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THE STATUS OF LIGHTWEIGHT PHOTOVOLTAIC SPACE ARRAY TECHNOLOGY BASED ON AMORPHOUS SILICON SOLAR CELLS*

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Ultralight, flexible photovoltaic (PV) array of amorphous silicon (a-Si) has been identified as a potential low-cost power source for small satellites. We have conducted a survey of the status of the a-Si PV array technology with respect to present and future performance, availability, cost, and risks. For existing, experimental array "blankets" made of commercial cell material, utilizing metal foil substrates, the BOL performance at AM0 and 35°C includes total power up to 200 W, power per area of 64 W/m^2 and power per weight of 258 W/kg. Doubling of power per weight occurs when polyimide substrates are used. Estimated EOL power output after 10 years in a nominal low-earth orbit would be 80% of BOL, the degradation being due to largely light-induced effects (-10 to -15%) and in part (-5%) to space radiation. Predictions for the year 1995 for flexible PV arrays, made on the basis of published results for rigid a-Si modules, indicate EOL power output per area and per weight of 105 W/m^2 and 400 W/kg, respectively, while predictions for the late 1990s based on existing U. S. national PV program goals indicate EOL values of 157 W/m^2 and 600 W/kg. Cost estimates by vendors for 200 W ultralight arrays in volume of over 1000 units range from \$100/watt to \$125/watt. Identified risks include the lack of flexible, space compatible encapsulant, the lack of space qualification effort, recent partial or full acquisitions of U. S. manufacturers of a-Si cells by foreign firms, and the absence of a national commitment for a long-range development program toward developing of this important power source for space. One new U. S. developer has emerged as a future potential supplier of a-Si PV devices on thin, polyimide substrates.

INTRODUCTION

Photovoltaic (PV) arrays serve as very reliable power sources for space application. Recent developments in small satellite technology give rise to several important issues with regard to the use of existing PV arrays. Among them are: the mass of the array, stowed volume, deployability, total power limitation, vulnerability to natural and man-made threats and array cost. Existing arrays for the most part fail to satisfy present small satellite requirements. Stella and Scott-Monck (ref. 1) identified four PV technologies as candidates for advanced photovoltaic space arrays which included (a) thin crystalline silicon (50 µm), (b) thin-layer GaAs CLEFT cells, (c) copper indium diselenide and (d) amorphous silicon (a-Si). Subsequently NASA selected case (a) for a 5 kW prototype demonstration which will result in a deployable and restowable PV array having a beginning-of-life (BOL) specific power of 130 W/kg.

We have conducted a survey with the objective of identifying the best candidate from the preceding four technologies for a PV array for small satellites, having a power output of about 200 W at air mass zero

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(AM0) in normal sun vector at the end of life (EOL) of 10 years in a low earth orbit. Mass limitations of 1 kg for the array and 1 kg for the deployment have been set. It became apparent at the outset that the technical and cost objectives could be possibly best realized with a-Si arrays for a target date in the mid 1990s, hence they became the subject for our survey.

AMORPHOUS SILICON PHOTOVOLTAIC TECHNOLOGY

The key issues toward a successful product and widespread terrestrial and space application are conversion efficiency and stability, hence their current status will be summarized following a brief review of some aspects of the a-Si solar cell technology.

Amorphous Silicon Materials and Processes

The semiconductor materials used in a-Si cells are often referred to as a-Si alloys as they consist of a combination of several elements which serve various functions. Thus, hydrogen up to 15% atomic, and fluorine, less than 1%, act as defect passivating agents in the intrinsic, or I-type layer where conversion of photons to photogenerated carriers takes place. Partial substitution of silicon by carbon or germanium widens or narrows the energy gap, respectively, to make the I-layer responsive to a broader spectrum of light. Finally, doping with boron and phosphorus leads to the synthesis of P-type and N-type conductivity layers, respectively, which are needed in the fabrication of solar cell diode structures. The P- and N-type layers can also be made in a microcrystalline form which has certain advantages from the standpoint of higher conductivity and optical transmission. Various thin-film deposition techniques are available, all of which are from the gas phase. The most versatile is plasma-enhanced chemical vapor deposition (PECVD) which is used in large-scale manufacturing. Being amorphous, a-Si alloys do not require epitaxy during the deposition. Hence, they can be deposited on a variety of surfaces, including glass, metals, and high temperature polymers. Deposition on different amorphous or crystalline semiconductors is also possible, which allows fabrication of hybrid diode structures and multijunction solar cells.

