Cryocooler Options for NGST and other Space Applications

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Abstract

We present a summary of cryocoolers that are presently available or in development and would be suitable for support of mid-infrared camera on the Next Generation Space Telescope. From this summary we recommend that a mid-infrared camera use a hydrogen/metal hydride 18 K precooling stage and a 6 to 8 K helium-cooled Joule-Thomson stage. The helium stage can be driven by a mechanical compressor that is already available from Rutherford Appleton Laboratories or a helium/charcoal sorption compressor system. We present a conceptual design for such a helium/charcoal sorption cooler. To provide 10 mW of heat lift at 6 K, such a cooler would require a total input power of approximately 93 W and have a system mass of ~33 kg.

1 Status of Cryocooler Technology for MIR Applications

The nominal operating temperature for the NGST Integrated Science Instrument Module (ISIM) while in orbit will be in the range of 30 K to 40 K from passive. Since passive cooling becomes extremely ineffective below 30 K, the detectors for the mid-infrared camera option will require active cooling to lower temperatures. As shown in Table 1, there is a trade-off between the IR detector wavelength and its operating temperature range. The broadest IR frequency range will require the detectors to be cooled to 4 – 8 K, but significant extension of the cut-off wavelength is possible for cooling below ~ 15 K. The cooling loads for the <10 K detector arrays is estimated to be about 1 mW per detector array, and less than 10 mW for up to seven detector arrays, including parasitic heat loads.

There are two general approaches to produce the temperatures needed by the MIR detectors. First, stored cryogens (i.e., liquid helium for T ~ 4 K or solid hydrogen for ~6.5 K to ~13 K) can be used. While such storage dewars have been used on previous space flight missions of duration less than 1-2 years, many issues involving mass, volume, lifetime, safety and risk suggest that stored cryogens are inappropriate for NGST. The second approach is to use long life closed-cycle cryocoolers[1]. Table 1 summarizes the viable choices for mechanical coolers that will produce temperatures below ~25 K. Although multiple-staged Stirling cycle coolers can operate below 20 K[2], these mechanical coolers are very power inefficient - a small Stirling cycle cooler would typically operate[2] with a Carnot coefficient of performance of 2% at 16 K and even less at lower temperatures. This inefficiency, common to all regeneration cycle coolers, is associated with the regenerator heat capacity. Unfortunately, the heat capacity of conventional regenerator materials also falls by T^3 as the temperature decreases making it very difficult to reach very low temperatures without using novel regenerator materials[2]. Stirling cycle coolers are also plagued by residual vibrations over a wide frequency band. The pulse-tube variant[1] of Stirling cycle coolers significantly reduce electromagnetic interference and vibration levels. A commercial laboratory 2-stage pulse-tube cryocooler has been recently announced[3] that can produce 0.5 W cooling at 4.2 K for 5.5 kW of input power. A conceptual configuration of a 4 K pulse-tube cooler that may be adaptable for space applications has been reported[4]. Disadvantages[5] of the pulse-tube design include a slightly lower Carnot efficiency than the Stirling cooler due to irreversibilities in the pulse tube expansion (which also exacerbates the regeneration problems < 20 K) and integration difficulties due to the configuration of the cooler components and the location of the cold block. Stirling and pulse-tube coolers do not scale well for cooling capacities below 200 mW. The input power requirements for cooling to these low temperatures are higher due to poor regenerator performance and real-gas effects. Hence, the Stirling and pulse-tube coolers are presently not viable options for the NGST MIR detectors.

