Development and Orbital Operation of a Two-Stage Solid Cryogen Cooler

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The development and orbital operation of a two-stage solid cryogen cooler for use with a satellite-borne infrared radiometer is described. The primary coolant, methane, maintained the focusing optics and detector at 64 K, while the secondary coolant, ammonia, cooled portions of the collecting optics to 152 K and provided a thermal guard for the methane. A unique shrink-fit interface permitted a "drop-in"-type detector capsule module with no optical and electronic interfaces with the cryogenic system. The system was placed into orbit on the Nimbus 6 Spacecraft in June 1975 and provided the specified sensor cooling for six months with a temperature variation of approximately 1 K. A second cooler of essentially the same design is scheduled to be launched on Nimbus G in 1978.

Introduction

VARIOUS space-borne systems employ infrared or gamma-ray detectors. Cooling these sensors to cryogenic temperatures results in improved sensitivity, and cryogenic systems have recently been employed in long-term orbital operations lasting up to eight months.

One technique employed to cool these detectors is the sublimation of solid cryogens. This technique has been under development for approximately 10 years and has recently matured from the laboratory development stage to flight hardware status.

Initial orbital demonstration of this technique was made in 1972 when two single-stage solid carbon-dioxide coolers provided eight months of orbital cooling at 126 K for a gamma-ray detector system.[1] These coolers store their expendable coolant as a solid during orbital operation by maintenance of their vapor pressure below the triple point. They inherently provide exceptional temperature stability, due to the vapor pressure-temperature relationship of the subliming cryogen. Large changes in the vapor pressure over the solid corresponding to changes in the heat rate lead to small temperature variations. An increase in the heat rate to the primary cryogen of 50% for the cooler described here would change the detector temperature by only 0.6 K.

This paper describes the development of a two-stage solid cryogen cooler for use with a satellite-borne infrared radiometer which was flown aboard a Nimbus 6 weather satellite. The cooler was employed to cool a tri-metal detector array and the associated focusing optics and filters to 63-67 K and also provided cooling to other optical elements at 152 K. The radiometer measured the Earth's limb radiance to permit determination of the vertical distribution of temperature, ozone, and water vapor from the lower stratosphere to the lower mesosphere.[2]

The design of the cooler was based upon the following primary specifications: system weight—53lb max., length—27 in. max., diameter—14 in. max., detector operating temperature—63-67 K, lifetime goal—1 yr, orbital temperature stability—± 2 K, structural safety factor—1.5 at yield, outer shell temperature—300 K, detector capsule assembly heat loads—to be determined (20 mW initially estimated to primary), and maintenance of detector alignment as follows: axial ± 0.005 in., lateral ± 0.005 in., angular movement ± 1 min arc (0.3 mrad).

Presented as Paper 76-475 at the AIAA 11th Thermophysics Conference, San Diego, Calif., July 14-16, 1976; submitted May 9, 1977; revision received Nov. 1, 1977.

Index category: Thermal Control.

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Principle of Operation

The coolers store their expendable coolant as a solid during orbital operation by maintenance of their vapor pressure below the triple point so that sublimation occurs. Heat is removed from the system by the subliming solid whose vapor is vented directly to space.

These systems may be employed in one or more stages to minimize the system weight by employing a "guard" cryogen which operates at a higher temperature than the experiment requirement, but has a substantially higher heat of sublimation than the primary cryogen. Utilization of the cryogens in solid form rather than as a liquid has the advantage of simple coolant management in the low-*g* orbital environment and also provides higher density and more heat absorption.

A schematic of a dual-stage solid cooler is shown in Fig. 1. The primary cryogen maintains the desired detector temperature, while the higher-temperature secondary cryogen intercepts heat from the outer shell and provides cooling to the optical elements. The essential features of the system consist of an efficient thermal isolation system for the cryogens, a vent line to space, and thermal connections between the instrument and the solid cryogen. The most challenging and difficult part of the design is the thermal isolation system. Since the system weight is directly related to the total heat input from the experiment and cooler, a high premium is placed on efficient thermal isolation. As a result the structural supports must have a low thermal conductance, and this dictates minimum structural safety margins for supports. In many designs the supports are constructed of low-conductivity epoxy-reinforced fiberglas. The insulation around the containers consists of multilayer insulation (MLI) which may utilize as many as 200 aluminized mylar radiation shields separated from each other by an appropriate spacer material to prevent layer-to-layer thermal shorting. The vent lines which discharge the cryogens overboard are carefully designed to provide the desired vapor pressure for the cryogen, which in turn establishes the equilibrium temperature in a completely passive manner. The vent lines are opened after orbit has been achieved and the cryogen vapors are vented directly to space through this line. Figure 2 shows a typical phase curve and indicates that the operating pressure must be maintained below the triple point in order to prevent

