500 WATT SOLAR AMTEC POWER SYSTEM FOR SMALL SPACECRAFT

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14. Abstract The two main objectives of this project were to complete the first conceptual design of an innovative, low cost, reliable, low mass, long life 500 watt Solar Alkali Metal Thermal to Electric Converter (SAMTEC) power system for small spacecraft, and predict the performance of the SAMTEC space system. The proposed concept uses an innovative, high voltage Alkali Metal Thermal to Electric Converter (AMTEC) cell, called the multi-tube cell, integrated with an individual Thermal Energy Storage (TES) unit. The multi-tube AMTEC cell provides a low cost, reliable, long life static converter for space systems. The SAMTEC system could use batteries for energy storage but the TES unit eliminates the thermal fluctuations associated with operation in Low Earth Orbit and offers a low cost reliable energy storage system. The chosen TES material is the LiF-22%CaF(2) currently being developed at NASA Lewis Research Center for the Solar Dynamic Ground Test Demonstration Program.

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1.0 EXECUTIVE SUMMARY

The two main objectives of this project were to complete the first conceptual design of an innovative, low cost, reliable, low mass, long life 500 watt Solar Alkali Metal Thermal to Electric Converter (SAMTEC) power system for small spacecraft, and predict the performance of the SAMTEC space system. The proposed concept uses an innovative, high voltage Alkali Metal Thermal to Electric Converter (AMTEC) cell, called the multi-tube cell, integrated with an individual Thermal Energy Storage (TES) unit. The multi-tube AMTEC cell provides a low cost, reliable, long life static converter for space systems. The SAMTEC system could use batteries for energy storage but the TES unit eliminates the thermal fluctuations associated with operation in Low Earth Orbit (LEO) and offers a low cost reliable energy storage system. The chosen TES material is the LiF-22%CaF_2 currently being developed at NASA Lewis Research Center (LeRC) for the Solar Dynamic Ground Test Demonstration (SDGTD) Program.

The conceptual design is based on a set of Phillips Laboratory-furnished design requirements. The system was required to provide 500 watts electrical power at 28 volts to the payload in Low Earth Orbit (800 km, 28.5° inclination) for 5 years. Based on the optical and thermal analyses, the Phase I effort showed that the conceptual design met or exceeded all of the design requirements that could be addressed during Phase I.

The SAMTEC power system is predicted to have a specific power of 5.3 to 8.9 We/kg (including the concentrator, receiver, AMTEC cells, gimbals and drives, structure, power processing and control, and a 30% mass contingency) at the 500 watt power level, and 12 to 17 We/kg (including all of the components listed above) at the 5,000 watt power level. The SAMTEC system, including all of the components listed above, is anticipated to cost $1,000/We once development is complete and production begins. The SAMTEC system provides 92% of its Beginning of Life (BOL) power after a 5 year period in LEO, and SAMTEC systems should provide 10 to 15 years of life in LEO. Current AMTEC cells have demonstrated 18% efficiency in the laboratory and have been heated radiatively, with propane flames and electrical resistance heaters.

The SAMTEC system has certain unique performance characteristics. AMTEC cells can be operated using any heat source (solar, combustion, nuclear, etc.). Radioisotope power system designs have been completed (currently AMTEC is the conversion technology of choice for the Pluto Express mission at the Jet Propulsion Laboratory), and the several combustion heated AMTEC systems are currently in conceptual design stages (including auxiliary electric power supplies and hybrid electric vehicles). A SAMTEC power system can be made to operate in high radiation environments, like that encountered in the Van Allen belts. These unique capabilities will lead to a wide range of applications, and take advantage of greater economies of scale. This will lower the cost of space systems.

The Phase I produced a significant milestone for AMTEC technology - the first detailed system design and performance prediction of a solar powered AMTEC space power system. There are several key steps that need to be completed to successfully develop AMTEC cells and systems for space and terrestrial applications. The first is to fully develop the multi-tube AMTEC cells and integrate them with the TES units. The first multi-tube AMTEC cell was successfully tested in February of 1995, the first AMTEC/TES cell will be tested in summer of 1995, and multi-tube cell development will continue in Phase 2 of this Small Business Innovative Research (SBIR) program. The second is to complete a detailed system design, and spacecraft integration of the SAMTEC space power system, which will also be completed during Phase 2. The third step is a flight test of the AMTEC cells, which has been proposed (and is currently under review) to NASA under the In Space Technology Experiment Program (InSTEP). The final step is to fabricate and test a system prototype in the relevant environment, high vacuum, which will also be completed at the end of Phase 2. Once these steps have been completed, SAMTEC will have the necessary background to begin convincing satellite users to adopt AMTEC technology.

2.0 INTRODUCTION

2.1 SMALL SPACE POWER SYSTEM NEEDS

There is a strong drive to reduce the cost of both government and commercial space operations. This reduction in system cost must not be made at the expense of mission performance, lifetime, and reliability. Since the electrical power system and related components in today's state-of-the-art, small spacecraft account for 30%-60% of the total spacecraft mass and 10%-20% of the cost, a smaller, less expensive power system would help satisfy this need. The challenge of Phase I was to provide the desired performance increase at a lower cost and acceptable technical risk, while maintaining or improving system lifetime, durability, and reliability. The results of the Phase I effort show that this is feasible, if AMTEC cells are combined with TES units.

2.2 CURRENT SPACE POWER SYSTEM LIMITATIONS

For spacecraft operating on solar input in earth orbit, normal operation requires a power supply that can function throughout the orbit, in spite of the frequent eclipse periods experienced due to passage through the earth's solar shadow. Provision of the energy storage to maintain operation during eclipse periods is a critical element in power systems for such applications.

Current approaches to providing electrical power for spacecraft in earth orbit rely primarily on PhotoVoltaic (PV) cells with batteries for eclipse periods. Current PV power systems have a specific power of approximately 4-5 We/kg, at the 500 We power level, and cost approximately $5,000-$10,000/We for the entire power system (system includes PMAD, batteries, PV arrays, etc.). The large mass, and resulting low specific power, can be attributed to both the mass of the required energy storage and the need to oversize the system, to compensate for the degradation of PV output with time.

Current space solar power systems rely heavily on batteries for storing the energy required during eclipse periods. With current and projected near term battery technology, a high number of cycles is required in long term, low to middle earth orbits. Therefore, the batteries satellites must use for energy storage have a shallow depth of discharge. This results in a massive energy storage system; approximately 20 kg for a 500 We power system (NiH_2, 50 W hr./kg, 30 % Depth of Discharge).

The time dependent degradation mechanisms for PV systems can be classified into four main types: 1) charged particle degradation of the active cell; 2) Ultra-Violet (UV) darkening of the adhesive used to hold the cover glass; 3) natural and man-made debris damage and 4) power losses through random failure of cells, connections, circuits, etc. According to Kimber and Goodbody (1994) PV arrays typically retain 75%-85% of their BOL power after 5 years in LEO. The array degradation due to charged particle/radiation levels in the "middle" Van Allen belt orbits is so severe that it makes long term PV operation difficult. Japan's ETS-6 satellite is an example of how radiation can severely degrade the performance of PV arrays. The ETS-6 satellite produced 5.8 kWe on September 3, 1994 and 10 days later produced only 5.3 kWe. The satellite was accidentally placed in an elliptical orbit (4,800 x 24,000 mile, through the Van Allen belts) when its apogee kick motor failed to achieve proper pressure. The power is predicted to be below 2 kWe in approximately 12 months making the satellite unusable (Ref. 2).

Because the PV's proposed for space systems can use only direct solar energy, they do not easily lend themselves to numerous large scale terrestrial applications. Many terrestrial PV systems must use a fuel fired system, or batteries, as a backup to the PV's to produce electricity in the absence of solar insolation. The reduced ability of PV systems to be utilized in some of the high volume terrestrial markets reduces cell production volume and reduces the cost advantages attributed to high volume production. This, indirectly, sustains the high cost of space power systems. The results of the Phase I effort show that the AMTEC conceptual design has the potential for eliminating all of the current space power limitations, and has numerous commercial space and terrestrial applications. Commercial interest in AMTEC has been demonstrated by industrial corporations such as, Arthur D. Little, Teledyne Brown, Global Thermoelectric, and Rocketdyne.

2.3 AMTEC SYSTEM ADVANTAGES

The results of the Phase I effort show that combining an innovative AMTEC generator concept with a fully integrated TES system produces a small, high performance, and inexpensive power system that maintains or improves lifetime, durability, and reliability of the satellite.. The conceptual design of the 500 We SAMTEC system was completed during the Phase I effort. The results indicate that the SAMTEC power system is predicted to have a specific power of 5.3 to 8.9 We/kg (including the concentrator, receiver, AMTEC cells, gimbals and drives, structure, power processing and control, and a 30% mass contingency) at the 500 watt power level, and 12 to 17 We/kg (including all of the components listed above) at the 5,000 watt power level. The SAMTEC system, including all of the components listed above, is predicted to cost $1,000/We once development is complete and production begins. The SAMTEC system provides 92% of its Beginning of Life (BOL) power after a 5 year period in LEO, and SAMTEC systems should provide 10 to 15 years of life in LEO. The SAMTEC system's resistance to radiation also allows operation in Middle Earth Orbits (MEO) where it encounters the Van Allen radiation belts. Operation in such orbits can significantly reduce the number of satellites required for global coverage, thus reducing the overall cost of a global communications satellite constellation. The AMTEC cells designed and used for the solar system can also be used in systems heated with a reactor, radioisotope, or combustor for other space or terrestrial applications. This capability will lead to a large markets for AMTEC cells and thus to large economies of scale in production.

2.4 PHASE I GOALS

The two main goals of the Phase I program were to complete the conceptual design of an innovative, low cost, reliable, low mass, long life 500 watt solar power system for small spacecraft, and predict the performance of the SAMTEC space power system. Sections 4.0 describes the conceptual design of the 500 We SAMTEC system, and section 5.0 describes the components selected for the system design. Section 8.0 shows the predicted performance of the SAMTEC system, and compares it to the performance of current PV systems. The Phase I program provided the proof-of-principle necessary for a SAMTEC system by producing the first detailed system design and performance predictions. The results of the Phase I effort demonstrate SAMTEC's ability to provide high system performance at a low system cost while maintaining or improving system lifetime, durability, and reliability.

2.5 AMTEC DEVELOPMENT NEEDS

There are several key steps that need to be completed to successfully develop AMTEC cells and systems for space and terrestrial applications. The multi-tube AMTEC cell needs to be developed to a level consistent with the single tube AMTEC cell now being produced at Advanced Modular Power Systems, Inc. (AMPS), and it needs to be integrated with the TES. The first is to fully develop the multi-tube AMTEC cells and integrate them with the TES units. The first multi-tube AMTEC cell was successfully tested in February of 1995, the first AMTEC/TES cell will be tested in summer of 1995, and multi-tube cell development will continue in Phase 2 of this Small Business Innovative Research (SBIR) program. System design and performance models should be refined in order to determine, with a very high confidence level, the performance of the proposed AMTEC technology in comparison with the established space power systems. A detailed system design, and spacecraft integration of the SAMTEC space power system is also necessary, and will be completed during Phase 2. The cell and system development can then converge to produce a working system prototype in the relevant environment, high vacuum, which will also be completed at the end of Phase 2. The final step is a flight test of the AMTEC cells, which has been proposed (and is currently under review) to NASA under the In Space Technology Experiment Program (InSTEP). Once these steps have been completed, SAMTEC will have the necessary background to begin convincing satellite users to adopt AMTEC technology.

