Sandwich Module Testing for Space Solar Power

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Abstract—Solar power satellites have been envisioned as a means to provide electricity for terrestrial use. The approach entails collection of solar energy in space and its wireless transmission to the earth. This potentially gives the benefit of provision of baseload power while avoiding the losses due to the day/night cycle and tropospheric effects that are associated with terrestrial solar power. Proponents have contended that the implementation of such systems could offer energy security, environmental, and technological advantages to those who would undertake their development. Among recent implementations commonly proposed for SSP, the Modular Symmetrical Concentrator and other modular concepts have received considerable attention. Each employs an array of modules for performing conversion of concentrated sunlight into microwaves or laser beams for transmission to earth. The research described herein details efforts in the development and testing of photovoltaic arrays, power electronics, microwave conversion electronics, and antennas for 2.45 GHz microwave-based “sandwich” module prototypes. Prototypes were designed, fabricated, and subjected to the challenging conditions inherent in the space environment, including the solar concentration levels in which an array of modules might be required to operate.

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1. INTRODUCTION
Global climate change looms as a potential threat. Consequently, attention has been directed to the development of energy sources that avoid further contribution to climate degradation. It is generally accepted that many sources of fossil fuels are either at risk of depletion or otherwise undesirable because of their contributions to greenhouse gases. While many carbon-free or nearly carbon-free energy alternatives exist, they often suffer from significant problems such as intermittency, locale dependence, or safety risks.

The sun is an effectively clean and unlimited energy supply. However, terrestrial collection of solar energy has limitations. The diurnal cycle, atmospheric attenuation, and weather effects all diminish access to solar power. Collection of solar energy in space via satellite coupled with its wireless transmission to the ground largely overcomes these limitations, but it poses considerable engineering challenges and serious questions of economic viability. Thoughtful criticisms [1] [2] and counter-criticisms [3] of this concept appear in the literature.

Solar power satellite concepts have been examined in depth on several occasions in the past [4] [5], and interest has been renewed in recent years [6] [7] [8] because of improvements in a number of relevant technologies. These include: solar cell efficiency, solid state power amplifier efficiency, large space structures, and robotic assembly in space. Recent solar power system studies have been significantly limited in their ability to accurately determine the costs and challenges of deploying an operational system by the small amount of actual hardware development that has been done to show the feasibility of key technological elements. This work seeks in part to address this gap. Additional background information on this research effort can be found in [9], though key points are summarized in this paper for the reader’s convenience.

2. MODULAR SOLAR POWER SATELLITE
ARCHITECTURES
Recently proposed space solar power system designs include the Modular Symmetrical Concentrator (MSC) architecture [10], Solar Power Satellite via Arbitrarily Large Phased Array (SPS-ALPHA) [11], and others that employ a high degree of element modularity. These approaches typically utilize optical energy routing and a large microwave transmit aperture constructed from essentially identical elements. This avoids the need for a potentially failure-prone, large, conductive rotating joint and limits wiring mass compared to historical reference concepts. The use of modular elements offers the possibility of economy through mass production. Employing solar concentration could reduce the required launch mass and as a result lower the system cost, but it increases the magnitude of the thermal challenges. Geosynchronous orbit is envisioned for this and most SSP implementations due to its enabling of constant ground coverage. A depiction of a proposed MSC
SSP satellite is shown in Figure 1. Though this image shows a monolithic structure, it might also be possible to use several satellites flying in formation to dispense with the connecting structures. Assessment of the technical soundness of modular SSP architectures is hampered by a dearth of substantive efforts to identify and resolve concerns about their component technologies, most notably those pertaining to the sandwich module. The prime motivation for this effort is the need for a critical examination of the challenges associated with sandwich module development.

