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HIGH ENERGY ADVANCED THERMAL STORAGE FOR SPACECRAFT SOLAR THERMAL POWER AND PROPULSION SYSTEMS

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ABSTRACT

Solar thermal propulsion offers a unique combination of high thrust and high specific impulse levels that can provide competitive advantages relative to traditional satellite propulsion systems. In order to enhance the functionality of this technology, thermal storage combined with a means of thermal-to-electric conversion is suggested, with the idea of providing a dual-mode power and propulsion system based on thermal energy. A system including silicon (moderate performance) or boron (high performance) phase change material for storing energy, an insulating containment system consisting of boron nitride, carbon bonded carbon fiber, and vacuum gap insulation is proposed, with thermophotovoltaics used for electrical conversion. A laboratory solar concentration system has been constructed and experiments to directly heat small quantities of candidate materials have begun, so that the nature and challenges of this system can be evaluated. A modeling effort to optimize the solar receiver/absorber/converter system is also underway and will be discussed.

INTRODUCTION

Solar Thermal Propulsion (STP) systems, with a unique balance between propulsive efficiency and available thrust, are known to offer significant advantages over chemical and electric propulsion for some mission scenarios. A recent review of micropropulsion technologies¹ has indicated the particularly strong potential performance offered by Solar Thermal Propulsion in microsatellite systems. Analysis shows that STP systems currently in development, with specific impulse (I_{sp}) values of 400-1000 seconds, can provide a propulsion system mass fraction (including propellant) of less than 50%, with a 1.5 km/s velocity increment (ΔV) capability. With microsatellite STP thrust levels of 1 Newton, the entire velocity increment could plausibly be delivered in less than one day, providing the potential for a highly capable, light-weight spacecraft.¹

Traditionally, however, STP has been viewed as somewhat limited due to the requirement for solar illumination of the collector during times when propulsion is needed. Proposed fiber optic collection of concentrated sunlight can yield some extra flexibility in terms of spacecraft attitude and positioning by decoupling precisely-aimed collectors from the thruster and other physical components.²⁻⁶ Combining STP with a means of thermal storage, however, would allow for augmented thrust even during times of

spacecraft eclipse, and could vastly increase the utility of the propulsion system for a variety of missions; adequate thermal storage could potentially yield a high-efficiency, high-thrust spacecraft that can produce thrust on-demand even when in eclipse, offering the flexibility of a conventional chemical or electric system with the superior performance and robustness of an STP system. Further, a thermal storage system could yield benefits in terms of augmented thrust relative to a similarly sized non-storage STP system if both direct-gain solar illumination and stored thermal energy can be used simultaneously; this sort of design could likewise be used to decrease the size of the overall solar concentration system for a spacecraft with only intermittent propulsion requirements.²

An additional perceived disadvantage of an STP system is the need for additional large solar concentrators. While the electrical power requirements for chemical and electrical rockets can generally be met via the power subsystem (i.e.: photovoltaic cells and batteries) on board the spacecraft, the solar thermal propulsion system would require its own, additional, dedicated solar concentrators. This thermal collection system requires an additional budget for space and mass on board the satellite and launch vehicle, appearing as a significant disadvantage for the propulsion technology. It is suggested here, however, that the use of an effective thermal storage system, combined with a means to convert thermal energy to on-demand electrical power, could eliminate the need for photovoltaic systems and accompanying batteries. Powering the entire spacecraft, including both electrical and propulsive needs, via a thermal collection, concentration, storage, and conversion system, could yield a highly efficient and high performance satellite system.

This paper will analyze the prospect of utilizing a solar thermal system with thermal storage as the primary propulsive device and energy source onboard a microsatellite. This study will not offer a complete design of any particular subsystem, but will seek to survey each area of technological interest for such a thermal power and propulsion system. The details of an ongoing experimental effort to characterize the nature of concentrated solar power systems and thermal storage materials will also be discussed.

PROPULSION AND ΔV FOR MICROSATELLITES

A large variety of solar thermal propulsion systems for microsatellites have been proposed and studied in ground tests and simulations.⁴⁻¹⁰ However, no solar thermal rockets, much less those intended for microsatellites, have ever been flown.¹⁰ The literature does note that a well-implemented STP system on board a microsatellite would be a significantly enabling technology due, in part, to the fact that microsatellites are often launched as secondary payloads accompanying higher budget missions, and are therefore typically placed in sub-optimal orbits for their own mission goals. In many cases, the required ΔV to reposition the microsatellite into the desired orbit is several hundred meters per second, with the more extreme cases requiring up to 2 km/s. Present propulsion technologies utilized on microsatellites are inadequate for this purpose.¹

It has been noted that providing a microsatellite with an STP system could allow up to a 1.5-2 km/s ΔV maneuver, opening up a wide range of mission scenarios. By providing a ΔV of several hundred meters per second or larger, the microsatellite operating regime (assuming various starting orbits as a secondary payload) could be widened to include maneuvers from Geosynchronous Transfer Orbit (GTO) to Geosynchronous Earth Orbit (GEO), insertion into lunar orbit, highly eccentric orbits for observation and analysis, LaGrange point and Earth-trailing orbits, and even Earth escape.⁷ Even end-of-life deorbiting of microsatellites would be economical with an STP system.⁹ Table 1 lists some mission scenarios and the required ΔV values that have been studied. Note that while these missions may also be possible with electric propulsion systems, the time to complete the maneuver via STP would be significantly reduced, perhaps by a factor of three or greater depending on the burn strategy selected (e.g.: continuous firing of thrusters vs. firing only at apogee and/or perigee).

Table 1. Example Missions for Microsatellite STP System Studies.⁷

Mission Description	Required range of ΔV [m/s]
Near Escape: Assumes starting from GTO, and maneuvering for flybys of near-Earth objects, magnetospheric characterization in highly eccentric Earth orbits, positioning at LaGrange points, or Earth-trailing orbits.	770-1,770
GEO Insertion: Assumes starting from GTO and transferring to geosynchronous Earth orbit.	~1,760
Other Body Capture: Assumes starting from a fly-by orbit and subsequent capture into lunar or planetary orbit.	1,100-4,000
- Lunar Orbit Insertion	2,103

In addition to these somewhat exotic mission scenarios, an STP system could be utilized to provide a highly dynamic and responsive microsatellite, or to simply reposition a non-optimally placed satellite to a new inclination, orbit altitude, or orbit phase. A calculation of the combinations of inclination change and altitude change from a circular 200 km orbit that becomes possible with large ΔV values is provided in Figure 1. In producing 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 high altitude. Attitude control, precise approach to another orbiting body, and minor orbit rephasing are likely to consume significantly less ΔV than major changes to the altitude or inclination of the orbit.

SOLAR THERMAL POWER AND PROPULSION SYSTEM

Previous studies have examined the prospect of STP with thermal storage^{2,3} and major developmental projects, including the Solar Orbit Transfer Vehicle (SOTV)¹¹⁻¹⁴ and the Integrated Solar Upper Stage (ISUS),^{15,16} have included both thermal storage and a means of thermal electric generation.

