Solar Cell and Array Technology for Future Space Missions

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Written by Team Members

Rao Surampudi	NASA-JPL – Chairman
Tom Hamilton	NASA-JPL – Coordinator
Donald Rapp	NASA-JPL
Paul Stella	NASA-JPL
Nick Mardesich	NASA-JPL
Jack Mondt	NASA-JPL
Bill Nesmith	NASA-JPL
Robert L. Bunker	NASA-JPL
James Cutts	NASA-JPL
Sheila G. Bailey	NASA-GRC
Henry B. Curtis	NASA-GRC
Mike Piszczor	NASA-GRC
Ed Gaddy	NASA-GSFC
Dean Marvin	Aerospace Corp.
Larry Kazmerzki	DOE-NREL

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December 2001

Foreword

NASA's Office of Space Science (OSS) requested JPL to lead a team to delineate the power requirements for potential NASA space science missions and assess the capability of the present solar cell and array technologies to meet these requirements. Based on the potential NASA mission set, the team was asked to recommend investment strategies and technology roadmaps necessary to develop advanced solar cell and array technologies that would meet these requirements.

JPL assembled an assessment team of NASA, DOE and AFRL engineers to assess the state-of–the-art of space solar cell/array technology and compare this with projected requirements for potential NASA OSS missions. The assessment ream recommended a number solar cell /array technology tasks needed to advance these technologies from NASA Technology Readiness Level 3 (TRL 3) to NASA TRL 6 to meet the potential NASA OSS space science missions requirements. This work was completed in mid-2001.

The recommended tasks were 1) high-power, low-mass arrays for solar electric propulsion (SEP) for comet, asteroid, and outer and inner planet missions, 2) electrostatically clean arrays for sensitive Earth orbit missions, 3) solar cells and arrays for Mars for dusty environment missions, 4) high temperature arrays for near-sun missions, 5) high efficiency cells for all missions, 6) LILT arrays for outer planet missions and 7) radiation resistant cells for Jupiter missions. These tasks are listed in Executive Summary Table ES-1.

The costs provided in this report for implementing various technology programs are very rough estimates to give NASA guidance as to expected orders of magnitude. They should not be taken literally as actual costs to implement a technology program.

The mission set used in this report was the one prevailing in early calendar 2001. it is likely that significant changes may results from an ongoing study by the National Research Council which is expected to release its report in the summer of 2002.

Since this report was drafted, NASA has announced its intention to implement a new nuclear technology initiative. In view of this, it is likely that missions to Jupiter and Europa, and beyond, will be nuclear-powered. However, some proposals for solar-powered missions to the Jupiter system were quite competitive. If the nuclear power initiative is funded, the priority for technology development of solar cells and arrays that can function in the very strong radiation/LILT environments of Jupiter and Europa will have to be reduced significantly. Similarly major missions to Mars (Smart Lander and Sample Return) may use nuclear power if it is affordable, although Scout missions and short duration missions will likely still rely on solar power. Arrays that can perform under LILT conditions may still be needed if solar electric propulsion systems are needed to thrust as far out as ~ 5 AU.

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Part I - Executive Summary

Recommendation

The Assessment Team recommends a number of solar cell and array technologies that need to be advanced from NASA Technology Readiness Level 3 (TRL 3) to NASA TRL 6 to meet the needs of potential future NASA OSS space science missions. The recommended advanced solar cell/array technologies involve applications and space environments that are not encountered in commercial near-Earth space applications and require NASA support to be developed.

The recommended tasks are 1) high power low mass arrays for solar electric propulsion, 2) electrostatically clean arrays, 3) Mars arrays for dusty environments, 4) high temperature arrays, 5) high efficiency cells, 6) LILT arrays and 7) radiation resistance cells, as shown in Table ES-1. The tasks are prioritized as listed in the table.

The estimated funding required for the recommended tasks is summarized in Table ES-2. In addition, NASA needs to maintain its infrastructure for testing and modeling cells and arrays.

Table ES-1: Recommended Technology Tasks to Meet NASA Potential Future Science Missions

Advanced Technology	Driving Missions	Requirements	State of the Art	Needed Technology
1) High Power Arrays for SEP	CNSR, outer planet missions, VSSR, MSR	• >150 W/kg specific power • Operate to 5 AU	• 50-100 W/kg • Unknown LILT effect	• High efficiency thin-film cells • High-power, low -mass arrays
2) Electrostatically Clean Arrays	SEC missions: MMS, MC GEC, SP, Sentinels	• < 120% of the cost of a conventional array	•~300% of the cost of a conventional array	• Transparent plastic covers • Glass covers for multiple cells
3) Mars Arrays(*)	MSL, MSR, Scouts	• 26% efficiency • >180 sols @ 90% of full power	• 24% efficiency • 90 sols @ 80% of full power	• Optimized cells for Mars • Dust mitigation
4) High Temperature Solar Arrays	Solar Probe, Sentinels, PASO	•350°C operation (higher temperatures reduce risk and enhance missions)	• 130°C steady state; 260°C for short periods	• Adapt cells and arrays to high temperatures based on AFRL technology
5) High Efficiency Cells	All missions	•> 30+ %	• 27%	• Adapt AFRL and commercial progress to NASA needs
6) LILT Resistant Arrays(#)	Outer planet missions, SEP missions	•No insidious reduction of power under LILT conditions	• Uncertain behavior of MJ cells under LILT conditions	• Adapt cells/arrays to avoid LILT problems • Test cells at LILT conditions
7) High Radiation Missions(#)	Europa and Jupiter missions	• Radiation resistance (> 10^{15} 1 MeV electrons/cm^2) with minimal weight and risk penalty	• Thick cover glass • Significant mass penalties	• Radiation resistant thin film and concentrator arrays • Adapt commercial and military cells to meet radiation requirements

(*) The MSL and MSR missions may turn out to be powered by new RTGs developed under the proposed nuclear technology initiative, in which case, solar power would only be used by Scout and other short duration missions. This will depend on how affordable the RTGs turn out to be.

(#) Outer planet missions are likely to be powered by new RTGs developed under the proposed nuclear technology initiative, in which case the need for LILT technology would only be for SEP if thrusting is required out to 3-5 AU. Resistance to the radiation environment in the Jupiter system may not be required if these missions are powered by RTGs.

Table ES-2: Rough Estimates of Funding Required for Each Task

Technology Program	FY03	FY04	FY05	FY06	FY07
High Power Arrays for SEP	$0.8 M	$2 M	$2 M	$2 M	$2 M
Electrostatically Clean Arrays	$0.5 M	$0.5 M	$0.3 M		
Mars Surface Solar Arrays	$1.2 M	$3.0 M	$3.5 M	$1.0 M	
High Temperature Solar Arrays	$1.3 M	$1.8 M	$1.2 M	$0.7 M	
LILT Resistant Cells/Arrays	$0.5 M	$0.9 M	$0.9 M	$0.6 M	
High Radiation Cells/Arrays	$0.9 M	$0.6 M	$0.7 M	$0.5 M	$0.2 M
High Efficiency Cells	$0.5 M	$1.5 M	$2 M	$2 M	$1 M

ES-1. Introduction

NASA's Office of Space Science requested JPL to lead an assessment of advanced power source and energy storage technologies that will enable future (beyond 2007) NASA Space Science missions, and prepare technology road maps and investment strategies. In the first phase of this work, an assessment of Advanced Radioisotope Power System (ARPS) technology was conducted. The *Advanced Radioisotope Power System Report,* JPL D-20757, was published June 2001. Solar Cell and Array Technology is the subject of the present report.

Solar array technology has made tremendous advances in the last two decades starting from the rather humble 10% efficient single crystal silicon solar cell. Cell efficiencies have increased by a factor of 2.5, and the specific power (W/kg) at the array level has increased by a factor of about 5. Many NASA spacecraft have already benefited from these improvements. However, some future NASA OSS missions require power systems that must perform in harsh environments such as:

- Large dynamic range of solar intensity (e.g., Solar Probe)
- High intensity/high temperatures (Mercury and solar missions)
- Low-intensity/low-temperature (solar missions beyond Mars) (However, these missions may end up being powered by RTGs.)
- Very high power for solar electric propulsion
- High radiation fields (Europa, Jupiter) (However, these missions may end up being powered by RTGs.)
- Electrostatically clean arrays for fine magnetic measurements
- Solar power in dusty environments (surface of Mars) 9However, the long-life missions may end up being powered by RTGs.)

ES-2. Study Overview and Description

Objectives

The purpose of the study is to assess the potential of solar cell and array technologies to enable and provide the most cost-effective power generation for NASA Space Science missions launched in the 2007 to 2020 time period, and to define a roadmap for developing the needed technologies. The specific objectives of the proposed study are:

- Review NASA Code-S future mission needs for solar cell/array technologies.
- Assess the status of solar cell/array technologies used in space missions.

- Assess the potential of advanced solar cell/array technologies to meet future mission needs.
- Conduct cost/benefit trade studies to select solar cell/array technology investments.
- Recommend appropriate investment strategies for developing advanced solar cell/array technologies to meet future mission needs.

Approach

The study began with selection of a technical assessment team of knowledgeable photovoltaics (PV) power experts and power system engineers. The Team conducted four multi-day meetings to collect data inputs during March-May of 2001. The first meeting was held at JPL, the second was held at NASA-GSFC, the third meeting was at GRC, and a fourth meeting was held at JPL in May, 2001. The data were analyzed and processed at JPL. The final report was prepared as a draft on November 26, 2001 for review by a wide range of stakeholders, and was revised to final form on December 31, 2001. The results are documented in this report.

ES-3. State of the Art Space Power Solar Cells and Arrays

At the start of the space age, solar arrays produced about 15W/kg and the cells were about 10% efficient. Power output ranged from a few watts to a few tens of watts, although it quickly grew to hundreds of watts. At present, arrays produce 70W/kg, and the cells are ~27% efficient. Power ranges from tens of watts for very small spacecraft, to tens of kilowatts for commercial spacecraft to 200kW for the International Space Station. A summary of the status of existing solar cell and array technologies is given next.

High Efficiency Solar Cells

Single-crystal silicon solar cells have been used for electrical power on almost all space satellites since 1958. Their scalability, reliability, and predictability have made solar cell/arrays the prime choice for spacecraft designers. Early silicon solar cells were typically ~11% efficient, and the conversion efficiency of silicon cells currently flown varies between 12.7% and 14.8%. Advanced solar cells with improved efficiency developed over the past fifteen years include 1) single junction GaAs solar cells, 2) dual junction III-V compound semiconductor solar cells utilizing atoms from the 3rd and 5th columns of the periodic table, and 3) triple-junction III-V compound semiconductor solar cells. GaAs/Ge cells currently available on the market have an average conversion efficiency of 19% at AM0. The GaAs-type solar cells have higher radiation resistance than silicon solar cells. Dual-junction and triple-junction solar cells are presently available from several U. S. vendors. Commercially available dual-junction solar cells are 21-22% efficient. Currently, triple-junction cells consisting of GaInP, GaAs, and Ge layers, are grown in series-connected layers, and are 27% efficient in production lots. A summary of important characteristics of solar cells used in space is given in Table ES-3.

Solar Arrays

Solar array designs have undergone a steady evolution from the first array launched on the Vanguard 1 satellite. Early satellites used silicon solar cells mounted on the honeycomb panels of the spacecraft body. This type of solar array can only produce a few hundred watts of power. However, many modern satellites require low-mass solar arrays that produce several kilowatts of power. Several new solar array structures have been developed over the past forty years to improve the array specific power and reduce the stowed volume during launch. The solar arrays presently in use can be classified into the following six categories:

- Body-mounted Arrays: Early spherical satellites and spin-stabilized cylindrical satellites used silicon solar cells mounted on the honeycomb panels of the spacecraft body. This type of array is simple and past applications had no major problems with reliability. Body-mounted arrays are still used on short duration planetary rover missions.
- Rigid Panel Planar Arrays: State-of-art rigid panel commercial arrays have a specific power of 40-60 W/kg. These types of arrays are being used in many Earth-orbiting spacecraft.

- Flexible Panel Array: Flexible fold-out arrays are attractive for missions that require several kilowatts of power because of their high specific power and high packaging efficiency (low stowed volume). They are available presently in two configurations: 1) Flexible flat panel/rectangular array with linear deployment 2) Flexible round panel array with circular deployment. The round panel flexible array developed for the Mars '01 lander mission has a specific power of up to 100 W/kg.
- Flexible Roll-out Arrays The flexible roll-out array is similar to the accordion-folded array mentioned earlier except that the semi-flexible or flexible substrate is rolled into a cylinder for launch. The Hubble Space Telescope originally used such a roll-out array.
- Concentrator Arrays: Concentrator arrays use either refractive or reflective optics to direct concentrated sunlight onto a smaller active area of solar cells. The SCARLET array used on DS-1 uses a refractive concentrator scheme (linear distributed focus) with a 7.5X concentration ratio and has a specific power of 70 W/kg BOL. The technical challenges involved in using concentrating arrays are: precision pointing, thermal dissipation, non-uniform illumination, optical contamination, environmental interactions, and complexity of deployment.
- High Temperature/intensity Arrays The SOA high temperature arrays required for inner planetary missions employ modified rigid panel arrays with some Si cells replaced by mirrors to cool the array and off pointing the arrays from the Sun. At least two missions have already flown and functioned well at high intensities: Helios A, which reached 0.31 AU; and Helios B, which reached 0.29 AU. Both of these spacecraft used silicon cells that were slightly modified for high intensity use in conjunction with second surface mirrors to cool the array. These devices produced useful power only up to temperatures of ~200°C due to their unfavorable temperature coefficients. The SOA high temperature solar arrays are not mass-efficient and cannot operate at temperatures greater than 200°C for long periods.
- Electrostatically Clean Arrays Electrostatically clean arrays do not allow the array voltage to distort the plasma, and additionally, the entire exterior surface of such an array is maintained at approximately the same potential as the spacecraft structure. For an electrostatically clean array, the solar cell covers are coated with a conductor, typically, indium tin oxide, and the spaces between the cells are also covered with a conductor. Such arrays are being presently used in many of the Sun-Earth connection (SEC) missions.

A summary of the characteristics of some of the above arrays with is given Table ES-3.

Table ES-3: Summary of Existing Space Solar Cell Performance

Parameter	Silicon	High Efficiency Silicon	Single Junction Ga-As	Dual Junction	Triple Junction
Status	Obsolete	SOA	Obsolete	Nearly Obsolete	SOA
STC Efficiency (%)	12.7 - 14.8	16.6	19	22	26.8
STC Operating Voltage (V)	0.5	0.53	0.90	2.06	2.26
Cell Weight (mg/cm^2)	13 - 50		80 - 100	80-100	80-100
Temp Coefficient at 28°C	-0.0055%/C		-0.0021%/C		-0.0019%/C
Cell Thickness (μm)	50 - 200	76	140 to 175	140 to 175	140 to 175
Radiation Tolerance(*)	0.66 - 0.77		0.75	0.80	0.84
Absorptance	0.75		0.89	0.91	0.92
Vendors	Spectrolab, Tecstar	ASE, Sharp	Spectrolab, Tecstar	Spectrolab, Tecstar	Emcore, Spectrolab, Tecstar

(*) Fractional output after exposure to 10^{15} 1 MeV electrons per cm^2.

ES-4. NASA OSS Mission Needs

NASA OSS future mission needs were reviewed to identify requirements for future solar cell and array technologies. The missions were grouped and addressed according to the particular NASA OSS theme that maintains responsibility for the mission. These themes include Exploration of the Solar System (ESS), Mars Exploration Program (MEP), Sun-Earth Connection (SEC), Astronomical Search for Origins (ASO) and Structure and Evolution of the Universe (SEU). There are also a number of Discovery Mission concepts that may be enhanced or enabled by developing solar cell/array technology. Most missions that require solar arrays share these common needs: low cost, low mass, high reliability, low stowed volume and high efficiency. NASA OSS conducts many Earth-orbiting missions with solar array requirements similar to those of typical commercial and government satellites. These missions will benefit from the ongoing evolution of improved cell efficiencies motivated by commercial space ventures. However, there are a number of planned NASA missions that have solar array requirements unique to NASA, summarized below by OSS theme.

Exploration of the Solar System Program . The NASA ESS Program has plans for further exploration of the solar system with emphasis on the outer planets, inner planets and small bodies. The mid-term and far-term missions under consideration include: (1) Comet Nuclear Sample Return (CNSR), (2) Neptune Orbiter (NO), (3) Venus Surface Sample Return (VSSR), (4) Titan Explorer (TE), (5) Saturn Ring Observer (SRO), and (6) Europa Lander (EL). (Note added in proof: These mission priorities are now under study and are likely to change in late-2002.)

Table ES-3: Characteristics of Solar Arrays

Technology	Max Power per Wing @1AU, AM0 (kW)	Sp. Power W/kg (BOL) @ Cell Efficiency	Cost $K/W	TRL	Inverse Power Density (m^2/kW)
HES Rigid Panel		58.5 @ 19%	0.5-1.5	9	4.45
HES Flexible Array (Round/Ultra-Flex)	< 20	114 @ 19%	1.0-2.0	8	5.12
TJ GaAs Rigid	< 20	70 @ 26.8%	0.5-1.5	9	3.12
TJ GaAs Ultraflex	< 20	115 @ 26.8%	1.0-2.0	7	3.62

The CNSR, VSSR, NO, TE, and SRO missions require solar electric propulsion (SEP). SEP missions require low-cost, high-power arrays with high specific power (>100 to >300 watts/kg). The power requirements for SEP for these missions are not fixed quantities. As the power is increased, the trip times decrease and the delivered payloads increase, making the missions more attractive. In general, the minimum practical power level is in the 10-15 kW range, and 25 kW is the desired power level for launches between 2010 and 2020. SEP often requires thrusting out as far as 5 AU, thus requiring efficient solar cell/array performance under LILT conditions. Low stowed volume (~20 kW/m^3) is also a critical requirement for these missions. The VSSR mission requires solar cells/arrays that can operate at high solar fluxes and high temperatures. Advanced cells/arrays with high specific power and high temperature survivability are needed.

In principle, solar power could also be used to operate spacecraft and instruments while the spacecraft is far from the sun. Such potential missions include Europa Orbiter, Europa Lander, various Jupiter Orbiters. These missions require solar cells/arrays that can operate efficiently in a LILT environment. In addition, these solar arrays must be capable of operating in extreme radiation environments. However, the recently proposed NASA nuclear technology initiative may allow thee missions to be powered by RTGs, in which case it would be unlikely that they would be solar-powered.

Mars Exploration Program. In situ exploration is a central element in the Mars Exploration Program (MEP) Plan. The MEP will also launch Mars orbiting spacecraft, and these will be used as telecommunication relay stations after they carry out their primary science missions. In addition, the MEP will fund Scout missions on a competitive basis. These missions are presently undefined in scope, but might vary from polar landers to airplane or balloon observers. Mars Orbiters will benefit from advances in cell and array technology made for Earth-orbiting satellites.

The MEP is planning two surface missions for the next decade or so, the Mars Smart Lander mission and the Mars Sample Return mission. Present plans call for a 2009 launch for the MSL and a launch for the MSR no earlier than 2013. The MEP might use solar power on these missions, which will require dust mitigation technologies and cells tailored for high efficiency in the solar spectrum on Mars, and long-life batteries. On the other hand, the recently proposed NASA nuclear technology initiative may provide the MSL and MSR missions with the option to be powered by RTGs. Since RTGs will be considerably more expensive than solar power, it remains to be determined whether these missions will be solar-powered or RTG-powered. The Scout missions would likely remain solar-powered.

Sun-Earth Connection Program. Sun-Earth Connection spacecraft frequently measure fields and particles. For this reason, these spacecraft need electrostatically clean arrays. Sun-Earth Connection spacecraft also tend to be placed in high-radiation-orbits. This means that the cells must be protected against the radiation with either thick cover glasses or other shielding such as refractive concentrator optics.

The SEC Program includes plans for a number of missions (e.g., Mercury Orbiter, PASO, Inner Heliospheric Constellation and Solar Flotilla missions) that must survive and operate in a high intensity, high temperature environment and remain electrostatically clean.

The Solar Probe mission has unique operating environments that require a power subsystem capable of delivering power from 5.2 AU to within 4 solar radii from the center of the sun. The Solar Probe mission will present several challenges to solar array technologies. The Jupiter Polar Orbiter and Io Electrodynamics missions are similar to other SSE Jovian system missions, and if they are solar-powered, they must deal with LILT, high radiation environments and also be electrostatically clean.

Astronomical Search For Origins Program. ASO missions currently are conceived to be Earth-orbiting or near-Earth orbit satellites with no severe or unique challenges to the solar arrays.

Structure And Evolution Of The Universe Program. SEU missions are similar to ASO missions and these missions present no unique technical requirements for advanced solar arrays; however, future missions may depend on achieving low-cost solar arrays.

ES-5. Advanced Solar Cells and Arrays

This section describes the status of the advanced solar cell and array technologies presently under development in U. S., and identifies further improvements that are required to meet future NASA OSS mission needs.

Advanced Solar Cells. Most of the R&D work in this area is focused on developing multi-junction III-V cells with 30-35% efficiency and low-cost thin film cells with large-scale efficiency greater than 12%. Some limited work is in progress on the development of solar cells that can function efficiently in low intensity and low temperature and high intensity and high temperature environments. Several universities and R&D laboratories are developing advanced concepts, including quantum dots and ultra thin film solar cells.

High Efficiency Multi-Junction III- IV Cells

More efficient solar cells are essential to providing increased power for payloads on existing solar array designs. The most direct application of advanced multi-junction cell technology is to inner planet orbiting missions in the ASO, SEU, and SSE themes. These missions have similar requirements to other Earth-orbiting spacecraft and will benefit from the significant cost-per-watt reductions resulting from this work

Improvements in the efficiency of multi-junction cells continue to be made. Large area triple-junction cells of 29.3% have been achieved in laboratory prototypes. There are three ways in which III-V cells are likely to be improved.

- A fourth junction can be added to the current lattice-matched triple junction cell. Such a cell is projected to achieve an efficiency of about 35%.
- Use of a more optimal set of bandgaps to maximize conversion efficiency, grown on a substrate that is not lattice-matched.
- Development of a lighter, stronger, less expensive substrate than germanium. Silicon is the obvious choice but there is a large lattice-mismatch that must be overcome.

Thin Film Cells

Low-cost, low-mass, thin-film cells with moderate-to-high efficiency are attractive for SEP missions. Only moderately efficient thin-film cells (~10-15%) are necessary to match the mass performance of arrays using much more efficient (but heavier) crystalline cells, given a lightweight substrate. The present state of the art in flexible substrate a-Si (amorphous silicon) devices is about 8% efficiency at the sub-module level. Small area (< 1 cm^2) cells have been demonstrated at over 12% efficiency, and 11 cm^2 cells have reached 10.7% efficiency. Copper Indium Diselenide (CIS) cells on glass have had efficiencies as high as 18%, but these are too heavy for space use. Current thin film efficiencies are too low and substrates are too heavy to be practical in space.

The challenge is to reduce the mass of the substrate and increase the efficiency of the cells, for example by developing a process to deposit a high efficiency cell on a lightweight substrate. This can be addressed by two approaches: (1) develop better substrates for current deposition systems, or (2) develop appropriate deposition techniques for currently available substrates.

LILT Cells

The term low-intensity, low-temperature (LILT) is used to refer to solar arrays operating under conditions encountered at distances greater than about 2-3 AU from the sun. Typical Earth-orbiting solar arrays have steady-state illuminated temperatures of approximately40-70°C. Typically the efficiency is found to increase down to temperatures of about –50°C (at a solar distance of ~3 AU), and then fall at greater distances from the Sun, where the combined effect of low solar intensity and low temperature reduces the conversion efficiency. Thus "low-temperature" refers to temperatures well below this value. Cells that can function efficiently under LILT conditions are required to enable solar powered missions beyond Mars.

SOA solar cells have uncertain performance capability under LILT conditions. A three-step process should be used to develop LILT cells: (1) create a database for current high performance cells under LILT conditions; (2) carry out investigations to determine the cause of any degradations in performance and possibly identify solutions; (3) develop cell processes to reduce/minimize/eliminate LILT degradation. The need for LILT technology depends on whether future NASA missions will employ solar power beyond Mars. If the nuclear technology initiative is funded, the need for LILT technology may diminish, although LILT tolerance may still be needed for SEP.

High Intensity and High Temperature Cells

At present, solar cell technology is just sufficient to meet the needs of MESSENGER or other spacecraft that approach the sun to about 0.3 AU. Closer encounters to the sun will require further development.

Solar cells used for the majority of previous near-sun missions were made from silicon. These devices produce useful power only up to temperatures of ~200°C due to their unfavorable temperature coefficients. Practical operating temperatures for these cells are well below 200°C. Existing III-V solar cells can survive temperatures of 200°C continuously and up to 450°C for periods of a few minutes. At the higher temperatures the contact metallizations will diffuse and fail. Improved contacts with diffusion barriers are required for sustained long-term operation at high temperature.

Several forms of silicon carbide have bandgaps on the order of 3 eV, and they are also attractive for their high thermal stability (> 700°C), expected high radiation tolerance, high thermal conductivity, and good mechanical strength. Although the material is being developed commercially for high power transistor applications, it is very immature with respect to solar cell application. Chief among its present shortcomings are high dislocation densities, low carrier mobility, very limited availability, and high cost (~$1,000-3,000/wafer, versus about $25 for a germanium wafer). In summary, the near term "low-cost approach" would be a GaInP cell, while SiC might offer better performance and cost but only after millions of dollars of investment over 5-8 years of development.

Another approach to high solar insolation operation is to develop high-temperature, high-emissivity selective coatings. These can limit the amount of unusable IR entering the solar cells thereby reducing the steady state temperature. At the very least a high performance coating combined with louvers could be used to adjust the spacecraft emissivity as the distance from the sun varies.

Advanced Arrays. Most the work in this area is focused on developing mission-specific solar arrays. AFRL is actively supporting the development of advanced flexible arrays and thin film arrays. Some limited work is in progress on the development of concentrator arrays and electrostatically clean arrays. No support is presently available for the technology development of high temperature arrays, and Mars surface solar arrays.

High Power Arrays For Electric Propulsion

SEP missions require arrays with high output power, high specific power, low cost and low stowed volume to be most effective. High power and low mass arrays required for electric propulsion can be achieved potentially by 1) advanced flexible fold out arrays, 2) thin film arrays and 3) concentrator arrays.

Advanced Flexible Arrays

The UltraFlex™ solar array system developed for the Mars '01-Lander by Able Engineering Corporation (AEC), has a specific power of 103 W/kg BOL with 17% high efficiency silicon cells. The system is at NASA TRL 6. It is claimed that using 27% triple junction cells, arrays with 180 W/kg (BOL) can be achieved. If thin film blankets with 10% efficiency become available, this may rise to 300 W/kg (BOL). The stowed packaging density is projected to be 50 kW/m^3.

Thin Film Arrays

AFRL has begun a $6M, 3-year program with two prime contractors (Boeing and Lockheed Missile and Space Co.) to investigate and design complete arrays uniquely tailored to thin film solar cells. The SquareRigger™ solar array (under development at AEC) is a flexible blanket system that is composed of modular "bays" that may lead to ultra-high power capability (>30 kW) at a high-stowed packaging efficiency beyond 2010. The SquareRigger™ solar array system is projected to achieve a specific power between 180 W/kg to 260 W/kg BOL, depending on PV type and efficiency. When populated with thin film PV the SquareRigger™ system is projected to offer an order of magnitude cost reduction when compared to conventional rigid panel systems. The SquareRigger™ system is at NASA TRL 4.

Concentrator Arrays

The benefits of concentrator arrays for NASA SEP missions are: (1) they can mitigate LILT effects and allow conventional solar cells, both high efficiency and thin film, to be used at distances of > 3 AU, and (2) cost reduction for arrays above a few hundred watts, due to the reduced number of cells that must be purchased.

Concentrator arrays that are presently being developed for commercial spacecraft applications can be broadly categorized as refractive or reflective, depending on the type of optics used to achieve concentration of the light. The SCARLET array used on Deep Space 1 is a refractive type, whereas the channel array used on the Boeing 702 satellite is a reflective type. The SCARLET Stretched Lens Array (SLA) is suitable for SEP missions that require 10 to 25 kW of power at a specific power of 70 W/kg, and accommodate the intrinsic off-pointing power production limits. TECSTAR has teamed with NRL to commercialize their V-trough reflector system. The AEC Cell Saver™ Concept uses distributed reflective elements, and low-cost collapsible reflectors. The United Innovations 100X to 1000X design funded by National Renewable Energy Laboratory (NREL) combines high ratio concentration with the concept of spectral splitting. The performance estimates for these concepts have been provided by the manufacturers and they range from 50-250 W/kg.

Electrostatically Clean Arrays

There is a need to develop transparent plastic materials that can withstand the space environment. These plastics can be coated with Indium Tin Oxide (ITO) or other transparent conductors and used to cover large sections of solar arrays. This will readily produce the desired electrostatic cleanliness with a minimum of expense, weight, and cost. In addition, this approach will yield a readily repairable array. Further, such plastics are extremely desirable for thin film arrays. Transparent plastics may also serve as covers for dust mitigation on Mars.

A research area that is appealing but risky is extending typical glass or fused silica to cover several cells. This has been tried in the past, but without success due to delamination or failure of interconnects in thermal cycling. Also, such covers can cause difficulties of repairs because there is no cost-effective way to replace a broken cell under such a cover. These issues can probably be overcome with additional research.

High Temperature Arrays

An advanced high temperature array is being developed for the MESSENGER Discovery mission that is planned for travel to 0.31 AU. The MESSENGER array contains GaAs cells and operates at a temperature of 130°C. (Most arrays operate at around 70°C). Some of the cells in the array were replaced by optical solar reflectors (OSRs). The MESSENGER array was designed to operate off-pointed from the sun in order to maintain the array at ~130°C. However, should the spacecraft attitude control system or the array drive temporarily malfunction, the array could point directly at the sun. In this case, the array will be heated to 260°C, and will not generate significant power. It is designed to survive at that temperature for one hour.

However, such arrays are not suitable for the solar probe mission. One of the problems facing closer encounters to the sun is that the substrate adhesives weaken at high temperatures. Research is needed to identify and test adhesives that show promise of operating at higher temperatures than those encountered by the Helios and MESSENGER spacecraft in order to enable the Solar Probe, Solar Sentinels, Enterstellar Probe, and PASO missions, all of which approach the sun to within about 0.2 AU.

Coatings may also be developed further to limit the amount of unusable IR entering the solar cells as well as for controlling the solar array substrate temperature. Ideally, a switchable electrochromic coating could be developed that reduces or eliminates the need for array feathering. A high performance coating combined with louvers could be used to adjust the spacecraft emissivity as the distance from the sun varies.

High Radiation Environment Solar Arrays

If missions to the Jovian system are to be solar-powered, they will endure very strong radiation environments (see Sec. 5.5).

There are four possibilities for a mission to deal with such high radiation environments: (1) accept gradual reduction in power and use over-size arrays, (2) use thick cover glasses, (3) use concentrating arrays with thick cover glasses over the small areas of cells, and (4) develop radiation-resistant cells. The first approach is not feasible in most cases. To utilize the second approach, NASA would need fused silica cover glasses with thicknesses of 0.5-1.5 mm, which presently lack a commercial source. NASA may have to reestablish this capability by providing funds to industry. Concentrating arrays for use in high radiation fields will require an extra effort to select and qualify radiation-resistant materials for the concentrators, be they refracting or reflecting. The fourth approach requires a comprehensive test program to evaluate radiation-resistant cell technologies. This program will have much in common with the program recommended in LILT arrays, with the addition of radiation effects evaluation under mission conditions. Many of the high radiation NASA missions considered here occur at distances much greater than 1 AU, so combined LILT/radiation effects must be evaluated for both high performance cells and thin film cells. AFRL is funding an extensive program in thin film solar cell development and thin film array engineering. NASA may find some of this technology suitable for high radiation missions, but a substantial NASA testing program will be required to characterize and qualify thin-film cells. However, the recently proposed NASA nuclear technology initiative may allow these missions to be powered by RTGs, in which case it would be unlikely that they would be solar-powered.

Mars Surface Solar Arrays

The surface area available on Mars Landers is very limited and is critical on a Mars Rover for hazard avoidance and ground clearance. Increasing the efficiency of the PV array to reduce its area may enable a mission to survive for much longer periods. The reduced stowed volume that results from higher efficiency provides benefits in both mass and volume for the mission since entry, descent, and landing (EDL) requirements to the surface of Mars tend to be design drivers. In addition, arrays required for Mars surface missions need dust mitigation devices to enable long-term missions. At present no work is in progress on the development of such technologies. There are three technology areas that need development support.

- Modify commercial 3-junction cells to optimize them for use in the blue-depleted spectrum on the surface of Mars. This technology program should be formulated so that as 4-junction cells become available, the same methodologies can be transferred to 4-junction cells.
- Develop a fundamental understanding of the physics of dust adhesion and accumulation. This understanding can be achieved by laboratory simulation studies of Mars dust deposition and removal processes, the relation between deposited amount and optical obscuration, the effect of surface dust on array performance, and the effectiveness of dust removal procedures.
- Develop a dust tolerance/mitigation approach, based on the fundamentals studied in the dust physics activity. This should be based on the mission needs and surface operations strategy. It may vary from developing dust-tolerant systems such as arrays that can be periodically tilted, to arrays with overt dust mitigation such as blowers, scrapers, covers, electrostatics, etc.

On the other hand, the recently proposed NASA nuclear technology initiative may provide the MSL and MSR missions with the option to be powered by RTGs. Since RTGs will be considerably more expensive than solar power, it remains to be determined whether these missions will be solar-powered or RTG-powered. The Scout missions would likely remain solar-powered.

Infrastructure. It is necessary that NASA have available resources for solar cell measurement, analysis, and characterization. These facilities are needed to assess the suitability of the various technologies to specific missions. In addition, they maintain the required calibration standards for these measurements. For properties of photovoltaics under special conditions such as LILT, high intensity, dusty conditions such as occur on Mars, or high radiation environments, special test facilities are required. In addition to test capabilities, it is necessary to provide mission performance analyses using analytical tools for radiation, temperature, illumination, and other effects. The facilities that are best qualified to represent NASA interests in solar cell technology are distributed among NASA-GRC, NASA-GSFC, and NASA-JPL. Without this infrastructure, it will be difficult to estimate the performance and lifetime of new solar cells in various environments.

ES-6. Recommendations

The Study recommendations for a photovoltaics investment program to advance solar cell/array technologies to TRL 5/6 are summarized in descending priority order in the sections that follow. TRL definitions are given in Section 2.7.

ES-6.1 High Power for Solar Electric Propulsion

The Team recommends that advanced technology for large thin film arrays and concentrator arrays be developed for solar electric propulsion (SEP). AFRL is executing a large program in thin film cell technology development, including development of encapsulated blankets, interconnects, array structure and deployment systems. The Team recommends that NASA co-fund the thin film prototype and demonstration phases of the AFRL work at $1M per year and then establish an independent technology transition and qualification effort tailored to unique NASA requirements.