![Figure 1: Modular Symmetrical Concentrator Architecture [6].](image)

### 3. SANDWICH MODULE

The key element in the many modular SSP architectures is the “sandwich module”, an element which had originally been investigated in association with the NASA/DOE studies of the late 1970s. The sandwich module performs functions separable into three layers: solar energy collection and conversion to direct current electricity, generation of a microwave signal of suitable frequency and amplitude for transmission, and formation of a spaceborne transmit antenna aperture that provides beam coupling sufficient to provide meaningful energy transfer to the ground. A simple functional representation of a sandwich module appears in Figure 2.

![Figure 2: Depiction of the functional layers of the sandwich module [12].](image)

Chief among the design challenges of a practical sandwich module are the integration of the various required elements, allowing for retrodirective phased array beam control, and effective thermal management under adverse conditions. These aspects have received some attention from researchers in the past, but to our knowledge there had not been prior to this effort any detailed physical characterization of a sandwich module’s performance in a realistic space environment scenario, nor had there been a comprehensive analysis of the limitations levied by sun concentration level, thermodynamics, materials, and specific power.

An initial examination of the sandwich module concept was performed by Owen Maynard in 1980 [13]. His paper “Progress Report on Solid State Sandwich Concept – Designs, Considerations, and Issues,” outlines many of the obstacles and sensitivities associated with the sandwich design. Maynard proposed using solid state FET amplifiers instead of the vacuum electronics microwave sources that had been suggested in much of the NASA/DOE study documentation. He identifies the maintenance of low junction temperatures of the solid state amplifiers used in a sandwich approach as a key point in assuring that acceptable operating lifetimes result. Solid state amplifier efficiency plays a major role in determining the amount of heat that must be dissipated, as does the efficiency of the adjacent solar cell layer. Lower efficiencies produce more waste heat and thus raise the junction temperature. Maynard points out that an advantage of the solid state amplifiers over vacuum devices is that they do not require high voltages. The many thousands of volts needed for magnetrons and klystrons are difficult to manage in the space environment and necessitate the inclusion of high voltage power converters, introducing another source of conversion inefficiency. Among the issues and possible resolutions Maynard summarizes, charged particle radiation effects and topological considerations stand out as some that specific part selection and module fabrication could address.

This paper focuses principally on recent testing efforts in the development of two varieties of sandwich module prototypes for photovoltaic collection, DC-to-RF conversion, and wireless power transmission for space solar power. Previously, the scale of the challenges involved with sandwich module development from a thermal perspective [14], as well as prototyping and early testing efforts, have been discussed. The most critical points are summarized here.

A first order study of the thermal problem for the sandwich module shows some of the limitations imposed by the radiative heat transfer relation, (1):

\[ P = \epsilon \sigma A T^4 \]  

(1)

Where \( P \) is the heat power transmitted, \( \epsilon \) is the emissivity of the material, \( \sigma \) is the Stefan-Boltzmann constant, \( A \) is the radiating area, and \( T \) is the temperature. Assuming that a flat sandwich module can only use the top and bottom for radiating heat, since it would be adjacent to other modules needing to also dissipate heat at its edges, bounds can be established by specifying the desired operating temperature. Though it may be possible to move heat from a module in
the center of a photovoltaic and transmit array using heat pipes or other means, radiator area for heat rejection is still required. Complexity and challenges to the modular approach inherent in creating a heat pipe network to meet the needs of a structure likely to be on the order of a kilometer in diameter were deemed beyond the scope of our effort; thus each module is required to be “thermally self-sufficient.”

The sun’s power flux in space in earth orbit is approximately 1400 W/m². Multiplying probable efficiencies of the component layers gives a rough total module efficiency as shown in Figure 3. In this case, a square module made of four rows of seven cells with each cell measuring 4 cm x 7 cm is assumed for simplicity.

![Figure 3: Solar power intercepted at one sun by a 28 cm by 28 cm module and combined efficiency.](image)

If the sun concentration is varied for different emissivities for modules at different desired operating temperatures, the resulting required radiator area can be found, and is shown in Figure 4. Because this is a somewhat idealized model, the temperature effects on the efficiency of the layers, most notably the photovoltaic and DC-to-RF conversion layers, are not accounted for. The efficiencies of these two layers will tend to decrease with rising temperatures, in turn resulting in more heat that must be dissipated, further raising the module temperature.