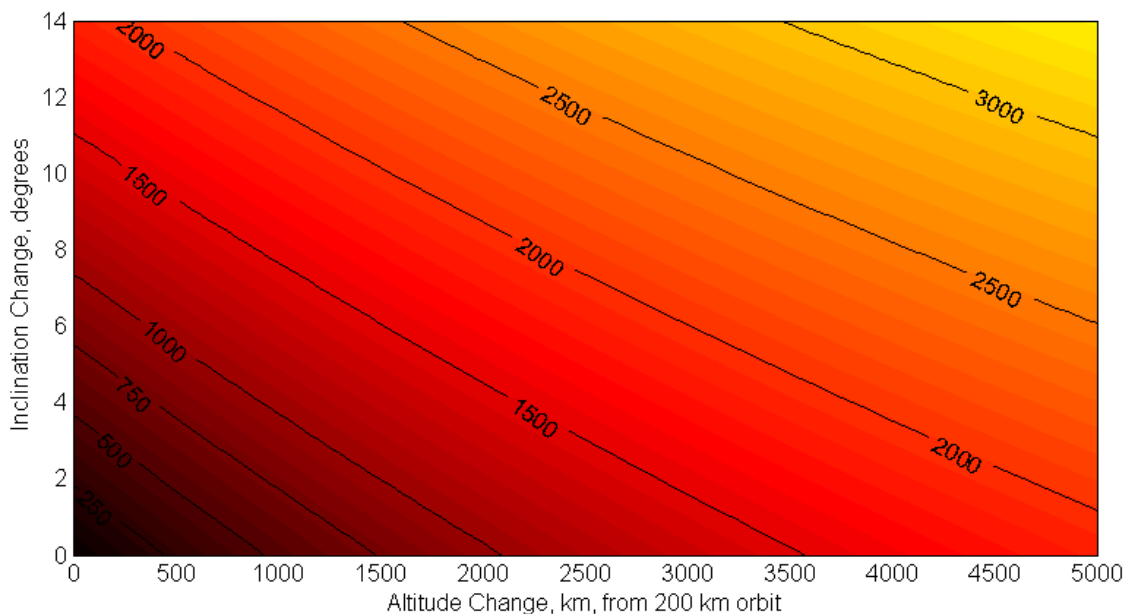


Figure 1: Color map and contours indicating the required ΔV values to achieve a given combination of altitude increase and inclination change. Units of ΔV , indicated on the contours, are given in m/s.

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. Additionally, while high-performance full-sized satellites are currently available, practical designs and propulsion systems for microsattellites with large ΔV capabilities and high thrust levels (i.e.: rapid response time) are not. With this in mind, the goal of this work is to edge closer to a full bimodal thermal power and propulsion system design through determination of current materials capabilities and analysis of the technological developments (in terms of material properties and system designs) required to make such a system feasible and competitive against traditional chemical and electric rockets coupled to battery-based electrical systems. The basic performance targets, for a 100 kg microsattellite in Low Earth Orbit (LEO), include continuously available electrical power rated at 100 Watts, continuously available propulsion with performance on the order of 1 Newton of thrust and a 300-400 second I_{sp} , an energy collection system capable of drawing in several hundred Watts per kg, and an energy storage density of at least 750 kJ/kg.¹⁷ If these goals can be met via the proposed bimodal system, then significant improvement relative to conventional systems, will be shown, and a significant advancement in the utility of microsattellites becomes plausible. In fact, the specific targets are overly demanding since the entire propellant load would be consumed in less than 24 hours if the propulsion system was operated at a thrust of 1 Newton.

PROPULSION REQUIREMENTS

The most critical requirement for the proposed bimodal thermal system will be to ensure optimal operation of the propulsion mechanism. In order to provide a propulsion system that not only competes with existing flight-ready technologies, but also demonstrates enough significant advantages that a full redesign of the satellite power system is justified, we must demand high performance. The primary competitors for the high-thrust, mid- I_{sp} capabilities of an STP system are in-space chemical and electric rockets. In order to compete with these systems, an STP system must provide similar or greater thrust relative to a chemical rocket, with a notable increase in I_{sp} . It has been shown in the literature that an STP system sized for a microsattellite is capable of producing a relatively high thrust level of 1 Newton.^{1,5} In order to surpass the best chemical systems available for microsattellites, a target I_{sp} in the range of 300-400 s is the goal, and is certainly achievable.^{1,3,5}

The primary propellant options discussed in the literature for STP systems are hydrogen and ammonia. Hydrogen can offer I_{sp} values on the order of 1000 s, but is not space-storable.² Ammonia, on the other hand, is readily storable in space, and several studies show that with a pre-nozzle temperature above 2500 K, I_{sp} values of 407 s can be achieved.^{2,5} Ammonia propellant also offers additional advantages in terms of system simplicity: the vapor pressure of the ammonia propellant can be used to pressurize the propellant and move it from the storage tank to the thruster,² so an active feed system is not required. Ammonia also thermally dissociates into hydrogen and nitrogen at high temperatures; this provides lighter exhaust species that can be ejected at higher velocity. However, this comes with the simultaneous disadvantage of the absorption of significant heat when bonds are broken.⁴

Theoretically, the exhaust velocity and the I_{sp} of a rocket can be calculated as:

$$V_e = I_{sp} g = \sqrt{\frac{T k_B}{m} \frac{2\gamma}{\gamma - 1} \left[1 - \left(\frac{P_e}{P} \right)^{\frac{\gamma - 1}{\gamma}} \right]}, \quad (1)$$

where V_e is the exhaust velocity, T and P are the upstream propellant temperature and pressure, respectively, P_e is the exit pressure from the nozzle, m is the average propellant particle mass, γ is the ratio of specific heats for the propellant, g is Earth's gravitational constant, and k_B is Boltzmann's constant.

Direct calculation of the exhaust velocity from temperature alone requires assumptions of the upstream pressure, the degree of disassociation of ammonia (a function of temperature and time¹⁸), and calculations based on the nozzle area ratio to determine the exit pressure. Additionally, even with the assumption that ammonia does not disassociate, the ratio of specific heats, γ , will vary with temperature.

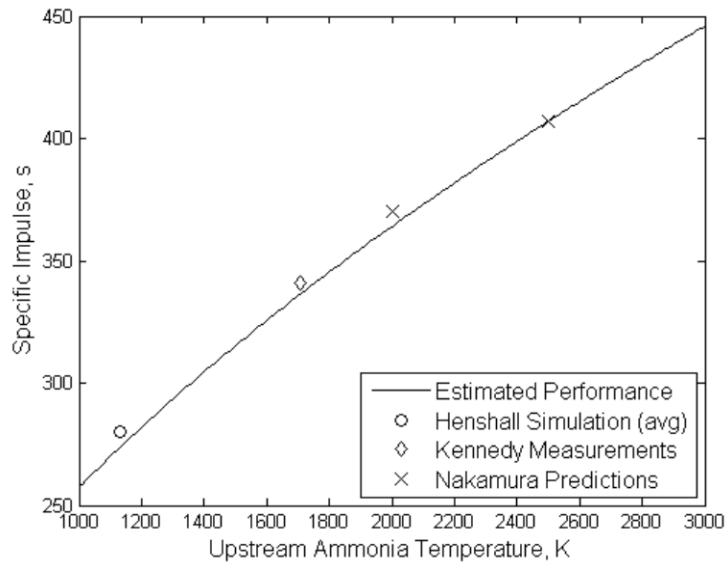


Figure 2: I_{sp} vs. upstream temperature for an ammonia-fueled solar thermal rocket. Note the strong agreement between the assumed model and data from the literature.³⁻⁵

At low temperatures, in which only the translational and rotational modes of molecular motion are activated, γ for pure ammonia is given as 1.31. As temperature increases and the 6 vibrational modes are activated, the ratio of specific heats will decrease, ultimately yielding a γ value closer to 1.1. A combination of varying energy states and ammonia molecules that can disassociate into nitrogen and hydrogen¹⁸ represents a significantly complex problem.

Therefore, for this analysis, we will choose a basis value that has been noted in the literature: a temperature of 2500 K for ammonia should yield an I_{sp} of 407 s in a typical solar thermal rocket.^{2,5} For estimating performance with varying temperature, a rough scaling with the square root of T is utilized; the result is displayed in Figure 2. Note that the estimated performance curve closely approximates predicted and measured performance of solar thermal rockets under development.

Throughout the rest of this paper, the analysis will focus on the requirements associated with concentrating solar flux onto a thermal storage medium in order to achieve something near the 2500 K target temperature. This requires a solar concentration ratio of 10,000:1,^{2,14} which has been demonstrated experimentally.⁴ The thermal storage medium must be able to adequately store energy in this temperature regime, and insulators need be able to maintain that temperature for a significant amount of time during eclipse. Further, a heat exchanger for transferring energy from the thermal storage medium to the propellant must be developed, and a means of thermal-electric conversion will need to be devised. All materials in contact with the thermal storage medium must, of course, tolerate the highest system temperatures without undergoing significant chemical or physical changes.

