CLAUDE S. LEFFEL, JR.

THE APL SATELLITE REFRIGERATOR PROGRAM

The first satellite experiment utilizing mechanical refrigerators to cool germanium gamma-ray detectors was launched on February 24, 1979. These refrigerators, developed and constructed by the Applied Physics Laboratory and Philips Laboratories, are still operating after more than 28 months in orbit and represent the first instance where mechanical refrigerators have survived for more than a few weeks in satellite orbit. Furthermore, the length of time that the gamma-ray spectrometers have been operated in space exceeds by more than a factor of two the time of operation of any germanium gamma-ray detector cooled by any method.

INTRODUCTION

Gamma-ray spectroscopy as a new "window to the universe" has been discussed in several recent papers.[1,2] By measuring the most energetic form of electromagnetic radiation, it can provide information about transformations arising at the nuclear level during the cosmic synthesis of chemical elements in supernova or the annihilation of protons and electrons. This paper describes the APL effort in selecting, designing, constructing and testing Stirling cycle refrigerators for a gamma-ray spectrometer satellite experiment designed and flown by the Lockheed Palo Alto Research Laboratory (LPARL).

THE PROBLEM OF COOLING DETECTORS IN SPACE

For gamma-ray detectors, which can resolve gamma energies that differ by 1% or less, crystals of germanium have been the preferred material. "Drifted" germanium detectors, in which very small quantities of lithium have been implanted within the crystal lattice to counteract the effect of impurities, have been available for some years. But that detector has the disadvantage that it must be continuously cooled to cryogenic temperatures (typically 77 K in the laboratory) to prevent the migration of lithium out of the lattice. In the early 1970's, the "intrinsic" germanium detector, which consisted of a crystal so pure that no compensation by the insertion of another element was required, was developed. This crystal provides high resolution only at cryogenic temperatures but can be warmed and recooled without destruction of the crystal's resolving power. When the APL refrigerator program began in 1973, the maximum temperature at which the intrinsic germanium detector would operate was not precisely known; results obtained by LPARL several years later indicated that adequate resolution was maintained for temperatures as high as 130 to 140 K.

Gamma-ray spectrometers in space[2,3] have customarily been cooled by solid cryogens such as dry ice (CO_2) vented to space vacuum. This method of cooling has the advantage of providing a constant temperature independent of heat load for as long as the cryogen lasts, but it has the disadvantage that, unless some electrical or mechanical method of warming is provided, the detector will, over a period of time, collect a miasma of gaseous effusions from the satellite by depositing them on the cooled surfaces and thus will become inactive. The mechanical refrigerator has several advantages: it is lighter in total weight, can be turned on and off on command (permitting the warming of the cold surfaces to free them of deposits) and, potentially, will have a long life in space. Perhaps the biggest obstacle to using mechanical refrigerators in space has been their poor reputation for reliability, a reputation that—prior to the development discussed here—was well founded in experience. Reference 4 contains a general discussion of the problem of cooling detectors in space and assesses the relative merits of cryogens and mechanical refrigerators.

The choice of mechanical refrigerators for a satellite mission is relatively limited,[4,5] narrowing down to the Vuilleumier and Stirling cycles. While the U.S. Air Force has conducted an extensive development program for Vuilleumier refrigerators, no appreciable time in orbit has been achieved. Because this cycle requires heat as the major part of its energy input, it loses a substantial part of its attractiveness unless a nuclear heat source is available.

THE STIRLING CYCLE REFRIGERATOR

The preferred choice for a refrigerator capable of producing temperatures below 100 K is the mechanical Stirling cycle.[6] This cycle, first designed as an engine to produce mechanical power, was patented by the Rev. Robert Stirling of Scotland in 1816. By 1818, without the benefit of thermodynamic analysis, he had it at work pumping water.

The advantages of the Stirling cycle as a cryogenic refrigerator were first realized in the early 1940's by Philips Laboratories in the Netherlands in conjunction with their work on this cycle as a heat engine.[7] Since then, Philips Laboratories, in Europe and America, has been the leading proponent of the Stirling cycle as both a prime mover and a cryogenic refrigerator.

In the refrigerator mode of operation, the Stirling cycle uses a gas such as helium at a pressure of about 5 atmospheres. No change of phase is involved. Figure 1 illustrates the operation of the refrigerator. It is a reciprocating device employing a piston for the compression and expansion of the gas and a displacer to move the gas from the warm (compression) volume, V_C, to the cold (expansion) volume, V_E. In moving from V_C to V_E and back again, the gas flows through a regenerator consisting of a mesh of metal wires. The specific heat of the regenerator is very high compared with that of the working gas. With very little change in temperature, the regenerator absorbs and returns heat to the gas as it passes through. In Fig. 1, as on the APL refrigerator, the displacer and regenerator are combined in a single physical element that leads the motion of the piston by about 90°; in effect, the regenerator "walks" the heat absorbed in V_E down the cylinder into V_C where the heat is expelled by the compression stroke of the piston. Because, ideally, the compression and expansion strokes are isothermal, the thermal contact between the heat exchangers and the gas must be very effective; this results in design complications of the working refrigerators that are not shown in Fig. 1.

Figure 2 shows the thermodynamic cycle of the Stirling cycle refrigerator on pressure-volume and temperature-entropy diagrams. Unlike the Carnot cycle, which is virtually impossible to carry out in a practical mechanism, the Stirling cycle can be closely approximated by driving the displacer-regenerator and piston in harmonic motion, provided the phase difference is maintained.

