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Experimental Results From the Thermal Energy Storage–2 (TES–2) Flight Experiment

Carol Tolbert
Glenn Research Center, Cleveland, Ohio

April 2000

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EXPERIMENTAL RESULTS FROM THE THERMAL ENERGY STORAGE-2 (TES-2) FLIGHT EXPERIMENT

Carol Tolbert
National Aeronautics and Space Administration
Glenn Research Center
Cleveland, Ohio 44135

SUMMARY

Thermal Energy Storage-2 (TES-2) is a flight experiment that flew on the Space Shuttle Endeavour (STS-72), in January 1996. TES-2 originally flew with TES-1 as part of the OAST-2 Hitchhiker payload on the Space Shuttle Columbia (STS62) in early 1994. The two experiments, TES-1 and TES-2 were identical except for the fluoride salts to be characterized. TES-1 provided data on lithium fluoride (LiF), TES-2 provided data on a fluoride eutectic (LiF/CaF_2). Each experiment was a complex autonomous payload in a Get-Away-Special payload canister. TES-1 operated flawlessly for 22 hr. Results were reported in a paper entitled, *Effect of Microgravity on Materials Undergoing Melting and Freezing—The TES Experiment*, by David Namkoong et al. A software failure in TES-2 caused its shutdown after 4 sec of operation. TES-1 and 2 were the first experiments in a four experiment suite designed to provide data for understanding the long duration microgravity behavior of thermal energy storage salts that undergo repeated melting and freezing. Such data have never been obtained before and have direct application for the development of space-based solar dynamic (SD) power systems. These power systems will store energy in a thermal energy salt such as lithium fluoride or a eutectic of lithium fluoride/calcium difluoride. The stored energy is extracted during the shade portion of the orbit. This enables the solar dynamic power system to provide constant electrical power over the entire orbit.

Analytical computer codes were developed for predicting performance of a space-based solar dynamic power system. Experimental verification of the analytical predictions were needed prior to using the analytical results for future space power design applications. The four TES flight experiments were to be used to obtain the needed experimental data. This paper will address the flight results from the first and second experiments, TES-1 and 2, in comparison to the predicted results from the Thermal Energy Storage Simulation (TESSIM) analytical computer code. An analysis of the TES-2 data was conducted by Cleveland State University Professor, Mounir Ibrahim. TESSIM validation was based on two types of results; temperature history of various points on the containment vessel and TES material distribution within the vessel upon return from flight.

The TESSIM prediction showed close comparison with the flight data. Distribution of the TES material within the vessel was obtained by a tomography imaging process. The frozen TES material was concentrated toward the colder end of the canister. The TESSIM prediction indicated a similar pattern. With agreement between TESSIM and the flight data, a computerized representation was produced to show the movement and behavior of the void during the entire melting and freezing cycles.

INTRODUCTION

The Thermal Energy Storage (TES) experiments were designed to provide data for understanding the long-duration microgravity behavior of thermal energy storage fluoride salts that undergo repeated melting and freezing. Such data have never been obtained before and have direct application to using space based solar dynamic power systems. These power systems will store solar energy in a thermal energy salt such as lithium fluoride (LiF) or a eutectic of lithium fluoride/calcium difluoride ($LiF-CaF_2$). The energy is stored as the latent heat of fusion when the salt is melted by absorbing solar thermal energy. The stored energy is then extracted during the shade portion of the orbit, enabling the solar dynamic power system to provide constant electrical power over the entire orbit.

The principal investigator of the TES-2 experiment was Carol Tolbert, of the Power & On-Board Propulsion Technology Division at the NASA Glenn Research Center (GRC), Cleveland, Ohio. Project management for the experiment was performed by Frank Robinson Jr., of the GRC Space Experiments Division. Task work was accomplished by an in-house project team consisting of GRC and NYMA Technology, Inc., engineers and technicians. The project was supported by the NASA Headquarters Office of Space Access and Technology (OAST).