THERMAL COLLECTION

The collection of thermal energy from the sun appears to be a solved problem, with collectors appropriately designed for in-space use that achieve concentration ratios over 10,000:1 in ground-based experiments.⁴ There is significant confidence that an adequate solar concentration and collection system can be designed to produce temperatures over 3000 K, and that the target temperature of 2500 K¹⁸ can certainly be achieved.⁵

Variations of solar concentration and collection exist in currently developed STP designs, in ground-based solar thermal power generation, and even in concentrated photovoltaic systems with both terrestrial and space-based applications. Proposed designs for propulsion systems include parabolic, spherical, and Fresnel concentrators used to focus sunlight by orders of magnitude onto a small surface.^{2,4} For light-weight, imperfect primary concentrators, small secondary concentrators (with high

temperature handling capabilities) can be added to more precisely focus the collected light.² Concentrator designs include inflatable and deployable systems as well as light-weight rigid mirrors,^{2,4,5,11-14} concentrator masses below 1 kg per square meter are common,² and concentrators weighing under 200 g/m² while providing a concentration ratio near 10,000:1 have been shown.^{4,9,19} Concentrator mass will certainly compete well with that of a photovoltaic (PV) system. Further, due to the higher efficiency of solar reflection compared to photoelectric conversion, the size of a concentrating system can be notably smaller while providing the same power output. The use of fiber optic lines to couple together the collected light from multiple small concentrators could also result in a decrease in the mass of an STP system since smaller concentrators may have a much lighter mass for a given surface area.²⁻⁴

It is expected that an efficiency of greater than 70% for the entire solar collection system can be achieved; this includes inefficiencies associated with collecting (reflecting) and concentrating the incident light, collecting and transmitting the concentrated light along a fiber optic cable, and delivering it to the thermal storage medium.⁵ It should be noted, however, that current engineering systems in the lab are only 35% efficient. Even at this lab prototype level, the efficiency is close to that of high-end triple-junction PV panels for use in space, although the "downstream" efficiencies of a solar thermal system will likely be considerably less than that of the simple batteries and power supplies that might be used to handle PV-generated energy. Nakamura⁵ also indicates that there are a few simple upgrades to his basic engineering systems that would more than double the overall efficiency. For example, a relative efficiency increase of 9% will be achieved by simply operating the solar concentrators in space where conditions of the air will not affect the path of light.⁵ Additionally, Nakamura, et al., state that in laboratory models, a concentrator with a reflectivity of 80% was used and reflectivity above 90% requires only careful engineering.⁵ Targeting these and a few other minor design improvements, researchers expect overall efficiencies over 70% for a fully space-qualified collection system. There is, however, some disagreement as to the absolute maximum that can be achieved: Henshall, et al., for example, place the fiber optic transmission efficiency at a maximum of 80%,^{2,3} while Nakamura suggests that 90% is readily achievable.⁵ Significant improvement over the 35% starting point, however, is certainly likely as a system is developed and optimized for use in space.⁵ With the expected improvements in optical system efficiency achieved, well-designed storage, heat transfer, and electrical conversion subsystems should be able to achieve a marked step forward relative to traditional PV-battery systems.

THERMAL STORAGE MATERIALS

Materials typically used for terrestrial thermal storage systems are not applicable to microsatellite power systems like that proposed here: the range of operating temperatures and the energy storage density are both too low.¹⁷ However, the basic concepts of terrestrial thermal storage systems can provide the direction of investigation for in-space systems. Storing thermal energy can generally be accomplished by either a sensible heat system, which operates on the principle of raising the temperature

Table 2. Relevant Properties for Candidate High Temperature Sensible Heat Storage Materials.⁷

Material	T _{melt} [K]	C _{p,s} [kJ/kgK]	□E/m _{2000-2600K} [MJ/kg]	□H _{us} [kJ/kg]
CARBON	3923	2.09	1.25	---
Tungsten	3643	0.134	0.0804	284
Rhenium	3453	0.15	0.09	325
Boron Nitride	3273	1.99	1.194	---
BeO	3010	2.43	1.458	3,410
Molybdenum	2890	0.255	0.153	391
Silicon Carbide	2818	1.47	0.882	---
B ₂ C	2673	2.51	1.506	1,900
Boron	2570	2.93		4,650
Al ₂ O ₃	2322	1.36		4,580
Silicon Nitride	2173	1.13		---
Silicon	1685	0.963		1,800

of a material with a high specific heat, or by a latent heat system, which operates on the principle of energy storage due to the change of state or phase (typically the solid-liquid transition) of a material.

In evaluating the potential of a microsatellite system with sensible heat storage, materials with melting points significantly above the planned operation temperature were reviewed. Table 2 summarizes the relevant properties for candidate high temperature sensible heat energy storage materials. The materials below the dashed line are applicable for phase change applications and other support roles, and are included for completeness.

Previous work on sensible heat thermal energy storage for spacecraft applications has determined that boron carbide and carbon were optimum materials for the applications studied.⁷ The performance of these materials is ultimately limited by the allowable temperature change defined by mission requirements. Larger temperature changes will reduce the power conversion efficiency, cause variations in thruster performance, and place additional stress on materials due to temperature cycling. For this reason, even these high-performance materials are unlikely to compete with a latent heat energy storage system that can achieve a similar or greater energy storage density for spacecraft applications, while maintaining a relatively constant temperature.

When considering a latent heat energy storage system, in which the energy storage comes primarily by way of a material that changes phase, the additional difficulties of working with a liquid material must be considered including the material compatibility of a chosen material and a properly matched melting temperature. Table 3 lists the most important considerations that were assembled from previous material reviews and from the early analysis in the present work. The first three properties,

Table 3. High Temperature Phase Change Material Considerations.

PCM Consideration
- Properly Matched Melting Temperature.
- High Energy Density.
- Good Material Compatibility.
- Good Material Stability.
- High Thermal Conductivity.
- Low Vapor Pressure at Melting Temperature.
- Small Volume Change During Transition.
- High Emissivity.

Table 4. Potential High-Temperature Phase Change Materials.

Material	Melting Temp. [K]	Heat of Fusion [kJ/kg]	Thermal Conductivity [W/mK]
Manganese	1519	235	7.8
Magnesium Fluoride	1536	940	
Beryllium	1560	1312	200
Silicon	1687	1785	149
Nickel	1728	298	90.9
Cobalt	1768	272	100
Yttrium	1799	128	17.2
Iron	1811	247	80.4
Scandium	1814	313	15.8
Palladium	1828	157	71.8
SiO ₂	1923	188	~1
Lutetium	1925	126	16.4
Titanium	1941	295	21.9
Zirconium	2128	153	22.7
Chromium	2180	403	93.9
Vanadium	2183	422	30.7
Rhodium	2237	258	150
Boron	2570	4600	27.4
Hafnium	2506	152	23.2
Ruthenium	2607	381	117
Iridium	2739	213	147
Niobium	2750	323	53.7
Molybdenum	2896	390	138

melting temperature, energy density, and compatibility (including wettability and CTE matching) are critical enabling considerations, while the others also play a strong role in determining a PCM.

A thorough search was conducted for phase change materials that met the melting temperature and energy density requirements and Table 4 shows those initially identified. For the high-performance microsatellite system described here, boron has been selected as the thermal storage medium. Boron has the highest energy density (4.6MJ/kg) and a melting temperature that coincides well with the optimal operating temperature of an ammonia-fueled STP rocket. However, limited research has gone into using the material at high temperatures. Therefore, one of the key goals of this research project is to evaluate the use of boron in terms of its energy storage capacity, reusability over repeated cycling, and interaction with other materials in the system. Molten silicon was also chosen as a material of interest. It has lower potential for microsatellite systems due to its lower melting temperature and energy density. Preliminary systems level experiments will use molten silicon because all of the required materials and subsystems to construct such a system already exist for molten silicon while molten boron systems will require advancements in multiple areas before a complete system could be built.

