EXPERIMENTAL RESULTS FROM THE THERMAL ENERGY STORAGE-1 (TES-1) FLIGHT EXPERIMENT

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ABSTRACT

The Thermal Energy Storage-1 (TES-1) is a flight experiment that flew on the Space Shuttle Columbia (STS-62), in March 1994, as part of the OAST-2 mission. TES-1 is the first experiment in a four experiment suite 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 for the development of space-based solar dynamic (SD) power systems. These power systems will store solar energy in a thermal energy salt such as lithium fluoride or calcium fluoride. 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 have been developed for predicting performance of a space-based solar dynamic power system. Experimental verification of the analytical predictions is needed prior to using the analytical results for future space power design applications. The four TES flight experiments will be used to obtain the needed experimental data. This paper will focus on the flight results from the first experiment, TES-1, in comparison to the predicted results from the Thermal Energy Storage Simulation (TESSIM) analytical computer code.

The TES-1 conceptual development, hardware design, final development, and system verification testing were accomplished at the NASA Lewis Research Center (LeRC). TES-1 was developed under the In-Space Technology Experiment Program (IN-STEP), which sponsors NASA, industry, and university flight experiments designed to enable and enhance space flight technology. The IN-STEP Program is sponsored by the Office of Space Access and Technology (OSAT).

INTRODUCTION

The Thermal Energy Storage (TES) experiments are 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-1 experiment was David Namkoong, of the Space Power Technology Division at the NASA Lewis Research Center (LeRC), Cleveland Ohio. Project management for the experiment was performed by Andrew Szaniszlo, of the LeRC Space Experiments Division. Task work was accomplished by an in-house project team consisting of LeRC and NYMA Technology, Inc., engineers and technicians. The project was supported by the NASA Headquarters Office of Space Access and Technology.

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 on the order of 60 minutes sun and 34 minutes 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 are generally non-corrosive. 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 LeRC Internal Fluid Mechanics Division, has developed the TESSIM (Thermal Energy Storage Simulation) computer code. TESSIM can 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.

PROJECT OBJECTIVE

The objective of this flight project work is to develop and flight-test long-duration microgravity experiments for obtaining data that characterize the void behavior in TES fluoride salts. This project is the first in which TES materials will be subjected to an extended microgravity environment during a number of phase change cycles.

EXPERIMENT APPROACH

Four experiments are needed to provide the necessary data to validate the TESSIM computer code. The first two flight experiments, TES-1 and TES-2, were developed to obtain data on PCM behavior in cylindrical canisters. The TES-1 and TES-2 experiments are identical except for the fluoride salts to be characterized; TES-1 uses lithium fluoride (LiF) salt which melts at 1121 °K, and TES-2 uses a fluoride eutectic salt (LiF/CaF_2) which melts at 1042 °K. Both experiments use a sealed cylindrical canister fabricated from Haynes-188 steel to contain the salts. Flight data are stored in the random access memory of each payload. A postflight tomographic scan of each TES canister will provide data on void location, size, and distribution for comparison with preflight predictions.

The final two experiments, TES-3 and TES-4, currently under development, will obtain data on PCM behavior in wedge-shaped canisters. TES 3 will use LiF salt, with a canister interior that is wetting to the salt. TES 4 will use the same LiF salt with a canister interior that is non-wetting to the salt.

FLIGHT HARDWARE

The TES-1 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 in 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) 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-1 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 in 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 battery 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.

The TES-1 experiment was mounted on a HH-M bridge, along with the other OAST-2 experiments, and placed within the payload bay of the shuttle. TES-1 occupied roughly 0.14 m^3 (5 $ft.^3$) and had a mass of roughly 110 kg prior to placement in the GAS payload container.

OPERATION SEQUENCE

The operations sequence for TES-1 is shown in Fig. 3. Upon launch, the GAS Payload container is vented into the payload bay and ultimately to space. After a minimum of 24 hours, which provides for an adequate vacuum environment to be achieved in the payload, the experiment is activated by an astronaut and begins a 5-hr heatup 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 desired time for the experiment heating cycle was 60 minutes, which would simulate the solar heating period for a typical LEO SD power system. The actual heating cycle time was about 80 minutes, due to the requirement to minimize thermal gradients and hence thermal stress of the Haynes 188 canister. The circumferential heater was designed from ground test data to provide the necessary heating to transition the salt from the incipient melt state to the fully molten condition within the 80 minute period.