Three distinct types of cryocoolers remain as viable options for NGST-MIR coolers: (1) Joule-Thomson (J-T) cycle coolers with sorption compressors; (2) J-T cycle coolers with mechanical compressors; and (3) miniature Turbo-Brayton mechanical coolers. The operating temperatures and development status for different variations of these coolers are compared in Table 1. While the mechanical coolers would probably use only He as the refrigerant fluid, the sorption coolers

						Closed Cycle Continuous Coolers								Stored Cryogen	
						Sorption Compressors						Mechanical			
	Detector					Periodic		Continuous				continuous			
Temp (K)	Si:Sb	Si:As	Si:Ga	HgCdTe	QWIP	Liquid helium-Charcoal	Solid Hydrogen-Metal Hydride	Liquid helium-charcoal compressor	Supercritical Helium JT-Charcoal compressor	hydrogen, liquid w/ sorption compressor	hydrogen, solid w/sorption compressor	helium J-T mechanical compressor	Turbo-Brayton	Solid Hydrogen	Passive Cooling
3						2 He stages		2 He stages							
4	▨					1 He stage		1 He stage				SD			
5						POP		POP				(Ranck)			
6		▨							development				development	SD	
7		▨							at JPL				(Goddard)		
8		▨									concept				
9		▨					SD				only				
10		▨					(BETSCE)								
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Table A1. The operating temperature ranges for available mid-IR detectors along with their effective wavelengths are compared to the temperatures provided by various cooling options. The status for the different coolers are: POP = Proof-of-Principle by ground test, OTS = Off-the-Shelf for ground applications, SD = Space Demonstration.

use either helium (with a charcoal pump) or hydrogen (with a metal hydride pump) over the cooling range ~1-8 K or 8–25 K, respectively. The sorption coolers can also function in either a periodic mode (i.e., intermittent cooling for short times) or continuous operation to provide a constant cold temperature.

There are presently no space flight demonstrated, long-life cryocoolers available in the temperature range desired for MIR detectors. However, several of the coolers are in various stages of development for cooling applications below 25 K.

1.) Creare, Inc. is currently developing a two-stage 25K/6K Turbo-Brayton demonstration cooler[6] under the sponsorship of the GSFC for potential NGST application. This type of cooler[7] has been demonstrated for long-life engineering tests and space flight as a multi-watt cooler at T > 65 K and as a 1 W cooler at 35 K in the laboratory[8]. It remains to be demonstrated whether the Turbo-Brayton coolers can operate efficiently at low power loads and temperatures below 30 K, since parasitic heat losses impact scaling to smaller designs. Furthermore, 20 mW T-B coolers will require reduced dimensions for critical components such as the turboalternator and heat exchanger unit, which will impose significant manufacturing challenges for machining tolerances, etc. and increased risk of instability during operation. Turbo-Brayton coolers also require that the waste heat be exhausted near the point of cooling; in the case of NGST this would require about 100 W to be rejected at 220 K from the ISIM. Technology demonstrations are planned[6] for late 1999 to validate operation of a minitarized turbine rotor and self-acting gas bearings with a flight version cooler to be available in 2003.

2.) A helium Joule-Thomson cycle cooler[9] with a mechanical compressor has been demonstrated at 4 K by Rutherford Appleton Laboratory/ Matra Marconi Space Ltd. (RAL/MMS), using a 20 K Stirling upper stage cooler. It is currently being developed as an intermediate cooler[10] (with an 18 K hydrogen-sorption cooler upper stage) for the High-Frequency Instrument on the the ESA Planck mission.

3.) Ball Aerospace has a development project with the USAF for a hydrid 10 K cooler that combines a helium J-T stage coupled to a three-stage Stirling cooler[11]. A new type of rotary vane compressor is being developed for the helium J-T stage. Work has concentrated on developing the He pump, with delivery of a 100 mW at 10 K Engineering Design Model cooler planned by the end of 2000. Taking advantage of the passive thermal cooling of the NGST ISIM to ~35 K, Ball has very recently proposed a two-stage J-T 6 K cooler that would use independent helium and hydrogen J-T loops with separate rotary vane compressors[12]. This cooler would reject ~30 W at 220 K, near the ISIM, and 50 W at 270 K on the spacecraft bus.

4.) A periodic solid hydrogen sorption cooler[13] (BETSCE) demonstrated cooling to 10 K during flight operation onboard the Shuttle in May 1996. Pre- and post-flight ground tests produced minimum temperatures down to 9.4 K. Currently, no further development of periodic solid hydrogen sorption cooling is planned.