BACKGROUND

An advanced solar dynamic power system utilizing either a Brayton or Stirling Power Conversion System has the potential for high efficiency with weight, cost and area advantages over other solar power systems. When operating in a low earth orbit (LEO), the power system will experience a sun/shade cycle which is approximately 60 min of sun and 34 min of shade. Delivery of continuous electric power over the entire orbit requires a method of storing energy during the sun cycle for use during the shade cycle. An efficient method of accomplishing this is to utilize the high heat-of-fusion associated with TES phase change materials. These TES materials possess the physical properties that are desirable in advanced solar dynamic heat receiver designs. Such properties include high values of the heat-of-fusion, very low toxicity and general compatibility with containment materials in a vacuum environment. However, they also possess properties of low thermal conductivity, low density, and most significantly, high specific-volume change with phase change. This last characteristic leads to formation of a void, or voids, that can degrade heat-receiver energy transfer performance by the formation of local hot spots on the container wall or local distortion of the wall. Since void formation and location are strongly influenced by gravitational forces, it is necessary to be able to understand and predict this phenomenon in the on-orbit microgravity environment in order to achieve optimum design for the heat receiver canisters. This is especially important since the canister and heat receiver are significant elements of the overall weight and cost of a SD power system.

Dr. David Jacqmin, of the GRC Internal Fluid Mechanics Division, has developed the TESSIM computer code. TESSIM is a time-accurate three-dimensional code that calculates the behavior of phase change material within the canister. The code can also predict the migration of voids and the resulting thermal behavior of SD receiver canisters. It is currently useful as a qualitative design tool but requires further experimental validation before it can be reliably used for critical design decisions. Once thoroughly validated, the code will be invaluable in the detailed design of lighter, more efficient solar dynamic receivers.

OBJECTIVE

The intent of this payload is to successfully operate the TES-2 experiment as was originally planned for the STS-62 flight mission. The objective of this flight project is to develop and flight-test a long-duration, microgravity experiment for obtaining data that characterize the void behavior in TES salts. This project represents the first experimental data in which TES materials will be subjected to an extended microgravity environment during a number of phase change cycles.

EXPERIMENTAL APPROACH

Four TES experiments are necessary to provide sufficient data to validate the TESSIM computer code. The first two flight experiments, TES-1 and TES-2, were developed to obtain data on TES material behavior in cylindrical, Haynes 188 steel canisters. The TES-1 and TES-2 experiments were identical except for the fluoride salts in each canister. TES-1 contained lithium fluoride (LiF) salt which melts at 1121 K, and TES-2 contains a fluoride eutectic salt lithium fluoride-calcium difluoride (CaF_2) which melts at 1042 K. Flight data are stored in the random access memory of each autonomous payload. A post flight tomographic scan of each TES canister provided data on void location, size, and distribution for comparison with TESSIM predictions.

Experiments TES-3 and TES-4 are developed and will obtain data on TES material behavior in wedge-shaped canisters. TES-3 will use LiF salt, with a canister interior that is wetting to the salt. TES4 will use the same LiF salt with a canister interior that is non-wetting to the salt. To date, neither TES-3 or TES-4 have flown.

FLIGHT HARDWARE

The TES-2 payload consists of the three hardware subsystems (fig. 1). The top section, or the experiment section (fig. 2), is made up of a cylindrical canister assembly, a two-zone radiant heater, high temperature multilayer insulation (MLI), and an MLI shutter and drive mechanism. The entire canister assembly is enclosed within the MLI and MLI shutter. The primary components of the canister assembly are the Haynes-188 canister, the boron nitride radiant heater, and the thermal radiator disc. The canister has an annular cross section with a solid conductor rod of Haynes-188 in the center of the annulus. The purpose of the rod is to conduct heat away from the inside of the canister to the radiator disk, simulating the thermal response of a SD power system. The annular cylindrical volume contains the TES salt. The canister is welded closed in a vacuum after the salt is loaded into the canister. The experiment section also includes temperature measurement instrumentation, consisting of swaged 20-mil, type K thermocouples at many different locations in the section.

Thermal energy needed to melt the TES salt each canister is provided by the two-zone radiant heater. The cylindrical heater material consists of boron nitride with a graphite conductive path. Two radiant heater zones create a temperature difference in the salt resulting in buoyancy forces in the molten salt which are large compared to the low gravitational forces present during space flight. In general the buoyancy forces cause any void to move towards the high temperature zone of the heater. Prior to launch the void is preferentially located by melting the salt in the canister, with the canister in the desired orientation in a 1-g field.

