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Development and Verification of a Cryogenic Brilliant Eyes Thermal Storage Unit

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The authors present a summary of the design, development, and verification of the Brilliant Eyes thermal storage unit experiment. The Brilliant Eyes thermal storage unit utilized 2-methylpentane as a 120 K phase change material and was flown onboard the shuttle in March 1994. Prior to the flight, there had been very limited experience with the zero-gravity performance of devices using cryogenic phase change materials. Space applications for a cryogenic thermal storage unit include the storage of energy for the cooling of temperature-sensitive sensor components such as focal planes, optics, mirrors, and telescopes. The Brilliant Eyes thermal storage unit was the coldest recyclable thermal storage device (by over 40°C) in space-flight history and successfully demonstrated the capability to reduce the weight of cooling systems for future spaceborne infrared sensors. Based on ground and flight test results on energy storage capacity and temperature stability, trade studies were performed, which show the significant weight and cost benefits of the Brilliant Eyes thermal storage unit technology.

Introduction

THIS paper presents a summary of the design, development, and ground verification of the Brilliant Eyes thermal storage unit (BETSU) Shuttle experiment. The BETSU contained a 120 K phase change material (PCM) and was flown onboard the Shuttle STS-62 in March 1994 as part of the cryogenic two-phase (CRYOTP) experiment package. The working fluid was 2-methylpentane (or isohexane) with 3% acetone added to minimize supercooling effects. The CRYOTP experiment was a NASA Hitchhiker canister, which contained the BETSU and a nitrogen heat pipe experiment.

At cryogenic temperatures, there was very limited experience with the space flight of PCMs and the effects of zero gravity on their performance. To the best knowledge of the authors, only one spacecraft program had previously flown a cryogenic PCM, and that program's transition temperature was over 50 K higher than that of BETSU. The BETSU program objectives were to design and fabricate a cryogenic thermal storage unit (TSU) for space applications, to verify its flight performance, and to correlate the flight and ground test results. The ground and flight timelines included multiple phases for the evaluation of supercooling (the cooling of a liquid below its transition temperature) and freeze–thaw cycling over a range of heating and cooling rates and depths of energy discharge (storage). Through the correlation of ground and flight data, the goal of the program was to improve the understanding of TSU space operation and enhance the utility of future ground testing.

PCM Space Applications

The space applications for a cryogenic TSU include the cooling of temperature-sensitive sensor components, such as focal planes, optics, mirrors, and telescopes, which have variable heat loads. Figure 1 shows the application of PCMs to cool the primary mirror and baffles of a telescope assembly. The source of the heat load variation is typically related to the sensor operation. During operation, sensors have higher electrical heat loads. For a gimbaled sensor system, the environmental heating of the focal plane, optics, or telescope can increase significantly during operation (earth viewing) over that during nonoperation (space viewing).

The use of a TSU allows for the averaging of the cooling load. During peak operating heat loads, the PCM changes phase from solid to liquid and absorbs heat in excess of the refrigerator or radiator capacity, During nonoperating periods, the PCM is refrozen using the excess cooling capacity. When a TSU is employed in series with a refrigerator or radiator, the refrigerator or radiator size can be significantly reduced to accommodate the average instead of the maximum heat load. The resulting weight and power savings are several times greater than the additional weight of the TSU.

Throughout the operating and nonoperating cycles, the cooling interface will be maintained near the phase transition temperature of the PCM. Thus, the TSU can also provide tighter temperature control than that of a typical refrigerator or radiator system.

BETSU Design Requirements

The requirements for the BETSU were based on a preliminary Brilliant Eyes government spacecraft design, which utilized several refrigerators in conjunction with TSUs to cool a primary mirror and telescope. Table 1 contains the important BETSU requirements.

Table 1 BETSU design requirements

Description	Requirement	Performance	Verification method
PCM refer. temp.	120 ± 1 K @ 1 W for 1500 J	119 ± 2.0 K @ 1 W for 1500 J	Test
Min. storage capacity	1500 J	2500 J latent (>3000 J total)	Test
Min. storage efficiency	60%	100%	Test
Max. rate	4 W	4 W	Test
Sensor accuracy	±0.1 K	±0.1 K	Test
Q-meter accuracy	±0.05 W @ 1 W (5%)	±0.03 W @ 1 W (3%)	Test
Max. TSU weight	7.0 kg	0.9 kg can (1.5 kg TSU)	Inspection
Max. PCM can L/D	0.5	0.5	Inspection
Max. PCM volume	1000 cm^3	54 cm^3	Inspection

