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GODDARD SPACE FLIGHT CENTER SOLAR ARRAY MISSIONS, REQUIREMENTS AND DIRECTIONS

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ABSTRACT

The Goddard Space Flight Center (GSFC) develops and operates a wide variety of spacecraft for conducting NASA's communications, space science, and earth science missions. Some are "in house" spacecraft for which the GSFC builds the spacecraft and performs all solar array design, analysis, integration, and test. Others are "out of house" spacecraft for which an aerospace contractor builds the spacecraft and develops the solar array under direction from GSFC. The experience of developing flight solar arrays for numerous GSFC "in house" and "out of house" spacecraft has resulted in an understanding of solar array requirements for many different applications. This presentation will review those solar array requirements that are common to most GSFC spacecraft. Solar array technologies will be discussed that are currently under development and that could be useful to future GSFC spacecraft.

BACKGROUND

The GSFC both purchases and manufactures spacecraft. For the purchased spacecraft, GSFC supplies a spacecraft specification to a manufacturer who then purchases or fabricates the array. The spacecraft specification usually has in it a general specification which covers the power system and the solar array. Such spacecraft under development by the GSFC are: Total Ozone Mapping Spectrometer (TOMS), National Oceanic and Atmospheric Administration Spacecraft (NOAA)-J, NOAA-K, NOAA-L, NOAA-M, NOAA-N, and NOAA-N prime, Global Geospace Science (GGS)-WIND, GGS-POLAR, Geostationary Operational Environmental Satellite (GOES)-J, GOES-K, GOES-L, Tracking and Data Relay Satellite (TDRS) F-7, Landsat-7, Advanced Composition Explorer (ACE), Earth Observing Spacecraft (EOS)-AM, EOS-PM, SPEC, CHEM, TDRS H, I J, and Hubble Space Telescope (HST) Servicing Mission Replacement Array. Some of the characteristics of the arrays on these spacecraft is summarized in Table I.

The GSFC also manufactures some spacecraft. In these cases, GSFC and specifically the Space Power Applications Branch develops and purchases solar arrays. GSFC has a greater influence on the specifics of these solar arrays as opposed to the arrays on the out of house spacecraft. These arrays have provided us with knowledge of the requirements for spacecraft solar cells and some insight into what technologies will be most helpful for the future. Spacecraft in this group include the Small Explorer (SMEX)- 2 also known as the Fast Auroral Snapshot (FAST), the X-Ray Timing Explorer (XTE), SMEX -3 also known as the Submillimeter Wave Astronomy Satellite (SWAS), the Tropical Rainfall Measuring Mission (TRMM), SMEX 4, 5, and 6; and the Far Ultraviolet Spectroscopic Explorer (FUSE). Table II summarizes some of the array characteristics of the spacecraft in this category.

The GSFC also operates spacecraft. Some of the spacecraft the center currently operates include: the International Ultraviolet Explorer (IUE), the International Sun Earth Explorer subsequently renamed the International Cometary Explorer (ICE), the Earth Resource Budget Spacecraft (ERBS), the Cosmic Origins Background Explorer (COBE), the Hubble Space Telescope (HST), the Gamma Ray Observatory (GRO), the Upper Atmosphere Research Satellite (UARS), the Extreme Ultraviolet Explorer (EUVE), and the Solar Magnetospheric Particle Explorer (SAMPEX).Table III summarizes some of the array characteristics of the spacecraft arrays in this category.

Table I
GSFC Out of House Solar Arrays Currently in Development

S/C	Launch	Life (yrs)	Orbit	Array Type	Cell Type	Array/Cell Manufacturer
TOMS	1994	3	LEO	rigid, deployable	BSFR, silicon	TRW, ASEC
NOAA-J	1994	2	LEO	rigid deployable, tracking	BSR, silicon	MM, ASEC
GGS WIND	1994	3	sun earth libration	rigid, body mount, electrostatically clean	BSFR, silicon	MM, ASEC
GGS POLAR	1995	3	elliptical	rigid, body mount, electrostatically clean	BSFR, silicon	MM, ASEC
GOES-J	1995	5	GEO	rigid, deployable, tracking	BSR, silicon	Loral, Spectrolab
TDRS-7	1995	10	GEO	rigid, deployable, tracking	BSR, silicon	TRW, ASEC
Landsat -7	1998	5	LEO	rigid, deployable, tracking	BSR, silicon	MM, TBD
ACE	1997	2	sun earth libration	rigid, deployable	BSFR, silicon	APL, Spectrolab
EOS-AM	1998	5	LEO	flexible, deployable, tracking	5.5 mil GaAs/Ge	MM, TRW, ASEC
NOAA K, L, M	1996-1999	2	LEO	rigid, deployable, tracking	BSR, silicon	MM, TBD
HST Servicing	1999	5	LEO	TBD	TBD	TBD
EOS-PM SPEC CHEM	1998-2003	TBD	TBD	TBD	TBD	TBD
TDRS H, I, J	1999-2001	TBD	TBD	TBD	TBD	TBD