During the freeze portion of the cycle the MLI shutter mechanism opens the shutter doors (#2, fig. 2) to allow the radiator disk to transfer heat to the top of the GAS can lid. At the completion of the freeze cycle the mechanism closes the shutter doors in preparation for the next heating cycle or at the completion of the experiment.

The middle section of the TES-2 payload is occupied by the data acquisition and control system (DACS), which controls heater power levels and the MLI shutter operation. The DACS also periodically records the instrumentation output signals. An 80386SX central processing unit is used in the DACS to provide the needed data collection speed and processing. Solid state memory is used for on-orbit data storage of temperatures and experiment engineering data. In addition to the DACS, independent high-temperature control units are located in this section on order to provide added control for maintaining a safe maximum temperature level associated with these 1200 K temperature level experiments.

The bottom section consists of a batter box that contains 23 silver-zinc cells which provide all the electrical energy required for the two-zone radiant heater and the DACS. Each cell contains a potassium hydroxide electrolyte. The initial electrical energy level provided by the battery box for each payload prior to placement in the shuttle is about 6300 Wh, which accounts for any battery degradation over time. The energy expected to be used on-orbit by each experiment is about 3400 Wh.

Thermal energy needed to melt the TES salt in the canister is provided by a two zone heater. The cylindrical heater material consists of boron nitride with a graphite conductive path. Two radiant heater zones create a temperature difference in the salt which causes void movement in the TES salt. The void movement is from its initial location toward the high temperature zone of the heater.

The TES-2 experiment was integrated on the SLA-01/GAS bridge, along with other experiments and placed within the payload bay of the shuttle. TES-2 occupied approximately 0.14 m^3 (5.0 ft^3) and had a mass of approximately 110 kg prior to placement in the GAS payload container.

OPERATION SEQUENCE

The operations sequence for TES-2 is shown in figure 3. Upon launch, the GAS Payload container is vented into the payload bay and ultimately to space. After a minimum of 24 hr, which provides for an adequate vacuum environment to be achieved in the payload, the experiment is activated by an astronaut and begins a 5-fur heat-up phase. After the heatup phase the on-orbit melt-and-freeze thermal cycles begin. A total of four thermal cycles over a 10-hr period are needed for characterizing the void behavior of the TES salt in a 10^{-3}g environment.

The experiment heating cycle was nominally 60 min to simulate the solar heating period for a typical LEO SD power system. The actual heating cycle time was about 80 min, due to the requirement to minimize thermal gradients and hence thermal stress of the Haynes 188 canister, and from the rod to the thermal radiator disc. The disc radiates the stored thermal energy (latent heat of fusion for the salt) to the GAS payload container upper end-plate. This plate in turn radiates the thermal energy out to space. At the end of the freeze phase, the MLI shutter is then closed and the next cycle begins.

Flight data is recorded at 5-min intervals and primarily consists of the time variation of temperatures and heater power during the heat-up to incipient melt, melt-and-freeze, and cool-down phases of the experiment. Other data include the remaining in the battery cells. After the thermal cycles are completed and the experiment section cools down to approximately 750 K, the experiment is deactivated by the crew. At this point, a vent valve in the GAS payload container is closed to seal off the GAS container prior to the shuttle de-orbit.

FLIGHT DATA AND RESULTS

TES-2 was flown on STS-72 on January 11, 1996. The experiment was activated during the crew sleep period so that all four cycles coincided with a low 9 period. TES-2 operated for about 14 hr in space.

From the data collected on-orbit figure 4 shows one set of thermocouple locations and the temperatures from the canister recorded during the four melt/freeze cycles of the LiF/CaF_2 salt. All four melt/freeze cycles were identical. In general, after the first melt/freeze cycle, the temperatures show repeatability from cycle to cycle at each location.

After the data was downloaded from the experiment, TES-2 was partially disassembled and the canister removed. Computer-Aided Tomographic (CAT) scanning was performed on the canister at Wright Patterson Air Force Base in order to record the final location and distribution of the voids in the canister. In general TESSIM predicted void behavior accurately and agreed with the tomographic data. From the tomographic photos it appears the void did not migrate as anticipated, instead the void started to move from the starting position at 180° to the 0° position figure 4. With additional melt/freeze cycles the void would have completely migrated to the 0° position. In general, TESSIM appears to have predicted void behavior accurately, as is evidenced by comparing the tomographic images with the TESSIM images. The initial results from TES-1 and 2, of high-temperature fluoride salt melting and freezing under microgravity, do not absolutely validate TESSIM, but the comparison of the predictions with the data establishes a basic confidence in the code. Future experiments such as TES-3 and 4 will contribute further validation of TESSIM.