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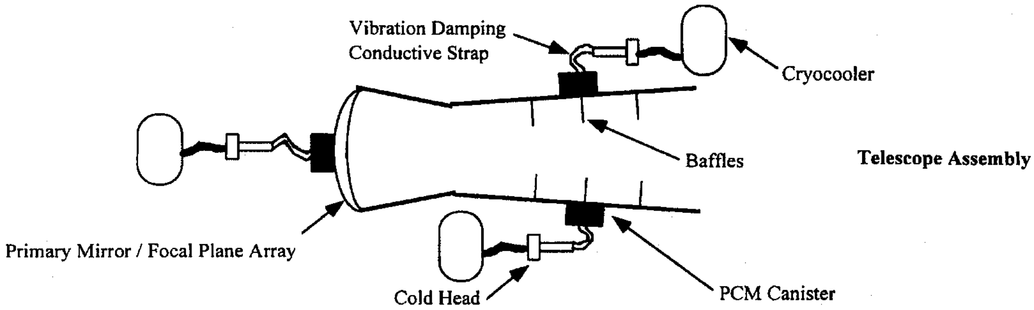


Fig. 1 Application of cryogenic PCM to telescope assembly.

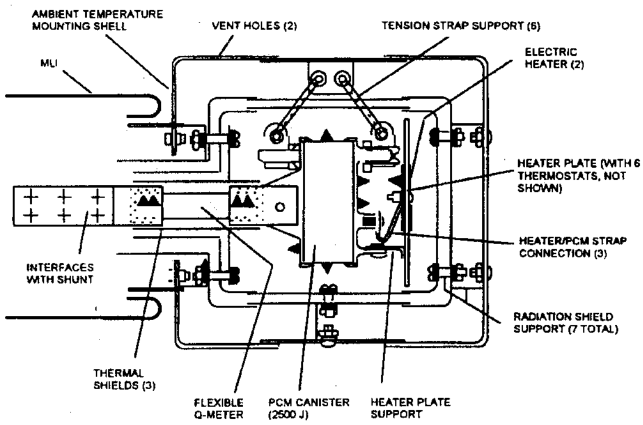


Fig. 2 BETSU mechanical assembly: ▲, platinum resistance thermometers (10).

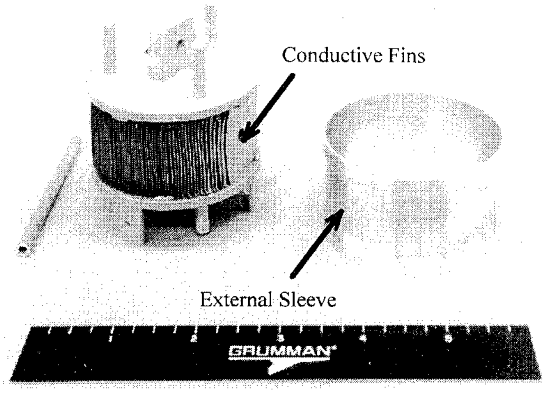


Fig. 3 BETSU PCM canister.

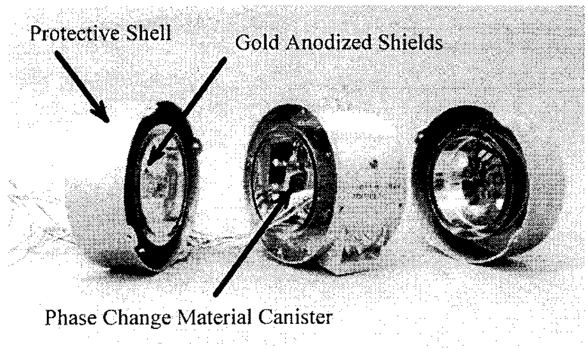


Fig. 4 Complete BETSU.

The BETSU 1500-J energy storage capacity was approximately the same as that required for each TSU in the preliminary Brilliant Eyes design. A minimum specified energy storage efficiency or effectiveness (the ratio of actual to theoretical capacity) of 60% resulted in the charging of the BETSU with 2500 J of PCM (35 g of 2-methylpentane). The baseline energy storage rate was 1 W, with a maximum of 4 W. The temperature stability criterion was ± 1 K for 1-W heating and cooling rates at a reference point on the hot end of the PCM canister. The maximum weight limit for the entire TSU was 7 kg.