The freeze or solidification phase of a thermal cycle is initiated when heater power is turned off and the MLI shutter is opened. This period was desired to be roughly 30 minutes but the experimental time was about 60 minutes, due to the design of the experiment section. Thermal energy dissipation needed to freeze the salt is achieved by conducting the thermal energy out of the salt into the solid rod in the center of the 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 melt cycle begins.

Flight data is recorded at 5-min. intervals and primarily consists of the time variation of temperatures and heater power during the heatup to incipient melt, melt-and-freeze, and cool-down phases of the experiment. Other data include the time elapsed from the startup of the experiment, time of each data sample, power level, and estimated electrical energy 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-1 was flown on STS-62 in March 1994. TES-1 was activated by the crew 48 minutes prior to the desired time of activation. This moved part of the first melt/freeze cycle into a time that coincided with astronaut activity and subsequently some higher level of environmental g forces. The remaining three melt/freeze cycles did coincide with the desired low g period of crew pre-sleep and sleep activities. TES-1 operated for roughly 14 hours in space.

From the data collected on-orbit Fig. 4 shows one set of thermocouple locations and the temperatures from the canister recorded during the four melt/freeze cycles of the LiF salt. The first melt cycle shows some erratic behavior when compared to the remaining three melt/freeze cycles. This was believed to be caused by migration of the void and/or by the g forces present during this period. 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-1 was partially disassembled and the canister removed. Computer-Aided Tomographic (CAT) scanning was performed on the canister in order to record the final location and distribution of the voids in the canister. Figure 5 [ref. 1.] shows the tomographic data taken on the TES-1 canister for nine "stations" along the length of the canister along with the predicted results from TESSIM. Salt locations are shown in black. In general, TESSIM appears to have predicted void behavior accurately, as is evidenced by comparing the tomographic images with the TESSIM images. These initial results from TES-1, 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-2, 3 and 4 will contribute to further validation of TESSIM.

CONCLUSIONS

The TES-1 flight experiment has 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. David Namkoong, David Jacqmin, and Andrew Szaniszlo: "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.