3.0 SAMTEC SYSTEM MODEL

The SAMTEC system model was developed to predict conservative estimates of the mass and performance for several receiver, AMTEC cell, TES, and concentrator design options. Receiver design options include single and multi-tube AMTEC cells, LiF and LiF-22%CaF_2 Phase Change Material (PCM) for TES, and overall receiver configuration/geometry. The system model does not calculate individual cell performance. The cell performance is calculated with independent AMTEC cell models developed at Advanced Modular Power Systems, Inc. (AMPS) and then used as input to the system model. This allows several different AMTEC cell designs to be evaluated in the system without changing the entire system model. The system model requires the following information about the AMTEC cells used in the system: Outside Diameter, Length, Mass, Power, Efficiency.

The system model also requires a choice of PCM. The two candidate materials are LiF-22%CaF_2 and LiF. The characteristics of the materials are as shown in Table 1. The diameter or the height of the TES canister must also be specified. The model calculates the diameter or height (which ever is not given) based on the amount of energy the PCM must store. Material thicknesses and density as well as the orbit period and eclipse time are also required input parameters. The following are important assumptions made in the system model:

Table 1: PCM Characteristics

	LiF-22%CaF_2	LiF
Heat of Fusion (kJ/kg)	815	1087
T_{melt} (°C)	765	850
Density (g/cm^3)	2.1	1.83

1.) Mirror Efficiency at end of life is 90%
2.) Solar Flux constant is 1323 W/m^2

The mirror efficiency and solar flux can be adjusted. The receiver geometry is assumed to be a regular polygon of N sides each of equal length. This geometry was chosen to increase the strength of the receiver and simplify the integration of the cells with the receiver walls. The number of sides of the receiver is chosen so that each side can be connected in series to form a single string the required voltage. For example, if the cells are 3.5 volts and the requirement is 28 volts the receiver would have 8 sides. The number of cells per side is then increased to provide the desired output power. This allows a number of different cell voltages to be analyzed.

The system model attempts to account for every major loss in the system. Table 2 shows the power flow through the SAMTEC system and the following paragraphs describe the calculations used to predict these numbers. The solar insulation to the mirror is calculated as the projected area of the mirror times the solar flux constant. The blockage losses due to the receiver are then calculated as the receiver projected area times the solar flux constant. Subtracting these two numbers gives the power incident on the mirror. The power incident on the mirror is then multiplied by the end of life mirror efficiency to calculate the reflection losses. Subtracting the reflection losses from the power incident on the mirror gives the power to the focal plane. This number is then multiplied by the aperture efficiency to calculate the spillover due to sizing of the aperture hole.

Table 2: System Power Flow

	Watts
Solar Insolation	4299
Blockage Losses	209
Incident on Mirror	4090
Reflection Losses	409
To Focal Plane	3681
Spillover	3
Into Receiver	3678
Thermal Losses	116
Absorbed	3562
Q_{PCM}	1324
Q_{AMTEC}	2238
$Q_{Rej.}$	1760
Electrical Power	546

The diameter of the image formed on the focal plane is needed to calculate the efficiency of the aperture and the amount of heat spilled on the aperture shield or "spillover". The image diameter is calculated as the focal length of the mirror multiplied by the subtense angle. The subtense angle, for space systems, is defined as the diameter of the light source, which for the Sun is $139x10^4$ km, divided by the distance away from the Sun, which is $149x10^6$ km, resulting in 0.00929 radians. Using Simpson's rule to integrate the function describing the flux distribution at the focal plane the spillover and aperture efficiency can be calculated. The spillover is subtracted from the power to the focal plane giving the power into the receiver. The heat loss through the multi-layer heat shields is then calculated. Determan et al (1989) gives the following equation, determined experimentally, for the heat loss through Multi-Layer Insulation (MLI):

$$Q = \frac{A\,1.06E{-}8\,(T_1^4 - T_2^4)}{(0.788\,N + 1.11E{-}2\,N^2)},$$

where A is the area normal to the heat flux, T_1 and T_2 are the boundary temperatures, and N is the number of layers of heat shields. The loss out the aperture hole is calculated as blackbody radiation to space. These two losses combine to give the total thermal losses out the receiver. Subtracting these losses from the power into the receiver yields the power absorbed by the PCM and AMTEC subsystems. The heat that the PCM requires to keep the system running during the eclipse period is calculated as follows:

$$Q_{PCM} = \frac{te\,(P_{tot} + Q_{rej} + Q_{oh})}{ti},$$

where te is the eclipse time, ti is the insolation time, P_{tot} is the system power output, Q_{oh} is the heat radiated out the aperture hole, and Q_{rej} is the heat rejected from the system to space and is calculated as follows:

$$Q_{rej} = \frac{P_{tot}}{E_{sys}} - P_{tot} + Q_{ths},$$

where E_{sys} is the AMTEC cell efficiency, P_{tot} is the system output power, and Q_{ths} is the losses through the heat shields as described earlier. The final power flow calculation is the power required by the AMTEC cells which is the cell output power over the cell efficiency. The system model also calculates certain optical properties of the parabolic concentrator, diagramed in Figure 1. The equation describing the surface of the parabola, from Spiegel (1968) is $y^2 = 4Fx$, where F is the distance to the focal point, the x and y axes are as shown in Figure 1, and the origin is at the center of the parabola. The rim angle, shown in Figure 1, is defined as the angle between an incoming light ray, at the rim, which is parallel to the focal plane and a line tangent to the parabola at the rim. The slope of the tangent line is equal to the tangent of the rim angle and also equal to the derivative, at the rim, of the equation describing the parabolic surface. Taking the required derivative and substituting the tangent of the rim angle for dy/dx gives the following equation for calculating the focal length: F = Y/2*TAN(alpha), where alpha is the rim angle, and Y is the radius of the concentrator determined by the area required to intercept the desired solar flux. Once the focal length and radius of the concentrator have been determined they can be used, by substituting into the equation describing a parabola, to calculate the depth, or x coordinate corresponding to the radius, of the concentrator. These equations produce reasonable calculations of the optical properties of a parabolic concentrator which help in sizing the system and its integration with the satellite.

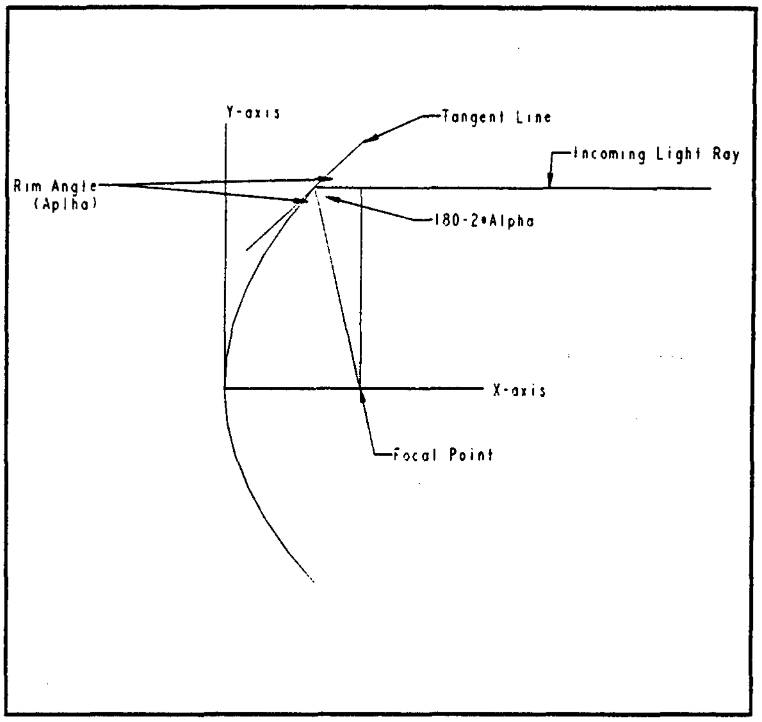

Figure 1 Diagram of Parabolic Concentrator

The final unknown in this system of equations is the radiator area or temperature. If the radiator area is assumed to be the surface area of the receiver then these equations can be iteratively solved based on the radiator temperature. If the area is assumed to be a variable then the desired radiator temperature is specified and the equations iteratively solve around the radiator area. A sample copy of the model inputs, outputs, and equations is included at the end of this report in Appendix B. The model described here was used to complete the trade studies and component selection described in section 4.0 and 5.0 of this report.

4.0 SAMTEC SYSTEM CONCEPTUAL DESIGN

The two main goals of the Phase I program were to complete the conceptual design of an innovative, low cost, reliable, low mass, long life 500 watt solar power system for small spacecraft, and predict the performance of the SAMTEC space power system. The conceptual design is based on a set of Phillips Laboratory-furnished design requirements which can be found in Appendix A. The system was designed to provide 500 watts electrical power at 28 volts to the payload in Low Earth Orbit (800 km, 28.5° inclination) for 5 years. Based on the optical and thermal analyses, a conceptual design of a 500 watt solar AMTEC space power system has been recommended. The Phase I effort showed that the conceptual design met or exceeded all of the design requirements that could be addressed during the project. Section 5 describes the trade studies used to select the system components, and Section 4 describes the conceptual design of the 500 We SAMTEC system. Section 8 shows the predicted performance of the SAMTEC system and compares it to current PV arrays.

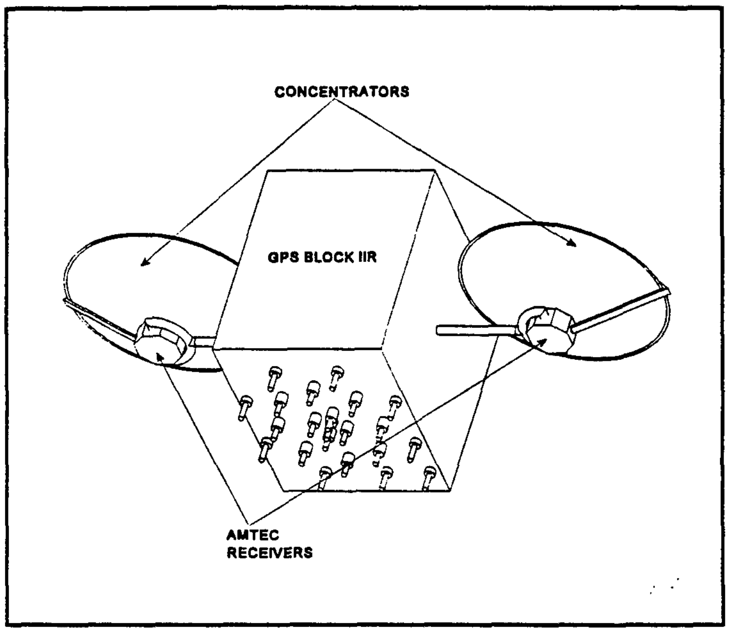

Figure 2: 500 Watt SAMTEC Satellite Power System

Figure 2 shows the conceptual design of a 500 watt SAMTEC, integrated with the GPS Block IIR spacecraft. The GPS Block IIR was used only as a concrete example of a spacecraft bus. This power system was designed during Phase I to provide a low cost, reliable, low mass, long life power system for small spacecraft. The SAMTEC system consists of the following four main sub-systems:

1.) Concentrator (Fresnel, Newtonian, or Cassegranian, Fresnel shown)
2.) Multi-Tube AMTEC cells

3.) LiF-22%CaF_2 Thermal Energy Storage (TES)

4.) State-of-the-art Power Management and Distribution (PMAD)

The receiver, shown in Figure 3, is comprised of the required number of AMTEC/TES units to produce the desired voltage and power. Each AMTEC/TES unit contains a single LiF-22%CaF_2 TES unit and a single multi-tube AMTEC cell.