BETSU Design Overview

The design of the BETSU is shown in Figs. 2–4, which are schematics and pictures of the hardware. The 2-methylpentane fluid was housed in the PCM canister along with a relatively dense aluminum fin matrix. The aluminum fins (shown in Fig. 3) provided the conduction path within the canister for heat transport to the PCM liquid–solid interfaces. The ratios of the PCM to fin and PCM to wall conductances were optimized to minimize the temperature drop across the canister (which affects the temperature stability requirement) and maximize the heat transport to (but not around) the PCM material. A 5-W variable heater simulated the load from a mirror or telescope. The heater was mounted on a plate that was thermally connected to the PCM canister by copper straps to simulate the actual flight application.

The cold end of the PCM canister was attached to a calibrated flexible heat flow meter (or Q meter). The heat flow meter consisted of two copper end blocks with flexible copper braids in between. Two sets of platinum resistance thermometers (PRTs) on the ends of the heat flow meter measured the temperature drop, which was converted to heat flow using a calibration curve from test data. The heat flow meter was attached outside the BETSU enclosure to the CRYOTP insulated aluminum thermal shunt. The shunt provided the conduction path from two dedicated cryogenic refrigerators (Hughes Model 7044). At steady-state conditions at 100 K, the refrigerators were capable of providing over 3 W of cooling at the BETSU interface.

A unique system was developed to structurally support the cryogenic PCM canister, but thermally insulate it from the environment. The canister was supported from the BETSU outer shell by six titanium tension straps. The small cross-sectional area of the straps minimized the conductive heat leaks to the cryogenic canister. Two concentric gold anodized aluminum shields provided a thermal radiation barrier between the canister and shell. The tension straps penetrated the shields through holes cut out of the aluminum. A third radiation shield surrounded the heat flow meter to provide additional insulation. As verified in the system-level tests, the canister support system provided adequate structural performance to withstand launch vibration loads and resulted in total heat load parasitics of less than 0.35 W on the cryogenic portions of the BETSU.

During the ground tests and in flight, the BETSU data acquisition and control were accomplished in real time. As indicated in Fig. 2, the BETSU had ten PRTs for the measurement of cryogenic temperatures. The mission timeline was followed by controlling the BETSU cooling rate (using three heaters on the CRYOTP side of the thermal shunt), the heating rate (using the BETSU heater), and the duration of cycles.

Approximately 50 wires for the PRTs and heaters exit the BETSU at the heat-flow-meter opening and were conductively heat-sunk to the CRYOTP shunt to minimize parasitic heat loads.

CRYOTP Design Overview

The BETSU was flown inside the CRYOTP canister, which was part of the primary-payload Office of Aeronautics and Space

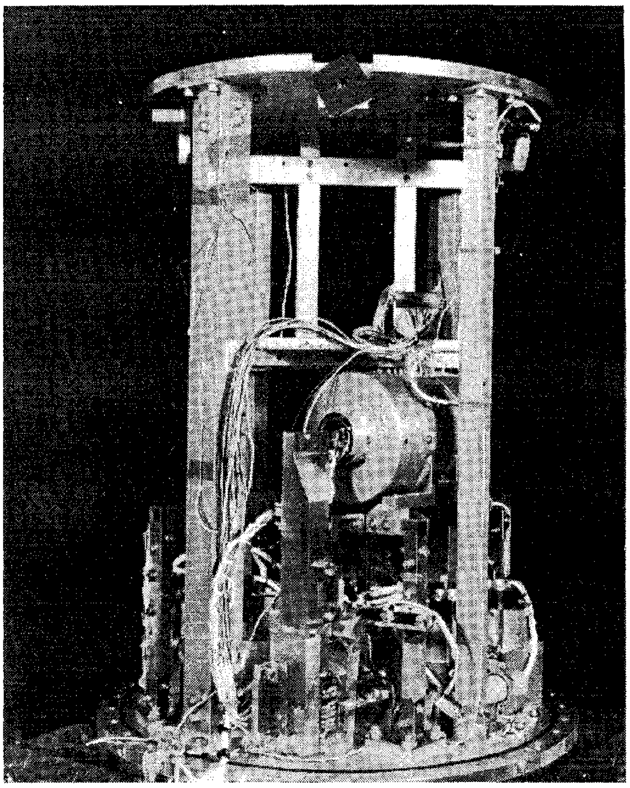


Fig. 5 CRYOTP integrated with BETSU.

