Development of a High-Performance Cryogenic Radiator with V-Groove Radiation Shields

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A feasibility demonstration model of a new-technology, high-performance, cryogenic radiative cooler has been successfully tested in a helium-cooled vacuum chamber. Thermal isolation of the radiator cold stage from the warm spacecraft and instrument is achieved by a novel arrangement of lightweight radiation shields which form large V-groove cavities, and by the use of low-conductance structural supports. The vacuum chamber experiments demonstrate the thermal isolation capability of the radiator design. Analytical model predictions are all within 1 K of the measured test temperatures. Utilization of this design enables reasonably sized radiative coolers (≤ 0.3 m^2) to achieve operating temperatures below 60 K at Earth, Mars, and beyond for useful cooling loads below 75 mW. The design can be scaled to accommodate larger heat loads. The reduction in operating temperature of over 15 K relative to any radiative cooler flown in the past will allow the V-groove Isolation Radiator to meet the challenging instrument cooling requirements of many future space missions.

Nomenclature

A_R = surface area of cold stage radiator plate
C = thermal capacitance of radiator plate (product of mass times specific heat)
T_R = steady-state radiator plate temperature
T_R' = radiator temperature at end of test run
T_E = effective environment temperature
T_W = wall temperature of helium-cooled shroud
$\dot{Q}_{IN}$ = sum of all heat inputs to radiator plate
dT_R/dt = rate of change of radiator plate temperature
ϵ_R = radiator plate infrared emissivity
ϵ_S = sunshade infrared emissivity
$F_{R\text{-}E}$ = radiation interchange factor between the radiator plate and chamber environment
σ = Stefan-Boltzmann constant = 5.6693×10^{-8} W/m^2-K^4

Introduction

PASSIVE radiators have been widely used to cool spaceborne instruments which require cryogenic temperatures in the 80–120 K range in order to obtain acceptable detector sensitivities.[1] Many future space missions will require detector temperatures below 80 K and plan to carry several cryogenically cooled instruments aboard a common spacecraft. For example, the planned NASA Mars Observer mission and several Mariner Mark II missions may each include as many as three instruments requiring sensor temperatures between 70 and 100 K. These instruments will need separate large radiative coolers which will compete for an unobstructed clear field of view of space. These requirements are challenging the capabilities of conventional radiative cooler designs.

A new design concept was recently described for a V-groove isolation radiator (VGIR)[2,3] which offers significant performance improvements over conventional designs and enables the achievement of many of the ambitious cooling requirements of planned future space missions. In this design, the parasitic radiative heat leaks to the cold stage are greatly reduced by an arrangement of lightweight, low-emissivity, highly specular and reflective radiation shields. Large V-groove cavities are created by arranging adjacent shields with an included angle of 1.5 deg expanding outward from the cold stage. The shields intercept radiation from the warm spacecraft/instrument and by multiple reflections direct the energy out the openings to space. Parasitic conductive heat leaks are reduced by the use of low-conductance structural supports. This thermal isolation of the cold stage from the radiator mounting interface eliminates what is often a major heat load in conventional radiative coolers,[4] thus increasing the useful cooling capacity and allowing colder operating temperatures. The VGIR concept enables the design of smaller radiators, thereby easing the task of integrating several coolers on one spacecraft.

The original concept described in Ref. 2 included a separate structural support system that detaches after launch in order to reduce the conductive heat leaks. However, the V-groove radiation shields combined with the use of low-conductance fiberglass structural supports offer major performance improvements by themselves and the increased complexity, mass, and cost of a detachable launch support system is not justified at this time.

A VGIR thermal feasibility model was built for specific application to an earth-orbiting flight instrument and successfully tested in a liquid-nitrogen (LN_2)-cooled vacuum chamber in 1981.[2] Since the LN_2-cooled vacuum chamber is not very representative of space for these low temperatures, flight temperature predictions had to be extrapolated from the test results with the use of an analytical model, as described in Ref. 2. The engineering thermal feasibility model has now been modified for a Mars orbit configuration and experiments were performed recently in a helium-cooled vacuum chamber. These experiments and the current status of the VGIR development are the subject of this paper. The experiments demonstrate the thermal isolation capability of the V-groove radiation shields and clearly indicate the superior performance of the VGIR design compared to existing radiators.