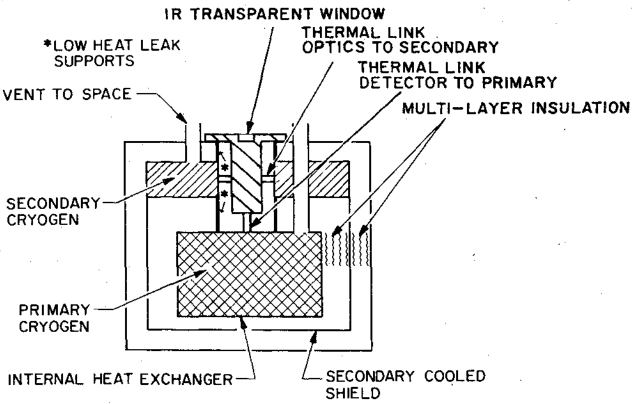

Fig. 1 Basic concept, dual-stage cooler.

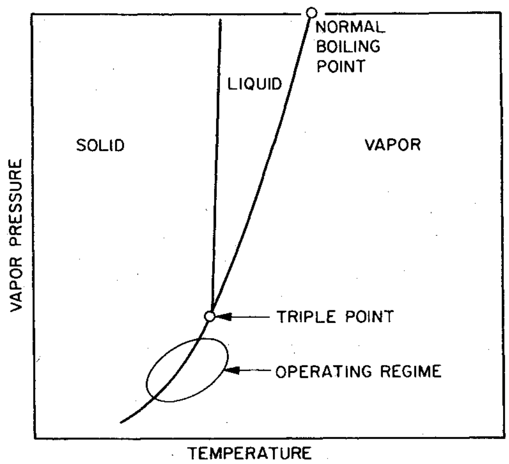

Fig. 2 Operating regime for maintenance of solid phase.

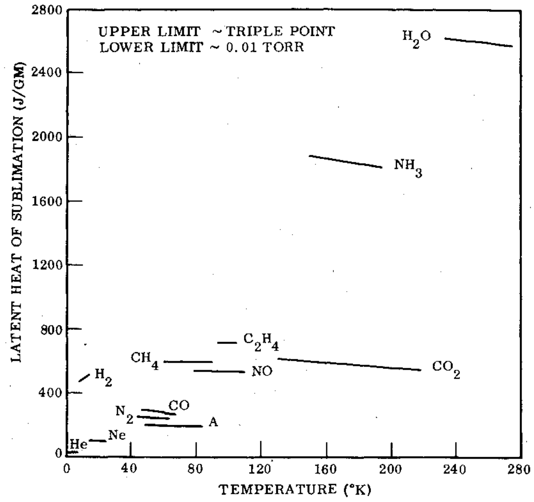

Fig. 3 Heat of sublimation vs operating temperature for solid cryogens.

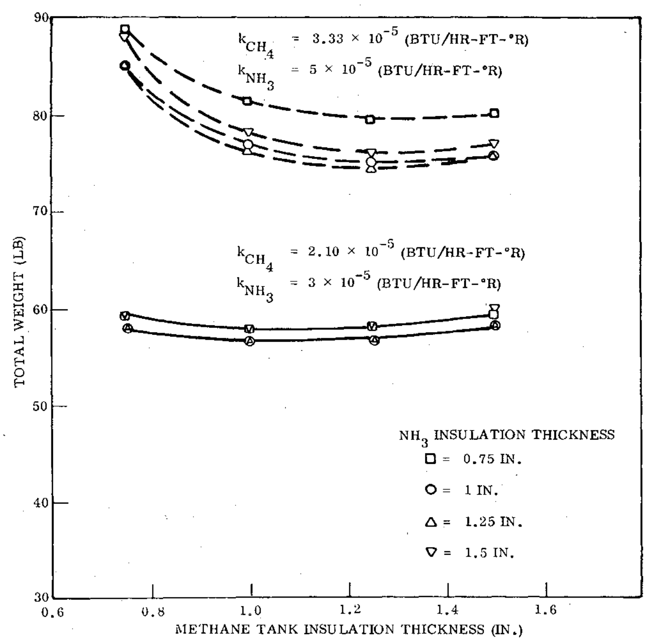

Fig. 4 Effect of insulation on cooler weight.

