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14. ABSTRACT Detailed understanding of turbulent combustion in liquid rocket engines (LRE) requires an ability to predict the coupling between the transient features, acoustics, vortex/shear layer dynamics and the unsteady combustion heat release. Conventional and ad hoc models that mimic or match one set of conditions but fail in another test case cannot be used for reliable predictions. This paper presents a simulation strategy based on Large-Eddy Simulation (LES) that uses a finite-volume scheme on multi-block, structured grids and solves the full multi-species, compressible LES equations using a hybrid central-upwind scheme to capture both turbulence shear flow and large density gradients. The sensitivity of predictions to the real gas equation of state such as the Peng-Robinson one is addressed in this study. The main modeling challenges concern the simultaneous capture of the flame structure, the flame-turbulence interactions and the regions of compressibility. The current work focuses on turbulent combustion in three single injector configurations for these objectives: (a) trans-critical liquid oxygen (LOX) / gaseous hydrogen (GH2) combustion, (b) trans-critical LOX/methane combustion and (c) high-pressure GOX/methane combustion with thermo-acoustic instabilities. Results will be reported on the flame structure, liquid core length and spreading rate, and comparison with data where appropriate. Finally, for LES of such problems, a more fundamental challenge is to determine the implication of the LES subgrid closures for real gas flame dynamics. As a preliminary effort, the Linear-Eddy sub-grid model (LEM) is being applied to some of these cases.					
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AUGMENTATION OF SOLAR THERMAL PROPULSION SYSTEMS VIA PHASE CHANGE THERMAL ENERGY STORAGE AND THERMAL ELECTRIC CONVERSION

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ABSTRACT

Solar thermal propulsion offers a unique combination of high thrust and high specific impulse that can provide competitive advantages relative to traditional satellite propulsion systems. Enhancing the functionality of this technology requires a robust thermal energy storage method, and it is suggested that this could be combined with thermophotovoltaic thermal-electric conversion to provide a dual-mode power and propulsion system based solely on thermal energy and eliminating the need for a traditional photovoltaic-battery power system. An energy storage system utilizing the phase change of molten elemental materials is proposed as an enabling technology. Molten boron is identified as an optimal energy storage material, but presents significant engineering challenges due to its high melting temperature and a lack of research on its use. Molten silicon is identified as a high-performance material with near-term potential for application. Micro-satellites, often inserted into non-ideal orbits and limited by propulsion capability, are identified as an ideal application for such a bi-modal solar thermal system. Systems level analysis is presented to illustrate the advantages of the bi-modal solar thermal system by comparing the total microsatellite mission ΔV and total maneuver time for the proposed system and several current and future traditional microsatellite power and propulsion systems. Early experimental progress in the development of the test facilities that will be used to validate the system are also discussed, including the basic design of the system, various diagnostics in use, results of initial tests, and future modifications for improved performance.

1. INTRODUCTION

Solar thermal propulsion offers a unique combination of high thrust and high specific impulse (I_{sp}) which can offer significant advantages over chemical and electric propulsion systems in certain mission scenarios. Microsatellites, in particular, show strong potential performance using an STP system and analysis indicates that a system can be devised with a less than 50% propulsion mass fraction (including propellant) and a 1.5 km/s velocity increment (ΔV) capability.

Traditionally, however, STP has been viewed as somewhat limited due to the requirement of solar illumination of the collector during times when propulsion is needed. Combining STP with a means of thermal energy storage, however, would allow for augmented thrust even during times of spacecraft eclipse and could vastly increase the utility of the propulsion system yielding a high-efficiency, high-thrust spacecraft with on-demand performance.

An additional perceived disadvantage of an STP system is the need for large solar concentrators. Unlike chemical or electric propulsion systems that draw from the power subsystem onboard a spacecraft (i.e. photovoltaic cells and batteries), a solar thermal propulsion system requires its own dedicated collection system. This thermal collection system requires its own budget for volume and mass and appears to be a significant disadvantage to the technology. However, it is suggested here that combining a robust thermal energy storage solution with high performance thermal-electric conversion would allow both propulsion and power needs to be satisfied exclusively via the thermal collection system.

A bi-modal solar thermal system could power the entire spacecraft, including electric and propulsive needs via thermal collection, storage and conversion, and yield a highly efficient and high performance satellite. This work proposes that the latent heat of molten elemental materials, specifically silicon or boron, can provide the required level of thermal energy storage to overcome issues associated with intermittent solar illumination and provide a constant energy source for electric conversion.

The current research effort is focused on determining the feasibility of using a bi-modal solar thermal system as the primary energy source and propulsive device on board a microsatellite. As will be discussed later, apart from effective thermal energy storage, the majority of required technologies for such a system have already been demonstrated in proof of concept, making a high performance thermal storage device the key technology to unlocking the potential of a bi-modal system.