Solar Cell Structures

In its simplest configuration a-Si solar cell consists of an intrinsic (I) layer sandwiched between thin P- and N-type layers. The P-layer is preferably at the front side of the cell, for a more efficient collection of holes, the minority carriers. Transparent conducting metal oxide (TCO), such as indium tin oxide (ITO) is used as the front electrode layer, while a textured metallic layer also known as "back reflector" is used as the rear electrode of the cell.

Multijunction solar cells of a-Si alloys consist of two or more P-I-N cells deposited on top of each other. Each component cell is thinner than a single cell structure, which leads to greater stability. Incorporation of progressively wider bandgap I-type layers from the rear to the front of a multijunction cell structure leads to the absorption of a broader range of the solar spectrum and thereby to enhanced conversion efficiency.

Conversion Efficiency of a-Si Solar Cells and Modules

Progress in conversion efficiency of a-Si cells and modules worldwide has been summarized most recently by Stone (ref. 2). Selected data appear in Table 1, which shows that the highest efficiency for a-Si cells to date of 13.7% has been obtained with a triple-junction, dual-gap cell structure. A historical progress of the efficiency of cells and modules appears in Fig. 1 which shows that the difference between the efficiency of small cells (1 cm^2) and modules (1200 cm^2) is shrinking. In the case of Fuji Electric the difference is only 11%, because of good material uniformity, the use of the monolithic structure and laser patterning. Data in Table 1 have been used to calculate the AM0 power at the beginning of life (BOL) output of potential space PV modules. For this purpose the AM1.5 values were multiplied by a factor of 1.25 determined independently by two sources, Gay et al. (ref. 3) and Abdulaziz et al. (ref. 4).

TABLE 1. PERFORMANCE OF AMORPHOUS SILICON SOLAR CELLS AND MODULES AT BOL

Efficiency* at AM1.5 (%)	Device Area (cm^2)	Pmax (W)	**Calculated Pmax at AM0 (W/m^2)**	Cell Structure	Source
Single Junction					
12.0	≤ 1.0 (act)		**150**	glass/p-i-n (all used a-SiC p-type and a-Si i-type layers)	Hitachi, TDK-SEL, MitsuiToatsu, Osaka University Solarex
11.28	1.2 (act)		**141**	a-Si/polymer	Teijin
9.8	933 (ap)	9.2	**115**	glass/a-Si	Solarex
6.4	1200 (t)	7.3	**80**	a-Si/polymer	Teijin
8.4	4800 (t)	40.3	**105**	glass/a-Si	Fuji Electric
6.4	11613 (t)	74.3	**80**	glass/a-Si	Chronar
Multijunction					
13.7	0.25 (act)		**171**	a-Si/a-Si/a-SiGe/SS	ECD
12.4	1.0 (act)		**155**	glass/a-Si/a-Si/a-SiGe	Sumitomo
11.3	1.0 (act)		**141**	glass/a-Si/a-Si/a	Fuji Electric
8.4	838 (ap)	6.84	**105**	a-Si/a-Si/a-SiGe/SS	ECD
9.27	940 (ap)	8.7	**111**	glass/a-Si/a-Si/a-SiGe	Solarex
10.05	1200 (t)	12.06	**125**	glass/a-Si/a-Si	Fuji Electric
5.8	4104 (t)	23.9	**72**	a-Si/a-Si/SS	Sovonics
9.06	4800 (t)	43.5	**113**	glass/a-Si/a-Si	Fuji Electric