Table 2. Cooler System Properties for Various 6 K Cooling Loads. For all cases the combined electronics package is assumed to have a mass of 8 kg and an additional power requirement of 10 W. The radiator mass for the hydride cooler system compressors is assumed to be 10 kg.

Heat Lift At 6 K (W)	Charcoal Input Power (W) (at 18 K)	Charcoal Sys Mass (kg)	Hydride Input power (W) (at 270 K)	Hydride System Mass (kg)	Total System Power (W)	Total System Mass (kg)	Passive Cooling requirements (W)	
							At 35 K	At 270 K
0.005	0.43	.56	66.4	12	76.8	30.6	0.44	66.4
0.010	0.81	.95	82.6	13.7	93.4	32.6	0.82	82.6
0.015	1.20	1.34	98.9	15.4	110.1	34.7	1.21	98.9

5.) Several organizations have built laboratory liquid hydrogen sorption coolers[14,15] that operated at cooling temperatures in the range 18 K to 28 K. Currently, JPL is developing a continuous 18-20 K-hydrogen cooler[16,17] for the Planck mission. An Elegant Breadboard (EBB) cooler is be to operating in the laboratory in 2001 with two flight units to be delivered to Europe by 2004.

6.) A Proof-of-Principle (PoP) demonstration of continuous formation of solid hydrogen has been performed[18] in 1993. However, no additional experimental work has been done to demonstrate a continuous solid hydrogen sorption cooler using appropriate hydride compressors.

7.) Helium-carbon sorption coolers are well established for periodic operation on the ground[19] and there has been use for short duration rocket flights in space[20]. The continuous He-charcoal sorption cooler has been demonstrated in the laboratory[21] but not yet developed for space coolers. The JPL sorption team has developed a basic design[22] for 10 mW helium-charcoal coolers to operate in the 5–8 K region as part of this study. PoP demonstrations are planned for 2000 with demonstration of a complete cooler in 2002 using the 20K EBB hydrogen cooler as the upper stage.

Two-stage sorption coolers offer three attractive options to satisfy the temperature requirements for MIR detectors in the NGST instrument. The low-temperature cooling requirement is presumed to be 10 mW or less. All would use the nominal 18 K liquid hydrogen upper stage cooler being developed for Planck. If the ISIM radiators can reject sufficient heat loads at 30 to 35 K, a substantial reduction in size, mass, and power for the hydride compressor would be realized from the Planck cooler.

1. For cooling to the 8-14 K region, a continuous solid hydrogen metal hydride compressor could be developed. This option requires near term development and demonstration of the integration of the solid hydrogen J-T cryostat and low-pressure (i.e., absorption pressures below 1 torr) sorbent bed compressors.
2. For cooling to the 5–8 K region, the sorption helium-charcoal cooler would provide the least vibrations and should also be scaleable to smaller loads. Although many of the basic principles of this cooler are understood and have been demonstrated, substantial technology

development is required to develop a flight-qualified continuous-cycle cooler. This option is described more fully in the next section.

3. For cooling to the 4–8 K region, the mechanical compressor helium J-T cooler from either RAL/MMS or Ball could be integrated to the sorption 20 K cooler. Since the RAL/MMS cooler is to be mounted to the Planck sorption cooler, a combination that will be fully flight qualified by Planck, this is the least expensive, lowest risk, and most expeditious choice. However, potential vibration issues from the mechanical helium compressors remain.

2 Sorption Cooler Design for an NGST MIR Camera

System Level

A cooler system designed to provide base temperatures of 6 to 8 K will consist of two stages – a precooler to reach ~18 K and the final low-temperature stage. Additionally, the precooler will require precooling of the working fluid to less than ~60 K, which will be provided by passive radiation. For the NGST ISIM cooler, the precooling temperature is expected to be 35-40 K. In this section, we present a design for a two-stage continuous sorption cooler system capable of achieving 6 K. Details of each of the stages will be presented separately, along with a summary of the combined system, because either of the stages could be used separately in a combination sorption/mechanical cooler system, as described in above.