This paper aims to briefly outline the key requirements for a bi-modal system and present a systems level analysis that

shows an STP system combined with advanced thermal energy storage offers performance that is “off the curve” when compared to traditional microspacecraft propulsion options. Effective implementation of a bi-modal system can provide mission designers with a high ΔV that can be delivered on time scales that are an order of magnitude less than competing propulsion systems enabling a new class of high performance microsattellites.

Additionally, this paper will discuss an ongoing experimental effort that seeks to demonstrate a proof-of-concept satellite system. A solar furnace facility is currently being characterized and analysis methods are being developed for measuring PCM performance.

2. SOLAR THERMAL PROPULSION FOR MICROSATELLITES

Solar thermal propulsion has been presented in a recent review as an enabling technology for microsattellites due to a unique combination of propulsive thrust and efficiency and, in part, to the fact that microsattellites are often launched into sub-optimal orbits as secondary payloads accompanying higher budget missions [1]. While high performance full-size satellites exist, there are currently no practical designs and propulsion systems for microsattellites that combine a high ΔV with high thrust.

A number of solar thermal propulsion systems for microsattellites have been proposed and studied in ground tests. However, no solar thermal rockets, much less those intended for microsattellites, have been flown. An STP system that combines both thermal energy storage and thermal-electric energy conversion could overcome the typical drawbacks of an STP system and unlock the potential of this technology for high performance microsattellites.

2.1. Propulsion and ΔV for Microsatellites

The literature indicates that a well designed STP system could yield 1.5-2 km/s total ΔV which would dramatically open up the operational microsatellite envelope. By providing several hundred meters per second ΔV , missions could include maneuvers from Geosynchronous Transfer Orbit (GTO) to Geosynchronous Earth Orbit (GEO), insertion into lunar orbit, LaGrange point insertion, highly eccentric observation and analysis orbits, and even Earth escape [2]. It is important to note that missions of this scale may be possible with electric propulsion systems. However, the high thrust offered by an STP system reduces the total maneuver time dramatically.

In addition to the exotic mission profiles listed above, a large ΔV capability could provide a highly dynamic and responsive satellite or simply reposition an existing satellite into a new inclination, orbit altitude, or orbit phase. For a microsatellite in a circular 200 km orbit, combinations of inclination change and altitude change possible with large values of ΔV are provided in Fig. 1. For this plot it was assumed that altitude change maneuvers utilized a Hohmann transfer (or series of Hohmann-type burns at perigee and apogee), and that any inclination change was completed at a high altitude. In comparison to these large changes, attitude control, precise approach to another body, and minor orbit rephasing are likely to consume significantly less ΔV .

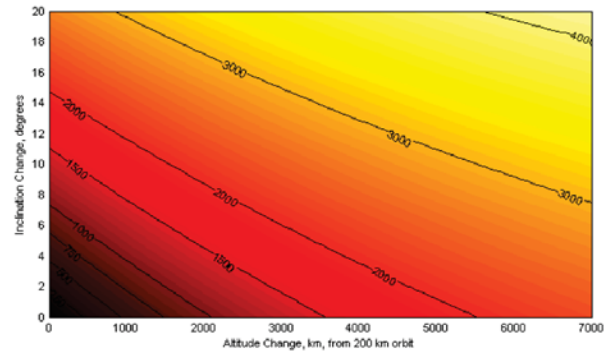


Figure 1. Color map and contours indicating the required ΔV values to achieve a given combination of altitude increase and inclination change. Units of ΔV indicated on the contours are given in m/s

2.2. System Requirements

Previous studies have examined the prospect of STP with thermal storage [3, 4] and major developmental projects, including the Solar Orbit Transfer Vehicle (SOTV) [5] and the Integrated Solar Upper Stage (ISUS) [6] included both thermal storage and a means of thermal electric generation. Typically, however, thermal storage systems proposed for STP satellites are based on the sensible heat in a solid material such as graphite. The key difference to be explored here is the optimization of thermal storage using a phase change material (PCM), which should allow for a greater energy density of the storage system, combined with relatively constant-temperature operation.

In order to complete favorably with other technologies, it is proposed here that a well designed bi-modal STP system for a 100 kg microsatellite in low earth orbit (LEO) needs to provide 100 W of continuous power, have continuously available propulsion with thrust performance on the order of 1 N at an Isp of 300-400 s and an energy collection system with a specific power density of hundreds of Watts per kilogram. In order to achieve this performance with a significant mass savings compared to typical systems, the energy storage system is also required to have an energy storage density of at least 750 kJ/kg [7].