A regular octagon configuration was used to increase the strength of the receiver and simplify the integration of the cells with the receiver. The number of sides of the receiver is chosen so that each side can be connected in series to form a single string the required voltage. In this design, each cell provides 3.5 volts at the normal operating point, and the 28 volt requirement is met with a receiver having a cell mounted on each of its 8 faces. The number of cells mounted to each face is then increased to provide the desired output power. In this design, each cell provides 23 watts of electricity and each string can deliver 184 watts. Since the system requirement is 500 watts (500 watts to the payload and 52 to the PMAD system), three strings (3 cells per side) provide the required power. The cells are connected in a series/parallel ladder arrangement to provide the

Table 3: 500 We SAMTEC Power System Mass

Electrical Power (W)	500
Specific Power (W/kg)	8.2
Cell Eff. (%)	24.4
Net System Eff. (%)	19.8
Component Mass (kg)	
Electrical Insulation	0.39
Receiver	1.43
TES	9.32
MLI	0.98
AMTEC Cells	3.31
Concentrator	2.76
Aperture Shield	0.82
Gimbals and Drives	3.00
Structure	3.00
PP&C	22.00
Mass Contingency	14.10
Total	61.11

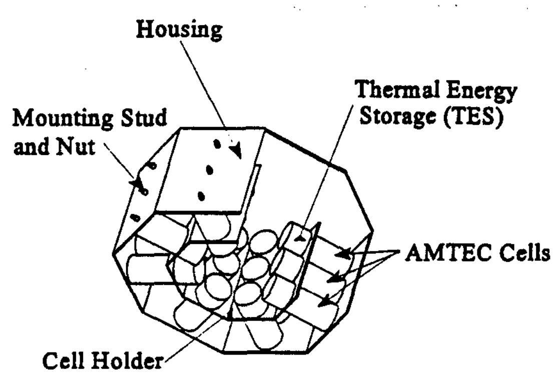

Figure 3: 500 Watt SAMTEC Receiver

highest level of system reliability. Table 3 shows the estimated mass of the components in the 500 We SAMTEC pictured in Figure 2. The receiver housing is made from carbon-carbon composite material to lower the mass of the system. The TES canisters are made form Haynes 188 alloy (the material used for the SDGTD Program TES units), the multi-layer heat shields use molybdenum foil, and the cell walls are Inconel. Mass could be saved by selecting different materials for these components, but they account for only 15% of the system mass, and any mass savings would only have a minimal effect on the overall system mass.

Table 3 indicates that the Power Processing and Control (PP&C) accounts for approximately 36% of the power system mass. The PP&C system was designed as a unit totally separate from the satellite, and has several components that can be, and typically are, integrated with the spacecraft PMAD system. Even small fractional savings in the PP&C mass due to such integration will have a significant impact on the mass attributable to the power system and thus to the specific power. Table 4 shows a breakdown of the PP&C component masses, and shows that 86% of the PP&C mass

Table 4: Power System PP&C Mass Breakdown

AMTEC Dedicated PP&C Components	Quantity	Component Mass (grams)	Total Mass (grams)
Main Bus	3	160	480
Shunt Regulator Input Bus	3	60	180
Shunt Regulators	3	600	1800
Parasitic Load Radiators & Wiring Harnesses	3	170	510
Subtotal AMTEC PP&C Mass			2970
Spacecraft Shared PP&C Components *			
Control Computers	2	1900	3800
Start Up Batteries	2	2700	5400
Start Up Battery Charger/Discharger	2	1080	2160
Electronics Bay Housing	1	3500	3500
Electronics & Battery Radiator & Coldplate	1	3900	3900
Subtotal Shared PP&C Mass			18760
Total PP&C Mass			21730

is due to components that can be combined/shared with the existing spacecraft PMAD system. This indicates that the system component with the largest mass is comprised mostly of components that can be combined with the spacecraft, thus lowering the power system mass and increasing the specific power. However, even without credit for any component sharing, the system pictured in Figure 2 is predicted to have a specific power of 8.2 We/kg and a system efficiency of 19.8% based on the intercepted solar radiation.

5.0 SAMTEC SYSTEM COMPONENT SELECTION

The following is a list of the recommended components for the 500 We SAMTEC power system and a brief justification for the selection.

5.1 THERMAL ENERGY STORAGE

LiF-22%CaF_2 PCM - This material is chosen based on the results of the development funded under the SDGTD Program at the NASA Lewis Research Center. The system trade study, results in Table 5, show that LiF provides only a modest increase in performance (specific power increases of only 0.7-1.0 We/kg) compared to the LiF-22%CaF_2, with a substantial increase in receiver temperature (765°C to 850°C). The higher temperature operation using LiF could require the use of refractory materials, which could effect lifetime and would increase the cost for developing and producing the system. Therefore, LiF-22%CaF_2 is the PCM chosen for this system. The cell efficiency is higher for the LiF PCM because the operating temperature is higher. The models used for this analysis indicate that the gain in efficiency is small, but more detailed cell models, which are to be used during Phase 2, may show a greater difference between the two operating temperatures.

5.2 AMTEC CELL

Multi-Tube AMTEC Cells - The system trade showed that the multi-tube AMTEC cells provide a significant increase in system performance (efficiency increased from 17.6% to 24.4% and the mass decreased by 34 kg for a specific power increase of 3 We/kg) compared to single tube AMTEC cells. The increase in risk for selecting the multi-tube cell is minor (single-tube cells are NASA Level 4 and multi-tube are NASA Level 3). However, all of the development that has gone into single-tube cells is directly applicable to multi-tube cells. Table 5 shows the performance and mass of several AMTEC cell/TES systems, predicted using the analytical system models developed during Phase I and described in Section 3.0 of this report. The multi-tube AMTEC cell was chosen based on its substantial increase in performance, compared to the single-tube, and only minor increase in risk. However, it should be noted that even the off-the-shelf-system comprised of single-tube

AMTEC cells, which are 18% efficient, and LiF-22%CaF_2 TES units would have a specific power of 5.3 We/kg. The predicted performance of the SAMTEC system is compared to PV/battery systems in section 8.0 of this report.

Table 5: AMTEC/TES Trade Study Results

	Multi-Tube	Multi-Tube	Single Tube	Single Tube
TES Material	LiF	LiF-22%CaF_2	LiF	LiF-22%CaF_2
Electrical Power (W)	500	500	500	500
Specific Power (W/kg)	8.9	8.2	6.3	5.3
Cell Eff. (%)	29.4	24.4	21.0	17.6
Net System Eff. (%)	23.5	19.8	15.8	13.7
# of Cells	24	24	120	160
Masses (kg)				
Electrical Insulation	0.39	0.39	1.40	1.86
Receiver	1.22	1.43	3.14	3.98
TES	6.41	9.32	10.85	15.93
MLI	0.88	0.98	3.03	4.06
AMTEC Cells	3.31	3.31	10.08	13.44
Concentrator	2.33	2.76	4.00	4.67
Aperture Shield	0.69	0.82	1.00	1.01
Gimbals and Drives	3.00	3.00	3.00	3.00
Structure	3.00	3.00	3.00	3.00
PP&C	22.00	22.00	22.00	22.00
Mass Contingency	12.97	14.10	18.45	21.88
Total	56.20	61.11	79.95	94.83

5.3 CONCENTRATOR

Fresnel or Newtonian Concentrator - Both reflective and refractive concentrator options were considered. For reflective concentration one may choose a simple, parabolic, Newtonian mirror system used either on-axis or off-axis, or a Cassegrainian optics approach using a large primary mirror and a small secondary mirror to complete the focusing. For refractive optics, only the Fresnel lens concentrator was considered, since ordinary lenses are almost certainly too massive for practical use in space. The Fresnel concentrator offers several advantages relative to reflective concentrators, and the development of the key components is being funded under space and terrestrial concentrated PV programs. A description of the advantages a Fresnel concentrator offers, relative to various reflective concentrator options, is included below. The Phase I effort could not provide the detail necessary to select the best concentrator. Based on the information gathered in the Phase I effort the Fresnel has definite advantages over reflective concentrators and if the materials issue has been solved should be the concentrator of choice. However, until a detailed spacecraft integration analysis can be completed in Phase 2 the only recommendation is that reflective and refractive concentrators should be further analyzed.

6.0 CONCENTRATORS

6.1 NEWTONIAN

The simple Newtonian mirror system requires high accuracy pointing and minimum slope errors in order to achieve the concentration ratio required to reach AMTEC operating temperatures. A portion of the reflecting area is blocked by the receiver, which must be located in front of the mirror surface. A degradation of the reflectivity to about 90% is to be expected over a period of 10 years in orbit. Of the reflective concentrators, this is probably the best choice for simplicity, mass, and minimal degradation with exposure time.

6.2 CASSEGRANIAN

A Cassegranian concentrator was also evaluated and this approach was not chosen for several reasons. The two-mirror configuration will have higher reflection losses simply due to the second reflection required. If a single mirror is expected to be reduced to 90% reflectivity at the end of ten years, Cassegranian optics would be expected to suffer a reduction to 81% over the same period. Compensation for this would require a larger system and the added beginning of life power would then have to be dissipated (larger PMAD system and larger concentrator area further complicating stowage and deployment). Further, the Cassegranian optics tend to form a sharp solar image on the back wall of the receiver increasing the local flux and temperature at this point relative to either Newtonian or Fresnel optics. For high concentration ratios, the secondary mirror suffers from another problem. A small fraction of the concentrated solar flux, intercepted by the primary mirror and directed toward the secondary mirror, is absorbed by the secondary mirror. Methods to keep the secondary mirror cool, must therefore be incorporated, to prevent undesirable optical distortions and/or shortened mirror lifetimes, from occurring. While adjusting a small secondary mirror to fine tune the collector pointing is possible in principle, achieving this in practice poses a difficult control problem (i.e. pointing two mirrors instead of one) and this then lowers the overall system reliability. These difficulties are not present in either Newtonian or Fresnel optics.

6.3 FRESNEL

A parabolic concentrator has several disadvantages for space power applications-which use of a domed Fresnel lens eliminates. The receiver, and any required radiator, and the structure of an on-axis parabolic concentrator system must be located at or near the focal point of the dish. In this location, these elements of the system shade the concentrator aperture and reduce the solar energy collection efficiency of the concentrator. For a system using a domed Fresnel concentrator, all of these elements are behind the lens, and thus do not interfere with the collection or concentration of the sunlight.

In addition to shading problems, parabolic concentrators require precise shape maintenance for reasonable performance. In operation under varying temperature conditions, precise shape control of reflectors has proven to be exceptionally difficult even for relatively massive terrestrial concentrators. The large temperature variations associated with the eclipse periods encountered when operating in a LEO, will make precise shape control very difficult for the ultra-light concentrators needed for space solar systems. A dome shaped Fresnel lens, using a unique optical design, eliminates the precise shape control issue. These lenses are designed such that for each individual prism the angle of incidence of the light at the smooth outer lens surface is equal to the angle of emergence at the inner lens surface. This symmetrical refraction condition leads to the lowest reflection losses for each prism, and thus maximizes the transmittance through the lens, and hence the lens efficiency. In addition to the transmittance advantage, the symmetrical refraction prism produces a much smaller solar image than non-symmetrical refraction prisms at the same total turning angle when effects such as; finite solar disk size, chromatic aberration, prism manufacturing inaccuracies, and orientation are considered. Prism orientation inaccuracies correspond directly to concentrator slope errors which makes image defocussing, due to this inaccuracy, extremely important. Compared to reflective solar concentrators, this Fresnel lens allows 200 times the slope error for equivalent image defocussing. The greater slope error tolerance of the Fresnel lens means that for good optical performance, the shape is less critical. The accuracy required for concentrator manufacturing and deployment can be relaxed, and the allowable structural deformations are larger.