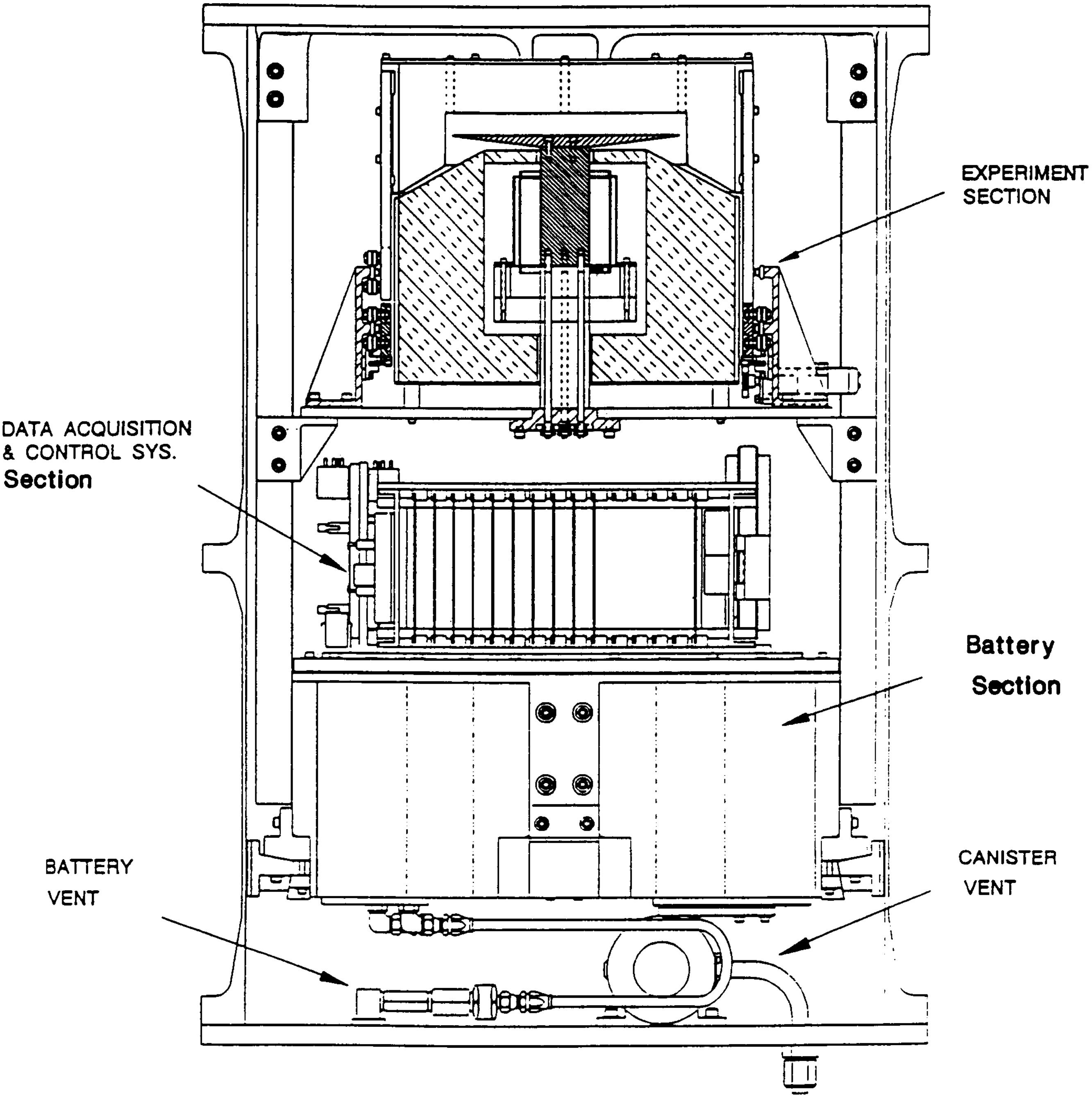

Fig. 1 TES-1 Payload

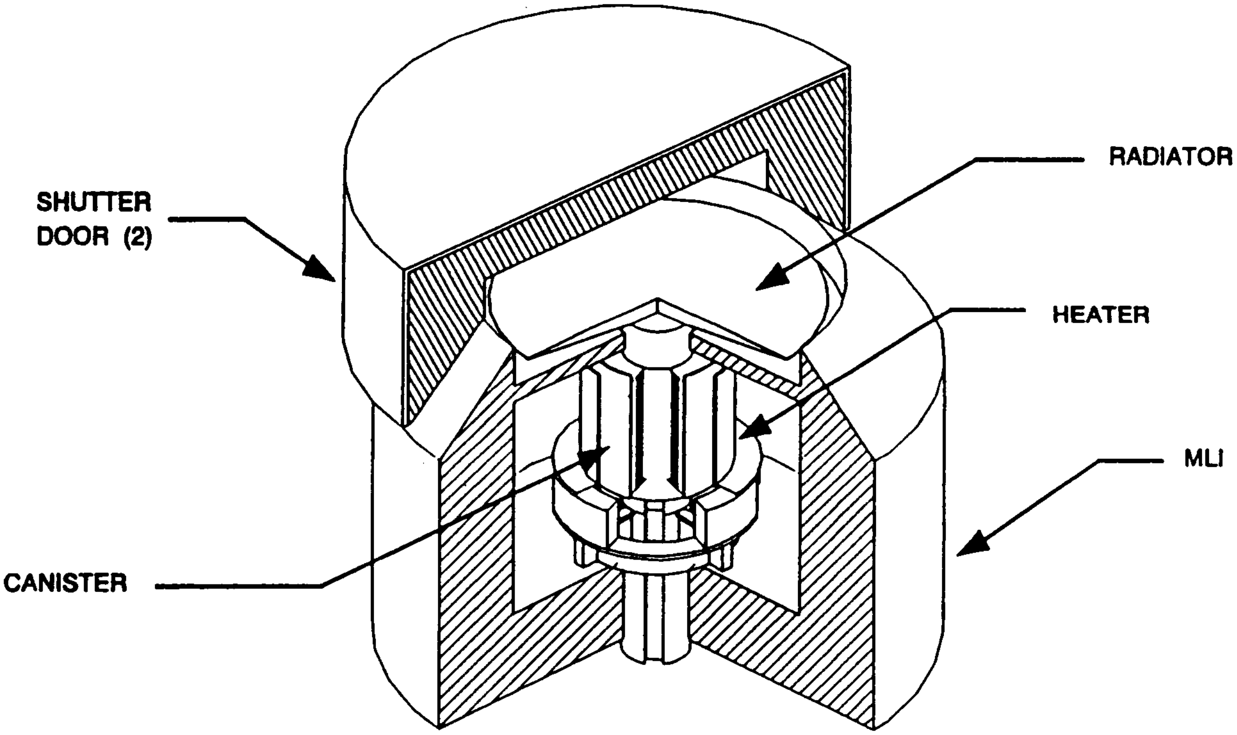

Fig. 2 TES-1 Experiment Section

