator, which was used on a sounding rocket launched instrument to examine the background radiation from the big bang. This cooler provided 100 microwatts at 346 mK.

APPLICATIONS: TWO EXAMPLES

This section describes two very different missions, FIRST (an ESA cornerstone mission) and WIRE (a NASA small explorer) as brief examples to outline the potential benefits available to mission designers through adoption of a more integrated thermal design strategy.

FIRST

FIRST has two major instruments requiring cooling: the Far Infra-Red (FIR) direct detection instrument and the N4ulti-Frequency Heterodyne (MFH) instrument. Each of these instruments require cooling at 65 K, 20-30 K and 4 K nominally. In addition, a 150 K thermal shield is planned, The 1 SO K thermal shield would be cooled by a radiator. The 65 K cooling requirement would be met by two operating 50-80 K BAe Stirlings cooling a common shield and one redundant cooler. The ?.0-30 K requirement would be met by two operating and one redundant ?0-S0 K BAe cooler per instrument. The 4 K cooling requirements would be met by one operating and one redundant 4 K cooler per instrument. This baseline design has 13 coolers (8 active and 5 redundant).

The FIRST orbit (L2 halo) is thermally favorable and compatible with a 60-65 K radiator. Therefore, in an alternate design, the 65 K common thermal shield cooling would be provided by a radiator, thereby eliminating all three 50-80 K Stirling coolers. This 65 K thermal shield can also be used as a thermal sink to the 20-50 K Stirling coolers. If the 65 K thermal heat interceptor can be assumed to double the capacity of the 20-50 K Stirling (this is just a crude extrapolation, tests must be conducted on a two-stage Stirling to provide a more dependable estimate) then only one operating Stirling per instrument would be required. As these are separate instruments, one redundant 20-50 K Stirling would still be needed. Finally, if the 20-50 K Stirling precooler is replace by a 10 K sorption cooler then its capacity would be increased enough to provide cooling for both instruments. This could be achieved by using one compressor pair connected to two 4 K J-T expansion valves. Thereby, only one operating and one redundant 4 K cooler per instrument would be required. This alternate design concept would then utilize only 6 active coolers (3 operating and 3 redundant), thus eliminating 7 cooler-s (5 operating) relative to the baseline design,

Table 3 presents the weight and power of the baselined coolers and their electronics[18] compared with that of the alternate design. Note that one set of redundant electronics is required per compressor pair. As the BAe 4 K cooler has two compressor pairs, two sets of control electronics are required per 4 K cooler. The 10 K sorption/BAe 4 K J-T hybrid cooler only requires one set of electronics. No interfaces and mechanical supports are included in these totals. Nor is the mass of the 65 K radiator included. A spacecraft weight penalty factor of 0.25 W/kg is used [19] to estimate the mass required to supply electrical power (solar cells, power conditioning and batteries) combined with the mass of the 275 K heat rejection radiator. This is an optimistic number based on the most advanced available technology.

Clearly, the satellite power and mass budgets are being heavily driven by the huge 860 W power allocation required to operate the coolers baselined for this mission. While the analysis presented here is clearly very simplified, it is clear that substantial benefits are possible. This analysis indicates that the alternative design requires 562 W less power, giving a system total mass savings of 274 kg. A more thorough analysis, which considered the true mass of the heat rejection radiators, 65 K radiator, mechanical supports, etc., would likely indicate an even greater system mass savings. in addition, the reduction from 8 coolers to 3 would have a profound effect in reducing EMI, and vibration effects on the spacecraft. It is conceivable that the simplification of interface and sensor interference issues[12] resulting from adoption of the alternate design could be enabling for the FIRST mission.

Table 3. Cooler mass and Power Budget for the baseline FIRST design compared with an alternate.

	Baseline Design Total Coolers	Mass	Alternate Design Total Coolers	Mass	Baseline Design Operating Coolers	Power	Alternate Design Operating Coolers	Power
65 K requirement	3 coolers x 4.33kg/cooler	13 kg	0 coolers	0 kg	2 coolers x 50 W/cooler	100W	0 coolers	0W
20/30K requirement	6 coolers x 8.3 kg/cooler	49.8kg	4 coolers x 8.3 kg/cooler	33.2kg	4 coolers x 60 W/cooler	240W	2 coolers x 60 W/cooler	120W
4 K requirement	4 coolers x 16 kg/cooler	64 kg	2 coolers x 16 kg/cooler	32 kg	2 coolers x 110 W/cooler	220W	1 cooler x 80 W/cooler	80W
Electronics	17 elec. sets x 8 kg/set	136kg	8 elec sets x 8 kg/set	64 kg	10 elec sets x 16 W/set	160W	3 elec. sets x 16 W/set	48W
Power Conversion efficiency: 80 (%)	N/A	N/A	N/A	N/A	560 W (cooler total) / 0.8	700W	200 W (cooler total) /0.8	250W
Power (0.25 kg/W)	860 W x 0.25 kg/W	215kg	298 W x 0.25 kg/W	74.5kg	N/A	N/A	N/A	N/A
Totals		478kg		204 kg	cooler total + electronics	860W	cooler total + electronics	298W

WIRE

The Wide-Field Infrared Explorer (WIRE)[20] is on the opposite end of the mass, power, schedule and cost spectrums from FIRST. WIRE is a NASA funded small explorer mission. As such it has a $35 M mission cost cap, and is designed to weigh less than 250 kg with less than 300 W total power available.

The baseline mission will last only 4 months, during which will survey 40% of the sky in two spectral bands between 5 and 28 microns. The WIRE instrument is diffraction limited at 28 microns. If the cooling requirement was met by a long life cooler, the FOV could be reduced until the instrument was diffraction limited at 5 microns. This is a 5.6 times improvement in resolution. To resolve at the 5 micron diffraction limit, assuming one now considerably smaller diffraction disk per pixel, and to achieve a 100% sky coverage, a 5 year mission would be required (2,8 microns/5 microns x 100% / 40% x 4 months = 56 months). With a long life cooler, 2.5 times more sky coverage could be achieved by the WIRE instrument at up to 5.6 times higher resolution.

The currently baselined solid hydrogen dewar weighs 38 kg and provides 8.9 mW of cooling at 7 K. A two stage sorption cooler, which provides 10 mW of cooling at 8 K and 100 mW at 20 K would weigh only 25 kg and require 25 W of input power. This does not include the 65 K radiator which would be required to reject approximately 100 mW. With this radiator included, the total mass would be somewhat smaller for the cooler than for the dewar, while providing >5 years of life versus the 4 months provided by the dewar. Note that the thermal design for both concepts would include a 130 K sunshield. Clearly there is substantial benefit available by considering alternate technologies to cryogen dewars even for very mail missions,

CONCLUSIONS

The clear advantages of hybrid radiative/active cooler designs when combined with a thermally advantageous orbit will enable a number of long term astrophysics missions and miniature astrophysics missions. The long life permitted by such designs can significantly affect mission design: data rates, FOV/resolution vs. sky coverage, apel-tare size, etc. and improve instrument performance. in summary, all cooling requirements down to approximately 45 K can be met radiatively (thanks to clever orbit selection). Stirling, hybrid J-T/Stirling, hybrid BAe J-T/sorption and sorption coolers ail have the potential to support all projected IR sensor sub-45 K cooling requirements, while achieving lifetimes of up to 10 years. These coolers are being actively developed by ESA, BMDO, DoD, and NASA.

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