*Efficiency for (act) active cell area, (ap) aperture area and (t) for total area

Conversion Efficiency of Large, Terrestrial a-Si Arrays

Since mid 1980s amorphous silicon PV arrays have been subjected to field tests with the goal of large-scale utility applications. Numerous arrays with an initial DC power output in the range of 1 to 100 kW have been constructed and are now providing valuable data base on longevity and reliability. A summary of initial and current performance data are given in Table 2 for three selected arrays which are representative of the state of the art. Calculated EOL power output at AM0 is also included to assess the power output of larger potential space arrays, having a power output up to about 22 kW, based on the technology of the late 1980s.

TABLE 2. PERFORMANCE OF LARGE TERRESTRIAL AMORPHOUS SILICON PV ARRAYS*

BOL Power Rating (kW)	BOL Efficiency (%)	Period of Operation (months)	Power Degradation (%)	**Calculated EOL Pmax at AM0 (W/m^2)**	Location of Array	Source & (Substrate or Superstrate)
17.4	5.3	21	17	**55**	Florida	ARCO Solar (glass)
4.0	4.16	38	12.5	**46**	Michigan	Sovonics (stainless steel)
22.0	4.0	10	3.3	**48**	Maui, HI	Sovonics (stainless steel)

*Data based on Townsend et al. (ref. 5), Atmaran et al. (ref. 6) and Pratt (ref. 7).

Factors Affecting the Long-Term Performance of a-Si PV Arrays

A-Si solar cells are subject to degradation in power output by exposure to light via the Staebler-Wronski effect. Furthermore, in the space environment, they will be affected by strong ultraviolet light, electron and proton radiation, atomic oxygen and severe temperature cycling. The effects of these ambients on EOL performance are discussed next.

The Staebler-Wronski effect, is marked by a sharp decrease of dark and photoconductivity in a-Si materials upon prolonged exposure to light. In solar cells it is manifested by an asymptotic decrease in conversion efficiency. While early a-Si cells have shown a degradation of as much as 50% in a few days of exposure to light, recent results indicate the first year degradation to be in the range of 10 to 14%. In addition, degradation has been shown to saturate to a constant value within about a year for ground-based modules. Wagner and coworkers (ref. 8) have shown that the limit of degradation is governed by saturated defect density N_{sat} which is independent of light intensity and further illumination. There is a consensus that the most probable causes for the degradation are hydrogen, impurities, nanometer-scale inhomogeneities and strained bonds. Recent improvements in the stability of a-Si cells include a partial replacement of hydrogen by deuterium reported by Suzuki et al. (ref. 9), exposure to intense light followed by annealing reported by Nevin et al (ref. 10), and chemical annealing in hydrogen plasma described by Shirai et al. (ref. 11). The latter leads to a-Si material having reduced hydrogen content and energy gap and a tenfold increase in photoluminescence. In addition to showing a slow photodegradation rate, these materials may be suitable for multi-gap, multijunction cells. The most practical partial cure to date for a-Si cell degradation follows from the work of Hanak and Korsun (ref. 12) who observed an inverse relationship of cell stability with cell thickness and a higher stability for multijunction than for single junction cells. Cell degradation is a reversible process which can be annealed by heating the cell above 160°C for one or more hours, less at higher temperatures. Furthermore degradation is lower at elevated temperatures. This is quite evident from data on large arrays, such as that reported by Pratt (ref. 7), which show a seasonal variation in efficiency. In space, where array temperatures are expected to be about 80°C, compared with a maximum of about 50°C for terrestrial arrays, the saturated value of degradation is expected to be about 7 %.