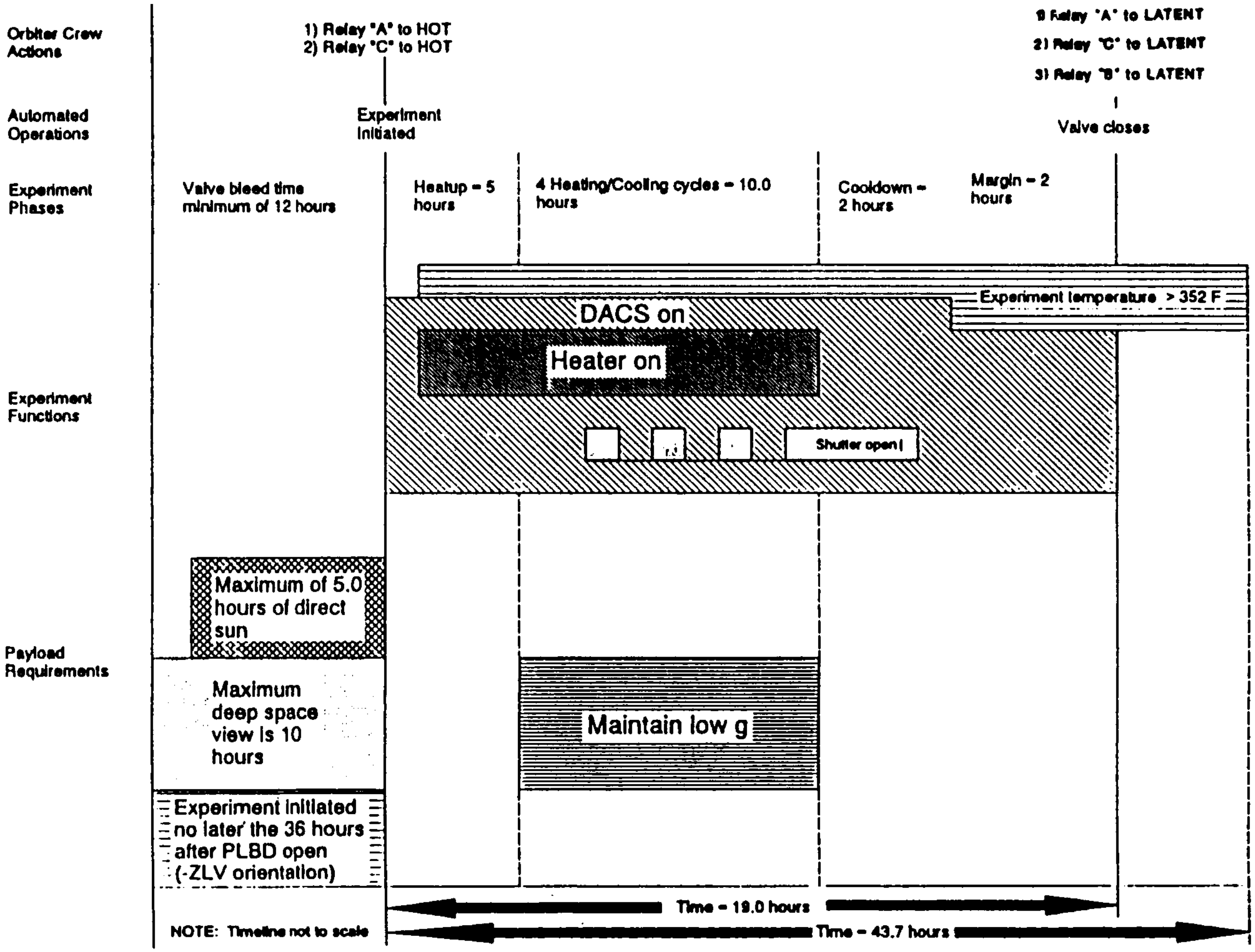

Fig. 3 TES-1 On-Orbit Operations Timeline

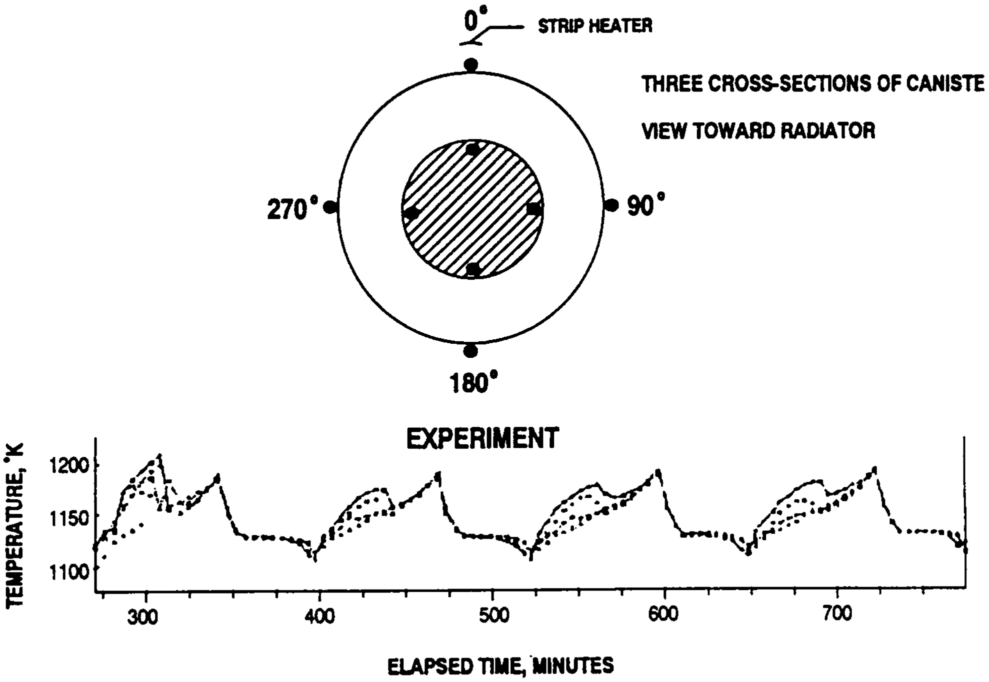