The Team recommends NASA fund a high voltage solar array two-year study (at the $500K/year level) to define the feasibility and technical issues associated with developing a solar array with voltage outputs of 3000 to 5000 volts dc to match the required input voltage of the electric propulsion engine.

It is recommended that NASA fund a task that compares the AEC-Able Engineering Stretched Lens Array with other lightweight, high-ratio reflective concentrators for SEP missions. NASA funding would develop one of these technologies as a power source SEP. It is recommended that NASA provide $500K over 18 months for evaluation of reflective and refractive concentrator arrays for use on various future missions.

It is recommended that one or two concepts be selected for prototype development and testing. This would include a one-year $300K qualification panel coupon task to validate the thermal survivability, high voltage operation and LILT performance, and then a full-scale qualification wing program should be pursued at an estimated cost of $1M per year for three years.

ES-6.2 Electrostatically Clean Arrays

The Team recommends a $300K per year three-year effort on transparent, conductive materials and plastic coatings that are subsequently coated with transparent conductive coatings that can withstand the space environment.

The Team also recommends a $200K per year two-year effort in extending typical glass or fused silica to cover several cells.

ES-6.3 Solar Arrays on Mars

At the time this report was written, the Mars 2009 Smart Lander was planned to be solar powered. As this report went to press, the current plan is to provide power with a radioisotope power system (RPS). However, the RPS is considerably more expensive than solar power, and it is possible that financial constraints may dictate a return to solar power as planning continues. In any event, solar power should be provided as a possible "back-up" for RPS as well as a primary source for Scout missions. Furthermore, in seeking launch approval for an RPS-based mission, one must show that an honest attempt was made to use solar power, but solar would not suffice. The Team recommends that NASA should conduct the following three tasks: (1) optimize cell design for the spectrum at the surface of Mars, (2) study the properties of simulated dust and its effect on photovoltaic arrays, and (3) develop dust tolerance/mitigation systems. A long-life solar array should be available for the Mars 2009 Smart Lander mission. A rough estimate of the funding required for these three tasks is as follows:

Technology Program	FY03	FY04	FY05	FY06
Optimized cells for the Mars surface spectrum	$0.5 M	$1.5 M	$1.5 M	$1.0 M
Physics and effects of Mars dust on PV	$0.2 M	$0.5 M	$0.5 M	
Dust tolerance/mitigation technology	$0.5 M	$1.0 M	$1.5 M	
Total Mars arrays	$1.2 M	$3.0 M	$3.5 M	$1.0 M

ES-6.4 High Solar Intensity Arrays

A number of proposed future missions will approach the Sun to within about 0.2 AU. These include Solar Probe, Solar Sentinels, Interstellar Probe, and PASO missions. The Team recommends a $300K per year three-year technology development task to develop multi-junction cells that can operate efficiently at much higher temperatures than the 130°C limit on MESSENGER. Temperatures of 300-350°C should be feasible, and 600°C may be possible. Specific concerns are diffusion of metals and dopants within the solar cells.

The Team also recommends a $500K per year four-year technology development task to develop solar arrays that tolerate temperatures from 300-600°C, for six months or more. Specific concerns are adhesives used in the array. A thermal analysis is recommended of the entire array/cell structure for solar inner planet missions that will define the solar cell/array temperature environment.

The Team recommends a $300K per year four-year advanced coatings task to develop coating that limit the amount of unusable IR entering the solar cell and to control the solar array substrate temperature. Ideally, a switchable electrochromic coating might be developed that reduces or eliminates the need for array feathering.

ES-6.5 Low Intensity Low Temperature Arrays

The Team originally recommended that NASA develop a LILT Test Plan geared to the use of III-V cells (GaAs, triple junction, etc.) and thin film cells. The following four-step process was recommended (1) create a database for current cells under LILT conditions, (2) conduct investigations to determine the cause of any degradations and possibly identify solutions, (3) develop cell processes to reduce/minimize/eliminate LILT degradation and (4) confirm the optimized cells LILT behavior by testing and qualifying the cells for space. A rough estimate of the funding required for these tasks is as follows:

Technology Task	FY03	FY04	FY05	FY06
(1) Database for current cells under LILT conditions	$150 K			
(2) Determine cause/mechanisms for LILT degradation	$250 K	$600 K	$300 K	
(3) develop processes to minimize LILT effects		$300 K	$600 K	$300 K
(4) Verify LILT mitigation processes				$300 K
Total LILT Resistant Arrays	$450 K	$900 K	$900 K	$600 K

ES-6.6 High Radiation Cells and Arrays

The Team originally recommended that NASA OSS investigate the following two approaches for obtaining solar arrays that function well in the high radiation environments of the Jovian system: (1) provide shielding (cover glasses or concentrator optics) to protect cells from direct exposure and (2) develop radiation-resistant cells. The Team recommended NASA fund a testing task to determine the radiation resistance of thin film cells/arrays and concentrator arrays developed by AFRL. The Team also recommended that NASA fund an effort to select and qualify radiation resistant materials for concentrator arrays for use in high radiation fields. A rough estimate of the funding required for these tasks is as follows:

Technology Program	FY03	FY04	FY05	FY06	FY07
Thick silica cover glasses	$250 K	$700 K*			
Radiation resistant high efficiency cells	$150 K	$300 K	$400 K	$500 K	$200 K
Radiation properties of thin film cells	$200 K	$100 K	$100 K		
Radiation resistant concentrator materials	$300 K	$200 K	$200 K		
Total High Radiation Missions	$900 K	$600 K	$700 K	$500 K	$200 K

* If study deems necessary

However, in view of the proposed nuclear initiative, the priority for this technology may have to be greatly reduced.

ES-6.7 High Efficiency Cells

The Team recommends that NASA co-invest $1 M per year for three years in the AFRL advanced technology development of multi-junction cells with greater than 30% efficiency to insure that NASA requirements are recognized.

The Team recommends that research on lattice-mismatched multi-junction devices and alternative substrates be supported, while maintaining coordination with similar AFRL programs involving different vendors and approaches. Funding of $500 K per year in FY03-05 is recommended, with an increase to $1 M per year starting in FY'05, assuming a successful design is selected in FY'04 for transition to manufacturing. The funding amounts are based on the assumption that AFRL continues to provide comparable funding. A joint transition program will be most cost-effective.

ES-6.8 Infrastructure

A number of the tasks recommended here require support in the form of solar cell and array materials measurement, characterization, and test. The Team recommends that the facilities and personnel at GRC, GSFC, and JPL that are uniquely qualified to support the above recommended tasks continue to be funded by NASA.

ES-7 Recommended Roadmap

Roadmaps are shown in Figures ES-2A and ES-2B.

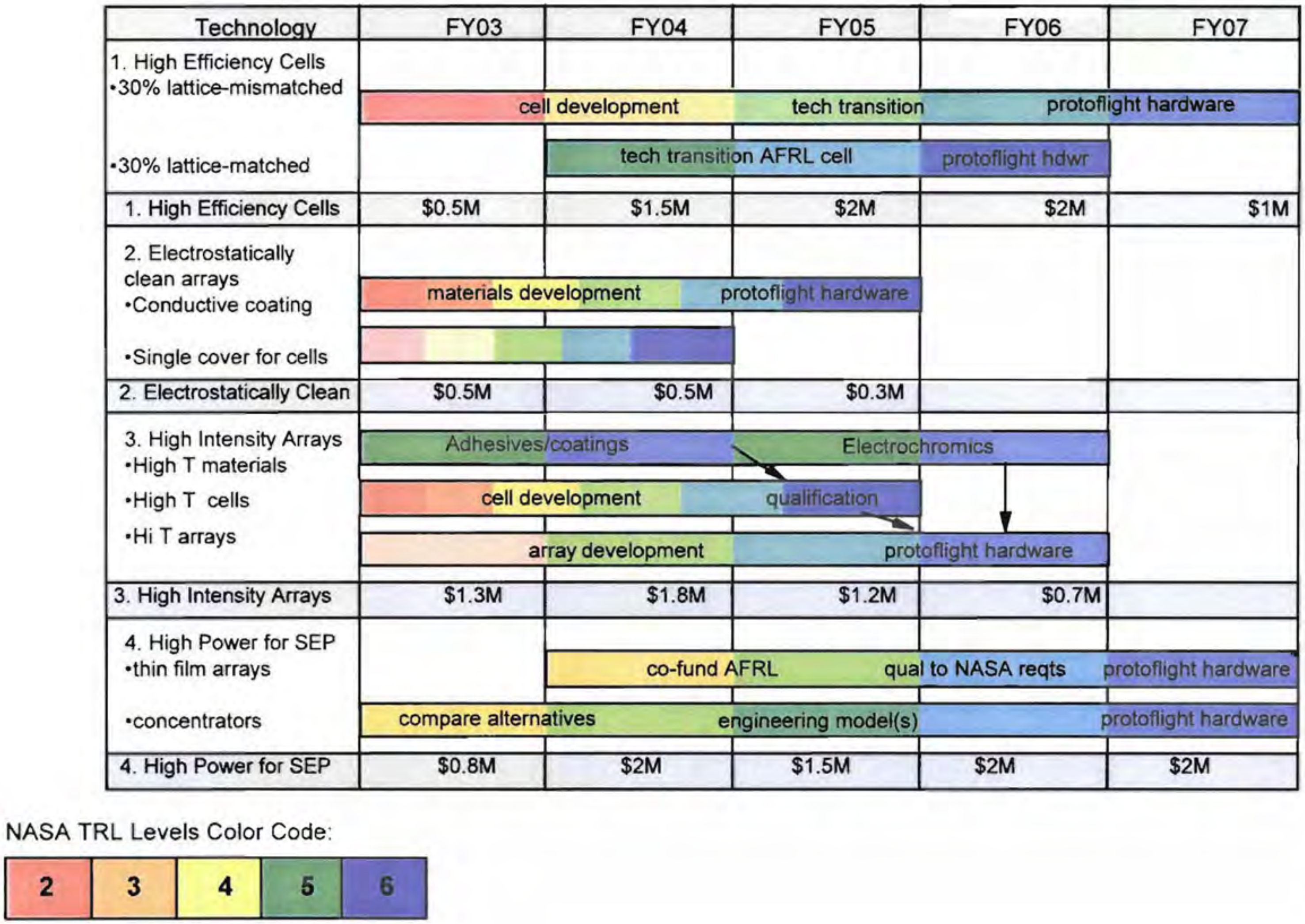

Figure ES-2A: Roadmap for Four Elements of PV Technology

Technology	FY03	FY04	FY05	FY06	FY07
5. LILT					
•cell characterization	characterize cell performance				
•LILT Mitigation		develop process		verify process	
5. LIIT	$0.45M	$0.9M	$0.9M	$0.6M	
6. High radiation arrays					
•Thick silica covers	evaluate	implement if needed			
•Thin film cell assess	characterize		adapt		
•Optimized hi-rad cells	design	develop	test	tech transition	
•Concentrator mods	matls evaluation	rad hard mtls	engr model		
6. Rad-resistant Arrays	$0.9M	$0.6M -$1.3M	$0.7M	$0.5M	$0.2M
7. Mars arrays					
•spectral cells	design	prototypes	verification	qualify	
•dust physics	fundamental studies				
•dust mitigation	options	test	engr model	verify in chamber	
7. Mars arrays	$1.2M	$3M	$3.5M	$1M	

NASA TRL Levels Color Code:

2	3	4	5	6

Figure ES-2B: Roadmap for Three Elements of PV Technology

Space Solar Power
2001 Technology Assessment and Recommended Roadmap
for Potential NASA OSS Missions Beyond 2007

Part II - Final Report

1.0 Introduction

NASA's Office of Space Science requested that JPL lead an assessment of advanced power source and energy storage technologies that will enable future (beyond 2007) NASA Space Science missions and prepare technology road maps and investment strategies. The power source technologies to be reviewed are advanced radioisotope power sources (ARPS), solar cells and arrays, and fuel cells. The energy storage technologies are batteries, regenerative fuel cells and flywheels.

In the first phase of this work, an assessment of Advanced Radioisotope Power System technology was conducted. The *Advanced Radioisotope Power System Report,* #JPL D-20757, was published June 2001.

The next advanced power source to be assessed within this overall activity is Solar Cell and Array Technology, and this is the subject of the present report. The objectives of this effort are to assess the potential of solar cell and array technologies to enable or provide the most cost-effective power generation for NASA Space Science missions launched in the 2007 to 2020 time period, and to define a program to develop these technologies.

1.1 Spacecraft Power Technology

All spacecraft require electrical power in order to accomplish their missions. Power is provided either by a photovoltaic (PV) array with batteries or by radioisotope thermoelectric generators (RTG). Over the years, the efficiency, specific power and lifetime of PV arrays have steadily improved. PV arrays are the power source of choice for most space missions within 2 AU of the sun because of their high specific power, efficiency, and reliability.

The efficiency of a solar cell will vary, depending on the solar spectrum to which it is exposed. The solar spectrum at the surface of the Earth after sunlight passes vertically through a clear atmosphere is called "airmass one" or AM1. Most terrestrial solar cells are evaluated at AM1.5 due to the longer path length when the sun is at some average elevation angle. The solar spectrum in space (above the atmosphere) is called "air mass zero" or AM0. In this report, all solar cell efficiencies given without explicit mention of the airmass imply AM0.

However, NASA is planning missions for which the present state of solar power technology was not explicitly designed. This includes missions that

- Go far from the sun
- Endure very high radiation fluences
- Require very high power levels and high voltages with light weight for solar electric propulsion
- Must operate in the dusty environment of Mars
- Carry sensitive instruments that require that solar arrays be electrostatically clean
- Will approach the sun and experience high temperatures.

Missions such as Solar Probe would present unique challenges to PV arrays due to the 75,000/1-ratio change in solar flux from 5 AU at Jupiter to 4 solar radii from the center of the sun.

Solar cells and arrays have performed as designed for NASA missions for many years. At the start of the modern satellite era in the 1960s, silicon (Si) solar cells were universally used on solar powered spacecraft. By 1980, the growing power demands of military satellites spurred a concerted effort to develop more efficient solar cells based on gallium arsenide (GaAs). Such devices had been demonstrated as early as 1954. Unlike Si solar cells that are simple to grow by diffusion of dopants into a silicon wafer, GaAs cells require more complex methods. At first they were grown by liquid phase epitaxy (now obsolete) and later by metal-organic chemical vapor deposition (MOCVD). These methods require precise temperature and reactant flow control, and entail working with a broad range of atomic species. With a concerted 4-year effort, including millions of dollar in capital investment to buy MOCVD equipment, the efficiency of single junction GaAs cells was increased to 18% by the late 1980s. The intrinsic costs of GaAs substrates, MOCVD equipment, and source gases dictated that these cells would always be more costly on a per-watt basis than silicon cells. But for missions with limited solar array area, the GaAs cell was an enabling technology for increasing power. The most significant cost reduction strategy involved replacing the originally used GaAs substrate with a germanium (Ge) substrate that is less costly and less fragile, thus reducing breakage losses. The GaAs/Ge cell was useful to NASA and defense missions in which the solar array area was limited by sensor view factor considerations or spacecraft size limitations. The Iridium satellite program was the only large commercial user, and it selected these cells to produce compact arrays that enabled multiple satellite deployment from a single launch vehicle.

By the early 1990s a number of R&D programs, funded primarily by the Air Force, NASA and NREL, had demonstrated the feasibility of multi-junction (MJ) solar cells in which junctions in several III-V materials (utilizing atoms from the 3rd and 5th columns of the periodic table) are grown in a single monolithic stack. The semiconductor materials used in these MJ cells must be lattice-matched, chemically compatible, and have appropriate band gaps. In 1994, the two U. S. space cell vendors were selected to develop production of the most promising design and funded by a joint NASA/Air Force Manufacturing Technology Program. The main objectives of the program were achieving 23% efficiency at a cost per watt less than that of GaAs/Ge, with radiation resistance as good or better than GaAs/Ge. Both vendors eventually produced GaInP/GaAs/Ge triple junction solar cells that met these objectives. The triple junction cells were rapidly adopted for use by the commercial satellite industry and for many NASA and military missions. The benefits included system-level cost per watt comparable to silicon, better temperature coefficients, better radiation tolerance, and about one-half the required array area to produce a given power level, compared to silicon. As a result of this success, single junction GaAs/Ge cells are no longer produced with the exception of a few heritage programs.

During the development of MJ cells in the mid-90s, progress was made in other cell technologies. The efficiencies of silicon cells for terrestrial use were improved from about 18% at AM1.5 (air mass 1.5) to better than 22% through the use of light trapping textured surfaces, careful interface passivation, and higher quality substrates. These so-called "high eta" devices are about 16% efficient under AM0 conditions and have seen some use on spacecraft. However, they are only suitable for low radiation missions and still have the inferior temperature coefficient typical of silicon cells as compared to MJ devices.

1.2 Reasons to Develop Advanced Space Solar Power Technology

The reasons to develop space solar power technologies are:

- To increase the performance of solar cells and arrays (increase specific power and efficiency; decrease cost)
- To provide a cost-effective alternative to RTGs for missions that go far from the sun
- To enable solar-powered missions in strong radiation environments
- To make solar electric propulsion affordable and practical
- To provide an alternative to RTGs for missions that must operate in the dusty environment of Mars
- To provide affordable electrostatically clean arrays that will enable missions with sensitive electromagnetic sensing instruments

- To provide an alternative to RTGs for missions that approach the sun and experience high temperatures.

The challenge to NASA is to support research and development that augments the main commercial thrust of solar array technology in order to provide unique capabilities needed by future NASA missions, but not necessarily needed by commercial spacecraft. However, there may be a payoff to commercial spacecraft in exceptional cases.

2.0 Study Overview and Description

2.1 Objectives

The purpose of this study is to recommend to NASA investment strategies for solar power technology to assure that solar power systems will be available for future NASA solar system exploration missions. There are many proposed missions for which present solar power technology is inadequate either to power the mission, or to provide an advantageous solar alternative to RTGs.

The following itemized topics were studied in the review process.

- Review NASA Code-S future mission needs for solar cell and array technologies
  - Exploration of the Solar System
  - Mars Exploration Program
  - Astronomical Search for Origins
  - Sun-Earth Connection
  - Structure and Evolution of Universe
- Assess the status of solar cell and array technologies presently being used in various space missions and establish a baseline.
- Assess the status and potential of advanced solar cell/array technologies to meet future mission needs including:
  - Low-cost cells/arrays
  - High-efficiency and low-mass solar cells/arrays
  - Advanced low mass, reliable deployment and retraction mechanisms
  - Low intensity, low temperature (LILT) capability
  - Radiation tolerant solar cell/arrays
  - Performance and reliability in high-temperature environments
  - Mitigation of dust on Mars
  - Large power systems (>10 kW) for solar electric propulsion
  - Electrostatically clean arrays
  - Electrically conductive arrays resistant to environmentally induced arcing
- Conduct objective trade studies to define cost and benefit of various solar cell power system technology investments.
- Recommend to NASA appropriate investment strategies for developing advanced solar cell power system technologies to meet future mission needs.

2.2 Study Approach

The study approach began with selection of a technical assessment team of knowledgeable photovoltaics (PV) power experts and power system engineers to gather technical information, discuss the technical data in detail, draw conclusions, make recommendations, and document the results in a report. We were fortunate that most of the people that were approached kindly consented to donate their time and energy to this review. The Team conducted four multi-day meetings to obtain mission requirements and constraints for photovoltaics and the technical status of as many PV technologies as possible.

To make the study tractable, the technology needs of a large number of potential future missions were distilled into a limited number of generic types of technology needs. For each generic type of need, we summarized needs, available technology, gaps between current capabilities and needed capabilities, and defined the steps needed to develop technology to fill the gap.

These results were analyzed and interpreted to identify the most promising advanced technologies with the greatest potential impact on enabling and enhancing future missions. The team then prepared roadmaps for developing these technologies, including estimated resources required and appropriate gates for review of progress.

The assessment team examined each PV technology to try to answer the following questions:

- How does it function?
- What is the present status of the technology?
- What programs are presently funded?
- What is the future potential of the technology in terms of performance parameters such as specific power and efficiency under various conditions?
- What would be the impact of such improvements on future missions?
- What technical challenges remain and are they well defined?
- What resources are needed to advance the technology to NASA TRL 5-6?

The final results are documented in this report.

2.3 Schedule

The assessment team conducted four multi-day meetings to collect data inputs during March-May of 2001. The first meeting was held at JPL, the second was held at NASA-GSFC, the third meeting was at GRC, and a fourth meeting was held at JPL in May, 2001. The final report was prepared as a draft on November 26, 2001 for review by a wide range of stakeholders, and was revised to final form on December 31, 2001.

2.4 Participants

The Solar Cell/Array Technology evaluation team members and alternates are given in Table 2-1. In addition, John T. (Tim) VanSant, NASA-SEC, 301-286-6024, Chris Schwartz, NASA-SEU, 301-286-0172, and James A. Cutts, JPL, 818-354-4120, provided very valuable inputs to the Team for SEC, SEU, and ESS, respectively.

Outside participants who generously provided presentations and supporting material, as well as their time and effort, are listed below:

At JPL

- Spectrolab
- Able Engineering
- TRW
- Tecstar
- Lockheed-Martin
- DayStar Technologies

At GSFC

- Navy Research Laboratory (NRL)
- Applied Physics Laboratory (APL), Johns Hopkins University
- Orbital Sciences Corp.

At GRC

- Ohio Aerospace Institute (OAI)
- Rensselaer Institute of Technology
- Ohio State University
- Emcore
- United Solar
- ITN

At JPL

- Composite Optics
- L'Garde
- Ball Aerospace
- ISET

Table 2-1: Solar Cell/Array Technology Evaluation Team Members

Name	Role	Phone	E-mail
Rao Surampudi	NASA-JPL – Chairman	818-354-0352	subbarao.surampudi@jpl.nasa.gov
Tom Hamilton	NASA-JPL – Coordinator	323-290-0246	hamiltongroup@mediaone.net
Don Rapp	NASA-JPL	818-354-4931	donaldrapp@aol.com
Paul Stella Alt.-Nick Mardesich	NASA-JPL NASA-JPL	818-354-6308 818-354-9520	paul.m.stella@jpl.nasa.gov nick.mardesich@jpl.nasa.gov
Bill Nesmith	NASA-JPL	818-354-3478	bill.j.nesmith@jpl.nasa.gov
Jack Mondt	NASA-JPL	818-354-1900	jack.f.mondt@jpl.nasa.gov
Robert L. Bunker	NASA-JPL	818-354-4555	Robert L. Bunker@jpl.nasa.gov
Sheila G. Bailey	NASA-GRC	216-433-2228	Sheila.Bailey@grc.nasa.gov
Henry B. Curtis	NASA-GRC	216-433-2231	Henry.Curtis@grc.nasa.gov
Mike Piszczor	NASA-GRC	216-433-2237	m.piszczor@grc.nasa.gov
Ed Gaddy	NASA-GSFC	301-286-1338	edward.m.gaddy.1@gsfc.nasa.gov
Dean Marvin	Aerospace Corp.	505-872-6230	dean.c.marvin@aero.org
Larry Kazmerzki	DOE-NREL	303-384-6600	kaz@nrel.gov
Advisor- Carol Lewis	NASA-JPL	818-354-3767	carol.r.lewis@jpl.nasa.gov

2.5 Scope Of The Study

This study is concerned with photovoltaic cells, modules, arrays and ancillary technologies needed to assure that photovoltaics can operate successfully in their intended environments. This category includes packaging and deployment systems, as well as dust mitigation on Mars, radiation protection, and other technologies needed by PV arrays.

2.6 Critical Parameters

Engineers have worked over the years to improve arrays in terms of the following important figures of merit:

- Power per unit mass (also known as specific power)(W/kg)
- Efficiency (%) (equivalent to power per unit area (W/m^2))
- Cost per unit power ($/W)
- Radiation resistance (allowable dosage)
- Moment of inertia ($kg*m^2$)
- Stowed volume (m^3)
- Resistance to attack by atomic oxygen (Earth orbit missions)

The first four figures of merit are of the widest interest, although the latter three can be very important for some applications.

In a number of instances, spacecraft designers have options whereby they can make trades that involve increasing the power per unit mass while allowing the array cost to increase. Studies performed in this area have shown that even extremely high array costs can be worth the investment when they result in lower array mass. Generally, if the entire cost of a program, for say, a low Earth-orbiting spacecraft is divided by the mass of an instrument or payload, the result is on the order of $600 K per kg. In other words, the bottom line is that it costs about $600 K to put 1 kg of payload into such an orbit. If a decrease in array mass allows the spacecraft to increase the payload mass by one kg, the decrease in array mass has an apparent equivalent value of $600 K. If the cost of achieving this 1 kg mass reduction is less than $600 K, it would appear to be a worthwhile investment. The actual situation is somewhat more complex than this. If the array mass is reduced by 1 kg while retaining full power output, and one attempts to increase the instrument mass, several factors act to constrain the allowable mass gain by the instrument. One factor is that generally, the additional mass assigned to the instrument will increase its capabilities and thus require more power. Therefore, the solar array will have to be made slightly bigger, resulting in a reduction in the original 1 kg mass gain. In addition, the more capable instrument will generally require additional support from the spacecraft, such as from command and data handling (C&DH), structure, attitude control, etc. The additional C&DH capability will take its toll in cost and mass, and possibly power. Thus, the "value" attributable to a 1 kg reduction in solar array mass, is probably more like $200 K for an Earth-orbiting spacecraft in low-Earth orbit (LEO), and somewhat higher for spacecraft in geosynchronous orbits or traveling on interplanetary paths. Nevertheless, it is clear that increasing the specific power of a solar array can be a very worthwhile investment.

Any discussion of figures-of-merit is somewhat inexact because there is no standard method of reporting data relevant to figures-of-merit. For example, power per unit mass is reported by various organizations at test conditions, at beginning of life, at end of life, with various parts of the array included or not, etc.

Power per Unit Mass. Many arrays presently in space produce between 20 and 40 W/kg. From anecdotal reports, the best state-of-the-art arrays that fly on some commercial communication spacecraft produce about 70 W/kg. One fully qualified solar array has produced slightly more than 100 W/kg. That array was made by AEC for the Mars-2001 Smart Lander spacecraft, which was cancelled for other reasons. The substitution of multi-junction solar cells for the silicon solar cells on the Mars-2001 array would raise the specific power of that array to about 150 W/kg, although some of this would be offset for a Mars surface application by the need to increase structural mass to meet strength requirements. This is not necessarily a simple upgrade because of the difficulty in combining the relatively fragile multi-junction cells with the flexible substrate of the cells.

Efficiency (Power per Unit Area). Solar cell efficiency can be reported on several bases, depending on the solar spectrum, the operating temperature, and the length of time that the cells are exposed to radiation. The usual standard for comparison is at "air mass zero" (AM0) which implies that the cells are outside of the Earth's atmosphere at 1 AU from the sun where the solar intensity is 1367 W/m^2. The standard temperature is usually taken as 28°C. Sometimes, cell efficiencies are reported at "beginning of life" (BOL) and "end of life" (EOL) for missions that expose the cells to radiation.

Solar cell efficiency for triple junction cells is now of the order of 26.8% under test conditions at AM0. The higher the efficiency, the smaller is the area required for any given power level. A smaller array area is easier to integrate on the spacecraft, easier to deploy and orient in space, and has less mass.

Radiation and Atomic Oxygen Resistance. Radiation resistance is a very important characteristic for most space missions. Typical solar cells degrade significantly from BOL to EOL due to radiation. JPL, GRC, and AFRL have studied radiation effects on solar cells in great depth and have prepared extensive databases and models to estimate radiation damage. However, these databases need to be extended to the latest cells.

For missions in Earth orbit, atomic oxygen can attack surface coatings, and materials must be used that resist atomic oxygen attack.

Cost per Unit Power. The values in this paragraph are based on the costs of eight Goddard Space Flight Center (GSFC) solar panels. The costs include only the photovoltaics stack, interconnects, string terminations, temperature sensors, harness, diode boards, and diodes. Omitted are the costs for substrates, deployment mechanisms, launch tie-downs and snubbers, and solar array drives. The costs include a qualification coupon vibrated and thermal cycled and thermal vacuum and acoustic tests on the flight arrays. The costs run from a low of $588 per test-condition watt to a high of $7415 per test-condition watt. Eliminating four of the eight arrays as being atypical for one reason or another leads to an average cost of $1,794 per test-condition watt and $2,544 per end-of-life watt. These costs represent data from the past eight years exclusive of the last two years. Anecdotal reports testify that costs have dropped very roughly 40% from that quoted. Thus, costs are now approximately $1,100 per test-condition watt. The actual cost will also reflect the amount of development required in producing the array. Reliance on heritage designs can minimize costs.

If the cost of the mechanical gear that is needed to stow and deploy the array is included, the cost increases by roughly 50%. Thus the cost of an array that includes substrates, deployment mechanisms, launch tie-downs and snubbers is about $1,650 per test-condition watt. This cost does not include the solar array tracking drive.

These costs are summarized below:

Solar Panels	Cost/Watt
All eight GSFC panels	$588 to $7,415
Four typical panels - average for 1990's	$1,794
Estimate for year 2001 average	$1,100
Panels with mechanical hear for stowage and deployment - year 2001	$1,650

2.7 NASA Technology Readiness Scale

The team used the NASA TRL scale to characterize the relative maturity of PV technologies. A brief description of this scale is given in Table 2-3. NASA's Code R is responsible for developing new technologies in the TRL range 1-3, and the NASA Space Science Office advances technologies from the 2-4 range to the 6-7 range, where they can be adopted by missions. JPL requires that a technology must reach a minimum TRL of 6 by Preliminary Design Review (PDR) in order to be accepted as ready for implementation by a project.

The primary emphasis in this study is on PV technologies presently at TRL 2 to 3 that have potential to enable and enhance future NASA missions. We then estimate a development schedule that could advance these technologies from TRL 2/3 to TRL 6.

Table 2-3: NASA Technology Readiness Scale

TRL	Accomplishment
1-2	Concept and application are formulated. Basic phenomena are observed in a laboratory environment.
3	Critical functions are tested in a laboratory environment of breadboard configuration to validate proof-of-concept's potential performance and lifetime.
4	A breadboard system (or at least all the major components of the system) are tested in the laboratory and it is verified that components will work together effectively in a system. At this level, preliminary analytical and experimentally data is available to calculate lifetime performance of critical components.
5	A realistic breadboard portion of the system is thoroughly tested in a relevant environment that demonstrates the flight system design. Lifetime performance predictions of critical components are validated with accelerated tests.
6	System engineering model with approximate "form fit and function" of a flight systems or prototype demonstration tested in a relevant environment on ground or in space. System lifetime performance prediction validated based on accelerated life testing of components and subsystems.

3.0 State of the Art Space Power Solar Cells and Arrays

3.1 Introduction

This section describes state-of-the-art solar cell and array technologies. The section was not intended to describe solar cell and array technologies that are under development or in the technology validation stage. These will be covered in Section 5. However, a few cases, such as thin film technology, where the technology is SOA in terrestrial (but not space) applications are covered in Section 3.

Solar energy has powered practically all unmanned American and European spacecraft since the launch of Vanguard I in 1958. The only significant exceptions have been for planetary missions traveling farther than two astronomical units (AU) from the sun where low solar intensity dictated use of radioisotope power. At the start of the space age, solar arrays produced about 15W/kg and the cells were about 10% efficient. Power output ranged from a few watts to a few tens of watts, although it quickly grew to hundreds of watts. At present, arrays develop 70W/kg, and the cells are almost 27% efficient. Power ranges from tens of watts for very small spacecraft, to tens of kilowatts for commercial spacecraft to 200kW for the International Space Station.

The most recent progress has resulted from research and development sponsored by the Department of Energy and the Department of Defense with some assistance from NASA. Although NASA need not develop high efficiency cells on its own, it does need to invest in the DoE/DoD programs to assure that the cells will be developed with NASA requirements involved. This was done effectively in the 1990s when multi-junction cells were first developed. A summary of the status of the existing space solar cell and array technologies is given in the sections that follow.

3.2 Solar cells

A solar cell is a solid state device that converts light energy (photons) into electrical energy. The important characteristics of solar cells required for many space missions are:

- High efficiency
- Good radiation tolerance
- Tolerance to UV radiation and atomic oxygen
- Long life
- Robustness to withstand mechanical stresses during launch
- High reliability
- Low cost

In addition to these characteristics, some planetary missions may require operational capabilities at low or high temperatures, at low or high solar intensities, and in high radiation fields. Inner planetary missions require solar cells that can function at very high temperatures and high solar fluxes. Outer planetary missions require solar cells that can function at very low solar intensity/flux and very low temperatures.

Single-crystal silicon solar cells were used to produce electrical power on most of the early space satellites since 1958. The scalability, reliability, and predictability of single crystal solar photovoltaics made them the prime choice for power sources by spacecraft designers. Cell efficiencies at AM0 have grown from ~10% for silicon cells in the late 1950's to the ~27% efficient multi-junction cells available today. It is likely that efficiencies will exceed 30% in a few years. The progress in improved cell efficiency is illustrated in Figure 3-1.

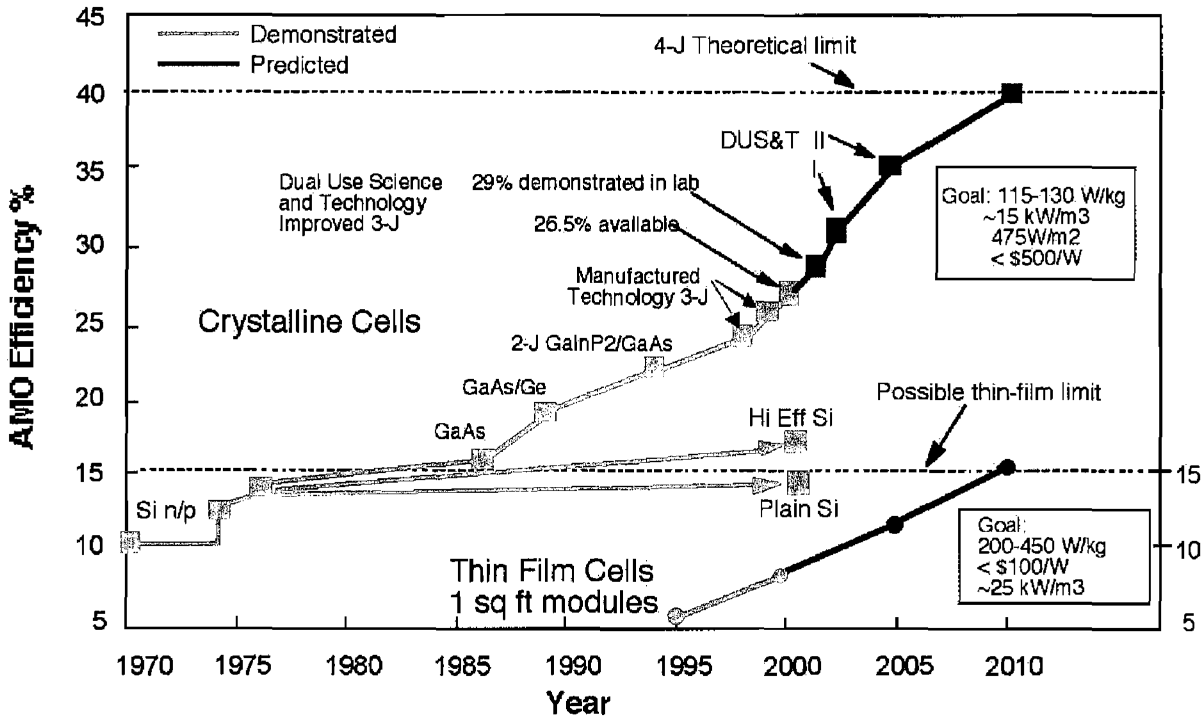

Figure 3-1: Brief History of Advances in Photovoltaic Efficiency.
The upper curves represent crystalline cells and the lower curve to the right represents thin-film cells. Red lines are already demonstrated.
Blue lines are extrapolated to the future

Solar cells that are presently being used in various space missions are:

- Single crystal silicon solar cells
- Single junction GaAs solar cells
- Multi-junction III-V compound semiconductor solar cells

Spectrolab and Tecstar are the major manufacturers of space solar cells in the U. S. Other emerging manufacturers such as Emcore, are also developing significant capabilities. A summary of important characteristics of solar cells used in space is given in Table 3-1. A description of the status of these space solar cell technologies is given in the sections that follow.