The most critical requirement for a solar thermal propulsion system is proper performance of the propulsion mechanism, and improvements in performance must be significant enough that a full re-design of the satellite power system is justified. As has been stated in previous work, utilizing ammonia as a propellant for an STP rockets offers significant advantages compared to hydrogen at a systems level despite lower peak Isp values. Ammonia is readily storable and self pressurizing at low temperatures and with an exhaust temperature approaching 2500 K , an Isp of approximately 400 s is theoretically predicted [8].

In order to achieve the target exhaust temperature of 2500 K , the solar collection system of the satellite must operate at concentration ratios on the order of 10,000:1. This problem appears to have already been investigated and concentrators designed for in-space use have achieved this level of performance experimentally [9]. Additionally, the use of fiber optics can de-couple the attitude of the spacecraft from the pointing direction of the concentration system. While current laboratory fiberoptic-coupled concentration systems operate

Table 1. Potential high temperature phase change materials.

Material	$T_{melt}[K]$	$\Delta H_{fus}^o[kJ/kg]$	$k_{th}[W/mK]$
MgF ₂	1536	940	-
Beryllium	1560	1312	200
Silicon	1687	1785	149
Nickel	1720	298	90.9
Scandium	1814	313	15.8
Chromium	2180	403	93.9
Vanadium	2183	422	30.7
Boron	2570	4600	27.4
Ruthenium	2607	381	117
Niobium	2750	323	53.7
Molybdenum	2896	390	138

at efficiencies of only 35%, basic changes in materials and careful engineering can raise the overall efficiency to over 70% [4, 10, 11].

2.3. Boron and Silicon as PCMs

The propulsion and specific power requirements for an operational satellite are the primary drivers for any thermal energy storage solution. Specifically, the optimal ammonia exhaust temperature requires that a thermal energy storage system be capable of releasing heat at approximately 2500 K. Previous work has looked at the possibility of storing thermal energy in the sensible heat of materials, specifically carbon (graphite) and boron carbide. However, storing energy in this manner is fundamentally limited by the allowable temperature change throughout a mission [2]. High energy storage densities are possible across large temperature ranges (1.5 MJ/kg in graphite with a ΔT of 600 K), but this large ΔT will reduce electrical power conversion efficiency, cause variations in thruster performance, and induce additional stress on system components due to thermal cycling. For these reasons, it is unlikely that a sensible heat storage method can compete with a system utilizing latent heat.

A latent heat energy storage system can offer similar or greater energy storage densities than sensible systems and has the key advantage of operating at a near constant temperature. However, current state of the art PCMs developed for terrestrial systems have energy densities and thermal conductivities an order of magnitude too low, temperatures well below those required for STP, and suffer from decomposition after repeated cycling. For a spacecraft system a PCM will have to have a properly matched melting temperature, a high energy density, and good material stability and compatibility. From a survey of candidate materials, molten elemental materials, specifically boron and silicon, appear to be the most promising. A sample of high temperature materials is given in Table 1. In addition to high temperatures and high heats of fusion, elemental materials inherently avoid decomposition concerns.

Boron has been selected as the ideal PCM due to its extremely high heat of fusion (4.6 MJ/kg) and a melting temperature near the optimal performance point for an ammonia-fueled STP rocket. However, limited research has gone into using this material at high temperatures. Therefore, silicon is also being considered as a moderate performance option for near term studies.

Using latent heat in the place of sensible heat for energy stor-

age does add complexity to the system, requiring a container that is compatible with the molten PCM over the long term, perhaps ten years or more at operational temperatures. Since the container material selection is made primarily through material compatibility considerations, it is directly coupled to the chosen PCM. Boron is highly reactive in the liquid state, and has been melted in the presence of refractory metals, graphite, and ceramics with varying contamination levels. Boron nitride ceramic is currently the most promising containment material for both boron and silicon based systems due to low reactivity in the case of boron, and what appears to be self limiting contamination with molten silicon [7, 12].

In addition to containing the PCM, consideration must be made to prevent the escape of stored energy from the system. Very high temperature thermal insulation materials must meet a long list of exacting requirements, including the ability to withstand storage temperatures over a long period and the possibility of many thermal cycles. Based on current technology estimates, it is likely that a successful insulation method will combine low emissivity coated vacuum gaps and advanced insulation such as carbon bonded carbon fiber (CBCF) or high performance ceramic aerogels [13]. It is conceivable that actual energy storage densities with a boron based system could be 2-4 times higher than conventional lithium ion batteries, and a system that collects and stores thermal energy directly will result in additional downstream efficiencies.

2.4. Thermophotovoltaic Based Bi-Modal Operation

In addition to the propulsive power draw, a successful energy storage method must supply electrical power to the satellite if molten boron or silicon is to be the primary method for energy storage. When comparing the state of the art thermal-electric conversion technologies, thermophotovoltaic (TPV) systems present themselves as the best option for satellite applications based on relatively high conversion efficiency and the ability to operate at high temperatures by managing the incoming thermal radiation flux [8]. Conversion performance is further enhanced by tuning a TPV system to the radiative output of a constant temperature phase change based system. It is also expected that TPV technology will benefit from the same advances in specific power density as photovoltaic systems.