The coefficient of performance (COP) for a mechanical reversible refrigerator is given by

$$\mathrm{COP} = \frac{Q_E}{W} = \frac{Q_E}{Q_C - Q_E} , \tag{1}$$

where the net work, W, for the cycle is $Q_C - Q_E$. All symbols are as defined in Fig. 2, and the heat, Q, is always taken to be positive. By using the relationship between heat and entropy for a perfect gas, it can be shown (e.g., Ref. 8) that

$$\mathrm{COP} = \frac{T_E}{T_C - T_E} . \tag{2}$$

This is the Carnot result that would be expected for a reversible refrigeration cycle that operates between the isotherms T_E (the cooled space) and T_C (the heat sink).

While the analysis of thermodynamic cycles adds an aura of legitimacy to a mechanical device, it is not very informative about either the performance that can be achieved in practice or the mechanical difficulties of constructing it. Reference 9 contains a brief description of the refrigerator as it was constructed for flight; Ref. 10 contains a detailed description of the refrigerator and discusses the departure of the performance of a realizable machine from that of the ideal Stirling cycle.

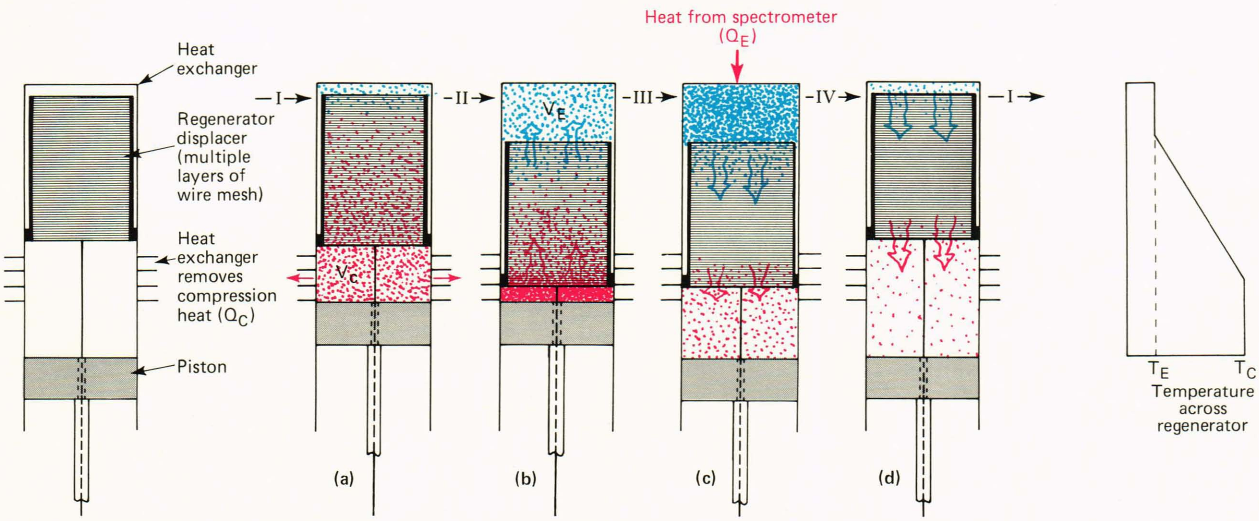
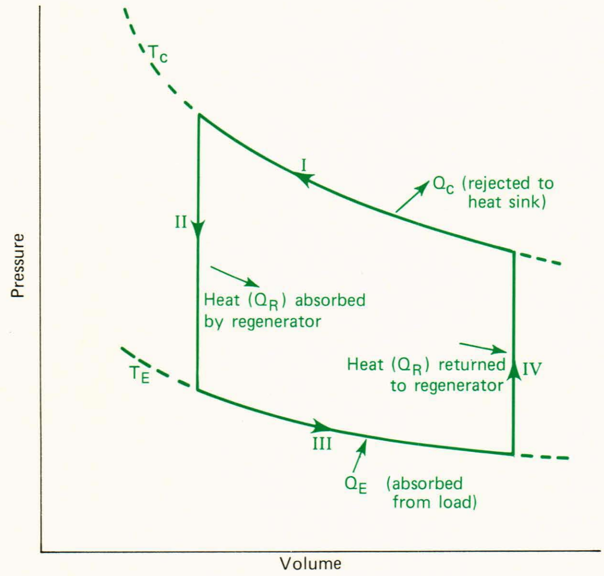


Fig. 1—Operation of Stirling cycle refrigerator in which the displacer and regenerator are physically combined.

a. The piston isothermally compresses gas in V_C; heat Q_C is rejected by the heat exchanger.
b. The displacer moves down, forcing gas into V_E. Regenerator absorbs heat from the gas passing through it, and stores it.
c. The piston moves down, isothermally expanding gas in V_E. Heat Q_E is absorbed by V_E.
d. The displacer moves up, forcing gas from V_E to V_C. Heat stored in the regenerator is returned to the gas now in V_C.

V_E denotes the expansion volume, V_C the compression volume. For a refrigerator, V_E is cold and V_C is warm.



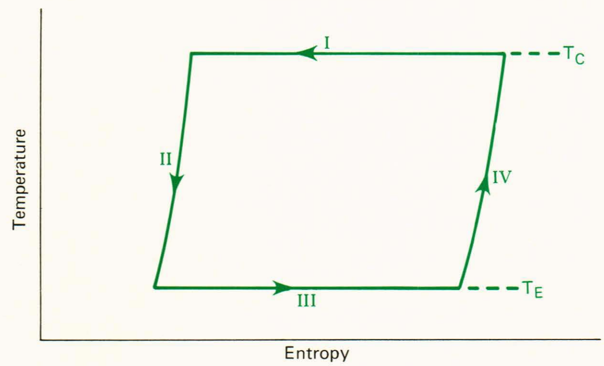


Fig. 2—Pressure – volume and temperature – entropy diagrams for the Stirling cycle. Ideally, the Stirling cycle works along isothermal contours for the compression and expansion strokes. Movement of the displacer-regenerator occurs at constant volume. Cycles shown in roman numerals are identical with those shown in Fig. 1.

