FLIGHT EXPERIMENT OF THERMAL ENERGY STORAGE

David Namkoong
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135

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 analyzing 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, and no density change with phase change, and one that does not corrode its container. Materials that meet 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. TES 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 STAR-DYN 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. The analytical phase of the project began with a comprehensive search to locate existing computer programs that might be applied to TES. Programs such as NASTRAN and its variations, ANSYS, ABAQUS, ADINA, and STAR-DYN 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.

The experimental phase of the project was submitted as an In-Reach program in mid-1985. Subsequently, In-Reach 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. Such a doubling of 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 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 tests 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 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 tests 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.

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 Gateway 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 shading. The heater, canisters, and conductor rod-radiator are thermally insulated from its surrounding by multilayer insulation. The multipe
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 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 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 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 sur-
face 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 experimen-
tal canister surface temperatures will be a direct
comparison with, and therefore a measure of verifi-
cation of the code output. Posttest examination of
the canister will reveal the solid and void loca-
tions 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

### TABLE I

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

<table>
<thead>
<tr>
<th>Test</th>
<th>Candidates</th>
<th>Geometry</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>LiF wetting</td>
<td>Annulus</td>
</tr>
<tr>
<td>2</td>
<td>LiF nonwetting</td>
<td>Annulus</td>
</tr>
<tr>
<td>3</td>
<td>Fluoride eutectic wetting</td>
<td>Wedge</td>
</tr>
<tr>
<td>4</td>
<td>Fluoride eutectic nonwetting</td>
<td>Wedge</td>
</tr>
</tbody>
</table>

### FIGURE 1

- TES Experimental Package

### FIGURE 2

- Experimental Package in "Gas" Container

### FIGURE 3

- Temperature Contours, 1-g, 30 MIN.
FIGURE 4. - TEMPERATURE HISTORY, 1-g.

FIGURE 5. - TEMPERATURE HISTORY, 0-g.

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

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