Although the thermal feasibility model has been designed for a Mars orbit configuration, the VGIR design offers the same performance advantages for Earth-orbiting and other outer planet applications.

Experiment

The VGIR feasibility model is shown in Fig. 1. Figure 2 shows an exploded view of the VGIR which should aid in understanding the design.

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The sunshade was designed for the near-polar, 361-km altitude, 2:00 p.m. sun-synchronous Mars orbit planned for the Mars Observer mission. The beta angle, which is defined as the angle from the sun vector to the plane of the sun-synchronous orbit, is ≥ 14 deg throughout the proposed 2-year mission. The sunshade geometry and cooler orientation protect the cold stage from direct solar emission at all times. The cold-stage radiator plate is located in the same plane as emission from the planet limb and thus cannot be irradiated by direct planet emission. The shade curvature and orientation are designed so that planet emission and planetary reflected solar energy are reflected to space off the highly specular inside shade surface, except for a small portion which is diffusely reflected onto the cold stage.

The aluminum sunshade was supported and thermally isolated from the housing with eight fiberglass/epoxy tubes. The side of the shade facing the cold-stage radiator plate was mechanically polished and coated with a thin layer (about 0.1 μm) of vacuum-deposited aluminum in order to obtain a very low emissivity. Kapton film heaters, which can be thermostatically controlled to simulate various Mars orbit temperatures, were bonded to the outside of the shade.

The $58.4 \times 30.5 \times 0.127$ cm ($23 \times 12 \times 0.50$ in.) cold-stage radiator plate was coated with about a 400-μm-thick (0.02 in.) Chemglaze Z-306 high-emissivity ($0.85 \leq \epsilon_R \leq 0.9$) black paint. Kapton film heaters were bonded to the back of the plate and covered with an aluminized Mylar sheet. The heater input power could be varied to simulate various instrument heat loads and was accurately determined to within ± 1 mW by measuring the current and voltage drop.

The outer support housing was made of 0.3175-cm-thick (0.125 in.) aluminum plates and was covered with multilayer insulation in order to maintain a uniform temperature. The housing simulated the instrument interface and was thermostatically controlled at 294 ± 3 K with 34 distributed resistance heaters.

The four V-groove shields were constructed of 0.0127-cm-thick (0.005 in.) Mylar, vapor-deposited with a thin layer (about 0.1 μm) of aluminum on each side. The shields and cold-stage radiator plate were supported from the housing with 0.028-cm-diam (0.011 in.), 8–10 lb test, nylon monofilament tendons bonded at the corners. The tendons were spring-loaded at the four housing extensions in order to maintain the correct tension and to accommodate thermally induced dimensional changes.

A room-temperature normal infrared emissivity value below 0.02 was measured for both the sunshade and the V-groove shields with a Gier-Dunkle reflectometer. The total hemispherical emissivity of these vacuum-deposited aluminum surfaces is expected to be below 0.02 for temperatures below 180 K.[5] A value of 0.02 for the total hemispherical emissivity and 0.2 for the solar absorptivity are assumed in the thermal analysis for these surfaces.

Contamination of these surfaces during the two-year Mars Observer mission will be minimized by the use of a controllable door during orbit correction maneuvers. There is no direct solar irradiance of these surfaces, so the effect of ultraviolet degradation is minimized. A flight cooler will contain vacuum-deposited gold shields, which will have an even lower emissivity than vacuum-deposited aluminum,[4] and a small degree of contamination may be tolerated. As a final measure, a flight cooler will also include decontamination heaters.

Figure 2 shows the location of the 20 40-gauge (0.0076-cm-diam, 0.003 in.) ANSI Type E (chromel-constanten) thermocouples on the VGIR. An additional silicon diode temperature sensor (cryodiode) was located at the center of the radiator plate to provide accurate cryogenic temperature measurements to within ± 0.1 K.