For a theoretical solar power satellite orbiting in geosynchronous orbit, radiating surfaces will in different parts of the orbit alternately face deep space, the sun, and variations in between. This further hampers the module’s (and by extension, the satellite’s) ability to radiate waste heat. This analysis assumes only one side of the module is illuminated and that the other side faces deep space.

![Figure 4: Radiator area required to maintain temperature equilibrium for a 28cm square module at 23% efficiency](image)

Inserting more or less optimistic combined module efficiencies allows plotting the resulting temperatures as a function of sun concentration. The plot seen in Figure 5 shows that to operate below 150°C with reasonable efficiency assumptions limits the sun concentration to below three suns.

![Figure 5: Temperature of a 28 cm by 28 cm module with both sides as black body radiators for various module efficiencies.](image)

Keeping the module temperature below 150°C helps limit the efficiency degradation due to the temperature of the photovoltaics and the DC-to-RF converters. In practice, individual efficiency degradations are dependent on the temperature gradient across different parts of the module. A thermal analysis using Thermal Desktop performed for a flat module, or “tile module”, design operating under three suns shows the peak temperature indeed surpasses 150°C, as seen in Figure 6.
The limits imposed by the thermal analyses presented here offer two possible paths to creation of sandwich module suitable for SSP: (1) a high specific power flat module at moderate sun concentration (below three suns), or (2) a departure from the flat sandwich module to allow for an increase in radiator area. Thus, my team has also pursued a second module concept approach, dubbed the “step module.”

In the step module design, upper and lower radiator surfaces are added to provide for additional heat rejection. The length of these radiators is arbitrary, but as the distance from the heat source increases, the benefit of the additional radiator surface tends to diminish because of the inefficiencies associated with the longer heat conductance path. The location of the electronics is moved from being in close proximity to the hot solar panel to a cooler place on one of the radiator panels. To visualize this departure from the original tile module, consider the depiction in Figure 7, which shows a close-up view of the photovoltaics and transmission antenna of the Modular Symmetrical Concentrator from Figure 1.

Figure 6: Thermal Desktop simulation of a tile module under 3 suns of illumination.

A thermal simulation shows that the step approach effectively lowers the maximum temperature of the module by 63% when compared with the tile module under the same test conditions. Furthermore, the DC and RF conversion electronics operate about 20°C cooler than in the tile module. The results of the thermal simulation can be seen in Figure 8.

Contrast this with the photovoltaics and transmission antenna portion comprised instead of “step” sandwich modules as seen in Figure 8.

Figure 7: Photovoltaics and transmit antenna comprised of tile modules.

Figure 8: Photovoltaics and transmission antenna comprised of step modules.

Note that suitable transmit antenna apertures can be created using the step modules as elements to form structures in the shapes of cones, inclined ridged discs, and other shapes with varying radiator views of deep space for heat rejection. In any case, from above or below the optical projection will very closely resemble the original flat disc, allowing it to be used essentially interchangeably with the rest of a given solar power satellite architecture that employs the sandwich module concept. Since the modular aspect is common to both the tile and step, techniques that envision self-organizing structures for assembly are still usable. The effects of solar pressure and gravity gradients should be considered for an ultimate satellite design.
in Figure 9: Thermal Desktop simulation of a step module under 3 suns of illumination.

Both tile and step module prototypes were pursued in order to evaluate the relative merits and disadvantages of each; in particular to determine whether the thermal benefits of the step module are outweighed by the increase in mass required for the additional radiator area.