The slope-error tolerance relates directly to lower concentrator mass, lower manufacturing cost, and easier manufacturing techniques.

The domed Fresnel lens also provides the capability to tailor the radiant flux profile. The Fresnel lens consists of thousands of microscopic prisms which individually produce an image on the focal plane. This image can be directed to almost any desired location on the focal region by selecting the prism apex angle accordingly. Since the flux profile on the focal plane is the sum of the contributions of all of the prisms, the lens has several thousand degrees of freedom with which to adjust the flux profile. This flux profile tailoring has been successfully accomplished for several different versions of terrestrial solar concentrators of similar design. The flux intensity profile over the absorption surfaces inside the receiver cavity, can also be designed to more closely match the heat transfer requirements, by modifying the lens prism angles. The flux profile can thus be designed to avoid the intensely focused spots at the center of the focal plane, associated with parabolic concentrators, which can, and do cause safety problems if the sun-tracking system malfunctions for any reason. There are limits and trade-offs associated with tailoring the flux, but these can only be fully evaluated with detailed design and analysis.

There is a potential materials issue associated with the light weight Fresnel lens. These lenses are made from silicone rubber which is attacked by ultra violet rays (UV) and atomic oxygen (AO). A coating has recently been developed that appears to eliminate this problem. The durability of the coating is currently being tested in space. Prototypic mini-dome Fresnel lenses are on a test satellite in an elliptic orbit reaching a maximum of 1365 nautical miles (just inside the Van Allen belts). In this orbit they are being exposed to UV, AO, and radiation at a greater rate than had been planned since the satellite is a higher orbit than expected. According to Mike Piszczor of NASA Lewis, and Mark O'Neill of ENTECH the lenses have shown no degradation after five months of operation. While this data is still preliminary and of relatively short duration, the results look promising. All of the information on the Fresnel lens presented here originated from discussions with Mike Piszczor at NASA Lewis and Mark O'Neill at ENTECH and from a NASA Lewis technical report prepared by ENTECH (Ref. 5).

6.4 SECONDARY

One of the key issues of a SAMTEC space power system is the required pointing and tracking accuracy. The SAMTEC system with a single reflective or refractive concentrator is predicted to require pointing precision in the range of $<\pm 1°$, which is well within current state-of-the-art technology. However, this may impose requirement on the spacecraft that designers will not accept, but a secondary concentrator can "loosen" this requirement to $<\pm 5°$ (typical of PV systems). The following advantages of using a secondary concentrator in conjunction with a primary mirror were identified during the Phase I effort:

1) Primary mirrors generally require pointing errors of less than 0.25 degrees, to be captured by a minimally oversized cavity aperture opening while the use of a secondary concentrator will relax pointing and tracking error effects. A properly designed secondary concentrator can typically accept ±1.0 to ± 5.0 degree pointing errors, without any loss of solar flux into the cavity.
2) Use of a secondary concentrator can typically reduce cavity opening size by a factor of 1.5 to 3.0, reducing re-radiation thermal losses by similar factors.
3) Secondary concentrators accept diffuse sunlight, such that any sunlight ray hitting any surface (within the designed apex acceptance angle) will be 100% absorbed without re-reflecting out.
4) Secondary concentrators can be fabricated with highly reflective, and low emissive surface materials to virtually eliminate surface losses.

A detailed analysis would be needed to determine if the secondary concentrator would have to be actively cooled, its mass penalty, and determine the magnitude of the performance gain with a chosen primary concentrator. Based on the potential benefits of the secondary concentrator it should be considered in any future effort.

7.0 STOWAGE AND DEPLOYMENT

The integration of the power system with the spacecraft is a major design consideration for a satellite. The stowage and deployment of the satellite and power system is a critical element of the integration. The SAMTEC space power system, once integrated with the spacecraft, must stow in the same launch vehicle as the PV system it is replacing, and have a reasonable deployment scheme. This section will show the conceptual stowage/deployment design for a SAMTEC system with a Newtonian and a Fresnel concentrator. This will offer a proof-of-concept understanding associated with these issues, and not a detailed design.

7.1 NEWTONIAN CONCENTRATOR

Figure 4 shows two (one on each side of the satellite) 500 We SAMTEC power systems integrated with the GPS Block IIR satellite in its stowed configuration (Newtonian concentrator is sectioned to show detail). The 9.5 ft. Delta rocket faring is also shown, in cross-section, to demonstrate the stowage configuration and clearance. Figure 5 shows a top view (top of the faring removed to show detail) of the stowed satellite/solar powered AMTEC system. This shows that the minimum clearance points are at the four corners of the GPS body (identical to PV minimum clearance points), and the concentrator clears the faring envelop with room to spare. However, these figures show that a larger concentrator would be a problem in this

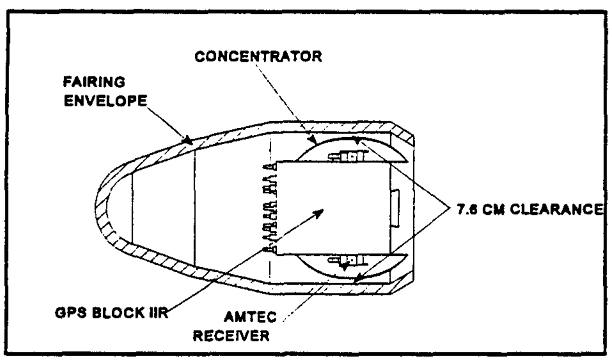

Figure 4: Side View of Stowed Satellite

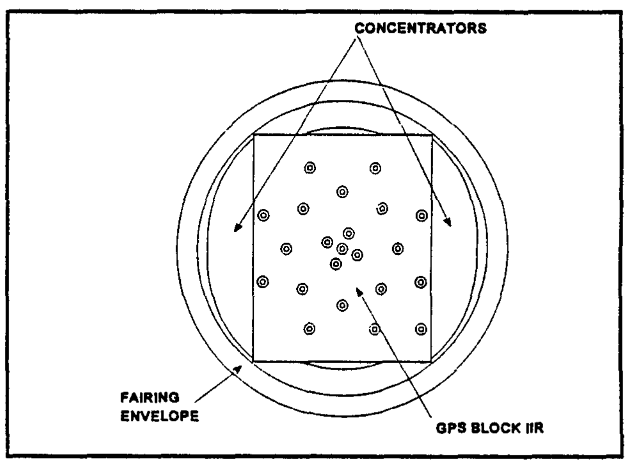

Figure 5 Top View of Stowed Satellite

configuration and a different stowage/deployment scheme would be required. There are several options such as; sunflower, spline radial, folding petal that could be looked at if the concentrator size increased.

During launch the concentrators can be stowed in direct contact with the satellite for rigid support. Cables, connected with explosive bolts or cable cutters, could be wrapped around the concentrators to hold them against the satellite body. Once in orbit the cables are released and the concentrators, which are connected to the receiver with a spring loaded structure, will spring into the deployed position as shown in Figure 6.

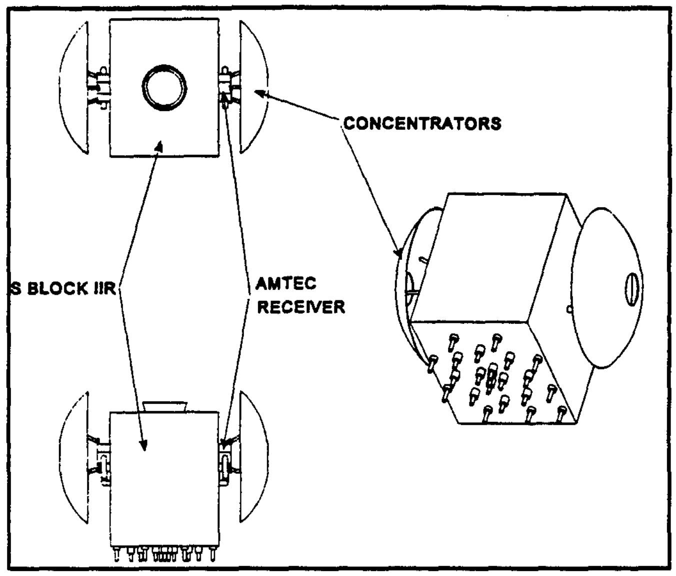

Figure 6 Concentrators Deployed

Once the concentrators are deployed the collapsible structure connecting the receiver to the satellite body will then deploy the receiver/concentrator to its deployed position as shown in Figure 7. Then the rotary actuator at the elbow of the boom, and/or rotary actuators that connect the boom to the receiver housing, can rotate the receiver/concentrator into its deployed position as shown in Figure 8. These actuators would provide pointing and tracking once the system is deployed and, if actuators are placed at the boom elbow and connection to the receiver housing, would eliminate single point failures by providing redundancy.

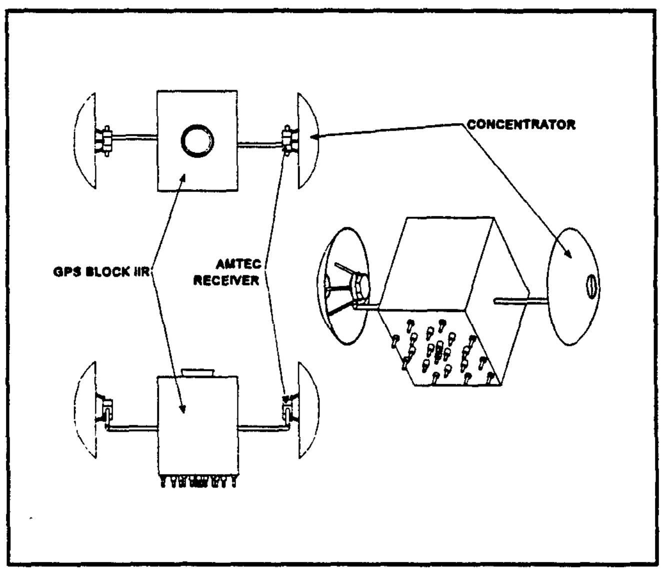

Figure 7 Boom Deployed

This analysis shows that the parabolic and Fresnel concentrator will fit inside the faring and a reasonable scheme can be identified to deploy the system once in orbit, but a detailed analysis is required to improve the design, and size the boom and gimbals. The domed Fresnel lens could be stowed and deployed in a nearly identical procedure, but a lower volume scheme has been developed by ENTECH.

