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Flight Experiment of Thermal Energy Storage

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FLIGHT EXPERIMENT OF THERMAL ENERGY STORAGE

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ABSTRACT

Thermal energy storage (TES) enables a solar dynamic system to deliver constant electric power through periods of sun and shade. Brayton and Stirling power systems under current considerations for missions in the near future require working fluid temperatures in the 1100 to 1300+ K range. TES materials that meet these requirements fall into the fluoride family of salts. These salts store energy as a heat of fusion, thereby transferring heat to the fluid at constant temperature during shade. The fusion temperature range of pure salts and eutectics fall into that required by the power systems.

The principal feature of fluorides that must be taken into account is the change in volume that occurs with melting and freezing. Salts shrink as they solidify, a change reaching 30 percent for some salts. The location of voids that form as result of the shrinkage is critical when the solar dynamic system reemerges into the sun. Hot spots can develop in the TES container or the container can become distorted if the melting salt cannot expand elsewhere.

Analysis of the transient, two-phase phenomenon is being incorporated into a three-dimensional computer code. This program is being developed by Oak Ridge National Laboratory. The code is capable of analysis under microgravity as well as 1 g.

The objective of the flight program is to verify the predictions of the code, particularly of the void location and its effect on containment temperature. The four experimental packages comprising the program will be the first tests of melting and freezing conducted under microgravity. Each test package will be installed in a Getaway Special container to be carried by the Shuttle. The package will be self-contained and independent of Shuttle operations other than the initial opening of the container lid and the final closing of the lid.

Upon the return of the test package from flight, the TES container will be radiographed and finally partitioned to examine the exact location and shape of the void. Visual inspection of the void and the temperature data during flight will constitute the bases for code verification.

BACKGROUND

The advanced solar dynamic power system utilizing either a Brayton or Stirling power conversion system (PCS) has the potential for high efficiency with weight 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 min sun and 34 min shade. Delivery of continuous electric power over the entire orbit requires a method of storing sufficient thermal energy during the sun cycle for use during the shade cycle. An efficient method of storing energy is to utilize the heat of fusion of materials.

The ideal thermal energy storage (TES) material for this kind of application is one that changes phase at high temperature for an efficient dynamic system, a high heat of fusion, high conductivity, high density, no density change with phase change, and one that does not corrode its container. Materials that meets the more critical requirements of TES fall into the fluoride family of salts. Pure fluoride salts and their eutectics span the temperature range of interest, 1100 to 1300+ K, are noncorrosive, and have high values of the heat of fusion. Other TES materials, such as the silicides and germanium, have other desirable properties as well, but are highly corrosive. These materials are continuing to be developed.

Advanced receiver designs utilize fluorides as the TES material. The principal feature of fluorides that must be taken into account is that of the change in density with the change of phase. LiF, for instance, contracts to 71 percent of its liquid volume as it freezes. Voids are formed. When subjected to the solar heat load, a proximate void location can cause local overheating of the container. In the other possible extreme, recognizing that this salt expands 40 percent on melting, the liquid can cause distortion of the TES container.

Recognizing the criticality of TES in advanced solar receiver designs, NASA Lewis Research Center embarked upon a program to understand the transient behavior of TES materials, particularly the void shape and location, under microgravity. The project operated under two prime objectives. The first to embody the analyses of melting and freezing of TES materials into a computer program. The second to simulate the heating and cooling of a test package in a microgravity environment and thereby verifying the computer code. The project has been entitled Thermal Energy Storage Technology or TEST.

The understanding of the transient behavior of TES materials in solar heat receivers was recognized in May 1985 as essential to making important strides in advanced solar dynamic (ASD) technology. TEST was presented as a proposed flight experiment for the ASD technology program at the OAST Workshop at the Williamsburg Conference in October of the same year. Such a flight test is not required for early use on Space Station Freedom.

The analytical phase of the project began with a survey to locate existing computer programs that might be applied to TES. Programs such as NASTRAN and its variations, ANSYS, ABAQUS, ADINA, and STARDYNE were all investigated; but none was found adequate. Discussions were carried on within NASA Lewis, Los Alamos National Laboratory, and Oak Ridge National Lab. The conclusion reached after the comprehensive search was that no analytical tool was available to predict size and location of the void on a transient basis in microgravity. Oak Ridge, however, was judged to have the capability and experience to develop a code. As a result, they were awarded a contract in January 1987 to develop such a code.