The heat load on the low-temperature stage is expected to be < 10 mW, depending on the number and characteristics of the specific detector arrays used in the MIR focal plane. Each array will dissipate approximately 1 mW, with the parasitic heat leak from lead wires (~20/array, plus 16 for temperature monitoring and control) contributing an additional 0.03 mW/array. The heat leak through the supporting structure will also be small, assumed to be 0.16 mW independent of the number of arrays. We expect that seven 1024x1024 arrays would require ~10 mW of heat lift at 6 K (including parasitic heat loads to a single support structure from an 18 K precooling stage); the dependence of the cold-stage heat load on the number of detector arrays is shown in Figure A1.

In order to provide 10 mW of heat lift, which would be sufficient for 7 detector arrays, the complete cooler system is expected to weigh 15 kg, requiring a total input power of 83 W, with

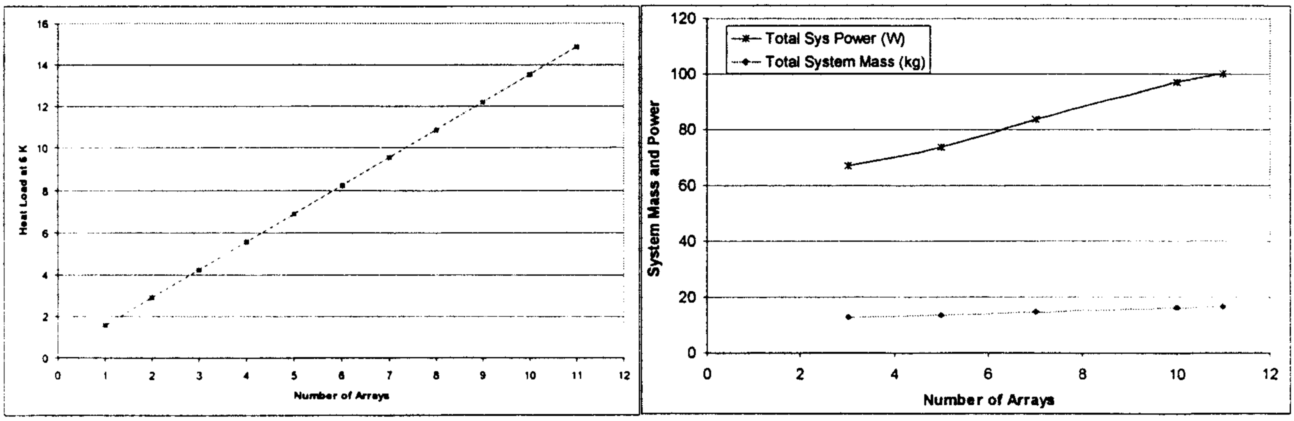

Figure A1. A) The heat lift required at 6 K as a function of the number of detector arrays. B) the total system mass and power as a function of the number of detector arrays.

a cooling efficiency of 8300 watts input power per watt of heat lift at 6 K. Table 2 shows the mass and power requirements of each of the stages, as well as the complete system, for heat lift of 5, 10, and 15 mW at 6 K.

18 K Sorption Cooler

The precooler design favored in this study is a hydrogen-sorption refrigerator, based on the cooler in development for the Planck Surveyor mission[16,17]. The compressor system is composed of a number of sorbent beds, each of which contain a $LaNi_{4.8}Sn_{0.2}$ alloy that is capable of absorbing (and also desorbing) a substantial amount of H_2. Typical operation temperatures are 270 K for absorption of hydrogen and 470 K for desorption. The heat-exhausted in cooling from 470 K back to 270 K is dissipated to space by a passive radiator located on the warm side of the spacecraft bus. The compressed hydrogen gas produced by the compressor system is cycled through a Joule-Thomson constriction at the cold head (~18 K) to provide precooling for the 6 K cooler and to cool the detector enclosures. The heat removed from the 18 K stage is rejected almost entirely at the 35 K ISIM radiator.