Technology (OAST-2) Shuttle bridge pallet. The CRYOTP design is shown in Fig. 5. Except for the experimental payloads, nearly all of the CRYOTP components (including five cryogenic refrigerators) were used on the cryogenic heat pipe (CRYOHP) mission that flew in December 1992 with two oxygen heat pipes. The refrigerators were mounted to the upper end plate. The BETSU, the nitrogen heat pipe, and the electronics (for power distribution, data acquisition, and control) were supported from a frame structure, which was mounted by pillars to the upper end plate. The experiments occupied the middle portion of the CRYOTP can, and the electronics were located near the lower end plate. The significant heat generated by the hardware was conducted to the upper end plate and radiatively rejected to space from either the plate or the canister shell.

Thermal Model and Energy Algorithms

It became apparent early in the ground tests that it was very difficult to separate the effects of sensible (or heat capacity) energy changes from the PCM transition energy changes. The timeline was developed using the PCM transition energy level as the key control parameter. Following the component test, algorithms using a simplified thermal model were developed for the real-time separation of the sensible energy effects. The heat balance algorithms utilized data from a calibrated heat flux meter, a load heater, several temperature probes, and the component material properties to continuously determine the fraction of PCM in the solid and liquid states. The transition energy algorithms were included in the real-time command and data acquisition system for the system and flight test.

The simplified thermal model of the BETSU included about 10 nodes and the associated capacitances (used in the sensible heating calculations), resistances, and boundary conditions (heating, cooling, and parasitic rates). During the BETSU flight experiment, 20 steady-state calibration points were recorded at several different temperatures, cooling rates, and heat loads. These calibration points were used to correlate the thermal model in flight. The model was used to generate and predict the mission and test timelines, to control the experiment in real time, and a postflight data reduction tool.

The transition energy level was calculated by continuously integrating the changes to the total BETSU energy. The total energy change was equal to the applied heater power plus the estimate of the internal parasitic heat load minus the cooling rate through the heat flow meter. The changes in sensible heat energy were then subtracted from the total energy to yield the transition energy. The sensible energy change was equal to the sum of the individual temperature changes of the BETSU components multiplied by their heat capacities and masses. The PCM (2-methylpentane) represented a significant portion of the total heat capacity. The BETSU sensible energy was significant relative to the PCM transition energy. The PCM and its canister had about 200 J/K of sensible heat. A temperature change of a few degrees could result in a change in sensible energy that was significant relative to the 2500 J of maximum transition energy. With the occurrence of two-phase supercooling (and the associated temperature decrease below the transition temperature), the noise effects of sensible heating were magnified.

Ground Tests

Similar versions of the flight timeline were duplicated during the thermal vacuum tests of the CRYOTP system and BETSU components. These tests were successful in verifying the BETSU 1-g performance, confirming the CRYOTP performance, and establishing procedures for controlling the experiment to the required mission timeline.

Flight Mission and Timeline

During the 14-day Shuttle flight, the BETSU completed 13 phases, 55 cycles, and over 200 h of operation. During each cycle, the phase-change material was alternately heated and cooled. Each phase of the flight was composed of multiple cycles and had a unique objective. The objectives of the phases included verifying the design requirements for energy storage and temperature stability over a range of cooling and heating rates, verifying the single-phase-to-single-phase melting and freezing, characterizing the transitions between two-phase liquid–solid and single-phase solid, and verifying the off-design energy storage during two-phase conditions. The mission timeline was achieved by controlling the BETSU cooling rate (using three heaters on the CRYOTP side of the thermal shunt), the heating rate (using the BETSU heater), and the duration of cycles.

Verification of Design Requirements

Table 1 contains a comparison of the BETSU requirements with the actual performance, either measured in test or verified through inspection or analysis. The only requirement that was not met was the temperature stability. Stability of ±1.0 K was required for continuous thermal cycles with 1-W heating and 1-W cooling of the PCM in a two-phase state (no complete melting or freezing) with the alternating removal and addition of 1500 J. As shown in Fig. 6, the flight-tested temperature stability was about ±2.0 K (±1.5 K on the ground). The temperature stability was worse than predicted as a result of the two-phase supercooling. However, the specification was based on a very conservative estimate of the required spacecraft stability for telescope baffles and primary mirror. As the spacecraft design has become more defined, the 120 K stability requirement has expanded and will probably exceed ±2.0 K. Thus, the temperature stability of the BETSU design should be adequate for the flight application.