Table II
GSFC In House Solar Arrays Currently in Development

S/C	Launch	Life (yrs)	Orbit (km)	Array Type	Cell Type	Array/Cell Manufacturer
FAST	1994	1	350 x 4200	rigid, body mount, faraday cage	GaAs/Ge	TRW, ASEC
XTE	1995	2	600	rigid, deployable, tracking	BSFR, silicon	Spectrolab
SWAS	1995	3	600	rigid, deployable	GaAs/Ge	Spectrolab
TRMM	1997	3	350	rigid, deployable, tracking	GaAs/Ge	TRW, ASEC
SMEX 4, 5, 6	1996 - 1999	TBD	TBD	TBD	TBD	TBD
FUSE	2000	TBD	TBD	TBD	TBD	TBD

REQUIREMENTS FOR SOLAR CELLS

A solar cell of a given type must have undergone the following tests before we will consider it for use on a in house spacecraft solar array. Except as noted below, existing silicon and gallium arsenide and gallium arsenide on germanium solar cells meet these requirements almost flawlessly. These requirements are frequently not explicitly stated by GSFC specifications, but in one way or another they are present.

1. The solar cell's beginning of life current versus voltage characteristics must be determined as a function of temperatures from -80C to +80C for low earth orbits. Ideally, this range is extended to -180C to +80C to cover geosynchronous orbits.

2. The solar cell's current versus voltage characteristics must be determined as a function of amount and kind of hard particle radiation. In other words, the solar cell must be exposed to electrons and protons of varying energies and of varying amounts in ground tests to determine suitability for use on spacecraft. This exposure must generally be thorough enough so that the radiation in space can be converted into an equivalent number of 1 Mev electrons and to determine the solar cell's end of life current versus voltage characteristics as a function of temperature from -100C to +100C.

3. The solar cell's performance must be determined as a function of its degradation due to the exposure to sunlight, particularly the ultraviolet component. The equivalent of a one year's exposure on an accelerated basis is considered to be satisfactory.

Table III
In - Orbit Spacecraft Currently Operated by GSFC

Spacecraft	Launched	Orbit Altitude (km) and Inclination (°)	Solar Array Type	Solar Cell Type	Array/Cell Manufacturer
IUE	1/78	30,210 x 41,343, 33.8°	rigid, deployable, fixed	BSR, silicon	GSFC, ESA AEG
ISEE-3 later known as ICE	8/78	sun earth libration point, followed by lunar swing by and cometary encounter	rigid, body mounted	BSFR, silicon	GSFC, Spectrolab
ERBS	11/84	590, 57	rigid, fixed		Ball, Spectrolab
COBE	11/89	873 x 885, 99	rigid, deployable, fixed	BSFR, silicon	GSFC, Solarex
HST	4/90	600, 28.5	flexible, roll out, tracking	BSFR, silicon	Marshall, ESA, BAe, AEG
GRO	4/91	370, 28.5	rigid, deployable, tracking	BSR, silicon	TRW, ASEC
UARS	9/91	570, 57	rigid, deployable, tracking	BSFR, silicon	GE, ASEC
EUVE	6/92	520, 28.4	rigid, deployable,	BSFR, silicon	GSFC, FSC Solarex
SAMPEX	7/92	509 x 679, 82	rigid, deployable fixed	GaAs/Ge	GSFC, FSC Spectrolab

4. The solar cell's performance must be determined after exposure to thermal cycling. Generally, a solar cell in a low earth orbit will be exposed to on the order of 5,500 cycles from -80C to +80C each year. Most GSFC spacecraft have a lifetime of two years or more, and the cell must be tested to such a flight environment. Further, the test showing competence in this area should have the solar cell fixed to a panel as this is the condition under which the solar cell must actually perform. The condition of making electrical connection to the solar cell and mounting it to a substrate makes this test significantly more strenuous than just cycling the solar cell. If the solar cell is to be used in a geosynchronous orbit, it must be able to withstand very roughly eighty cycles per year as extreme as -180C to +80C.