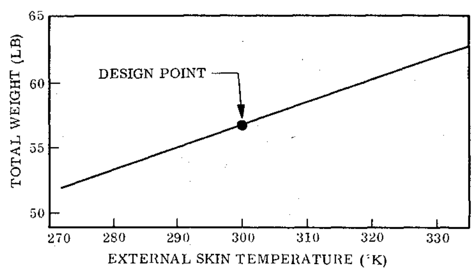

Fig. 5 Total weight vs external skin temperature.

formation of liquid and possible liquid loss in the low-*g* orbital environment.

The choice of cryogen is dictated primarily by the experiment temperature requirement. Figure 3 shows the heat of sublimation of various candidate cryogens and the corresponding temperature range over which they may be operated in the solid regime. The upper temperature limit is set by the liquefication point (triple point) and the lower limit by a vapor pressure of approximately 0.01 Torr, which has been found to be the approximate minimum practical pressure. Helium is also shown for comparison with the solids. As the figure shows, ammonia has a very high heat of sublimation and is often chosen for a secondary guard cryogen.

An open-cycle cryogen cooling loop for ground operation is necessary for two purposes. It is used to form the solid cryogen during fill operation, and for periodic cooling of the solid during vehicle integration and checkout in order to maintain the cryogens in a no-loss (nonvented) condition. Liquid nitrogen can be utilized as the coolant for many of the cryogens, while liquid helium is required for the lower-temperature cryogens such as neon and hydrogen.

Design Approach

For this cooler the design was based upon meeting the primary goals of a one-year life with a maximum weight of 53 lb and detector temperature of 63-67 K. Initial studies comparing the temperature ranges, latent heats of sublimation, and densities of various cryogens resulted in a two-stage design approach utilizing solid methane as the primary cryogen and solid ammonia as the secondary cryogen. The methane directly cooled the Detector Capsule Assembly (DCA) to a temperature of 65° ±2 K. The solid ammonia was used as a guard at 152 K to isolate the methane from the outside thermal environment of 300 K and to cool the DCA optics. The support system consisted of a single set of four concentric fiberglas tubes connected to form a single compact support structure connecting the cryogen tanks to the mounting plate. The interface between the cooler and DCA consisted of a "drop-in" design using a shrink-fit thermal connection which allowed independent development of the cooler and DCA. This approach also eliminated optical and electronic interfaces with the cooler.

In the preliminary design, tradeoff studies were performed to minimize the weight and volume of the cooler. Computer programs were developed to make the necessary tradeoffs and to determine the sensitivity of the parameters on the cooler size and lifetime. The effect on performance of support tube dimensions, insulation thickness and conductivity, ammonia temperature, external shell temperature, vent line sizing, and tank ullage percent were all investigated. Shown in Figs. 4 and 5 are some of the principal results of the studies. Figure 4 shows that the insulation thickness has a small effect on total system weight; however, the insulation conductivity appreciably affected the weight. Additional studies showed that the cooler size varied appreciably with insulation thickness. Figure 5 indicates an approximately linear variation in weight with external skin temperature.

In the detail design phase, a thermal analyzer program was used to obtain a detailed temperature distribution and heat map of the cooler. A number of computer runs were made to explore the sensitivity of the system to various design points and uncertainties in material properties. These studies included effects of boundary temperatures, various modes of vent gas cooling and insulation uncertainties. Extensive transient analyses were also conducted on the cooler. These transient studies were performed primarily in the interest of safety to determine the required reaction time in the event of a vacuum leak. These studies also provided the basis for necessary planning in the routine servicing requirement prior to launch. From these studies, the frequency of LN_2 recooling to maintain the methane and ammonia in a nonvented condition was determined.

Configuration

The final configuration of the cooler is shown in Fig. 6. The primary components are the detector capsule assembly, the concentric four fiberglas tube support structure, the tanks containing solid methane (the primary coolant) and solid ammonia (the secondary coolant), a cooled shield grounded to the ammonia, insulation around the tanks and fiberglas tubes of multilayer insulation (MLI) and Dexiglas, various Teflon tubing plumbing lines, and the vacuum shell. Fiberglas tube 1 connected the main support flange to tube 2 which was connected to the ammonia tank. Fiberglas tube 3 connected the ammonia tank to tube 4, which was connected to the methane tank. An aluminum tube thermally grounded to the ammonia tank was used to decrease the heat transfer between