A 3×3-m LN_2-cooled vacuum chamber containing a helium-cooled shroud was the test chamber used for this equipment. The vacuum pressure in the chamber was maintained below 7.4×10^{-8} Torr and the helium shroud wall temperature was maintained between 13 and 17 K throughout the experiment. The effective environment temperature was measured to within about ± 3 K with a silicon diode temperature sensor mounted on a small, $7.6 \times 7.6 \times 0.051$ cm ($3 \times 3 \times 0.02$ in.), black aluminum square suspended, but conductively isolated, from the helium shroud. The black square's field of view was similar to that of the cold stage radiator plate.

Thermal Analysis

A simple steady-state energy balance on the cold stage gives

$$F_{R-E} A_R \sigma (T_R^4 - T_E^4) = \dot{Q}_{IN} \tag{1}$$

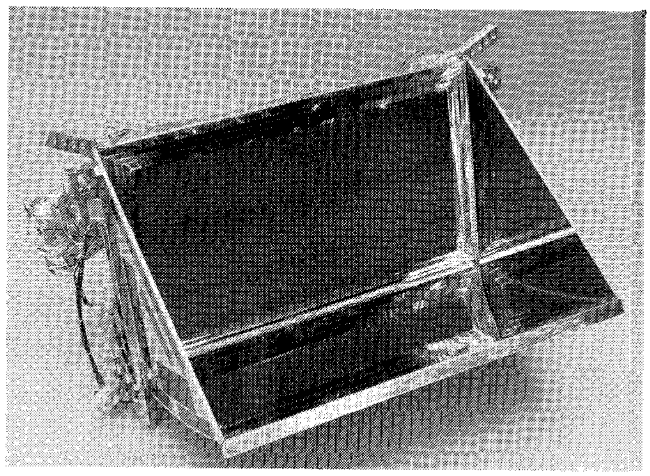

Fig. 1 V-groove isolation radiator (VGIR) feasibility demonstration model. The cold-stage radiator plate dimensions are $58.4 \times 30.5 \times 0.127$ cm ($23 \times 12 \times 0.05$ in.).

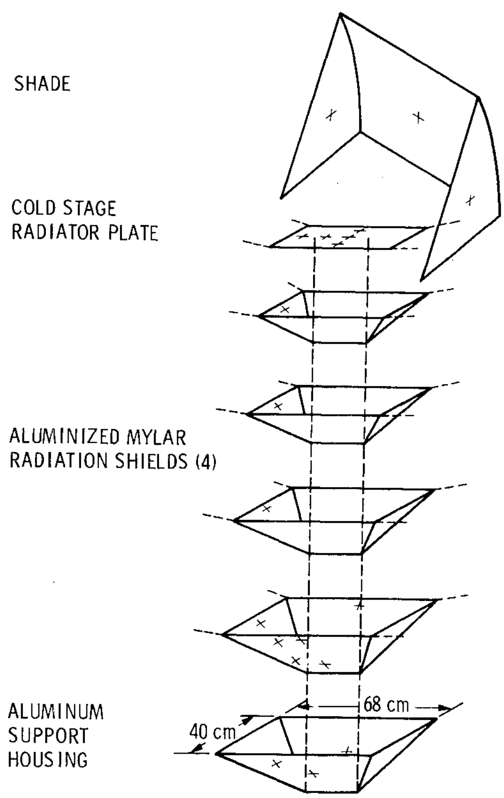

Fig. 2 Exploded view of VGIR feasibility demonstration model including thermocouple locations (+) and tension supports (---).

The total energy absorbed by the cold stage, $\dot{Q}_{IN}$, represents all the radiative and conductive heat loads from the shade and support housing, the planet emission, and planet reflected solar energy which is diffusely reflected onto the cold stage, as well as the useful detector cooling load. The useful detector cooling load consists of detector Joule heating, conductive and radiative heat leaks to the detector from its mounting interface through structural supports and electrical leads, and any energy transmission through an optical aperture.

The detailed thermal analysis is described in Ref. 2 and will not be repeated here. A Monte Carlo technique was used to determine radiation configuration factors between the cold stage and the specular low-emissivity sunshade, and between the V-groove shield. An orbital heating analysis was used to calculate the orbital average solar, reflected solar, and planetary infrared energy incident on the sunshade at Mars. The shade temperature was varied between 140 and 180 K during the test in order to simulate the expected orbital temperature range. The thermal emission from the shade which is absorbed by the cold-stage radiator plate ranges from 25 to 70 mW for this shade temperature range. The orbital average energy incident on the sunshade and diffusely reflected onto the radiator plate was computed to be 3 mW. This is based on a shade specularity of 98%. As described in the next section, predicted temperatures agreed well with experimental values.