CONCLUSION

The TES-1 and 2 flight experiments have provided the first experimental data on the long duration effects on TES salts used for space-based solar dynamic power systems. Good correlation between the predicted on-orbit characteristics of the salt and the actual flight data indicate that, for the configuration tested, the TESSIM code is basically sound. The additional flight experiments in the four experiment suite will provide the opportunity for the complete validation of the TESSIM code. The flight experiments will provide data from different canister configurations and both wetting and non-wetting interfaces for the TES salts. In addition, the effect of heat leakage will be studied more closely.

REFERENCES

1. Namkoong, D., Jacqmin, D., and Szaniszio, A.: "Effect of Microgravity on Material Undergoing Melting and Freezing-The TES Experiment," NASA TM–106845, Lewis Research Center, Cleveland, Ohio. Presented at the 33 Aerospace Sciences Meeting and Exhibit, sponsored by the American Institute of Aeronautics and Astronautics, Reno, Nevada, January 1995.
2. Wald, L.W., Tolbert, C., and Jacqmin, D.: "Experimental Results from the Thermal Energy Storage-1 (TES-1) Flight Experiment," Reprint from CP–3310, "1995 Shuttle Small Payloads Symposium," sponsored by NASA Goddard Space Flight Center, Camden Yards, Baltimore, Maryland, September 25–28, 1995.
3. Eliasen, D.S.: "Computed Tomography Inspection of thermal Storage Unit," NASA Scanning Services Agreement 94-003 ARACOR, Wright Patterson Air Force Base, Ohio.
4. Ibrahim, M., Kerslake, T., Sokolov, P., and Tolbert, C.: "Experimental and Computational Investigations of Phase Change Thermal Energy Storage Canisters," NASA TM–107382, Lewis Research Center, Cleveland, Ohio. Prepared for the International Congress of Fluid Dynamics and Propulsion sponsored by the American Society of Mechanical Engineers and Cairo University, Cairo, Egypt, December 29–31, 1996.