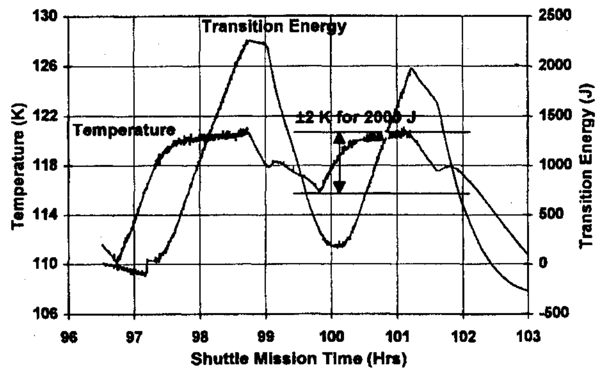


Fig. 6 Flight-test temperature stability (phase 4, cycle 1 of flight test; 1.0-W heating, 1.0-W cooling).

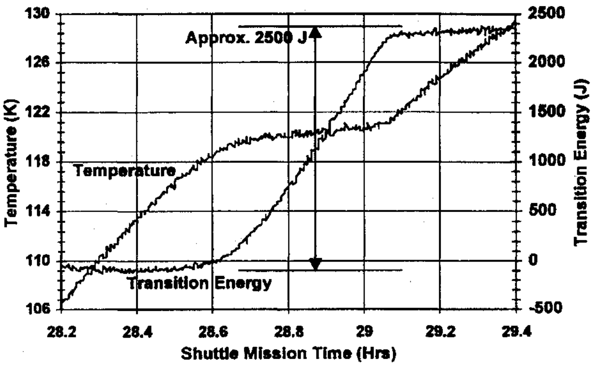


Fig. 7 Flight-test storage capacity (calibrations from flight test; 2.2-W net heating).

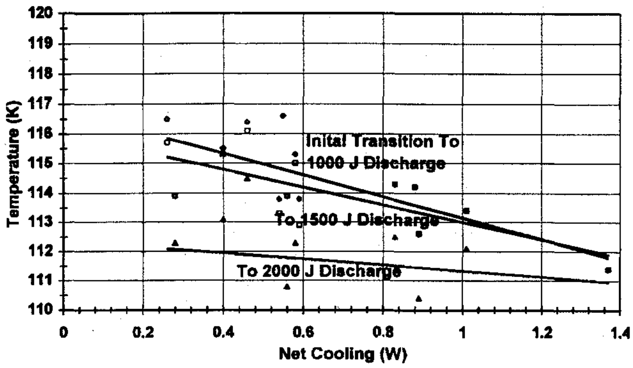


Fig. 9 Summary of single-phase supercooling: temperature vs rate and energy discharge.

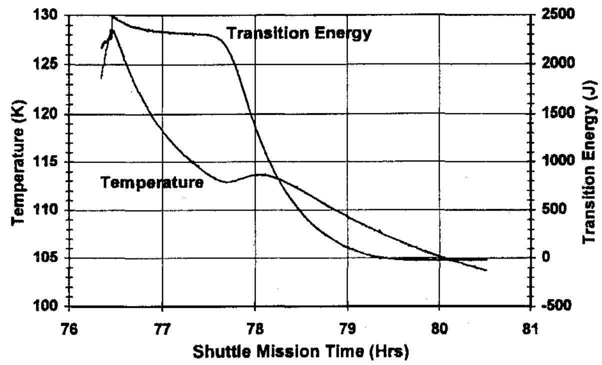


Fig. 8 Example of single-phase supercooling (phase 2, cycle 3 from flight test; 1.0-W cooling).

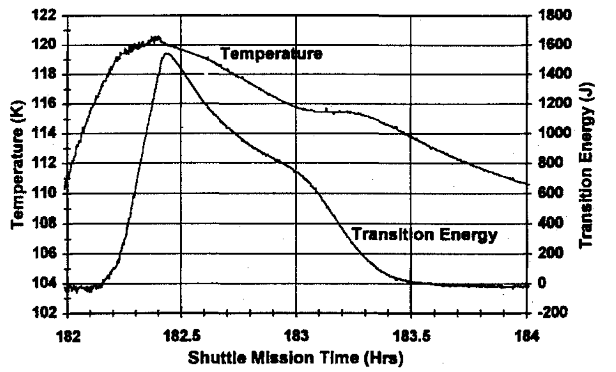


Fig. 10 Example of two-phase supercooling (phase 5, cycle 3 of flight test; 0.7-W cooling).

The thermal storage unit was charged with 35 g of 2-methylpentane. Based on the latent heat, the BETSU had a theoretical transition energy capacity of 2472 J. The requirement specified that the thermal storage unit have a minimum energy storage efficiency (or effectiveness) of 60% to yield a capacity of at least 1500 J. As demonstrated many times during the ground and flight tests and shown in Fig. 7, the actual BETSU efficiency (from pure liquid to solid or vice versa) was nearly 100%, with a latent capacity of about 2500 J (with a measurement error of roughly ± 50 J). Including sensible heat, this 2500 J of latent energy capacity corresponded to over 3000 J of total capacity.