At this point the Oak Ridge code, known as the NASA/Oak Ridge Void Experiment or NORVEX, has completed development of the code for the 1-g condition. Completion for microgravity is expected by the time of this conference.

The experimental phase of the project was submitted as an In-Reach program in mid-1986. Subsequently, TEST experiments were approved by NASA Headquarters and selected by In-Reach for the definition phase.

TEST EXPERIMENT

Four experimental test packages are planned to elicit maximum information on TES materials undergoing freeze/thaw. Two geometries, two TES materials, and wetting and nonwetting conditions will be tested. The specifics in order of priority are listed in Table I.

The TES material candidates are listed as separate tests. These tests can be installed on separate flights, all on a single flight, or any combination thereof. The results are essentially independent of each other and do not require a sequential series of tests. Each test will contribute information relevant to code validation on a specific area which together will cover much of the range of interests in thermal energy storage freezing and thawing.

LiF has been selected as the pure fluoride salt candidate for several reasons. This salt has a high heat of fusion at a melting temperature (1121 K) that is within the range of interest for higher efficiency, lower specific weight solar power systems. There has been extensive experience gained with the salt, and all of the pertinent thermophysical properties are known. Also, LiF undergoes a large change in specific volume, as mentioned previously. This can be an advantage in that void location and behavior will be that much easier to detect during the test.

Liquid LiF characteristically wets the inner surface of its enclosure, and Test 1 will be conducted accordingly. Realizing that void location and behavior are powerfully influenced by surface tension and wetting under microgravity, it was decided to impose the same conditions for Test 2 except to coat the inner surface to produce nonwetting. A eutectic TES salt will be tested under the same conditions as for LiF to determine the effect of a wedge geometry on void behavior and location during the melting and freezing process. As in the case of Test 1 and 2, the eutectic TES material will be tested under wetting and nonwetting conditions (Tests 3 and 4, respectively). These test are not dependent upon one another in the sense that all of the results from one must be analyzed before the next experimental package is flown. These tests are intended to illuminate a matrix of conditions that most impact the location and behavior of voids; that is, geometry and wetting, for pure and eutectic salts, under microgravity.

Experimental Concept

The TES material will be encapsulated in an annulus of a rectangular cross section, Fig. 1. Solar input will be simulated by an electrical heater transferring heat to the outer surface of the canister. The canister will be cooled by the transfer of heat from the TES material through the inner surface to the conductor rod, and radiated to space across the flared surface of the rod. The experiment melt/freeze times, nominally 60 and 34 min respectively, represent real orbit times of sun and shade.

The annulus and wedge geometries have been selected as being representative of TES designs, currently and in the near future. Advanced receivers may influence a change in the test package.

The experimental package will be installed within a Getaway Special container, Fig. 2. Operations within the container are independent of the Shuttle other than the opening of the GAS container lid at the beginning of the experiment and the closing of the lid at the conclusion.

The experimental package is installed in a section nearest the GAS container lid. During the experimental period when the lid is open, the package is still thermally insulated from space by a shutter. The shutter is comprised of two halves and is controlled within the logic of the experiment. It is closed during heating and opened during shade. The heater, canisters, and conductor rod-radiator are thermally insulated from its surrounding by multilayer insulation. The multiple layers serve as radiation shields which are effective for high temperature applications where radiation is the principal method of heat transfer.

Supporting components for the experimental package include a 28-V silver-zinc battery pack sufficient to supply the 2 kWh for the total electrical power requirement. The electronic package is designed wherever possible to be simple, passive, and with on/off modes. The heater control, for instance, will not include any kind of programmed input. Thermocouples on the specimen will dictate when the power will be fully on and fully off. Similarly, shutter controls will be based on thermostatic readings with limit switches to signal the fully-open and fully-closed positions. Electrical safety features have also been designed for simplicity and reliability. A thermostat in the heater circuit will shut power off if overtemperature is sensed. In addition, a microprocessor will monitor data and will shut power down if an anomaly is detected. Finally, fuses in the lines will open the circuit upon excessive current. Data acquisition will monitor data at 5-min intervals. Storage will be temporary in RAM initially. Data will then be transferred to EEPROM for permanent storage.