3.2.1 Single Crystal Silicon Cells

Silicon solar cells were used on practically all near-Earth spacecraft since the inception of the space program in the early 1960's; it is the most mature of all solar cell technologies. Early 1960s silicon solar cells were typically ~10% efficient, relatively inexpensive, and well suited for the low power (100s of watts), short duration (3-5 years) missions of the time.

Table 3-1: Summary of Existing Space Solar Cell Availability

Parameter	Silicon	High Efficiency Silicon	Single Junction Ga-As	Dual Junction	Triple Junction
Status	Obsolete	SOA	Obsolete	Nearly Obsolete	SOA
STC* Efficiency (%)	12.7 - 14.8	16.6	19	22	26.8
STC* Operating Voltage (V)	0.5	.53	.90	2.06	2.26
Cell Weight (mg/cm^2)	13 - 50	Not Available	80 - 100	80-100	80-100
Temp Coefficient at 28°C	-.0055%/C	Not Available	-.0021%/C		-.0019%/C
Cell Thickness (μm)	50 - 200	76	140 to 175	140 to 175	140 to 175
Radiation Tolerance	.66 - .77	Not Available	.75	.80	.84
Absorptance	.75	Not Available	.89	.91	0.92
Vendors	Spectrolab, Tecstar	ASE, Sharp	Spectrolab, Tecstar	Spectrolab, Tecstar	Emcore, Spectrolab, Tecstar

* STC = Standard temperature conditions

The conversion efficiency of standard-technology silicon cells currently flown varies between 12.7% and 14.8% at Standard Test Conditions (STC). The lower efficiency cells are generally more resistant to radiation. Cell efficiencies for any application should be adjusted for the array packing factor, radiation damage, ultraviolet degradation, assembly losses, and for corrections due to variations in intensity and temperature from standard conditions. At operating temperature, a silicon solar cell will degrade about 25% over 10 years in goesynchronous orbit (GEO) orbit due to charged particle irradiation. The performance of these cells degrades significantly (often exceeding a 50% loss) in very high radiation environments such as experienced near Jupiter over a period of about a year. The relatively large temperature coefficient of silicon cells results in large reductions in efficiency at high temperatures and large increases in efficiency at low temperatures.

There are several enhancements that have been used to make silicon cells more efficient. Among these are textured front surfaces for better sunlight absorption, extremely thin cells with back surface reflectors, internal light trapping, and passivated cell surfaces to reduce losses due to recombination effects. Currently, high efficiency Si cells approaching 17% efficiency at AM0 in production lots are available from Japanese and German producers. Tecstar and Spectrolab, the two large U.S. companies that have produced virtually all of the domestic silicon space solar cells, only offer the conventional type of silicon cells with efficiencies around 14.8% because they have concentrated their development efforts on GaAs-based, multi-junction cells. The advantage of high efficiency silicon cells lies in their relatively lower cost and lower material density (compared to III-V cells).

3.2.2 Single Junction GaAs (III-V) Based Cells

Growing power demands of military satellites spurred a concerted effort to develop more efficient solar cells based on gallium arsenide (GaAs). Unlike Si solar cells that are grown simply by diffusion of dopants into a silicon wafer, GaAs cells are more difficult to fabricate. At first they were grown by liquid phase epitaxy and later by metal-organic chemical vapor deposition. These methods require careful temperature control and working with a broader range of atomic species, some of which introduce environmental challenges. With a concerted 4-year effort, including substantial capital investments to buy MOCVD equipment, the efficiency of a single junction GaAs cell was increased to 18% by the late 1980s. The most significant cost reduction strategy involved replacing the GaAs substrate with a germanium (Ge) substrate that is less costly and mechanically stronger, thus reducing breakage losses.

GaAs/Ge cells currently available on the market have an average conversion efficiency of 19% at AM0. The GaAs-type solar cells have higher radiation resistance than silicon solar cells. For a given amount of shielding in some missions with radiation exposure, these cells degrade about one-third to one-half as much as silicon. This is a sufficient improvement to actually enable some missions with moderately high radiation exposures. Further, these cells have lower temperature coefficients than silicon cells. This property of lower temperature coefficients makes these cells attractive for use at high temperatures, and they are generally preferred over silicon for use with concentrator arrays. However, the performance of these cells is not enhanced as much as Si at very low temperatures. These cells are also heavier and more costly than silicon solar cells.

GaAs/Ge cells were useful to NASA and DoD missions in which the solar array area was limited by sensor view factor considerations or spacecraft size limitations. JPL used GaAs/Ge cells on the Mars Pathfinder mission. The Iridium satellite program was a large commercial user, and it selected these cells in order to enable multiple satellite deployments from a single launch vehicle. The reason that use of GaAs/Ge didnt spread even further was due to delays in availability at a predictable cost, and the inertia in adopting new technology. Eventually, however, the fast development of higher performance multi-junction cells eclipsed the GaAs/Ge cells, and multi-junction cells are now the state of the art.

3.2.3 Multi-Junction GaAs (III-V) Based Cells

Most of the energy in the AM0 solar spectrum (the spectrum in space) is in the wavelength range of 0.25 to 3.0 microns. There is an optimum band gap for a single junction solar cell to obtain maximum power from this spectrum. This optimum arises through the competing trends of higher current output as the bandgap is lowered (due to absorption of more of the light spectrum) versus higher voltage output as the bandgap is increased (due to the inherent band structure of the material). The band gap of GaAs (1.43 eV) is near the optimum for a single layer operating across the solar spectrum. To further optimize the use of the solar spectrum, multi-junction cells are used in which each individual cell has a band gap selected to utilize the portion of the solar spectrum for which it has a high quantum efficiency. In this system, thin layers of two or more photovoltaic materials are stacked on top of one another, each with a different innate bandgap. The material with the highest bandgap is placed on top. It converts the shorter wavelengths of incident sunlight to electric power. The longer wavelengths pass through this layer. Each successive layer has a smaller bandgap and converts longer wavelengths to electric power. Ideally, the same current flows through all layers but the voltages are additive. The quantum efficiency of each junction in a typical three-junction commercial cell for various wavelengths of sunlight is shown in Figure 3-2.

Dual-junction and triple-junction solar cells are presently available from several U. S. vendors. Commercially available dual-junction solar cells are 21-22% efficient. Currently, triple-junction cells consisting of GaInP, GaAs, and Ge, are grown in series-connected layers, and are ~27% efficient in production lots. These high-efficiency cells were developed under the programs funded primarily by the NREL, Air Force, and NASA. The advent of a new competitor in 1998 and other factors combined to reduce space cell costs by ~40% of their 1997 cost. Figure 3-3 provides a schematic representation of double junction and triple junction solar cells.

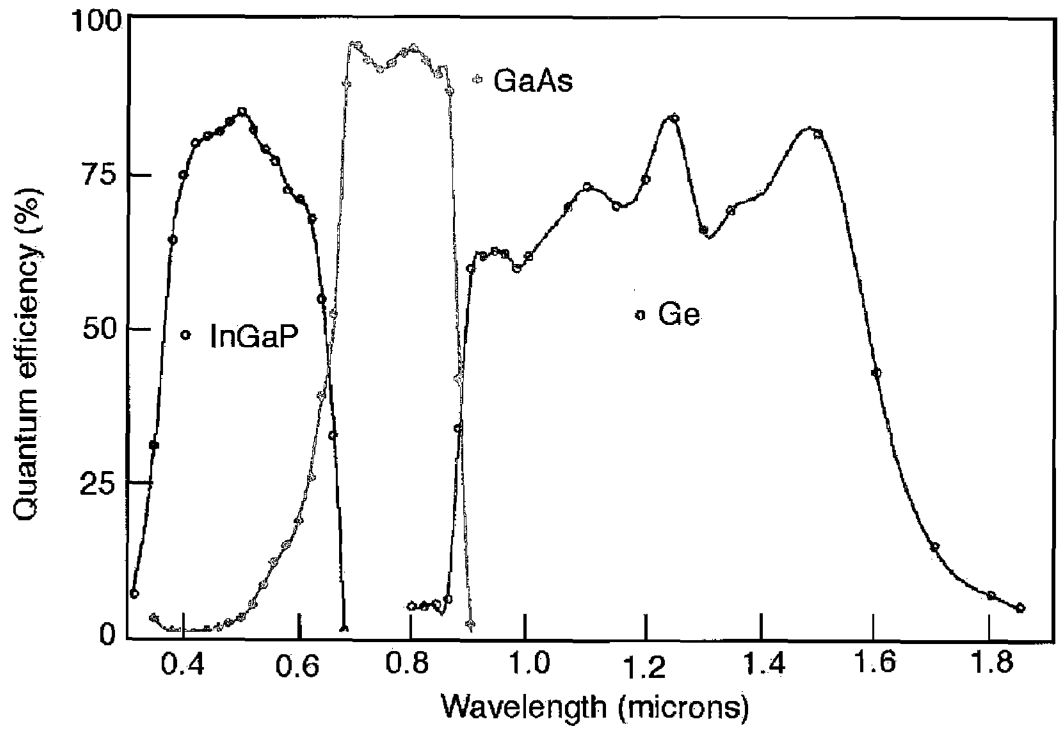

Figure 3-2: Quantum Efficiency vs. Wavelength for Each Layer of a Triple Junction Cell. The InGaP is the uppermost layer and it is used to convert the highest energy part of the spectrum.

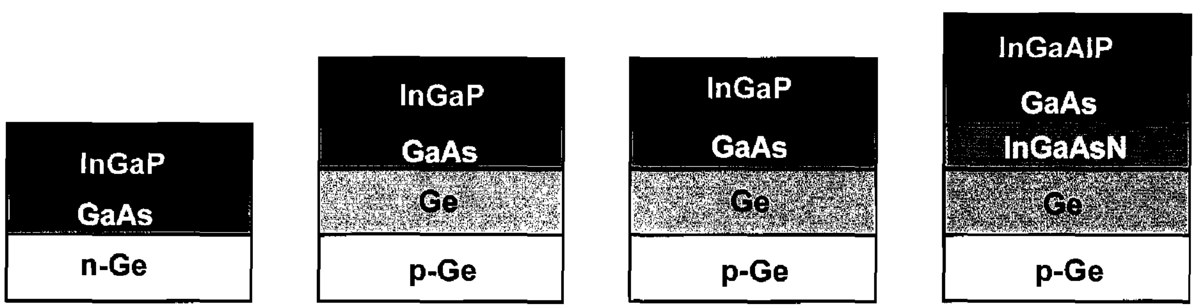

Figure 3-3: Schematic Representation of Double, Triple, and Quad Junction Solar Cells. The lowermost layer is the substrate and does not produce any electrical power.

High efficiency multi-junction solar cells result in a power system that can either be made lighter by about 25% than single-junction GaAs cell technology for a given output, or can provide about 25% more power by maintaining the same mass as single-junction GaAs cell technology. Therefore, high-efficiency multi-junction solar cells were rapidly adopted for use by the commercial satellite industry, as well as by many NASA and military missions. The benefits included system-level cost per watt comparable to silicon, better temperature coefficients, better radiation tolerance, and about one-half the required array area to produce a given power level, compared with silicon. Multi-junction solar cells are the baseline for most NASA missions today including the Mars Exploration Rovers (2003 launch). These multi-junction cells were developed primarily with DoD support, but NASA funds were also contributed in the latter stages to assure that NASA requirements were considered in the final product.

3.2.4 Amorphous/Polycrystalline Solar Cells

Solar cells utilizing amorphous or polycrystalline materials are commonly referred to as Thin Film Cells (TFC). The use of this term is somewhat confusing since the active region in all solar cells, excepting single crystal silicon cells, is a thin film on the order of a few microns thick. The term TFC is used to distinguish these materials from the single crystals from which high efficiency multi-junction cells are made.

The terrestrial photovoltaics market has commercialized amorphous silicon (a-Si), polycrystalline copper indium diselenid, and polycrystalline cadmium telluride. These applications typically use inexpensive glass substrates since weight is not an important consideration. Efficiencies as high as 10% for a-Si and 18% for CIS have been achieved in small sizes. The lack of crystalline perfection in the devices makes them very resistant to displacement damage effects from space radiation. However, since weight is a primary factor for space applications, a great effort is being made to adapt deposition processes to thin stainless steel (SS) and Kapton substrates. The best square-foot-size a-Si cells on SS and Kapton substrates are about 9.8% and 7.5% efficient, respectively. The best CIS cells on SS are about 10% efficient with areas of about 10 cm^2, and about 5% efficient on Kapton. These efficiencies drop off rapidly with increasing area, and this is the primary challenge facing scale-up of thin film technologies. The thin films made with silicon, gallium arsenide, copper indium diselenide, and amorphous silicon are listed in order of increasing radiation resistance. The last two materials are very thin polycrystalline or amorphous films, with relatively low efficiencies, but they are extremely radiation-hard compared to the first two single crystal materials. Thin film silicon cells have been tested on MIR spacecraft. It should be emphasized that use of polycrystalline and amorphous materials on lightweight substrates is still not state of the art technology and is not ready for any missions in space.

3.3 Solar Arrays

Since each solar cell produces power typically in the range from a few hundred mW to more than a Watt, hundreds to thousands of cells are required to meet current, voltage and power requirements of a modern satellite. The International Space Station 100-kilowatt solar power system utilizes about 262,400 cells. Solar cell manufacturers usually package solar cells into panels. Each panel contains solar cells connected in a series /parallel configuration to meet the specified current and voltage output of the panel. Solar panels are then integrated into an array with appropriate deployment mechanisms to meet current, voltage, and power requirements of the satellite. Each satellite is usually equipped with two such arrays (also known as "wings"). Solar arrays are folded for launch so that they can be stowed inside launch vehicle fairings. The International Space Station 100-kilowatt solar power system has eight solar arrays.

Solar array designs have undergone a steady evolution from the first array launched on the Vanguard 1 satellite. Early satellites used silicon solar cells mounted on the honeycomb panels of the spacecraft body. This type of solar array structure can only produce a few hundred watts of power. However, many modern satellites require low-mass solar arrays capable of producing several kilowatts of power. Several new solar array structures have been developed over the past forty years. These new arrays provide significant mass and volume savings and reduced stowed volume during launch. State-of-the-art rigid panel commercial arrays have a specific power of 40-60 W/kg. One advanced flexible array has a specific power of up to 100 W/kg.

The major components of the solar array are: cell assembly, panel assembly, and array structure. A cell is the fundamental building block of the solar array and the cell assembly consists of the solar cell, the cover glass, and the interconnect tabs. Cell assemblies with multi-junction cells usually contain a diode for current bypass; assemblies with single junction cells do not. Some modern cells have built-in bypass diodes. A panel assembly consists of a substrate, a cell assembly, hinges, and a wiring harness. The mass of the panel assemblies varies from 50 to 75% of the mass an array. The array structure consists of a deployment mechanism, a support structure, and (in some cases) a containment box. The mass of the array structure may comprise up to 30-50% of the array mass.

The most important characteristics of solar arrays required for space applications are

- High specific power (W/kg)
- Low stowed volume (W/m^3)
- Low cost ($/W)
- High reliability

Several planetary missions have significant additional requirements. Some Earth orbiting missions require electrostatically clean arrays. Inner planetary missions require solar arrays capable of withstanding 300-400°C temperatures and functioning at high solar intensities. Outer planetary missions require solar arrays that can function at low solar intensities and low temperatures. Some of the missions to Jupiter and its moons require solar arrays that can withstand high radiation levels.

The solar arrays presently in use can be classified into seven categories:

- Body-mounted arrays
- Rigid panel planar arrays
- Flexible panel array
- Flexible roll-out arrays
- Concentrator arrays
- High intensity arrays
- Electrostatically clean arrays

A summary of the important characteristics of these arrays with is given Table 3-2.

Table 3-2: Characteristics of Solar Arrays

Technology	Max Power per Wing @1AU, AM0 (watts)	Sp. Power W/kg (BOL) @ Cell Efficiency	Cost $K/W	TRL	Area per KW (m^2/kW)
High Efficiency Silicon Rigid Panel		58.5 @ 19%	0.5-1.5	9	4.45
HES Flexible Array (Round/Ultra-Flex)	< 20K	114 @ 19%	1.0-2.0	8	5.12
TJ GaAs Rigid	< 20K	70 @ 26.8%	0.5-1.5	9	3.12
TJ GaAs Ultraflex	< 20K	115 @ 26.8%	1.0-2.0	7	3.62
CIGS / Thin Film (*)	< 20K	275 @ 11%	0.1-0.3	3-4	7.37
Amorphous-Si MJ / Thin Film (*)	< 20K	353 @14%	0.05-0.3	3-4	5.73

(*) Projected. These arrays are not currently feasible.

3.3.1 Body-Mounted Arrays

Body-mounted arrays are preferred for small satellites that only need a few hundred watts. Early spherical satellites and spin-stabilized cylindrical satellites used silicon solar cells mounted on the honeycomb panels of the spacecraft body. This type of array is simple and past applications had no major problems with reliability. One of the limitations of this type array is that only a part of the array faces the sun at any time. This type of array is still used on smaller spacecraft and spin stabilized spacecraft. Body-mounted arrays are still used on planetary rovers. Mars Pathfinder Sojourner Rover and the Mars Exploration Rovers use body-mounted solar arrays.

3.3.2 Rigid Panel Planar Arrays

Rigid panel arrays are attractive for missions requiring several hundred watts to many tens of kilowatts of power. These consist of rigid honeycomb core panels that are hinged together and folded against the side of the spacecraft for launch (Figure 3-4). An individual panel is very stiff and strong, but relatively lightweight. In recent years, honeycomb panels have been made from materials other than aluminum, most notably from graphite/epoxy sheets and ribbons. Hybrid panels with aluminum honeycomb covered by epoxy/glass face sheets have also been used. Subsequent to achieving the desired orbit, these arrays are released by means of pyrotechnic, paraffin or knife blade actuators and deployed by damper-controlled springs.

The BOL power density of the rigid panel array depends on the type of solar cell. In general the BOL power densities range from 35 to 65 W/kg for silicon cells, and 45-75 W/kg for GaAs/Ge cells. Typically, for a rigid panel array, the panel assembly accounts for 75-80% of the total mass and the stowage and deployment structure make up the rest. The Tropical Rainfall Measuring Mission (TRMM) and Rossi X-Ray Timing Explorer (XTE) arrays exemplify this arrangement on scientific spacecraft. Rigid panel arrays can run the gamut in size from very small to in excess of 100kW, though they are generally not the optimum choice at the larger sizes.

Figure 3-4 Rigid panel GaAs Solar Array

3.3.3 Flexible Fold-Out Arrays

Flexible fold-out arrays are attractive for missions that require several kilowatts of power because of their high specific power, high packaging efficiency (low stowed volume) and simple deployment system. These arrays are available in two configurations:

- Flexible flat panel/rectangular array with linear deployment (Figure 3-5)
- Flexible round panel array with circular deployment (Figure 3-6).

These arrays have flexible or semi-flexible panels that are stowed for launch with accordion folds between each panel. On reaching an appropriate orbit, these are unfurled by means of an Astromast™ , an Able-mast™ , or some other similar device. The specific power of these types of arrays varies from 40-100 W/kg, depending on the cell type, power, mission reliability requirements, spacecraft orientation and maneuverability capabilities, and safety requirements. Initially, they were marketed as a significant improvement in power produced per unit mass. However, even though flexible arrays have an excellent figure-of-merit in this regard, the best rigid honeycomb panels have thus far matched their specific power performance. Very large flexible blanket solar arrays present complex structural and spacecraft design issues. This type of array is used on the MILSTAR series of spacecraft, on the TERRA spacecraft, and on the International Space Station.

Figure 3-5. Flexible Flat Panel/rectangular Array with Linear Deployment

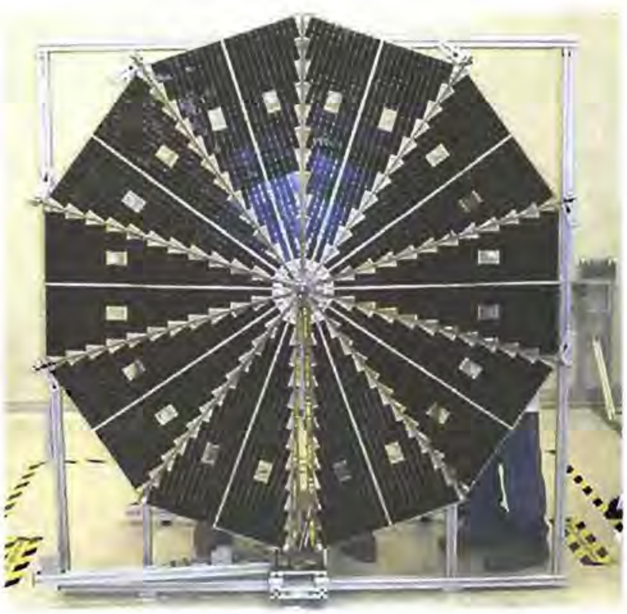

Figure 3-6: Flexible Round Panel Array With Circular Deployment

NASA developed a flexible flat panel/rectangular array in late 1980's known as the Advanced Photovoltaic Solar Array (APSA). TRW developed this array under contract to NASA/JPL. DoD also developed a similar array. Both array designs were based on the same fundamental concept of using polyimide panels stretched between lightweight hinges with the whole structure deployed by an extendible mast. The original APSA design was for 130 W/kg at 5.3 kW BOL in GEO. The specific power of this type of array does not scale linearly. Low power arrays of this design have considerably lower specific power, of the order of 40-60 W/kg. Silicon cells with an average efficiency of 14% at AM0 were initially baselined for this array. In this design, the structure (mast, release motor, containment box) accounts for about 51% of the array mass. The panel assembly consisting of polyimide substrate, cell assembly (cell, cover glass, and interconnect tabs), hinges, and wiring harness make up the rest. Projected specific power of the APSA array with various cell technologies available in the early 1990s are given in Figure 3-7. The TERRA satellite uses an APSA-type array. The specific power of this array is about 40 W/kg, because of the practicalities imposed by an operational spacecraft. These included the necessity of reinforcing the stowage box because the box could not be stiffened by the spacecraft structure as APSA had assumed would be possible, and because of the necessity of a stronger and heavier substrate than APSA had assumed would be necessary. The International Space Station Array (Figure 3-8) has a BOL specific energy of 40 W/kg due to maneuverability, safety, and reliability requirements.

3.3.4 Flexible Roll-out Arrays

The flexible roll-out array is similar to the accordion-folded array mentioned earlier except that the semi-flexible or flexible substrate is rolled into a cylinder for launch. The Hubble Space Telescope (HST) used such a roll-out array. It contained a polyimide blanket in a roll-up stowed configuration. The array was deployed by a tubular, extendable boom (Bi-STEM) deployment system. The flexible roll-out array design was developed for the US Air Force. But HST roll-out arrays were replaced by honeycomb core panels at the recent servicing mission because the roll-out array was perceived to be less reliable. Flexible roll-out arrays are now considered obsolete, displaced by the more reliable fold-out arrays.

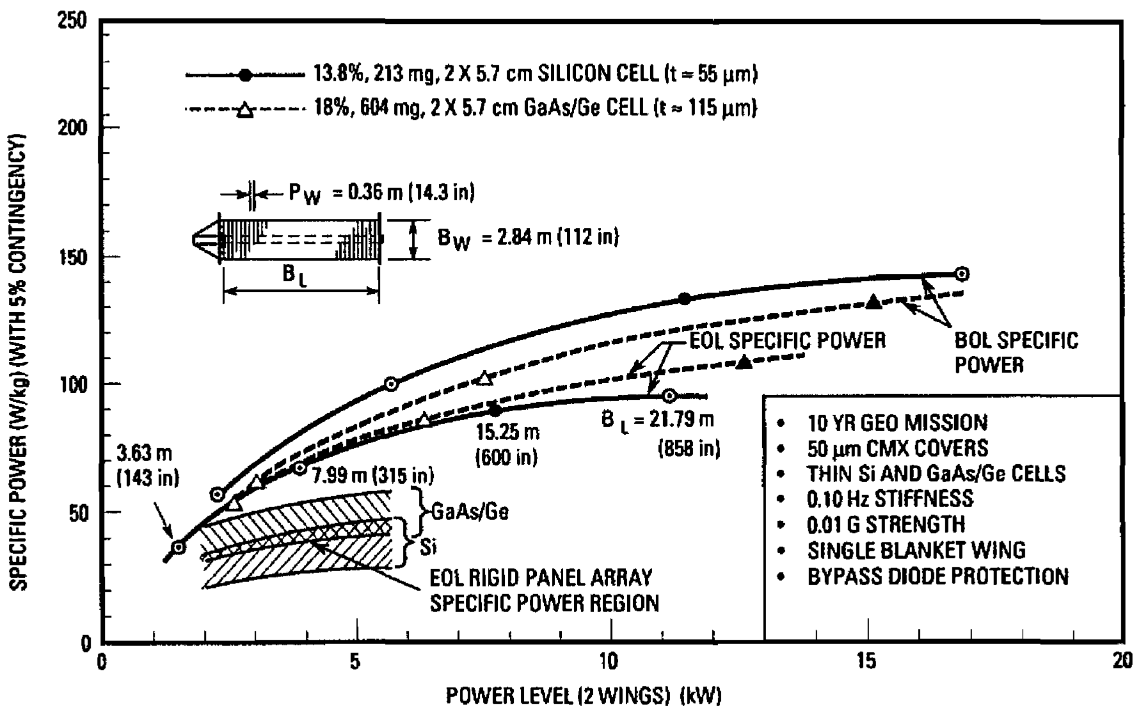

Figure 3-7: Projected Specific Power of the APSA Array with Various Cell Technologies

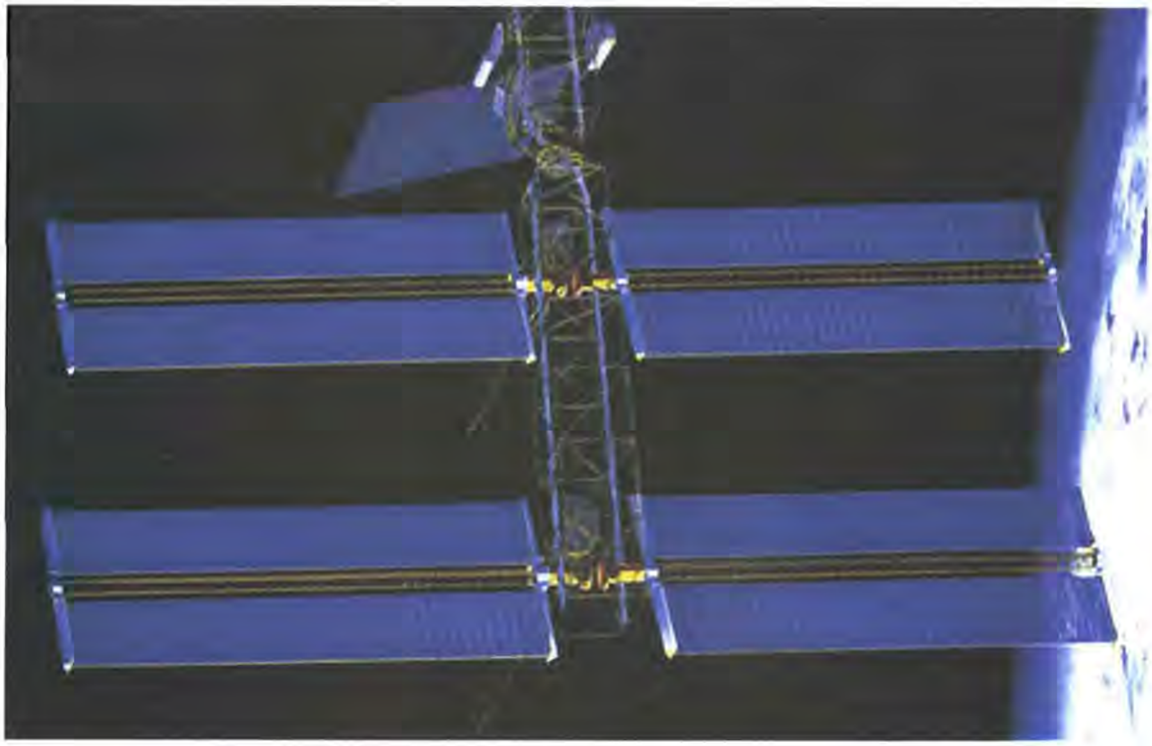

Figure 3-8: Space Station Solar Array

3.3.5 Concentrating Arrays

Photovoltaic concentrating arrays are candidates for use on missions to outer planetary missions, solar electric propulsion missions, and missions that operate in high radiation environments. These arrays are attractive for these missions because they have the potential to provide a high specific power, higher radiation tolerance, and improved performance in low intensity/low temperature environments. The technical issues in using concentrating arrays are: precision pointing, thermal dissipation, non-uniform illumination, optical contamination, environmental interactions, and complexity of deployment. They also decrease overall spacecraft reliability because a loss of pointing causes significantly more power loss to the spacecraft than with a flat panel array.

Concentrator arrays use either refractive or reflective optics to direct concentrated sunlight onto a smaller active area of solar cells. Reflective systems can have concentration ratios from 1.6X to over 1000X, at least in principle, although it is doubtful that concentration ratios beyond 100X will prove to be practical. Refractive designs are generally limited to the range of about 5X to 100X, but will probably be practical only up to perhaps 20X. Solar energy may be focused on a plane, line or point depending on the geometry of the concentrator design. These concentrators may be very small and numerous as in a distributed focus design, or a single large concentrator may be used in a centralized focus design.

The flight history of concentrators as spacecraft prime power providers began with the AstroEdge™ array on the NRO STEX spacecraft, launched in October, 1998. This system used a reflective trough design with a nominal 1.5X concentration. The flight results showed that the arrays deployed as expected and cell currents were slightly higher than predicted. Thermal problems occurred on some of the panels that had not been qualified for the higher concentrator operating temperature.

The Deep Space 1 spacecraft launched in October 1998, uses SCARLET arrays to provide power to its ion propulsion engines. It has two arrays and each array is capable of producing 2.5 kW at 100Vdc. The SCARLET array was developed by AEC under a program sponsored by Ballistic Missile Defense Organization (BMDO) (Figure 3-9).

Figure 3-9: SCARLET Array

The SCARLET array uses a refractive concentrator scheme (linear distributed focus) with a 7.5X concentration ratio. The array uses 720 lenses to focus sunlight onto 3600 solar cells. The spacecraft has two SCARLET solar array wing assemblies, each composed of a composite yoke standoff structure, four composite honeycomb panel assemblies and four lens frame assemblies. Multi-junction GaInP2/GaAs/Ge cells were used in this array. The characteristics of the SCARLET array are given Table 3-3.

The first commercial concentrator array in space was the Boeing 702 that was deployed January 12, 2000 on Galaxy XI. This concentrator reflects the sun's rays onto a single rectangular plane of solar cells making it a reflective planar centralized focus design. It uses a reflective trough design with 1.7X concentration, thin film reflectors, and was designed for power levels of 7 to 17 kW with a 16+ year design life. The array deployed as expected and orbital performance was initially within expected ranges. However, time on orbit anomalously and significantly degraded the concentratc surfaces. In the future, Boeing plans to use only flat panel arrays. The specific power of this array is abot 60W/kg using 24% efficient multi-junction solar cells. The similar Boeing 601 bus, which is equipped witl a planar solar array, is limited to about 15kW of power due to the array stowed volume limitations.

Table 3-3: Characteristics of the SCARLET Array

High efficiency triple-junction $GaInP_2/GaAs/Ge$ solar cells used Arched
Linear Fresnel lenses focus light onto spaced rows of solar cells
5X-7X cell area reduction
Wing Dimensions: 206 in. x 64 in.
Panel Dimensions: 45 in. x 63 in.
Wing Power: 1250 W (1 AM0)
Mass: 27.7kg (with tie-downs)
>70 W/kg BOL for standard platform
Prototype panel solar-to-electric conversion efficiency = 27.4% at AM0 & room temperature
Stowed Stiffness: 92 Hz
Deployed Stiffness: 0.35 Hz
Deployed Strength: > 0.015 g's
DS1 Launch Date: 24 October 1998
Total in-flight degradation due to lens, cover glass, structural distortion and cell radiation only 5% to date

3.3.6 High Temperature Arrays

The two mission destinations with a need for high temperature, high intensity, solar arrays are Mercury and close encounters to the sun. At least two missions have already flown and functioned well at high intensities: Helios A, launched on 10 December 1974, which reached 0.31 AU; and Helios B, launched on 15 January 1976, which reached 0.29 AU. Both of these spacecraft used silicon cells that were slightly modified for high intensity use in conjunction with second surface mirrors to cool the array. The remainder of their technology was close to that used on standard arrays. In addition to these missions, the MESSENGER Discovery mission (now in Phase C/D) is planned for operation to 0.31 AU. Its solar array design is already under development.

At present, solar array technology is just sufficient to meet the needs of MESSENGER or other spacecraft that approach the sun to about 0.3 AU, but with reduced performance and increased risk compared to other applications. Closer encounters to the sun will require further development.

One feature is present in the solar arrays that have operated at high intensities. This is the replacement of a significant fraction of the solar cells by optical solar reflectors (OSRs). This helps to control the array temperature at small distances from the sun but it reduces the power at larger distances.