Effect of Electron Irradiation. Effects of 1.0 MeV electron irradiation at fluences of 1E14 to 1E16 have been reported by Gay et al (ref. 3) for a a-Si cell structure consisting of Al/N-I-P/In_2O_3/glass. The cells were irradiated at fluences of 1E14 to 1E16 cm^{-2} through 1.1 mm thick glass layer (D. Tanner, private communications). Initial AM1.5 efficiency was given as 8.5%. The degradation in efficiency at a fluence of 1E16 cm^{-2} was 30%, witn most of the change occurring in the fill factor, 7% in V_{oc} and 4% in I_{sc}. Byvik et al. (ref. 13) with an older, inverted cell structure (the light entering through the N-layer) observed cell efficiency degradations of 7.4, 25 and 99.8%, respectively, at 1.0 MeV fluences of 1E14, 1E15 and 1E16 cm^{-2}. The significant differences in radiation damage are due partly to the difference in the cell structure and to partial shielding by glass in the prior case. In both cases a nearly complete recovery of PV efficiency occurred after annealing at 175 to 200°C.

Effect of Proton Irradiation. Radiation damage studies of both single junction and tandem a-Si cells with 1 MeV protons at fluences ranging from 1E11 to 1E15 cm^{-2} have been reported by Hanak et al. (ref. 14). The single cells included a-Si and a-SiGe alloy I layers, with E_g of 1.7 and 1.5 eV, respectively. The tandem cells contained same gap, a-Si I-layers. Additional studies by Hanak et al (ref. 15 and 16) included radiation damage with 200 keV protons and with dual-gap, tandem junction cells, containing a-Si and a-SiGe I-type layers. It has been shown that the a-Si dual-gap, tandem cells have 50 to 100 times higher radiation resistance than c-Si or GaAs cells and also higher than InP and $CuInSe_2$ (CIS) cells. It was also shown that the 200 keV protons produced about 5 to 10 times more degradation than 1.0 MeV protons in a-Si alloy cells and that the radiation damage was fully annealable at a modest temperature of 160°C. The superior tolerance to proton radiation is believed to be due to primarily the small thickness of a-Si cells and consequently a low number of knockon collisions. A further improvement in radiation resistance of a-Si cells to 1.0 MeV protons has been reported by Payson et al. (ref. 17) who made a side-by side comparison of solar cells fabricated in 1989 with cells of the preceding studies, made in 1985.

Effect of Operating Temperature on a-Si PV Array Performance. Osterwald et al. (ref. 18) have conducted a study of the effect of temperature on PV performance parameters for a variety of crystalline and a-Si solar cells. They have found that the variation of the maximum power output Pmax with increasing temperature is most favorable for a-Si cells, falling off at a rate of only -1320 +/- 105 ppm/°C, followed by GaAs at -2300, Si at -4210, and CIS at -5870 ppm/°C. This means that at higher operating temperatures in space a-Si array will make substantial gains in power output on other types of arrays.

Effect of Ultraviolet Light on a-Si Solar Cell Performance. U. v. light is converted to electricity by a-Si cells. Besides the Staebler-Wronski effect, no other effects of u. v. light are known. The main concern is the effect of u. v. light on the encapsulation, which still awaits development, in lowering its optical transmission.

Effect of Thermal Cycling on the Longevity of a-Si PV Arrays. Commercial a-Si arrays for ground use have been temperature cycled satisfactorily between -40°C and 90°C in acceptance testing over several hundred cycles. For space use, several ten thousand cycles are required over a much wider temperature range. With existing a-Si array the concern is about low-temperature printed silver grids, copper busbars utilizing organic adhesives and soldered contacts. Adhesion of encapsulation, still not defined, constitutes another unknown.

Ablation by Atomic Oxygen. For applications in low earth orbit a-Si solar cells and flexible polymeric substrate would be subject to rapid ablation by atomic oxygen. Hence, at least the external layers must consist of a transparent, inorganic material such as silica.

Tolerance to Physical Damage. PV modules on a-Si have been found extremely tolerant to physical damage as reported by Hanak (ref. 19). These tests included repetitive rollup (or flex) tests to diameters of 3 cm and penetration by projectiles. Nakatani et al. (ref. 20) have measured the effect of linear elongation on a-Si solar cells on polyimide and found that they can tolerate a strain of up to 0.7%, without damage. Calculations based on this result indicated that a-Si cells encapsulated in a thin flexible material can be bent to a radius of about 0.004 cm without damage.