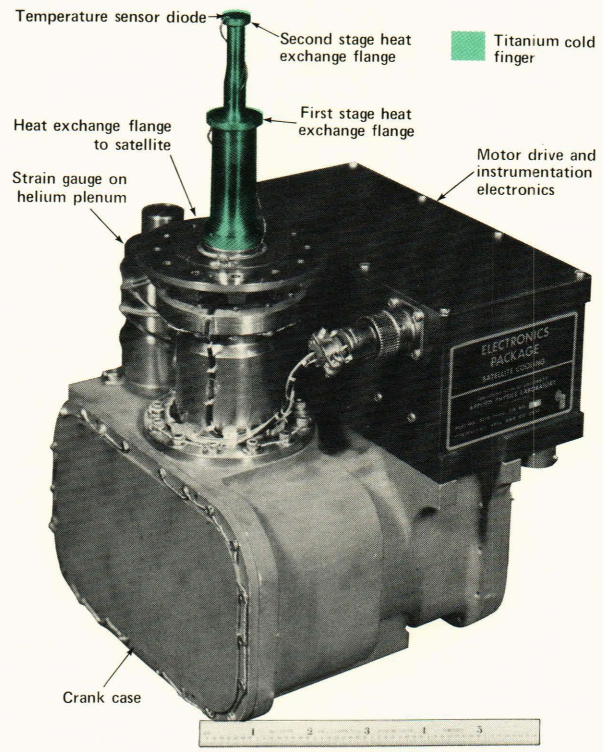


Fig. 3—Photograph of flight model refrigerator. Heat is removed at the second- and first-stage heat exchange flanges and is rejected at the heat exchange flange to the satellite.

Figure 3 shows the satellite refrigerator as it was delivered to LPARL. The satellite refrigerator was a two-stage machine; the first stage was designed to cool a heat shroud about the germanium detector to 140 K, the second stage to cool the detector to below 90 K. The problem of optimizing regenerator performance is somewhat reduced by using two stages,[10] but in the present instance the requirements of the experiment dictated two different temperatures and two heat loads. Figure 3 shows the placement and dimensions of the APL electronics package that controls the motors and provides the voltages and signal processing for the refrigerator instrumentation.

Figure 4 is a greatly simplified diagram of the interior of the refrigerator. In the original design, the crankcase and working volume of the refrigerator were separated by metal bellows. This permitted the crankcase to be charged with nitrogen instead of helium, which was used in the working volumes, and prevented the migration of impurities from the crankcase (which includes motors and greased bearings) into the volume above the piston. However, the bellows, made of electroplated nickel, presented a serious reliability problem. Since a bellows failure in orbit would result in debris that would probably jam the mechanism, bellows were omitted from all refrigerators delivered to APL. The crankcase and the working volume of the refrigerator were charged with helium at a pressure of 71 pounds per square inch absolute. The only isolation of the crankcase volume from the working volume was provided by the piston seal.

The problem areas of the refrigerator can be located in Fig. 4. As shown in Fig. 1, a temperature gradient between the cold space and the warm space must be established and maintained across the regenerator. For the first stage, this difference is between 140 and about 300 K. The regenerator must sustain this gradient while providing a specific heat that is high relative to helium and good heat transfer properties to the gas. The displacer seals must be tight enough to force essentially all the gas through the regenerator volume but must not produce appreciable heat from friction. This is not so difficult for the first stage since the displacer seal is located just above the heat exchange flange at ambient temperature. But the second-stage seal must operate at temperatures of 140 K and lower and be able to withstand the cooldown process from ambient to the low temperature.

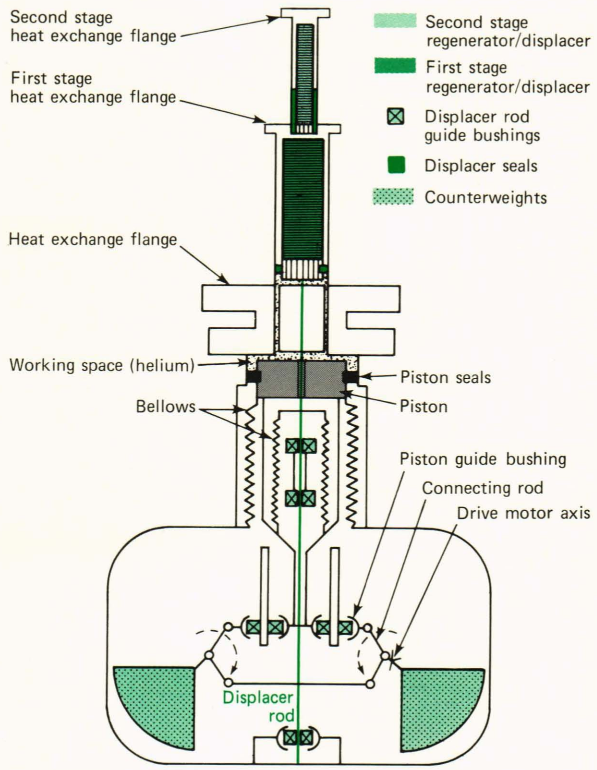


Fig. 4—Schematic drawing of refrigerator mechanism. The 0.30 inch displacer stroke and the 0.22 inch piston stroke are provided by the rhombic drive mechanism, which maintains the proper phase relationship and is balanced to reduce vibration. The piston and first-stage displacer seals are patented spring-loaded Teflon piston rings; the second-stage displacer seal is a precise fitted band of loaded Teflon. The regenerators, through which the helium gas must pass as the displacers move, are filled with layers of phosphor bronze mesh.