4. MODULE LAYERS

Photovoltaics

In order to complete a prototype within a reasonable period of time, commercially available photovoltaics (PV) for space applications were used. Though there exist a multitude of promising high efficiency technologies in laboratory settings, they were not available for inclusion in a prototype. PV cells used for space are readily available from two companies: Emcore Corporation and Spectrolab Incorporated, a division of Boeing. Both currently offer triple junction cells with conversion efficiencies quoted at around 30%. At the time of our solar array procurement, we selected Spectrolab’s Ultra Triple Junction (UTJ) Solar Cells with an efficiency of 28.3%, as the most recent high efficiency versions were not yet available. SpaceQuest, Ltd. produced our solar arrays and employed methods like those used on the MESSENGER mission to Mercury to foster high temperature tolerance during cell to substrate integration. The finished panel for the prototype tile module is shown in Figure 10, and the panel for the step module is shown in Figure 11.

Figure 9: Thermal Desktop simulation of a step module under 3 suns of illumination.

RF & power electronics go here to lower heat exposure; note electronics temp is ~20° cooler than tile

Figure 10: Tile module solar panel.

DC-to-RF conversion

The conversion electronics must simultaneously achieve cost, weight, efficiency, and output power requirements. Considerations and trade options are considered in greater detail in a previous paper [15]. While vacuum electronics have a number of advantages, their bulkiness and need for high voltage rendered them less attractive than solid state alternatives, specifically Gallium Nitride (GaN) which offers the benefits of higher operating temperatures and power densities over other semiconductors. The smaller available output power levels per solid state device also allow more latitude in varying the transmit aperture power density while maintaining a more evenly filled aperture. Because single stage high efficiency solid state power amplifier (SSPA) devices have not been demonstrated at the likely greater than 30dB levels of gain required, the construction of a suitable multi-stage amplifier chain was central to this layer of the module. Monolithic microwave
integrated circuit (MMIC) options could be considered in the future to potentially reduce cost, size and weight, in particular as GaN semiconductor process reliability matures and gains widespread adoption in military and civilian systems.

The frequency source can be either a voltage controlled oscillator (VCO), or may be derived from a pilot signal used for retro-directive beam steering, as explored and demonstrated extensively by Kaya [16] and others.

Frequency selection in past studies has focused on Industrial, Scientific, and Medical (ISM) bands due to their perceived amenability to high-power transmissions. Considerable attention has been given to 2.45 GHz, 5.8 GHz, and other frequencies below 10 GHz because of their low susceptibility to atmospheric, cloud, and hydrometeor attenuation. The prototype developed here was targeted for 2.45 GHz because of the comparatively larger selection of available devices versus higher frequencies, though it is recognized that lower frequencies necessitate larger apertures to achieve comparable beam coupling efficiencies.

Due to emerging wide band-gap semiconductors, SSPAs are beginning to encroach on applications where formerly only traveling wave tube amplifiers (TWTA) were feasible. SSPAs offer system designers significant benefits and challenges to system integration. Besides being small and lightweight, an SSPA can be a factor in reducing the cost of a system requiring significant power levels, in particular in an array configuration, where the transmit aperture gain and large numbers of moderately powered devices can be coherently combined to provide a microwave beam of substantial power. Although GaN offers the benefits of higher operating temperatures and power densities over other semiconductors, it also brings challenges that arise from its generally lower gain per amplifier stage, requiring a multistage architecture.

Power to feed the two-stage 2.45 GHz RF amplifier architecture was generated by power circuitry painstakingly designed to maximize efficiency. The resulting power board demonstrated an efficiency in excess of 97%, and is shown in the context of the DC and RF electronics baseplate for the tile module as shown in Figure 12. The overall DC-RF conversion efficiency fell short of initial expectations, but still was demonstrated at an impressive 50% for one design.

Figure 12: Tile module DC power and RF electronics baseplate prior to the installation of thermal features.

For the step module, the RF chain was multiplied by three, the integer number of suns that simulations suggested the step module should be able to operate under. This scales with the multiplicative current increase associated with increasing sun concentration. The baseplate layout can be seen in Figure 13 and the context in the module itself is visible in Figure 14.