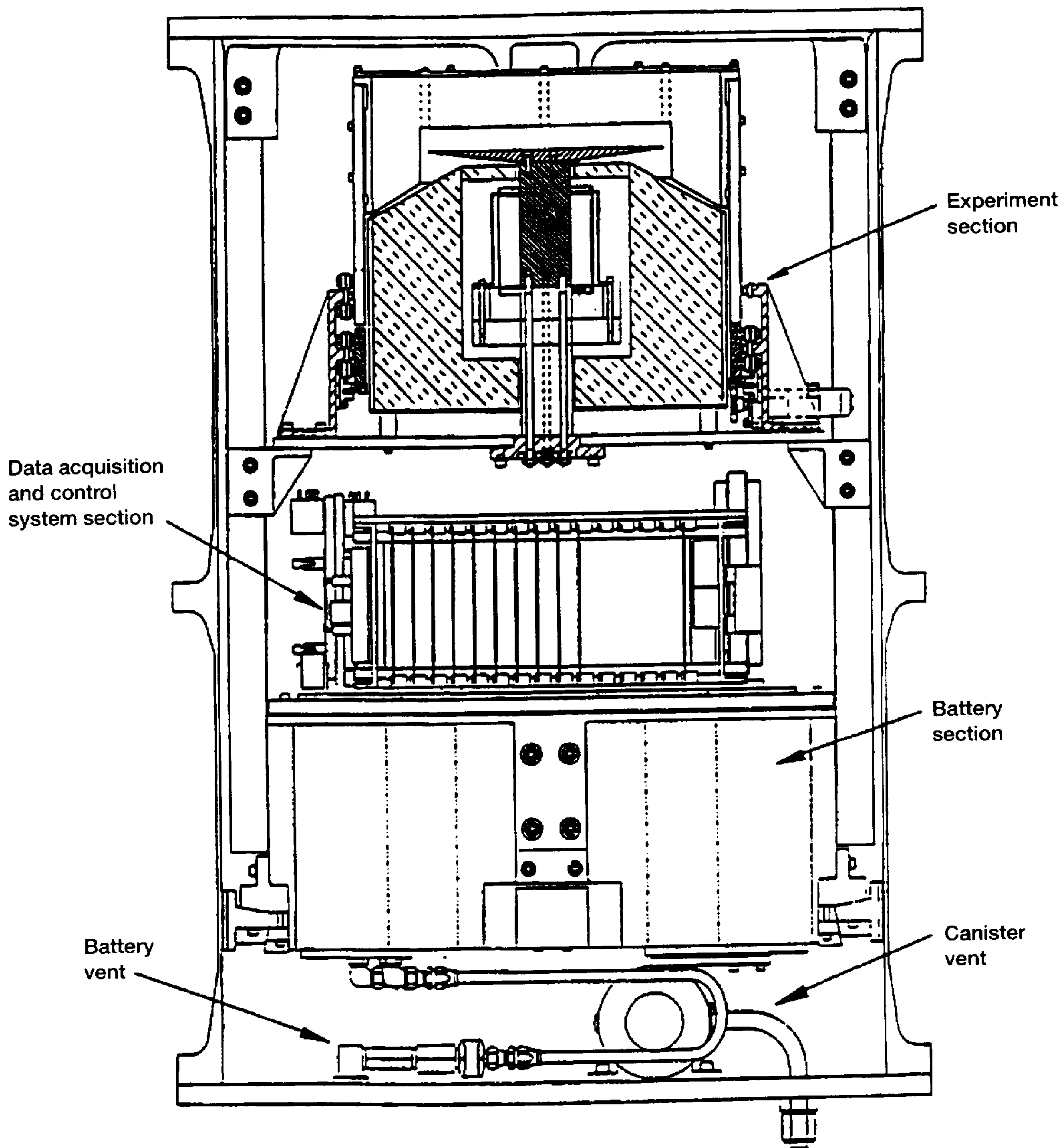

Figure 1.—TES–2 payload.