PHASE CHANGE MATERIAL CONTAINMENT AND INSULATION

Utilizing latent heat energy storage versus sensible heat energy storage adds complexity to the system design since the storage material for the PCM must be structurally sound at high temperatures and chemically compatible with the liquid PCM. The container material must also maintain these properties during high temperature operation for long periods of time, perhaps 10 years or more. Since the container material selection is made primarily through compatibility considerations, it is therefore completely coupled to the chosen phase change material. Molten boron is highly reactive with a variety of elements, and while the literature concerning molten boron compatibility is limited, materials exist that appear capable of resisting boron attack, as will be discussed in the experimental section of this paper.

Another critical technology required for containing the molten boron phase change material will be preventing the escape of stored energy. Very high temperature thermal insulation materials must meet a long list of exacting requirements, including the ability to withstand the storage temperatures, potentially operate through a large number of thermal cycles, compatibility with the other materials involved, and maintain certain structural properties. Table 5 lists a select group of common high temperature thermal insulation materials along with a select group of other materials that represent high-performance for other required properties. Aerogel is listed to demonstrate a material that is fully optimized for minimal thermal conductivity even though it can clearly not meet the high temperature requirements. Also, the effective thermal conductivity for blackbody radiation transport across a 1 cm vacuum gap from a surface at the specified temperature to a surface at 300 K is also given since it is common for solar thermophotovoltaic (TPV) systems to use a vacuum gap with low emissivity surfaces on either side as the first insulating layer.²⁶ Based on the comparison in Table 5, Carbon bonded carbon fiber (CBCF) appears to be an excellent insulator at the high temperatures required for the proposed system.

Table 5. Properties of High-Temperature Insulation Materials.

Material	Density [kg/m ³]	T _{melt} [K]	k _{th,500K} [W/mK]	k _{th,1000K} [W/mK]	k _{th,1500K} [W/mK]	k _{th,2000K} [W/mK]	k _{th,2500K} [W/mK]
Aerogel ²⁰	80	600	0.01				
Fused Silica ²¹	2200	1985	1.5	2.1	2.1		
Sapphire ²²	4000	2313	20	8	---	---	
Alumina ²²	4000	2345	21	5	5	8	
Boron Carbide ²³	2520	2673	12.5	9	6.5	---	---
Silicon Carbide ²⁴	3210	3003	120	60	38	28	---
Boron Nitride ²¹	3487	3246	37	22	21	19	---
Carbon Bonded Carbon Fiber ²⁵	180	3273	---	0.4	---	0.9	---
Vacuum [Δx=1cm]	---	---	0.15	0.80	2.39	5.33	10.1

ELECTRIC ENERGY CONVERSION

Table 6 provides a summary of the comparison of the states-of-the-art for different energy conversion technologies and comments about the future potential of each technology. There are a wide variety of options for thermal-to-electric systems that operate at a hot-side temperature (T_h) below 1300K and are not mass constrained including thermoelectrics, alkali metal thermoelectric converters (AMTEC), and free piston Stirling engines. These methods, however, would require significant development efforts to operate at the required T_h for high-temperature thermal-to-electric conversion on spacecraft. Closed Brayton cycle systems that can operate at the required high temperatures are not currently available, but it is likely that with further development the technology may be advanced significantly with carbon-carbon systems. But, it is also important to note that both Brayton and Thermionic systems are typically more advantageous at high power levels. Nantenna based conversion systems have significant theoretical potential, but have yet to achieve any significant fraction of this. This leaves thermophotovoltaic systems as the most promising candidate for the near term. TPV systems will be chosen as the representative solution for the discussion to follow.

Note that while thermophotovoltaic systems are much heavier than PV at 15 W/kg, TPV will likely benefit from the same type of development that has advanced standard PV over the past decade. In 2001, Kessler noted that state of the art 3-junction photovoltaic arrays developed for space weighed in at 15 W/kg.²⁸ Surprisingly, this is the same value at which TPV systems sit today. Yet, in just over a decade, NASA is targeting nearly 10 times lighter systems (140 W/kg by 2012).²⁹ It is reasonable to assume, then, that advanced materials and other developments should push TPV systems down to similar power-per-mass levels in a similar time span. The value quoted in Table 6 also includes the mass for the radiator that is required to remove that waste heat. Advances in radiator design could lead to additional mass reductions.

THERMAL CONVERSION FOR PROPULSION

While the majority of the designs for solar thermal propulsion systems do not include a significant means of thermal storage, they can still provide a starting point for the design of the means of heat transfer to the propellant. In typical solar thermal designs, there are two primary means of heating the propellant: either the propellant is heated directly by the concentrated sunlight, or the concentrated flux is used to heat an amount of solid material, which then transfers heat to the propellant through convective

Table 6. Electrical Energy Conversion Options.²⁷

Technology	Specific Power [W/kg]	Efficiency	Maximum Temp. [K]	Comments
Thermoelectric	9.4	6.3%	1273	<ul style="list-style-type: none"> Limited temperature operation. Incremental development OK for specific power & efficiency.
Thermophotovoltaic	15	19%	None	<ul style="list-style-type: none"> Long lifetime demonstration required. Operation in space environment required.
Thermionic	100@ 1kWe	> 10%	2200	<ul style="list-style-type: none"> Baselined for another application at higher power levels.
AMTEC	14	16%	1300	<ul style="list-style-type: none"> Unlikely to achieve required temperatures.
Nantenna	Unknown	<1%	None	<ul style="list-style-type: none"> Significant uncertainties in all aspects. Current concern: efficient rectifying diode.
Closed Brayton	Varies w/ power	29%	1700	<ul style="list-style-type: none"> Possible to achieve required temperatures. Mass may be high for low power levels.
Free Piston Stirling	100	35%	1050	<ul style="list-style-type: none"> Unlikely to achieve required temperatures. High performance & long lifetime demonstrated.

transfer.⁶ Typically, the convective heat transfer method can allow a higher flux of higher temperature propellant, resulting in a more efficient and higher performing vehicle. In the proposed research in which significant thermal energy is stored on-board, this effect would be even more dramatic as the radiation emitted from the phase change material would be even less concentrated than the focused solar flux. Therefore, a convective heat transfer method has been selected for the system proposed here.

In systems designed with sensible heat thermal storage, the convective heat transfer is generally accomplished by flowing the propellant either through a tortuous foam of heated particles or through narrow channels within the storage material.^{30,31} While these systems rely on the sensible heat capacity of the material as its temperature increases, they can be used as the basis for designing a system with the high heat capacity and isothermal operation of phase-changing boron. As a first step, for example, the boron nitride-coated boron carbide foam discussed by Kennedy and Palmer⁷ could be modified into phase-changing boron particles contained and protected by boron nitride. Likewise, the graphite heat storage and exchange system designed for the ISUS RAC^{30,31} could also be modified to contain boron-based storage. It is noted that thermal conduction within a foam of spherical particles to ensure even temperature distribution would present a significant challenge. Additionally, boron is known to react with carbon at high temperatures, so directly incorporating boron into the ISUS RAC system would require layering additional materials for compatibility. As a first design, therefore, it is proposed that the graphite thermal storage block designed for ISUS, with included channels for heating the flowing propellant, be replaced with boron nitride for chemical compatibility with the propellant⁷ and the boron phase change material. This boron nitride structure could be further hollowed and filled with boron to allow for phase change thermal storage; the boron nitride structure and channels would serve to contain the boron, to allow additional thermal conduction throughout the thermal storage medium, and to maintain a barrier between the molten boron and the flowing propellant.