5. The solar cell must not degrade due to the humidity in an air-conditioned room over many years. The solar cell must not degrade due to humidity exposer in an unconditioned atmosphere for several days, such as at launch and during shipment. The solar cell's resistance to humidity is traditionally proven by exposing the solar cells to 90% relative humidity at 45C for 30 days with the requirement that the solar cell not degrade more than 2% in peak power. This test is to some degree arbitrary. Exactly how well a cell must do in the test to show that it performs well under the conditions of the real world is not well determined. Consequently, this test could be weakened if it a cell manufacturer could show that it made an unduly pessimistic prediction for a new type of solar cell.

6. The solar cell's absorptance must be measured.

7. The solar cell's weight density must be determined.

8. The GSFC occasionally has missions with magnetic specifications that require no magnetic materials be used in the fabrication of the solar cell.

9. A darkened solar cell must be able to withstand reverse bias to approximately 10 percent more current than its short circuit current or to a voltage, typically around 50 volts, that is determined by a combination of the power system and array performance. Whichever of the requirements is least severe governs. This requirement is not met flawlessly by gallium arsenide or gallium arsenide on germanium solar cells unless they are first screened.

10. Although GSFC frequently does not specify cell size, sizes under 2 cm by 4 cm are not practical due to laydown cost. This requirement is of course flexible if the benefits of a small solar cell can be shown to outweigh the cost penalty. For example, we would gladly fly 50% efficient 2 cm by 2 cm solar cells.

11. It must be possible to fix an interconnect strongly enough to a cell so that it can take small bumps and thermal cycling without coming off. To prove this, the contacts on the solar cell must withstand a 1.5N pull test before and after being exposed to humidity. As in the case of the humidity test, this requirement is somewhat arbitrary and can be modified if it can be shown that it is too severe for a particular solar cell.

12. A completely new type of solar cell must be flown on a balloon to determine its output.

13. Very likely. a completely new type of solar cell would have to be flown on a limited basis in space before using it as a primary source of power.

15. Any organization manufacturing solar cells must have a significant quality assurance effort and be financially stable. In terms of quality, this means that the organization should meet or come close to meeting the requirements of MIL-Q-9858.

REQUIREMENTS FOR GSFC IN HOUSE SOLAR ARRAYS

In addition to the above for solar cells, the following requirements for solar arrays apply. These requirements are explicitly stated in GSFC specifications.

The array must meet configuration, maximum weight, minimum beginning of life power, insulation resistance, cleanliness, outgassing, mechanical, and miscellaneous requirements such as temperature sensor accuracy. The array must also meet specifications on resistance to accidental damage, resistance to damage by storage temperature and humidity, and resistance to: ultraviolet radiation, atomic oxygen, micrometeroids and space debris and shadowing.

The array's performance after thermal cycling must be proven in a life test which includes samples of every component which will be mounted on the flight arrays. Although solar arrays have been manufactured for many years, this requirement is still frequently not met flawlessly. The array's performance test must be proven after exposure to vibration or acoustic. This test is generally met without difficulties.

The flight array must be acceptance tested by exposure to eight thermal vacuum cycles and exposure to acoustic. The thermal vacuum cycles again are frequently not flawless.

We occasionally require that no magnetic materials be used on the solar array and/or that the array be electrostatically clean. This usually means that the upper surface of the array be conductive. The requirement is sometimes tightened to the extent that virtually every surface on the array be conductive.

GALLIUM ARSENIDE VERSUS SILICON

Table IV summarizes the array characteristics of the spacecraft for which GSFC or its contractors did a trade off between GaAs solar cells and silicon solar cells. The GaAs arrays cost approximately 70% more on a per watt basis than silicon solar arrays, but because of the benefits they provide, their system level cost is actually lower than silicon. For each spacecraft array in Table IV, but with emphasis on TRMM, we summarize below the factors used in determining whether to use GaAs or silicon.