One-g and Flight Tests

Extensive qualification tests will be conducted during the preflight period. The purposes for such tests are (1) to assure that components, subsystems, and the full system meet design requirements and are capable of withstanding the launch environment of the Shuttle, and (2) to assure the safe and reliable operation of the experiment.

In addition, technical data will be obtained on the experimental package in ground tests that can be used in conjunction with the data obtained in flight. The heat lost through the multilayer insulation (MLI) is one case in point. Though the loss is small, it is significant in accounting for the heat flow not being transferred to the TES canister. In a ground test, optical heat measurement tools can be used that would be inappropriate in flight. Thermography can be used to determine temperature level and temperature distribution to assess heat loss. Technical data obtained in ground tests will also verify the computer model developed for TEST by Oak Ridge National Laboratory. The model, termed NORVEX, is intended ultimately to predict TES void location and behavior under microgravity. It has been developed for 1 g also and serves as an early verification point for the computer code.

In flight, an astronaut will activate the switch which opens the GAS container lid. This action will signal the heat-up phase. The battery circuit is closed and the heater starts to raise the temperature from its cold soak condition. The time period required to reach operational temperature is calculated to be approximately 2 hr. Heating will continue through the first melt cycle. When temperature measurements indicate that the TES material is completely liquid, the heaters will be turned off and the shutters will open, initiating the first freeze cycle. Melt/freeze cycles will continue four additional times consecutively, the number of cycles that thermal analysis indicates is required for repeatability. On completion of the last freeze cycle, the shutter is closed and the signal transmitted to the astronaut to close the GAS container lid.

Upon return, the TES canisters will be radiographed to determine void distribution in its undisturbed state. The center canister will be sectioned at 45° segments corresponding to thermocouple locations to identify the final void shape and location. The stored data and postflight observations will be compared to the computer model predictions to determine the degree of verification.

COMPUTER MODELING OF FREEZE/THAW ANALYSIS

Oak Ridge National Laboratory has been contracted to develop NORVEX, a three-dimensional computer program describing TES material behavior undergoing melting and freezing under microgravity. The result of the effort is to profile a realistic temperature history within the TES container. Particular emphasis is placed on the effects of the vapor void which forms during the freezing phase.

Accurate portrayal of the temperature behavior requires that a number of concurrent phenomena be taken into account. Motion of the solidification front affects the heat balance and the heat transport behavior due both to thermal conductance differences between the liquid and solid and the availability of liquid volume for convection. In addition, vapor void formation occurs, common to all fluoride TES systems, resulting from the higher density of the solid relative to the liquid. Thus a three phase system exists within the canister in which the solid and vapor phases grow during cooling, and the liquid phase grows on heating.

The heat transport mechanisms and phenomena are taken into account in the computer model by categorizing them into separate modules. These are listed as follows:

Module 1	Core conduction
Module 2	Flare conduction
Module 3	Canister conduction
Module 4	TES material conduction Convection Internal radiation Solidification/melt front
Module 5	Void heat transfer
Module 6	Melt velocities
Module 7	Void shape and location

One subroutine stores the input parameters of thermophysical properties, boundary conditions, geometry, etc. A second subroutine's function is that of integrating all of the modules and the input.

The output of the program will be in a form that can be compared directly with the experimental results. The kind of output will be the same as reported by Wichner et al. (1988) in Figs. 3

to 7. In that earlier paper, the analysis was two-dimensional whereas the present study will be three-dimensional. Nevertheless, the output will be similar. The maximum and minimum canister surface temperatures are mapped as a function of time through sun and shade. Phase maps indicate the area of TES liquid, solid and void. Both 1-g and microgravity conditions are shown. The experimental canister surface temperatures will be a direct comparison with, and therefore a measure of verification of the code output. Posttest examination of the canister will reveal the solid and void locations and will serve as verification of NORVEX's predictions of such locations.