Results and Discussion

Twelve test conditions, consisting of various power inputs and shade temperatures, were run. The initial cool-down to the test 1 condition required about 40 h, although it took only 20 h to cool the cold stage to below 70 K. The complete experiment lasted about 7.5 days. Each test was concluded when the radiator plate temperature changed less than 0.075 K/h.

Steady-state temperatures were projected from the end-of-test data as follows. During the cold-stage cool-down, an energy balance gives

$$C\mathrm{d}T_R'/\mathrm{d}t = \dot{Q}_{IN}' - F_{R-E}A_R\sigma[(T_R')^4 - T_E^4] \tag{2}$$

where T_R' and $\dot{Q}_I'$ represent the end-of-test values for these variables. At steady state, $\mathrm{d}T_R'/\mathrm{d}t = 0$ and Eq. (2) reduces to Eq. (1). If the end-of-test data are sufficiently close to steady state, then $Q_{IN}' = \dot{Q}_{IN}$ and Eqs. (1) and (2) combine to give the projected steady-state temperature as

$$T_R = [(T_R')^4 + (C/F_{R\text{-}E}A_R\sigma)\mathrm{d}T_R'/\mathrm{d}T]^{1/4} \tag{3}$$

The end-of-test data are given in Table 1 along with the projected steady-state temperatures and the analytical model predictions. The projected steady-state test temperatures are also compared to the analytical model predictions in Fig. 3. The experimental temperatures are within 1 K of the analytical predictions.

Table 2 shows a cold-stage energy balance for a typical test condition (test 4). Note that the warm chamber environment relative to space contributes 14% of the total heat load. In space, the cold stage is oriented so that it will view only cold space and the 35.9 - mW chamber environmental load would be reduced to a negligible value, thereby allowing the radiator temperature to become about 2.4 K colder than it did in the test chamber. The "sunshade conduction" term represents heat transferred through the cold-stage thermocouple, cryodiode, and heater wires, which are thermally grounded to the shade. The energy balance shows that the cold stage is essentially thermally isolated from the housing, which demonstrates the effectiveness of the VGIR design.

The effective environment temperature in the test chamber, T_E, ranged between 48 and 50 K, while the He-cooled shroud wall temperature, T_W was maintained between 13 and 20 K. T_E is significantly greater than T_W because of all the energy reflected off the shroud walls which is absorbed by the radiator plate (as well as by the black square environment temperature sensor). The source of this parasitic energy is heat leakage from the outer LN_2 shroud through the baffles of the inner He shroud, as well as energy emitted by the VGIR shade and support housing. Even though the shroud walls are painted black, their infrared reflectance at 13 K may be greater than 0.4, so a significant portion of the energy input to the inner chamber cavity is absorbed by the radiator plate through multiple reflections off the shroud walls. For the conditions in Table 1, the analytical model indicates that a decrease of 1.4 to 7 K in the radiator plate temperature would be expected if the effective environment temperature was that of space.

An actual flight VGIR will have greater conductive heat leaks than the feasibility model due to stronger structural supports which are needed to withstand the launch loads. A thermal conductance value of 4.5×10^{-7} W/K has been calculated here for the nylon tendons between the support

Table 1 Experimental and predicted VGIR temperatures

			Radiator temperature			
Test run	Useful cooling load P, mW	Shade temperature T_S K,	Exper end of test[a] T_R' K,	Exper steady state[a,b] T_R, K	Analytical model prediction[a] T_R K,	Predicted flight VGIR temperature[c] T_R, K
1	25	140	56.7	56.4	56.6	52.0
2	50	140	59.3	59.6	60.1	56.3
3	100	140	65.4	65.5	65.8	62.9
4	200	140	73.7	73.9	74.0	72.0
5	400	140	85.1	85.1	85.2	83.9
6	50	160	62.7	62.5	62.5	59.2
7	100	160	67.6	67.4	67.6	65.0
8	200	160	75.3	75.2	75.3	73.5
9	400	160	85.9	85.8	86.0	84.8
10	50	180	66.4	66.1	65.5	62.7
11	200	180	78.0	77.9	77.1	75.4
12	400	180	87.1	87.1	87.3	86.1

[a] $T_E = 45$ K (chamber effective background temperature). [b] Projected from Eq. (3). [c] Includes flight structural supports and assumes space background temperature.