Table IV
Summary of GSFC Solar Arrays with a GaAs versus Silicon Tradeoff

Spacecraft	Cell Type	Array Cell Area (m^2)	Lifetime (yrs)	Altitude (km)	Equivalent 1 Mev Electrons	Array Delivery Date
SAMPEX	GaAs/Ge	1.7	3	450 x 830	1.1×10^{13}	Launched
XTE	Silicon	15.5	2	600	4.6×10^{12}	Aug. 94
FAST	GaAs/Ge	2.6	1	350 x 4200	1.5×10^{14}	May 94
TRMM	GaAs/Ge	18.1	3	350	1.7×10^{12}	May 95
SWAS	GaAs/Ge	3.6	3	600	9.6×10^{12}	Sept. 94
EOS	GaAs/Ge	35	5	705	5.4×10^{13}	Feb. 96

SAMPEX

The solar array for SAMPEX is very small. A silicon array could not meet the power requirements for the spacecraft. This solar array and its cells were supplied by Spectrolab.

XTE

The solar array for the X-Ray Timing Explorer is fully designed and a contract has been let to Spectrolab for its fabrication. The solar array consists of silicon solar cells on an aluminum face sheet honey comb core substrate. Silicon solar cells were selected for this spacecraft primarily because of the difficulties in obtaining accurate prices for gallium arsenide solar arrays. We had limited pricing experience with the cells and most of the panel manufacturers had limited experience working with the cells and hence a high price uncertainty. Had the array used gallium arsenide solar cells, it would have been the first GSFC spacecraft array of a moderate size, approximately 2,000 watts, to do so. The advantage of the gallium arsenide solar cells was that their use would have prevented the necessity of a tracking solar array which would have increased spacecraft reliability and removed the substantial costs associated with the tracking mechanisms.

FAST

The solar array for FAST has been fabricated through a contract with TRW. The solar array for the Fast Auroral Snapshot satellite is gallium arsenide. This array is area limited and the silicon solar array of the required size could not supply the needed power. The cells are on an aluminum face sheet honeycomb core that forms the outside of the spacecraft body.

As an aside, this array is particularly interesting in that it has no magnetic materials, has magnetic compensation wiring directly under the solar cells and has a Faraday cage over its entire surface. The Faraday cage primarily consists of covers with conductive indium oxide coatings. The covers are interconnected in such a way that interconnects completely cover any insulating area on the array.

TRMM

The solar array for the Tropical Rainfall Measuring Mission is fully designed and a contract has been let to TRW for its fabrication. The solar array consists of gallium arsenide/germanium solar cells on an aluminum face sheet honeycomb core substrate. Both gallium arsenide and silicon solar cells were considered for the TRMM array. Table V provides a comparison of the resulting arrays. In Table V the delay actuator is a device which prohibits fouling by the premature deployment of one panel prior to deployment of another panel. The potentiometers are used to monitor the deployment of the various panels.

The silicon solar cell array is, from Table V, approximately 45% larger than the gallium arsenide array, a figure which G. C. Datum and S. Billets have also reported.[1] The smaller area reduced the spacecraft's fuel consumption and increased the probability of meeting a three year life. This was a particularly important consideration. Table II also shows that silicon array is 36% heavier. The areal and weight advantage of the gallium arsenide array results because the gallium arsenide solar cells offer approximately 40% more power on a per area basis at operating temperature. The GaAs solar cells greatly simplified the deployment of the solar array. This is important because deployables are historically among the less reliable components of spacecraft. Further, the array deployment would have to be tested on the ground and making a g-negation mechanism to allow the TRMM silicon array to deploy would have been difficult almost to the point of impracticality as each array wing would have consisted of six hinged panels.

Table V
TRMM Silicon versus GaAs Technical Factors Comparison

Parameter	Si	GaAs
Weight of Cell Stack, Wiring, Connectors and Miscellaneous	48 kg	47 kg
Array Area	26.2 m^2	18 m^2
Array Operating Temperature	74C	87C
BOL Efficiency @ Operating Temperature	11.3%	15.8%
EOL Efficiency	9.4%	13.3
Number of Individual Panels	12	4
Number of Panel Hinges	20	4
Number of Delay Actuators	2	0
Number of Potentiometers	12	2
Mechanical System Weight	144 kg	94 kg
Total Weight	192 kg	141 kg

SWAS

The solar array for the Submillimeter Wave Astronomy Satellite is gallium arsenide. This array is area limited and a silicon solar array of the required size could not supply the needed power. The solar array for SWAS is fully designed and a contract has been let to Spectrolab for its fabrication.