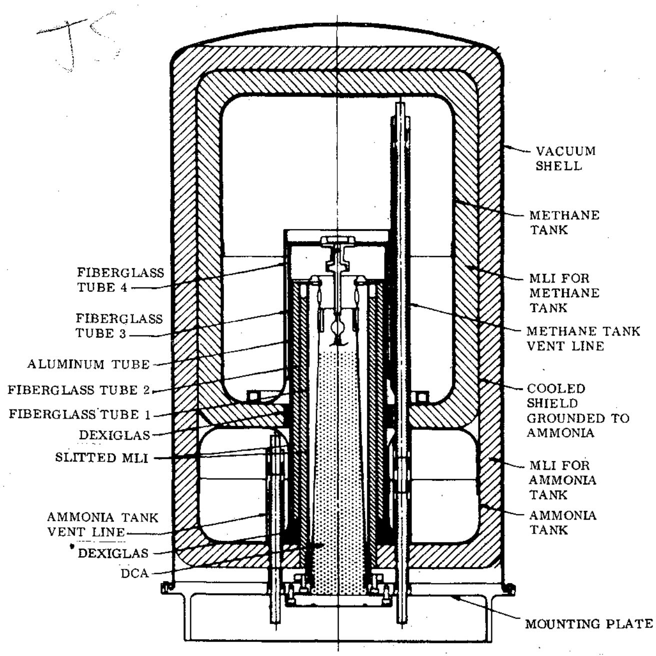

Fig. 6 Physical configuration of Nimbus F solid cryogen cooler.

tubes 2 and 3 and transfer heat from the DCA optics. Slitted MLI was used between tubes to minimize radiation coupling between them. MLI also insulated the methane tank from the ammonia tank and its grounded shield and insulated the ammonia tank and shield from the vacuum shell. The final design had a total loaded weight of 53 lb which included 14 lb of solid methane and 11.8 lb of solid ammonia. The diameter was 14 in. and the length was 25¾ in. The various components are described in the following.

Experiment Interface

The DCA was a source of heat to both the methane and ammonia through the attachment points. It also resulted in thermal coupling with the cooler through contoured MLI between fiberglas tube 1 and the DCA fiberglas support. The DCA interfaced with the cooler through two shrink-fit connections. The first shrink-fit assembly connected the detector focal plane to the methane tank while the second connected the DCA thermal guard and optics to a thermal path to the ammonia tank. These assemblies allowed the DCA to be removed at room temperature, while at operational temperatures the differential contraction of the shrink-fit members provided good thermal contact and structural integrity.

Insulation

The multilayer insulation (MLI) consisted of double aluminized Mylar and Tisuglas spacers at a layer density of 110 layers/in. The concept definition studies (Fig. 4) showed that a 1-in. MLI thickness was optimum for both cryogens' MLIs and that the optimum thicknesses were largely independent of the other parameters.

Support Structure

The support tubes were made of 1543/E787 fiberglas. The tubes' thicknesses were sized for their structural requirements for the longest feasible length to minimize the heat loads. The MLI placed between tubes was slitted to reduce parallel MLI heat transfer.

Cryogen Containers

The tanks were made of 6061 aluminum. An internal heat exchanger was used in the methane tank to promote cooling during fills and to maintain isothermal conditions during orbital operation.

Internal Plumbing

Vent lines were required to vent the sublimation gases to the surroundings. These internal plumbing lines were a source of heat leak to the cryogens and were constructed of convoluted Teflon, which minimized heat leak and retained a high degree of flexibility at cryogenic temperatures.

The sensible heat of the vent gas was utilized to remove heat from the ammonia tank. Effective vapor cooling of both vent lines also occurred. A limited amount of vapor cooling of the MLI occurred; however, the effectiveness of this was not determined. Liquid nitrogen cooling lines were also required for the fill processes and for maintaining the cryogens in a no-loss condition prior to the launch.

Vacuum Shell

The vacuum shell consisted of a 6061 aluminum cylinder with a spun elliptical dome bonded to the cylinder and a flange which contained an O-ring and provided the main vacuum seal.

Mounting Plate

The mounting plate was a 6061 aluminum web stiffened structure to which the exterior plumbing, vacuum shell, and cooler were attached.

Assembly

The assembly of the system was based on a modular approach in which the following major sub-assemblies were fed into the assembly flow: fiberglas support tube bundle, methane tank, ammonia tank, vacuum shell, and external and internal plumbing lines. The internal components were assembled into the tank half-shells, and the final tank assembly was achieved by epoxy bonding techniques.