PRELIMINARY RECEIVER/ABSORBER/CONVERTER DESIGN

Combining all of the above components, a baseline system can be imagined. As a first step, the RAC system pictured in Figure 3 is proposed for further analysis and modeling. Note that the system includes a central core of boron phase change material surrounded by boron nitride and that the crucible is insulated with layers of conventional and vacuum insulation. Incoming pre-concentrated solar light enters through the top of the system, as pictured, where a secondary concentrator further focuses the light. Thermophotovoltaics positioned above what is likely to be the hottest surface will convert radiated power to electricity, and a shutter assembly can be used to throttle the system and/or close off the

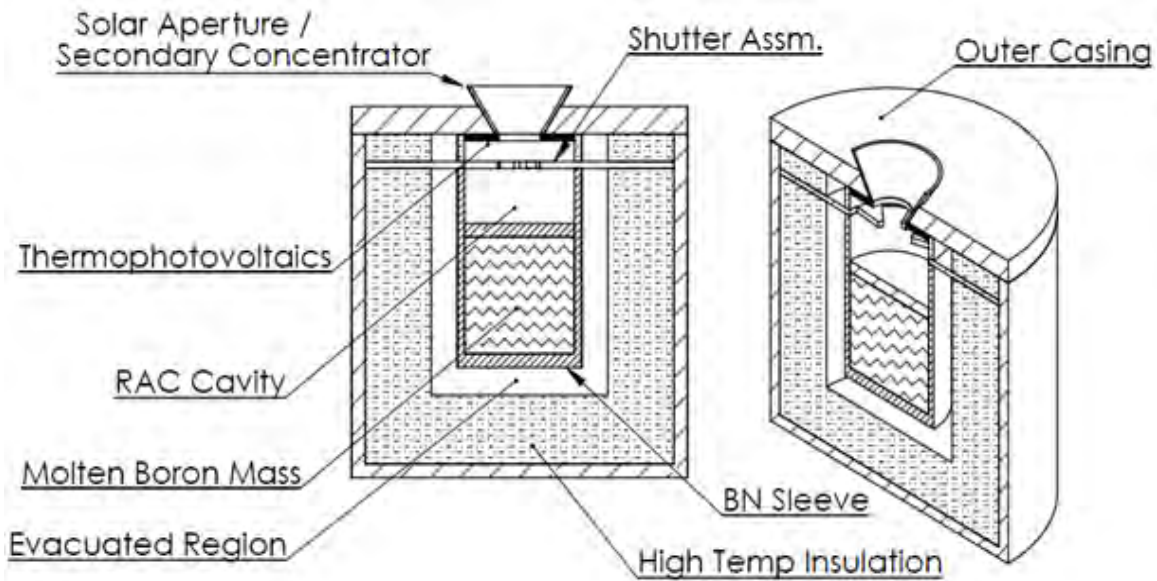


Figure 3. Nominal design for Receiver/Absorber/Converter (RAC) analysis.

aperture during times without illumination. At this early stage, the means of heat transfer to the propellant has been left out of the design, but can be added in later, either starting from a modification to previous designs (as discussed above) or taking a simulation-suggested design as the heat transfer analysis of the system progresses.

For a high performance microsatellite system in a 100 minute low Earth orbit with 40 minutes in eclipse, a constant electrical draw of 100 Watts combined with a thermal draw of 100 Watts for propulsion is assumed. Allowing for a per-cycle storage efficiency of 75%, and an easily-achieved electrical conversion efficiency of 20%, less than 0.5 kg of boron would be required for energy storage. With a basic insulation design, just over 1 kg of CBCF insulating material would be required; it is assumed that notably less mass would be required with a well designed system combining vacuum insulation and CBCF layers. In this way, an energy density for the storage system of 2-4 times that achievable with conventional lithium ion batteries is likely. Further, assuming a 1360 W/m² solar constant, and a 50% efficient solar concentration and collection system (an efficiency likely to be exceeded), just over 2 square meters of solar concentrator would be required, weighing well under 0.5 kg.⁹ Assuming a reasonable mass level can be achieved with fiber optics used to guide the concentrated solar light, the secondary concentrator, the shutters, and the TPV energy converter, it is likely that the hybrid propulsion and energy storage system for a high performance microsatellite could have a mass of well under 15 kg, leaving a significant mass budget on board a 100 kg microsatellite for propellant and payload.¹

INITIAL RECIEVER/ABSORBER/CONVERTER ANALYSIS

A computational evalutaion of the heat transfer in the nominal RAC design shown in Fig. 3 was performed. The nominal design geometry was used, however, component materials were modified for use with molten silicon as a PCM as opposed to molten boron. A molten silicon system will be more

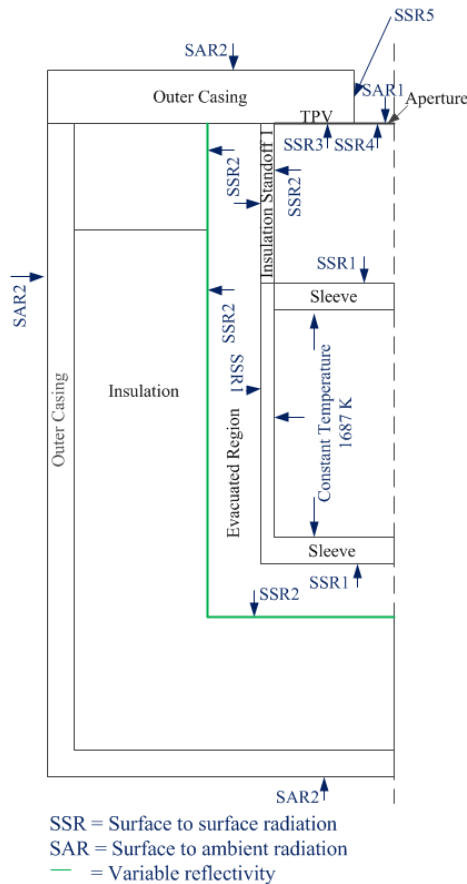


Figure 4. Computational model boundary conditions.

tractable to validate experimentally and is still suitable for a moderate-performance system. The primary focus of this effort was characterize the system heat transfer by determining total system heat losses and the irradiation and temperature of the TPV.

A three-dimensional model, generated in the commercially available COMSOL Multiphysics simulation software, was generated. The phase change material was assigned to be silicon, the sleeve to silicon carbide, all insulation to carbon bonded carbon fiber, and the outer casing to graphite. The TPV was assumed to be a blackbody and the aperture was constructed from anodized aluminum. The steady-state heat transfer was modeled using COMSOL's Surface-to-Surface Radiation physics module. The system boundary conditions are shown in Figure 4. The system was meshed with tetrahedral elements using the physics-controlled mesh setting and an element size of "finer." An iterative generalized minimum residual (GMRES) solver with left preconditioning was employed.

The model results showed adequate TPV irradiation. The analysis also indicated the TPV temperature was higher than the desired operating temperature and system losses were significant. More importantly, the model results provided invaluable insight into the heat transfer mechanisms and interactions. As can be seen in the temperature contour plot shown in Figure 5, areas with significant thermal gradients were identified and heat flow direction was established. In order to further identify geometric parameters critical to improving the heat transfer performance of the nominal design, a parametric study was performed. PCM length and diameter, RAC cavity length and diameter, insulation thickness, and the width of the evacuated region were varied and the results compared to those of the preliminary design. In general, changes in cavity length and PCM length did not significantly impact the system heat transfer. For example, a 40% increase in cavity length, decreased the TPV temperature by 3%, TPV irradiation by 11%, and heat loss from the system by 4%. Insulation thickness and evacuated region width had a larger impact; a 50% increase in insulation thickness and 50% decrease in evacuated region width decreased TPV temperature by 16% and heat loss by 42%. Finally, a reflective shield was added to the inner diameter of the insulation and the reflectivity of the shield was varied from 75 to 95%. Adding a 95% reflective shield to the nominal design dropped system losses by 22%. These results will be leveraged by future designs.

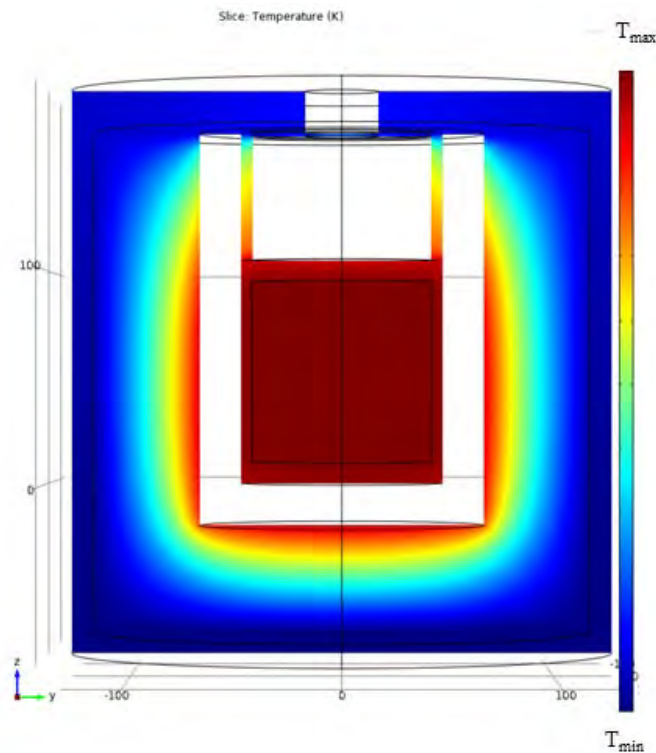


Figure 5. Temperature contour in the nominal design where the PCM is molten silicon.