With the addition of TPV electrical generation, a STP system utilizing high temperature phase change energy storage becomes a true bi-modal system capable of using thermal energy collection and storage for propulsive and electrical requirements. With a bi-modal system, the photovoltaics and batteries typical of satellite design can be eliminated. Instead, a dedicated high performance thermal energy system for propulsion and power is used, providing significant weight savings compared to a typical STP system that has both thermal collection and photovoltaic panels.

A nominal schematic for an energy storage system with thermal electric conversion is shown in Fig. 2. Future modeling, and proof-of-concept studies will use a similar geometry with a centrally insulated storage mass and thermophotovoltaics positioned to take advantages of the highest storage temperatures. This schematic currently doesn't include a mechanism for heat transfer to propellant; this feature will be added as the concept progresses by either adapting existing STP designs or taking simulation-suggested results from

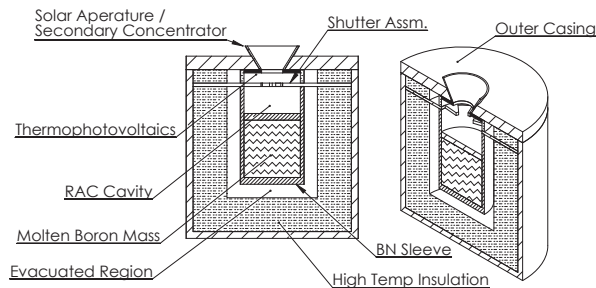


Figure 2. Nominal design for a Receiver/Absorber/Concentrator (RAC) indicating key requirements for a functional thermal energy storage system.

further analyses.

3. SYSTEM COMPARISON

In order to directly compare the proposed bi-modal STP system with existing technologies, two bi-modal STP systems were sized, using either molten silicon or molten boron as PCM options, for a 100 kg microsatellite capable of achieving 1500 m/s ΔV . The sizing of the bi-modal STP system was based upon previous research using conservative values for achievable technology [1, 2, 11, 14, 8]. During this process, parameters of interest were the weight of the solar concentration system (fiber optics, primary concentrator and support structure), thermal energy storage weight (PCM, container, insulation, and thermal radiators), power system weight (TPV and electronics), and the weight of the ammonia STP rocket (tankage, flow system, engine and total propellant weight). Analysis resulted in 100 kg satellites with a constant 100 W payload power draw capable of 1500 m/s ΔV and a 45% combined propulsion and power mass fraction using Boron as a PCM and a 52% combined propulsion and power mass fraction using silicon as a PCM. The time to deliver the entire ΔV budget was dependent on the relative I_{sp} and estimated thrust level of the STP rocket with the boron based satellite capable of delivering the entire ΔV in 23 days and the silicon based satellite being capable of delivering the entire ΔV in 28 days.

For comparison, two conventional hydrazine monopropellant systems, a sample EP system, and a solar thermal system without energy storage were sized using the same available mass fraction for propulsion and power as the bi-modal STP systems. Without TPV power generation and thermal energy storage, all propulsion methods require additional mass for conventional batteries and photovoltaic panels. These subsystems were sized using the NASA specific power goals for 2020 to provide an accurate comparison with future technologies [15]. As with the bi-modal system sizing, the relative weights of power systems, tankage, and thrusters were determined through previously established sizing metrics [16, 17].

The two hydrazine thrusters used as a basis for chemical propulsion system comparison are commercially available and provide either 1 N or 20 N of thrust [18, 19]. For the non-storage STP system, the propulsion system was kept the same and the thermal storage and TPV systems were removed. This omission required the addition of batteries and photovoltaic panels to provide energy to the payload.

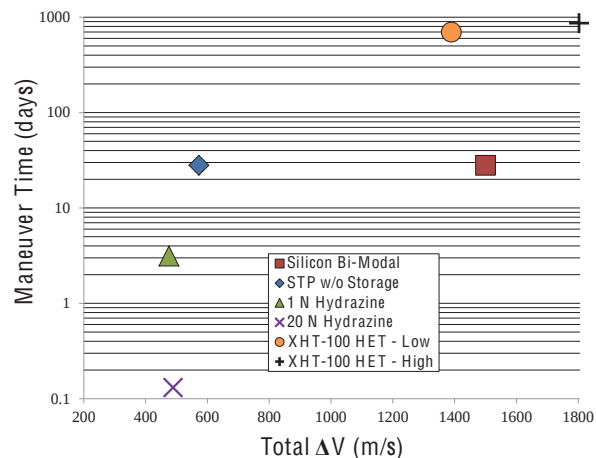


Figure 3. Total propulsive time vs. total ΔV capability for different satellite propulsion systems having identical combined propulsion and power mass fractions (45%) on a 100 kg microsatellite with a payload power draw of 100 W continuous.