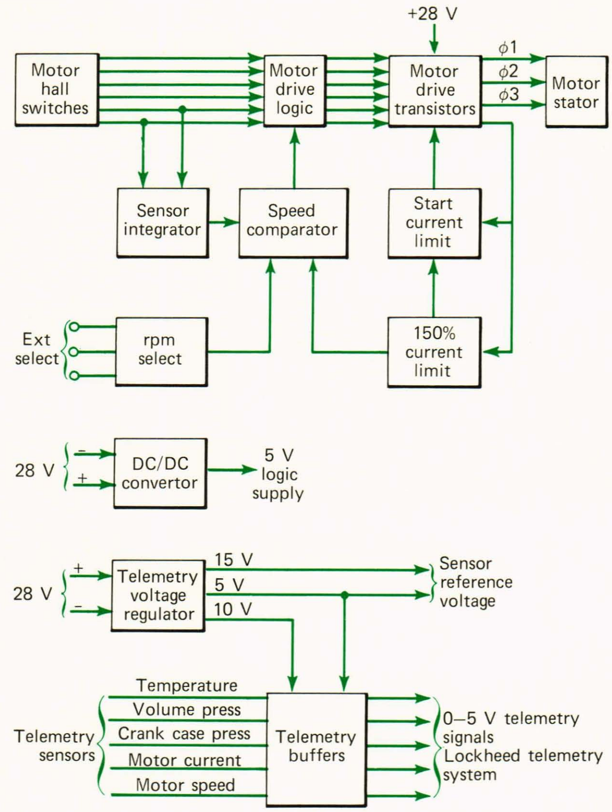


Fig. 5—Block diagram of motor drive and telemetry circuits. Hall switches sense the position of the permanent magnet motor armature and, by means of the logic circuits, switch the motor drive transistor, which rotates the motor stator field. Motor speed control and starting and operating current limiting circuits protect the satellite power supply. Motor drive and telemetry circuits can be switched separately.

The extension displacer shown below the first-stage displacer forces the helium gas into good thermal contact with the heat exchange flange that, on the satellite, is bolted to the vehicle heat sink.

The mechanical power to operate the refrigerator is supplied by two counter-rotating electric motors. These motors consist of a permanent magnetic armature surrounded by an 18 pole electromagnetic field. The electromagnetic field is switched by external circuitry contained in the electronics box; the position of the armature is sensed by Hall effect switches, located within the crankcase, that provide the signals to rotate the electromagnetic field as the armature rotates. A block diagram of the electronics box is shown in Fig. 5. The motor speeds are controlled by pulse-width modulation of the motor drive circuits transistors at 10 kilohertz; an integrated signal from a Hall switch is compared with a reference voltage to control the width of the current pulses entering the motor field coils. Three motor speeds, which can be switched from the ground control, are provided: 850 rpm, 1000 rpm, and, on the flight models, a free-running speed. This free-running speed is typically 1100 to 1150 rpm on a new refrigerator; it is determined by the voltage of the power supply and the thermal load on the refrigerator.

The APL instrumentation consisted of a silicon diode to measure the second-stage temperature, a strain-gauge bridge to measure the helium pressure, a pressure transducer within the crankcase to measure the helium pressure, a voltage comparator circuit to measure the voltage across a 0.1 ohm fusing resistor in the main power line yielding the total current consumption, and a voltage measurement of the integrated output of a Hall switch that was proportional to motor rpm. The outputs of these sensors were processed to yield the 0 to 5 volt signal required by the LPARL 8 bit telemetry system. A few seconds after the refrigerator is started, a current-limiting circuit is activated that limits the motor current to about 1.8 amperes, 150% of the normal operating current.

For a Stirling cycle refrigerator, all that is required to change the direction in which heat is pumped is to reverse the direction of motor rotation. Thus, the motor-drive logic circuit is designed so that the sequence of Hall switch signals can produce rotation in only one direction. Extensive investigations of the motor-drive circuit have not uncovered a failure mode that would result in such a disastrous motor reversal. There are, of course, many failure modes that will produce no motor rotation at all.

The original design specifications and the specifications of the refrigerators as delivered to LPARL are listed in Table 1. Philips Laboratories constructed six refrigerators, four of which were used in the LPARL satellite experiment, one served as the flight spare, and one served as the engineering model. The ability of these units to meet and exceed the thermal performance specifications indicated the ability of Philips Laboratories to predict, by means of their proprietary computer programs, the performance of a refrigerator design before it had been extensively tested.

THE APL TEST PROGRAM

The APL test program had two primary objectives: (a) to conduct performance and environmental tests that qualified the refrigerator for space operation, and (b) to conduct a life-test program that gave a reasonable assurance of a one year operation in orbit. This latter objective was particularly important because mechanical cryogenic refrigerators had a dubious reputation for reliability. The need to establish a creditable lifetime as early as possible, while at the same time meeting the delivery program for the flight model refrigerators, determined the sequence of events in the APL test program.

The first assembled refrigerator, Serial No. 1 (the engineering model) was delivered to APL on April 30, 1975. After the APL electronics and instrumentation were incorporated, the unit was installed on the test stand shown in Fig. 6. This test stand, mounted in a vacuum bell jar capable of maintaining a vacuum of about 10^{-6} Torr, provided the heat loads, instrumentation, and temperature ranges to perform