EXPERIMENTAL TEST FACILITY

In order to develop a practical understanding of the challenges described above, an experimental effort is underway at the University of Southern California to physically investigate phase change thermal energy storage. The near term goal of the system is to generate and maintain a molten boron sample, with minimal contamination, through the use of concentrated solar radiation. This experimental effort will allow for the evaluation of PCM technological requirements and is intended to aid in determining the technical challenges involved. Utilization of concentrated solar radiation as the experimental heat source ensures direct correlation of data and techniques with future solar thermal applications.

INITIAL SOLAR FURNACE DESIGN

A schematic of the initial design for the USC solar concentration system can be seen in Figure 6. The system consisted of a heliostat, offset parabolic concentrator, and redirection mirror to bring concentrated solar radiation into a vacuum chamber and ultimately into the test section. As described in previous work, the system was sized for a total power output of 1000 W and system placement on the urban USC campus allowed for approximately 4 hours of full illumination per day.³²

This initial solar furnace design never achieved full operational status and was not operated above 5-10% design power due to manufacturing difficulties in the offset parabolic concentrator. The mirrorization process used on the fiberglass dish template failed due to difficulties in controlling extra reactions during chemical spraying. This degraded the clear coat protecting the deposited silver surface and resulted in an uneven surface. In addition to the issues with manufacturing the reflector, this experimental design also suffered from persistent alignment issues due to the inclusion of the re-direction mirror which served to amplify any aberrations in the incoming radiation. This effect, when combined with the efficiency losses inherent in adding another optical component to the system, made the re-direction mirror another key factor in lowering maximum power delivery.

Despite the ability to only achieve low power levels, this system was able to produce peak experimental temperatures in excess of 1600K during the initial round of testing. The first iteration of experimental hardware, which was designed around the envisioned input profile of this solar furnace, provided useful insights into material compatibilities, crucible design, radiation shielding, and thermal gradients that will be applied to future versions.

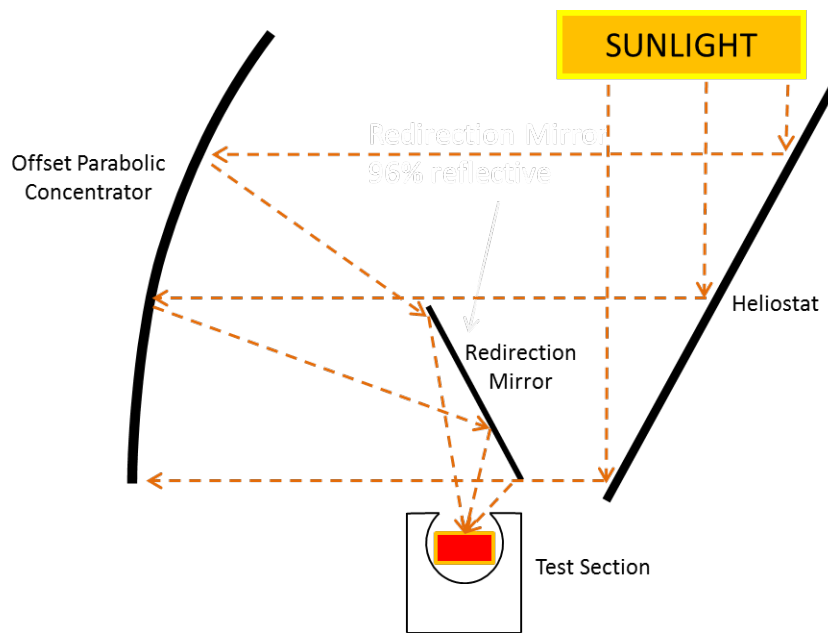


Figure 6. Schematic of the three-stage solar concentration system.

MATERIALS CONSIDERATIONS AND CRUCIBLE DESIGN

Elemental boron is highly reactive in both solid and liquid forms as temperatures approach the melting point³³ (approx. 2570 K for amorphous boron³⁴). As a result, physically containing boron with minimal contamination in a liquid state is highly problematic due to the limited number of materials capable of withstanding both boron attack and the necessary experimental temperatures. A literature review indicated that molten boron has been created in the presence of refractory metals, graphite, and ceramics with varying contamination levels.¹⁷

Refractory metals have been utilized for the construction of effusion cells to create high purity boron thin films via vacuum vapor deposition.³⁵⁻⁴⁰ In these studies, however, contamination is measured in the thin films and not within the bulk boron source. Further, these tests do not specify if the contaminating compounds formed at high temperature might produce a protective layer that prevents further reaction between the cell and the boron mass. Inferences made from effusion cell testing data, combined with results of hot filament testing which showed significant boron penetration⁴¹, indicate that refractory metals will be an unsuitable crucible material.

Work by Stout, et al., has directly evaluated the use of pure graphite as a crucible material with molten boron.⁴² This testing yielded heavy boron carbide contamination of the bulk sample, indicating that solid boron carbide did not remain at the boron-graphite interface, but rather moved through the molten boron mass. It is important to note that this contamination process began only once the boron had melted, providing a further indication of the increased reactivity of boron after the transition to the liquid state.

Due to possible contamination issues with graphite and the refractory metals, ceramics, particularly boron nitride (BN), are the predominant crucible material for containing molten boron. Multiple studies cite negligible contamination of a boron sample melted in contact with BN,⁴²⁻⁴⁵ which is attributable to BN's low reactivity at high temperatures and a resistance to attack in a boron-rich environment. However, additional experimental considerations must be made in the use of BN due to its strong tendency to disassociate into liquid boron and nitrogen gas at temperatures above 2300 K.⁴⁶ This disassociation can be prevented by maintaining a system pressure above the equilibrium pressure of disassociated nitrogen, and it is estimated that this pressure will be between 0.1 and 10 torr (13-1300 Pa).^{47,48} Previous experimental efforts have maintained a suitable system pressure by operating in inert gas environments, or in the case of Stout et al., by sealing the boron nitride in a graphite vessel and allowing disassociated nitrogen to pressurize the container and prevent further decomposition.⁴² Let it be noted that experimental temperatures have yet to reach the region of significant disassociation concern and future iterations of the experimental design will utilize sealed crucibles to prevent crucible failure.

HBC grade hot-pressed boron nitride crucibles were selected to hold the boron in the initial design of the experimental system. The crucible, shown in Figure 7, was designed to be a 0.6 x 0.6 x

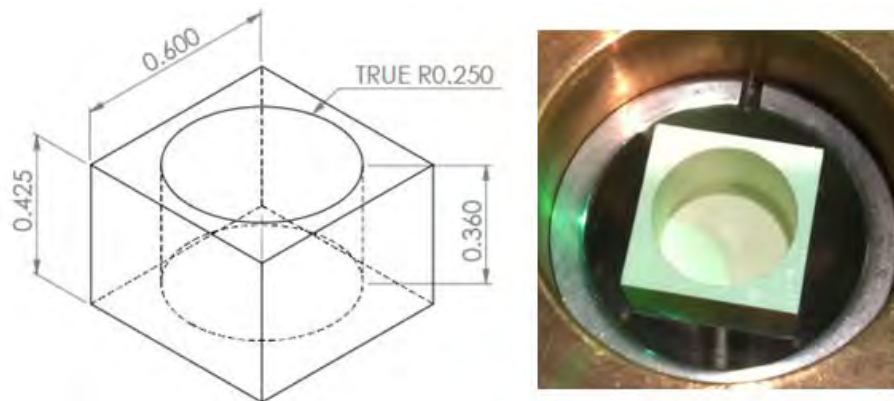


Figure 7. Schematic of the BN crucible design along with a photograph of the crucible resting in the experimental radiation shield with the top section removed.