Fig. 4 Canister Temperatures vs. Time

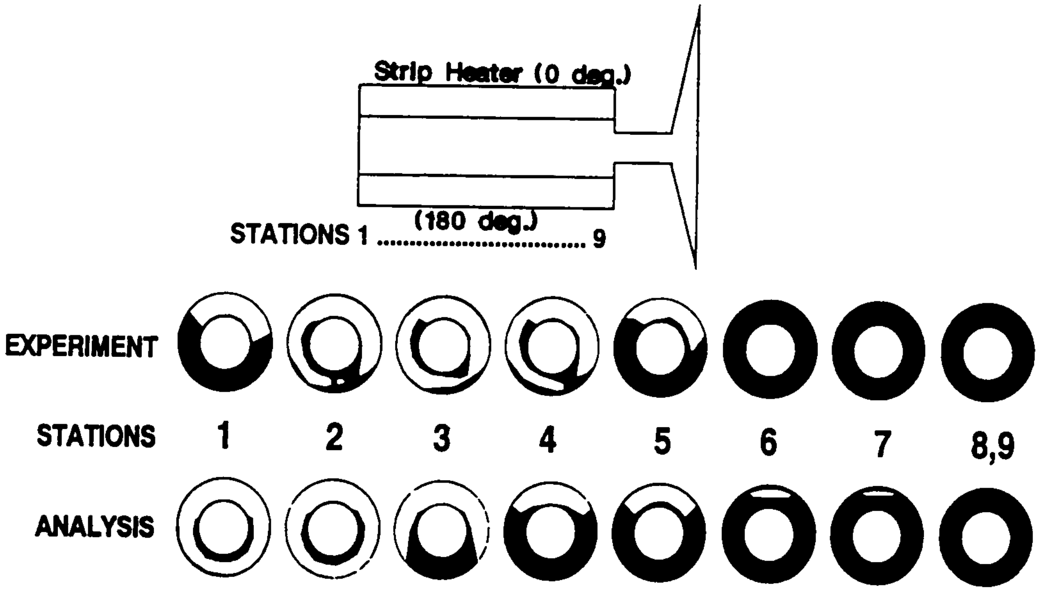

Fig. 5 Comparison of Void Location Between TESSIM and Flight Data