EOS

Although, most of the conclusions we draw below follow from our experience with in house arrays, we here mention our most technologically advanced array which is for the Earth Observing System, an out of house project. The EOS carries a flexible deployable array powered with 5.5 mil thick gallium arsenide solar cells. This represents the first such use of these cells on a flexible array. The trade which drove this array to the gallium arsenide solar cells was that the array is on one side of the spacecraft and tended to rotate the spacecraft in flight. Using the gallium arsenide array thereby enabled the attitude control system to use existing reaction wheels rather than developing new ones.

TRENDS

The gallium arsenide solar cell offers a substantial improvement over silicon. Silicon solar arrays are generally on the order of 40% larger when the operating temperature of the array is taken into account. In most cases, the gallium arsenide solar cell offers a dramatic weight reduction compared to silicon even though the gallium arsenide cells are heavier than silicon. This is because reducing the array area reduces the size of the substrate, harnessing, number of covers, amount of adhesive etc. This reduction more than compensates the weight difference between the solar cell types. This is true in the overwhelming number of spacecraft solar arrays because they use aluminum face sheet over aluminum honeycomb core substrates. As the weight of the substrate decreases, the weight advantage of gallium arsenide solar cells becomes less. It is only with extremely lightweight solar arrays that gallium arsenide on germanium solar cells result in an array which approaches the weight of a silicon array for the same power. This happens on lightweight deployable solar arrays using the thinnest commercially available silicon, 55 microns thick, compared to the same array with gallium arsenide cells, 115 microns thick.[2]. Because these arrays represent advanced technology they do receive a great deal of attention in the literature, however there are only a handful of them flying and therefore their practical effect on cell technology is limited.

The advantages of the GaAs solar cell, which derive primarily from its greater efficiency, suggest that spacecraft solar cells for future spacecraft will be driven primarily by a greater power density. With this statement in mind, the authors believe that the following solar cells offer the greatest opportunity to improve spacecraft performance.

MULTI JUNCTION SOLAR CELLS

The authors believe that the qualification and development for production of these cells would provide the greatest benefit at the least cost in the shortest time. Such solar cells have been produced in the laboratory[3,4,5] with AM0 efficiencies of over 25%. If these solar cells are mass produced at 24 percent efficiency they represent over a 30 percent improvement in state of the art gallium arsenide solar cells. These cells will therefore multiply the considerable advantages the gallium arsenide cells have provided. Additionally, the method of manufacture of these solar cells suggests that the price will be competitive to gallium arsenide on germanium. This statement is based on the assumption that making the cascade cell primarily entails leaving it in the reactor which grows the various cell layers somewhat longer than is required for the gallium arsenide on germanium solar cell. During this time, the reactor will automatically control the flow of gasses to grow the additional layers. The time and labor involved in this additional processing is probably minimal. There will also be an additional yield loss.

Because of the improved power density is so welcome, because the solar cell is in many ways similar to gallium arsenide solar cells, because the cell is probably not significantly more expensive and because several organizations have successfully produced versions of the cell, we believe that the next most probable step in improving array performance is with the multi-junction solar cell.

IMPROVED GALLIUM ARSENIDE SOLAR CELLS

Gallium arsenide solar cells have been fabricated with air mass zero efficiencies in excess of 21 percent.[6] These solar cells offer a significant improvement to spacecraft power systems using improved versions of existing solar cells. These are therefore a very valuable asset, if they can be put into production.

INDIUM PHOSPHIDE SOLAR CELLS

These solar cells have been fabricated with air mass zero efficiencies of over 19 percent.[7] The effect of radiation on these solar cells is significantly less than that for gallium arsenide cells of approximately the same efficiency. Tobin reports that cells of this approximate efficiency degrade 4.7% after irradiation with 10^{14} 1 Mev electrons. GaAs cells degrade 9% after the same irradiation.[8] At this radiation level, these cells will therefore show about a 4% advantage over gallium arsenide solar cells, provided both cells have the same initial efficiency. At 10^{15} 1 Mev electrons, GaAs solar cells have a degradation of 26%. At these radiation levels, and presuming the InP cells retain an approximate 2 to 1 advantage over the GaAs cells in degradation means that the indium phosphide solar cell will have about a 13% advantage over the GaAs solar cell. However, the advanced GaAs solar cell has about a 10% advantage over the InP cell at beginning of life and the multijunction cell has an approximate 30% advantage over the indium phosphide cell at beginning of life. This means that only under the most extreme conditions of radiation will the InP cell show an advantage over an advanced gallium arsenide cell and that it will never show an advantage over a multi junction cell. As can be seen from Table I which is typical for most of our spacecraft, the radiation damage is generally under 10^{14} equivalent 1 Mev electrons.