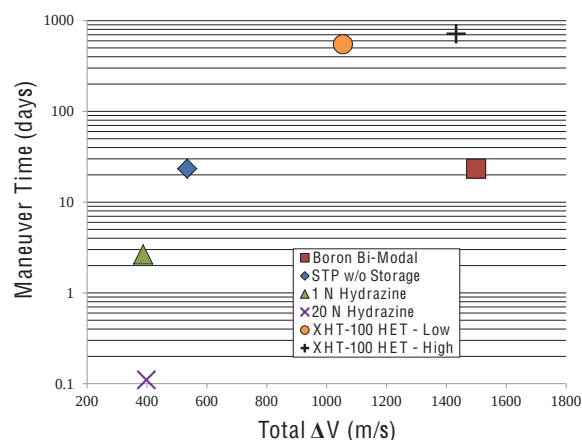


Figure 4. Total propulsive time vs. total ΔV capability for different satellite propulsion systems having identical combined propulsion and power mass fractions (45%) on a 100 kg microsatellite with a payload power draw of 100 W continuous.

An existing hall effect thruster, the XHT-100 was chosen as the basis for an EP system. Sizing this thruster results in two different performance values depending on the payload power draw. If an additional 95 W is required from the power subsystem beyond the existing 100 W capability for optimal thrust performance, additional weight must be added representing the “low” performance value. If it is assumed that the existing 100 W power subsystem is sufficient for both the payload and propulsion system, the overall power system weight is less, representing a “high” performance value.

With all satellites having the same propulsion and power mass fraction, the primary performance metrics become the total ΔV capability and the total time required to deliver this capability.

Figure 3 shows the performance of different propulsion systems, all having an identical combined propulsion and power

mass fraction to the proposed bi-modal STP system using silicon as the PCM. It can be seen that chemical thrusters offer significantly less ΔV than the bi-modal STP option with a much quicker total burn time. In contrast, both EP systems offer comparable ΔV with greatly lowered responsiveness. The non-storage STP system provides similar responsiveness to the bi-modal STP system, however, the total ΔV is lower due to the additional mass added for batteries and photovoltaics.

Figure 4 represents a similar performance comparison to a bi-modal system using boron as the PCM. The trends are the same, however, due to the mass savings from the high energy storage density of boron, the common propulsion and power mass fraction is lower for the same total ΔV in the bi-modal system. This furthers the advantage of the bi-modal system and the total ΔV possible from competing systems is reduced.

It can be seen in both Figures 3 and 4 that chemical, STP and electric propulsion technologies lie on a similar curve that trades total ΔV for satellite responsivity with a given mass fraction. The proposed bi-modal STP system lies well below this curve and allows for large ΔV with a response time an order of magnitude less than electric propulsion options. Additionally, the ΔV available to mission designers is provided by a high enough thrust level to be used effectively with impulsive burns providing further advantages relative to the spiral-out maneuvers required for EP systems.

This systems comparison shows that a bi-modal STP system, enabled by the significant weight savings of a combined high-performance propulsion and power system, deviates from the standard performance metrics of current technologies. The performance estimates predicted above are very reasonable based on technologies currently being developed and it is likely that future advancements in key aspects can improve the performance of a bi-modal system even further.

4. EXPERIMENTAL DEVELOPMENTS

An experimental effort is currently underway at the University of Southern California to provide physical insight during the development of a bi-modal STP system and evaluate the potential of the technology. The near term goals of the project are to complete the construction of a research grade solar furnace and produce molten silicon samples in a laboratory environment while evaluating material compatibility and uncovering issues associated with concentrated solar power (CSP) as a primary energy source. In the far term, the USC facility will be used to produce and maintain molten boron samples and validate a proof-of-concept satellite system.

4.1. Construction and Characterization

4.1.1. Solar Furnace: Using CSP as the basis for experimentation ensures strong correlation between experimental data and the final spacecraft system. The USC solar furnace currently has a two stage design using a 5.75 m^2 heliostat and 1 m^2 acrylic Fresnel lens. Previous versions of the USC furnace used a three stage system with a re-direction mirror to provide “top down” radiation input into the test section, however, this mirror has been removed to increase total power delivery [8].