CONCLUSION

The flight experiment of thermal energy storage materials will be the first time these materials will have been tested under extended microgravity conditions. Extensive ground tests, and a detailed computer analysis are planned to provide complete preflight preparations, as a basis to compare the flight information.

REFERENCES

1. R.P. Wichner, A.D. Solomon, J.B. Drake, and P.T. Williams, "Thermal Analysis of Heat Storage Canisters for a Solar Dynamic, Space Power System," ORNL/TM-10665, 1988.

TABLE I

[Each test independent. Tests can be installed on separate flights, all on a single flight, any combination.]

Test	Candidates	Geometry
1	LiF wetting	Annulus
2	LiF nonwetting	Annulus
3	Fluoride eutectic wetting	Wedge
4	Fluoride eutectic nonwetting	Wedge

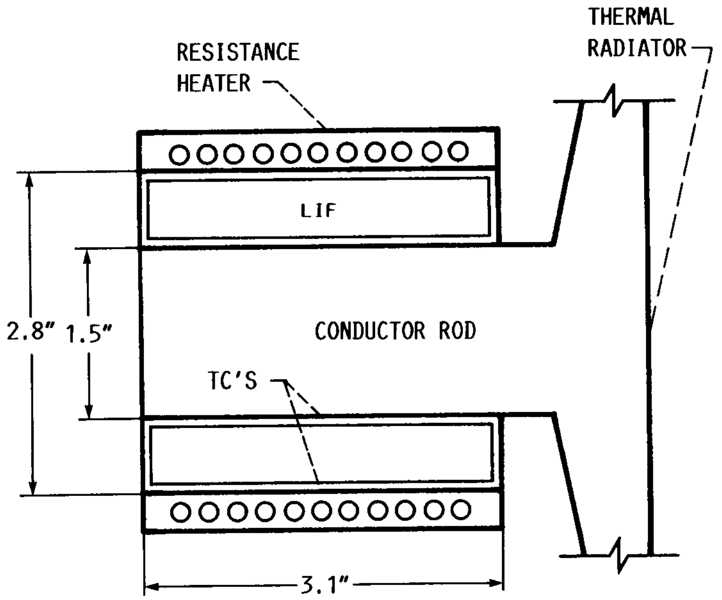

FIGURE 1. - TES EXPERIMENTAL PACKAGE.

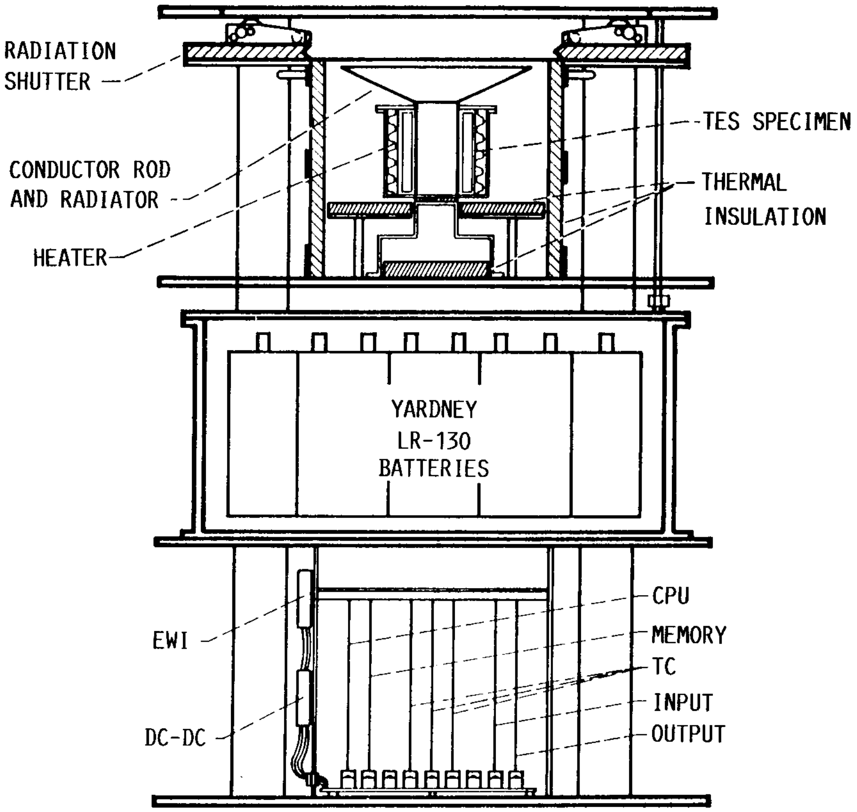

FIGURE 2. - EXPERIMENTAL PACKAGE IN "GAS" CONTAINER.