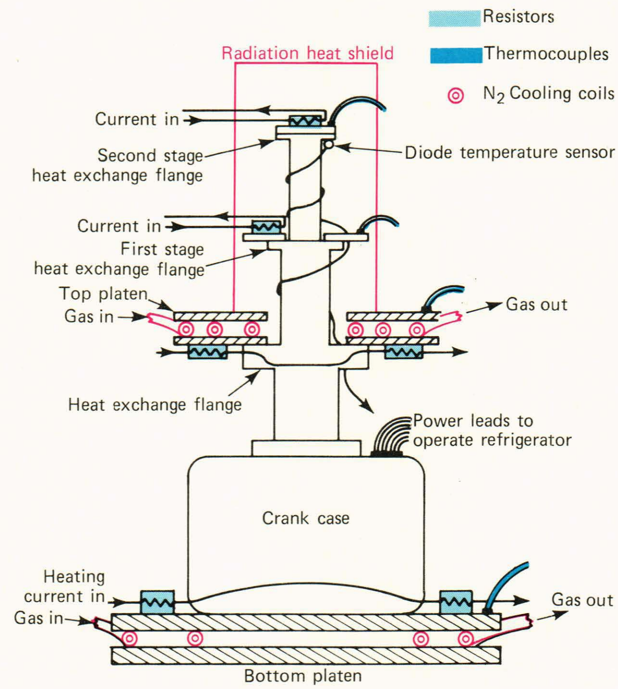


Fig. 6—Schematic diagram of refrigerator mounted on thermal performance test stand. This test stand, mounted in a vacuum bell jar, provided the reference temperatures for the crankcase and heat exchange flanges, the heat loads for the first and second stages, and the temperature sensors for performance and acceptance testing of the refrigerators. The platen (reference) temperatures, which simulated satellite orbit temperatures, were varied from −20 to +45°C by a combination of cool nitrogen gas and electrical heating elements.

Table 1

SATELLITE REFRIGERATOR SPECIFICATIONS

Item	*Design Specifications*	*Delivered Specifications*
Cooling capacity		
First stage	<170 K at 1.5 W	140 K at 1.5 W
Second stage	<90 K at 0.30 W	65-75 K at 0.30W
Power consumption	<30 W, 24 to 30 V	30 to 35 W
Speed	3 selectable	1000 ± 150 rpm
Weight	4.6 kg w/o electronics	5.36 kg w/o electronics 7.18 kg with electronics
Dimensions	16.5 × 16.5 × 32.0 cm	15.37 × 18.03 × 30.68 cm
Heat sink temperature	0 to 45°C	−10 to +45°C
Vibration	<0.001 cm in any direction	<0.00033 cm
Starting torques	0.0007 dyn-cm	≪0.0007 dyn-cm
Launch environment	18.9 g rms for 2 min, three axes	met design specifications
EMI	minimize	acceptable to payload contractor
Lifetime	8000 h, continuous or intermittent	8100 h, at least 400 h continuous

the space qualification and acceptance tests. Thermal testing of the engineering model began in August 1975.

The modifications in the refrigerator design and assembly dictated by the APL test program are briefly described below.

1. In early September 1975, the gold-plated titanium cold finger failed in the random vibration tests. The masses of the first- and second-stage heat exchange flanges were reduced and the cold finger was replaced.
2. After 870 hours of satisfactory operation on life test, the performance of the Serial No. 1 refrigerator showed a serious degradation in mid-February, 1976. This was caused by excessive wear on the second-stage displacer and seal and by debris in the second-stage regenerator. The regenerator was cleaned and the displacer seal replaced.
3. Back on life test at APL, the unit showed a rapid rise in temperature after 8 to 18 hours of operation. This difficulty was traced to a high concentration of water vapor within the working volume of the refrigerator. To overcome the problem, Philips Laboratories developed an improved method of charging the refrigerators with helium.

When the Serial No. 1 refrigerator was placed back on life test on September 2, 1976, its performance was the best that had been observed under laboratory conditions. The unit operated until March 3, 1978, when the test was terminated because the lifetime specifications had been met. During that period, no failures or difficulties were experienced. The helium charge was unperturbed and, except for interruptions caused by the acceptance testing of flight model refrigerators, holidays, vacations, power outages, and maintenance of the test facility, the life test was run to completion. The longest uninterrupted runs were about 400 hours.

Performance maps to determine the effects of changing the heat loads, heat exchange temperatures, and motor speeds were run on the Serial No. 1 refrigerator. Typical results are shown in Fig. 7.

Early in the life test program (January 1976) it was found that the temperature of the first stage rose about 2.6 K per day and that of the second stage about 4.1 K per day. If the refrigerator was turned off, allowed to warm to ambient (room) temperature, and restarted, the temperatures returned (or nearly returned) to their values at the beginning of the previous run. This result was clearly related to the freezing-out of impurities (probably water vapor), either on the outside surface of the cold finger or within the regenerator passages inside the cold finger.

When in the life-test chamber (or the bell jar), the refrigerator cold finger is a relatively small surface with a temperature gradient varying from the heat exchange temperature, T_1 to the second-stage temperature, T_2, surrounded by a large surface at ambient temperature (which is, on the life-test apparatus,