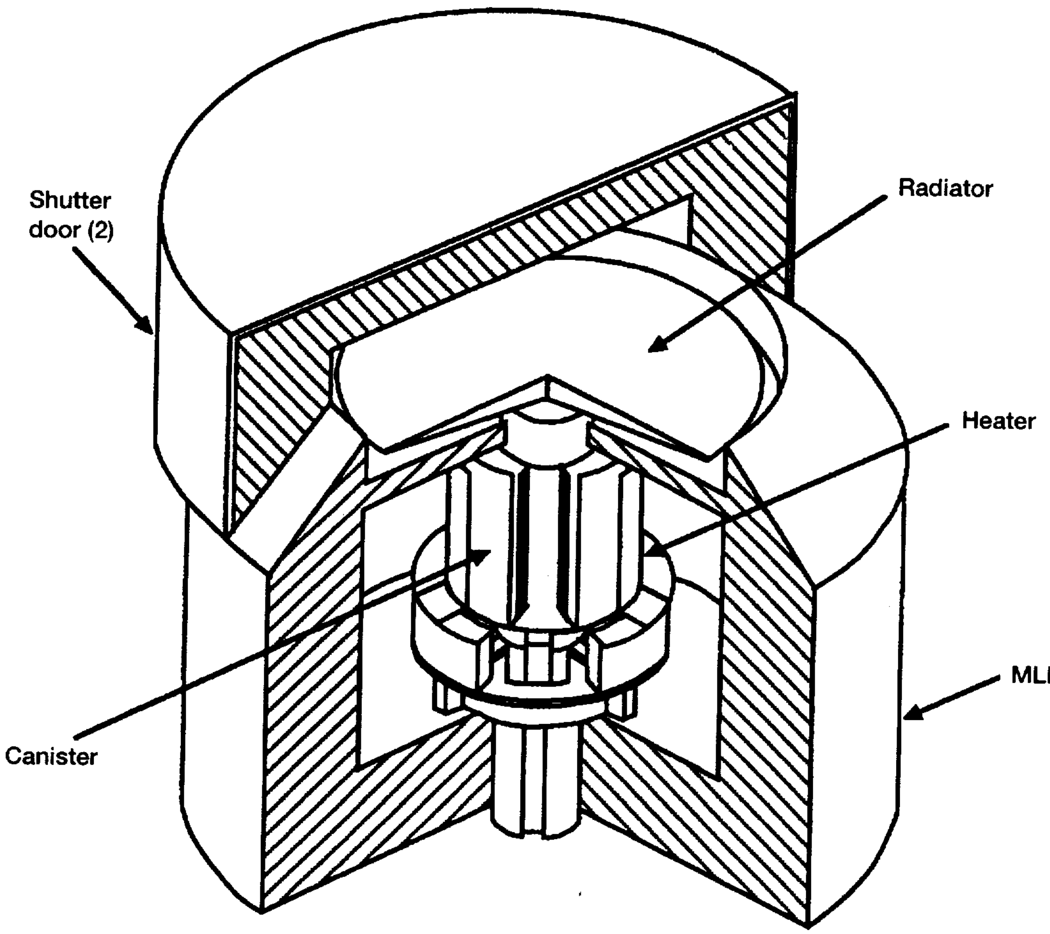

Figure 2.—TES–2 experiment section.