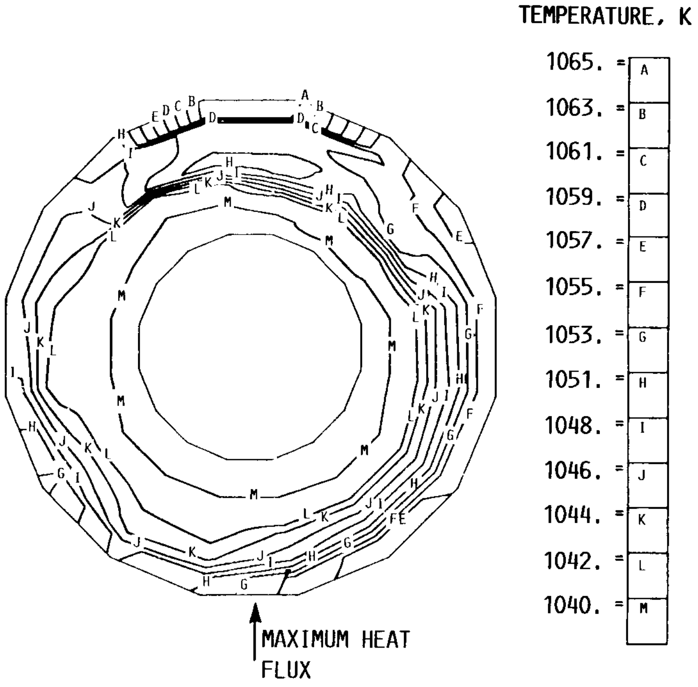

FIGURE 3. - TEMPERATURE CONTOURS, 1-g, 30 MIN.

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OF POOR QUALITY**

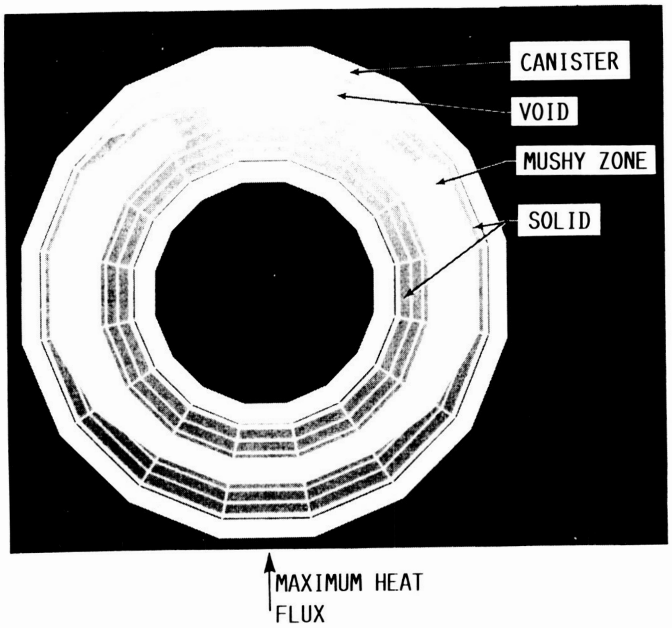

FIGURE 6. - PHASE MAP, 1-g, END OF COOLING.