ADVANCED SILICON SOLAR CELLS

A variety of high efficiency silicon solar cells have been developed.[9,10,11,12] These cells may find application in space as competitors to GaAs and production silicon solar cells. To do this, they must be tested to the cell requirements mentioned earlier, particularly because the cells may be quite sensitive to radiation. Even if they are resistant to radiation or can be made so, the authors believe that they do not overcome the advantage of the higher efficiency multi-junction solar cells even considering the greater expense of the later technology.

THIN FILM SOLAR CELLS

Thin film solar cells offer the advantage of an enormous power to weight gains over any of the solar cells discussed previously. To utilize this advantage a mechanism must be developed to deploy them and this mechanism must also be light enough to not cancel the cell's inherent advantage. These cells are at a disadvantage at lower altitudes because of their larger area, which is almost twice that of state of the art GaAs arrays. At these altitudes the large area creates an adverse impact on the spacecraft attitude control system and on the ability of the spacecraft to maintain altitude.

CONCENTRATOR SOLAR CELLS

The authors believe that concentrator solar cells are not useful to NASA spacecraft. This is because they have a significantly detrimental effect on spacecraft reliability. If non concentrating solar cells are used on a spacecraft, the spacecraft can lose its ability to drive the arrays or it can tumble for many hours and still be recovered. This is because arrays will supply about 30% of their rated power in a random spacecraft tumble, about enough to keep a powered down spacecraft going indefinitely. If concentrator arrays are used, the arrays will supply only small fraction of their rated power in a random spacecraft tumble. Under these circumstances the typical spacecraft batteries will discharge after about four hours or three orbits. In short, the concentrator arrays impose very strict requirements on the short term pointing reliability of the spacecraft attitude control system and the solar array drive. These requirements would be very difficult to convincingly achieve. The likelihood of ever using these cells is therefore small.

FLEXIBLE SOLAR ARRAYS

The development of flexible, deployable solar array such as the Advanced Photovoltaic Solar Array, (APSA)[13] , the Solar Array Flight Experiment (SAFE) and the Flexible Rolled Up Solar Array (FRUSA) have enabled NASA to enhance the capability of two of its larger spacecraft, namely EOS and HST. From the user's point of view these deployable arrays enable a large array to be packed in a small volume on the spacecraft. Unfortunately these arrays are very difficult to analyze mechanically, particularly with respect to the effect they have on the spacecraft's attitude control system, they are mechanically complex and they are impossible to end to end test. For these reasons, we avoid them until their advantages become very large . However, as we gain experience with them, the authors believe that they will become more popular.

The weight advantage of these arrays is substantial, although not as great as the prototype arrays suggest. For example, the APSA has a power to weight ratio of 130W/kg. The EOS array, that derived from APSA but had to overcome various practical constraints, has a power to weight ratio of 32 W/kg. As an aside, this decrease is not due to the change from the thin silicon cells on APSA to the GaAs cells on EOS, if the EOS array had weightless cells and covers, it would have a power to weight ratio of only 43 W/kg. For reference the TRMM array has a power to weight ratio of 20W/kg, typical of many spacecraft.

FLIGHT TESTING ADVANCED SOLAR CELLS

To insure that advanced solar cells are flown as soon as practicable, it is necessary to fly them on spacecraft as soon as ground testing indicates that they are a promising candidate but before ground testing has fully qualified them. This is because even when solar cells are completely qualified through ground testing, many projects are reluctant to fly them unless they have flown before. The flight of small numbers of these cells on otherwise conventional arrays will provide experience to the manufacturers, will gain the confidence of spacecraft managers, and will complement ground based qualification. Such use of advanced solar cells will not generally enhance a given project's capability to meet its requirements and will therefore be resisted. However, the price to be paid by the project is small, provided only minimal telemetry is specified, and the benefits to the space program are large particularly in view of the several very promising advanced solar cells. The Space Power Branch at GSFC is therefore recommending that inexpensive low risk flight experiments be undertaken.