Bypass Diodes. Bypass diodes are used to protect PV arrays against reverse bias voltage, which occurs when a cell is selectively shaded. The diode is connected across one or more cells. In the case of a-Si tandem cells it has been shown by Hanak and Flaisher (ref. 21) that a bypass diode should be placed across at least every 3 tandem cells (each 5 V). For the monolithic ultralight cells incorporation of diodes externally is cumbersome and counterproductive with respect to array mass. For this case they have developed "integral diodes" which are made of the same material and on the same substrate as the cells. Every cell in the module can be protected individually at the expense of 2% of the cell area and with no additional processing steps.

Estimate of EOL Performance of a-Si Arrays in LEO

Estimates of normallized EOL efficiencies have been calculated for several LEO orbits for a-Si arrays. Only the effects of electron and proton radiation and of Staebler-Wronski effect were considered. Worst-case radiation damage estimates were made for a single-junction PIN a-Si cell consisting of SiO_2(5µm)/ITO/P-I-N/Al/St.Steel (20µm). The procedure and the fluence data were based on the JPL Radiation Handbook which gives fluence data relating to crystalline silicon. Equivalent 1.0 MeV electron fluences for trapped electrons and trapped protons were added. The value for the protons was divided by 50, which is the observed factor for the difference in proton-induced damage between c-Si and a-Si. Radiation resistance data for 1.0 MeV electrons of Gay et al. (ref. 3), corrected for glass shielding, were used to predict 1, 5 and 10 year EOL values of normallized efficiency for 3 assumed LEO orbits. The resulting data, presented in Table 3, indicate that for orbits up to 450 nmi and EOL of 10 years space radiation would decrease a-Si array power output only by of 1 to 4.6%. Estimates have been also made for a-Si PV arrays of the EOL power output as percent of the BOL values after combined degradation by light and electron and proton radiation in various LEO orbits. For this purpose an estimated 15% saturated degradation for multijunction a-Si cells due to light was combined with the EOL radiation results for single-junction cells given in Table 3. The resulting EOL power output normallized to the BOL values are shown in Table 4.

TABLE 3. ESTIMATED NORMALLIZED EFFICIENCY OF A PIN AMORPHOUS SILICON CELL vs. TIME FOR SELECTED CIRCULAR ORBITS AFTER COMBINED TRAPPED ELECTRON AND PROTON IRRADIATION

Time in Orbit (years)	EOL Cell Efficiency (% of BOL) for Various 60° Orbit Heights		
	150 nmi	300 nmi	450 nmi
1	99.0	98.7	97.8
5	98.2	97.3	96.2
10	97.9	96.8	95.4
Equivalent Total1 MeV Electron Fluence ($cm^{-2}year^{-1}$)	5.96E11	1.91E12	7.00E12

TABLE 4. ESTIMATED EOL NORMALLIZED POWER OUTPUT OF AN AMORPHOUS SILICON PV ARRAY AFTER DEGRADATION BY LIGHT AND ELECTRON AND PROTON RADIATION AT AMO AND 25°C

Time in Orbit (years)	EOL Array Power Output (% of BOL) for Various 60° Orbit Heights		
	150 nmi	300 nmi	450 nmi
1	84.0	83.7	82.8
5	83.2	82.3	81.2
10	82.9	81.8	80.4

Flexible Lightweight a-Si PV Modules and Arrays

Solar arrays of a-Si cells are less than one micrometer thick and utilize about 11 pounds (5 kg) of a-Si per acre. When constructed with thin, flexible substrates and encapsulants, the arrays are very thin, ultralight weight and flexible. One of two types of ultralight arrays made consists of monolithic modules, reported by Hanak (ref. 19) and Hanak et al. (ref. 15). It employs series and parallel cell interconnections in a rectangular matrix of relatively small solar cells. This type of module utilizes an insulating substrate such as polyimide. The modules are fabricated from large sheets of tandem a-Si cells coated in the roll-to-roll processor. The fabrication consists of patterning the layers into cells by masking and etching, screen printing of grids and cell interconnections, application of terminal busbars and encapsulation. For a 2 sq. ft. unencapsulated module, on a 7-µm thick polyimide substrate, specific power of 2.4 kw/m^2 has been reported at AM1.5 illumination.