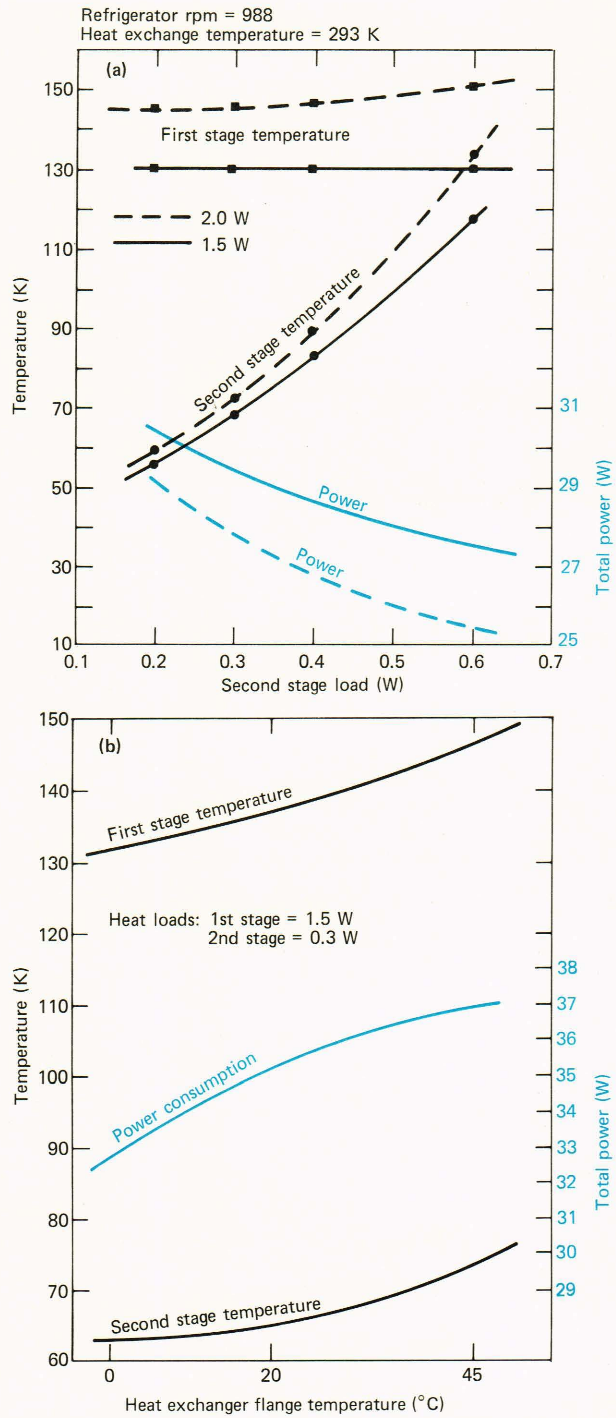


Fig. 7 — Typical performance maps for the serial No. 1 refrigerator. These graphs indicate the manner in which the first-and second-stage refrigerator temperatures vary with heat loads, heat exchange temperatures, and (not shown) motor speed. They are required for in-orbit analysis of system thermal performance.

a. First- and second-stage temperatures and power consumption versus second-stage heat load for first-stage heat loads of 1.5 and 2.0 watts; motor speed and heat exchange flange were held constant.
b. First- and second-stage temperatures and power consumption versus heat exchange temperatures; heat loads and motor speed were held constant. Note that the second-stage temperature is relatively insensitive to the heat exchange (rejection) temperature.

identical to T_1). Assuming that the emissivity of the gold-plated cold finger is 0.02 for the 15 square centimeter area between the first and second stages, the radiation heat load is calculated to be

$$H = 0.0137 \text{ watts.} \tag{3}$$

Since the applied load to the second stage is 0.300 watt the effect of the radiation load is not negligible, and if the effects of frosting increase the emissivity to 0.1, the heat load increases to 0.3685 watt. From the performance map of Fig. 7, the resulting change in heat load would increase the temperature of the second stage by 9 K. Because water vapor constitutes a large part of the partial pressure in a conventional vacuum system and since cryogenic pumping is very effective, it is easy to show that for a vacuum of about 10^{-6} Torr, the cold finger could accumulate about 0.001 cm of frost a day. The effects of frosting on the emissivity of a gold surface are unknown, but from Ref. 11, a convincing case can be made that this frosting effect could explain the daily temperature rise of the first and second stages.

When the life test was resumed in September 1976, the rate of temperature increase on the first and second stages showed a significant decrease, from 2.6 to 0.66 K per day on the first stage and from 4.1 to 0.93 K per day on the second stage. Since all other conditions were the same, it must be assumed that this improvement in performance was caused by the greater purity of the helium within the refrigerator as a result of the better method of charging the refrigerator. Throughout the life test, the daily temperature rise of the second stage was about 1 K per day. Again, when it was warmed to ambient temperature and restarted, the refrigerator performance returned almost to the initial performance of the previous run. The daily slow rise of temperature was acceptable for any experiment that LPARL contemplated in space, and by the end of 1976, the design and method of assembly of the flight model refrigerators were frozen.

The first flight model refrigerator, Serial No. 2, fitted with the redesigned heat flanges, was delivered to APL on December 24, 1975, and, after acceptance testing, was delivered to LPARL on January 29, 1976. Delivery of the five flight units, with all modifications, was completed by April 27, 1978.

RESULTS OF THE LIFE-TEST PROGRAM

The life test was terminated on March 3, 1978, after 8140 hours of operation. Superimposed on the daily temperature increase discussed above was a slower degradation of performance following restart of the refrigerator. Figure 8 shows the refrigerator performance, measured about 24 hours after each start, throughout the duration of the life test. For this figure, the heat loads and refrigerator speed were held constant. The first-stage temperature increased at a rate of 2.36 K per month and the second stage at 3.62 K per month, where time is measured in units of accumulated operating time.

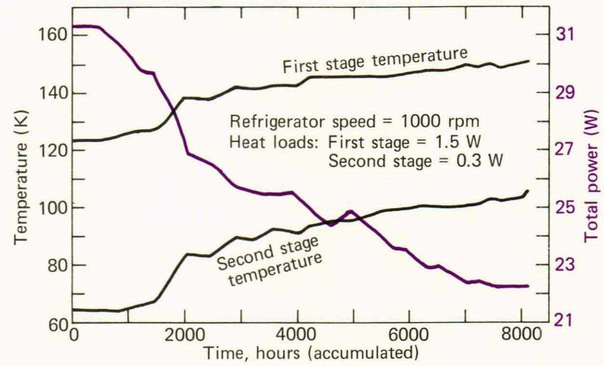


Fig. 8—Life test results: first- and second-stage tempera-tures and power consumption versus accumulated hours of operation. Heat loads, refrigerator speed, and heat exchange flange temperature were held constant.

At the end of the life test, the operating speed of the Serial No. 1 refrigerator was increased to 1150 rpm. The second-stage temperature was 82.4 K and the power consumption was 24.4 watts, well within the original specifications for the refrigerator.