The assembly sequence starts with the innermost component and builds out toward the outer vacuum shell. The initial step consisted of bonding the fiberglas support tube module to the methane tank. After instrumentation and plumbing were installed, the insulation was applied to the methane tank.

After the insulation wrap was completed, the ammonia tank was bonded in place to the support tube bundle, and the ammonia guard shield which surrounds the methane insulation was bonded in place. The ammonia insulation was then applied to complete the assembly of the thermal section of the cooler.

Final assembly consisted of bolting the support tube flange to the mounting plate which served the functions of optical bench for the radiometer, vacuum interface for the cooler vacuum shell, and interface and support for the external plumbing lines. Completion of the experiment assembly consisted of mounting the "drop-in" DCA assembly and the optical mechanical package to the mounting plate.

Thermal Performance Predictions

A detailed thermal model containing approximately 240 nodes was made of the final design, and the temperature and heat flow at each node was determined. This model was utilized for final tradeoff studies, including the transient cases.

The predicted heat load, after a number of tradeoff studies, is given in Table 1. After the cooler had been built, additional thermal conductivity properties on the fiberglas and MLI became available.[3,4] The predicted heat loads with the new data are shown in Table 2.

Table 1 Heat load summary (preflight)

Source	Heat load, mW Ammonia Gross[a]	Methane Net
MLI	190	25
Fiberglas supports	24	18
Radiation	44	13
Vent gas	−29	...
Dexiglas intermediary	9	...
Slitted MLI	13	13
LN_2 and vent lines	16	4
Total	267	73

[a]The calculated net balance on the ammonia, which includes heat losses to the methane, is 194 mW.

Table 2 Heat load summary, using new property data

Source	Heat load, mW Ammonia Gross[a]	Methane Net
MLI	214	29
Fiberglas supports	44	31
Radiation	43	13
Vent gas	−27	...
Dexiglas intermediary	12	...
Slitted MLI	13	12
LN_2 and vent lines	16	4
Total	315	89

[a]Net heat load: 226 mW.

Ground Support Equipment

Ground Support Equipment (GSE) in the form of a vacuum and cryogen servicing cart and a shipping container were developed for the program. The equipment was designed for optimum personnel and systems safety and included provisions for fail-safe response to power failure. The servicing and vacuum equipment was enclosed in four panel racks whose combined size was 7-ft long, 4-ft high with a weight of approximately 1000 lb. Three of these units were constructed, and a unit was provided to each facility where servicing and/or testing occurred.

The shipping container was designed and fabricated to permit shipping the cooler with or without solid cryogens in accordance with the Department of Transportation requirements from facility to facility as required. This rather large shipping unit (2000 lb) was tested to ASME Unfired Pressure Vessel Specifications and certified to 350 psig working pressure, exceeding a "worst case" situation in which all cryogens were released to the interior of the container and allowed to come to equilibrium at an environmental temperature of 328 K (130°F). This shipping container could be evacuated to provide an additional measure of protection should the cooler vacuum shell integrity be impaired. A three-axis shock recorder was attached in order to determine if improper shipping conditions had occurred.

The GSE was designed so that, in the event of a power failure, a solenoid would automatically close the vacuum pump valve and isolate the cryogens from possible contamination from the oils in the mechanical pump. The diffusion pump valve would also close during a power failure, isolating the vacuum space from the environment.

The GSE was used for cryogen servicing during filling and venting and measurement of the flow rates during these operations. The methane and ammonia systems were separate modules of the same design. During filling, the methane and ammonia were supplied in a gaseous form at room temperature from a high-pressure storage cylinder and flowed through a pressure reduction valve then through a wet test meter to a throttling valve and then into the cooler plumbing and the cryogen storage tank. After completion of fill, pumping on the cryogens to bring their temperatures to operating conditions was accomplished by a mechancial vacuum pump. The exhaust of the vacuum pump passed through the wet test meter for measurement of the sublimation rates of the cryogens and the resulting lifetime.

The GSE provided satisfactory simulation of orbital conditions. The through-put of the GSE mechanical pump caused a significant pump inlet pressure (because of the relatively low pump speed) and this combined with the added pressure differential in the pumping line in the GSE caused the cryogen's temperature during ground testing to be slightly warmer than in orbit. The increase in methane temperature when using the GSE was only 0.5 K above the orbit temperature, while ammonia temperature on the ground was about 3 K above the orbit temperature.