In addition to the above, MESSENGER off-points the array as the spacecraft nears the sun. The array is designed to tolerate failures in the pointing mechanism as the array can withstand pointing at the sun for a minimum of one hour and probably much longer, although it cannot function under these extremes. In normal operation the array operates as high as 130°C, if the off pointing fails, the array may point directly at the sun reaching a temperature of 260°C.

SOA technology also includes work performed by the US Air Force and BMDO in the late 1980s to develop solar cells and arrays capable of surviving laser attack, among other threats. This work was performed under the names of Survivable COncentrating Photovoltaic Array (SCOPA) and SUrvivable PowER System (SUPER). The most common approach was to use concentrator arrays that kept the incident laser light from impinging on the solar cells. Although guided away from the solar cells, the laser did raise the array temperature by hundreds of degrees Celsius and therefore high temperature cells and array substrates were developed.

The principal modifications to GaAs solar cells that improved high temperature survivability were changes to the contact metallization composition and the introduction of diffusion barriers. Both Tecstar and Spectrolab participated in this effort and retain the knowledge base. Other smaller companies such as Astropower, Kopin, and Spire also developed cells but they have never been in the business of producing space solar cells. Using this approach, 18% efficient GaAs/GaAs cells were produced that degraded less than 10% in one-sun efficiency after annealing in vacuum for 15 minutes at 550°C. Concentrator cells were produced that survived repeated 7 minute excursions to 600°C and showed only a 10% loss after a single exposure to 700°C).

The present state of the art of high temperature arrays is inadequate, and advances are needed in substrate adhesives, high temperature substrates, high temperature cell contacts, second surface mirrors, coatings and mechanisms, and long term testing. These needs are described in Section 5 of this report.

3.3.7 Electrostatically Clean Arrays

Sun-Earth Connection spacecraft typically measure fields and particles, and therefore require arrays that do not distort the local environment. These are referred to as electrostatically clean arrays. These arrays do not allow the array voltage to contact and thereby distort the plasma, and additionally, the entire exterior surface of such an array is maintained at approximately the same potential as the spacecraft structure. This constancy of potential, chiefly obtained by replacing the array's insulating surfaces with conductive surfaces, is used to prevent distortion of the fields and particles that are measured by the spacecraft.

Fabricating an electrostatically clean array presently costs three to six times as much as typical arrays due largely to the amount of hand labor involved. In addition, the conductive coatings are less robust than desired. Because electrostatically clean arrays tend to be body-mounted, and therefore array area is limited, these spacecraft have a greater need for high-efficiency cells than many spacecraft. These solar arrays also need thicker covers because they typically operate in high radiation environments, and such covers are presently unavailable.

For an electrostatically clean array, the solar cell covers must be coated with a conductor, typically, indium tin oxide, and the spaces between the cells must also be covered with a conductor. However, the cell-interconnects cannot be directly covered with a conductor or they would short out the array. In practice this means that insulators must cover the interconnects, and conductors must cover the insulators. All of this must be done in a thickness of ~0.08 mm and within a width of about 0.8 mm. One method of doing this is to grout the areas between each cell with an insulating adhesive, and then cover that grouting with a stamped pieces of metal or "v-clips." This requires significant expense because of the grouting and the mounting of thousands of clips. It also poses some reliability issues because the clips had a tendency to fall off. (There are other methods; but they are equally problematic.)

Another significant expense involved in using electrostatically clean arrays is the extra cost manufacturers add to their bids because they are not familiar with electrostatically clean arrays due to lack of previous experience or a well known, proven method of fabricating the array. This is illustrated by the Fast Auroral Snapshot (FAST) solar array. The electrostatically clean body-mounted solar panels for FAST cost in excess of $7,400 per test condition watt.

One recent advance that is expected to reduce the cost of these arrays is the monolithic diode used on the latest generation of multi-junction solar cells. The presence of antennas, booms and outcroppings from a body-mounted array, typical for an electrostatically clean spacecraft, implies that the solar cells must have bypass diodes to reduce the shadowing losses to a tolerable level. The new built-in diodes are significantly less expensive than adding the diodes as a part of the array circuitry. This item has recently been fully developed.

The NASA Goddard Space Flight Center (NASA-GSFC) provided $300K in FY 2000 to study a method for improving and lowering the cost of solar arrays with electrostatic cleanliness (through the Solar Terrestrial Probe (STP) Program's Magnetospheric Multiscale (MMS) and Geospace Electrodynamic Connection (GEC) projects). A contract was awarded to Composite Optics Inc. (COI) to demonstrate their concept of covering the array with a thin graphite reinforced plastic aperture that is conducting on its "up" side and insulating on its down- or cell-side. This aperture has cutouts that allow sunlight to strike the cells, but covers the areas between the cells. The aperture also serves to make electrical connections to the ITO-coated solar cell covers. The work that has been performed to date is promising. The contractor successfully showed that registration between the solar cells and the aperture could be maintained and that the aperture would do its job at the beginning of life. However, after environmental exposure, many of the electrical connections between the aperture and the ITO failed. It appears that this can be fixed by changing the type of conductive adhesive used between the aperture and the ITO.

Partly as a consequence of COI's research funded by NASA-GSFC, COI is supplying the electrostatically clean solar panels for the Communication/Navigation Outage Forecast System (CNOFS), an Air Force Mission to demonstrate whether atmospheric disturbances that cause communication problems can be predicted. CNOFS should serve to define an improved the state of the art.

3.3.8 Mars Solar Arrays

Mars orbiters use photovoltaic arrays similar to those used in Earth orbit. Mars surface missions might employ either radioisotope power or photovoltaic power. Past surface missions that used photovoltaic power, relied upon conventional cells designed for Earth orbit and took no specific steps to mitigate the effects of dust accumulating on the horizontal array. By using conventional cells on the surface of Mars, where it is known that the solar spectrum is depleted at short wavelengths, the efficiency of the cells would be somewhat lower than if the cells were operated above the atmosphere of Mars. This effect reduces the cell efficiency by about 8% (i.e., a 26.5% cell in orbit would operate at around 24% on Mars). The effect of dust accumulating on arrays was observed on the Mars Pathfinder mission by means of cells exposed to the environment whose short circuit current could be monitored on a routine basis. One cell indicated an increase in obscuration of about 0.3%/sol for the first 20 sols (note a "sol" is a Martian day of 24.6 hours). The other cell indicated that over a longer period of ~80 sols, the obscuration flattened out and seemed to be approaching an asymptote of around 20% obscuration. Neither of these results is completely satisfactory, and the effect of Mars dust on performance of solar arrays remains somewhat in doubt. Nevertheless, dust accumulation does clearly present a challenge to long-term operation of solar arrays on Mars.

3.4 Infrastructure

NASA infrastructure plays two import roles in NASA photovoltaic technology:

- Facilities for NASA investigation of advanced (low TRL) photovoltaic concepts
- Measurement, test, and calibration of photovoltaic cells under a wide variety of environmental conditions

In the early days of space flight there were no commercial users of space. All missions were sponsored by NASA or DoD. The NASA infrastructure played a vital role in providing facilities for fabrication, test and calibration of photovoltaic cells. Eventually, as commercial satellites became more numerous, industry built up its capabilities. By the 1990s, commercial space applications became dominant in comparison with NASA. As a result, the need for NASA facilities for solar cell development and testing became less important to the commercial user. However, NASA facilities remain critical to test cells and array materials that are relevant to the unique environments that the NASA missions typically encounter. In addition, NASA capabilities remain the prime means of calibrating cells for space use and assessing radiation susceptibility of cells, for both commercial and government use. The need to retain and upgrade these capabilities remains vital to NASA interests.

In order to design a space power system for any mission, it is necessary to understand how the photovoltaic array will perform in the environments in which it will operate. Photovoltaic cells are constantly evolving and require calibration at frequent intervals. Measurement of fundamental characteristics such as cell efficiency, open circuit voltage, short-circuit current, etc., at air mass zero in the solar spectrum is not a simple thing. While a number of simulation facilities exist, each of these introduces uncertainties and inaccuracies. In order to make more reliable measurements, it is necessary to make measurements with airplanes or balloons. By flying an airplane at several altitudes, the properties can be plotted vs. airmass and extrapolated back to airmass = zero. The space measurements can determine performance to within 1%, whereas earth-based solar simulators can result in errors of several percent. Comparison of space measurements with simulator measurements can help calibrate the simulator.

For properties of photovoltaics under special conditions such as LILT, high intensity, dusty conditions such as occur on Mars, or high radiation environments, special NASA test facilities are required. But the role of NASA is not relegated only to test. Special facilities for testing cell performance, degradation, and lifetime under severe environments are not available in the commercial world. By appropriate analysis, it may be possible to reduce the number of tests required. For example, the Solar Array Verification and Analysis Tool (SAVANT) under development by the Ohio Aerospace Institute (OAI) will provide a user-friendly computer program to predict end-of-life characteristics of a solar array for any space mission with arbitrary radiation exposure. It will allow scattered measurements of radiation damage at several energies and doses using protons and/or electrons to be correlated into a single dose curve, equally applicable to electrons or protons.

4.0 Future Missions that Require or May Benefit from Solar Power

This section describes future NASA OSS potential future missions and their projected requirements for advanced solar cell and array technologies. Although some of these missions could utilize other power sources (e.g., radioisotope), there are many examples where the cost would be prohibitive and the supply of isotopes might be too limited to support them all.

The major strategic goals of the NASA Space Science Enterprise are to: (1) understand the evolution of the universe from origins to destiny and understand its galaxies, stars, and planets; (2) support human exploration; and (3) develop new technologies that will enable the exploration of the universe. Some of the specific goals of the NASA OSS enterprise are: (1) understand the nature and history of our Solar System, and what makes Earth similar to and different from its planetary neighbors; (2) understand the origin and evolution of life on Earth; (3) understand the external forces, including comet and asteroid impacts, that affect life and the habitability of Earth; (4) identify locales and resources for future human habitation within the solar system; (5) understand how life may originate and persist beyond Earth and (6) support human space flight. A number of challenging missions are being considered to realize these goals. These future missions are organized according to the following NASA OSS themes. The themes are:

- Solar System Exploration (including Mars Exploration Program)
- Sun-Earth Connection
- Astronomical Search for Origins
- Structure and Evolution of the Universe

NASA's Office of Space Science has an ambitious plan to implement future missions. These missions are divided into groups according to the themes of OSS. Table 4-1 lists the various missions, along with rough estimates of whether they are near-term (launch by 2009), mid-term (launch from 2010 to 2016) or far-term (launch beyond 2016).

A number of the future SSE, SEC, ASO, and SEU far-term missions under study require advanced solar cell and array technologies to meet their power requirements. Most of these missions require advanced solar cell/array technologies with high efficiency, low mass, low stowed volume, high reliability, and low cost.

Some missions may emphasize some of these characteristics over others due to unique requirements and/or environments. Some of the SSE and SEC missions have additional unique requirements such as: solar cells and arrays that function in low solar intensities and at low temperatures (outer planetary missions), highly radiation resistant solar cells and arrays (Jovian missions), solar cells/arrays that function at high temperatures and high solar fluxes (missions to planet Mercury and the Sun), solar cells and arrays that produce >10 to 25 kW (solar electric propulsion missions), and electrostatically clean arrays (Solar-terrestrial probe missions of SEC. Table 4-2 identifies the unique solar cell and array requirements of the SSE, SEC, ASO and SEU missions. Details of the future mission requirements for solar cell/array technologies of the SSE, SEC, ASO and SEU themes are discussed below in this section.

4.1 Solar System Exploration Program

The NASA SSE Division is planning a number of ambitious missions to several outer planets, inner planets, comets, asteroids, and Mars. The solar cell and array technology requirements for outer planet, inner planet, and Mars missions are quite different from one another and are dependent on the mission type.

Table 4-1: Planned NASA Missions near-term (launch by 2009), mid-term (launch from 2010 to 2016) or far-term (launch beyond 2016)

Acronym	Mission	Time Scale	Theme
MER	Mars Exploration Rover Mission	Phase C/D	ESS-Mars
MRO	Mars Recon Orbiter	Near Term	
CNES1	Mars CNES Orbiter Flight 1	Near Term	
CNES2	Mars CNES Orbiter Flight 2	Near Term	
MSL	Mars Smart Lander	Near Term	
Scout1	Mars Scout 1	Near Term	
ASI 1 & 2	Mars ASI/NASA Telesat and Science Orbiter	Near Term	
MSR	Mars Sample Return	Mid Term	
Scout2	Mars Scout 2	Mid Term	
EO	Europa Orbiter	Near Term	ESS Non-Mars
PKE	Pluto-Kuiper Express	Near Term	
EL	Europa Lander	Mid Term	
NO	Neptune Orbiter	Mid Term	
CNSR	Comet Nucleus Sample Return	Mid Term	
VSSR	Venus Surface Sample Return	Far Term	
SRO	Saturn Ring Observer	Far Term	
TE	Titan Organic Explorer	Far Term	
SIM	Space Interferometer Mission	Near Term	ASO
LISA	Laser Interferometer Space Antenna	Near Term	SEU
GLAST	Gamma-ray Large Area Space Telescope	Near Term	SEU
ACCESS	Advanced Cosmic-ray Composition Experiment for Space Station	Near Term	SEU
NGST	Next Generation Space Telescope	Mid Term	ASO
TPF	Terrestrial Planet Finder	Mid Term	ASO
ARISE	Advanced Radio Interferometry between Space and Earth	Mid Term	SEU
OWL	Orbiting Array of Wide-angle Light Collectors	Mid Term	SEU
Con-X	Constellation-X	Far Term	SEU
EXIST	Energetic X-ray Imaging Survey Telescope	Far Term	SEU
HSI	High Resolution Spectroscopy (HSI) Mission	Far Term	SEU
FAIR	Filled Aperture Infrared	Far Term	ASO
SUVO	Space Ultraviolet Observatory	Far Term	ASO
PI	Planet Imager	Far Term	ASO
LF	Life Finder	Far Term	ASO
MAXIM PF	MicroArcsecond X-ray Imaging Mission Pathfinder	Far Term	SEU
SPIRIT	Space InfraRed Interferometric Telscope	Far Term	SEU
MAXIM	MicroArcsecond X-ray Imaging Mission	Far Term	SEU

Table 4-1: Planned NASA Missions near-term (launch by 2009), mid-term (launch from 2010 to 2016) or far-term (launch beyond 2016) (Continued)

Acronym	Mission	Time Scale	Theme
MMS	Magnetospheric Multi-Scale	Near Term	SEC
SDO	Solar Dynamics Observatory	Near Term	
GEC	Geospace Electrodynamic Connections	Near Term	
LWS-GM	Living With a Star – Geospace Missions	Near Term	
Sentinels	Sentinels	Near Term	
MC	Magnetospheric Constellation	Mid Term	
SP	Solar Probe	Mid Term	
SPI	Solar Polar Imager	Mid Term	
RAM	Reconnection and Multiscale Probe	Mid Term	
ITM Waves	Ionosphere-Thermosphere-Mesosphere Waves Probe	Far Term	
JPO	Jupiter Polar Orbiter	Far Term	
SPECS	Submillimeter Probe of the Evolution of Cosmic Structure	Far Term	
ISP	Interstellar Probe	Far Term	
GSRI	Geospace System Response Imager	Far Term	
SI	Stellar Imager	Far Term	

Table 4-2: Unique Solar Cell/array Requirements of the SSE, SEC, ASO and SEU Missions

	Future Missions		
Solar Cell/Array Technology	SSE	SEC	ASO & SEU
Missions	MER, MRO, MSL, MSR, Scout, EO, PKE, EL, NO, CNSR, VSSR, SRO, TE	MMS, SDO, GEC, LWS-GM, Sentinels, MC, SP, SPI, RAM, ITM Waves, JPO, SPECS, ISP, GSRI	SIM, LISA, GLAST, ACCESS, NGST, TPF, ARISE, OWL, Con-X, EXIST, HSI, FAIR, SUVO, PI, LF, MAXIM PF, SPIRIT, MAXIM
Low-cost	X	X	X
High-efficiency and low-mass	X	X	X
Advanced deployment and retraction	X	X	
Low-intensity and low-temperature (LILT)	X	X	
Radiation tolerance	X	X	
High-temperature environments	X	X	
Dust mitigation on Mars	X		
Large power for SEP	X		
Electrostatically clean arrays		X	

4.1.1 Outer Planets

As of January 2002, some of the outer planetary missions under study (for >2007 launch) were:

- Europa Orbiter
- Pluto/Kuiper Express
- Europa Lander
- Neptune Orbiter
- Titan Explorer
- Saturn Ring Observer
- Jupiter Polar Orbiter.

A decadal survey is underway in 2002 to revise and update the candidate missions.

All of these missions have a common requirement of operating for the most part at significant distances from the sun. The solar intensity at Jupiter (5.1 AU) is 3.7% of that at AM0. At Saturn (9.5 AU) it is 1.1%, at Uranus (19.2 AU) it is 0.28%, and at Neptune (30 AU) it is 0.1%. In view of this, solar power was not considered in early planning for these missions. In the past, missions that travel far from the sun have used radioisotope thermoelectric generators, but there may be programmatic, economic, and political reasons to consider using solar power for some missions in the future. As a minimum, it is required that missions that plan to use radioisotope power, must demonstrate that a mission cannot be done effectively with solar power. Therefore, all missions must examine the possibility of using solar power, even those that go far from the sun. Solar power could be considered for future missions in two ways. One use of solar power would be to employ solar electric propulsion to accelerate the needed payload mass toward the planetary target while still in the inner solar system, with radioisotope power used for operations far from the sun. The other use of solar power would be to operate the spacecraft and instruments from solar power while the spacecraft is at its planetary target large distances from the sun.

Solar electric propulsion (SEP) is attractive for many outer planetary missions because it either significantly reduces the cruise time (time of flight) required to reach the outer planets, or increases the payload mass. Figure 4-1 illustrates the benefits for a Titan Explorer mission. However, it should be emphasized that although use of SEP produces significant benefits over chemical propulsion, use of aerocapture for orbit insertion also contributes to the total improvement over chemical propulsion.

Proponents of SEP tend to emphasize ion thruster development such as the "next generation NStar" thruster, and simply assume that large lightweight, radiation-resistant, LILT-resistant, low stowed volume arrays will be available. Such arrays will not be available if NASA doesn't develop them.

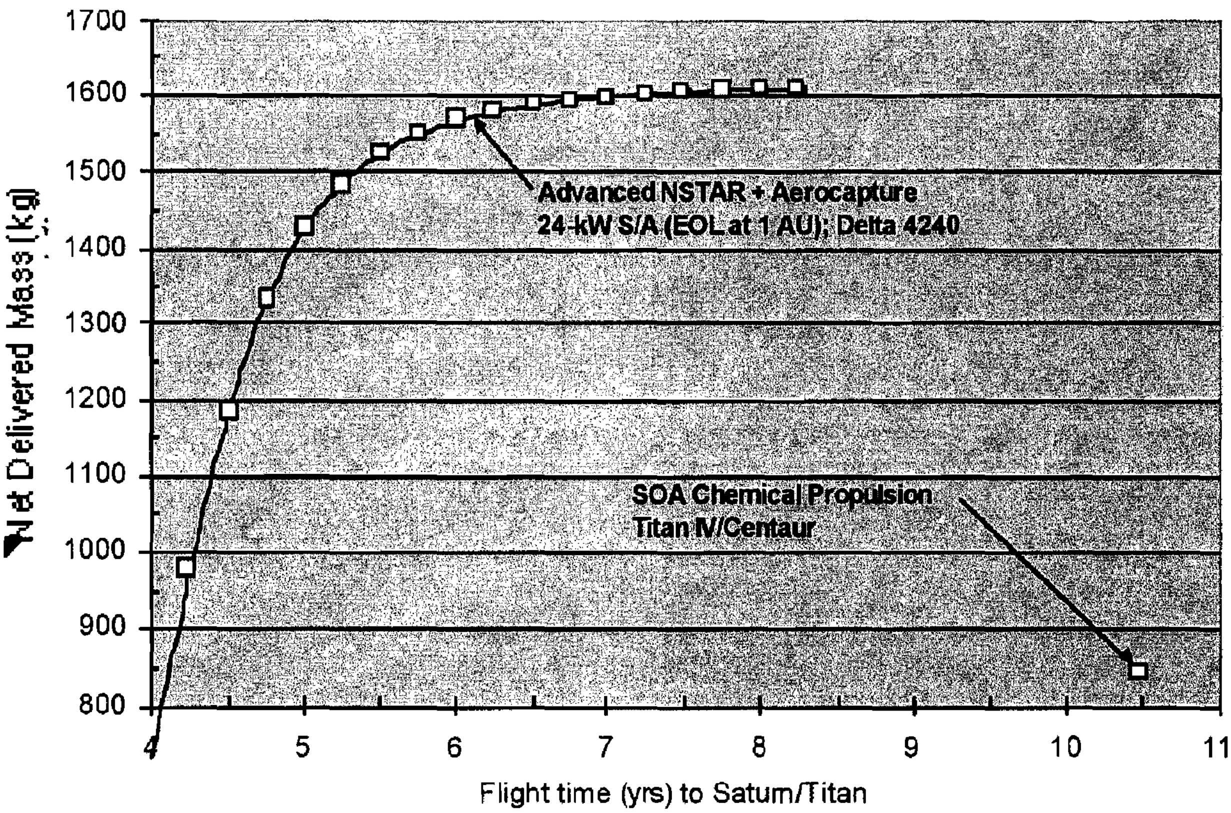

Figure 4-1: Comparison of flight time to Saturn/Titan using SEP or chemical propulsion. The SEP/aerocapture flight time depends upon how much mass is delivered, but in general, reduces the flight time significantly.

The SEP trip time depends upon how much mass is delivered. SEP missions require high specific power (100 to >300 watts/kg) and high power (10 to 25 kW) solar cells and arrays. The high power solar array must also have very high specific power (W/kg) as the most important parameter. SEP missions require advanced solar cells and arrays with a specific power of >150 W/kg. Solar-electric propulsion often requires thrusting out to 5 AU, thus requiring efficient solar cell and array performance under LILT conditions. Low stowed volume (20kW/m^3) is also a critical requirement for the arrays required for these missions. Detailed solar cell and array requirements for the outer planet future missions are not yet known. Some of the generic solar array requirements of the SEP missions are:

- Power levels: 10 kW to 25 kW
- Operating range 0.6 to 5 AU
- Specific Power: 150 W/kg minimum; 300 W/kg or higher desired (BOL at 1 AU)
- Output voltage constant to factor of 2 over solar range
- High radiation tolerance (exposure depends on trajectory but may be >10^{14} 1 MeV electrons/cm^2)
- Output voltage > 100 V (BOL at 1 AU)
- Small stowed/packaging volume: 20 kW/m^3 minimum; 40 kW/m^3 desired
- High natural frequency (> 0.5Hz)
- Cost: Less than $500/watt

If SEP systems require thrusting beyond about 3 AU, they must operate efficiently in a low intensity low temperature (LILT) environment. At low solar intensities, arrays must operate at very low-temperatures. Actual temperatures depend on various thermal parameters, but as a rule, a cell that operates at 30°C at 1 AU, will operate at about -60°C at 2 AU, and about -140°C at 5 AU.

A variety of phenomena may be observed under LILT conditions, all of which have the potential to produce detrimental effects on the solar cell performance. Missions to the Jovian system (Europa Orbiter, Europa Lander, Jupiter Polar Orbiter) will also experience high radiation doses (See Section 5.5). Advanced solar cell and array technologies for spacecraft power would have to be considered for Jovian missions. However, spacecraft solar power for missions to Saturn and beyond are major challenges due to mass and area requirements and become impractical at some point even with the use of concentrators.

Existing solar array technologies may have poor performance capability under LILT conditions. Advanced solar cells that can function efficiently under LILT conditions and withstand high radiation environments would be required for future outer planetary missions that depend on solar power. Low-mass solar arrays with low stowed volume are also required for SEP.

4.1.2 Mars Exploration Program (MEP)

NASA is planning a series of ambitious missions to explore the planet Mars. The primary technological drivers for these missions are: long-distance surface mobility, improved imaging, subsurface exploration, and life-detection technologies. The MEP plan includes for a series of missions on two-year centers, alternating between landers and orbiters.

The primary purpose of the orbiter missions is to explore the Mars climate and topography. In 2005, NASA plans to launch a powerful scientific orbiter, the Mars Reconnaissance Orbiter. This mission will focus on analyzing the surface at new scales in an effort to follow tantalizing hints of water detected in images from the Mars Global Surveyor spacecraft, and to bridge the gap between surface observations and measurements from orbit. For example, the Reconnaissance Orbiter will measure thousands of Martian landscapes at 20- to 30-centimeter (8-to-12-inch) resolution, good enough to observe rocks the size of beach balls. The orbiters will be used as telecommunication relay stations after they carry out their primary science missions. The orbiters will use power systems utilizing photovoltaics and batteries. Photovoltaic needs for future Mars orbiters are not fundamentally different from those for Earth orbiters and there are no vital technology needs other than the ever-present desire for lower cost, lighter weight, higher efficiency and higher reliability. These missions will use the best available solar arrays based on technology developed for Earth orbit.

The primary objectives of the surface missions are to explore the geology of Mars, detect water and investigate the existence of life. Several types of surface missions such as landers, rovers, penetrators, and subsurface explorers might be used for the exploration investigations. While use of radioisotope power for many (or all) of these missions is a possibility, it is vital to provide solar power alternatives as well. Solar power may well be adequate to carry out some (or all) of these missions, and may provide advantages in affordability, thermal integration with the spacecraft during cruise, and ease of launch approval. One of the difficulties in defining specific technology needs is the fact that the details of these missions have not yet been specified, including roles of fixed landers vs. rovers, power levels, duration of missions, latitude and season, etc.

The nearest term major Mars surface mission for which new technology can be made ready is the 2009 Smart Lander. It is likely that the principal payload of the 2009 Smart Lander will be an up-sized, improved rover. However, no firm decision has been made on allocation of resources between lander and rover, or on the required mission duration. If financial considerations dictate that solar power will be used, then the latitudinal and seasonal availability of solar energy will dictate which locations and durations are feasible. In the equatorial belt from -10° to +20° latitude, the solar availability is sufficiently constant during a Mars year that a long-duration solar mission should be possible. As the mission is moved further out of this belt, the variation in solar availability during the course of a Mars year increases ever more widely. This will necessitate accommodation of these variations in the mission plans, such as perhaps periods of "hibernation" when solar availability is low.

In general, regardless of the specifics of particular Mars surface missions, there are two major technology needs for solar-powered missions. However the proposed new nuclear technology initiative may provide RTGs for the MSL mission, in which case they would be used instead of solar power if the RTGs are affordable. Solar power would be relegated to only Scout and short duration missions.

One issue is that even if sufficient mass is available, the configurational complexities of deploying large arrays of photovoltaics from rovers and landers make it difficult to provide enough array area on a lander or rover to provide sufficient power for the mission. Figure 4-2 illustrates the difficulty in deploying sufficient array area from a rover.

Therefore, there is a need for the highest possible efficiency cells to minimize the deployed area of the arrays at any power level. Since the effective solar spectrum at the surface of Mars is depleted at short wavelengths, a cell designed to maximize the efficiency in the red-shifted spectrum on Mars would be very valuable for Mars surface applications. Existing high efficiency triple junction solar cells (efficiency ~27%) are tailored to the space solar spectrum. When these solar cells are placed on the surface of Mars the efficiency will be reduced to about 24%. By modifying the structure of the high-efficiency triple junction solar cells, it should be possible to again approach the 27% goal. This would reduce the required cell area by ~10% at any fixed power level. The effort will require a close relationship with a cell manufacturer to modify their processing to achieve this goal. Another critical need is the capability to evaluate the performance of cells in a simulated Mars environment.

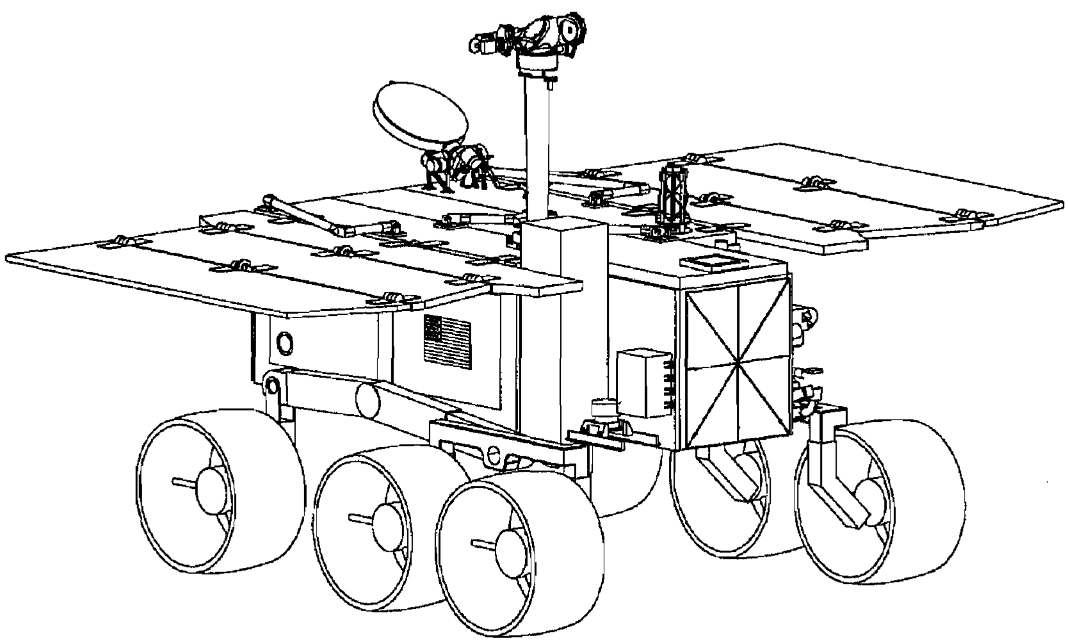

Figure 4-2: Conceptual Layout of Advanced Rover Showing Multiple Panels of PV Arrays Deployed

The other issue has to do with dust accumulation on the arrays. It is not yet understood how serious a problem this is, or what can be done to mitigate it. Dust will accumulate on arrays and partially obscure them, thus reducing their power output. If the obscuration remains within acceptable limits (not known but probably less than 20% reduction) it may be an expedient strategy for shorter missions to simply not use overt dust mitigation and tolerate whatever level of obscuration occurs during the mission. In this approach, one would allow extra array area to compensate for the expected obscuration up to perhaps 20%. For longer missions, there is great uncertainty as to how much obscuration will occur with time. If dust removal processes come into equilibrium with dust deposition processes, the build-up of dust on arrays may eventually "plateau out." Overt dust mitigation may be mandatory, depending upon the long-term behavior of dust accumulation.

The rate of deposition of dust on horizontal solar arrays on Mars can be estimated. In "clear weather" (optical depth ~ 0.5) this is estimated at about 0.15% per sol. The rate of dust removal is not understood. Very limited amounts of data taken on Mars Pathfinder suggest that eventually, the two processes may come into a quasi-equilibrium. Figure 4-3 shows these data. An alternative interpretation of the data is possible. If one fits straight lines to the data from 10 sols to 35 sols, and from 50 to 70 sols, the two straight lines have roughly the same slope of about 0.12% per sol. Thus one could assume that there was steady accumulation during those periods, with a sudden dislodgment of dust somewhere between 35 and 50 sols perhaps due to a gust of wind. However, the vertical error bars on the data in Figures 4-3 and 4-4 are likely to e large and one should not put too much credence in perceived variations from point to point.

If the rate of deposition is constant and the rate of removal of dust is proportional to how much dust is accumulated, integration of the rate equations yields an obscuration vs. time curve of the form

$$A*(1 - \exp(-B*sol)).$$

This is shown as the exponential curve in Figure 4-4. The constant A is the ultimate obscuration at long times, and B determines the time scale. There is no way to tell whether this model, or the one given in the previous paragraph, is correct.These data indicate that in the instance of the Pathfinder array, total obscuration due to dust (reduction in expected power level) reached about 17% after 83 Sols during a period of "clear" weather when the optical depth averaged around 0.5. It is not obvious how general these PF data are for Mars surface missions.

Overt dust mitigation techniques could be based on electrostatic, electrodynamic, gas jets, tilting, shaking, wiping or covers. None of these technologies has been explored for Mars solar arrays.

Deployment of arrays on Mars is required to reduce the stowed volume of the array. Most deployed arrays are designed for orbiting or interplanetary satellites. Mars has unique problems that will influence array design, particularly deployment on the Mars surface with a gravity vector and deployment in a terrain with obstacles. Arrays must be high enough off the ground so as not to impair mobility of rovers.

Power generation requires the highest possible cell efficiencies in order to minimize the extended area of the solar arrays hanging from a lander or rover. A high priority should be placed on achieving high conversion efficiency in the Mars surface spectrum to achieve a ~10% reduction in array area. The effect of accumulated dust on solar arrays needs to be understood. If dust build-up reaches a plateau that is not excessive, it may be possible to merely tolerate the dust. This might be aided by periodically tilting the arrays. However, if dust build-up continues to increase with time, dust removal may be needed to achieve the required mission duration, and some form of overt dust mitigation may be required. Understanding the physics of dust (deposition and removal processes, relation between deposited amount and optical obscuration, effect of surface dust on array performance, etc.) is fundamental to any system for dust mitigation. Therefore, a laboratory program to simulate Mars dust and its effect on photovoltaic cells is needed. The data and models that result from this work will be valuable in any plan to mitigate dust accumulation on cells.

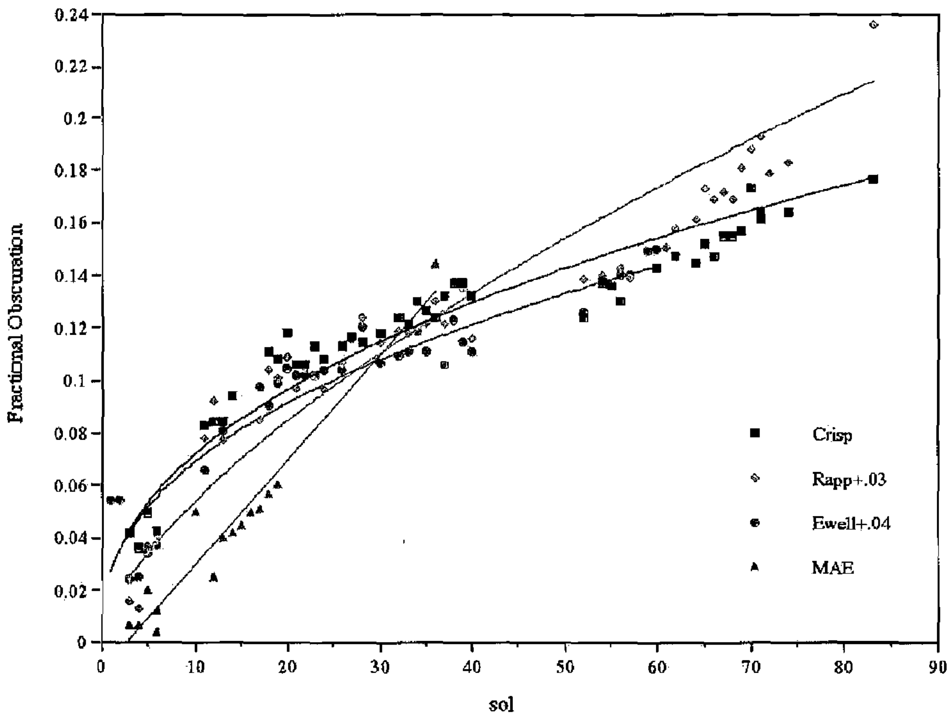

Figure 4-3: Pathfinder data on obscuration of a solar cell. The data marked Crisp, Rapp and Ewell are different interpretations of the same data on an exposed cell, whereas the data marked MAE is from the MAE experiment.