The long-time degradation of refrigerator performance and decrease in power consumption could have been caused by a loss of helium pressure, contamination of the regenerators by impurities in the helium charge, and wear on the piston and displacer seal. It was known from helium leak tests performed both at APL and Philips Laboratories that the refrigerators lost pressure at a rate of about ½ pound per square inch per month through the Viton O-ring seals on the crankcase end plates. The effect of helium loss on refrigerator performance was isolated by recharging it to the pressure at the beginning of the life test. It was observed that the temperature degradation was largely (68%) caused by the loss of helium pressure; the remaining 32% must have been caused by contamination and wear.

The Serial No. 1 refrigerator was returned to Philips Laboratories for disassembly and inspection. The interior of the refrigerator was found to be in very good condition.[12] The regenerators were sensibly clean and flow tests through them revealed no evidence of debris collection. The bearings within the crankcase had lost a portion of their lubricant (Dupont Kryton grease) but no grease was found in the working volume of the refrigerator. The second-stage displacer seal had lost about 0.0004 inch in diameter; the cylinder in which this displacer moves had increased in size about 0.0008 inch. No other evidence of wear that would affect performance was observed. Mass spectrographic analysis of the helium charge revealed that the gas was over 98% helium, 1% nitrogen and oxygen, and 0.34% other gases. The water vapor concentration, which could not have exceeded 0.5%, could not be measured because of limitations in the mass spectrographic and infrared scanning techniques. Philips estimates that the mechanical parts of the refrigerator would have continued to operate for three to four thousand additional hours.

PREFLIGHT PREPARATION AND LAUNCH

Since the flight model refrigerators were known to leak helium at a rate that produced a pressure loss of about ½ pound per square inch per month and since they had been delivered to LPARL over a wide interval of time, it was necessary to recharge them as close to launch time as possible. The recharging procedure provided the only opportunity to measure accurately the leak rates of each refrigerator over a lengthy time period and to check the long-time accuracy of the crankcase pressure transducers and helium-plenum strain-gauge pressure-measuring bridge. The helium leak rate was found to be about as expected, and only one pressure transducer showed a time-dependent error that would require correction in flight.

The thermal connection of the refrigerators to the germanium detector is shown in Fig. 9. Two detectors, designated Gamma 003 (cooled by refrigerators Serial Nos. 2 and 5) and Gamma 004 (cooled by refrigerators Serial Nos. 3 and 6), were mounted in the satellite.

REFRIGERATOR PERFORMANCE IN ORBIT

The P-78-1 satellite containing the DARPA 301 payload was successfully launched into a sun-synchronous polar orbit on February 24, 1979. Within a few hours following launch, LPARL started the refrigerators and determined that they operated satisfactorily.

The instrumentation available to measure the thermal performance of the refrigerators consisted of:

1. The thermal diode mounted by APL on the second stage heat exchange flange of each refrigerator;
2. A thermal diode mounted on the base of the first-stage heat exchange flange by LPARL;
3. Two platinum resistance thermometers that are mounted across the braid connecting the refrigerator second stage to the detector heat conductors; the difference in temperature of these thermometers was calibrated to read the heat flow across the braid (see Fig. 9); and
4. Equipment to measure the current to the Vacion pump, to give an indication of the pressure within the pumped space above the heat exchange flange.

As Fig. 9 shows, there was no thermal isolation between the paired refrigerators; thus if one refrigerator was operating, the other one presented an additional heat load.

Following launch, it was found that the refrigerator telemetry signals were as expected with the following exceptions:

1. The crankcase pressure transducer and plenum strain-gauge pressure measurement gave a low helium pressure indication on the Serial No. 6 refrigerator. From the agreement of the pressure measurements and performance data acquired later, the helium loss was real. Since the loss rate had been normal when the refrigerators were recharged in late November 1978, the probable explanation of the helium loss was a failure to reseal the crankcase refill valve properly after the recharging operation.
2. The second-stage temperature diode telemetry readout on Serial No. 3 was inoperative for unknown reasons. Thus, all second-stage temperature information on Gamma 004 must be inferred from the refrigerator Serial No. 6 temperature diode.
3. The LPARL heat load measurement on Gamma 004 was inoperative.

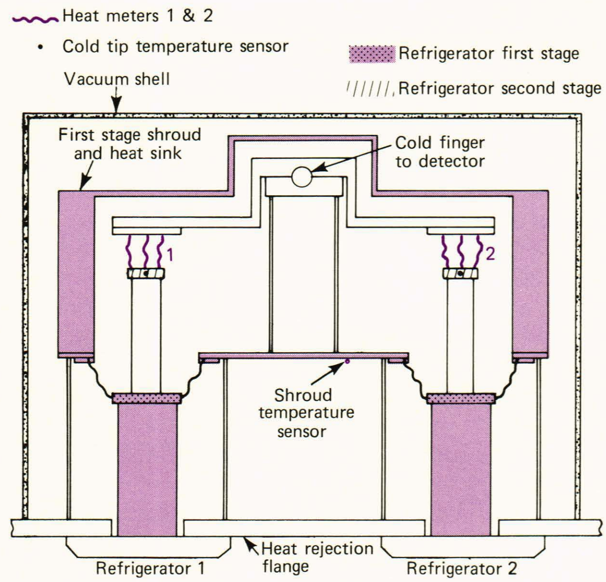


Fig. 9—Thermal connections and temperature sensors on the LPARL gamma-ray spectrometer. The thermal connections between the refrigerator's first and second stages and the spectrometer were made with copper braid to reduce the transmission of mechanical vibration. LPARL installed temperature sensors across the second stage braid to yield a measurement of heat flow into the refrigerator's second stage. The heat rejection flange was bolted to a heavy load-bearing plate in the satellite.

There was no direct way to measure the germanium detector temperature. From LPARL tests in a laboratory mockup, it was established that the detector temperature was 8 K higher than that of the second stage of the refrigerator.