It is significant to note that no accidental venting of methane or ammonia occurred during the program, attesting to the safe operation with the GSE. The same GSE is presently in use on a follow-on program for a similar cooler for Nimbus G.

Development and Test Program

Development Sequence

The evolution of the cooler is shown in the flow chart of Fig. 7. The program schedule did not permit series evolution of the various models. The engineering model was fabricated

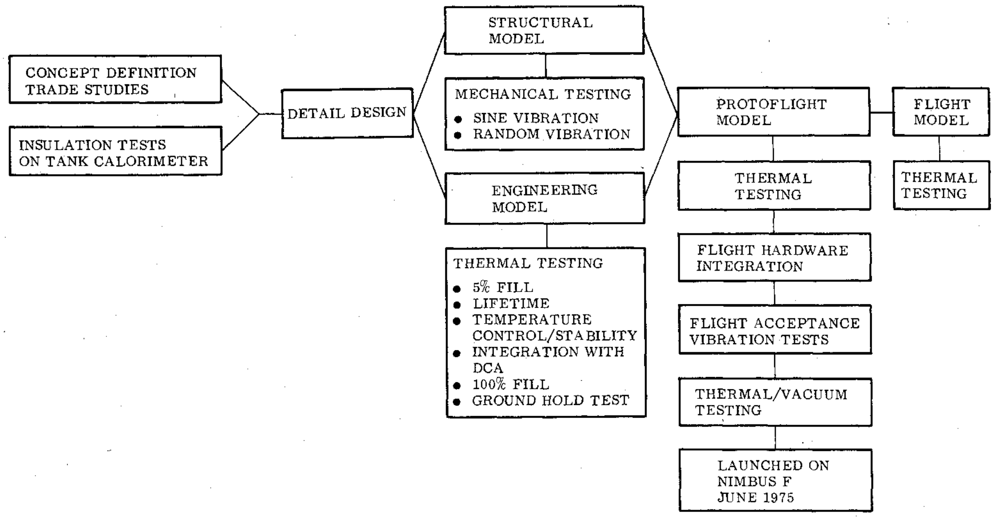

Fig. 7 Development sequence.

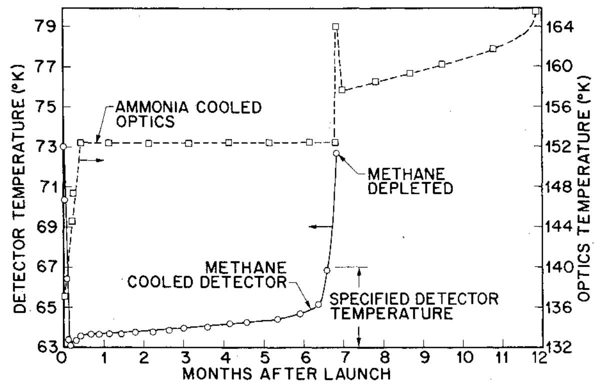

Fig. 8 Orbital temperature data.

before testing was performed on the structural model and the flight and protoflight models were built before vibration tests on a thermal model of any of the coolers could be performed. The "success oriented" approach led to a relatively high-risk program.

Since the thermal performance of the cooler was so intimately related to the thermal effectiveness of the insulation system, insulation tests on a tank calorimeter were performed early in the program and the experimental values were used in the final design. A structural/vibration model was built initially to determine the structural capability of the fiberglas support bundle. In this model the cryogen mass was simulated with foam of appropriate density.

The engineering model was fabricated and utilized for thermal testing and integration tests with DCA. The protoflight unit underwent flight acceptance test levels, thermal testing, and thermal/vacuum testing in the spacecraft configuration. This unit was launched into orbit in June 1975.

Thermal testing of the flight model revealed a chronic tendency of the methane vent line to partially plug with condensible gases, which prevented the unit from providing the specified temperature. This partial plugging was believed to be due to a fabrication defect in which the fill/vent line was thermally shorted to the liquid nitrogen heat exchanger during filling. Activity on this unit was terminated, and the protoflight model was selected for flight.

Insulation Testing

Although MLI thermal performance data are available from guarded flat-plate calorimeters, data on tank wraps for the size and boundary conditions for this design were not available. In order to determine the thermal performance of the selected insulation system as wrapped on the solid cooler tanks, a tank calorimeter of approximately the size and shape of the cooler tanks was fabricated and utilized for insulation testing.[4] For a 1-in. wrap consisting of 110 layers of double aluminized mylar with alternate Tisuglas spacers for a hot boundary temperature of 300 K and a cold temperature of 150 K (the ammonia tank boundaries) the effective conductivity was 3.1×10^{-5} Btu/h-ft-°R).