CONCLUSIONS

The GSFC has responsibility for a large number of solar arrays, some of which are powered by GaAs solar cells. These gallium arsenide solar cells have provided a wide variety of benefits including the preservation of spacecraft fuel, the enhancement of missions that would be severely power limited without them, the simplification of array deployment mechanisms, and the reduction of solar array weight. Because of the benefits these cells have provided are so useful, we believe that the further test and development of high efficiency solar cells, particularly multi-junction solar cells will further increase these already substantial benefits. These cells will provide additional power at a modest increase in price. We are recommending that the GSFC and other agencies start flying a small percentage of each of their state of the art arrays with advance solar cells so that experience can be gained with these cells even before they are fully qualified to be the primary source of power for spacecraft.

We have made the point that some areas of research seem to us to be less useful. In particular, the future development of concentrator solar arrays does not appear to be a fruitful avenue to pursue, at least for NASA spacecraft.

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[1]G. C. Datum *et al*, "Gallium Arsenide Solar Arrays - A Mature Technology," Proceedings of the 22nd IEEE Photovoltaic Specialists Conference, October 7, 1991, Las Vegas, NV p. 1422.

[2]P. M. Stella *et al.*, "Thin Film GaAs for Space - - Moving Out of the Laboratory" Proceedings of the 23rd IEEE Photovoltaic Specialists Conference, May 10, 1993, Louisville, KY. Figure 1, p. 22.

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[3]B. C. Chung *et al.*, "25.2%-Efficiency (1-Sun Air Mass 0) AlGaAs/GaAs/InGaAsP Three Junction Solar Cell," Proceedings of the 22nd IEEE Photovoltaic Specialists Conference, October 7, 1991, Las Vegas, NV p. 54.

[4]B. C. Chung *et al.*, "27.6% (1 Sun Air Mass 1.5) Monolithic Two Junction AlGaAs/GaAs Solar Cell and 25%(1 Sun, Air Mass 0) Three Junction AlGaAs/GaAs/InGaAs Cascade Solar Cell," Proceedings of the 21st IEEE Photovoltaic Specialists Conference, May 21 1990, Kissimimee, FL, p. 179.

[5]J. M. Olson *et al.*, "A 27.3% efficient $Ga_{0.5}In_{0.5}P$/GaAs tandem solar cell," Appl. Phys. Lett. 56(7) 12 February 1990, p. 623.

[6]S.P. Tobin, *et al.*, "Advances in High Efficiency GaAs Solar Cells," Proceedings of the 21st IEEE Photovoltaic Specialists Conference, May 21 1990, Kissimimee, FL, p. 158.

[7]C. J. Keavney, *et al.*, "Emitter Structures in MOCVD INP Solar Cells," Proceedings of the 21st IEEE Photovoltaic Specialists Conference, May 21, 1990, Kissimimee, FL, p. 141.

[8]B. E. Anspaugh, Addendum 1 to the Solar Cell Radiation Handbook," 1989, p. 37.

[9]M. A. Green, *et al.*, "Progress in High Efficiency Silicon Cell and Module Research," Proceedings of the 23rd IEEE Photovoltaic Specialists Conference, May 10, 1993, Louisville, KY, p.8.

[10]R. A. Sinton, *et al.*, "Large Area 21% Efficient Si Solar Cells," Proceedings of the 23rd IEEE Photovoltaic Specialists Conference, May 10, 1993, Louisville, KY, p.157.

[11]J. Knobloch, *et al.*, "High-Efficiency Solar Cells from FZ, Ca, and MC Silicon Material," Proceedings of the 23rd IEEE Photovoltaic Specialists Conference, May 10, 1993, Louisville, KY, p.271.

[12]V. Garboushian, *et al.*, "Radiation Hardened High Efficiency Silicon Space Solar Cell," Proceedings of the 23rd IEEE Photovoltaic Specialists Conference, May 10, 1993, Louisville, KY, p.1358.

[13]P. M. Stella *et al.*, "Thin Film GaAs for Space - - Moving Out of the Laboratory," Proceedings of the 23rd IEEE Photovoltaic Specialists Conference, May 10, 1993, Louisville, KY. Figure 1, p. 22.