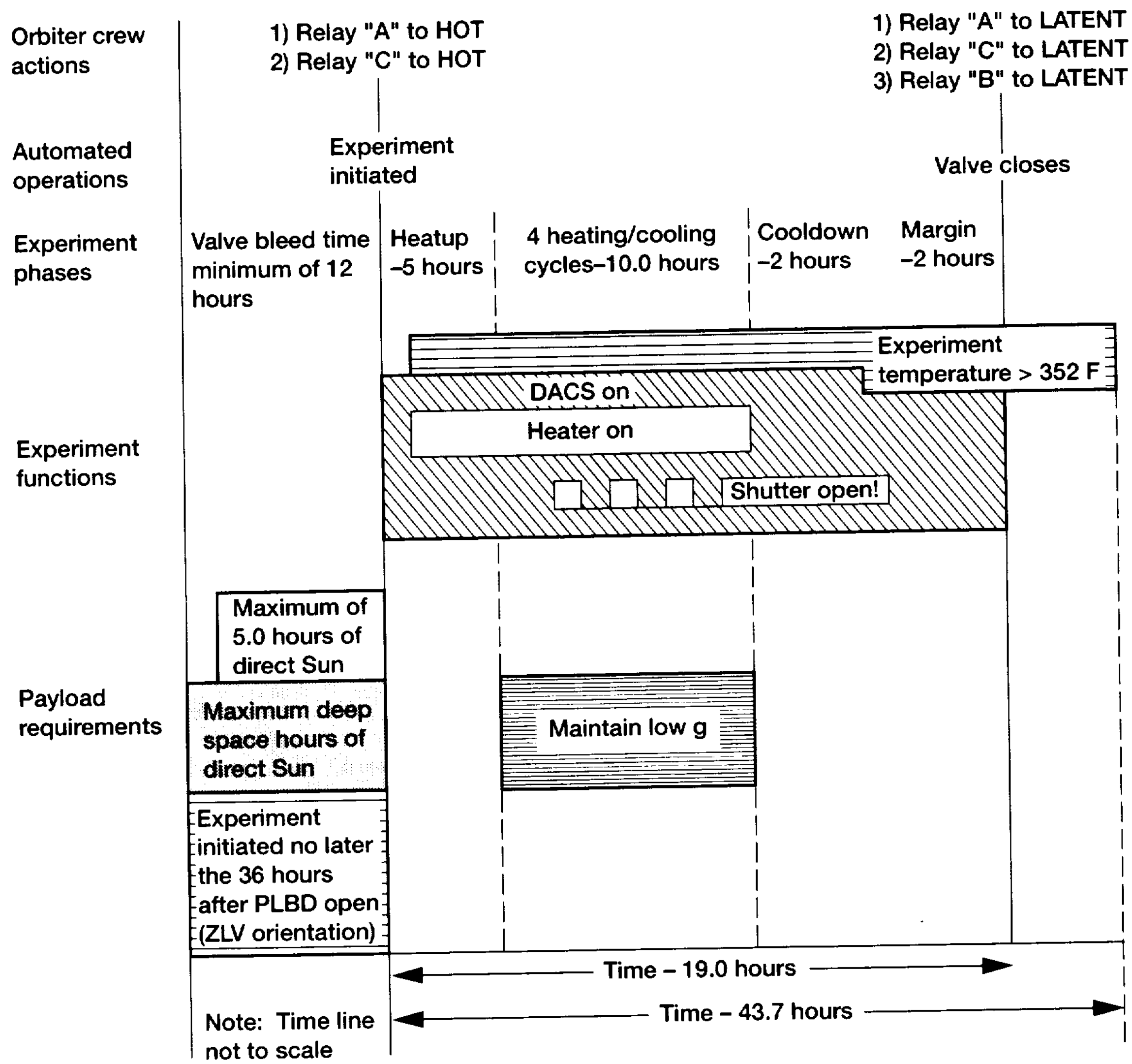

Figure 3.—TES-2 on-orbit operations timeline.

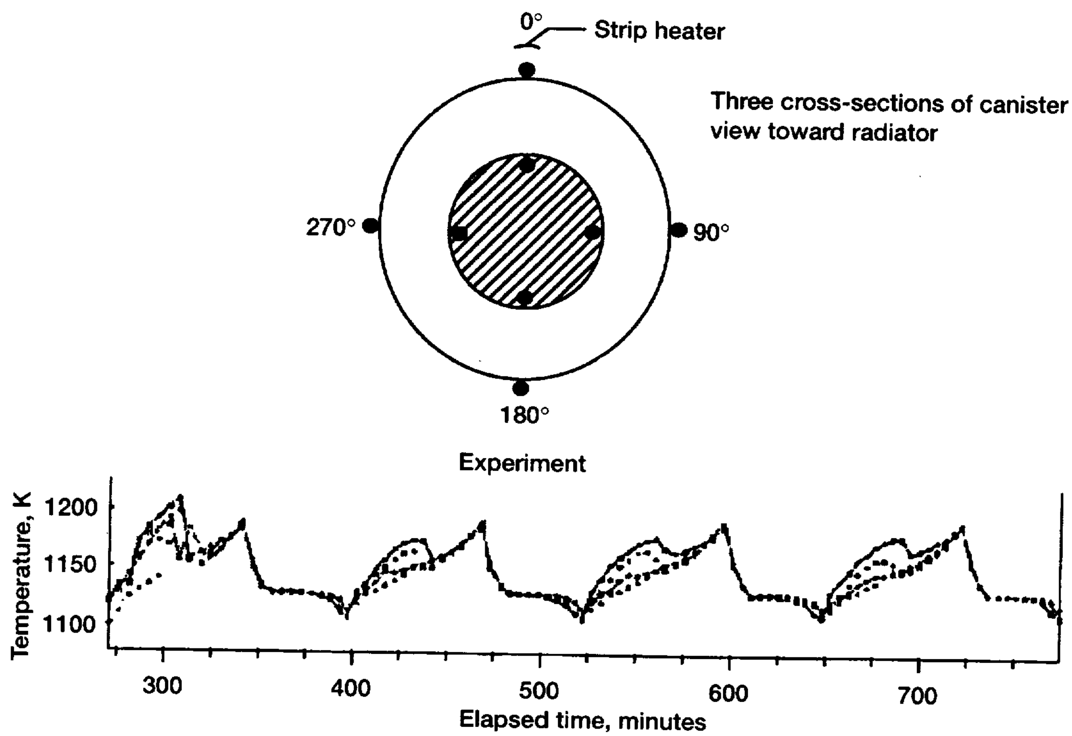

Figure 4.—Canister temperature versus time.

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13. ABSTRACT *(Maximum 200 words)*

The Thermal Energy Storage-2 (TES-2) is a flight experiment that flew on the Space Shuttle Endeavour in January 1996. TES-2 is one out of four TES experiments planned for space flight experimentation. The experiment was designed to provide data for understanding the long duration microgravity behavior of thermal energy storage salts that undergo repeated melting and freezing. Such data have never been obtained before and have direct application for the development of space-based solar dynamic power systems. These power systems will store energy in a thermal energy salt which is lithium fluoride or a eutectic of lithium fluoride/calcium difluoride. The stored energy is extracted during the shade portion of the orbit. This enables the solar dynamic power system to provide constant electrical power over the entire orbit.

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