The USC solar furnace has been fully characterized utilizing CCD diagnostics and flux maps of the image formed by the

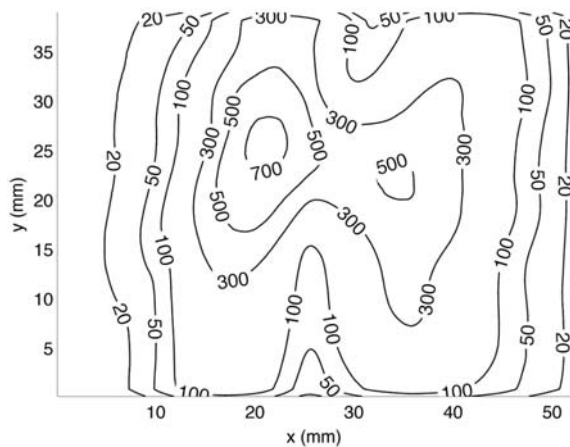


Figure 5. Solar flux profile measured at the apparent “visual focus” showing the effects of bowed mirror panels and a relatively low peak concentration ratio of 700:1. The units on the indicated contours are the number of suns, representing the concentration ratio.

Fresnel lens have been recorded. By placing the focal point of the system on a Lambertian surface and capturing the image at a set distance with a calibrated CCD camera, a highly detailed flux profile can be derived. Integration over these flux profiles indicates a total power delivery of 200-240 W (dependent on variations in the dependent normal insolation) into a 2 cm diameter spot. Total integrated flux measurements have been verified against a commercial thermopile laser power meter.

The overall system has a relatively low transmission efficiency due to the low quality of the Fresnel lens. Additionally, slight sagging of the heliostat which consists of two separate rectangular mirror panels further degrades the focal spot. When the system is imaged at the apparent “visual” focus (i.e. the smallest apparent spot), images of the two separate panels of the heliostat can clearly be seen and a peak concentration ratio of only 700:1 is possible. However, at other locations fore and aft of this focal point, lens aberrations produce areas of increased concentration ratio despite appearing worse visually. This effect has been optimized and it was found that 3 cm forward from the apparent focal point, there is a region with a vastly improved concentration at a peak ratio of 2500:1. Flux maps for both regions can be seen in Figures 5 and 6.

4.1.2. Radiation Shielding and Crucible: Using information from the the solar furnace characterization, a new radiation shield has been built based upon a design published by Steinfeld and Fletcher [20]. The radiation shield consists of two 7.6 cm diameter aluminum hemispheres with highly polished inner surfaces mounted in an aluminum support structure. The front hemisphere has been cut to allow the input of solar radiation and the entrance aperture has a 40° rim angle as seen from the center of the shielding cavity. A basic outline of the new shield can be seen in Fig. 7.

Bullet shaped graphite crucibles machined from 2 cm long, 2 cm diameter graphite rod, are mounted on a tantalum sheathed Type C thermocouple probe and positioned in the center of the spherical radiation shielding cavity. As seen in Figure 8, solid and hollow crucibles have been produced with

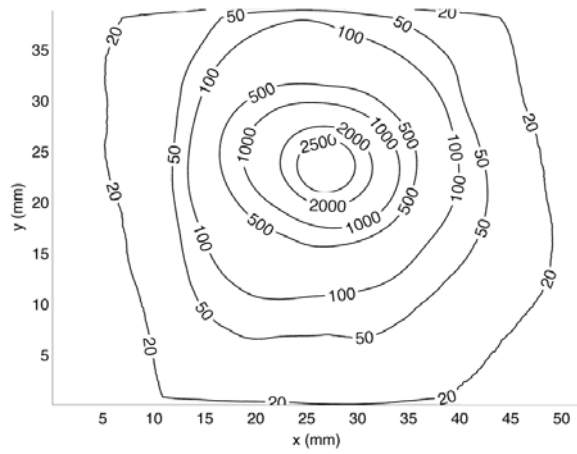


Figure 6. Solar flux profile measured 3 cm forward of the visual focus showing a region of greatly improved concentration with a peak ratio of 2500:1. The units on the indicated contours are the number of suns, representing the concentration ratio.

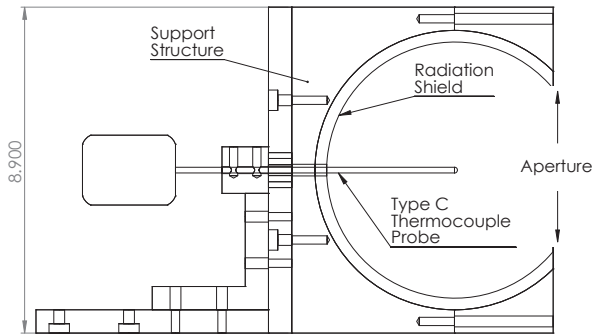


Figure 7. 2D schematic of the radiation shield and support structure showing spherical radiation shielding cavity and thermocouple sting mount.

solid crucibles being used for furnace characterization. The hollow crucibles are created by boring a 1.25 cm diameter hole into the front surface of a solid crucible. This cavity is then filled with the PCM of interest and a solid boron nitride (BN) liner can be used to prevent material contamination [8]. After loading, a graphite rod is slip fit into the bore hole and sanded down until the front of the crucible is a uniform flat surface.