Figure 13: Step module DC power and RF electronics layout.
Figure 14: Step module depiction showing electronics location on radiator.

In an ultimate module for use in a demonstration or operational space solar power system, electronics would also be implemented to effect the phase changes needed for the retrodirective control scheme described above. Similarly, such a flight module would also need to have very narrow bandpass filtering on the output of the final stage to suppress amplified harmonics and thermal noise.

Antenna

A wide variety of antenna types were considered for the microwave transmission face of the module. Ultimately a short backfire antenna was chosen by virtue of its high directivity, high efficiency, and ability to act as an effective thermal radiator. A depiction of the antenna surface current can be seen in Figure 15 and its simulated gain pattern is shown in Figure 16. Both the tile and step modules will employ the short backfire antenna described.

Module Architectures

Most previous sandwich module concepts have taken a hexagonal shape, ostensibly to maximize the usage of the volume of a cylindrical launch vehicle fairing. A preliminary analysis of current launch vehicle fairing volumes and throw weights suggests that a module of any reasonably achievable density will exceed the launch vehicle throw weight before exceeding the fairing volume. Because of this, module shape can be selected based on other factors, such as photovoltaic cell coverage. Since currently available PV cells are rectangular, a square or rectangular panel surface can be more efficiently filled than a hexagonal one. The module thickness is driven by the need to accommodate the DC-to-RF conversion electronics and the antennas, as well as by its ability to manage the transport and radiation of waste heat.
**Thermal Control Methods**

There are available many effective and novel means to transfer heat from one part of the module to another: diamond heat spreaders, pyrolitic graphite structures, microchannels, graphene nanomaterials, and two-phase heat pipes. Regardless of the transfer method, the waste heat needs to be radiated from the module. An appropriately anodized antenna surface closely approaches the emissivity of a black body. The area available for radiation of heat can be increased with judicious module design. In our prototypes, black kapton tape is used to maximize emissivity, multi-layer insulation blankets are used to minimize heat exposure to sensitive electronics, and thermal grease is used to reduce heat conduction inefficiencies at appropriate interfaces. The results can be seen in Figure 17 and Figure 18.

**5. Module Fabrication**

Upon satisfactory closure of the design tradeoff studies, the module fabrication process began. The build process proceeded iteratively, with breadboard level prototyping used initially to verify expected performance of the selected RF and supporting power architecture components. Necessary modifications to the design were identified and implemented prior to proceeding to the engineering model level prototype build. In tandem, the mechanical design and related incorporation of the solar array, antennas, and thermal control means proceeded first through scaled and then full mockups to identify possible design problems. Lessons from these exercises were applied to the construction and integration of the engineering module. As not all layers in both module prototypes were completely fabricated and tested at the time of this writing, focus is necessarily on results to date.

**6. Testing Approach**

As the various layers of each module type are completed, they are tested separately prior to full module integration. This allows careful characterization of each section of the modules in the event there is an unexpected interaction between the layers. As of January 2013, we have characterized power and RF chains of preliminary and intermediate designs for the tile module for ambient, temperature, and vacuum conditions. We have also tested the tile module solar array at different sun concentrations to find the illumination level which was then used with the integrated solar array and electronics. The solar array characterization configuration can be seen in Figure 19.

**Figure 17:** Tile module electronics baseplate with thermal features installed.

**Figure 18:** Bottom side of tile module solar panel after installation of black kapton and thermocouples.

**Figure 19:** Tile module solar array testing with 4000W Xenon light source and attenuating screens.

The evenness of the field and the absolute intensity of the light source were carefully measured and characterized using a digital camera, calibrated photodiode, and processing software written in Matlab. This was done to ensure that the strings were exposed to a known illumination condition, as the least-illuminated cell in the string restricts the output of the entire string. The results are
being validated with additional measurements taken with a Newport optical power meter and an Ophir-Spiricon beam profiling system.