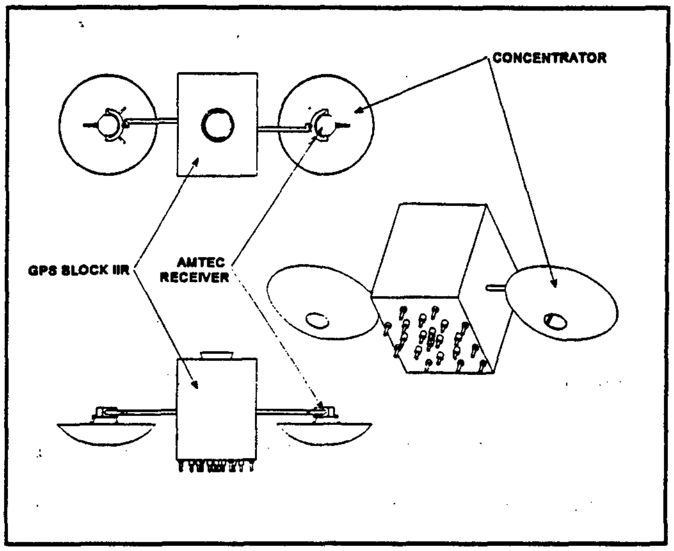

Figure 8 Fully Deployed

7.2 FRESNEL CONCENTRATOR

The domed Fresnel lens can be stowed and deployed in a manner similar to the scheme, described previously, for the parabolic concentrator. However, ENTECH developed a scheme that requires much less volume. This approach segments the lens into twenty-four equal sections or gores. The gores are stowed by stacking them on top of each other to form a bundle which is contained in a space-frame truss structure. Figure 9 shows the domed Fresnel lens in it fully stowed configuration inside the support structure.[2] The lens can be deployed automatically by holding the truss structure while each gore is sequentially lowered from the bottom of the stack to its

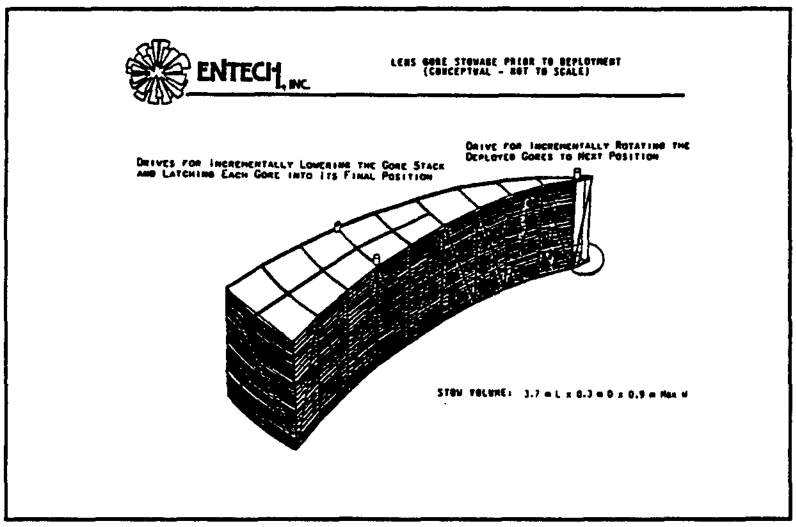

Figure 9 Domed Fresnel Fully Stowed (from Ref. 5)

[2] Figures 9 and 10 are used with permission from Mark J. O'Neill and are from Reference 5.

final position, latched to the adjacent gore and hub structure. Then the deployed gores rotate to provide space for the next gore to drop and latch into place. The last gore deployed will latch to the first gore completing the circle and forming an integrated concentrator. The drop, latch, and rotate functions will be performed by electric motor drives powered by the start-up batteries. Figure 10 demonstrates the drop, latch, rotate deployment sequence. The space-frame truss structure, which stored the stowed gores during launch, provides a rigid backbone to support the lens when fully deployed. The interlocking gores also provide a highly efficient way of supporting the lens.

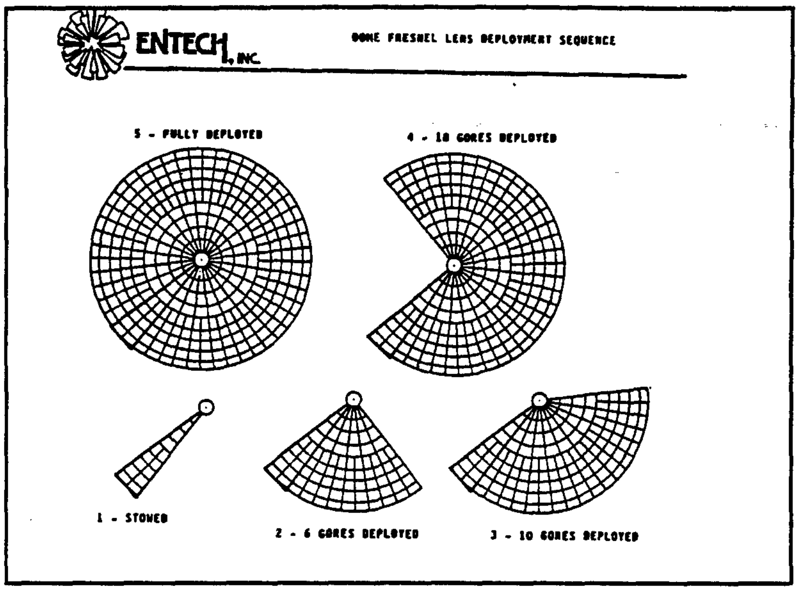

Figure 10 Deployment of Domed Fresnel Lens (Ref. 5)

8.0 SAMTEC DEVELOPMENT AND PRODUCTION COST ESTIMATES

The cost to develop and then to produce the SAMTEC space power system is an important factor in the systems acceptance. The previous sections have shown the conceptual design and expected

Table 6: 500 We SAMTEC Development Costs

Concentrator	4.00
Receiver	2.80
AMTEC/TES	12.50
PP&C	3.10
Total Hardware Development	22.40
System Hardware	0.38
System Ground Test	2.10
System SE&I and Management	5.90
Integration Contractor G&A	3.00
Contingency	5.07
Total Development	38.85

Note: Amounts are in Millions

Table 7: 500 We SAMTEC First Unit Production Costs

Concentrator	0.15
Receiver	0.11
AMTEC/TES	0.25
PP&C	0.25
Total Hardware	0.76
Integration, Assembly, Checkout	0.15
Acceptance Testing	0.09
Production Management	0.1
Integration Contractor G&A	0.11
Total Space Power System	1.21

Note: Amounts are in Millions

performance but the system must also be cost effective. The following two tables were prepared to estimate the development and production costs of the 500 We SAMTEC power system. The cost to develop the AMTEC cells is more than a third of the total development cost, as expected, because the other elements are at a much higher level of development.

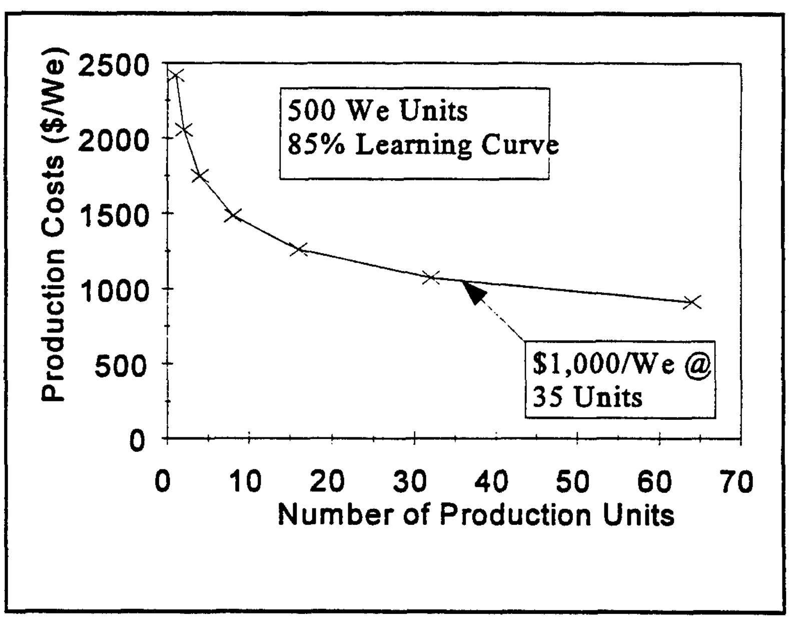

Figure 11: 500 We SAMTEC Production Cost Projection

However, once the development is completed and production begins the AMTEC/TES should conservatively cost $500/We. The initial system would costs $2,420/We and the goal of $1,000/We will be reached at the 35 unit production level, assuming a learning curve of 85% as shown in Figure 10. At this level, the AMTEC system would be approximately a factor of 10 below PV systems with comparable performance.

9.0 SAMTEC PERFORMANCE CHARACTERISTICS

The well established, conventional choice for LEO solar power is photovoltaic conversion with batteries for energy storage. The Phase I program compared the predicted performance, cost, energy storage mass, degradation, and lifetime/reliability of the SAMTEC system to PV/battery systems. This section covers the comparisons made during the Phase I program.

9.1 SPECIFIC POWER

At the 500 We power level, SAMTEC will increase the specific power (We/kg) of a satellite power system by a factor of 1.3 - 2.4 over current PV power systems. Table 8 lists the mass, power, and

Table 8: PV Power System Specific Power

Spacecraft	Power (Watts)	EPS Mass (kg)	Specific Power (W/kg)	Configuration
SAMPEX	80	161	0.5	Si-NiCd, LEO
TIMS	120	84	1.4	Si-NiCd, LEO
Sea Star	163	109	1.5	Si - NiH_2, LEO
GAMES	165	65	2.5	GaAs-NiCd, LEO
TIMED-H	186	145	1.3	GaAs-NiCd, LEO
TIMED-L	203	145	1.4	GaAs-NiCd, LEO
Milstar	4700	726	6.5	Si - NiH_2
LMSC Study	10000	1951	5.1	LEO
SSF	21000	5640	3.7	Si - NiH_2, LEO

specific power of numerous PV satellite power systems (LEO) in a variety of solar cell/battery configurations (Ref. 6).[3] Based on the information in this table, an estimate of the expected specific

[3] All of the data used in this table can be found in Reference 6, except as follows: the Milstar data is from a personal communication with Vince Teofilo, LMSC, 1991, the LMSC data is from Reference 7, and the SSF data is from a personal communication with SSF, Rocketdyne, Personnel, 1990.

power for a PV system at the 500 We power level (SAMTEC design point), can be made. Table 9 lists the mass and specific power of the 500 We SAMTEC satellite power system in a variety of AMTEC cell/TES configurations. The listed masses for the SAMTEC systems are conservative because the PMAD system, the largest single contributor to system mass, was designed as an entity totally separate from the satellite. Typical satellite designs integrate a certain amount of the power system PMAD with the satellite control in order to reduce system mass. The masses listed in Table 9 also include a 30% mass contingency.