Testing was not performed at that time at the boundary temperatures of the methane tank ($T_h = 152$K, $T = 62$ K) so it was necessary to extrapolate the test results to the appropriate boundary temperatures for the methane tank. The value selected for the final design was 1.4×10^{-5} Btu/h-ft-°R. Later testing on the tank calorimeter with modifications to provide a hot boundary temperature near 152 K was conducted and a conductivity of 1.2×10^{-5} Btu/h-ft-°R was measured.

Vibration Testing

Both random and sinusoidal vibration testing was conducted on the structural and protoflight models. Initial vibration testing of the structural model at qualification levels resulted in joint separation between two of the fiberglas tubes, and this joint was modified prior to final vibration tests. A summary of the vibration test conditions for the two models tested is presented in Table 3. The primary resonance of the system was found to be 18 Hz in the lateral axis and 153 Hz in the axial axis.

Thermal Testing

The objectives of the thermal testing were to obtain the following characteristics: 1) heat rates of ammonia and methane and resultant system lifetime, 2) temperature stability and level of the cryogens and the DCA, and 3) the temperature-time characteristic of the system under ground hold conditions. The thermal testing was performed with the external surfaces of the cooler at atmospheric pressure and room temperature. The ground support equipment was utilized to provide a hard vacuum for the insulation space in the range of 10^{-6} to 10^{-7} Torr and to pump on the ammonia and methane vent lines. The temperatures of the cryogens were from 0.5 K to 3 K higher than orbital conditions due to the higher pressures above the cryogen as mentioned previously.

Table 4 compares the test results and predicted values for the coolers during ground test. The predicted heat rates are from the thermal model discussed earlier utilizing the most recent conductivities for fiberglas and MLI. The predicted temperatures are from the pressure drop analysis program (PRES).

Table 3 Vibration testing

	Random		Sine	
	Frequency, Hz	Spectral density, g^2/Hz	Frequency, Hz	Acceleration, g
Structural model (qualification level)				
Lateral axes	20-100	0.02-0.0575	5-15	6
	100-2000	0.0575	15-16	6
			16-21	3
			21-36	6
			36-50	4.5
			50-200	6
			200-2000	5
Axial axis	20-2000	0.0575	5-18	8
			18-23	8
			23-60	6
			60-150	10
			150-2000	5
Protoflight model (acceptance level)				
Lateral axes	20-40	0.01-0.03	5-16	3
	40-1000	0.03	16-21	1
	1000-2000	0.03-0.01	21-36	3
			36-44	1
			44-200	3
Axial axis	20-1000	0.03	5-25	5
			25-34	4
			34-44	2
			44-120	4
			120-160	1
			160-200	4

Table 4 Thermal data

Heat Rates, mW		EM	PM	FM
Methane	Measured	128	138	148
	Predicted	89	89	89
Ammonia	Measured	175	195	230
	Predicted	226	226	226
Temperatures, K				
Methane	Measured	63.1	62.8	67 [a]
	Predicted	62.9	63	63.1
Ammonia	Measured	151.9	151.3	150.5
	Predicted	150.8	151	152

[a] Vent line partially plugged.

Very good agreement between predictions and measurements for all parameters with the exception of the methane heat rate was demonstrated. The reasons for the substantial difference between measured and predicted methane heat rates have not been determined.

The performance of the EM cooler when the DCA was integrated is summarized in Table 5. These data show a synergistic effect when combining the experiment (DCA) and the cooler. Thermal coupling between the DCA and the support tubes is partially responsible for the effect. This effect was typical for all of the cooler models.

Tests were also performed to determine the ground hold time. These tests were conducted by filling the cooler to the maximum fill condition, then subcooling both cryogens to 80 K by circulation of liquid nitrogen through the cooling coils. When 80 K was achieved, the evacuated insulation space was valved off along with the cryogen vents, and the temperature history of the cryogens was recorded.

The requirements for shipping a filled cooler under a Department of Transportation license and for safe operations were to limit the methane to 85 K and the ammonia to 168 K. These temperatures provided a safe margin below the melting points of 196 K and 90 K for ammonia and methane, respectively, corresponding to vapor pressures in the tanks of 38 Torr and 1.5 Torr for methane and ammonia, respectively.