Wire screens that allow different amounts of light to pass through were used to affect different illumination levels by hanging them in front of the lamp. Table 1 shows the amount of light passed for each of the five screens when used individually.

<table>
<thead>
<tr>
<th>Screen</th>
<th>Allowed</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>74.8%</td>
</tr>
<tr>
<td>B</td>
<td>65.9%</td>
</tr>
<tr>
<td>C</td>
<td>60.2%</td>
</tr>
<tr>
<td>D</td>
<td>50.7%</td>
</tr>
<tr>
<td>E</td>
<td>25.4%</td>
</tr>
</tbody>
</table>

The testing arrangement allowed collection I-V curves of the solar array strings over a range of illumination conditions. A representative I-V data plot is shown in Figure 20.

For power and RF electronics testing, the individual subassemblies were first bench tested and then integrated on the tile module baseplate. Temperature and vacuum testing of the electronics chains showed only limited variation in the output efficiency, on the order of ±2%. The range of temperature testing for the initial electronics chain in vacuum was from -20°C to +95°C, with the final RF amplifier stage as the control point. The initial RF chain demonstrated efficiency on the order of 50% to 54%, but the chain subsequently had to be redesigned to accommodate the revised solar array output. As can be seen in Figure 21, the efficiency of the redesigned chain when powered using the solar array is just over 40% under optimal illumination conditions. If the illumination level is too low, the efficiency drops to 22% or is unstable, as can be seen when screens E and D are used, respectively. In this test, screen C gave the maximum sustained efficiency while minimizing the equilibrium solar array temperature at about 95°C.

The electronics test support equipment used for the testing is shown in Figure 22. Use of LabView allows for automated data collection and ease of test repeatability.

The configuration used for testing in thermal vacuum conditions is shown in Figure 23 and Figure 24. Note the nearly invisible fused silica window that serves to seal the front of the chamber while allowing full illumination by the 4000W Xenon light source with only limited spectral filtering.
Figure 23: Tile module in thermal vacuum chamber with fused silica window sealing chamber opening.

Figure 24: Test configuration for vacuum testing with illumination.

Antenna pattern measurements will be taken using one of NRL’s onsite RF anechoic chambers, and the thermal vacuum chamber will be fitted with vacuum-rated RF absorber for testing the fully integrated module. Further details of the test approach and apparatus are described in [17].

7. PERFORMANCE METRICS AND MODULE RESULTS

Performance metrics are tied to economic considerations, but also can be used to help set targets for pushing technological boundaries. Outlined below are some of the probable figures of merit for a sandwich module or other conversion device for a solar power satellite that could provide a basis for performance goals or requirements:

Collect/transmit area specific mass [kg/m²]

This quantity is generally of greater significance than density because a typical solar power satellite’s structure is likely to be dominated by large surfaces for collecting or redirecting sunlight, and in the microwave transmission case, large transmit antenna apertures. Previous estimates of area specific mass for the transmitter portion of solar power satellite only have ranged from about 4 kg/m² [18] to 40 kg/m² [19]. As our prototypes are not complete, some contributions to the total mass, such as the antenna, are estimated. For the tile module, we have achieved an area specific mass of 10.4 kg/m² for the transmitter portion of the module and 19.2 kg/m² for the overall module. For the step module, we have achieved an area specific mass of 12.6 kg/m² for the transmitter portion of the module and 30.9 kg/m² for the overall module.

Mass specific transmitted power [W/kg]

Often quoted for solar arrays, this quantity helps assess amount of installed generating capacity would results from a given number of launches. In our case, the necessary reflector system to illuminate the array of sandwich modules is neglected. As in the specific mass, some component masses are estimated since the prototypes are not complete. The tile module gives a mass specific power of 7.8 W/kg at one sun simulated at 25°C, and the step module gives 13.8 W/kg for the estimated three suns case.