Table 9: SAMTEC Power System Specific Power

Spacecraft	Power (Watts)	EPS Mass (kg)	Specific Power (W/kg)	Configuration
SAMTEC	500	94.83	5.3	ST, LiF-22%CaF_2
SAMTEC	500	79.98	6.3	ST,LiF
SAMTEC	500	61.11	8.2	MT,LiF-22%CaF_2
SAMTEC	500	56.20	8.9	MT, LiF

The information from these two tables is combined into one graph, Figure 12, to provide a direct comparison between SAMTEC and PV specific power. It can be concluded from this graph, a 500 We PV power system would have a specific power of approximately 4 We/kg. Using current technology, (single-tube AMTEC and LiF-22%CaF_2 TES), a 500 We SAMTEC power system would

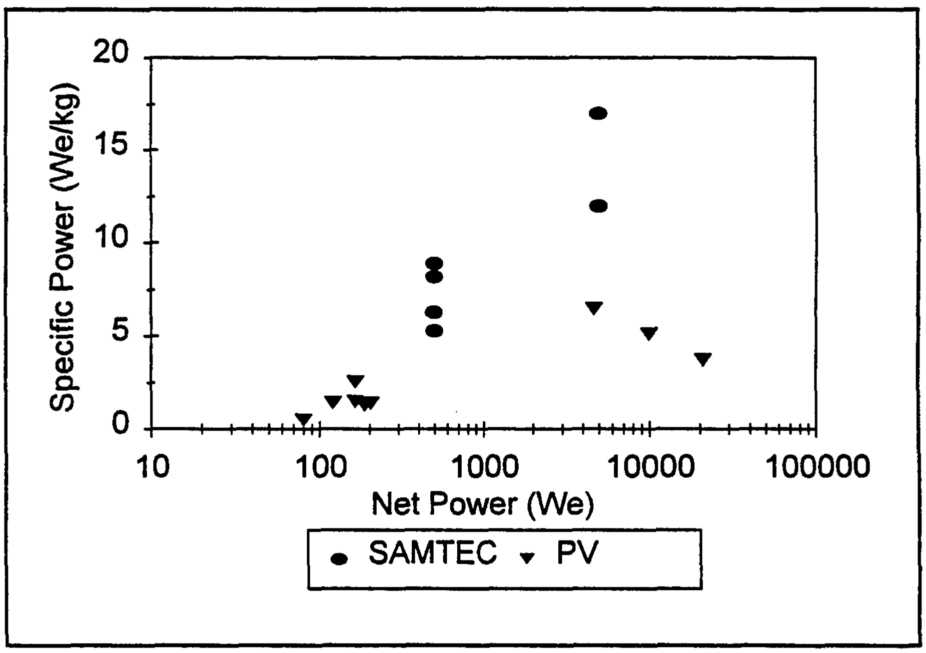

Figure 12: PV/AMTEC Specific Power Comparison

have a specific power of 5.3 We/kg, 1.3 times higher than that of the PV system. With the improvements in the technology, (multi-tube AMTEC and LiF TES), the SAMTEC system would have a specific power of 2.4 We/kg, a factor of 4 higher than the PV system, an overall mass saving of ~68 kg.

Using the models developed for analyzing the 500 We SAMTEC system (described in section 3 of this report), an estimate of the specific power for larger SAMTEC systems was completed. Figure 12 shows that at the 5,000 We power level the SAMTEC system is estimated to be 12 We/kg (single-tube LiF-22%CaF_2) and 17 We/kg (multi-tube LiF). The Phase I results show that SAMTEC systems offer high specific power at a low cost. The SAMTEC system also provides low degradation, long lifetime, and access to all orbits (all of which will be discussed in detail later in this section).

9.2 SYSTEM COST

AMTEC solar powered systems offer a low cost alternative to PV power systems, $1,000/We for AMTEC compared to $5,000 - $10,000/We for PV, and the cost savings is inherent in the AMTEC system. The overall cost for PV systems is not driven by the individual PV cell cost, but rather the complexity of manufacturing the arrays (arrays are assemblies of modules, each comprised of a number of parallel strings which are, in turn, sets of series connected individual cells). In spite of this cost differential for GaAs cells, cost studies indicate that system costs are lowered by using the more expensive, but higher efficiency, GaAs cells.[4] This indicates that the cost of individual PV cells is not the driver of overall PV system cost, and that lowering cell cost will not substantially reduce the overall system cost. The high system cost for PV cells can be attributed to the sheer numbers required (300 - 400 for 500 We), the hand assembly (securing them to the structure with adhesive and soldering the connections) of each individual cell into strings, modules and arrays to

[4] Discussions with Mike Piszczor at LeRC indicate that space qualified silicon PV cells cost approximately $60/We, and GaAs cells are approximately $200-$300/We.

make a system, and the cost of qualifying each individual cell and its connections. The addition of a cover glass to reduce the radiation degradation, and the use of cascaded cells to enhance efficiency and reduce the number of cells required, also increases the mass and complexity; thus further increasing the major cost factor and the specific power.

By understanding why PV systems cost so much, it can be seen why the AMTEC system will cost significantly less. Given that the materials used to manufacture AMTEC cells are abundant and inexpensive, (stainless steel and alumina), and that the manufacturing process can be relatively simple (similar to vacuum or television tubes), the $100/We predicted for the production cost of individual AMTEC cells appears to be reasonably conservative. Even though AMTEC cells, at efficiencies equivalent to that of GaAs cells (19%), will cost 2 to 3 times less, this alone will not provide a significant system cost savings because the individual cell cost is not the key to lower system costs. Simply increasing the power/basic unit can reduce the assembly costs significantly. The higher power of current single-tube AMTEC, compared to PV cells, reduces the required number of cells from 300 to 400 - approximately 100. Even if equally complex manufacturing techniques are used, the system cost would be lower by a factor of 3 to 4. If the advanced multi-tube AMTEC cell designs are used, it would lower the module assembly cost by a factor of 12 to 15. AMTEC cells should also be easier to integrate into a system than PV cells. AMTEC cells can bolt into the system, with no adhesive as required for PV cells, and electrical connections that do not require the delicate soldering of PV arrays. Taking all of these effects into account, we estimate that a SAMTEC <u>system</u> (includes concentration, conversion, energy storage, and PMAD) should cost less than $1,000/We.

9.3 ENERGY STORAGE

The most massive component in current space power systems is the energy storage subsystem. The SAMTEC system has the ability to use either batteries or a Phase Change Material (PCM) to store the energy needed for eclipse periods. The PCM uses the latent heat of the solid/liquid phase change for storing the energy needed for eclipse periods. Figure 13 directly compares current stat-of-the-art and advanced battery technology with current state-of-the-art and advanced TES. The following assumptions were used for this comparison:

1.) 500 We, LEO 800 km, 28.5° inclination, 36 min. eclipse, 7 year life (40,000 cycles).

2.) State-of-the-art-battery, NiH_2 (Ref. 8) - 50 W hr/kg (180 J/g), 30% Depth of Discharge (DOD).

3.) Advanced battery, NaS (Ref. 9) - 150 W hr/kg (540 J/g), 40% DOD.

4.) State-of-the-art-AMTEC/TES (Ref. 10 and Ref. 11) - 20% cell efficiency/78 W hr/kg (280 J/g). The TES units are those now being fabricated, tested, and qualified under the SDGTD and the AMTEC cells are those currently under development at AMPS for Space and Terrestrial power.

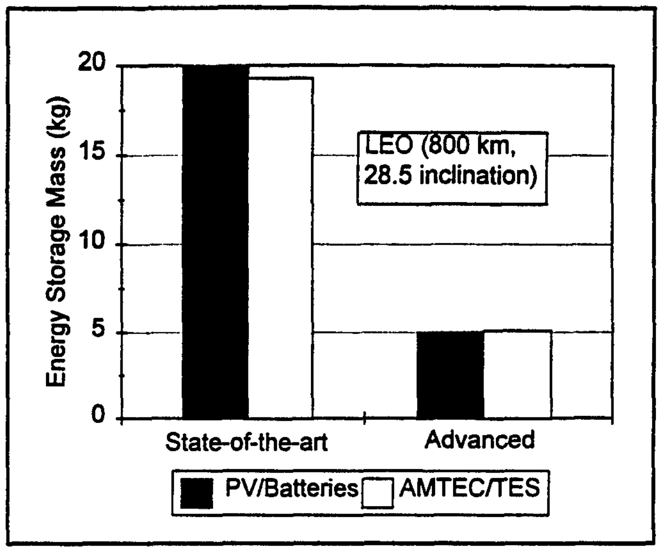

Figure 13: Energy Storage Mass Comparison

5.) Advanced AMTEC/TES - 38% cell efficiency/156 W hr/kg (560 J/g). The TES units are similar to the SDGTD but are assumed to be optimized for the SAMTEC geometry, and the cells are the advanced multi-tube cells currently under development at AMPS.

The results show that TES technology is competitive with battery technology (current and advanced technology). This means that the SAMTEC system is not dependent on a single technology to increase its specific performance because the SAMTEC system can use either batteries or TES. The TES eliminates the thermal cycling associated with the use of batteries during the eclipse period. The SAMTEC system can take advantage of the development of both of these energy storage technologies.

9.4 DEGRADATION

Loss of power over time is a substantial factor in sizing the Beginning of Life (BOL) power of a system that will meet the End of Life (EOL) mission requirements. For typical solar powered space power systems, the degradation over time, or EOL losses, can be categorized into four main time dependent types: 1) charged particle degradation of the active cell; 2) Ultra-Violet (UV) darkening of the adhesive used to hold the coverglass; 3) natural and man-made debris damage and 4) random losses through failure of cells, connections, circuits, etc. Table 10 shows the expected EOL losses as a percent of BOL power for PV and AMTEC power systems. The numbers used in this table for PV systems are typical of those used by solar array designers for a 5 year life in LEO (Refs. 1).

Table 10: System Degradation after 5 years in LEO

Degradation Mechanism	PV	SAMTEC
Ultra-violet	0.9850	1.0000
Man-made debris	0.9800	0.9800
Micrometeorite	0.9900	0.9900
Radiation	0.8800	1.0000
Random	0.9500	0.9500
Total (%)	79.9	92.2

UV will not affect the AMTEC/TES units, space testing of the Fresnel concentrator is underway with preliminary results showing no degradation, and reflective concentrators would not be affected by UV. Radiation is also not an issue for either the AMTEC/TES units or the reflective concentrator and may not be an issue for the Fresnel concentrator (testing is underway). Micrometeorite and small man-made debris should not damage AMTEC/TES units because they are contained inside a metallic canister which is contained inside another metallic cavity. In order to damage the cells, incoming debris would have to penetrate a metal canister, travel a distance and then penetrate another metal canister. Degradation rates for the refractive or reflective concentrator should be similar to that for the PV array due to micrometeorite and man-made debris. Finally, AMTEC cells have not yet been shown to degrade over time (two cells have been in operation for almost 11,000 hours with no apparent degradation in performance). Random cell failures due to manufacturing errors and quality control should be comparable to that of PV cells. Using this information, the degradation of SAMTEC can be compared to that of PV systems. The SAMTEC should retain 92% of its power level over a 5 year life. This low degradation allows selection of a small power system resulting in low direct and indirect costs, and/or may increase the life of the satellite by increasing the amount of propellant that can be carried.