The model proposed in Steinfeld and Fletcher suggests that this configuration should yield a 65% reduction in radiation loss and experimental testing shows an approximate reduction of 55% based upon the analysis of cooling curves. The discrepancy is likely due to the level of polish on the aluminum spheres and imprecise machining and positioning of experimental components compared with the theoretical inputs.

4.2. Testing

Current testing at USC is yielding peak temperatures below those needed for molten silicon due to optical inefficiencies

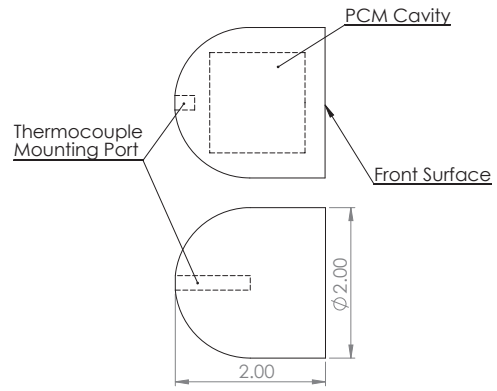


Figure 8. 2D schematic of both hollow and solid graphite crucibles showing a flat front to absorb incoming solar radiation and rear thermocouple mounting ports.

in the solar furnace. However, testing using copper as a sample PCM has already indicated necessary enhancements required for both the solar furnace and analysis methods. Copper has a relatively low heat of fusion. However, the lower operational temperatures result in similarly reduced radiative loss, producing a qualitatively similar system behavior to molten silicon. Temperature diagnostics are performed with both the Type C thermocouple sting mount, as well as an infrared, emissivity sensing pyrometer measuring the front surface of the crucible during cooling.

Graphite crucibles loaded with copper at a approximately 50% mass fraction have been tested in the furnace up to 1300 °C and cooling curves have been compared against a 1D model. Assuming negligible conduction losses through the sting mount, a cooling curve can be estimated for the graphite crucible using the following equation:

$$mC_p \frac{dT_{Crucible}}{dt} = -\epsilon A \sigma_{SB} (T_{Crucible}^4 - T_{Surr}^4) \times (1 - \eta_{Shielding}) + q_{Cond} + q_{Rad}. \quad (1)$$

Equation 1 describes the time rate of change of the crucible temperature with the left hand side representing the loss of sensible heat and the right hand side representing heat loss by radiation to the surroundings, heat input into the graphite form the PCM due to conduction and heat input from the PCM due to radiation. Both the PCM and the graphite are assumed to have a uniform temperature (infinite k_{th}) and it is assumed that the PCM is isothermal during the phase transition. Based on this, the conduction can be modeled with a known PCM-graphite contact area and an estimated thermal contact resistance. The radiation transfer between the PCM and the graphite is modeled as a two surface cavity with known emissivities. This arrangement can be solved numerically to produce a temperature curve for both a phase change and a non phase change case.

Figure 9 shows that the heat transfer between the PCM and the graphite results in a gradual slow down in crucible cooling during the period of phase change. Once phase change is complete, the crucible resumes the previous cooling curve. This gradual slow down is a function of the temperature difference between the graphite and PCM as well as the PCM

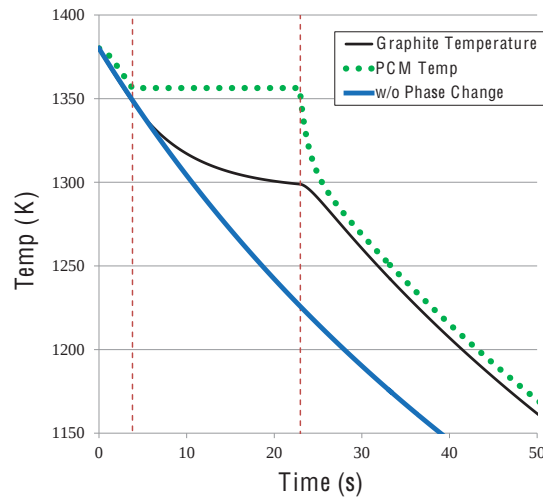


Figure 9. Sample temperature profiles derived from the 1D PCM heat transfer model showing the gradual reduction graphite cooling during the phase-change process (as indicated by the dashed red lines)

mass fraction within the test section. This model indicates that an isothermal heat release from the storage system will require a high PCM mass relative to the container.

Cooling curves were experimentally recorded for a 5.8 g graphite crucible containing 5.4 g of copper after heating well above the copper melting point. One of these curves is shown in Figure 10 compared with the 1D model.

The experimental cooling curve displays the expected behavior with a gradual reduction in cooling during the phase transition period. However, this process occurs much slower than the 1D model suggests. If the heat transfer between the PCM and the graphite is significantly reduced, as seen in Figure 11, the model closely follows the experimental data.