Single- and Two-Phase Heating

In contrast to cooling the transition temperature during the heating of the PCM was not a significant function of the heating rate. The initial phase transition temperature during heating was between about 119 and 119.5 K during the system test.

Single-Phase Supercooling

The classical single-phase supercooling phenomenon is evident in the temperature and transition-energy plot in Fig. 8 (where phase transition does not occur until about 6 K below the 119.3 K melting point). Supercooling occurs when a liquid is cooled during sufficiently vibration- and contamination-free conditions. Under these conditions, the material can remain a liquid even as its temperature decreases well below its transition temperature.

Eventually, the liquid supercools to a low enough temperature to initiate crystallization. Once crystals are formed, the supercooled liquid rapidly freezes. The freezing releases latent (or transition) energy. The rapid freezing can release sufficient energy to raise the PCM temperature. However, even though the temperature rises, it is still below the transition point and the freezing continues.

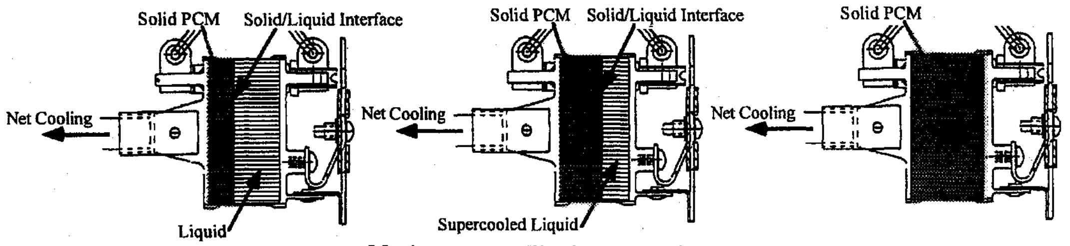
Previous tests of pure 2-methylpentane indicated that at least 40 K (below the 119.3 K transition temperature) of supercooling can occur. The addition of 3% acetone to the 2-methylpentane was found to significantly reduce the amount of supercooling and was the BETSU baseline working fluid mixture.

The cooling rate dependence of the single-phase supercooling transition temperature is shown in Fig. 9 as the initial transition curve. As the cooling rate increases, the temperature at which phase transition initiates decreased (about 3 K for every 1-W increase). Figure 9 also indicates the temperature decrease associated with different levels of energy discharge.

Two-Phase Supercooling

Supercooling of the BETSU while cooling from a partially frozen two-phase liquid was an unexpected phenomenon that was observed in the both the ground and the flight tests. The two-phase supercooling is evident in the temperature and transition-energy plots in Fig. 10 and illustrated in the schematic in Fig. 11. Once both solid and liquid phases are present, minimal supercooling was predicted. With the solid phase present, the liquid has crystallization sites available for freezing at the solid interface. However, the tests indicated that, even when cooling from a two-phase state, supercooling continued to occur (albeit to a lesser extent than for the complete liquid freezing).

The possible explanation behind this two-phase supercooling is that the crystallization rate is limited by the solid–liquid interface area and is exceeded by the cooling rate. The BETSU design had the heater at one of the canister, the cooling interface at the other end, and continuous aluminum fins that provide conduction paths through the PCM from one canister endplate to the other. Thus, during cooling, a fairly well-defined liquid–solid interface should exist in the canister and be parallel to the endplates. The liquid–solid interface area available for crystallization should be approximately equal to the canister cross section [π (radius)^2]. The theory is that the applied BETSU cooling rates exceed the maximum rate at which solid can crystallize over the limited interface area. This resulted in the supercooling of liquid that was not adjacent to the interface. While solid material froze at the maximum rate at the interface, the liquid behind the interface continued to supercool below its transition temperature unit nearly all of it rapidly froze. Thus, the liquid behind the interface experienced single-phase supercooling when the cooling rate exceeded the interface crystallization rate.



Cooling initiated with both solid and liquid PCM present

Maximum crystallization rate at interface with supercooled liquid behind interface

Supercooled liquid transitions to solid when critical temperature is reached

Fig. 11 Two-phase supercooling from partially frozen liquid: ■, solid PCM and □, liquid PCM.