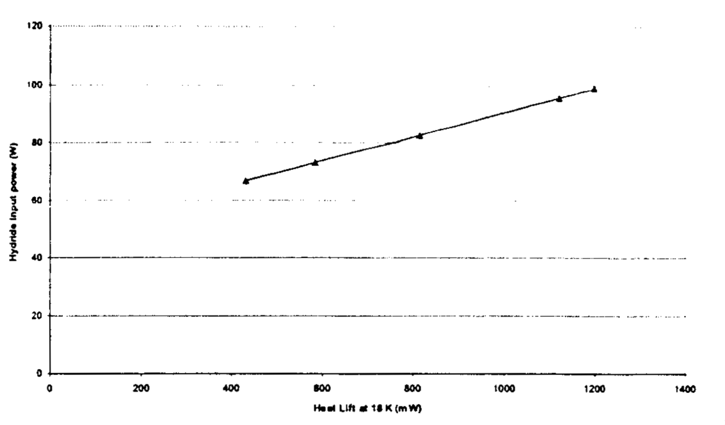

Figure A2. Hydride input power as a function of heat lift.

One of the major advantages of the hydrogen-sorption cooler is that it can be easily scaled to meet different requirements by simply changing the length of the compressor beds. The 35-40 K passive precooling provided by NGST will require very small compressor beds – only ~10 cm long. This is substantially smaller than the compressors for the Planck system, and a redesign of the mechanical support system will enable further mass and power savings. Input power as a function of heat lift at 18 K is shown in Figure A2. A scale drawing of the Planck Sorption cooler system (after resizing for NGST ISIM requirements) is shown in Figure A3.

For an NGST hydrogen sorption cooler, the hydrogen compressor beds would be located on the

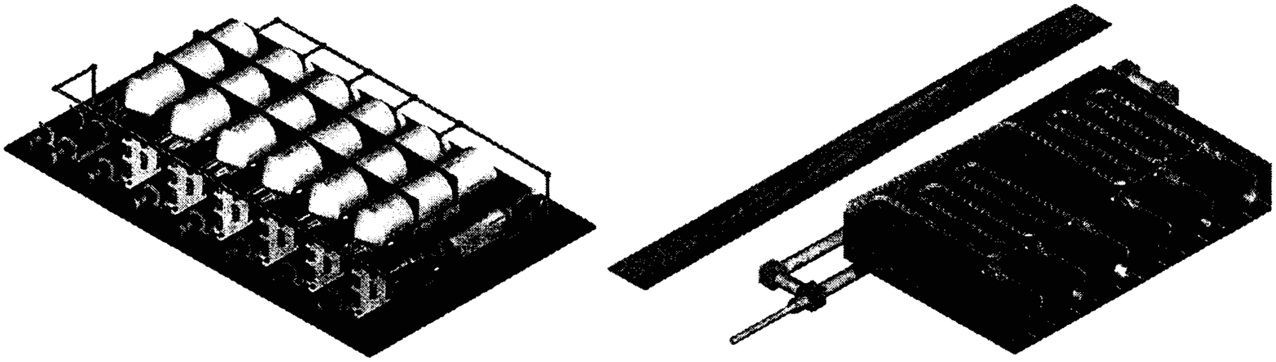

Figure A3. left) Scale drawing of the hydrogen sorption compressor system. The mounting plate is 500 mm x 800 mm x 7 mm. right) Scale drawing of the helium sorption cooler system design. The block containing the compressor elements also contains the Joule-Thomson constriction for the hydride cooler. The hydrogen precooling supply comes through the tube at the lower left. The outer block dimensions are 138 x 92 x 28 mm.

warm side of the spacecraft bus and coupled to a passive radiator at ~270 K. The temperature oscillations of the 270 K radiator due to cycling of the compressors are expected to be less than +-1 K at ~1 mHz. Gas-gap heat switches completely enclose the compressor beds, shielding the rest of the spacecraft from the 470 K compressors, and are used to couple(decouple) the compressor beds to(from) the radiator during absorption(desorption). The outer shells of the gas gap heat switches are tightly coupled to the radiator and remain at roughly the radiator temperature, even when the compressor beds are at 470 K. The heat switches also function by hydrogen sorption, but with different alloys as the sorbent material. The gas generated by the compressors is transported to (and from) the 18 K cold head through tubes that uncoil during deployment of the ISIM support. The transport tubes also function as a tube-in-tube heat exchanger and are heat-sinked to the radiation shields as they pass through them from the warm side to the cold side. A schematic of the complete system, including the low-temperature stage, is shown in Figure A4. The 18 K cooler can also cool the radiation shielding between the 6 K stage and the 35 K ISIM into its acceptable range.