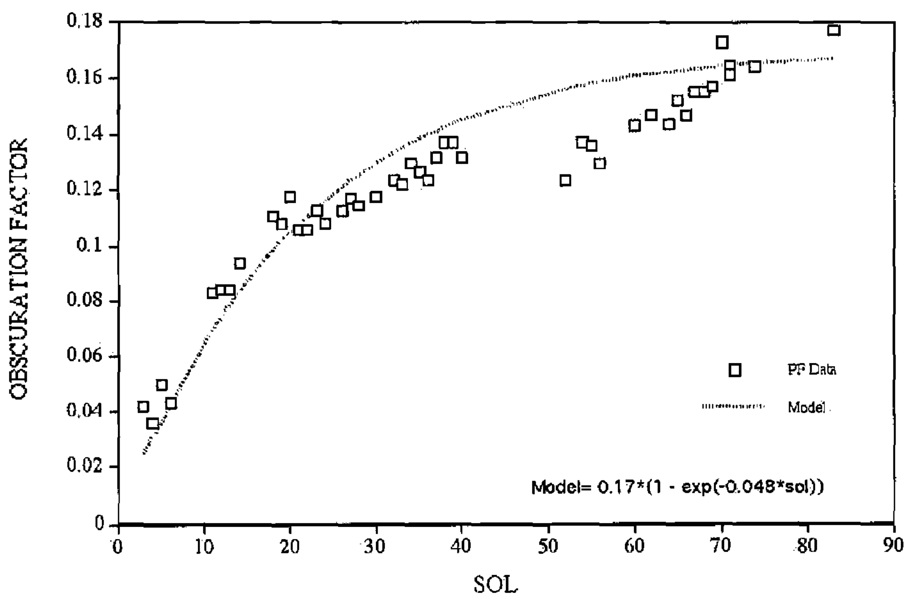

Figure 4-4. Exponential Curve Fitted to Obscuration Data.

4.1.3 Inner Planetary Missions

The MESSENGER Discovery mission (now in Phase C/D) is designed for operation at 0.31 AU. Its solar array design is already under development, and it is too late for advanced technologies to affect this mission. However, an examination of the MESSENGER solar power system can help define advances that can improve future missions to Mercury, Venus, and the Sun.

The proposed Solar Probe mission will be more demanding than MESSENGER because solar cells and arrays must operate at 0.1 to 5.3 AU distances from the sun. The present Solar Probe concept design includes multiple solar arrays, each optimized for a different AU range. Two significant compromises are made in solar power system designs for Mercury and Solar missions. One compromise is the replacement of a significant fraction of the solar cells by OSRs. This helps to control the array temperature at small distances from the sun but it reduces the power at larger distances. The MESSENGER design uses about 2/3-cell coverage and the Solar Probe uses about 50% cell coverage for the high intensity array. Another compromise that is made in solar power system designs is that the array must be off-pointed from the sun at close distances to avoid overheating.

A temporary upset of the Solar Probe spacecraft's attitude control system would result in immediate, irreversible solar array failure. MESSENGER solar array operates at a high temperature of 130°C, can be pointed directly at the sun for a minimum of 1 hour, and must reach temperatures of 260°C before irreversible solar array failure occurs. The risks to the Solar and Mercury missions would be greatly reduced by developing high temperature solar cell and array technologies. If advanced solar cells and arrays are developed that can withstand higher temperatures, the need to replace cells by OSRs and the required off-sun pointing would be reduced.

Other planned future solar missions include the following. The Solar Sentinels missions are scheduled to fly as close as 0.3 AU in about 2010. The Interstellar Probe mission is proposed to reach 0.25 AU in 2015, the Solar Orbiter mission (a European Space Agency Spacecraft) is planned to reach 0.21 AU in 2012, and the Particle Accelerator and Solar Orbiter (PASO) mission is proposed to fly to 0.17 AU in about 2015.

Existing solar array technology with reduced performance and increased risk meets the requirements for MESSENGER or other spacecraft that approach the sun to about 0.3 AU. Future sun encounters at less than or equal to 0.3 AU requires advanced solar cell and array technologies.

The MESSENGER array design uses about two-thirds cell coverage and one-third OSR coverage on the front of the array. Strings run orthogonal to substrate fiber to enhance thermal conduction between the cells and the mirror. The backside uses aluminized Kapton. The cells are 3 cm by 4 cm (nominal) 26% efficient triple-junction GaInP/GaAs/Ge, bonded with standard controlled volatility RTV adhesive and by-pass diode protected. The cover glass is 6-mil ceria doped micro sheet bonded with DC 93-500. All connections are welded or brazed (>300°C). Wiring uses Kapton encapsulated or Tefzel wire.

The MESSENGER array operates at a temperature of 130°C. (Most arrays operate at around 70°C). Its survival temperature is 260°C. The MESSENGER array was designed to operate off-pointed from the sun in order to maintain the array at ~130°C. However, should the spacecraft or the array drive temporarily malfunction, the array could point directly at the sun and become heated to 260°C. In this case, the array will not generate significant power, but it is designed to survive at that temperature for one hour.

The maximum survival temperature of the solar cells and the graphite epoxy substrate face sheets is approximately 300-350°C. However, the adhesives used to attach the cover glasses to the solar cells and the solar cells to the panels will deteriorate upon extended exposure to high temperatures. MESSENGER short-term data indicate that the onset of decomposition for a wide variety of silicones (CV 2568, DC 93-500, CV 1142, etc.) that are widely used for cover and cell bonding is around 350°C. However, long-term data are not available, and it is possible that lower temperatures are detrimental for long-term applications.

The Solar Probe mission faces the same problems encountered in MESSENGER, except that the range of solar distances is greater, creating even more difficulties. The U.S. Air Force and BMDO funded SCOPA and SUPER studies in the late 1980s to develop solar cells and arrays capable of surviving laser attack, among other threats. The most common approach was to use concentrator arrays that kept the incident laser light from impinging on the solar cells. Although guided away from the solar cells, the laser did raise the array temperature by hundreds of °C and therefore high temperature cells and array substrates were developed.

The principal modifications to GaAs solar cells that improved high temperature survivability were changes to the contact metallization composition and the introduction of diffusion barriers. Both Tecstar and Spectrolab participated in this effort and retain the knowledge base. Other smaller companies such as Astropower, Kopin, and Spire also developed cells, but they have never been in the business of producing space solar cells. Using this approach, 18% efficient GaAs/GaAs cells were produced that degraded less than 10% in one-sun efficiency after annealing in vacuum for 15 minutes at 550°C. Concentrator cells were produced that survived repeated 7 minute excursions to 600°C and showed only a 10% loss after a single exposure to 700°C.

Concurrent with the solar cell development was work on solar array substrates that can survive high temperatures. Replacement of the composite facesheets and aluminum honeycomb core with titanium sheet and foil respectively resulting in panels that can survive 600°C. These high temperature solar cell and array technologies needs to be funded and resurrected or reestablished for the inner planet and solar missions.

The Venus Surface Sample Return mission requires relatively conventional arrays, but would benefit from improvements in efficiency and specific power.

4.1.4 Comet and Asteroid Missions

Several mission concepts are under study to explore comets and asteroids. The Deep Impact mission that is scheduled for launch in 2004/2005 will study the composition of the comet Tempel 1. This mission has baselined solar cell/arrays technologies. The next mission under study to explore comets is Comet Nucleus Sample Return mission. The objective of this mission is to return a pristine sample of material from a comet nucleus for detailed chemical analysis. Solar electric propulsion is considered to be enabling for this mission. Solar cell/array technology requirements of this mission are similar to those of the SEP missions described in the outer planetary mission section. The CNSR SEP mission power requirements are in the range of 10-15 kW. This mission requires high efficiency solar cells and low mass arrays capable of providing an array specific power of at least 150 W/kg. Low solar array stowed volume is also another key requirement for this mission.

4.2 Sun-Earth Connection Program

The Sun-Earth Connection Program seeks to understand our changing Sun and its effects on the solar system, life, and society. Under the protective shield of a magnetic field and atmosphere, the Earth is an island in the Universe where life has developed and flourished. The origins and fate of life on Earth are intimately connected to the way the Earth responds to the Sun's variations. Understanding the connection between the Sun and its planets will allow us to predict the impacts of solar variability on humans, their environment, and the presence of life itself.

The SEC Program includes several Earth-orbiting missions, inner and outer planetary missions, and missions to the Sun. Some of the major planned SEC missions concepts are:

- Magnetospheric Multi Scale (MMS)
- Geospace Electro Dynamic Connections (GEC)
- Magnetospheric Constelation (MagCon)
- Solar Probe, Living with the Star
- Solar Farside Observer

- Solar Polar Imager
- Jupiter Polar orbiter
- Mercury Orbiter
- Mars Aeronomy Probe

Some of the key solar cell and array technology requirements are electrostatically clean "conductive" arrays, high-efficiency cells and low cost arrays, high temperature solar cell/arrays, solar cells and arrays that can function under LILT conditions and high power arrays for solar electric propulsion.

GEC and MagCon missions of the Sun-Earth Connection Program measure fields and particles. For this reason, these spacecraft are required to be electrostatically clean and need electrostatically clean arrays. Such arrays do not allow the array voltage to contact and thereby distort the plasma. In addition, the entire exterior surface of an array is maintained at approximately the same potential as the spacecraft structure. This constancy of potential, chiefly obtained by replacing the array's insulating surfaces with conductive surfaces, is used to prevent distortion of the fields and particles that are measured by the spacecraft. Historically, electrostatically clean spacecraft have tended to be "spinners" with body-mounted arrays. Spinning facilitates the scientific measurements. Large appendages such as solar arrays are presumably not desired because they can affect the fields and particles being measured by the spacecraft. This is true even if they are maintained at plasma potential.

Because electrostatically clean arrays tend to be body-mounted, and therefore the available area is limited, these spacecraft have a greater need for high-efficiency cells than many spacecraft.

Some of the Sun-Earth Connection spacecraft also tend to be placed in high-radiation orbits. This implies that the array's solar cells must be protected against the radiation with covers that are on the order of 0.75 mm to 1.5 mm-thick, which is much thicker than the usual 0.10-0.15 mm-thick covers.

The SEC Program also includes plans for a number of inner planetary missions (e.g. Mercury Orbiter, PASO, Inner Heliospheric Constellation and Solar Flotilla missions) that must survive and operate in a high intensity-high temperature environment and remain electrostatically clean.

The Solar Probe mission has operating environments that require a power subsystem capable of delivering power from 5.2 AU to within 4 solar radii from the center. The solar-powered Solar Probe mission presents challenges to the solar cell and array technologies. The solar cells and arrays must operate and survive the high, low, and variable solar flux and Jupiter radiation during the spacecraft fly by. Any Solar Probe high temperature array that is required before and after a perihelion pass must have a low re-stowed volume to fit within the spacecraft sunshade. This mission is so challenging to do with solar power that a radioisotope power system alternative should be maintained as an alternative to the solar powered option.

Some SEC missions requirements are similar to SSE Jovian missions. Solar-powered Jupiter Polar Orbiter and Io Electrodynamics missions must meet the requirements of LILT, high radiation environment, and be electrostatically clean.

4.3 Astronomical Search for Origins

The Origins theme seeks to answer the following two enduring human questions:

- Where do we come from?
- Are we alone?

Origins is the story of our cosmic roots, told in terms of all that precedes us: the origin and development of galaxies, stars, planets, and the chemical conditions necessary to support life. The planned Origins missions currently are conceived to be Earth-orbiting or near-Earth orbit satellites with no severe or unique challenges to the solar arrays. The science instruments for these missions appear to be the greatest challenge and this is the focus of their technology efforts. However, advanced low-cost, low mass, high specific power solar cells and array would enhance these missions.

4.4 Structure and Evolution of The Universe

The Structure and Evolution of the Universe theme embraces three fundamental scientific quests:

- To explain structure in the Universe and forecast our cosmic destiny
- To explore the cycles of matter and energy in the evolving Universe
- To examine the ultimate limits of gravity and energy in the Universe ranging from the closest stars to the most distant quasars.

The SEU missions are similar to the ASO missions in the respect that these missions present no unique technical requirements for advanced solar arrays. However, advanced low-cost, low mass, high specific power solar cells and array would enhance these missions.

5.0 Advanced Solar Cells and Arrays

The objective of this section is to describe potential advances in solar power technology, and how they would benefit the NASA OSS missions just discussed. The various advanced solar cell technologies will be addressed in Section 5.1, followed by advanced solar array technologies in Section 5.2.

5.1 Cells

The following subsections evaluate a number of cell technologies for future NASA OSS missions. Cell-level characteristics are important factors in determining overall array cost, area, mass, and functional temperature range.

5.1.1 Advanced Multi-junction Solar Cells

Introduction

The capability to manufacture III-V solar cells using Organo-Metallic Chemical Vapor Deposition (MOCVD) reactors has been available for the last 15 years. (The designation III-V refers to the composition of the semiconductor consisting of group III and group V elements from the periodic table.) Beginning with single-junction GaAs cells with 17% efficiency, three U. S. manufacturers have advanced the technology to the point of producing triple-junction solar cells for space applications with efficiencies as great as ~27%. While multi-junction III-V cells have high efficiency, they have higher mass per unit area than silicon, poorer mechanical strength, and an intrinsically higher manufacturing cost. Their benefit lies at the array level, where their higher efficiency results in smaller arrays requiring fewer cells. The overall system cost and mass (accounting for array panel substrate, cell lay-down, structure/frame, and launch) can thus be lower than for silicon cell arrays, even though the constituent cells are heavier and more costly.

These are the highest efficiency solar cells available and they result in solar arrays with minimum deployed area. Thus they are especially attractive for missions with body-mounted solar arrays where the available area is strictly limited. Among the rigid panel array designs, they also result in the most compact stowed volume, and are therefore almost universally used in commercial communications satellites where it is desirable to have the largest on-orbit power, subject to launch vehicle volume constraints.

Cell Description

Commercially available triple-junction cells use $GaInP_2$, GaAs, and Ge grown in series-connected layers, and are capable of about 27% efficiency in production lots. Each junction uses a different semiconductor with a bandgap tailored to optimally convert a certain wavelength range of light to electricity. These materials are also constrained to have the same crystal lattice constant, so that crystalline defects that spoil performance are not introduced during the growth process. Starting from the top of the cell, successive layers have decreasing bandgaps, so that photons with inadequate energy to excite upper layers, pass through to lower layers. This results in a higher overall energy conversion efficiency than when a single junction is employed due to the voltage addition that occurs in the series connection. Existing triple-junction cells are typically produced on 140-micrometer thick germanium substrates. This thickness has been found to be the optimum for low mass and low handling breakage.

The series connections in a triple-junction solar cell also result in current limiting behavior among the individual junctions. The typical triple-junction cell is designed so that the GaInP$_2$ top cell limits the current at the beginning of the mission, and is nearly current matched with the middle GaAs cell toward the end of the mission. This is done to take advantage of the greater radiation resistance of GaInP$_2$. This enables the reduction of the power management requirements of the satellite and effectively reduces the cell degradation during the mission. The bottom Ge layer is the highest current generator throughout the mission.

Technology Improvements

Improvements in the efficiency of multi-junction cells continue to be made. Large area triple junction cells of 29.3% have been achieved in the laboratory. Even without direct NASA support, there will probably be cells with 30% lot-average efficiency on germanium substrates within a few years, simply due to the military and commercial impetus to increase efficiency. There are three ways in which III-V cells are likely to be improved beyond this level.

- A fourth junction can be added to the current lattice-matched GaInP/GaAs/Ge triple junction cell.
- Use of a more optimal set of bandgaps that can be grown if the lattice matching constraint is relaxed.
- Development of a manufacturing process that uses a lighter, stronger, less expensive substrate than germanium. Silicon is the obvious choice but there is a large lattice mismatch that must be accommodated. Ceramics represent another possible option.

Conceptual cell designs for each of these approaches are illustrated in Figure 5-1, and present research activity follows.

The most straightforward approach to improving efficiency in triple junction cells is by means of a more optimal set of bandgaps. This requires the use of non-lattice-matched materials since the double constraint of lattice constant and bandgap is rarely met. Both AFRL and NASA-GRC have programs in this area, with vendors including Essential Research, Spectrolab, Tecstar, and Emcore.

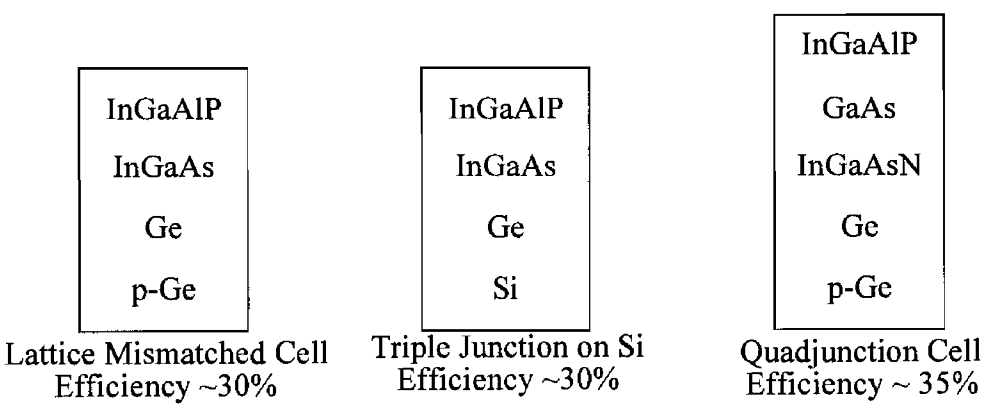

Figure 5-1: Conceptual Cell Designs. The lower most layer in each case is the substrate which does not contribute to power generation.

The second approach builds on the lattice mismatch idea and extends it to the use of a mismatched substrate such as silicon. This is more difficult because the large (8%) difference between GaAs and Si lattice constants normally leads to very high densities of performance-limiting dislocations. There is also a 63% difference in thermal expansion coefficients that causes cracking when samples are cooled from the growth temperatures of 400-650°C. The approach is very attractive however due to the cost reduction that would be achieved using a silicon (rather than a germanium) substrate since the substrate is ~65% of the cell cost. In addition, Si is less than half the density of the Ge it would replace, and is stronger allowing thinner substrates to be used. Both AFRL and NASA-GRC have small efforts in the development of lighter, stronger, less expensive substrates than germanium. Silicon is the obvious choice and it is being pursued by Ohio State University and Amberwave with promising results. Other alternative substrates, such as ceramics, could be used either for direct growth or in a film transfer process where the active device is grown on one substrate, removed, and then mounted on another.

The third approach shown in Figure 5-1 adds a fourth lattice-matched junction (InGaAsN) to the existing three junction device. The projected efficiency of this cell is 35%, a value probably not achievable by the other two approaches. AFRL is funding both Emcore and Spectrolab (with NREL as a subcontractor) and some progress has been made. The nitride material has proven difficult to grow with the desired 1.05 eV bandgap. A slightly different composition with 1.25 eV bandgap is of great importance in optical telecommunications equipment, and is thus receiving heavy industry funding. The solar cell contractors are studying how this material could be incorporated into a three or four junction cell instead of the 1.05 eV material.

Application to OSS Missions

More efficient solar cells are essential to providing increased power for payloads on existing solar array designs. Typically, existing spacecraft have been designed to make maximum use of payload fairing volume. Increasing the size of solar arrays to provide power for new payloads or to provide additional or restored margin is then not an option. In addition, the cost of redesign often exceeds the recurring cost of the array itself. Thus, more efficient solar cells are the most cost-effective way to increase the power available to payloads.

The most direct application of advanced multi-junction cell technology is to inner planet orbiting missions in the ASO, SEU, and SSE themes. These missions have similar requirements to other Earth-orbiting spacecraft and will benefit from the significant cost per watt reductions resulting from this work. The top curve in Figure 3-1 on page 25 shows the improvements in cell efficiency achieved since the MJ work began in the mid-1990s. For a spacecraft with a 1000 W solar array, the cost reduction is approximately $500K. This cost savings results not only from the lower cell cost, but also the smaller amount of labor associated with a smaller area array. Because these more efficient cells weigh no more than the earlier technology, the specific power of arrays has also risen substantially as the result of these advances. Instead of reclaiming mass and cost, the spacecraft designer can maintain the array size and make use of the roughly 50% increase in available power, enabling additional instruments or more powerful instruments to be operated. These advances are critical as higher power payloads are introduced such as radars and lidars, as well as the associated on-board data processing.

5.1.2 Thin Film Cells

Introduction

The TFCs described in Section 3.2.4 are unlikely to ever achieve the absolute efficiency of single crystal cells, but the savings in mass, cost, and stowed volume may be substantial enough in the future to compensate for their reduced performance. Advanced thin film cell technologies are most likely to be used on SEP missions that require high power levels with low mass and low cost. A 25 kW array would provide acceptable trip times to many regions of the solar system, but would cost on the order of $30 M at today's prices for single crystal cell arrays. Advanced TFCs are expected to reduce this cost significantly. The goal of

TFC R&D is to improve the efficiency of the cells and to modify deposition methods to be compatible with flexible, lightweight substrates such as metal foils and polyimides.

Cell Description

The present state of the art in flexible substrate a-Si devices is about 8% efficiency at the sub-module level, after Staebler-Wronski stabilization, on areas of about 650 cm^2. The blanket areal power density is about 684 W/kg or 2440 W/kg, on 0.5 mil stainless steel foil or 1 mil Kapton polymer, respectively. Small area (< 1 cm^2) cells have been demonstrated at over 12% efficiency, and 11 cm^2 cells have reached 10.7% efficiency. CIS cells on glass have had efficiencies as high as 18%, but these are too heavy for space use. Since the mass of the substrates dominates the blanket mass, the blanket-level specific power for CIS devices can be obtained from the a-Si values provided above by assuming direct scaling with efficiency. In addition, the process temperatures required are not compatible with thin substrates such as coated metal foils or polyimides. Several vendors have attempted low-temperature depositions of CIS on these materials, but uniformity and morphology problems have kept the efficiencies around 5% for moderate area devices.

Technology Improvements

Current thin film efficiencies are too low and substrates are too heavy to be practical in space. In addition, most existing thin film products use materials intended for terrestrial applications and cannot be space qualified. The challenge is to reduce the mass of the substrate and increase the efficiency of the cells, for example by developing a process to deposit a high efficiency cell on a lightweight substrate. This can be addressed by two approaches: (1) develop better substrates for current deposition systems, or (2) develop appropriate deposition techniques for currently available substrates.

In the case of a-Si, the commercial product from Energy Conversion Devices on glass is 10% efficient (Air Mass 1.5), and the best product on a flexible substrate is about 7% (Air Mass Zero). Iowa Thin Films is working on improvements to their a-Si on Kapton product. Both are funded by AFRL. It is hoped that these improvements in efficiency will lead to large-area production blankets with efficiencies at about 10% by about 2007.

CIS cells on flexible blankets are based on terrestrial products that use heavy glass substrates. The existing deposition technology requires high temperatures that are not compatible with the low-mass substrates of choice for space. State-of-the-art submodule performance is about 8% on Kapton and 12% on stainless steel foil. AFRL is funding the development of alternative, low-temperature deposition methods. Low temperature deposition approaches are being attempted directly onto metallized space-qualified Kapton™ substrates by low-temperature chemical vapor deposition, electrochemical deposition, sol-gel and chemical bath deposition. Material systems include $CuInGaSe_2$ (CIGS), $CuInS_2$ (CIS), and CdTe. Based on the 18% observed efficiency of CIS on glass substrates, the goals for flexible substrates are about 15% by 2010 and possibly 20% by 2020. This may be achieved through bandgap adjustment by substitution of sulfur for selenium, and the introduction of a second junction. GRC development of thin film cells with multiple junctions included a 9% AM0 $Cu(In,Ga)S_2$ thin-film "top" cell and a 12% AM0 $Cu(In,Ga)Se_2$ thin-film "bottom" cell demonstration.

AFRL is also conducting in-house efforts on TFC to evaluate radiation degradation properties, performance under LILT conditions, and high performance encapsulants. The latter two characteristics are key issues for SEP applications beyond 2 AU from the sun because the LILT behavior of these thin film materials must be considered. Preliminary results suggest that both a-Si and CIS will be useful to at least 3 AU from the sun in a planar configuration. Additional considerations arise from the operation of a-Si cells at low temperatures. It has been reported that Staebler-Wronski stabilized efficiencies stated above depend on the cells being at temperatures in the range of 50 to 60°C, which is expected in Earth orbit. In addition, desirable radiation annealing effects require these temperatures. Cell performance in missions with low operational temperatures will be compromised due to reduced annealing effects, but this behavior has not been quantified. The encapsulant is essential to development of high voltage TFC arrays that can provide direct drive of electric propulsion engines.

Application to OSS Missions

As stated in the introduction, TFCs are unlikely to ever achieve the absolute efficiency of the single crystal cells, so they will always have a larger deployed area than high efficiency cells. However, in every other respect they have the potential to be superior; lower mass, cost, stowed volume, and radiation degradation. They achieve these characteristics through an inherently low-cost manufacturing process and the use of lightweight, flexible substrates. Thus, for all but the most area-sensitive missions (e.g., those with body-mounted solar arrays) these devices might evolve to the best option. For very high power missions such as SEP, the absolute cost and mass savings over high performance cells could provide significant cost and mass advantages over crystalline cell technology. The SEP application will be discussed in more detail in Section 5.2. For low power missions, the cost savings will be lower but the impact of larger area arrays will also be lessened.

Space-qualified, moderate to relatively high efficiency thin-film cells on lightweight flexible substrates will offer significant cost benefits to most missions within 3 AU of the sun. Only moderately efficient thin-film cells (~10-15%) are necessary to improve upon the specific mass of conventional rigid arrays using much more efficient (but heavier) crystalline cells, depending on the array power and design. Although thin film cells may provide the lowest cost and most compact arrays when stowed, their inherent inefficiency compared with single crystal cells result in larger deployed arrays. In cases where atmospheric drag, gravity gradient torques, spacecraft slew rates, unobstructed instrument field of view or other size-dependent perturbations are critical, high efficiency cells may be necessary.

5.1.3 LILT cells

Introduction

The term low-intensity, low-temperature (LILT) is used to refer to solar arrays operating under conditions encountered at distances greater than 2-3 AU from the sun. Typical Earth-orbiting solar arrays have steady-state illuminated temperatures of approximately 40-70°C. Thus "low-temperature" refers to temperatures well below this value. Typically, the efficiency is found to increase down to temperatures of about –50°C at a solar distance of ~3 AU, and then fall at lower temperatures. The output current of solar cells falls linearly with illumination intensity down to 50% or so of AM0, and then may fall more rapidly depending on the cell type.

The degree to which various cell technologies lose performance under LILT conditions is difficult to determine *a priori*, and has even been found to vary on a lot-to-lot basis. At this time, the best that can be stated is that most cell types are useful under temperature and intensity conditions existing out to about 3 AU, but with reduced performance. There has been some success in engineering LILT-tolerant cells (e.g., the Rosetta mission silicon solar cells), but work is needed on multi-junction cells. An alternative solution to this problem that will be addressed later is to use concentrator arrays to increase the effective illumination of the solar cells.

Cell Description

Any type of photovoltaic cell may experience reduced performance as a result of exposure to LILT conditions. Under LILT conditions two competing effects occur. The cell efficiency increases roughly linearly with decreasing absolute temperature due to an increase in open circuit voltage. However, the effective doping of the semiconductor is reduced due to the smaller number of thermally excited carriers generated by the dopant atoms, resulting in so-called carrier freeze-out. This effect reduces cell efficiency rather abruptly through loss of conductivity in the various layers in the solar cell and a reduction in the junction electric field. A second gradual effect is for small losses in current (due to shunt leakage) to become magnified at low intensities as the overall cell current decreases. The temperature problem is fundamental, whereas the leakage problem can usually be mitigated by various techniques such as the use of mesa structures or guard rings. These are much more difficult to implement on thin film cells due to the absence of precise lithography steps.

Technology Improvements

The key issues for operation of standard solar cells under LILT conditions are shunt currents and carrier freezeout. A considerable database exists for silicon cells where shunting problems have been minimized by special designs. However, very little data exist for multi-junction cell technology. Recent tests of a few triple junction cells at JPL from 3 different cell manufacturers indicates that at least some currently available cells appear to perform well in the equivalent Jupiter LILT environment. Production amorphous silicon and CIGS remain largely unexamined under LILT conditions. The commercial and military sector are unlikely to provide support for such investigations.

The behavior of cells under these conditions vary widely from batch to batch, indicating a lack of correlation with the usual figures of merit such as efficiency. Further work is needed to understand how these effects might be controlled by changes in the manufacturing process and how they might be modeled. Degradation due to shunt leakage in silicon cells has been addressed using 1990s technology that may be applicable to multi-junction cells. The interaction of radiation degradation and LILT effects is also important for certain missions, but has not been explored.

Application to OSS Missions

Solar cells are the most cost-effective method of supplying electric power to spacecraft out to about 3 AU. There are two approaches to the use of solar cells beyond 3 AU under LILT conditions; one is gaining an understanding of the performance of existing cell designs under these conditions, and the second is investigating the improvements possible with development of cells optimized for use under LILT conditions. These considerations apply to both high efficiency single crystal cells and TFC. The work proposed here would extend the range of application of both cell types in planar arrays from about 3 AU to 5 AU or beyond. This extension has two implications for NASA missions. First, it opens the possibility of photovoltaic power for missions to Jupiter and its moons. Even though the weak solar intensity at 5.2 AU requires a 27X oversizing of an array, the cost of a thin film array might still be much lower than non-solar alternatives. This would be especially attractive for power intensive active sensors such as radars. Second, this technology would extend the range over which SEP missions could thrust, thus providing more options for SEP or mixed chemical/SEP mission profiles. While nuclear power may be favored for these missions, a solar alternative should at least be considered.

5.1.4 High Temperature Cells

Introduction

Future missions such as the Solar Probe that travel as close as 4 solar radii from the center of the sun provide the incentive to have solar arrays operate at these distances or as close as possible to the sun. If successful, such arrays would reduce or eliminate the need for primary battery storage and/or radioisotope power systems to replace or augment solar arrays.

Solar arrays may be designed to minimize the temperature of the cells in a number of ways. The array may be off-pointed from the sun using the cosine effect to reduce the solar flux incident on the array. Optical solar reflectors (OSRs) or second surface reflectors (SSRs) may also be used to reflect away most of the incident solar flux on them and act as cooling surfaces for the adjacent solar cells. The net effect is to reduce the operating temperature of the solar cells to maximize performance and increase survivability. These approaches are discussed in Section 5.3. In this section development work is discussed that can increase the high temperature survivability of solar cells, which reduces the burden at the array level by allowing higher temperature excursions.

Cell Description

Solar cells used for the majority of previous near-sun missions were made from silicon. These devices produced useful power only up to temperatures of ~200°C due to their unfavorable temperature coefficients. Modern cells based on III-V compounds, such as GaAs, are much more efficient at elevated temperatures and make the use of photovoltaics feasible nearer to the sun. The inherent limitation becomes survivability of the solar cell contacts, interconnects, and adhesives. However, improvements to these features are relatively easily implemented, while retaining the basic cell design. The poor temperature coefficient of the Ge junction in the existing triple junction cell design makes it probable that a dual junction or possibly a single junction cell would be best for this application. The options are discussed next.

Technology Improvements

Existing III-V solar cells can survive temperatures of 200°C continuously and up to 450°C for periods of a few minutes. At the higher temperatures the contact metallizations will diffuse and fail. Improved contacts with diffusion barriers were developed in the 1980s under an SDIO program, resulting in cells that could survive long term exposure to temperatures exceeding 500°C. Both Tecstar and Spectrolab participated in this effort and retain the knowledge base. Other smaller companies such as Astropower, Kopin, and Spire also developed cells but they have never been in the business of producing solar cells for use in space. Using this approach, 18% efficient GaAs/GaAs cells were produced that degraded less than 10% in one-sun efficiency after annealing in vacuum for 15 minutes at 550°C. Concentrator cells were produced that survived repeated 7-minute excursions to 600°C and showed only a 10% loss after a single exposure to 700°C. This prior work can be adapted to modern multi-junction cells. A critical part of the effort would be high temperature performance and survivability testing, since this is not done for other applications.

The available high solar flux means that it is not necessary to have a particularly efficient solar cell. It is important to have a favorable temperature coefficient and a design with few interfaces that must be provided with diffusion barriers. Generally speaking, higher bandgap semiconductors have smaller temperature coefficients. Thus, silicon cells with a 1.1 eV bandgap are not well suited to this application. Gallium indium phosphide is the 1.85 eV top cell material in the existing triple junction cell, and it would require little work to be adapted for use at high temperature. Several forms of silicon carbide have bandgaps on the order of 3 eV, and they are also attractive for their high thermal stability (> 700°C), expected high radiation tolerance, high thermal conductivity, and good mechanical strength. Although the material is being developed commercially for high power transistor applications, it is very immature with respect to solar cell application. Chief among its present shortcomings are high dislocation densities, low carrier mobility, very limited availability, and high cost (~$1000-$3000/wafer, versus about $25 for a germanium wafer). In summary, the near term low cost approach would be a GaInP cell, while SiC might offer better performance and cost but only after millions of dollars of investment over 5-8 years of development.

Another approach to high solar insolation operation is to develop high temperature, high emissivity selective coatings. These can limit the amount of unusable IR entering the solar cells, thereby reducing the steady state temperature. At the very least a high performance coating combined with louvers could be used to adjust the spacecraft emissivity as the distance from the sun varies. These developments would be of interest to Earth orbiting spacecraft missions because they would lower their array operating temperatures and thus improve efficiency.

Application to OSS Missions

Thermal technologies such as heat engines cannot readily make use of the high solar illumination, because heat engines generally require a relatively constant heat input temperature to achieve good efficiency. The variable solar flux experienced by missions such as Solar Probe do not match well with heat engine technology. Furthermore, the very limited number of missions would be unlikely to recoup the substantial nonrecurring costs of system design and qualification of a heat engine system. Photovoltaics are certainly a cost effective way of generating power for near-sun missions due to the high illumination levels available and the minor changes needed in existing technologies. The Solar Probe would be the first beneficiary. The Solar Sentinels are scheduled to fly as close as 0.3 AU in about 2010. The Interstellar Probe is designed to reach 0.25 AU in 2015, the Solar Orbiter (a European Space Agency Spacecraft) reaches 0.21 AU in 2012, and the Particle Accelerator and Solar Orbiter (PASO) attains 0.17 AU in about 2015.