Combined conversion efficiency [%]

The efficiency of the module is of great interest in that higher efficiencies help alleviate thermal dissipation problems by constraining the amount of heat that needs to be rejected. Though our cells are efficient, there is a penalty, the “packing factor”, in any solar panel implementation for the areas on the panel that are not covered with cells. Hence, our panel efficiency is lower than the cell efficiency. The power electronics efficiency is fairly high, due in large part to there being no conversion stage between the panel and the final RF stage, with DC-DC converters only employed where needed to produce bias voltages and the like. The RF chain efficiency is reasonable, but does not approach the upwards of 80% efficiency demonstrated by some researchers. The antenna efficiency shown here is the product of simulation. As seen in Table 2, the total tile module demonstrated efficiency is 11%.

<table>
<thead>
<tr>
<th>Element</th>
<th>Goal</th>
<th>Demonstrated</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar Panel</td>
<td>24%</td>
<td>24%*</td>
</tr>
<tr>
<td>Power Electronics</td>
<td>95%</td>
<td>96%</td>
</tr>
<tr>
<td>RF Chain</td>
<td>60%</td>
<td>50%</td>
</tr>
<tr>
<td>Antenna</td>
<td>95%</td>
<td>pending</td>
</tr>
<tr>
<td>TOTAL</td>
<td>13%</td>
<td>11%†</td>
</tr>
</tbody>
</table>

Table 2: Component efficiencies for the 2.45 GHz prototype sandwich tile module at one sun at AM0 at 25°C. *Calculated from quoted cell efficiencies and fill factor, †Using goal antenna efficiency value.

The projected efficiencies of our step module prototype are expected to be similar since it employs a nearly identical
solar array and RF electronics that are largely triplicated from the tile module.

While not necessarily numerical performance metrics, other module qualities of possible interest for the prototype and certainly for a flight unit would include adaptability for directional control of the microwave power beam, susceptibility to space environmental effects (radiation, UV exposure, charging), avoidance of radio frequency interference and multipactor effects, and a host of other factors outlined in a previous paper [20].

8. CONCLUSIONS

This paper summarizes selected highlights from our research efforts of the past year in developing designs, executing analyses, and fabricating and testing prototypes of sandwich modules for space solar power. Designs were iterated as new discoveries and realizations came to light. Tradeoff studies were concluded for each of the three functional layers inherent in the sandwich module: photovoltaic conversion, DC to RF conversion, and power radiation via antenna; as well as for thermal and architectural concerns. Solid state amplifier chains have been designed, assembled, and their performance characterized over a range of temperatures and in vacuum conditions. Mechanical drawings and thermal analyses have been undergone several design iterations, settling on two different module approaches. Our results affirm the initial impression that thermal concerns are paramount in sandwich module design, and suggest that a novel approach to the sandwich module architecture may effectively address this problem. Additionally, illumination testing has shown that there exists a narrow range of sunlight intensity in which our modules can operate at optimal efficiency while minimizing the module’s operating temperature. Future work will continue the fabrication and testing of the remaining layers of the prototypes and test the completed modules under space-like conditions. This work contributes to an empirical foundation for informing debates on the technical and economic viability of a prominent class of proposed space solar power systems.

REFERENCES


**BIOGRAPHY**

Paul Jaffe is an electronics engineer, researcher, and integration and testing section head at the Naval Research Laboratory. He has worked on over a dozen NASA and Department of Defense space missions, including SSULI, STEREO, TacSat-1, TacSat-4, and MIS. He developed standards and lead spacecraft computer hardware development as part of the Department of Defense’s Operationally Responsive Space effort. He served as a coordinator and editor of NRL’s Space Solar Power (SSP) study report and is presently the principal investigator for an SSP-related research effort. His current primary role is as the Electrical Segment Lead for the Weather Satellite Follow-on microwave sensor effort. Paul is also active in educational and STEM outreach. He has a B. S. from the University of Maryland and a M. S. from the Johns Hopkins University, both in Electrical Engineering. He is currently pursuing a Ph.D. at the University of Maryland.

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