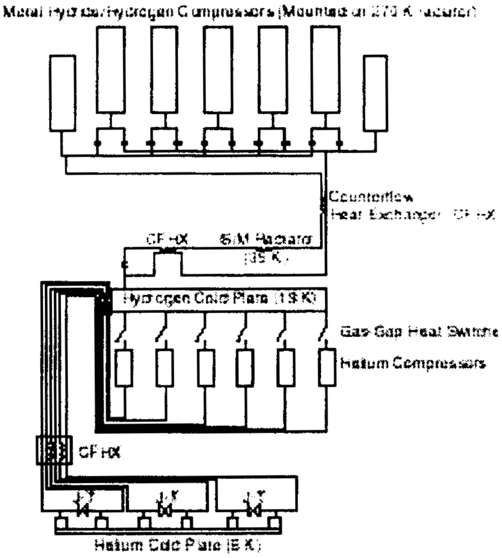

Figure A4. Schematic of the combined cooler system

6 K cooler

The 6 K cooler functions on a principle similar to that of the 18 K cooler, but uses carbon (charcoal) as the sorbent material and helium as the working fluid. Periodic charcoal-helium sorption coolers have been in common laboratory use for many years[19], and have been flown on sounding-rocket flights[20]. Mechanically driven 10 mW Joule-Thomson coolers have already been developed for flight applications[23], and are baselined as the 4 K cooler for ESA's Planck Surveyor mission. Charcoal-sorption coolers have the advantages of simplicity, easy scalability, and zero vibration because they have no moving parts. Low power, closed cycle operation of a Joule-Thomson cooler driven by charcoal compressors was demonstrated in the laboratory more than 10 years ago by Duband[21]. In such systems helium is physisorbed onto the charcoal, rather than chemisorbed, and the system is not susceptible to degradation of the sorbent materials due to cycling or overheating.

The basic design of the present cooler model uses charcoal compressor beds that cycle between 80 K for desorption of the helium and 18 K for adsorption. The compressor beds are paired such that each pair of compressors has its own Joule-Thomson constriction that can function for flow in either direction – the gas is driven back and forth between the two compressor beds by alternating which bed is hot and which is cold. Three pairs of beds, operating out of phase, are used to provide continuous cooling, with the three pairs sharing a common counterflow heat exchanger. For camera designs in which there are multiple focal planes that are spatially separated each focal plane can be provided with its own set of compressors. Because the mass and power requirements of the compressors scale nearly linearly with the heat lift, multiple smaller coolers (e.g. two 5 mW coolers) are only slightly more massive and require only slightly more power than a single 10 mW cooler. The main mass penalty is from multiple supporting structures. The main cause of power increase will be due to the parasitic heat loads on the multiple focal planes.

In the present design the helium is always maintained above its critical point (T_c=5.2 K, P_c=0.23 MPa for ^{4}He; T_c=3.32 K, P_c=0.117 MPa for ^{3}He), eliminating the need for reservoirs at the cold stage to capture liquid. The design can be readily modified to allow liquid production and capture. Heating and cooling of the beds is done with resistive heaters and gas-gap heat switches, respectively. Sorption driven gas-gap heat switches for the 4 to 10 K temperature range have been flown on sounding rocket flights[24]. Such heat switches work by alternately filling a narrow space between the compressor bed and the precooling stage with helium to provide thermal conduction between the stage and compressor and removing the gas to provide isolation. Separate small, low power (~mW) sorption pumps would be used to fill and evacuate the gas gaps. Figure A4 shows a schematic of the charcoal-helium system coupled to a hydrogen sorption cooler.