5.1.5 Far Term Cell Technologies

The technologies discussed in this section are presently near TRL Level 1 and are the subject of university research, rather than engineering studies. They are highly speculative and high risk, but do offer compelling advancements if successful.

5.1.5.1 Quantum Dots

A quantum dot is a granule of a semiconductor material whose size is on a nanometer scale. These nanocrystallites behave essentially as a potential well for electrons trapped within them (i.e., the quantum mechanical "particle in a box"). The size of the particle will dictate the threshold energy that it may absorb. The smaller the box, the more widely spaced the energy levels and the higher is the energy required for absorption (i.e., the bandgap). The use of size-graded quantum dots in a solar cell will allow the harvesting of a much larger portion of the available solar spectrum. Such a collection of different size quantum dots is shown schematically in Figure 5-2 can be regarded as an array of semiconductors that are individually size-tuned for optimal absorption at their bandgaps throughout the solar energy emission spectrum. This is in contrast with a bulk material where each absorbed photon yields only the bandgap energy and any excess energy in the photon is lost as heat. The quantum dots form an intermediate band of discrete states that allow for the absorption of sub-bandgap energies. However, when the current is extracted it is limited by the bandgap and not the individual photon energies. Two additional desirable features of quantum dot solar cell behavior is the expected superior radiation resistance of such devices and the independence of conversion efficiency with temperature. To a first approximation the energy levels of quantum dot structures are temperature-independent. In fact, thermal energy assists in populating those levels. This implies a greater thermal stability in contrast to a normal PN solar cell. It is difficult to estimate the potential temperature range due to the temperature dependence of other cell components.

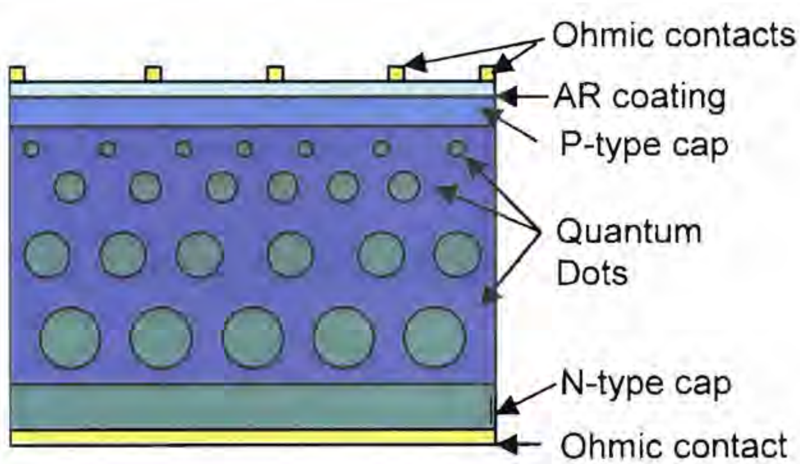

Figure 5-2: Graded Quantum Dots to Achieve a Suitable Range of Bandgaps.

Theoretical studies predict a potential theoretical maximum efficiency of 63.2%, somewhat better than the highest theoretical efficiency (~50%) of improved devices based on today's multi-junction cell designs. The degree to which practical attainable efficiencies will be lower than this maximum is unknown. Quantum dot solar cells have thus far been mainly a theoretical exercise. No quantum dot solar cell devices have ever been fabricated. To date, the exploration of quantum dots for potential solar cell applications has been investigated only in silicon and CdS. There will be substantial challenges in keeping manufacturing cost competitive with existing technology and in large area fabrication. It is probably appropriate to request NASA Code R funding to develop this technology.

5.1.5.2 Ultra-Thin Cells

Introduction

Ultra thin cells (UTCs) are those in which the 150-200 micrometer-thick substrate used for growth of the active region is subsequently removed, allowing the 3-10 micrometer-thick active region to be transferred to another (perhaps inert) substrate or superstrate with more desirable properties. These may include lower cost, lighter weight, or higher mechanical strength. An often-proposed example of this approach is a single junction GaAs cell that has been removed from its GaAs or Ge substrate and subsequently placed on a lighter, more robust substrate such as Si. Space cells require a transparent cover glass or superstrate to protect the cells from radiation damage and to provide a surface for protective coatings. These cover glasses and superstrates may also be the supporting structure for the UTCs.

Cell description

Three techniques for thinning the cell include Preferentially Etched Epitaxial Lift-Off (PEEL), Cleavage of Lateral Epitaxial Films for Transfer (CLEFT) and sacrificial etching of the substrate, stopping at an inert "etch stop" layer. Some of the organizations involved in the development of these processes include NASA-GRC, University of Nijmegan, Kopin Corporation, EEV, and ASE. The most developed of these technologies is CLEFT, in which an extremely thin (5 micrometer) large-area cell is separated from a single-crystal substrate. This technique was used by Boeing and Kopin to obtain a thinned GaAs device that was subsequently glued on top of a GaSb solar cell, producing a mechanically stacked, dual junction cell. The lattice constants of these materials are sufficiently different that direct epitaxy of GaAs directly on GaSb would not have been practical. These cells were flown on both the PASP-Plus experiments by the Air Force.

Technology Improvements

Work is continuing on semiconductor lift-off methods, primarily due to its potential use in integrated opto-electronic devices. Successful application of these methods to solar cells will have the added difficulty of requiring high yield processes that are effective on relatively large area devices. Additional work would be required to develop interconnect methods that do not damage the thin layers–conventional welding and soldering would not be suitable.

Application to OSS Missions

This technology will produce a deployed array with the best combination of small deployed area and low mass. Its usefulness to NASA missions will be determined by the tradeoff of these benefits against somewhat higher cost. Consider the mass per unit area of a solar array consisting of GaAs/Ge cells with 6 mil coverglasses on a Kapton blanket that might be used in a body-mounted configuration. A thinned GaAs device would reduce the areal mass by about 50%, after adhesive and conductor masses are included. The reduction would be less for a deployed array due to the structure and mechanisms needed. This gain would be tempered by the expected lower efficiency of the thinned cells and reduced packing factor, such that the final gain may be only 20-30%. There would be additional costs in laydown (due to the larger number of small area cells needed) and the lower cell manufacturing yields.

There may be a unique combination of mass and cost requirements that would make these cells competitive for SEP missions in the future. It seems unlikely that the relatively small demand created by NASA for this industry could drive the market in this direction. NASA would be best served by following the current industry trends to multiple junction cells and only test and modify existing production cell designs when a NASA specific benefit is probable.

5.1.6 Summary of Advanced Space Solar Cell Technology

A summary of important characteristics of advanced solar cells is given in Table 5-1. A description of the status of these space solar cell technologies is given in the sections that follow.

5.2 High Power Arrays for Solar Electric Propulsion

Introduction

The use of interplanetary electric propulsion essentially replaces chemical propellant mass with solar array mass. High performance arrays can make this trade more favorable than a kg-for-kg replacement. Thus, SEP missions place a premium on array cost and specific power (W/kg) due to the high power levels (up to ~25 kW) required. Furthermore, the increased solar array output might then be available for active sensor missions or extensive maneuvering upon arrival at the destination. In contrast, chemical propellant systems have no residual benefit. However, some missions will jettison the SEP system when thrusting is ended.

Table 5-1: Summary of Advanced Space Solar Cell Technology

Parameter	Advanced Multi-junction	Thin Film Cells	LILT Cells (TJ w/o reduction in efficiency)	High Temp. Cells (GaInP &/or GaAs opt.)	Quantum Dots	Ultra Thin Cells (UTCs)
TRL Status	3-5	3-5	4-6	4-6	1-2	1-3
STC Efficiency (%)	29.3-35	8-20	26.8	18-22	63.2 max	~15-19+
STC Operating Voltage (V)	2.26+	TBD	2.26	2.06	TBD	TBD
Cell Weight (mg/cm^2)	35-100	~1-5	80-100	80-100	TBD	~40-70
Temp Coefficient at 28°C	-.0019%/C	TBD	-.0019%/C		~0%/C	-.0021%/C
Cell Thickness (µm)	100 to 175	~3-15+	140 to 175	140 to 175	TBD	~3+ to 100
Radiation Tolerance(*)	0.84+	0.84+	0.84	.80	.84+	0.75
Absorptance	0.92+	TBD	0.92	.91	TBD	0.89
Potential Supporters/ Vendors/ Researchers	Ohio State University, Amberwave, Essential Research, Emcore, Spectrolab, Tecstar	Energy Conversion Devices, Iowa Thin Films	Emcore, Spectrolab, Tecstar	Emcore, Spectrolab, Tecstar, Astropower, Kopin, Spire	NASA Code R	NASA Code R, GRC, U of Nijmegan, Kopin Corporation, EEV, ASE, Boeing

(*) Fractional power output after exposure to 10^{15} MeV electrons/cm^2.

SEP missions require arrays with high output power, high specific power, low cost, and low stowed volume to be most effective. High power for electric propulsion can be achieved with arrays of multi-junction high efficiency cells, which produce the smallest deployed area. However, the mass, stowed volume, and cost associated with this approach may be unacceptable to many missions at the required power levels on the order of 30-50 kW. Two approaches for reducing these parameters are thin film arrays and concentrating arrays. The solar cells that would be used in these arrays were discussed in Section 5.1, while the supporting array technologies are discussed below.

It is desirable to operate solar arrays for SEP at as high a voltage as possible to minimize power conditioning requirements and losses. There are a number of unresolved issues associated with high voltage arrays. Progress has been made in recent years on eliminating electrostatic discharge damage and plasma leakage currents on conventional arrays. Thin film blanket arrays and concentrator arrays can readily avoid most of these problems by encapsulation of the solar cells and circuits. Continuation of the work on conventional arrays would be broadly applicable to many high power applications in space. Some of the approaches that have been proposed include bringing the conductor potentials up to nearly the plasma potential by using a plasma contactor, increasing the photoelectron emission area, or increasing the secondary electron emission area. Insulators can be coated with a conductor, and grounded to conductor potential with ITO or other very conductive material. High voltage conductors can be encapsulated in thick dielectrics. Paschen discharges can be prevented from occurring by using low-outgassing materials, and preventing inadvertent gas flows. To prevent adjacent solar cells or other power system conductors from arcing across a gap, intelligent solar array string or power system trace layouts can be used to minimize potential differences across adjacent cells, by physical barriers to arcing, and by other techniques. This work needs to be done as part of array development, regardless of which array technology is employed.

For SEP missions that encounter severe LILT conditions (certainly those that thrust out to 5 AU), it is possible that a concentrator array will be necessary, irrespective of the solar cell technology. Although this approach does not reduce the aperture size required to collect the necessary energy from the sun, it does allow solar cells with limited LILT capability to be used since they operate near AM0 intensities due to the concentrator. From a mission perspective, the amount of energy received beyond 5 AU is so small that future mission designs jettison the SEP system, use radioisotope power for the spacecraft functions, and coast to their destination from there. In a similar fashion, most solar sail mission designs assume that the solar sail is jettisoned at about 5 AU, since again the benefit is very small beyond this distance. Additional energy may be obtained by staying in close to the sun to obtain significant kinetic energy using either SEP or solar sails before heading to the outer solar system.

5.2.1 The UltraFlex™ Flexible Foldout Array

One of the most advanced flexible foldout arrays is provided by AEC. The UltraFlex™ is an "accordion-fan-fold" flexible solar array system that provides light weight and compact stowed volume at 5 to 20 kW power levels. The UltraFlex™ is composed of a number of isosceles triangular shaped open weave substrates that when deployed, form a tensioned polygon structure. Radial spar elements attached to each substrate are elastically deflected to form a preloaded shallow "umbrella" profile, providing high-deployed stiffness. The UltraFlex™ system accommodates crystalline high efficiency silicon cells, crystalline $GaInP_2/GaAs/Ge$ multi-junction cells or flexible thin film cells. The deployment sequence for the UltraFlex™ for the Mars '01-Lander spacecraft is shown in Figure 5-3. A photograph of the UltraFlex™ is provided in Figure 5-4.

The UltraFlex™ solar array system was qualified for the Mars '01-Lander and achieved a state-of-the-art specific power of 103 W/kg BOL with 17% high efficiency silicon cells while deploying in a 1g environment. The system is at NASA TRL 6.

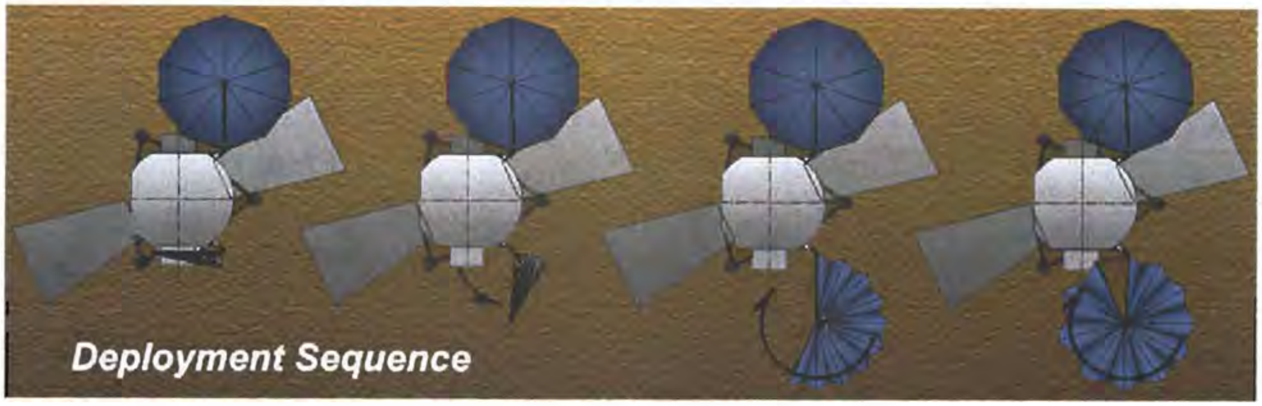

Figure 5-3: UltraFlex™ Solar Array Wing System for the Mars 01-Lander Spacecraft

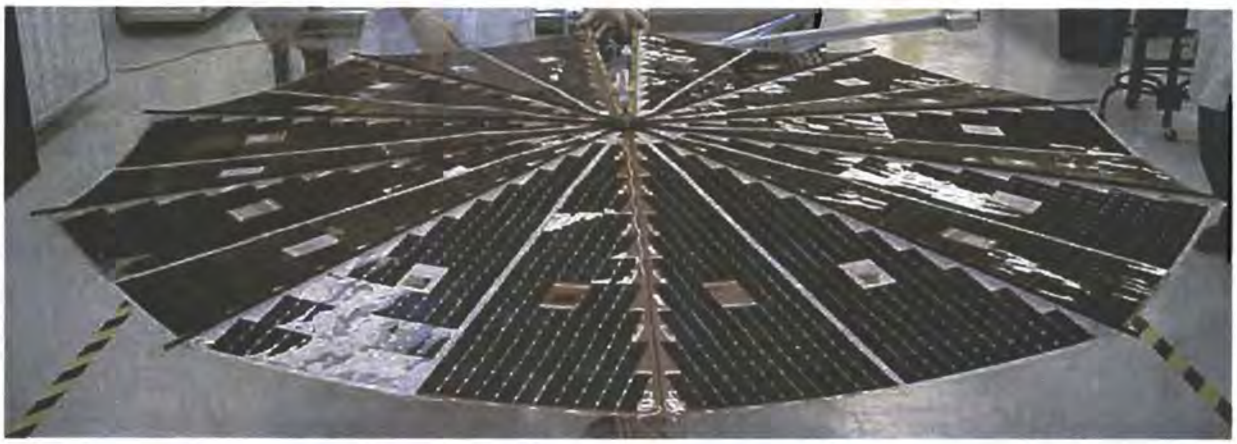

Figure 5-4. Ultraflex™ Array in Deployed Condition

It is claimed that using 27% triple junction cells, arrays with 180 W/kg (BOL) can be achieved. If thin film blankets with 10% efficiency become available, this rises to 300 W/kg (BOL). The stowed packaging density (i.e., stowed volume efficiency) is projected to be 50 kW/m^3.

One major limitation to UltraFlex™ is its stowed volume profile. The UltraFlex™ stows within a triangular envelope and its height is equivalent to the deployed radius of the wing. Therefore, as power increases so does the wing radius and stowed height.

5.2.2 The SquareRigger™ Solar Array

AFRL has begun a $6 M, 3-year program with two prime contractors (Boeing and LMSC) to investigate and design complete arrays uniquely tailored to thin film solar cells. The major challenge is to develop array-level hardware that retains the mass and cost benefits of thin film blankets. Use of conventional panels, tie downs, hinges, wiring, and deployment methods would largely eliminate the weight advantage of these blankets.

A flight demonstration is planned for 2004, although complete funding is not currently in place. At the array level, using 15% efficient cells, the performance is expected to be about 150 W/m2, 270 W/kg, $200/W, and 40-50 kW/m3. However, this program is likely to be limited by the rate of development of large-size thin film cells. Present technology is still a long way from producing thin film cells with 15% efficiency in moderate sizes. SquareRigger™ is an Able Engineering design developed under this program.

The SquareRigger™ solar array is a flexible blanket system that is composed of modular "bays" that may lead to ultra-high power capability (30 kW to 100 kW+) at a high-stowed packaging efficiency beyond 2010. The modularity of the SquareRigger™ system allows for scaling to nearly any power level. The SquareRigger™ structural subsystem deploys from a closely packed bundle of strut elements to the planar deployed configuration. A lightweight blanket assembly is flat-folded (or rolled) and contained on one of the adjacent struts when collapsed. Once the structural elements have completed deployment and are fully latched, the blanket assemblies are unfurled (i.e., hoisted) to a tensioned deployed state (Figure 5-5). The deployment sequence of an extremely high power SquareRigger™ system composed of multiple bays is shown in Figure 5-6.

The stowed packaging efficiency for SquareRigger™ arrays is extremely high and is projected to be between 40 kW/m^3 to 80 kW/m^3, depending upon PV type and efficiency. The stowed volume profile is intrinsically shaped to most optimally utilize stowage space between the spacecraft and launch vehicle. As power requirements grow, the stowed volume increases proportionally, but without significantly impacting traditionally designated launch volumes. The SquareRigger™ solar array system is projected to achieve a specific power between 180 W/kg to 260 W/kg BOL, depending on PV type and efficiency. When populated with thin film PV the SquareRigger™ system is projected to offer an order of magnitude cost reduction when compared to conventional rigid panel systems.

The SquareRigger™ system is at NASA TRL 4. SquareRigger™ components and breadboards have been validated in a laboratory environment as part of numerous AFRL programs. Work is progressing towards the integration of the basic mechanical and electrical subsystem elements. However, these arrays require efficient, large-size thin film solar cells, which are still in an early emergent state of technology.

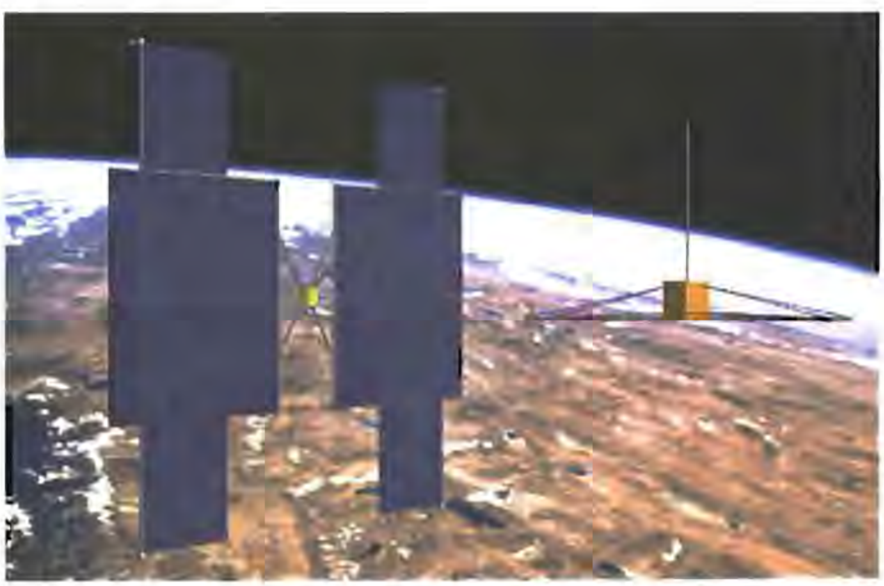

Figure 5-5. SquareRigger™ Solar Array System

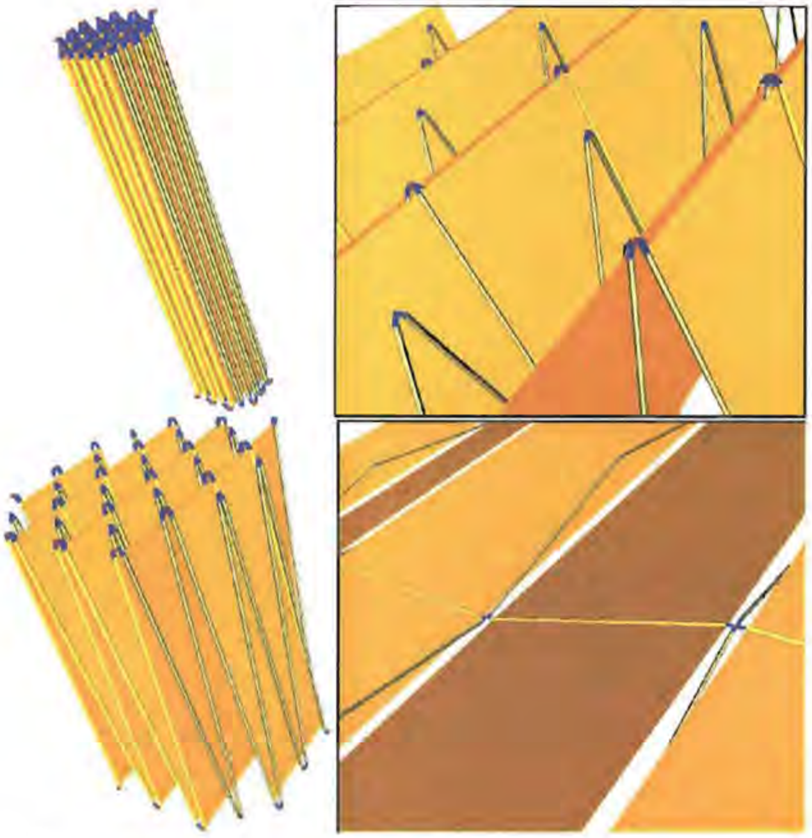

Figure 5-6. SquareRigger™ 1-Bay Deployment Sequence

5.2.3 Concentrator Arrays

The primary benefit of concentrators is a reduction in the cost of arrays. This is accomplished by having only a fraction of the array actually populated with solar cells, which are the most expensive component of the array. Concentrators do not significantly decrease the stowed or deployed size. Present-day concentrating arrays do little to reduce the mass unless the array is designed for a high radiation environment where heavy shielding is desired on top of the solar cells. Of course all of the array materials (coatings, optics, ...) must also be made compatible with the radiation environment.

Concentrator systems can be broadly categorized as refractive or reflective, depending on the type of optics used to achieve concentration of the light. The SCARLET array used on Deep Space 1 is a refractive type, whereas the channel array used on the Boeing 702 satellite is a reflective type. Both types involve a fundamental tradeoff between concentration ratio and required pointing accuracy. A higher concentration ratio reduces the number of solar cells needed, and therefore the mass and cost. However, beyond about 100X concentration the pointing requirement exceeds the normal pointing tolerance of typical spacecraft. In addition, special safe modes must be considered during loss of attitude events since the array produces no power when pointing control is lost, unlike conventional planar arrays which provide a reduced output.

A unique concept is under development by Composite Optics, Inc. that may be effective for the Solar Probe mission. Under a Phase I SBIR, COI is demonstrating the principles involved in the design of a "Deep Space Concentrator" that uses optical and thermal control techniques to allow operation of a solar array over a wide range of distances to the sun. The basic configuration of the design draws from the SLATS parabolic trough concentrator design developed during the 1980's. The optical control technique being proposed by COI considers the increase in the solar disk apparent width (i.e., the higher total collimation angle) of the sun to allow reflected energy to spill over a restrictive aperture placed in front of the solar cell receiver at the focus of a concentrator. In doing so, the intercept efficiency of the concentrator decreases as it gets closer to the sun. The thermal technique makes use of a proprietary thermal switch that disconnects the radiator from the solar cell at high and low temperatures to provide a solid-state thermostatic feature for limiting temperature swings both on the high side (which might come from inner planet albedo and radiation) and the low side (which comes from outer planet solar flux decrease).

5.2.3.1 SCARLET Stretched Lens Array

The SCARLET Stretched Lens Array (SLA) is applicable to missions in the 2005 to 2012 timeframe utilizing 10 to 30kW of power, high specific power, low recurring cost and missions that can accommodate the intrinsic off-pointing power production limits.

The SCARLET SLA is a concentrator solar array that uses proven linear refractive Fresnel lens technology to focus sunlight at ~8X concentration onto spaced rows of $GaInP_2/GaAs/Ge$ multi-junction cells to reduce system mass and cost compared to the original SCARLET design. SLA is an optimized descendent of the successful NASA/JPL Deep Space 1 (DS1) SCARLET solar array that was launched in October 1998 and has reliably powered both the spacecraft and ion engine for over three years at sun distances ranging from 1.0 to 1.4 AU. The SCARLET SLA achieves its high specific power (W/kg) by replacing the previous DS1 design's heavy glass-reinforced lenses, lens support structure, and honeycomb substrate panels with much lower weight flexible lenses that are tensioned, and an advanced "picture frame" panel substrate platform.

The SCARLET SLA is projected to achieve over 190 W/kg BOL for wings sizes beyond 10-kW when populated with 27% efficient multi-junction $GaInP_2/GaAs/Ge$ triple-junction cells. The stowed packaging density (i.e., stowed volume efficiency) is approximately 13 kW/m^3. Because SCARLET SLA utilizes about 15% of the cell area of a non-concentrated solar array, this system is more mass-efficient in minimizing BOL to EOL power degradation in the most demanding radiation environments where thick cell cover glass is required. Also, the reduced cell area minimizes recurring solar array cost. The large spacing between cells also facilitates complete encapsulation of the solar cells and interconnects permitting high voltage operation and complete isolation of the power circuits from space plasma.

The major limitations of the SCARLET SLA solar array are off-pointing acceptance angle and stowed packaging density. SCARLET SLA operates with an alpha off-pointing acceptance angle of ±2 degrees at 8X concentration, or ±5 degrees at 5X concentration. Power production fall-off beyond these alpha off-pointing limits is abrupt. For applications that can reliably maintain solar array pointing tolerance within these limits, such as DS1, this intrinsic feature is not a concern. SCARLET SLA's relatively high stowed volume profile may preclude the use of this technology for extremely high power applications in the >30 kW range.

The SCARLET SLA system is at or very near NASA TRL 5. SCARLET SLA components and breadboards have been validated in both laboratory and relevant environments as part of current NASA New Millennium ST6 and Cross Enterprise programs. In addition, the basic technology elements of SCARLET SLA (Figure 5-7) have been integrated and are nearing testing in a simulated environment.

Figure 5-7: SCARLET SLA

5.2.3.2 Low Ratio (1.5-3X) Reflector Designs

Tecstar has teamed with NRL to commercialize their V-trough reflector system that is quite similar to the BSS 702 array.

The ABLE Engineering Cell Saver™ Concept (Figure 5-8) uses distributed reflective elements, and low-cost collapsible reflectors.

Composite Optics Inc. has two designs. One uses a panel made from lightweight composites with good thermal properties that integrates the mirrors into the solar cell substrates (Figure 5-9). The other is similar to the ABLE Cell Saver™ .

Figure 5-8: ABLE Engineering Cell Saver™ Concept

5.2.3.3 Medium Concentration Ratio Refracting Designs

The ABLE/Entech Stretched Lens Array utilizes an evolved DS-1 design with distributed refractive elements at 7X to 20X concentration (Figure 5-10).

Figure 5-9: COI Trough Concentrator Design Flown on MightySat 2.1 for AFRL.

5.2.3.4 High Concentration Ratio Reflecting Designs

The United Innovations 100X to 1000X design funded by NREL combines high ratio concentration with the concept of spectral splitting. Rugate notch filters are used within the cavity to selectively pass appropriate wavelengths of light to the individual solar cell types. The concentrator portion of this concept may of course be used without the spectral splitting feature.

Although performance estimates for these concepts have been provided by the manufacturers, they are not quoted here because they vary substantially with array size and integration requirements. The range appears to be 50-250W/kg.

Application to OSS Missions

The Deep Space 1 mission has recently demonstrated the feasibility of solar electric propulsion in space. In order to make SEP effective and affordable for a wider range of missions, it is necessary to develop solar arrays with improved cost and specific power performance. The planar array concepts such as UltraFlex™ represent the state of the art in these respects, but emerging NASA SEP missions would benefit from still better performance and wing systems much larger than the UltraFlex™ system qualified for the NASA Mars 01-Lander program. The recommendations made in Section 6 address the needs for a full scale (8 kW and up) wing qualification programs in both UltraFlex™ and SquareRigger™ type arrays for high power SEP applications. These advancements in array technology are essential to obtaining cost effective electric power at the levels

Figure 5-10. ABLE Stretched Lens Concentrator

needed for SEP. Although cost sharing will be possible with the military sector for these large arrays, the NASA-unique aspects discussed in the introduction to Section 5.2 will require some separate efforts.

There are several compelling benefits of concentrator arrays for NASA SEP missions. First, they can mitigate LILT effects and allow conventional solar cells, both high efficiency and thin film, to be used at distances of at least 3 AU. This approach would be very cost-effective because it uses available technology without NASA-unique investment in cells. A second benefit is substantial cost reduction for arrays above a few hundred watts, due to the reduced number of cells that must be purchased.

5.3 High Temperature Solar Arrays

Introduction

Solar arrays have been used extensively for interplanetary missions at solar ranges from 0.7 AU (Venus) to ~1.6 AU (Mars). In addition, Mariner 10 flew by the orbit of Mercury (0.3 AU) three times between March, 1974 and March, 1975. At least two missions have already flown and functioned well at very high intensities: Helios A, launched on 10 December 1974, which reached 0.31 AU; and Helios B, launched on 15 January 1976, which reached 0.29 AU. Both of these spacecraft used silicon cells that were slightly modified for high intensity use in conjunction with second surface mirrors to cool the arrays. The other flights used near-standard arrays. It might appear at first glance that near-Sun missions would be ideal for photovoltaics. With close proximity to the sun, the solar energy power density increases dramatically. For example at 0.3 AU the solar intensity is 11 times that at Earth. At 0.1 AU, it is 100 times the intensity at Earth. Inasmuch as the sun is critical to the solar system's existence, near-Sun missions have great scientific potential.

Array Description

Due to the high solar intensities near the Sun, relatively small solar array areas are needed to obtain useful power levels. Due to the small area, overall mass and cost are expected to be relatively low. The corollary to the high intensity is that near-Sun spacecraft are heated to extreme temperatures. Much of the heating can be avoided by thermally shielding spacecraft components from direct solar illumination. The solar array, which converts solar illumination to electricity, must be directly exposed to the sun and cannot be totally shielded during operation.

The MESSENGER array operates at a temperature of 130°C. (Most arrays operate at around 70°C). Its survival temperature is 260°C. The MESSENGER array was designed to operate off-pointed from the sun in order to maintain the array at ~130°C. However, should the spacecraft attitude control system or the array drive temporarily malfunction, the array could point directly at the sun and become heated to 260°C. In this case, the array will not generate significant power, but it is designed to survive at that temperature for one hour. The Solar Probe mission faces the same problems encountered in MESSENGER, except that the range of solar distances is greater, creating even greater difficulties. The U.S. Air Force and BMDO funded SCOPA and SUPER studies in the late 1980s to develop solar cells and arrays capable of surviving laser attack, among other threats. The most common approach was to use concentrator arrays that kept the incident laser light from impinging on the solar cells. Although guided away from the solar cells, the laser did raise the array temperature by hundreds of degrees Centigrade and therefore high temperature cells and array substrates were developed as discussed in Section 5.1.4.

Technology Improvements

The maximum survival temperature of high-temperature solar cells and graphite epoxy substrate face sheets is approximately 300-350°C. However, the adhesives used to attach the cover glasses to the solar cells and the solar cells to the panels will deteriorate upon extended exposure to high temperatures. MESSENGER short-term data indicate that the onset of decomposition for a wide variety of silicones (CV 2568, DC 93-500, CV1142, etc.) that are widely used for cover and cell bonding is around 350°C. However, long-term data are not available and it is possible that lower temperatures are detrimental for long-term applications. Research is needed to identify and test adhesives that show promise of operating at higher temperatures than those encountered by the Helios and MESSENGER spacecraft, which are designed for approximately 0.3 AU. Naturally, this work will make use of the progress made by SCOPA and SUPER.

Additional work was done under these programs on solar array substrates that can survive high temperatures. Replacement of the composite facesheets and aluminum honeycomb core with titanium sheet and foil respectively resulting in panels that can survive 600°C. These high-temperature solar cell and array technologies need to be funded so they can be resurrected or reestablished for inner planet and solar missions.

JPL has been examining and developing concepts and designs for high temperature solar arrays. This includes not only high temperature capability of cells and structures but also novel coatings and materials to improve the array absorptivity/emissivity ratio in order to decrease operating temperatures. NASA-GRC has done some limited tests of cell performance at elevated temperatures. JHU-APL is presently developing the Mercury MESSENGER spacecraft with high temperature solar arrays. The long-term survivability characteristics of these materials must be tested.

Coatings may be developed further to limit the amount of unusable IR entering the solar cells as well as for controlling the solar array substrate temperature, both of which are strong functions of the angle of incidence on the array. Ideally, a switchable electrochromic coating could be developed that reduces or eliminates the need for array feathering. At the very least, a high performance coating combined with louvers could be used to adjust the spacecraft emissivity as the distance from the sun varies.

Application to OSS Missions

Photovoltaics are certainly a cost effective way of generating power for near-sun missions due to the high illumination levels available and the minor changes needed in existing technologies. An investment in the array technologies can substantially reduce the requirements imposed on the solar cells. In addition there should be some co-funding available from other sources since temperature control even for earth-orbiting satellites can benefit from advances in coating technology.

5.4 Electrostatically Clean Arrays

Introduction

This research area addresses need of spacecraft that measure fields and particles, and therefore require arrays that do not distort the local electric field environment. To date these missions have used conventional arrays that have been modified with special conductive coatings and intricate contacting clip or wire schemes to interconnect them. These approaches are expensive and fragile. Future missions of this type will need a more cost-effective approach, or they will be severely power limited.