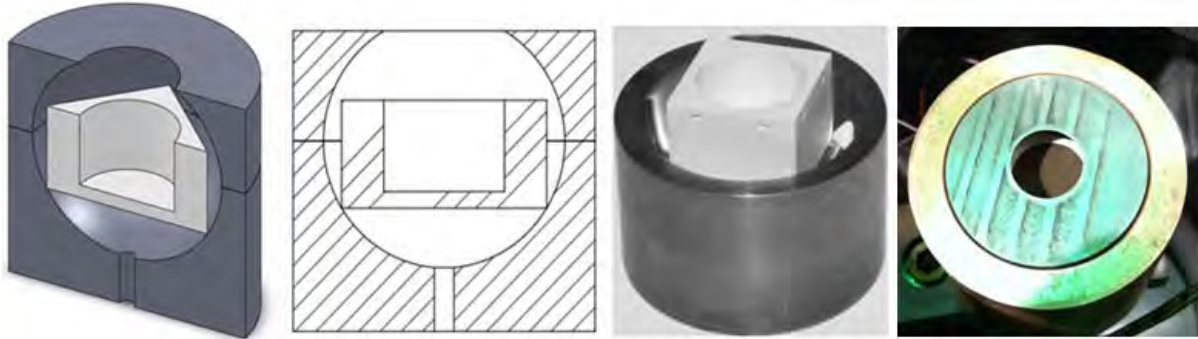


Figure 8. Model views and photographs of the BN crucible and molybdenum radiation shield. From left to right: 1) Cross section model view of shield with crucible, 2) Drawing view showing an overall high view factor from the crucible to the shield surface, 3) Photograph of the bottom section of radiation shield with crucible inset, 4) Top-down photograph of the assembled radiation shield with a boron filled crucible visible through the top opening.

0.425 inch (15.2x15.2x10.8 mm) block and contain 2 grams of powdered boron within a 0.5 inch (12.7 mm) diameter, 0.36 inch (9.1 mm) deep cylindrical cavity. This cavity design takes advantage of the top-down radiation input approach and the relatively high absorptivity of boron.

The thermal conductivity of BN is higher than that of most ceramics (25 W/mK), but is still low enough to allow relatively large thermal gradients during the heating process. Pyrolytic BN is favorable material for future crucible designs that mitigate these gradients as it possesses a high anisotropy with respect to directional thermal conductivity.⁴⁸ Differing thermal conductivities, along with a tapered crucible design, can be used to improve heat spreading within the crucible system.

RADIATION SHIELD AND SUPPORT STRUCTURE

At the melting point of amorphous elemental boron (2570K), an unshielded crucible would have grey body radiation losses in excess of 2300 W, necessitating the development of a radiation shield to reduce experimental power requirements. A solid molybdenum, 1 inch (25.4 mm) diameter, mirror-polished, spherical radiation cavity was designed and constructed as the primary shielding mechanism to reflect and re-radiate energy back to the crucible surface. Analysis of this system indicates an estimated reduction in radiation losses of greater than 70%, and a required input power of approximately 800 Watts for melting to occur.

As shown in Figure 8, the BN crucible rests within the mirrored cavity and maintains minimal contact with the molybdenum surface to limit conduction losses. The molybdenum shield is also split in two halves to facilitate loading of the crucible. A 0.5 inch (12.7 mm) diameter hole in the top of the system provides the input for concentrated solar light, and a port is machined in the bottom of the shield to allow

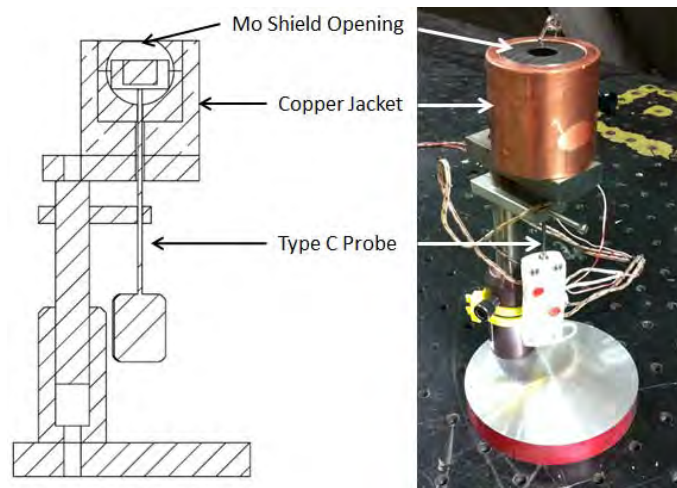


Figure 9. Copper jacket and support structure for radiation shield system.

direct Type C thermocouple measurements of the bottom of the crucible.

In the first design iteration, the molybdenum shield was supported in a cup machined from copper. However, the copper support, as shown in Figure 9, served to increase heat loss from the system due to its high thermal conductivity and larger exterior surface area. The next phase of this design will employ a cast zirconia oxide ceramic support to better insulate the system, assuming that the exterior surface of the molybdenum shield remains below the ZnO_2 breakdown temperature. Insulating the radiation shield will keep more heat in the molybdenum and improve re-radiation back into the crucible.

INITIAL DATA AND THERMAL CONCERNS

Under lower power testing with the initial design of the solar furnace, empty crucibles achieved temperatures above 900K. The system was then tested after packing sub-micron boron powder (over 99% pure) into the crucibles. Packing the boron powder created a smooth top surface for absorbing incoming radiation and reduced the quantity of trapped gasses within the powder. During boron testing, data taken at the bottom of the crucible showed temperatures roughly 100 K below those seen in empty crucible testing, however, optical inspection of the exposed BN surfaces indicated similar temperatures to those seen in the empty crucible tests. These observations led to an investigation of the potential thermal gradients within the boron-crucible system.

To determine the temperature gradient across the crucible, a bare, thin-wire type C thermocouple was buried in the boron sample and the first contact junction was positioned at the upper boron surface. Data taken using this method, illustrated in Figure 10, indicates a maximum upper surface temperature in excess of 1650 K, with a temperature difference of almost 900 K across the boron-crucible system. There also appeared to be large thermal gradients in the exposed boron surface itself and thermocouple measurements indicated a high sensitivity of this upper surface temperature to system optical alignment. Figure 11 illustrates the large thermal gradient in the radial direction across the upper surface of the crucible and it is assumed that this profile roughly corresponds to the relative intensity of the incoming solar radiation.

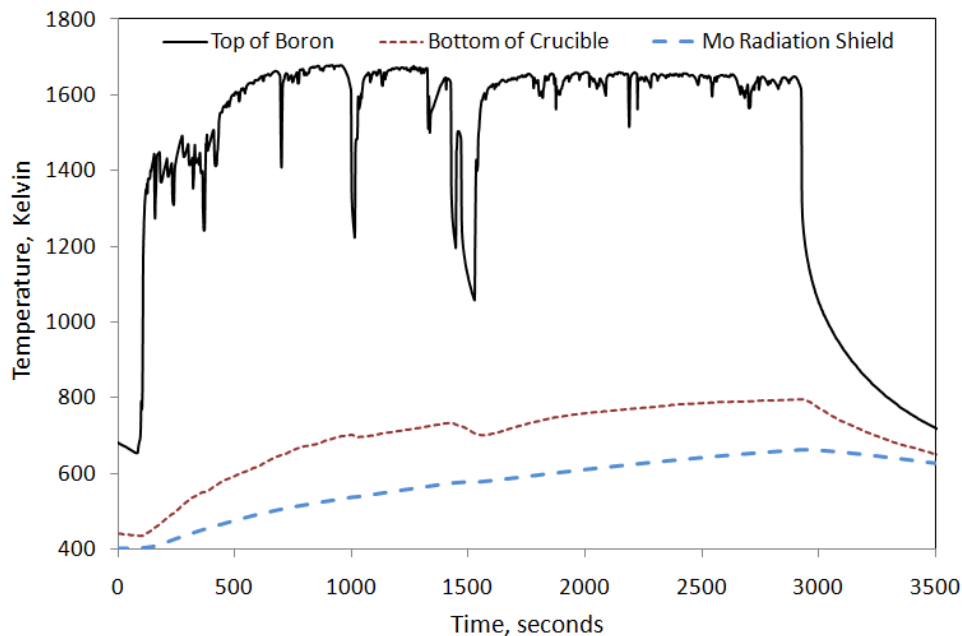


Figure 10. Sample data trace taken utilizing a thin wire thermocouple probe to measure the temperature of the top surface of the boron during on-sun testing. The fluctuations in the upper surface are the result of variations in the system optical alignment accuracy. The large dip at approximately 1500 seconds is the result of cutting radiation input to visually inspect the system.