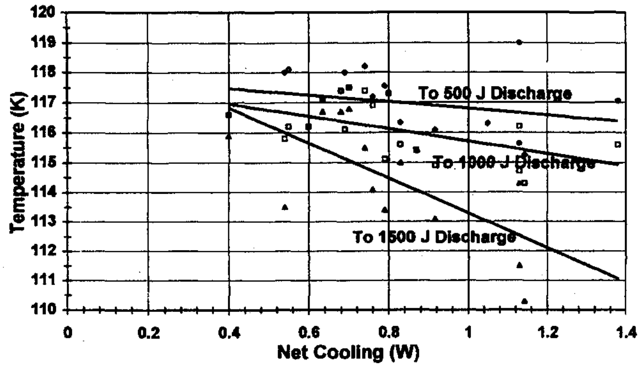


Fig. 12 Summary of two-phase supercooling: temperature vs rate and energy discharge.

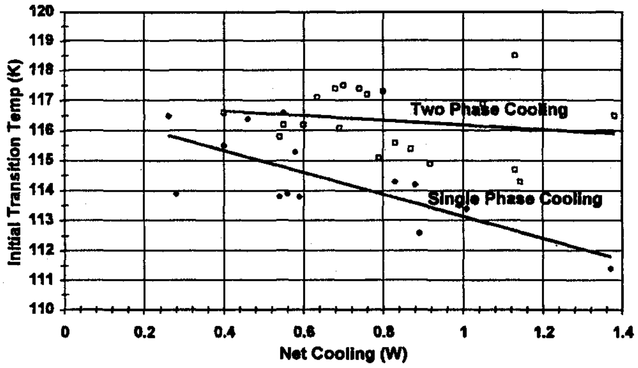


Fig. 13 One- vs two-phase supercooling: initial transition temperature.

The transition-energy plots support the two-phase supercooling theory and indicate the existence of two cooling segments. Initially during the cooling, a moderate-rate phase change occurs at the solid–liquid interface. However, once the liquid behind the interface reaches its supercooling transition temperature, the phase change rate increases significantly.

During two-phase supercooling, the dependence of the temperature decrease on cooling rate and energy discharge is shown in Fig. 12. Combined with the fact that the heating transition temperature is nearly constant, this plot allows the user to predict the temperature stability given the energy storage and rate requirements.

As shown in Fig. 13, the temperature of the PCM when the rapid phase transition occurs was significantly higher for two-phase than for single-phase supercooling. As the cooling rate increased, the phase transition occurred at lower temperatures (about a 4 K decrease for every 1-W increase in net cooling).

Comparison of 1-*g* with 0-*g* Performance

Except for temperature stability, there were minimal differences between the performance of the BETSU in the 1-*g* ground tests and the 0-*g* flight. The temperature stability was worse for the 0-*g* conditions (±2.0 K) than for the 1-*g* tests (±1.5 K). The decrease in performance can probably be attributed to the reduced contact interface area in 0 *g* between the aluminum fins and the liquid PCM.

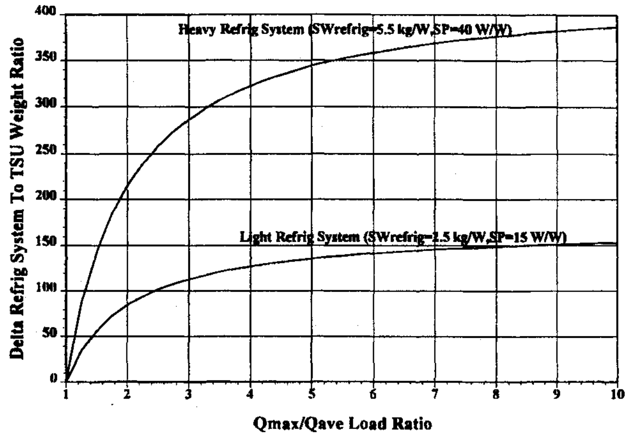


Fig. 14 Refrigerator system weight savings with PCM.

Technology Weight and Cost Benefits

Based on the ground- and flight-test data, trade studies were performed, which show the weight and cost benefits of the BETSU technology. The weight of a cryogenic refrigerator cooling system with the BETSU PCM was compared with those of systems without a TSU and also of systems having a single-phase sensible-heat TSU.