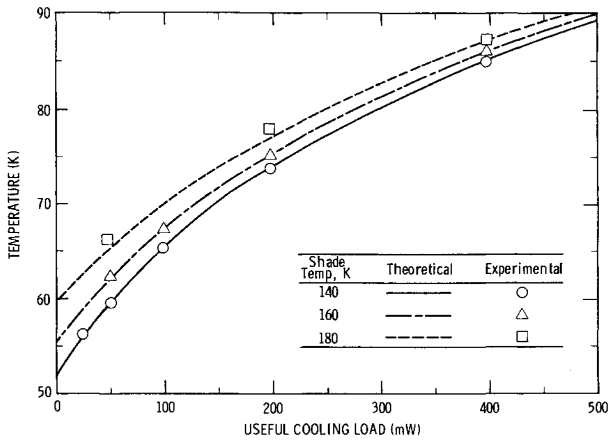

Fig. 3 Comparison of experimental and analytically predicted VGIR temperatures.

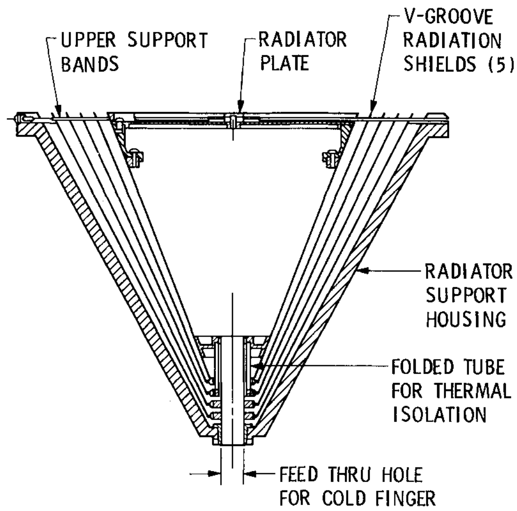

Fig. 4 Cross-sectional view of V-groove shield assembly and support structure of flight-like VGIR.

housing and the cold stage plate in the feasibility model. A "flight-like" VGIR, which has been developed and is described in the next section, has a completely different structural support system. It has an estimated effective conductance value of about 4×10^{-5} W/K between the support housing and cold stage. This two orders of magnitude increase in conductance would cause the 0.1-mW conduction value shown in Table 2 for the test 4 case to increase to 8.8 mW, thereby causing a 0.8-K rise in radiator temperature. However, operating in space would essentially eliminate the 35.9-mW environmental load shown in Table 2. The predicted temperatures of a VGIR flight model operating in space are shown in the final column in Table 1. It is clear that the increased heat load due to the stronger flight structural supports is more than compensated for by the colder effective environment in space relative to the test chamber. It is also clear that operating temperatures below 60 K are achievable with a reasonably small ($\leq$ 0.3 m^2) VGIR for useful cooling loads below 75 mW. The VGIR design can be scaled to accommodate larger cooling loads.

Earth Orbiting Applications

The original VGIR feasibility demonstration model described in Ref. 2 was designed for application to a specific Earth-orbiting flight experiment, the Advanced Moisture and Temperature Sounder (AMTS). The AMTS is an 833-km, near-polar, 8:30 a.m., sun-synchronous, Earth-orbiting infrared spectrometer. The infrared detectors require a 65-K operating temperature with a rather large useful cooling load of 258 mW.[6] The original thermal feasibility demonstration model was designed as a 0.58 linear scale model (i.e., it was designed with an 88 mW useful cooling capacity at 65 K). The Earth-orbiting configuration required a smaller sunshade, and the radiation interchange factor from the cold stage to the shade was approximately 1.6 times smaller, than for the current Mars-orbiting geometry.