Because the system has no moving parts, the failure modes are very limited; the most likely failure is plugging of the Joule-Thomson constriction due to contamination of the helium. This can be avoided by careful processing and handling of the system components during manufacture. By keeping the gas from each pair of beds isolated from the others, the system offers built-in redundancy against failure of a single subsystem. If one pair of beds fails, the timing on the remaining pairs can be adjusted to still provide continuous cooling, at the expense of somewhat larger temperature swings at the cold head. Micromachined check-valves are in

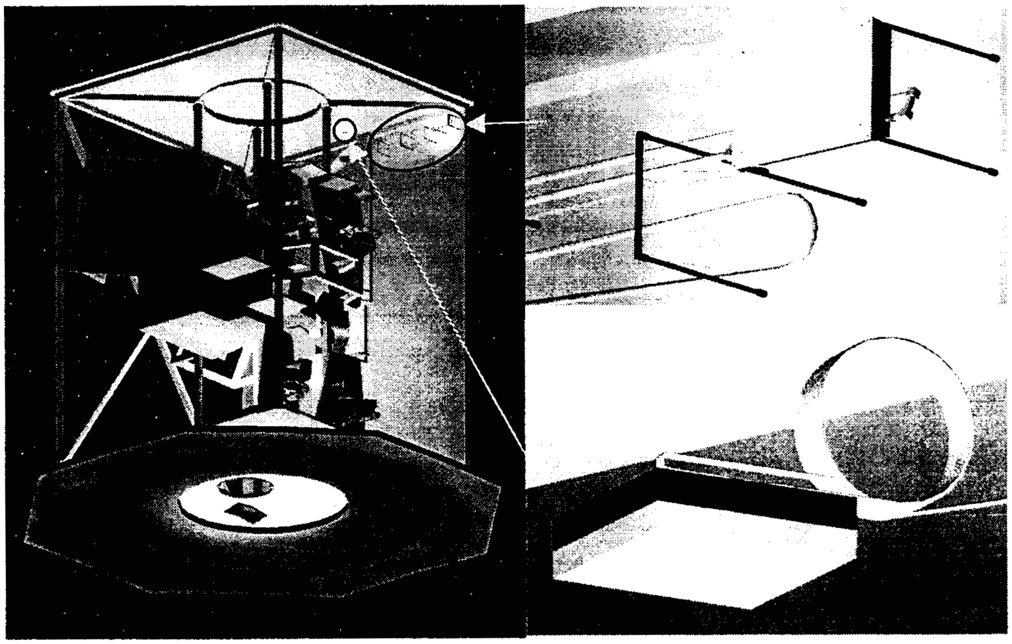

Figure A5. The lefthand figure shows how the charcoal compressor system might mount in the ISIM. The compressor is located in the upper right of the ISIM (inside the ellipse), and the focal plane is located slightly to the left of the compressor (circled). The figures on the right show details at the compressor (upper) and focal plane (lower). The tubes are gas supply and return lines. The yellow area at the focal plane indicates where the detectors would be mounted.

development at the University of Twente in the Netherlands[25], in cooperation with JPL, that would allow the complete system to operate with only a single Joule-Thomson valve. Check valves would reduce the complexity of the plumbing (making the system topology essentially the same as the hydrogen sorption system) at the possible expense of redundancy. If low-temperature check valves are used, the helium charcoal gas-flow circuit in Figure A4 would be replaced by a circuit much like that of the higher-temperature upper stage.

As shown in Table 2, a 10 mW charcoal helium cooler will require ~815 mW input power, which must be exhausted at the 18 K precooling stage, and would have a total mass of approximately 1 kg. Figure A3 shows preliminary designs of the hydrogen-sorption and helium-sorption compressors, and Figure A5 shows the same design as it might fit into the ISIM. The visible shells of the compressors beds in Figure A3 are the outsides of the gas-gap heat switches, and remain at approximately the temperature of the 18 K cold stage. The charcoal-containing compressor bed volumes are located inside of the gas-gap shells and are thermally isolated so that when a compressor bed is hot (~80 K) and desorbing there is less than 10 mW of heat leak to the 18 K stage.

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