The monolithic lightweight flexible array has been the subject of subsequent development effort at Energy Conversion Devices, Inc., sponsored by the SDIO under a Phase II SBIR contract NAS3-25458. Data for the monolithic array developed in this program are given in Table 5. Currently, NASA-funded development of monolithic a-Si space array is taking place at Iowa Thin Film Technologies, Inc., under SBIR Phase II contract No. NAS3-26244.

The second type of lightweight, flexible a-Si PV array consisting of "giant cells" has been reported by Hanak et al (ref. 22). These cells utilize a stainless steel substrate, thinned by etching to 20 µm. The PV array consisted of 20 cells 1566 cm^2 each in area and had a power output of 207 W at AM0. Data on this type of an array, the UL-200, are given in Table 6.

TABLE 5. CHARACTERISTICS OF ECD ULTRALIGHT AMORPHOUS SILICON PHOTOVOLTAIC ARRAY DEVELOPED UNDER CONTRACT NAS3-25458

Design characteristics		
Aperture area	0.49 m^2	
Mass	137 g	
Substrate	Kapton	
Front encapsulation	Tefzel (Dupont)	
Rear encapsulation	Thin Cr film over Kapton substrate	
Array design	Consisting of 36 monolithic submodules	
Calculated BOL and estimated 10 year EOL power output at AMO and 25°C		
	BOL	EOL
Power output (W)	30.4	24.8
Power per weight (W/kg)	222	181
Power per area (W/m^2)	62	51

TABLE 6. CHARACTERISTICS OF UL-200 LIGHTWEIGHT FLEXIBLE AMORPHOUS SILICON PHOTOVOLTAIC ARRAY (REF. 22)

Design characteristics		
Size (deployed)	2.92 m x 1.11 m x 0.01 cm	
Size (stowed)	1.11 m (length) x 6.3 cm (diameter), roll	
Mass	800 g	
Substrate	stainless steel, 0.002 cm thick	
Encapsulation*	polyester, 0.0038 cm, both sides	
Array design	20 "giant cells" in series, each 1566 cm^2 in area, each protected with bypass diodes	
BOL and estimated 10 year EOL power output at AMO and 35°C for a 300 nmi, 60° orbit		
	BOL	EOL**
Power output (W)	207	169
Power per weight (W/kg)	258	211
Power per area (W/m^2)	64	52

*This encapsulation is not space compatible.
**Projected values for an array having a top encapsulation of 5μm of SiO_2.

Projections for Ligtweight a-Si PV Arrays Based on Existing Results

Data in Table 1 for modules 0.08 to 1.2 m^2 (1 to 12.5 ft^2) in area are used as a basis for projecting 1995 performance for small space arrays, having a power output of about 200 W. The projected BOL power output ranges from 72 to 125 W/ m^2. Higher values of up to 171 W/m^2 for small cells indicate that arrays up to 152 W/m^2 are possible (using a derating factor of 11%). The data for cells on polymer substrates indicate a BOL value of 141 W/m^2, close to the best value of 150 W/m^2 for a similar cell on a glass substrate, which indicates that power per area for ultralight flexible devices should approach those on rigid substrates. Based on these results a conservative BOL value of 130 W/m^2 is projected for ultralight, flexible arrays for 1995. A summary of other performance parameters and 10 year EOL data for LEO is given in Table 7.