The method of refrigerator operation in space was dictated by the requirements of the LPARL experiment and the power budget of the satellite, which included many other experiments. After satisfactory operation of all refrigerators and the gamma-ray spectrometers had been demonstrated, LPARL began a long run on Gamma 003 cooled by Serial No. 2 and Gamma 004 cooled by Serial No. 3. Because of power limitations of the satellite, initial operation consisted of running the refrigerators for about seven orbits (about 11 hours), turning them off for one orbit, and restarting them. On Gamma 004, the second stage cooled to about 80 K, warmed to about 103 K during the orbit of drift, and then cooled down again to 80 K. Gamma 003 cooled to a little over 85 K at best and followed a similar cycle. This method of operation was continued for Gamma 003 for 78 days or 1198 orbits. At that time LPARL began a series of warming experiments and finally after 90 days in orbit warmed the experiment to 276 K (satellite ambient temperature). This warming released so many condensed impurities within the pumped vacuum space containing the detector that it was necessary to activate a squib that exposed the region about the detector to space vacuum. Thereafter, Gamma 003 was operated with the Vacion pump operating but the pumped volume vented to space vacuum.

According to the orbital data, the Serial No. 2 refrigerator second stage had warmed from 85 to 121 K in 98 days of operation, a rise rate of 0.38 K per day, about one-third that observed under laboratory conditions. Warming the refrigerator cold finger to ambient temperature and restarting did not significantly improve the performance of the refrigerator when restarted, a result that was contrary to laboratory experience. When both refrigerators on Gamma 003 were started after 129 days in orbit, the second-stage temperatures dropped to between 60 and 70 K. This temperature was low enough to assure that any degradation of detector performance was not caused by high-temperature effects.

The Serial No. 3 detector on the Gamma 004 refrigerator was operated for 119 days before a warming was attempted. The rate of temperature rise on this unit was 0.42 K per day. It was not necessary to open the system to space vacuum when the refrigerator was turned off; this difference from Gamma 003 is consistent with prelaunch data that always indicated a better pumped vacuum on Gamma 004.

The performance of the refrigerators on Gamma 003 is shown in Fig. 10 for the first 230 days of orbital operation.[13] At the end of this period it is clear that, with both Serial Nos. 2 and 5 operating, the detector could be maintained at temperatures well below those expected to cause degradation in performance (130 to 140 K). A similar graph could be given for Gamma 004.

CONCLUSIONS

The data from measurements of the refrigerator performance in orbital flight and the laboratory life test demonstrate that the objectives of the satellite refrigerator program were met. As of mid-1981, over 28 months of successful operation in space had been achieved. The only known factor that will limit the time of operation in space is loss of helium pressure. From the laboratory and orbital performance results, it can be concluded that:

1. The orbital thermal performance has been as good as or better than expected from the design parameters and laboratory tests. The mechanical design of these refrigerators is basically sound.

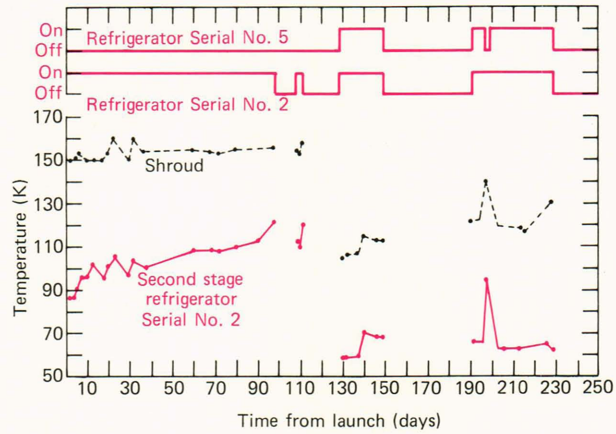


Fig. 10—Second stage and heat shroud temperatures versus time in orbit on Gamma 003. The time of operation of the two refrigerators is given on the top lines. Warm-up and cool-down times are very short (less than a day) on the time scale of the figure. After 128 days in orbit, both refrigerators were turned on, with a significant decrease in temperature on the refrigerators, first and second stages. When both refrigerators are off, the temperatures go to the satellite ambient temperature of about 275 K.

2. The flexibility of operation with the refrigerator has permitted LPARL to warm the detectors and free them from substances cold-trapped on their surfaces.
3. The use of two refrigerators on each detector has made it possible, even after two year's operation, to cool the detectors to a temperature well below that at which a temperature-caused degradation in resolution can be observed.
4. The flexibility of operation and the ability of the refrigerator to cool to sufficiently low temperatures permits the effects of radiation damage, surface contamination, and annealing to be studied for the intrinsic germanium gamma-ray detector while in orbit.

The results of the LPARL gamma-ray experiment are not the subject of this paper. However, it was observed that, in time, the gamma-ray spectrometers suffered a loss of resolution in orbit. Because the refrigerators were able to cool the detectors below 100 K, the degradation must have been due to radiation damage.

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ACKNOWLEDGMENTS—The APL satellite refrigerator program was funded by the Nuclear Monitoring Research Office of the Defense Advanced Research Projects Agency, Department of Defense. The cooperation and understanding of Col. G. V. Bulin of that office was always supportive. Many persons in several groups at APL contributed to this program of whom only a few are mentioned here. Dr. J. W. Follin, Jr., gave guidance and support on many difficult technical problems; Mr. C. A. Wingate performed the original thermal studies that led to the choice and design features of the Stirling cycle refrigerator and designed and actively contributed to the APL test program; Mr. Roy von Briesen performed the mechanical engineering design of the APL test setup and assisted the author in conducting the program and liaison with Philips Laboratories and LPARL; Mr. Gary Keys designed the electronics and Mr. Henry Lee performed the bench testing and trimming of the APL electronics box. The Environmental Test Laboratory provided and supported much of the laboratory test equipment. The excellent cooperation of Philips Laboratories and LPARL throughout all phases of the program is gratefully acknowledged.