9.5 ORBITS, HEAT SOURCES

The radiation degradation of PV cells constrains the possible orbits, primarily to LEO and Geosynchronous (GEO). PV cells degrade, due to radiation damage, at such a rate that operation in middle Earth orbits, which encounter the Van Allen radiation belts, is very difficult. The use of a thick cover glass and/or concentration will reduce the degradation rate but will increase both the mass and cost. The SAMTEC system is not predicted to be affected by such radiation and thus offers access to middle orbits (shielding of the Power Processing & Control may be necessary). The ability to operate in middle orbits would produce a substantial cost savings for global communications by reducing the number of satellites required for Earth coverage. Figure 14 shows the estimated relationship between orbit and number of satellites required for Earth coverage. The Iridium constellation of satellites for global communications is planned to consist of approximately 66 satellites in LEO, while the Comsat constellation consists of approximately 6 higher power satellites in GEO (Ref. 12). Increasing the orbit of the Iridium constellation, from 500 km to 3000 km, would decrease the number of satellites

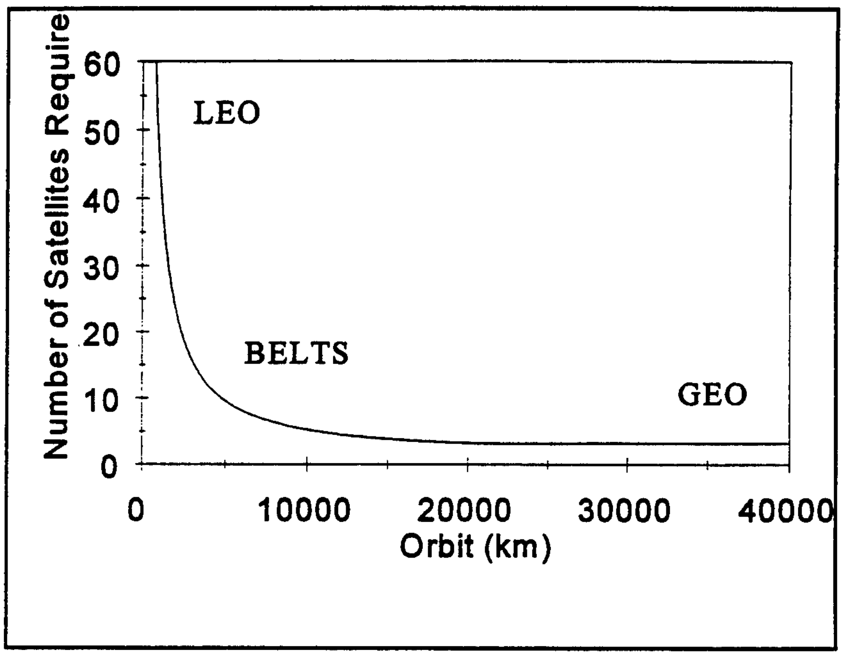

Figure 14: Effect of Orbit on Number of Satellites Required for Earth Coverage

required for full coverage to approximately 16 satellites, 4 times lower. The cost of the satellites in the higher orbit would be higher due to increased power requirements, complexity, etc. However, even if the cost of the higher orbit satellites were twice that of the LEO units, the cost savings for the constellation would still be approximately 50%, a significant net savings considering the cost of a satellite constellation.

The total market volume and the cost reduction available from high volume production of space and terrestrial PV systems is limited by the single, unreliable (insolation on the Earth is unreliable) heat source required to operate the cells. AMTEC systems can operate with any heat source of sufficient temperature (solar, combustion, nuclear, etc) which greatly increases the number of potential commercial markets and makes AMTEC more cost effective (since costs are reduced for all applications). Remote sites typically use combustion heated thermoelectric generators with an overall system efficiency of approximately 2-5%. PV systems are also used for some remote site power sites and offer substantial gains in efficiency over thermoelectric generators but cannot operate during bad weather and at night, or require a supplemental fuel-fired generator system or batteries. An AMTEC system could offer the best features of both systems by providing a single system with efficiency comparable to, or better than, PV systems and the capability of operating independently of the solar insolation with a single converter. According to Lamp and Donovan (Ref. 14), by doubling the efficiency of the converter in a propane-fired generator the United States Air Force (USAF) would save approximately $3 million per year for just two remote sites. Considering the total number of such sites operated by the USAF, the total savings could be in the hundreds of millions of dollars per year. Current AMTEC cells, 18% efficiency, more than double the efficiency of the thermoelectric units presently used in propane-fired generators (Ref. 11).

9.6 LIFETIME/RELIABILITY

The SAMTEC power system is expected to have a long life and high degree of reliability. The AMTEC system uses a PCM, with an anticipated life of 10 years, for TES during eclipse periods (but could use batteries). The selected TES modules are being developed under the SDGTD at

NASA LeRC and test specimens comprised of 24 TES canisters have been successfully tested in vacuum. There are four lifetime issues associated with the TES system; 1) cyclic stress due to the phase change (expansion and contraction); 2) rupture of the canister due to void formation and ratcheting; 3) corrosion of the canister due to exposure to the PCM, and 4) canister material loss due to operation at high temperature in a vacuum. The test specimens were successfully run for approximately 1500 hr (1000 freeze/thaw cycles) at temperature (767°C) in a vacuum to demonstrate the resistance to cyclic stress (Ref. 10). There were two separate heater locations used during this test to simulate the extreme melt orientations of the receiver, and test the resistance and effect of void formation on the TES. The canisters are designed with rounded edges to eliminate areas of stress concentration where ratcheting could cause failure. Test results have also shown that corrosion between the PCM and canister is not a life limiting issue and does not result in a degradation mode. These studies included the compatibility of three materials (HA 188, HA 230, and IN 617) with the LiF-22%CaF_2 in air at 1073 K for up to 22,000 hours and in vacuum for up to 10,000 hours (Ref. 13). The TES is projected to have a very high reliability, long lifetime, and no long term degradation mode is anticipated.

There are no identified degradation mechanisms for the AMTEC cells, and two AMTEC cells, currently being life tested at AMPS in air, have operated for approximately 11,000 hours with no apparent degradation in performance. Consequently, the AMTEC cells are also expected to have a very high reliability and long lifetime and no long term degradation is expected.

The reflective and refractive concentrators are expected to degrade with time due to the space environment. This degradation will be in the form of damage to the reflective or refractive surfaces with a reduction in the efficiency of the concentrator. The amount of degradation will be small, approximately a 5% drop in performance over a 10 year lifetime.

The reliability and lifetime for the remainder of the system (structure, PP&C, and deployment) are expected to be similar to that of a PV system. SAMTEC could have a finer pointing requirement (pointing accuracy better than ± 1° if a secondary concentrator is not used) than PV systems but this is well within the current state-of-the-art. A secondary concentrator could also be used to "loosen" the pointing requirements to approximately $\pm 5^{\circ}$ if necessary. The smaller planform area of the SAMTEC system will also lower the aerodynamic drag in LEO thus reducing propellant consumption and increasing satellite lifetime in orbit if propellant consumption and/or station keeping are the limiting mechanisms.

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11.0 NOMENCLATURE

AMPS	Advanced Modular Power Systems, Inc.
AMTEC	Alkali Metal Thermal to Electric Conversion
AO	Atomic Oxygen
BOL	Beginning of Life
DOD	Depth of Discharge
EOL	End of Life
GaAs	Gallium Arsenide PV cells
GEO	Geosynchronous orbit
GPS	Global Positioning Satellite
InSTEP	In Space Technology Experiment Program
LEO	Low Earth Orbit
LeRC	NASA Lewis Research Center
MEO	Middle Earth Orbit
MLI	Multi-Layer Insulation
NaS	Sodium Sulfur
NASA	National Aeronautics and Space Administration
NiCd	Nickel-Cadmium battery
NiH_2	Nickel-Hydrogen battery
PCM	Phase Change Material
PMAD	Power Management and Distribution
PP&C	Power Processing and Control
PV	PhotoVoltaic cells
SAMTEC	Solar AMTEC
SBIR	Small Business Innovative Research
SDGTD	Solar Dynamic Ground Test Demonstration
Si	Silicon PV cells
TES	Thermal Energy Storage

USAF	United States Air Force
UV	Ultra-Violet ray
We	Watt Electric

A0. APPENDIX A: SOLAR AMTEC REQUIREMENTS DOCUMENT

Version 1.3

12 June 1994

1 Power Generation

1.1 Net power to payload: 500 watts (system) at end of life

1.2 Steady state voltage: 28 ± 6 V DC at payload

1.3 Transient voltage: not to exceed ± 28 V with .003 V/s (Mil Std 1539)

1.4 Operational constraints
- 1.4.1 Assume an 800 km, 28.5° inclination, circular operational orbit
- 1.4.2 Assess the impact of a 90 minute shadow period (GEO)
- 1.4.3 Assess the impact of a 2000 km, 90° inclination, circular operational orbit
- 1.4.4 The power system shall not shall not prevent S/C from meeting operational requirements..
- 1.4.5 The power system shall provide continuous power to the satellite.

1.5 Off-normal operations
- 1.5.1 The power system shall be capable of operating for a minimum of two consecutive eclipse periods without solar energy input, while providing 50 watts to the bus.

1.6 Follow the guidelines from Mil Std 1539

2 Mass

2.1 System mass shall not exceed 50 kg for a 500 watt module
- 2.1.1 System mass shall include: solar collector, receiver, phase change material, conversion, wiring, instrumentation, control computer, power management equipment, pointing and tracking equipment, an emergency start/restart battery, and support structure.

2.2 The system mass goal shall be 25 kg.

3 Reliability

3.1 The reliability shall be shown by analysis to be ≥ .95 for the power system.

3.2 The reliability goal shall be $\geq .98$ for the power system.

4 Lifetime

4.1 The design lifetime requirement shall be 5 years in LEO of 10 years in GEO.

4.2 The design lifetime goal shall be 10 years in LEO of 15 years in GEO.

5 Cost

5.1 The estimated system production cost goal shall be < $1000/watt (electric) for the Nth unit of an N unit production run.

5.2 The project goal shall be to minimize life cycle cost of the power system.

6 Satellite Integration (items for evaluation) (use GPS satellite as "typical")

6.1 sensor field of view

6.2 electronics cooling radiators

6.3 structural dynamics (ringdown, thermal transients)

6.4 telemetry/control requirements

6.5 leakage currents/allowable spacecraft charging

6.6 diagnostics/health monitoring

7 Testing

7.1 Qualification testing

7.1.1 The system and its components, subassemblies, and assemblies shall be testable for qualification per Mil Std 1540.

7.1.2 Evaluate the cost impact of class B vs class C approach from Mil Hdbk 343

7.2 Acceptance testing

7.2.1 The system and its components, subassemblies, and assemblies shall be testable for acceptance per Mil Std 1540.

7.2.2 The system shall be testable for acceptance when mated with the satellite.

7.2.3 The system shall be capable of functional testing while mated with the satellite and/or launch vehicle.

8 Launch Segment

8.1 Shock and vibration

8.2 Launch vehicle integration
8.2.1 Stowed volume and configuration
8.2.2 Mating points

8.3 Launch operations
8.3.1 Hold on pad

9 Ground Handling

9.1 Transportation

9.2 Storage

9.3 Physical handling

10 Safety

10.1 Hazardous material containment

10.2 Flammable material containment

10.3 Personnel hazards
10.3.1 Thermal
10.3.2 Electrical

11 Physical Configuration

11.1 Stowed configuration
11.1.1 compatible with MLV
11.1.2 compatible with Pegasus/Taurus

11.2 Deployed Configuration

B.0 APPENDIX B: SAMTEC COMPUTER CODE LISTING

VARIABLE SHEET

St	Input	Name	Output	Unit	Comment
					500 Watt Solar System
		Sp	13.818	W/kg	Specific Power
		Nsef	0.202		Net System Efficiency
	8.000	Nsides			Number of Sides in the Receiver
	4.000	Ncps			Number of Cells per Side
		Eap	0.996		Efficiency of Aperature
	0.900	Emir			Efficiency of Mirror
		Cr	5828.143		Concentration Ratio
					Orbit Times
	100.000	to		min	Orbit Period
		ti	64.000	min	Insolation Period
	36.000	te		min	eclipse period
		Ptot	728.000	W	System Output Power Desired
	0.244	esys			AMTEC cell efficiency
		Ncells	32.000		Number of AMTEC cells
					Temperatures
	765.000	Trec		C	Inside of the Receiver (765 LiF-CaF, 850 LiF)
		Trad	296.679	C	Radiator
	30.000	Tsat		C	Satllite
	27.000	Tspace		C	Space
					Heat Balance
		Qint	5626.131	W	Intercepted by System
		Qmir	5418.151	W	Incident on Mirror
		Qfp	4876.336	W	To Focal Plane
		Qrec	4858.891	W	Into Receiver
		Qabs	4732.807	W	Absorbed by PCM canisters
		Qamtec	2983.607	W	Into AMTEC cells
					System Losses
		Qbloc	207.980	W	Blocked by Receiver
		Qref	541.815	W	Reflected from Mirror
		Qspill	17.445	W	Incident on Aperature Shield
		Qrl	126.084	W	Total Thermal Losses out Receiver
		Qpcm	1749.201	W	Into PCM
		Qwaste	2255.607	W	Waste Heat from AMTEC Cells
		Qoh	47.695	W	Radiated out Aperature
		Qths	78.388	W	Radiated through Housing
		Qrej	2333.995	W	Rejected to Space
					Heat Trasnferred from Receiver to
		Q12	931.700	W	Satellite