For the comparison with systems without a TSU, a range of weight and power penalties was assumed, based on data for existing long-life space cryogenic refrigerators. Figure 14 is a plot of the ratio of the reduction in the refrigerator-system weight using the BETSU PCM technology to the weight of the PCM. The analysis assumed 3000 J of energy storage, a 4-W maximum heat load, and a system power penalty of 0.4 kg per watt of refrigerator input power. The system power penalty estimates the weight increase in the power system for a spacecraft as well as the weight of the integrated cooling system to support the refrigerators (structure, heat transport, etc.). The plot contains two curves: for a heavy refrigerator system (with a refrigerator weight penalty of 5.5 kg per watt of cooling and a refrigerator power efficiency of 40 W per watt of cooling), and for a light refrigerator system (with weight penalty of 2.5 kg per watt of cooling and a power efficiency of 15 W per watt of cooling). The figure indicates that for typical ratios of maximum to minimum heat loads, the BETSU saves over 100 times its own weight in reduced cooling system weight.

When using a single-phase sensible-heat device (SHD) as a TSU, the temperature of the cooled component is allowed to rise during peak heat loads while the heat capacity of the sensible-heat material absorbs the load in excess of the average cooling. Figure 15 is a plot of the weight ratio of several SHDs (copper, aluminum 6061, and magnesium) to the BETSU PCM as a function of allowable temperature rise. For a typical allowable temperature rise of 4 K, the BETSU is five times lighter than any conventional SHD.

The weight savings using the BETSU technology can be roughly converted to cost by using an estimate of the launch weight penalty. The savings can be in the millions of dollars for a multisatellite constellation.

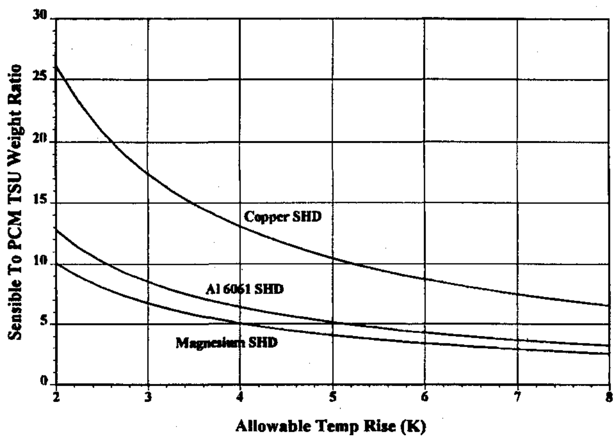


Fig. 15 PCM weight savings vs sensible (single-phase) TSU.

Summary and Conclusions

This paper has presented a summary of the design, development, and verification of the BETSU Shuttle experiment. The BETSU utilized 2-methylpentane as a 120 K PCM and was flown onboard the Shuttle in March 1994. The BETSU program objectives were to design and fabricate a cryogenic TSU for space applications, to verify the TSU's flight performance, and to correlate the flight and ground test results. There had been very limited experience with the space flight of cryogenic PCMs and the effect of zero gravity on TSU performance. Only one spacecraft program had previously flown cryogenic PCM units, and those units had transition temperatures that were over 50 K higher than that of BETSU.

The program were successful in verifying the 1- and 0-*g* TSU performance for multiple freeze–thaw cycles over a range of heating and cooling rates and depths of energy discharge (storage). During the 14-day Shuttle flight, the BETSU completed 13 phases, 55 cycles, and over 200 h of operation.

The tests provided excellent data for the evaluation of the classical single-phase (from a complete liquid) supercooling phenomena. The tests also indicated the unexpected occurrence of supercooling even when the solid phase was initially present. The two-phase supercooling is attributed to the cooling rate exceeding the maximum crystallization rate (for the limited solid–liquid interface area). All design requirements were met except for temperature stability. The BETSU demonstrated a 2500-J latent (over 3000-J total) capacity (with a PCM effectiveness of nearly 100%) vs the 1500-J requirement. Though outside the ± 1.0 K requirement for 1500 J, the TSU stability of ± 2.0 K appears to be adequate for the spacecraft application.

Space applications for a cryogenic TSU include the storage of energy for the cooling of temperature-sensitive sensor components such as focal planes, optics, mirrors, and telescopes, which have variable heat loads. Based on test data, trade studies were performed, which show the significant weight and cost benefits of the BETSU technology. When a TSU is utilized in series with a refrigerator or radiator, the cooling-system size can be significantly reduced to accommodate the average instead of the maximum heat load. The BETSU can result in a weight saving to the cooling system of over 100 times its own weight. Compared to conventional single-phase SHDs, the BETSU is over seven times lighter. For a constellation of spacecraft, the cumulative weight savings can result in a launch-cost reduction of millions of dollars.

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Associate Editor