Array Description and Technology Improvements

The COI work described in Section 3.3.7 and funded by GSFC provides a more cost-effective method for contacting ITO-coated solar cell covers. However, this method still results in a large number of electrical contacts that must maintain continuity through many thermal cycles. A better approach would be a large area transparent conductor that covers many solar cells with a single sheet of material requiring only one contact. It appears that the best candidate for such desired "clean" covers is a transparent plastic that can withstand the space environment. This plastic would be coated with Indium Tin Oxide (ITO) or other material to make it conductive. This will readily produce the desired electrostatic cleanliness with a minimum of expense, mass, and cost. In addition, this approach will yield a readily repairable array. The development of these plastics would be extremely beneficial to thin film array technologies as an encapsulant for high voltage SEP applications. Transparent plastics may also serve as covers for dust mitigation on Mars surface missions.

Associated with the plastic cover approach is an investigation of alternative transparent conductive coatings to replace ITO. The problems with ITO are significant absorption in the visible light band utilized by solar cells and susceptibility to radiation darkening. Other materials with the necessary conductivity properties have been identified, such as doped, wide bandgap semiconductors. The challenge is to find deposition methods that are compatible with plastic covers.

A near-term approach is extending typical glass or fused silica covers to shield several cells. This has been tried in the past. Indeed, the COI aperture array uses a single cover over two cells. There have been two difficulties with this approach. The first is that covering more than a few cells leads to delamination from one or more of the cells in thermal cycling. Apparently the different CTE of the cover and the substrate, the unevenness of cell height and the resulting unevenness of cover to cell adhesive thickness, and the weakness of the adhesive all contribute to the delamination. In addition, completely encapsulating the cell-to-cell interconnects in adhesive sometimes causes the interconnects to fail in thermal cycling. Multi-cell covers can introduce difficulties in repair because there is no cost-effective way to replace a broken cell under such a cover. Removing the cover to replace a damaged cell is a potentially very expensive because it is easy to damage the other cells. These issues can probably be overcome with additional research.

Application to OSS Missions

The performance of electrostatically clean solar arrays is not adequate to support anything beyond very modest mission power requirements, and the cost is 3-6 times higher than conventional arrays due to the large amount of by-hand customization. These problems can be overcome through higher performance solar cells, discussed in Section 5.1.1, and by developing new large area, low cost transparent conductors. Without these advances, future missions that probe the electrical environment of Earth and other planets will be severely restricted by the available electrical power.

5.5 High Radiation Environment Solar Arrays

Introduction

Solar-powered missions to the Jupiter/Europa system would encounter severe radiation environments that pose severe design challenges

- Significant fluxes of very high energy electrons (E > 10 MeV)
- Possible high fluxes of O^+ and S^+ ions
- Moderately severe high-energy proton fluxes.
- Environment models likely to contain more uncertainty than what is normally associated with earth models (~2X)
- Total ionizing doses will be very high inside packages -- 300 mils aluminum is ~ 1 Mrad(Si).

- Expected thick/high-Z shielding materials will generate significant secondary particles
- Displacement damage from both primary electrons and secondary particles may be very severe for sensitive parts (imagers, bipolar, etc.).
- Use of commercial off the shelf (COTS) parts will require significant RLAT testing and may not get us there
- Availability of rad-hard parts is limited.

Particle fluxes near Europa are expected to be as shown in Figure 5-11. It should be noted that these fluxes have the following character:

- Electrons
  - Range of 10 MeV electrons is ~2 cm in aluminum
  - Average 10 MeV electron flux is ~ $3x10^6$ e/cm^2-s
  - Peak fluxes could be significantly higher.
  - This is significantly different than earth environment
- Protons
  - Range of 50 MeV protons is ~1.2 cm aluminum
  - Average 50 MeV proton flux is ~700 p/cm^2-s
  - Peak fluxes could be significantly higher
  - Not very different from earth environment

The relative output of a double-junction GaAs based cell as a function of fluence of 1 MeV electrons is shown in Figure 5-12. The time of exposure at Europa is shown on the top horizontal axis.

Such a high radiation environment presents the solar array designer with a choice. Traditional crystalline silicon solar cells will suffer substantial degradation in these missions and therefore the solar arrays would have to be oversized, adding cost and mass. The choice is whether to add shielding in the form of thick cover glasses or to choose a more radiation resistant cell technology. The former is a straightforward, low risk approach. However, for missions to outer planets where the weight penalty may be unacceptable, the latter may be needed. The payoff from investment in radiation effects research is a reduction in the weight penalty of shielding, for example through the use of concentrator arrays, or more beneficially, to avoid it entirely by developing cells with adequate radiation resistance so that extra shielding is unnecessary. The concentrating arrays described in Section 5.2.3 can be adapted for use in high radiation fields by selecting and qualifying radiation- resistant materials for the concentrators, be they refracting or reflecting. For the refracting designs this is generally sufficient because the optical element provides shielding for the solar cells. In contrast, the reflecting designs generally leave the solar cells exposed to the environment, and they must be fitted with thick cover glasses. The benefit of the reflecting concentrator is that the solar cell area has been reduced so the weight impact of these cover glasses is greatly reduced.

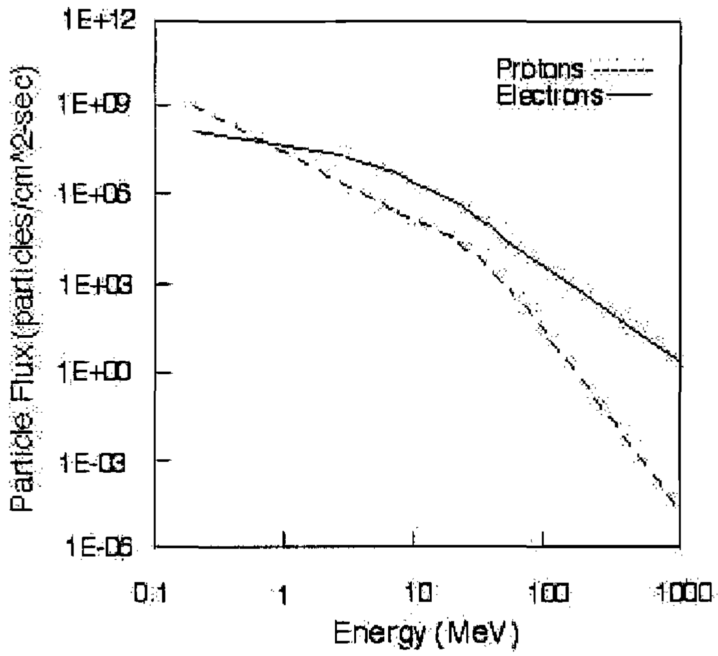

Figure 5-11. Particle fluxes in the Europa Vicinity

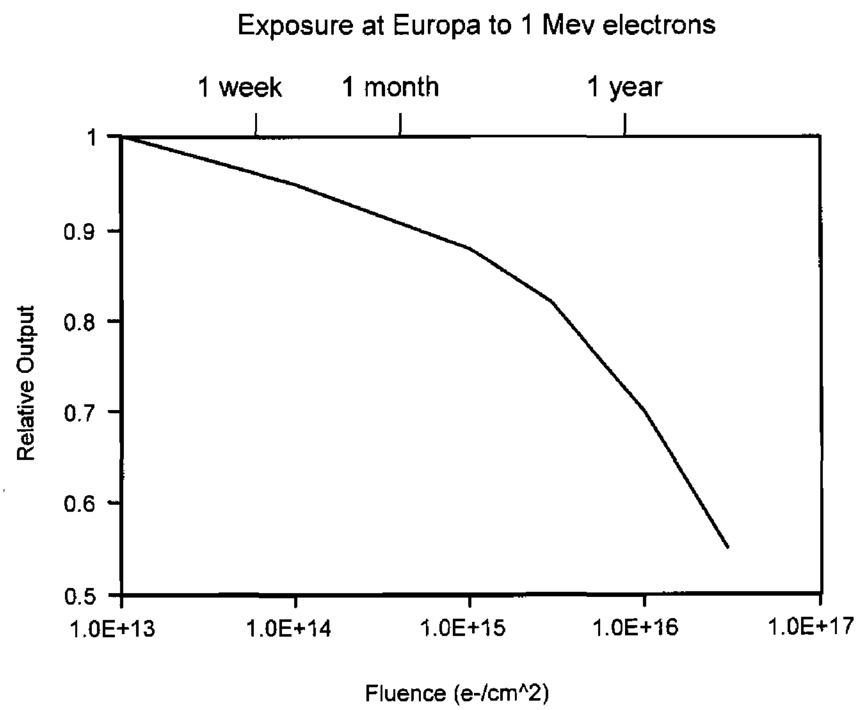

Figure 5-12. Relative output of 2-junction GaAs cell vs. fluence of 1 MeV electrons

Array Description and Technology Improvements

Early in the space program, solar cells were usually covered by one of two materials, microsheet (also known as Corning 0211) or fused silica (also known as Corning 7940). One exception was the Telstar spacecraft which used sapphire. Microsheet was only used in thicknesses of 0.15 mm (6 mils), because thicker sheets of the glass would darken significantly when exposed to radiation. Even a thinner product (0211) darkened too much. The Corning 7940 product could be produced in thicknesses up to 1.5 mm and did not darken due to radiation. However, the material was transparent to ultraviolet (UV) light and needed a UV filter to protect the cover adhesive from darkening. Fused silica, with its UV filter, was significantly more expensive than microsheet. After a time, ceria doped borosilicate glass was found to be ideal for most solar cell covers. This material did not darken appreciably under radiation because the ceria quenched the formation of color centers. In addition, it had a natural UV cutoff around 350 microns, so it did not need a UV filter. However, the material is only manufactured up to 0.50 mm thickness and may not be suitable for highest radiation environments. Optical Coating Laboratories Inc., one of only two cover glass suppliers, used to be the sole source for thick fused silica solar cell covers. The company's continuing presence in the cover glass business is uncertain at this time. The only sure supply of ceria oxide-doped borosilicate glass is available from the remaining supplier, Pilkington Ltd. As mentioned above, this glass is not made thick enough for high radiation environments. Even if it were, it would likely significantly reduce the amount of light that passes through to the cells. Either the sole current producer (Pilkington) needs to produce the fused silica glass or a new source must be found. Without the thicker glass, missions to high radiation environments will be extremely difficult to conduct using this shielding approach. The NASA need for thick fused silica cover glasses with thicknesses of 0.5-1.5 mm needs to be assessed on a mission-by-mission basis. Pilkington claims that it is in the process of developing a fused silica product for thick covers. This effort should be monitored and supported by NASA if the funding from the commercial and military users is not addressing NASA needs. It is likely that the mass of arrays with thick shielding will be unacceptable for some high radiation planetary orbiters. Therefore, a comprehensive test program is needed to evaluate radiation-resistant cell technologies. This program will have much in common with the program recommended in Section 5.1.3 for LILT arrays, with the addition of radiation effects evaluation under mission conditions. The high radiation NASA missions considered here occur at distances much greater than 1 AU, so combined LILT/radiation effects must be evaluated for both high performance cells and thin film cells. The development of radiation resistant, high efficiency GaAs-type cells is continuing, primarily with funding from the Air Force Research Laboratory as described in Section 5.1.1. NASA can make use of these cells provided that NASA qualifies them under the appropriate environment, e.g., high radiation plus low-temperature and/or low intensity. The typical military and commercial users are only concerned with radiation performance under one sun and nominal Earth orbit temperature conditions. AFRL is funding an extensive program in thin film solar cell development and thin film array engineering (Section 5.1.2). Again, NASA may find some of this technology entirely suitable for high radiation missions, but a substantial testing program will be required to characterize and qualify the cells and arrays under the appropriate conditions.

Application to OSS Missions

Sun-Earth Connection spacecraft tend to be placed in high radiation-orbits and most missions that flyby or target the Jovian system have a potential for high radiation exposure of the solar arrays. Even when the cost of this work is factored in, photovoltaics will be the least expensive option for powering spacecraft in radiation environments when the power level approaches 1 kW. The objective of development in this area is to minimize the effects of radiation on the solar array so that costly oversizing is not necessary. Much of the recommended work consists of characterization and qualification of cell and array technology that is already co-funded by others. This is an extremely cost effective approach to meeting these requirements in contrast to development of whole new technologies. Note added in proof: The need for solar arrays that operate in the high radiation environments of Jupiter and Europa appears to have been diminished by the new NASA nuclear initiative. It is now highly likely that these missions will be nuclear-powered.

5.6 Mars Surface Solar Arrays

5.6.1 Multi-junction Solar Cells for the Mars Surface

Introduction

The spectrum of illumination reaching the Mars surface is depleted at short wavelengths resulting in the performance of existing triple-junction cells being limited by the current generated in the top cell layer. Existing ~27% efficient solar cells will only be about 24% efficient at the Mars surface. With proper layer thickness and bandgap adjustment the solar cell should be able to approach the efficiency of ~27%, exclusive of any temperature effects. This represents a 10% reduction in cell area at any power level.

Technology Status

Modifications to multi-junction cells to match the solar spectrum on the surface of Mars have not been developed. The existing triple-junction solar cell used in the Mars surface solar spectrum environment has a power output that is controlled by the current-generating capability of the uppermost layer in the series. Since the radiation levels and thus the radiation degradation on the surface of Mars are minimal, this implies that the top cell layer remains current limiting throughout the mission instead of the more typical GaAs junction becoming current-limiting as a result of higher radiation fluence at the end of mission. Modifying the thickness or bandgap can increase the current generating capability of the top layer and thus increase the overall efficiency of the cell on the surface of Mars.

Table 5-3 illustrates the projected performance parameters of existing triple-junction cells, triple-junction cells adapted for use in the Mars spectrum, and the potential four-junction cells adapted for use in the Mars spectrum.

The effort will require a close relationship with a cell manufacturer to modify their processing to achieve this efficiency goal. Emcore Corp., Spectrolab Inc., and Tecstar Inc. are the only qualified domestic triple-junction solar cell manufacturers. Another critical need is the capability to evaluate and verify the performance of cells in a simulated Mars solar spectrum environment. Major cell manufacturers are actively engaged in developing new 4-junction cells (Section 5.1.1) with higher efficiencies. In most cases, the uppermost layers of the 4-junction cell are the same or similar to those of the current 3-junction cells. Therefore, any advances made on 3-junction cells for optimum efficiency in the Mars solar spectrum should be transferable to 4-junction cells.

Table 5-3: Existing and Projected Performance Parameters in the Mars Spectrum

	Triple-Junction:	Mars Triple-Junction	Four-Junction (projected)
Jsc (mA/cm^2)	5.34	5.93	5.93
Voc (Volts)	2.56	2.56	3.37
Jmp (mA/cm^2)	5.16	5.74	5.74
Vmp (Volts)	2.27	2.27	2.97
Pmax (mW/cm^2)	11.7	13.4	17.1
Efficiency (%)	24.1	26.8	35

Application to OSS Missions

A program to develop the Mars-optimized triple-junction solar cell would provide a solar power option for JPL's future objectives for Mars surface exploration. The benefits of using the high efficiency solar cells include reduced surface area and stowed volume. The surface area available on Mars Landers is very limited and is critical on a Mars Rover for hazard avoidance and ground clearance. Decreasing the array area by increasing the efficiency is critical to the design and may enable a mission to survive for much longer periods. The reduced stowed volume benefits both mass and volume for the mission since EDL requirements to the surface of Mars tend to be design drivers.

5.6.2 Array design

Technology Status

The surface area available for deployment of arrays on Mars is very limited and critical on a rover. Advanced design concepts and deployment techniques are an enabling technology for large rovers on the Mars surface. Able Engineering Company, Inc. and Lockheed Martin in Sunnyvale, CA are the two major solar array manufacturers in the U.S. who have advanced deployable designs that could be available for the Mars 2009 surface missions. Arrays such as UltraFlex™ (AEC) and the Lander Solar Array Assembly (Lockheed-Martin) designs are good concepts but require additional development and qualification before selection can be made. Array deployment must be part of the array design, and will require common development. AEC designed an Utra-Flex™ solar array for the Mars '01 mission that can be deployed in a one-g environment. This array droops too much to be useful for rovers. To insure low deployment risk and high array efficiency, a study and development must be conducted to evaluate array designs and deployment options, particularly for rovers that traverse rocky, bumpy terrain.

Application to OSS Missions

The benefits of using these high efficiency deployable arrays include low surface area and stowed volume during launch, entry, decent, and landing. These arrays have the possibility of being retracted if required to maintain a survivable mode during dust storms or the long winters. They can also be mounted on masts extending over a rover and not be limited to the rover deck or fold out arrays. Mounting the arrays on masts will enable additional scientific hardware to be placed on the rover's deck.

5.6.3 Mars Solar Array Dust Mitigation

Technical Status

Models of solar transmission through the dusty Martian atmosphere allow us to estimate solar intensities at the surface of Mars at any latitude for any season and optical depth of the atmosphere quite accurately. It is known that in typical repeatable clear weather, the optical depth is typically 0.5 ±0.1. During major global dust storms it can rise as high as 4 or 5 for brief periods.

Although reasonable estimates have been made of the effect of dust suspended in the atmosphere, much less is known about the effect of dust accumulating on solar arrays. There is some evidence from Viking that dust did not significantly affect cameras with vertical lenses, and there is evidence from pictures that dust deposition may have changed during the mission and may have been less severe on vertical surfaces than on horizontal surfaces. Recent work at JPL has measured the extinction curve for dust-covered solar cells as a function of the dust loading, using two simulants to Mars dust (Figure 5-11). These results show that dust loading required to produce any level of power reduction is surprisingly large. For example, to produce a 20% reduction in power, enough red dust must be spread on a cell to make it appear completely red, whereas the cell itself appears black in the absence of dust (Figure 5-12).

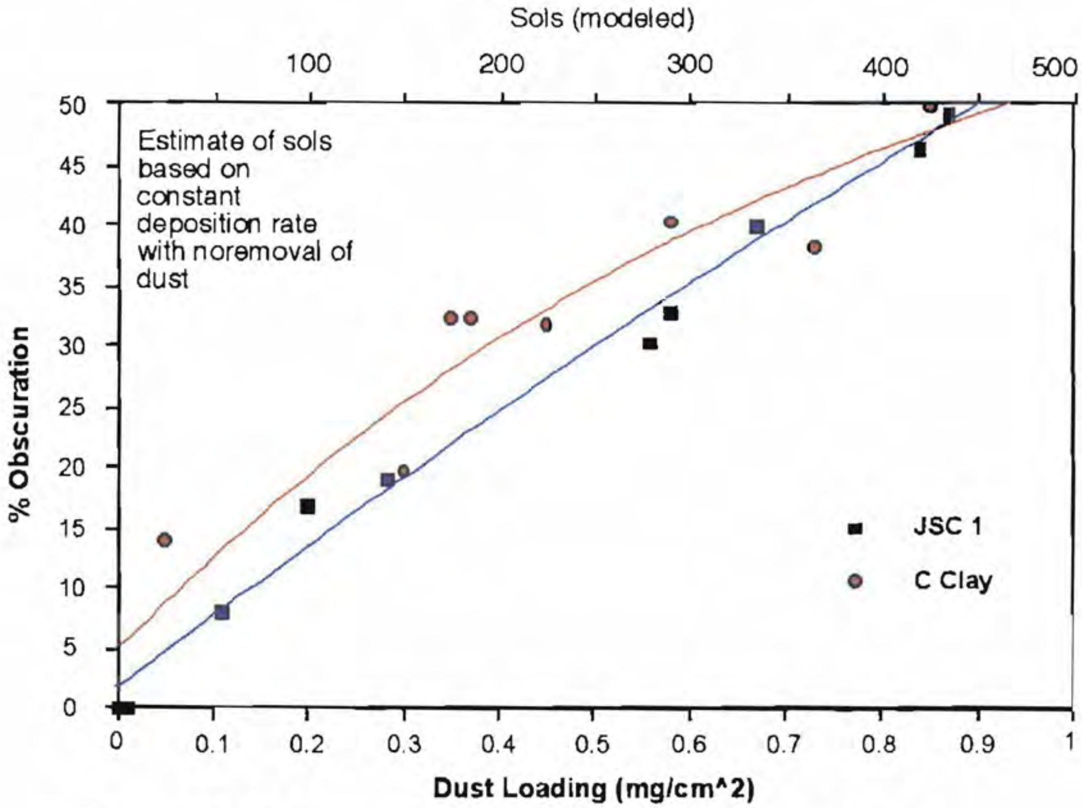

Figure 5-11: Measured extinction curve for two simulants to Mars dust. Vertical scale is the % power reduction due to dust loading.

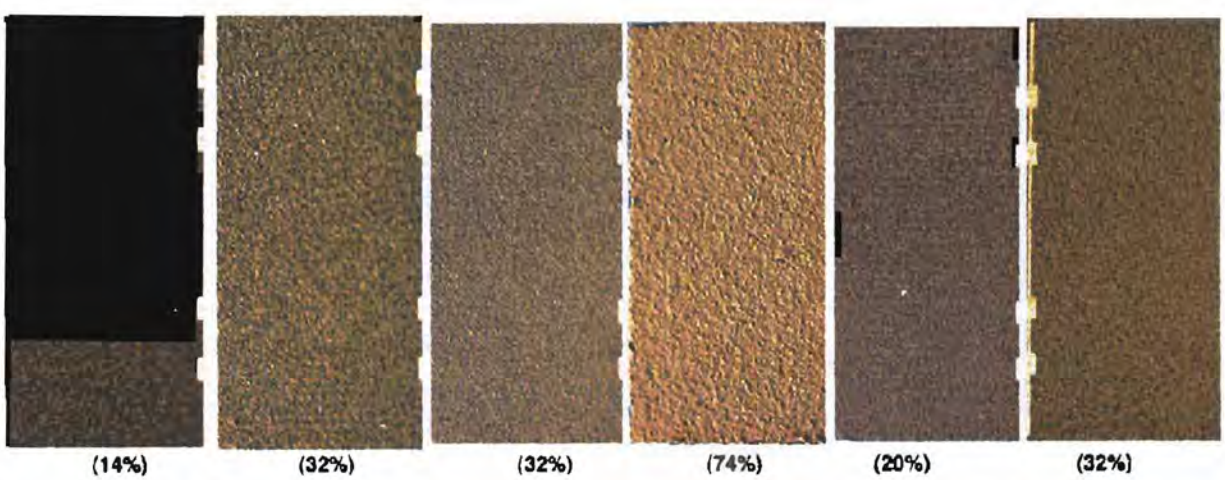

Figure 5-12: Photos of (Black) Solar Cell with Various Levels of Simulated Dust Loading Percentage reduction in power is shown for each dust laden cell.

While it is known that individual small (micron-size) dust particles are held by very strong forces compared to the gravitational force, it has also been observed on an anecdotal basis that heavily dust-laden surfaces are much more easily amenable to dust removal by blowing or shaking if the dust is clumped, agglomerated, or occurs in multiple layers. Considering the measured extinction curve, it appears likely that after enough dust builds up to reduce power by 20-25%, the upper layers of dust should be removable by aeolian forces and an equilibrium should eventually set in where dust removal balances dust deposition. While this point is not known accurately, it might be in the 20-25% range of power reduction. Analysis of Pathfinder data over 83 sols in which the power produced by a single exposed cell was compared with the expected power based on solar models, indicated that reduction in power due to dust appeared to be leveling off after 83 sols at 20% or less.

Based on the limited data available, it appears that there are two ways to conduct a long-life solar powered mission on Mars. One is to use no overt dust mitigation, and allow power reduction due to dust on arrays to gradually reach an asymptote of perhaps 20-25% over long periods (Figure 4-3). The other is to use overt dust mitigation (blowers, scrapers, brushes, covers, electrostatics, etc.) to maintain power reduction under 10% (due to residual small particles adhered to arrays). However, all of these data are limited in scope and more thorough experimentation and analysis is required.

Technology Improvements

In order to obtain an optimum solar power source for landers and rovers on the Mars surface, it is essential to develop a fundamental understanding of the physics of dust adhesion and accumulation by laboratory simulation studies of (1) Mars dust deposition and removal processes, (2) the relation between deposited amount and optical obscuration, (3) effect of surface dust on array performance, (4) dependence of dust accumulation and retention on array tilt, etc. This will eventually require verification through testing in the Martian environment.

Then a dust tolerance/mitigation approach must be developed based on the fundamentals studied in the dust physics activity. This approach should be based on the mission needs (particularly mission duration, latitude and season, configuration and other constraints, strategy for dealing with dust storms, and surface operations strategy). It may vary from developing dust-tolerant systems such as arrays that can be periodically tilted, to arrays with overt dust mitigation such as blowers, scrapers, covers, electrostatics, etc., or it might involve odd architectures such as low concentration Fresnel concentrators.

Eight methods for dust mitigation have been suggested as listed in Table 5-6. None have yet been pursued.

A detailed plan for dealing with effects of Mars dust on solar arrays was developed by JPL. It included preparing simulated Mars dust, measuring extinction curves of obscuration vs. dust loading for solar cells, and testing various alternatives for mitigation of dust. This program should be funded as planned.

Application to OSS Missions

Without an immediate and substantial investment in the study of dust on Mars surface solar arrays, it will not be possible to make reasonable estimates of the required array sizes for landers and rovers. Lacking this it will not be possible to ensure mission success in terms of duration and operation of surface instruments.

5.7 Far Term Array Technologies

These technologies are concepts near TRL 1-2 that are being funded at a low level to assess feasibility and benefits.

Table 5-6: Possible Methods to Mitigate Dust on Arrays

No.	Approach	Comments
1	Transparent cover	Cover remains over arrays at all times. After dust accumulates on currently used cover over perhaps 30-60 Sols, a new clean cover is rolled into place.
2	Opaque cover	Cover is retracted during the day to expose the arrays, and redeployed each night (about 7 hours off and 17.6 hours on per Sol). This reduces exposure of array by about 2/3.
3	Brushes	Brushes sweep over the array to remove dust. But it is not clear whether the dust can be swept away with reasonable force.
4	Blow dust off	Use high-pressure gas (~1 atm) to blow dust off arrays. But it is not clear whether the dust can be swept away with reasonable velocities. Some lab experiments indicate that very high gas velocities (> 40 m/s) may be needed to remove small particles adhered to a surface.
5	Electrostatic or electrodynamic repulsion of dust	Use electrical forces to repel dust.
6	Use tilted arrays or periodically tilt the arrays	Dust may "slide off" if tilt is great enough. Viking and PF evidence seem to indicate dust can slide off near-vertical surfaces.
7	Retract arrays at night	Retract to vertical position or to protected position to minimize dust collection for overnight (2/3 of Sol).
8	Use ~ 1.5X to 2X Fresnel concentrators	Need to model how much diffuse light is collected. Curved Fresnel covers tend to shed dust. May still need cleaning of Fresnel covers.

5.7.1 Multi-Bandgap High Efficiency Converter

A novel concept is the multi-bandgap high efficiency rainbow converter developed at JPL that uses Fresnel prisms to split the solar spectrum. This allows the use of multiple cells in parallel to maximize overall efficiency. Instead of monolithically growing thin junctions with different band gaps as in conventional multijunction cells, a Fresnel prism is used to spread the solar spectrum over a broad spatial area so that cells with appropriate band gaps can be placed sequentially along the spectral distribution. Theoretically, overall conversion efficiencies of 30-50% should be possible. An initial breadboard device achieved 17.5% conversion. (See Figures 5-14 and 5-15)

5.7.2 Power Beaming

Laser power beaming from Earth to satellites has been contemplated for over 20 years, but this concept is useful only for near-Earth missions. At larger distances, the size of the transmit and receive optics becomes unreasonably large due to simple diffraction considerations. The most effective scenarios are powering of large constellations of satellites with a single laser, and powering of very high power satellites. NASA appears to have neither of these mission types.

Alternatively, power may be beamed from one satellite (the PowerSat) to a consuming satellite (the LoadSat). Reasonable sized optics can relay power at distances up to about 20,000 km. An attractive application for this approach could be to place the PowerSat outside the radiation belts of a planet and beam power to a small, heavily shielded array on the LoadSat that is orbiting in the belts. This approach will make sense only for higher power loads or LoadSats where body-mounted arrays are dictated by sensor considerations. Another possible scenario is solar electric propulsion, where a large (20-50 kW) attached solar array might compromise the pointing of the thrusters or communications antenna. Instead a large PowerSat could fly in formation with the LoadSat and beam power to a much smaller receiver array. The PowerSat could in principle be reusable, especially if refueling capability is implemented. No trade studies of interplanetary mission of this type have been conducted.

5.7.3 Inflatables

Use of inflatables for solar power in space can take several forms. One approach is to develop relatively conventional appearing flat solar arrays that are stored in a folded-up condition and deployed by inflation. L'Garde, Inc. has proposed such an approach, which is illustrated in Figure 5-16.

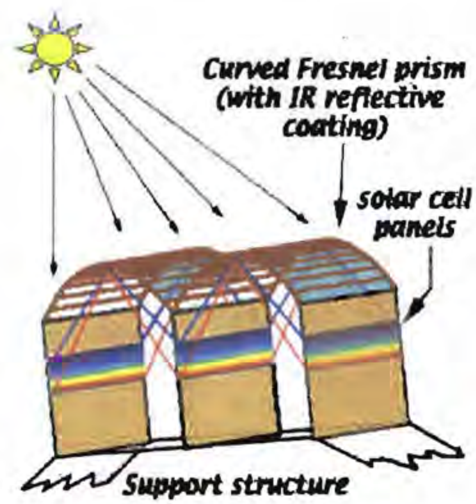

Figure 5-14. Multi-Bandgap High Efficiency Rainbow Converter

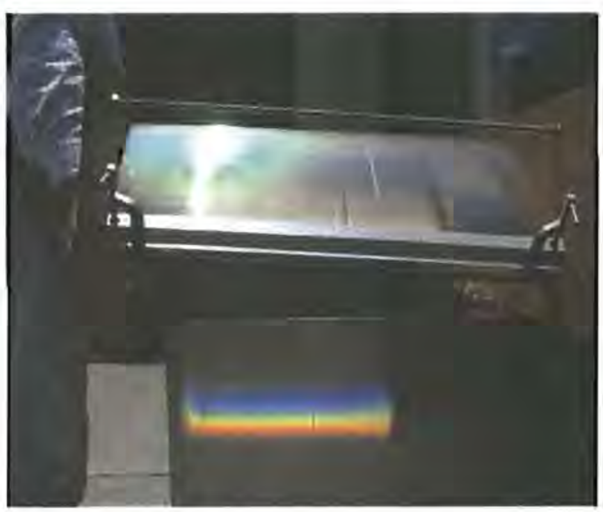

Figure 5-15. Fresnel Lens with the Rainbow Projected onto a Flat Plane using Sunlight

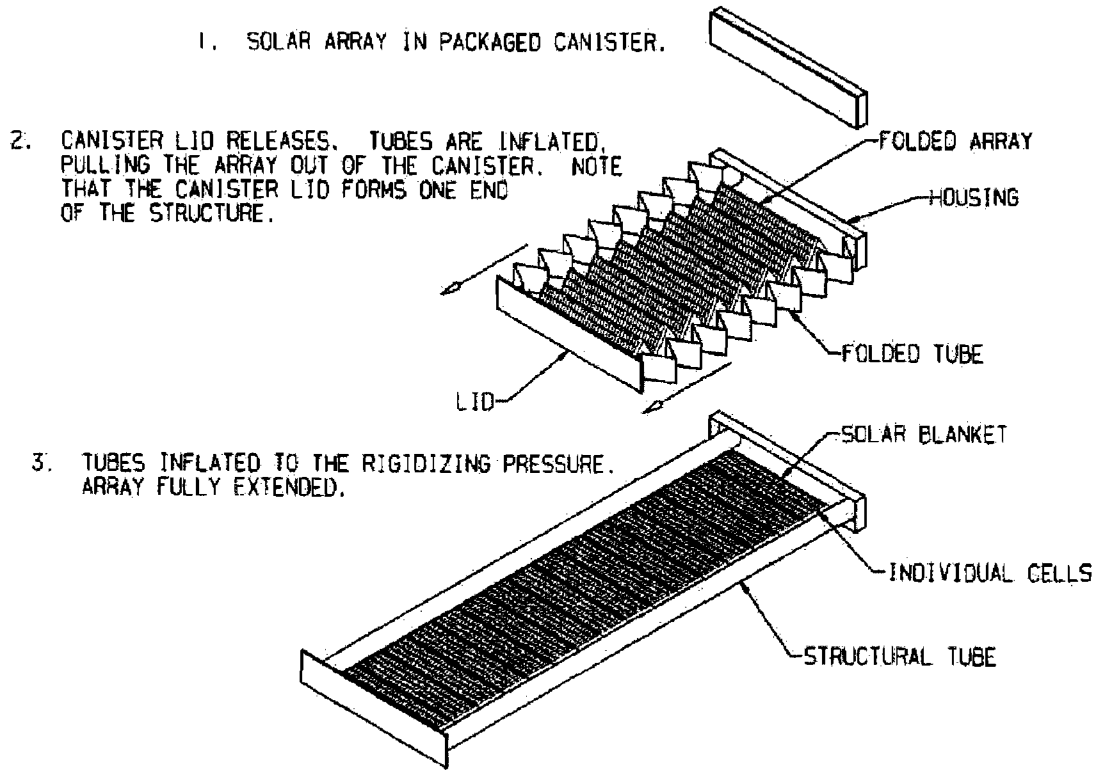

Figure 5-16: Inflatable Array Concept

This system is designed for small satellites with power requirements in the 200-1000 W range. The goal is to achieve very low mass, ~100 W/kg, very small and flexible stowed volume, and low cost compared to other systems. It can utilize a variety of cell types. Deployment is simple and passive, with orthogonal folds in the blanket and struts used to constrain deployment dynamics. It uses passive blowdown inflation, and no active control is required. After deployment, the structural tubes can be rigidized. The method preferred by L'Garde is use of aluminum laminate (tube wall is 1 mil Kapton, 3 mils aluminum and 1 mil Kapton). When the aluminum is expanded beyond its yield point it becomes rigidized. L'Garde successfully deployed a test device in a thermal/vacuum chamber simulating the space environment (Figure 5-17). Various tests confirmed predicted performance parameters.

A more speculative use of inflatables is based on the Power Antenna concept, originally proposed by Joel Sercel at JPL and now under study by L'Garde. It involves use of a large (> 10 m diameter) inflatable "lenticular structure," shown in Figure 5-18, that acts as a reflector for both RF communications and concentration of solar power. It will take a great deal more study and experiments to determine whether this approach is practical.