4.3. Results and Future Work

Based on recent testing, it is apparent that the 1D model currently being used to predict behavior is insufficient to describe the interaction of the PCM with the container material. While qualitatively correct, quantitative results will have to remove the assumptions of instant phase transition and isothermal materials to understand the relatively low heat transfer rates seen in the experimental data. The heat transfer between a PCM and a container material is a complicated process and is subject to limiting factors such as the formation of voids within the PCM. Future test and proof of concept system will have to include a means of heat spreading for maximum effectiveness.

It has also been shown that true isothermal heat release from the system will require a PCM mass that is far greater than that of the container so that the phase transition process dominates. Current experimental scales are limited in size due to the low power delivery of the Fresnel lens and the fact that radiation losses scale with the square of the crucible diameter. In order to achieve higher temperatures and increase the size of crucibles beyond 2 cm, a new concentrator is required.

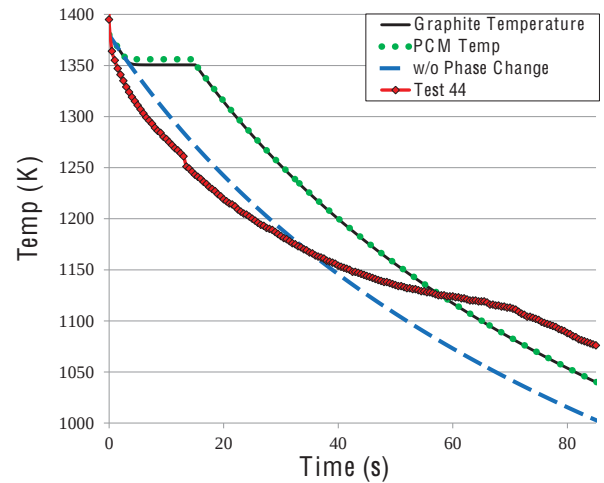


Figure 10. Experimental cooling curve plotted with the results from the 1D heat transfer model. Note that the experimental curve indicates a much slower heat transfer process than predicted.

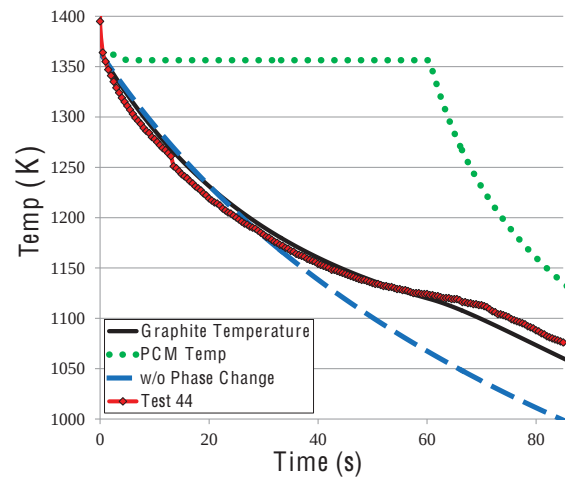


Figure 11. The same experimental data as Figure 10 plotted against the 1D model with greatly reduced heat transfer rates between the PCM and graphite crucible.

Work is progressing on the development of a concentrator with a 10,000:1 max concentration ratio that will allow for molten silicon testing at scales where the PCM will be the dominant system material. With this concentrator installed, testing will focus on understanding the PCM interaction with the container material and demonstrating throttling of the system through manipulating the phase transition of the PCM.

5. CONCLUSIONS

A systems level comparison has shown that a bi-modal solar thermal system with high performance thermal energy storage exists “off the curve” of traditional propulsion technologies that trade responsivity with total ΔV capability. Molten boron based thermal energy storage, when combined with ammonia propellant and thermophotovoltaics, eliminates many of the traditional drawbacks of STP systems and has the potential performance to create a truly bi-modal

propulsion and power system. Careful evaluation of the required technologies shows that many of the basic components to implement such a system currently exist. However, a significant effort will be required to integrate molten boron into a system design due to materials considerations and the high temperatures involved. Assuming that these challenges can be met, a bi-modal system based on boron as a PCM could yield a low mass combined propulsion and power solution for high capability microsatellites in earth orbit.

To resolve the challenges of a molten boron or silicon based system, an experimental effort is ongoing with the aim of demonstrating a ground based proof of concept. Current testing, despite being limited by low solar concentration ratios, has indicated that an effective thermal storage system will require a high PCM mass fraction for isothermal heat release and special attention must be paid to the interaction of the PCM with the container material which has been shown to deviate strongly from initial 1D performance estimates. Based on current data, a full scale concentrator is currently under development, and will allow for experimental testing at larger scales and higher temperatures.

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