	Q13	1402.295	W	Space
	Irec	258.089	W/m^2	Flux supplied to the Satellite from the Receiver
				System Masses
	Miei	0.129	kg	Inside Electrical Insulator
	Moei	0.124	kg	Outside Electrical Insulator
	Mqc	0.260	kg	Quartz Cloth
	Mic	0.568	kg	Inner Cell Holder
	Moc	1.142	kg	Outer Walls
	Mrec	1.710	kg	Receiver, Total
	Mpcm	8.242	kg	Phase Change Material (PCM)
	Mpcmc	4.074	kg	PCM canister
	Mtes	12.316	kg	Thermal Energy Storage (TES)
	Mhs	1.305	kg	Heat Shields
	Mcells	4.416	kg	AMTEC cells
0.000	Mfin		kg	Radiator Fins
	Mcon	3.615	kg	Concentrator
	Mas	0.811	kg	Aperature Shield
3.000	Mgd		kg	Gimbals and Drives
3.000	Mstr		kg	Structure
22.000	Mppc		kg	Power Processing and Control
	Mconv	30.686	kg	Converter
	Mtot	52.686	kg	Total
				Thermal Energy Storage
815.000	dHpcm		kJ/kg	Heat of Fusion (815 LiF-CaF, 1087 LiF)
1.940	Dtesod		in	canister O.D.
0.040	ttes		in	canister thickness
0.200	Cbtesc		in	Clearance between TES canisters
	Htes	2.532	in	canister Height
	Estor	6716.931	kJ	Stored Energy
				Concentrator
50.000	Rang			Rim Angle
	Dconc	91.611	in	O.D.
	Hconc	19.218	in	Height
	Focall	27.294	in	Focal Length
	Dgauss	0.254	in	Diameter of Image at Focal Plane
	Z	2.903		Function describing the distribution of Light at Focal Plane
	Fz	129.039		Sum of the function for the integral
				Receiver
1.200	Dhole		in	Aperature Hole Diameter
0.040	trec		in	Wall Thickness
20.000	Nahs			Number of Aperature Heat Shields

0.001	tas		in	Aperature Heat Shield Thickness
	Lioc	8.535	in	Radius of Inner Wall
	Looc	8.575	in	Radius of Outer Wall
	bioc	7.071	in	Length of Flat, Inner Wall
	booc	7.104	in	Length of Flat, Outer Wall
	Hrec	8.560	in	Height
	Dcav	5.166	in	Cavity Inner Diameter
				Inner Cell Holder
0.020	tic		in	Wall Thickness
	Liic	5.135	in	Radius of Inner Wall
	Loic	5.155	in	Radius of Outer Wall
	biic	4.254	in	Length of Flat, Inner Wall
	boic	4.271	in	Length of Flat, Outer Wall
	Hih	8.360	in	Height
				Heat Shields
40.000	Nhs			Number of Layers of Insulation
0.001	Ths		in	Thickness of Heat Shields
0.100	Tahs		in	Total Thickness of Axial Shields
	Dbhs	0.084	in	Distance between Heat Shields
				Quartz Cloth insulation
0.020	Tqc		in	Thickness
	Dqc	1.980	in	O.D.
				Electrical Insulators
0.020	toei		in	Thickness of Outside Electrical Insulator
0.020	tiei		in	Thickness of Inside Electrical Insulator
				Fins
8.000	Nfin			Number of
	Lfin		in	Length
0.200	tfin		in	Thickness
				Areas
	Ahole	7.297	cm^2	Aperature
	Aprec	243.666	in^2	Receiver, Projected
	Arec	4710.565	cm^2	Receiver
	Ahs	3452.492	cm^2	Heat Shields
0.000	Afin		cm^2	Fins
	Arad	0.471	m^2	Radiator
	Apc	4.253	m^2	Concentrator, Projected
3.610	Asat		m^2	Area of one side of the Satellite
				AMTEC Cells
1.940	Dcell		in	O.D.
3.360	Hcell		in	Height

138.000	Mcell		g	Mass of One
22.750	Pcell		W	Power Required by One
				Material Densities
4.000	rhoiei		g/cm^3	inside Electrical Insulator (Alumina 4 g/cm^3)
4.000	rhooei		g/cm^3	Outside Electrical Insulator (Alumina 4 g/cm^3)
1.200	rhoqz		g/cm^3	Quartz Cloth (Quartz is 2.2 g/cm^3)
10.200	rhohs		g/cm^3	Heat Shields (Moly 10.2 g/cm^3)
1.800	rhorec		g/cm^3	Receiver (Aluminum 2.7 g/cm^3)
9.100	rhotes		g/cm^3	TES (Haynes 9.1 g/cm^3)
2.100	rhopcm		g/cm^3	PCM (LiF CaF is 2.1 g/cm^3, LiF is 1.83 g/cm^3)
1.800	rhofin		g/cm^3	Fins (Carbon-Carbon 1.8 g/cm^3)
0.850	rhocon		kg/m^2	concentrator (FRESNEL 0.85)
				Emissivities
0.900	ϵrad			Radiator
				View Factors
0.400	F12			Receiver to Satellite
0.600	F13			Receiver to Space
				CONSTANTS
1323.000	Sc		W/m^2	Solar Flux Constant
5.670E-8	σ		W/m^2/K	S-B constant
96500.000	F		C/mole	Faraday
0.023	M		kg/mole	Na molecular weight
8.312	R		J/mole/K	Gas constant
	π	3.142		

```
=================== RULE SHEET ========================
S Rule-----------------------------------------------------------
  Ncells=Ptot/Pcell
  ti=to-te
  Pcell = Ptot/(Nsides*Ncps)
  Nhs*(Dbhs+Ths)=Lioc-Loic
   ;Dimensions
  Focall=Dconc/4*TAND(Rang)
  Hconc = (Dconc/2)^2/(4*Focall)
   ;The 0.0093 is the angle the sun appears to the concentrator approximatley 0.5328 degrees
  Dgauss = Focall*0.0093
   ;This is from a computer program at Rocketdyne
  Z = (Dhole/Dgauss)/1.62825
  call Spill(Z/100;Fz)
  Eap = Z/100/3*Fz*(2/π)^0.5
  Dqc = Dcell+2*Tqc
  Hrec = Ncps*Dtesod+(Ncps-1)*Cbtesc+2*Tahs
  Hih = Hrec-2*Tahs
  Nsides*(Dtesod+Cbtesc)=Nsides*Dcav*TAN(π/Nsides)
  Liic = Dcav/2+Htes+tiei
  biic = 2*Liic*TAN(π/Nsides)
  Loic = Liic+tic
  boic = 2*Loic*TAN(π/Nsides)
  Lioc = Loic+Hcell+toei
  bioc = 2*Lioc*TAN(π/Nsides)
  Looc = Lioc+trec
  booc = 2*Looc*TAN(π/Nsides)
  Aprec = 1/4*Nsides*booc^2*COS(π/Nsides)/SIN(π/Nsides)
  Arec = Nsides*booc*Hrec+1/4*Nsides*booc^2*COS(π/Nsides)/SIN(π/Nsides)
C Afin = 2*Nfin*Lfin*Hrec
  Arad = Arec+Afin
  Apc = π/4*Dconc^2
  Ahs = (Nsides*bioc*Hrec+Nsides*boic*Hrec)/2+(1/4*Nsides*bioc^2*COS(π/Nsides)/SIN(π/Nsides))-Ncells*π/4*Dcell^2
  Ahole = π/4*Dhole^2
   ;Thermal Energy Storage
  Estor = te*(Ptot+Qwaste+Qrl)
  Estor = Mpcm*dHpcm
   ;Heat Losses
  Qint = Sc*Apc
  Qbloc = Sc*Aprec
  Qmir = Qfp/Emir
```

```
Qfp = Qrec/Eap
Qspill = Qfp*(1-Eap)
Qpcm = Estor/ti
Qwaste = (Ptot/esys)-Ptot
Qrej = (Ptot/esys)-Ptot+Qths
Qrej = Q12+Q13
Qths = Ahs*1.06e-8*(Trec^4-Trad^4)/(0.788*Nhs+1.11e-2*Nhs^2)
Qoh = σ*Ahole*(Trec^4-Tspace^4)
Q12=Qbb(εrad,Arad,F12,Trad,Tsat)
Q13=Qbb(εrad,Arad,F13,Trad,Tspace)
Irec = (Q12/Asat)
 ;Heat Balance
Qint = Qmir+Qbloc
Qmir = Qref+Qfp
Qfp = Qspill+Qrec
Qrec = Qabs+Qrl
Qabs = Qpcm+Qamtec
Qamtec = Qwaste+Ptot
Qrl = Qths+Qoh
 ;Mass
Miei = Ncells*rhoiei*((π/4*Dtesod^2)*tiei+(π/4*((Dcell+2*tiei)^2-Dcell^2)*tic))
Moei = Ncells*rhooei*(π/4*Dcell^2)*toei
Mqc = Ncells*rhoqz*(π/4*(Dqc^2-Dcell^2)*Hcell)
Mhs = rhohs*(Ths/(Ths+Dbhs))*((1/4*Nsides*COS(π/Nsides)/SIN(π/Nsides)*(bioc^2-boic^2))*Hrec+2*(1/4*Nsides*biic^2*COS(
Mic = rhotes*((1/4*Nsides*COS(π/Nsides)/SIN(π/Nsides)*(boic^2-biic^2))*Hih-(Ncells*π/4*Dcell^2*tic))
Moc = rhorec*((1/4*Nsides*COS(π/Nsides)/SIN(π/Nsides)*(booc^2-bioc^2))*Hrec+2*(1/4*Nsides*bioc^2*COS(π/Nsides)/SIN(π/
Mrec = Mic+Moc
Mpcmc = Ncells*rhotes*π*(Dtesod*Htes+2*Dtesod^2/4)*ttes
Mpcm = rhopcm*Htes*Ncells*π*Dtesod^2/4
Mcells = Ncells*Mcell
Mtes = Mpcmc+Mpcm
C Mfin = Nfin*Hrec*Lfin*tfin*rhofin
Mcon = Apc*rhocon
Mas = rhohs*Nahs*((1/4*Nsides*booc^2*COS(π/Nsides)/SIN(π/Nsides))-Ahole)*tas
Mconv = Mtes+Mcells+Mrec+Mcon+Mhs+Mqc+Miei+Moei+Mas+Mgd+Mstr+Mfin
Mtot =  Mtes+Mcells+Mrec+Mcon+Mhs+Mqc+Miei+Moei+Mas+Mgd+Mstr+Mfin+Mppc
Sp = Ptot/Mtot
Nsef = (Ptot*to)/(Qint*ti)
Cr=Apc/Ahole
π=pi()
```

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