Figure 5-17. Deployment Test Setup Used In Thermal/Vacuum Chamber

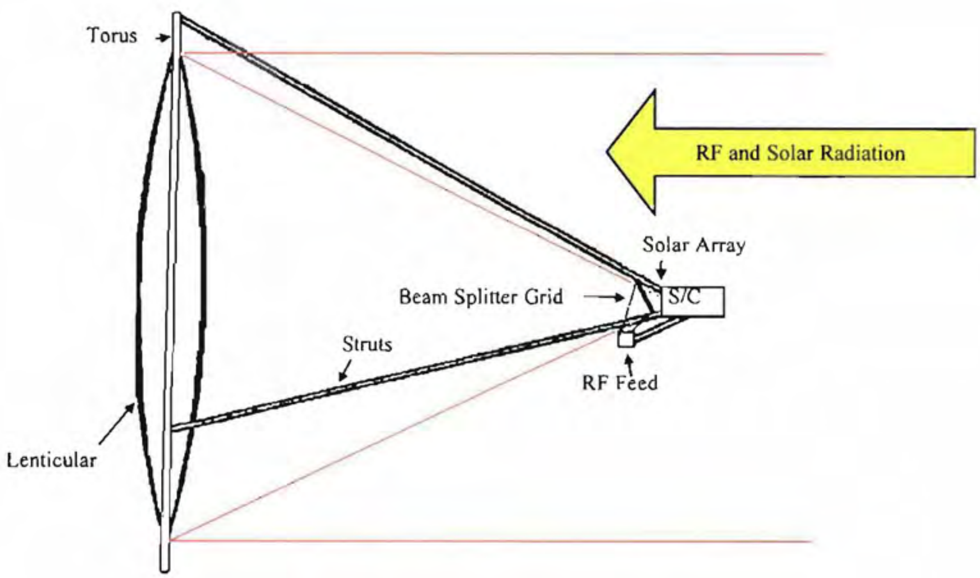

Figure 5-18. Inflatable Power Antenna Concept.

5.8 Infrastructure

It is necessary that NASA have available resources for solar cell measurement, analysis, and characterization. These facilities are needed to assess the suitability of the various technologies to specific missions. In addition, they maintain the required calibration standards for these measurements. For properties of photovoltaics under special conditions such as LILT, high intensity, dusty conditions such as occur on Mars, or high radiation environments, special test facilities are required. These capabilities have been built up at several NASA centers, expert personnel are in place to operate them, and they should be provided with funding to conduct the assessments recommended in this report. In addition to test capabilities, they have the analytical tools for mission modeling under conditions unique to NASA spacecraft. GRC provides solar cell measurement, characterization, and standards. GSFC conducts array design exercises, costing estimates, and spacecraft integration trade studies. JPL maintains a world-class radiation effects laboratory.

Photovoltaics are the cost effective choice for most NASA missions. Failure to take full advantage of the technology over-constrains the scientific payloads and the launch vehicle options, leading to higher costs. Relying on cell and array manufacturers for accurately predicting array or cell performance is costly and often lacking in consistency. Early detection of problems for a given mission is extremely cost effective. Without the use of long-standing expertise and facilities, NASA cannot make the most intelligent mission choices.

6.0 Results and Recommendations

6.1 Introduction

This section of the report summarizes the study results and recommends a photovoltaics investment program to advance the maturity of selected solar cell/array technologies to TRL 5/6. Solar photovoltaic power is the preferred power system for many future NASA OSS missions, and it must operate in unique environments. Advanced high power solar cell/array technology is required for SEP for many potential space missions. For some NASA OSS planned missions, solar photovoltaic power is an alternative to radioisotope power. In these cases, the technology goal is to make solar photovoltaic power as competitive as possible.

The unique NASA cell and array requirements of the major OSS themes are summarized in Table 6-1.

6.2 Results and Recommended Advanced Technology Investment Tasks

These assessment results of the advanced technologies needed to meet the requirements of future potential NASA OSS missions are briefly tabulated in Table 6-2. The recommended investment tasks needed to develop the advanced technologies to NASA TRL 5/6 are presented in the following sections by the particular solar cell type and solar array type in descending priority order.

6.2.1 High Power for Solar Electric Propulsion

The Team recommends that advanced technology for large thin film arrays and concentrator arrays be developed for solar electric propulsion. SEP reduces the required propellant mass of some missions by factors of 2 or 3 compared with chemical propulsion. The key to successful SEP missions is obtaining many kilowatts of cost-effective electrical power from low mass solar arrays. Thin film arrays and concentrating arrays have the potential to provide low mass and many kilowatts of power.

Table 6-1: Unique Solar Cell/Array Needs of the SSE, SEC, ASO, and SEU Missions

	Future Missions		
Solar Cell/Array Technology	**SSE**	**SEC**	**ASO & SEU**
Missions	MER, MRO, MSL, MSR, Scout, EO, PKE, EL, NO, CNSR, VSSR, SRO, TE	MMS, SDO, GEC, LWS-GM, Sentinels, MC, SP, SPI, RAM, ITM Waves, JPO, SPECS, ISP, GSRI	SIM, LISA, GLAST, ACCESS, NGST, TPF, ARISE, OWL, Con-X, EXIST, HSI, FAIR, SUVO, PI, LF, MAXIM PF, SPIRIT, MAXIM
Low-cost	X	X	X
High-efficiency and low-mass	X	X	X
Advanced deployment and retraction	X	X	
Low-intensity and low-temperature (LILT)	X	X	
Radiation tolerance	X	X	
High-temperature environments	X	X	
Dust mitigation on Mars	X		
Large power for SEP	X		
Electrostatically clean arrays		X	

Table 6-2: Technology Programs Needed Due to Gap Between Goals and State of the Art

Advanced Technology	Driving Missions	Requirements	State of the Art	Needed Technology
1) High Power Arrays for SEP	CNSR, outer planet missions, VSSR, MSR	• >150 W/kg specific power • Operate to 5 AU	• 50-100 W/kg • Unknown LILT effect	• High efficiency thin-film cells • High-power, low -mass arrays
2) Electrostatically Clean Arrays	SEC missions: MMS, MC GEC, SP, Sentinels	• < 120% of the cost of a conventional array	•~300% of the cost of a conventional array	• Transparent plastic covers • Glass covers for multiple cells
3) Mars Arrays(*)	MSL, MSR, Scouts	• 26% efficiency • >180 sols @ 90% of full power	• 24% efficiency • 90 sols @ 80% of full power	• Optimized cells for Mars • Dust mitigation
4) High Temperature Solar Arrays	Solar Probe, Sentinels, PASO	•350°C operation (higher temperatures reduce risk and enhance missions)	• 130°C steady state; 260°C for short periods	• Adapt cells and arrays to high temperatures based on AFRL technology
5) High Efficiency Cells	All missions	•> 30+ %	• 27%	• Adapt AFRL and commercial progress to NASA needs
6) LILT Resistant Arrays(#)	Outer planet missions, SEP missions	•No insidious reduction of power under LILT conditions	• Uncertain behavior of MJ cells under LILT conditions	• Adapt cells/arrays to avoid LILT problems • Test cells at LILT conditions
7) High Radiation Missions(#)	Europa and Jupiter missions	• Radiation resistance (> 10^{15} 1 MeV electrons/cm^2) with minimal weight and risk penalty	• Thick cover glass • Significant mass penalties	• Radiation resistant thin film and concentrator arrays • Adapt commercial and military cells to meet radiation requirements

(*) The MSL and MSR missions may turn out to be powered by new RTGs developed under the proposed nuclear technology initiative, in which case, solar power would only be used by Scout and other short duration missions. This will depend on how affordable the RTGs turn out to be.

(#) Outer planet missions are likely to be powered by new RTGs developed under the proposed nuclear technology initiative, in which case the need for LILT technology would only be for SEP if thrusting is required out to 3-5 AU. Resistance to the radiation environment in the Jupiter system may not be required if these missions are powered by RTGs.

At present, thin film efficiencies are too low, and the current substrates are too heavy. However, only moderately efficient thin-film cells (~10-15% over large areas) with a low mass substrate have the potential to match the specific power performance of arrays using much more efficient (but heavier) crystalline cells. Considerable challenges remain in developing moderately efficient thin film cells and low mass substrates and further technology development is needed.

AFRL is executing a large program in thin film cell technology development, including development of encapsulated blankets, interconnects, array structure and deployment systems. The Team recommends that NASA co-fund the thin film prototype and demonstration phases of the AFRL work at $1 M per year and then establish an independent technology transition and qualification effort tailored to unique NASA requirements.

A number of commercial companies are developing concentrating arrays for use in Earth orbit. An AEC-Able Engineering design, the Stretched Lens Array, is the baseline for the NASA ST5 mission. It is recommended that the Stretched Lens Array be compared with other lightweight, high-ratio reflective concentrators for SEP missions and NASA funding provided to apply one of these technologies to SEP. It is recommended that NASA provide $500 K over 18 months for evaluation of reflective and refractive concentrator arrays for use on various future missions. The study should address the benefits of concentrators with respect to cost and LILT mitigation, for example, but also the risks and additional requirements imposed on the spacecraft.

It is recommended that one or two concepts should be selected for prototype development and testing. This would include a qualification panel coupon program to validate the thermal survivability, high voltage operation and LILT performance, and then a full-scale qualification wing program should be pursued at an estimated cost of $1 M per year as shown below.

Recommended funding is as follows:

Technology Program	FY03	FY04	FY05	FY06	FY07
Thin film cells and arrays		$1 M	$1 M	$1 M	$1M
High voltage operation	$0.5 M	$0.5 M			
Concentrating array trade study	$0.3 M	$0.2 M			
SEP Concentrating array development		$0.3 M	$1 M	$1 M	$1 M
Total for High Power Arrays for SEP	$0.8 M	$2 M	$2 M	$2 M	$2 M

6.2.2 Electrostatically Clean Arrays

The Team recommends that there is a need to work on transparent, conductive materials that can withstand the space environment. These coatings could be plastics that are subsequently coated with ITO or other transparent conductive coatings such as wide bandgap semiconductors that have inherently suitable conductivity. Either of these approaches makes available a thin coating that conformably covers large sections of solar arrays. This could produce the desired electrostatic cleanliness with a minimum of expense, mass and cost. In addition, this approach could yield a readily repairable array. Further, such plastics are extremely desirable for protection of thin film arrays - so this work will facilitate that development.

The Team also recommends a small effort in extending typical glass or fused silica to cover several cells. This has been tried in the past, but without success due to delamination or failure of interconnects in thermal cycling. Also, such covers can cause difficulties of repairs because there is no cost-effective way to replace a broken cell under such a cover. Additional research is needed to develop methods to resolve these technical issues.

Recommended funding is as follows:

Technology Program	FY03	FY04	FY05
Transparent, conformal conductive coatings	$0.3 M	$0.3 M	$0.3 M
Glass covers to cover multiple cells	$0.2 M	$0.2 M	*
Total for electrostatically clean arrays	$0.5 M	$0.5 M	$0.3 M

* Depends upon whether results of first two years of work are encouraging

6.2.3 Solar Arrays on Mars

A Mars solar photovoltaic program has been fully planned. The Team recommends NASA conduct the following three tasks. (1) Optimize cell design for the spectrum at the surface of Mars (depleted at short wavelengths), (2) study the properties of simulated dust and its effect on photovoltaic arrays, and (3) develop dust tolerance/mitigation systems. All of these will be developed to NASA TRL 5/6. Solutions derived from these will be available for use on the Mars 2009 Smart Lander mission.

Recommended funding for these tasks are as follows:

Technology Program	FY03	FY04	FY05	FY06
Optimized cells for the Mars surface spectrum	$0.5 M	$1.5 M	$1.5 M	$1.0 M
Physics and effects of Mars dust on PV	$0.2 M	$0.5 M	$0.5 M	
Dust tolerance/mitigation technology	$0.5 M	$1.0 M	$1.5 M	
Total Mars arrays	$1.2 M	$3.0 M	$3.5 M	$1.0 M

6.2.4 High Solar Intensity Arrays

The Team recommends technology development of multi-junction cells that can operate efficiently up to 600°C. Missions that fly nearer to the sun than about 0.4 AU require solar cell/array materials that can withstand elevated temperatures. Specific concerns are diffusion of metals and dopants within the solar cells and adhesives used in the array. Work in the late 1980s under the SDIO program resulted in high temperature versions (up to 600°C) of single junction GaAs solar cells that incorporated new metallization and diffusion barriers with little sacrifice in performance. These cell designs are available, but their application to multi-junction cells need to be developed. Solar arrays tolerant of elevated temperatures were developed for transient events, not long-term exposure. A thermal analysis of the entire array/cell structure for solar inner planet missions that will determine the actual time/temperature profile for specific missions is recommended to define the solar cell/array temperature environment.

The Team recommends that advanced coatings be developed to limit the amount of unusable IR entering the solar cell and to control the solar array substrate temperature. Ideally, a switchable electrochromic coating might be developed that reduces or eliminates the need for array feathering.

Recommended funding for these tasks are as follows:

Technology Program	FY03	FY04	FY05	FY06
High temperature solar cells	$0.3 M	$0.3 M	$0.5 M	
High temperature array assemblies	$0.5 M	$1 M	$0.5 M	$0.5 M
Electrochromic coatings	$0.3 M	$0.5 M	$0.2 M	$0.2 M
Total for High Temperature Solar Arrays	$1.3 M	$1.8 M	$1.2 M	$0.7 M

6.2.5 Low Intensity Low Temperature Arrays

The Team recommends that NASA develop a LILT Test Plan geared to the use of III-V cells (GaAs, triple junction, etc.) and thin film cells. The primary goal would be for applications out to Jupiter (5.2 AU), with considerably lower priority for Saturn. Radiation behavior needs to be a part of this testing since radiation damage is likely to alter LILT behavior. A four-step process should be used: (1) create a database for current cells under LILT conditions, (2) conduct investigations to determine the cause of any degradations and possibly identify solutions, (3) develop cell processes to reduce/minimize/eliminate LILT degradation and (4) confirm the LILT behavior of optimized cells by testing and qualifying the cells for space use.

Required funding to reach NASA TRL6 is:

Technology Program	FY03	FY04	FY05	FY06
Database for current cells under LILT conditions	$150 K			
Determine cause/mechanisms for LILT degradation	$250 K	$600 K	$300K	
Processes to minimize LILT effects		$300 K	$600 K	$300 K
Verify LILT mitigation processes				$300 K
Total LILT Resistant Arrays	$450 K	$900 K	$900 K	$600 K

6.2.6 High Radiation Missions

The Team recommends that NASA OSS investigate the following two approaches to obtaining solar arrays that function well in high radiation environments: (1) provide shielding (cover glasses or concentrator optics) to protect cells from direct exposure and (2) develop radiation-resistant cells. The first approach is to use 0.5-1.5 mm thick cover glasses of fused silica material that are not presently available. This is a low risk approach, but costly in terms of establishing a limited production line and the mass impact to the spacecraft.

The second approach begins with a comprehensive test program to evaluate radiation-resistant cell technologies. This task has much in common with the task recommended for LILT arrays with the addition of evaluating the radiation effects that simulate the potential mission environment. The high radiation potential NASA missions are at distances much greater than 1 AU, so combined LILT/radiation effects must be evaluated for both high performance cells and thin film cells. The additional estimated costs of this investigation (beyond that of LILT) are listed below.

The Team recommends that NASA fund a testing task to determine the radiation resistance of thin film cells/arrays and concentrator arrays. AFRL is funding an extensive program in thin-film solar cell development and thin-film array engineering. NASA should determine if this technology is suitable for high radiation missions, by testing these cells to characterize and qualify the cells and arrays to meet NASA mission radiation requirements.

Concentrator arrays for use in high radiation fields will require an extra effort to select and qualify radiation resistant materials for the concentrators.

Recommended funding for these three tasks are as follows:

Technology Program	FY03	FY04	FY05	FY06	FY07
Thick silica cover glasses	$250 K	$700 K*			
Radiation resistant high efficiency cells	$150 K	$300 K	$400 K	$500 K	$200 K
Radiation properties of thin film cells	$200 K	$100 K	$100 K		
Radiation resistant concentrator materials	$300 K	$200 K	$200 K		
Total High Radiation Missions	$900 K	$600 K	$700 K	$500 K	$200 K

* If study deems necessary

6.2.7 High Efficiency Cells

A NASA co-investment of $1M per year is recommended for three years starting in FY04 to develop the next generation multi-junction cell. It is likely that a monolithic multi-junction cell with greater than 30% efficiency will be developed under the AFRL program. NASA should participate in the AFRL advanced technology development program to insure that NASA requirements are recognized. NASA-GRC co-funded the Manufacturing Technology Program with the Air Force in the early 1990s for the original multi-junction cells.

The Team recommends that research on lattice-mismatched multi-junction devices and alternative substrates be supported, while maintaining coordination with similar AFRL programs involving different vendors and approaches. Funding of $500K per year in FY03-05 is needed, with an increase to $1 M per year starting in FY05, assuming a successful design is selected in FY04 for transition to manufacturing. The funding amounts are based on the assumption that AFRL continues to provide comparable funding. A joint transition program will be the most cost-effective.

Recommended funding is as follows:

Technology Program	FY03	FY04	FY05	FY06	FY07
Technology transition of next generation cells		$1M	$1M	$1M	
Research on lattice mismatched multi-junction devices and alternative substrates	$0.5M	$0.5M	$1M	$1M	$1M
Total for High Efficiency Cells	$0.5M	$1.5M	$2M	$2M	$1M

6.2.8 Infrastructure

A number of the tasks recommended here require support in the form of solar cell and array materials measurement, characterization, and test. The facilities at GRC, GSFC, and JPL are uniquely qualified to conduct these tasks as the result of their long histories of NASA mission support in photovoltaics. Although the funding requests for these tasks are sufficient to complete them, it is assumed that the operating budget for the photovoltaics infrastructure facilities at these centers are maintained to provide support.

GRC maintains a high altitude aircraft for solar cell calibration, solar simulators for cell efficiency measurements, coupon fabrication facilities, and a broad range of characterization and analysis tools. GSFC has a solar simulator for integration-level testing and analytic tools for assessing system level performance and cost for different solar cell technologies. JPL maintains a world-class radiation effects laboratory, as well as an in-house cell characterization capability and mission analysis tools. More details on specific instruments and facilities are contained in Appendix A.

It should be noted that each element of this infrastructure is typically funded in part by direct charges to contracts for services rendered and partly by NASA funding to cover upgrades, maintenance, operations in between direct users, and development of new techniques. The latter funding is not specifically called out in this report, but is an essential part of the tasks.

6.3 Funding Roadmap

Funding roadmaps are shown in Figures 6-1A and 6-1B. The total program is summarized in the following table, with a total run-out cost of $36.6 M over five years.

Capability	FY03	FY04	FY05	FY06	FY07
High Power Arrays for SEP	$0.8 M	$2 M	$2 M	$2 M	$2 M
Electrostatically Clean Arrays	$0.5 M	$0.5 M	$0.3 M		
Mars Surface Solar Arrays	$1.2 M	$3.0 M	$3.5 M	$1.0 M	
High Temperature Solar Arrays	$1.3 M	$1.8 M	$1.2 M	$0.7 M	
LILT Resistant Cells/Arrays	$0.5 M	$0.9 M	$0.9 M	$0.6 M	
High Radiation Cells/Arrays	$0.9 M	$0.6 M	$0.7 M	$0.5 M	$0.2 M
High Efficiency Cells	$0.5 M	$1.5 M	$2 M	$2 M	$1 M

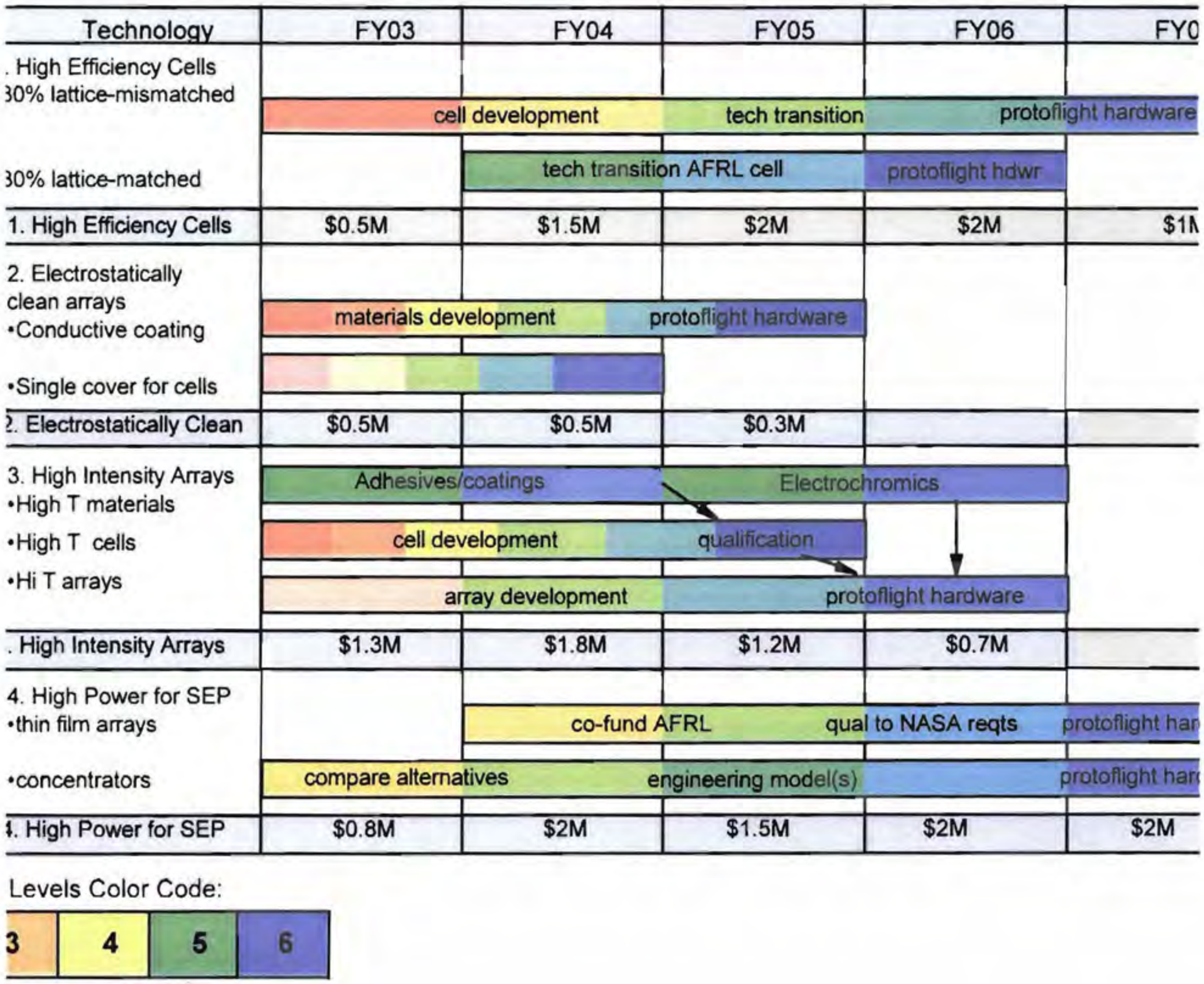

Figure 6-1A. Roadmap for Four Elements of PV Technology

Technology	FY03	FY04	FY05	FY06	FY07
5. LILT					
•cell characterization	characterize cell performance				
•LILT Mitigation		develop process		verify process	
5. LIIT	$0.45M	$0.9M	$0.9M	$0.6M	
6. High radiation arrays					
•Thick silica covers	evaluate	implement if needed			
•Thin film cell assess	characterize		adapt		
•Optimized hi-rad cells	design	develop	test	tech transition	
•Concentrator mods	matls evaluation	rad hard mtls	engr model		
6. Rad-resistant Arrays	$0.9M	$0.6M -$1.3M	$0.7M	$0.5M	$0.2M
7. Mars arrays					
•spectral cells	design	prototypes	verification	qualify	
•dust physics		fundamental studies			
•dust mitigation	options	test	engr model	verify in chamber	
7. Mars arrays	$1.2M	$3M	$3.5M	$1M	

Figure 6-1B: Roadmap for three elements of PV technology

7.0 Abbreviations and Acronyms

Term	Definition
AEC	Able Engineering Corporation
AFRL	Air Force Research Laboratory
AM0	Air Mass Zero (solar spectrum in space)
AM1.5	Air Mass 1.5 (solar spectrum at the earth's surface)
APSA	Advanced Photovoltaic Solar Array
AR	antireflection
ARPS	Advanced Radioisotope Power Source
ASE	Alternative Energy Systems, Co.
ASO	Astronomical Search for Origins
AU	Astronomical Unit
BMDO	Ballistic Missile Defense Organization
BOL	Beginning of Life
C&DH	Command and Data Handling
CIS	Copper Indium Diselenide
CLEFT	Cleavage of Lateral Epitaxial Films for Transfer
CNOFS	Communication/Navigation Outage Forecasting System
CNSR	Comet Nucleus Sample Return
COI	Composite Optics Inc.
CVD	Chemical Vapor Deposition
DoD	Department of Defense
DoE	Department of Energy
DUS&T	Dual Use Science and Technology
EDL	Entry, descent and landingE
EEV	EEV Ltd. a European solar cell company
EL	Europa Lander

Term	Definition
EOL	End of Life
ESS	Explore the solar system
EUV	Extreme Ultra Violet
FAST	Fast Auroral Snapshot
GEC	Geospace Electrodynamic Connection
GEO	Geosynchronous Earth Orbit
GRC	Glenn Research Center
GSFC	Goddard Space Flight Center
Isc	short circuit current
ITN	ITN Energy Systems, Inc.
ISET	Instit für Solare Energieversorgungstechnik (Germany)
ITO	Indium tin oxide
JHU	Johns Hopkins University
JPL	Jet Propulsion Laboratory
LAPSS	Large Area Pulsed Solar Simulator
LEO	Low Earth Orbit
LILT	Low Intensity Low Temperature
LMSC	Lockheed Missiles and Space Co.
MagCon	Magnetospheric Constelation
MC	Magnetospheric Constellation
MEP	Mars Exploration Program
MESSENGER	MErcury Surface Space ENvironmental GEochemistry and Ranging
MILSTAR	A series of advanced U.S. military communications satellites designed to provide global jam-resistant communications for military users
MIR	Russian Space Station
MJ	Multi-junction
MMS	Magnetosphere Multiscale
MSL	Mars Smart Lander (MSL) mission
MSR	Mars Sample Return (MSR) mission
MOCVD	Metal Organic Chemical Vapor Deposition
NASA	National Aeronautics and Space Agency
NO	Neptune Orbiter
NREL	National Renewable Energy Laboratory
NRL	Navy Research Laboratory
NRO-STEX	National Reconaissance Office-Space Technology Experiment
OAI	Ohio Aerospace Institute
OSR	Optical Solar Reflector
OSS	Office of Space Science
PASO	Particle Accelerator and Solar Orbiter

Term	Definition
PDR	Preliminary Design Review
PEEL	Preferentially Etched Epitaxial Lift-off
PMAD	Power Management and Distribution
PV	Photovoltaics
R&D	Research and development
RPS	Radioisotope Power Source
RTG	Radioisotope Thermal Generator
SAVANT	Solar Array Verification and Analysis Tool
SBIR	Small Business Innovative Research Program
SCARLET	Solar Concentrator Array with Refractive Linear Element Technology
SCOPA	Survivable Concentrating Photovoltaic Array
SDIO	Strategic Defence Initiative Organization
SEC	Sun Earth Connection
SEP	Solar Electric Propulsion
SEU	Structure and Evolution of the Universe
SLA	Stretched Lens Array
SLATS	Solar Concentrator, better known as "SLATS" was submitted by General Dynamics. Sunlights in concentrated by a parabolic trough mirror into a line focus.
SOA	State of the art
SRO	Saturn Ring Observer
SP	Solar Probe
SS	Stainless steel
STC	Standard Test Conditions
SUPER	Survivable Power System
TE	Titan Explorer
TFC	Thin film cells
TRL	Technology Readiness Level
TRMM	Tropical Rainfall Measuring Mission
UTC	Ultra Thin Cells
UV	Ultraviolet
Voc	Open Circuit Voltage
VSSR	Venus Surface Sample Return
XTE	X-ray Timing Explorer

Appendix A. Infrastructure Facilities

Measurement and Calibration Facilities at NASA-GRC

- NASA-GRC has a High Altitude Aircraft Facility for the calibration of AM0 standards. This Lear jet can fly to ~50,000 ft. and uses the Langley plot calibration method. It averages 20 flights per year. The PV lab currently has over 100 AM0 calibration standards.
- A Solar Cell Evaluation Laboratory with a Spectrolab X25 (3KW) Solar Simulator illuminating a 13 inch diameter area with less than 1% flicker and 1 degree collimation. Attached to the simulator is a 9" diameter closed chamber for temperature dependence that can operate between -100 and +100°C.
- A Flash Lab with two Spectrolab LAPSS100 pulsed solar simulators can illuminate larger arrays to 6'x 6'at AM0 and even larger areas if done outside the facility. Two additional lamps support light concentration in a flash system to 300X (based on Isc ratio) on small-area cells. A third pulse simulator is being developed with 1-degree collimation to measure lens efficiencies.
- A portable spectral radiometer that can measure spectral irradiance from 350-2500 nm with resolution between 6 and 20 nm in as fast as 100 ms.
- Two high temperature (up to 1700°C) emittance measurement facilities. One for atmospheric conditions and the other for vacuum conditions.

Fabrication Facilities at NASA-GRC

- Electrochemical Deposition Laboratory: low-temperature electrochemical deposition of thin film solar cell materials ($CuInSe_2$, $CuInS_2$).
- Chemical Synthesis Laboratory: Handling and synthesis of chemical compounds for application in thin film batteries and thin film solar cells; includes capability of chemical manipulation under inert gas atmospheres as well as under high vacuum condition.
- Physical Vapor Deposition Laboratory: Magnetron sputtering, e-beam and thermal evaporation of metal and oxide films from powder or metals to enable fabrication of devices such as solar cells and batteries.
- Chemical Vapor Deposition Laboratory: Spray CVD, low-pressure CVD (LPCVD) and Plasma Enhanced CVD (PECVD) of thin film solar cell materials at low-temperatures.
- Organo-metallic vapor phase epitaxy reactors (2) are used to deposit III-V semiconductors. An upgrade to the reactor facility is planned for 2003.
- Photolithography, annealing, diffusion, electron beam, sputtering and evaporation facilities complete the cell fabrication capability.

Characterization and Analysis at NASA-GRC

- Traditional electronic characterization equipment includes dark diode, Isc vs. Voc for ideality factor and dark current, capacitance-voltage measurements both static and dynamic as a function of temperature, and a Hall system and Polaron for carrier concentration determination.
- Optical characterization includes a Lambda 19 (transmission, reflectance, and absorptance measurements), photoluminescence and minority carrier lifetime laboratory.
- A field emission SEM is also equipped with an Electron Beam Induced Current measurement capability as a function of temperature for determining diffusion lengths and correlating with optical defects. A second SEM is equipped with energy dispersive spectroscopy for structural and elemental analysis.

- Powder and rocking x-ray crystallography, high resolution profiling, nuclear magnetic resonance, Fourier transform infrared spectroscopy, gas chromatography/mass spectrometry, deep level transient spectroscopy, and precursor analysis and characterization tool are in house capabilities.
- A rapid thermal cycling facility (for LEO and GEO) can accommodate array coupons. A plasma interactions facility adaptable for both LEO and GEO environments can test array arcing for a range of voltages. A UV exposure facility and atomic oxygen facility are also available at NASA-GRC in our Electro-Physics Group.
- A new atomic force microscopy (scanning tunneling microscope) with scanning tunneling optical spectroscopy is currently being developed for quantum dot and other nano-structures.
- NASA-GRC has cooperative arrangements at Kent State for electron irradiation, NRL and the University of Michigan for proton irradiation.

MSFC ED11 Solar Array Laboratory

- The MSFC ED11 Solar Array Laboratory has a Spectrolab Large Area Pulsed Solar Simulator (LAPSS). The LAPSS is capable of illuminating a target area of 12 feet by 12 feet to the air-mass-zero (AM0) intensity level of 140 milliwatts per square centimeter (mW/cm^2) or one sun, with an overall uniformity within two percent. The Solar Array Laboratory is being upgraded with the addition of a Multi-Junction LAPSS Lamphouse designed to provide additional control of spectral distribution needed for testing the current generation of multi-junction solar cells. The MJL upgrade should be completed by FY02. This will enable the calibrated measurement of state-of-the-art space qualified multi-junction solar cells currently in production.

NASA-GSFC Large Area Pulsed Solar Simulator

NASA-GSFC has a Large Area Pulsed Solar Simulator and associated room with anti-reflection baffles. The simulator has not been upgraded to handle multi-junction solar cells.

JPL

JPL has two solar simulator laboratories for measuring the illuminated electrical characteristics of solar cells. One laboratory is equipped with a Spectrolab X-25 solar simulator that projects a uniform (1%) beam 13 inches in diameter. The simulator optical system is equipped with an adjustable filtering system to balance the light spectrum for properly measuring multi-junction solar cells. This chamber can be used to characterize solar cells at temperatures between -160 and +160°C and at simulated solar intensities ranging between 5 and 200 mW/cm^2.

Another laboratory is equipped with a Spectrolab Large Area Pulsed Simulator (LAPSS). This simulator is capable of illuminating a 7 ft x 7 ft area at one solar intensity to a uniformity of ± 1.5%. This chamber also contains a temperature controllable target plate, that can be operated between -160 and +160°C with simulator beam intensities between 5 and 1200 mW^2.

The JPL solar cell group has a Dynamitron electron accelerator. This accelerator can be operated between approximately 0.6 and 2.0 MeV. It can produce beam intensities of up to 10^{12} electrons/cm^2 on a 5-inch square target plane. The target plane is temperature controlled to maintain the solar cells at any temperature between 100 and +140°C during irradiation.

JPL has developed working relationships with 3 proton irradiation facilities, Cal Tech, University of California at Davis, and the University of Washington. Fixtures for measuring proton beam intensities and fluences have been established at each of the facilities. The electron and proton irradiation facilities have been extensively used to develop models for solar cell degradation in the space environment. The data has been compiled into two handbooks, "Solar Cell Radiation Handbook," and "GaAs Solar Cell Radiation Handbook."

Various solar cell measurement capabilities have been developed at JPL to support the simulator and radiation facilities. These include spectral irradiance measurement of the simulator beams, solar cell spectral response, dark IV measurement, voltage vs. capacitance measurement, and minority carrier diffusion length measurement using the electron beam. A technique has also been developed to measure the ac impedance characteristics of cells and panels so that power conditioning circuitry can be designed to match the impedance of the solar panels.

Illumination intensity standards are an important part of all simulator measurements performed on solar cells and panels. JPL set out to produce such standards in the 1960's by flying solar cells on high altitude balloons and measuring their output during flight. The balloons reach altitudes as high as 120,000 ft. where they are above 99.5% of the atmosphere, in an area that very closely approximates the true solar irradiance of outer space. This technique proved to be very successful and is in use today.

National Aeronautics and Space Administration

Jet Propulsion Laboratory

California Institute of Technology
Pasadena, California