An Earth orbital heating analysis projected an orbital average sunshade temperature of 160 K. Table 1 suggests that a cold-stage temperature of 65 K is achievable even with the larger Mars sunshade and a 100-mW useful cooling load, as indicated by the VGIR flight prediction for the test 7 case. For an actual flight cooler, temperature stability can be maintained within 0.1 K by use of a cold-stage control heater.

With the correct Earth-orbiting configuration, the analytical model indicates that 65 K is achievable with about a 116-mW useful cooling capacity. Therefore, the 0.27-m^2 feasibility demonstration model is actually a 0.45 scale model by area, or a 0.67 linear scale model of the VGIR required for the AMTS. The VGIR performance is significantly better than originally predicted.

The analytical model indicates that other Earth-orbiting instruments in a similar orbit to AMTS can achieve operating temperatures below 60 K for useful cooling loads below 75 mW, with a relatively small, 0.27 m^2, VGIR. Note that 75–100 mW is a more typical useful cooling load for infrared detectors than the 258 mW required by the large AMTS, 112 detector, array.

Current Development Status and Future Activities

A flight-like VGIR containing all the relevant features of a flight model has been built. This flight-like cooler includes a low-conductance structural support system which is designed to withstand the dynamic and acoustic vibration environment of a Shuttle orbiter launch. It has passed qualification level vibration tests for the Mars Observer mission. A thermal vacuum test is planned. Details of the flight-like VGIR design and vibration tests are in Ref. 7.

Figure 4 shows a cross section of the radiation shield assembly for the flight-like VGIR. The cooler contains 4

Table 2 Cold-stage energy balance for test run 4

Energy source	Heat load, mW	Percentage of total heat load
Chamber environment radiation	35.9	14
Sun shade radiation	24.5	9
Sun shade conduction	2.2	1
Support housing radiation	0.0	0
Support housing conduction	0.1	0
Useful cooling load	200.0	76
Total cold-stage heat load	262.7	100

aluminum and 1 fiberglass/epoxy V-groove shields. The shields and the inside of the sunshade have a highly reflective and specular vacuum-deposited gold coating. Vacuum-deposited gold has a slightly lower emissivity than vacuum-deposited aluminum,[5] and thus offers a small thermal performance improvement over the feasibility model. A folded fiberglass/epoxy tube supports the V-groove shields and provides thermal isolation from the warm housing. The radiator plate is supported by the inner fiberglass/epoxy shield, which is part of the structure, and by the four spring-loaded fiberglass/epoxy tension rods at the top. The complete flight-like VGIR, including the Mars sunshade and a 20.3×20.3 cm (8×8 in.) cold stage, weighs about 9.7 kg and is expected to operate at 78 K with a 75-mW useful cooling load.

Steps are being taken to reduce the effective environment temperature in the vacuum chamber during the thermal test of the flight-like VGIR. The heat load from the outside of the shade to the chamber will be reduced by blanketing it with MLI. In addition, there are plans to mount an MLI blanket between the outer N_2 shroud and inner He shroud. This will reduce the energy which is currently leaking from the outer shroud through the baffles of the inner shroud. The initial cooldown of the VGIR shade and inner chamber shroud will be shortened by backfilling the chamber with cold N_2 gas. With these steps, the thermal test of the flight like VGIR will be more representative of the VGIR performance in space.

Conclusions

A VGIR thermal feasibility model in a Mars orbit configuration has been built and tested in a helium-cooled vacuum chamber. Experimental temperatures were within 1 K of those predicted by an analytical computer model, as indicated in Table 1 and Fig. 3.

An actual flight VGIR will require stronger structural supports than the feasibility model, but the increased conductive heat load is more than compensated for by the colder effective environment temperature in space relative to the test chamber, as indicated in the final column in Table 1. A flight-like VGIR, incorporating a flight structural support system, is currently being developed and is shown in Fig. 4.

The thermal feasibility experiment clearly demonstrates the radiative isolation capability of the V-groove concept, as indicated in Table 2, and also demonstrates the potential of the VGIR design to meet the cooling needs of many planned future space missions. Practical operating temperatures of reasonably sized ($\leq 0.3 m^2$) radiative coolers can now be extended to below 60 K, with useful cooling loads up to 75 mW, at Earth, Mars, and beyond with the use of this new technology. The design can be scaled to accommodate larger useful cooling loads.

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