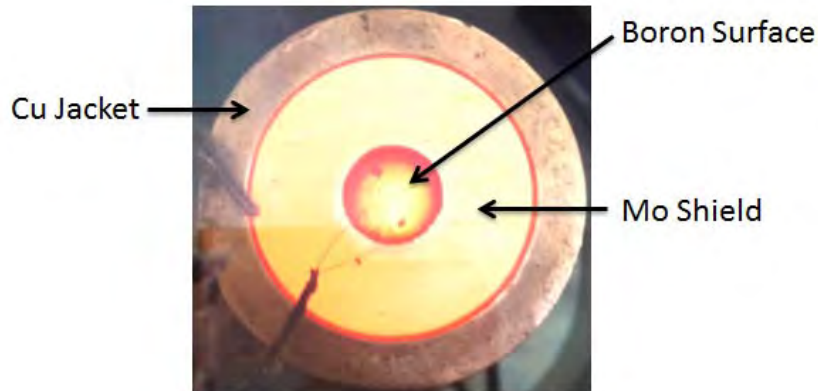


Figure 11. Top-down photograph of the experimental test section immediately after halting the solar radiation input. The center area is the boron surface and shows relatively steep thermal gradients in the radial direction. The dark spots in the center of the image are larger masses of boron disturbed during installation of the embedded thermocouple.

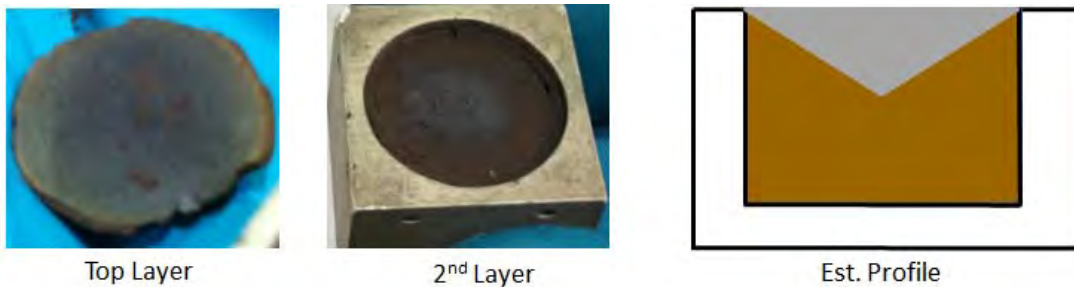


Figure 12. Discoloration pattern in the boron sample indicative of large thermal gradients.

All boron testing has resulted in a discoloration of the boron surface which can be seen in Figure 12. The changes in the upper boron surface match the thermal profile apparent in Figure 11, with the (cooled) boron powder transitioning from a grey-black surface at the hottest point to the original brown color at the crucible edges. This discoloration is believed to be a temperature dependent process and it is possibly due to crystallization of the boron from amorphous to β -rhombohedral form at the hottest areas.^{49,50} This phenomena also continues down into the boron mass and reveals the basic shape of thermal gradients within the bulk boron sample. As shown in Figure 12, removing layers of boron from the top of the sample after testing reveals a discoloration area of decreasing radius, indicating a low thermal conductivity within the packed powder and qualitatively confirms the thermal gradients measured via thermocouples. Due to the use of sub-micron particles, the effective thermal conductivity of the boron mass is less than 10 W/mK which is considerably lower than that of the surrounding BN container resulting in ineffective heat spreading throughout the system.⁵¹

These initial results indicate that the relatively low thermal conductivities of system components will result in localized temperatures far exceeding the system design temperature of 2570 K before uniform melting of the boron sample occurs. Since radiation energy is being brought in at a single point in the system, future designs must include a means of conducting the incoming heat energy throughout the entire PCM to reduce localized thermal loads and create an isothermal state within the boron mass.

FUTURE EXPERIMENTAL WORK

Based upon the experience gained utilizing the first version of the USC experimental hardware, work has begun on the second iteration of both the USC solar furnace and the crucible system. To facilitate greater power input into the crucible, the redirection mirror has been removed from the system and the experiment has shifted to a side input approach which can be seen in Figure 13. The system has

been outfitted with a 1 m² Fresnel lens to continue sub-scale experimental investigations during the concurrent development of a full scale solar concentrator similar to that developed by Diver, et al.⁵² The Fresnel lens, due to low acrylic transmission efficiency and reflection losses, is only able to deliver approximately 250W at the focal point as measured by a high power radiative flux meter. According to ray tracing results, this value will be further reduced by ~25% at the test section due to reflection and transmission losses when passing through the quartz window into the testing chamber. However, it is important to note that despite these losses, the removal of the redirection mirror and switching to a side input method will more than double the power delivery of the previous experimental effort even during sub-scale testing. This system will also allow preliminary molten silicon tests to be conducted.

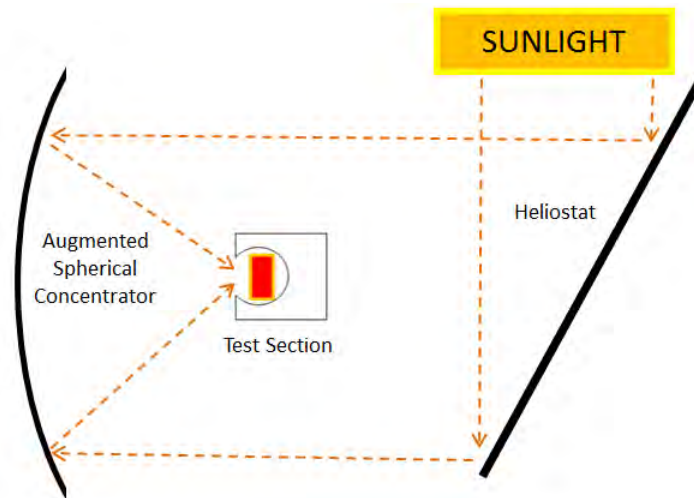


Figure 13. Schematic of the two stage solar concentration system.

SUMMARY AND CONCLUSIONS

Research indicates that a bimodal solar thermal system utilizing boron as a thermal storage medium could provide significant advancement for microsattellites by offering large ΔV capability with a low mass fraction. Molten boron based thermal energy storage, when combined in a system with ammonia propellant and thermophotovoltaics, eliminates many of the traditional drawbacks of STP systems. Evaluation of the required technologies for a truly bimodal system reveals that the basic components currently exist, however, a significant effort will be required to integrate molten boron into a system design due to material compatibility and insulation considerations. Assuming that the challenges of building and demonstrating a molten boron system can be met in the relatively far-term, a boron based system could provide a low mass, high-efficiency energy storage and propulsion system, enabling very high capability microsattellites in low Earth orbit.

Experimental and modeling efforts are underway at both USC and UCCS, respectively, to further evaluate the potential of molten boron phase change thermal energy storage. Modeling at UCCS is evaluating the performance of different insulation techniques and determining the effects differing geometries on TVP placement within a nominal system. Simultaneously, work at USC is focused on identifying key challenges in the construction and demonstration of a prototype system, including solar concentration requirements, material compatibilities, and suitable diagnostics. Initial results from both studies indicate that significant thermal insulation and heat conduction concerns aside, melting boron with concentrated sunlight and demonstrating phase change energy storage is within probable experimental capabilities.

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