Table 5 DCA integration tests (EM)

	Methane		Ammonia	
	Temp	Heat rate	Temp	Heat rate
Cooler only	63.1	128	151.9	175
DCA only	...	43	...	91
Cooler/DCA combined	63.5	186	152.5	239

Table 6 Comparison of ground and orbital data

	Prediction from ground test data	Orbital data
Temp, K		
Detectors	64	63.5 - 64.5[a]
Optics	154.5	152.4[b]
Lifetime, months		
Methane	6.8	7
Ammonia	11.9	12

[a] Neglecting initial transient, and "end of life" transient
[b] Before methane depletion.

The ground hold test for the EM indicated a hold time of 11 days for the methane and a temperature rise to 143 K for the ammonia at 11 days. This 11-day hold time set the servicing interval for the system, and for normal conditions the cryogens were recooled to 80 K and the insulation vacuum was "rehardened" with a LN_2 trapped diffusion pump at this interval. Servicing in this manner maintained the cryogens in a no-loss condition for an indefinite period. This duration also set the allowable transportation time for the cooler in its shipping container.

Orbital Operation

The cooler was launched aboard the Nimbus 6 vehicle on June 12, 1975, into a nominal 685-mile Sun-synchronous orbit. The methane was vacuum-pumped prior to launch in order to cool it below the 77 K obtained by LN_2 circulation, and thereby to extend the ground hold time. At the time of launch the methane and ammonia were at 73 K and 137 K, respectively. On the fourth orbit the explosive valve which vents the methane to space was fired, and the initial high methane flow rate temporarily upset the spacecraft in the roll axis. Spacecraft control was re-established after a short period of time. Subsequent investigations indicated that the exhaust plume from the methane vent line was impinging on the spacecraft, resulting in higher impulses than expected during the initial "blow-down" period.[5] Relatively high flow rates existed during the early stages of operation because of the high vapor pressure resulting from the 73 K temperature at the time of valve deployment. Analysis of this event indicated that a simple modification of the external vent line geometry will eliminate this problem.[5]

The insulation vacuum space and ammonia valves were fired on the 19th and 31st orbit without incident. At the time of firing of the ammonia vent valve the ammonia temperature was 139 K so that negligible vapor pressure and flow rates existed at that time.

The temperature history of the infrared detectors and the optics obtained from platinum resistance thermometers is presented in Fig. 8. Ground test data indicated that the methane temperature was 1.5K lower than the detectors, and the ammonia was 3.5 K lower than the optics temperature. The detectors remained within the specified temperature for over six months. The temperature increase near the end of life is believed to be due to the increasing temperature gradient between the small remaining volume of solid cryogen and the container walls. The predicted rate of temperature rise of the empty methane tank occurred after approximately seven months when it is believed the methane was completely spent.

The ammonia lifetime exceeds the methane by a large value as shown in Fig. 8. The ammonia temperature was constant within the data resolution, at which time the ammonia established a new equilibrium temperature due to the absence of heat losses to the methane. After 12 months the ammonia was expended.

The comparisons between prelaunch life and temperature predictions and those which occurred in orbit is presented in Table 6 and are based on launch methane weight of 12.7 lb and a ground measured heat rate of 196 mW, which included the load from the DCA (43 mW) for the methane stage. The launched ammonia weight was 11.8 lb, and the ground measured heat rate was 259 mW, inclusive of DCA.

The agreement is very good and does not show any unexpected orbital effects. No detailed prediction of the orbital temperature variation as a result of cryogen depletion was made; however, the internal heat exchanger limited the detector temperature variation to about 1 K except for the end of life warmup.

Conclusions

Orbital operation has been demonstrated for the first time on a two-stage solid cryogen cooler. The cooler demonstrated excellent temperature stability, was very reliable, and had no operating problems during its orbital lifetime. An infrared detector was continuously maintained within the specified operating temperature for six months while the secondary stage provided 12 months of cooling for the optics. A second cooler of essentially the same design is scheduled to be launched aboard Nimbus G in 1978 for infrared detector cooling.

Acknowledgments

The cooler described in this paper was developed under a subcontract with Honeywell Radiation Center, Lexington, Mass., as part of the Nimbus F Limb Radiance Inversion Radiometer (LRIR) developed for NASA Goddard Space Flight Center. The collaborative efforts of the members of the Honeywell Radiation Center and L. Wilson, NASA Goddard Space Flight Center technical officer, in discussions of system operation are much appreciated. Also, the authors wish to acknowledge the efforts of G. Bell for interface design and coordination and special testing, G. Grozenski during assembly and testing, and other members of the Lockheed team for their dedicated efforts.

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