TABLE 7. FORECAST FOR 1995 BOL AND EOL PV PERFORMANCE FOR 200 W ULTRALIGHT FLEXIBLE A-Si ARRAYS BASED ON 1990 DATA FOR SOLAR CELLS AND MODULES

	BOL	EOL
Power output (W)	244	200
Power per area (W/m^2)	130	105
Power per weight (W/kg)	500	409
Deployed area (m^2)	1.88	1.88
Mass (kg)	0.5	0.5

TABLE 8. DEVELOPERS AND MANUFACTURERS OF AMORPHOUS SILICON PV DEVICES

Organization	Kind	Type of PV Product				Comments
		Rigid	Flexible	Single	Tandem	
ARCO Solar	M	x		x		Sold in 2/90 to Siemens Solar Industries
Chronar	M	x		x		Chapter 11
Solarex	M	x		x	x	See Table 1
UPG	M	x			x	
Energy Conversion Devices/Sovonics Solar Systems	M		x		x	Ceased mfg. in '90; formed partnerships with Soviet# and Japanese* firms.
(*) United Solar Systems Systems	M		x		x	To start mfg. in mid '91 in former, upgraded Sovonics plant in Troy, Michigan.
(#) Sovlux (USSR)	M		x		x	A plant for a-Si dual-gap, triple-junction cells is being built by ECD for manufacture in the USSR.
Center for Amorphous Semiconductors Inc. (CASI) (Iowa State University)	D		x	x	x	A roll-to-roll pilot plant operational in 1991.
Iowa Thin Film Technologies, Inc.	D		x	x	x	Contractor for CASI; also for space PV development.
Teijin	D		x	x		See Table 1.
Fuji Electric	D	x		x	x	See Table 1.
Kanegafuchi Chemical	M	x		x		
Sanyo Electric Co.	M	x		x		Has made flexible cells for an experimental manned airplane
Hitachi, Ltd.	D	x		x	x	

Projections Based on Nationally Funded PV Programs.

Both USA and Japan have maintained a substantial support for more than a decade toward the development of low-cost, thin-film photovoltaics as a potential power fource for the future. The FY 1993 SERI goals call for 10% and 13% stabilized AM1.5 efficiency for same-gap and multiband-gap multijunction, large-area (>900 cm^2), a-Si modules, respectively. Somewhat less ambitions goals for 1992 exist for Japan's NEDO program. The SERI goals translate to an EOL power output at AM0 of 121 and 157 W/m^2, for same-gap and different-gap cells, respectively, after 10 years in a circular, 300 nmi, 60° orbit, which includes degradation by light and radiation. At this point it is too early to forecast successful fabrication of lightweight flexible arrays based on these goals.

AVAILABILITY OF FLEXIBLE LIGHTWEIGHT a-Si PHOTOVOLTAIC ARRAYS

To date, most of the a-Si PV products have been made for terrestrial applications. For space use, suitable materials are preferably tandem-junction cells deposited on high temperature polymer substrates such as polyimide, or metal foil, or on polyimide-coated metal foil. Cells deposited on glass substrates are not suitable because of excessive mass. Manufacturing processes consist of two general types, one being deposition on discrete areas such as glass plates, the other being a roll-to-roll process suitable for long, continuous flexible substrates supplied on a roll. Table 8 lists the manufacturers (M) and developers (D) in the USA and abroad who have a near-term capability of a limited production and who have been contacted for this survey. Table 8 identifies five manufacturers or developers having past or future capability of producing lightweight, flexible a-Si cells by the roll-to roll process.

PROJECTED COST OF FLEXIBLE LIGHTWEIGHT a-Si PHOTOVOLTAIC ARRAYS

Estimated cost and delivery data in Table 9 on 200 W, lightweight, flexible a-Si arrays have been provided by one manufacturer in early 1990. Although this data is no longer relevant, it is to be noted that in large quantities, the manufacturer projected cost of a-Si arrays was about one order of magnitude less than existing crystalline arrays.

TABLE 9. PROJECTED COST AND DELIVERY FOR 200 W LIGHTWEIGHT a-Si PV ARRAYS

Number of arrays	1 Prototype	10-99	100-999	1000+
Delivery of 1st unit (months)	4	6	12	24
Delivery per month	1	10-50	100	100
Estimated unit cost ($/W)	500	200	150	100

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