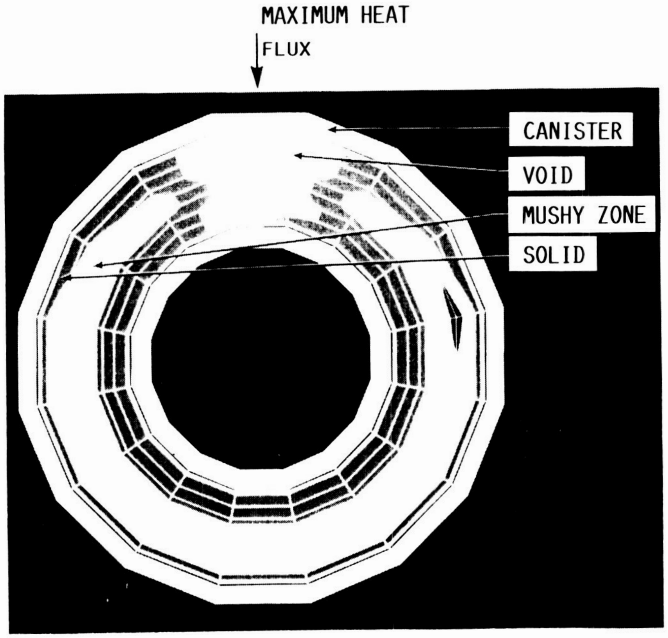

FIGURE 7. - PHASE MAP, 0-g, END OF COOLING.

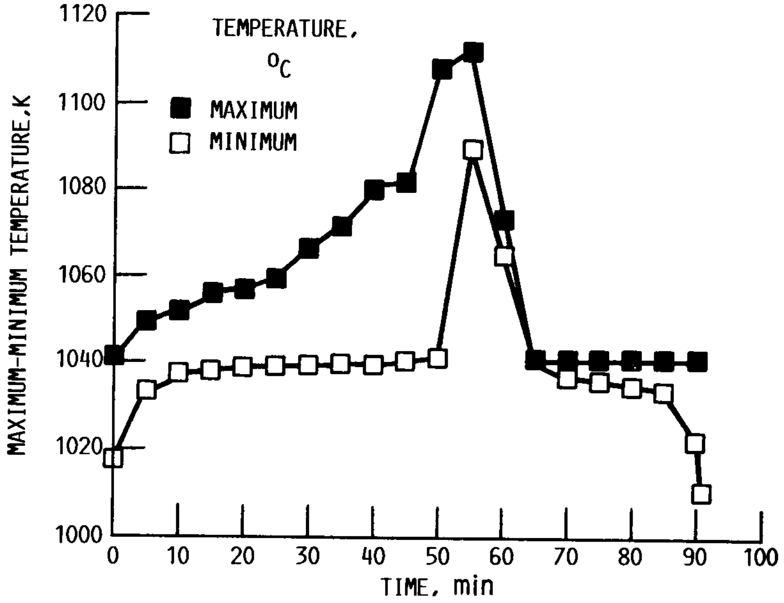

FIGURE 4. - TEMPERATURE HISTORY, 1-g.

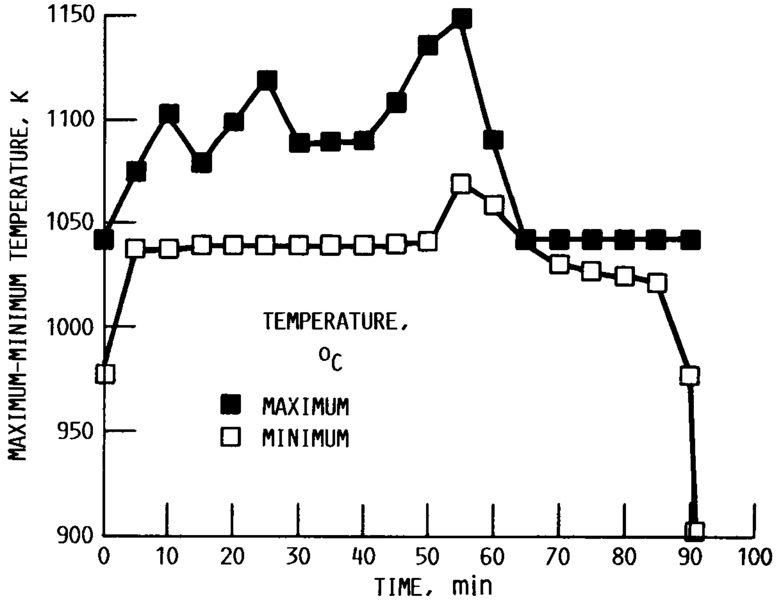

FIGURE 5. - TEMPERATURE HISTORY, 0-g.

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16. Abstract

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