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EXPERIENCE IN DESIGN AND TEST OF TERRESTRIAL SOLAR-CELL MODULES*

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ABSTRACT

Solar-cell module design and test have evolved during the past six years to the point where there is confidence in the ability to field modules that have reasonable life expectancy, with competitive costs for some applications. This paper shows progress made in such characteristics as module power, module efficiency and cost and it describes the trends in design details that have contributed to this progress. Also noted is the evolution of module test criteria, its dependency on field experience, and the role that these factors have played in improvement of module design for reliability and durability. The continued interplay of these program aspects are vital to further success in the development of photovoltaic technology as a major alternative energy source.

1. INTRODUCTION

A principal objective of the Flat-Plate Solar Array (FSA) Project is to advance photovoltaic technology so that it will constitute a major viable alternative energy option. An important part of the program is the advancement of module design technology, both as a means of evaluating advances in component materials and in fabrication and design techniques, and to provide a vehicle for measuring progress toward the long-term reliability essential to the accomplishment of the project objective. Progress in reliability is measured by performing qualification tests (accelerated life tests) and field tests. The methods for performing qualification tests have required continuous development to reflect improvements in criteria based on better understanding of field conditions. The methods for conducting field tests have been improved to induce early detection of module problems.

2. MODULE DESIGN TRENDS

The FSA Project plan for advancing module design technology includes making periodic procurement of modules against successively more definitive and more appropriate requirements and subjection of these modules to qualification life tests and field tests. The principal procurements to date have consisted of a succession designated as Block I through Block V, covering the period from 1976 to the present. In each case modules were purchased from several manufacturers. A review of the characteristics of all these modules (1,2,3) has shown a variety of design features in each Block that reflects, inclusively, the applicable state of the art at the time of the procurement. However, the review has also disclosed considerable commonality among the modules within each Block and a stepwise evolution from the common features of one Block to those of the succeeding Block. Therefore, a blockwise comparison of these common features is a convenient way of determining module design trends. Table 1, a vehicle for demonstrating these trends lists a single, representative set of characteristics for each Block. The set does not compose a description of a specific module because each feature is individually chosen for being most representative of that Block and most revealing of design trends.

Understanding this table requires some knowledge of the Block procurements (4). Block I was a procurement of existing terrestrial modules from four manufacturers in early 1976, at the infancy of the technology. The Block II procurement, initiated in late 1976 and setting higher performance and reliability standards, also involved four manufacturers. Block III procurement started in early 1978. It consisted of large orders (30 to 50 kW each) of modules, from five manufacturers, to only slightly revised specifications; therefore, the technology was primarily that of the Block II modules. For this reason there is no

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TABLE 1. REPRESENTATIVE CHARACTERISTICS OF BLOCK PROCUREMENT MODULES

	I	II	III	IV	V (PROPOSED)
AREA (m^2)	0.1	0.4	0.3	0.6	1.2
WEIGHT (kg)	2	5	5	9	17
SUPERSTRATE OR TOP COVER	SILICONE RUBBER	SILICONE RUBBER	SILICONE RUBBER	GLASS	GLASS
SUBSTRATE OR BOTTOM COVER	RIGID PAN	RIGID PAN	RIGID PAN	FLEXIBLE SHEET	FLEXIBLE LAMINATE
FRAME	NO	YES	YES	YES	NO
CONNECTIONS	TERMINALS	J-BOX	TERMINALS	PIGTAILS	PLUG-IN
ENCAPSULATION SYSTEM	CAST	CAST	CAST	LAMINATED	LAMINATED
ENCAPSULATION MATERIAL	SILICONE RUBBER	SILICONE RUBBER	SILICONE RUBBER	PVB	EVA
CELLS					
QUANTITY	21	42	43	75	86
SIZE (mm)	DIA: 76	DIA: 76	DIA: 76	95 x 95	100 x 100
CONFIGURATION	ROUND	ROUND	ROUND	SHAPED	SHAPED
MATERIAL	CZ	CZ	CZ	CZ	CZ
JUNCTION	N/P	N/P	N/P	N/P P^+	N/P P^+
FAULT TOLERANCE					
PARALLEL CELL STRINGS	NONE	NONE	NONE	3	5
INTERCONNECT REDUNDANCY	NONE	MINOR	MINOR	MUCH	MUCH
BY-PASS DIODES	NONE	NONE	NONE	1	3
PACKING FACTOR	0.54	0.60	0.65	0.78	0.83
NOCT[a]	43	44	48	48	48
PERFORMANCE AT 28°C CELL TEMP.[b]					
POWER, MAX. (W)	8	24	26	54	92
MODULE EFFICIENCY (%)	5.8	6.7	7.4	9.1	9.6
ENCAPSULATED CELL EFFICIENCY (%)	10.6	11.2	11.5	11.8	11.6

[a]NOMINAL OPERATING CELL TEMPERATURE: CELL TEMPERATURE IN OPEN-CIRCUITED MODULE EXPOSED TO 80 mW/cm^2 INSOLATION IN AMBIENT OF 20°C, 1 m/s WIND VELOCITY.
[b]AT 100 mW/cm^2, AM 1.5 INSOLATION.

significant difference between those two columns in Table 1. The Block IV program, initiated in 1980, included a pre-production phase followed, after satisfactory completion of qualification tests, by small production contracts. This program has now produced eight qualified designs from seven manufacturers. The Block IV qualification tests are more rigorous than those for Blocks II and III, reflecting increased experience with module failure modes. Additional test and field experience led to the still more rigorous Block V specification. Six Block V contractors have produced preliminary designs, which are the basis of all Block V data in this paper. At this time, because of funding limitations, it cannot be predicted how many, if any, of the Block V designs will be pursued to the level of design qualification.

Table 1 shows that for all five Blocks the module area has increased more than tenfold, the quantity of cells has about quadrupled, the cell size has increased, the cell configuration has changed from round to shaped, and the packing factor has increased about 50%. These physical changes are the principal reason that module power has increased from about 8 W to about 92 W and module efficiency has increased from about 5.8% to about 9.6%. A sense of the changes can be gained from Fig. 1, which shows five modules, one from each Block.

The Block I features (see Table 1) that predominantly limit power are 0.1 m^2 area, 21 cells, a 0.54 packing factor and 5.8% module efficiency. The only other directly contributing factor is encapsulated cell efficiency, 10.6%. However, perusal across the table shows about an 11.8% cell efficiency in Block V, only an 11% improvement from Block I. Cell efficiency is very important because cell cost is the major driver of module cost. However, cell efficiency has clearly been a minor factor in increasing module power. A greater effect was achieved by improving the module packing factor. This was achieved directly by manufacturing cells that are semi-round or rectangular rather than round, thereby permitting close spacing. An additional increase in the packing factor has resulted from reducing the frame area directly or from reducing the ratio of frame area to active module area, a normal outcome of the increased module area.

Obviously, the major techniques for raising module power have involved (1) increasing the cell area, (2) using larger cells (enabling better packing factor), and (3) using more cells (requiring larger module area). The advantages of higher power modules are reduction in $/W cost of manufacture and reduction in field-site labor. The latter follows because a given application will involve fewer modules to install and to interconnect. However, there are application-related limits on module size. For example, in a residential roof-top array, module replacement cost or the desire for simple installation and replacement may set an upper limit. And even in a central station application, where the foregoing considerations would probably not apply, the advantages of a larger module may be overweighed by inherently reduced reliability. For these reasons the need for modules larger than the Block V sizes is not now predictable.

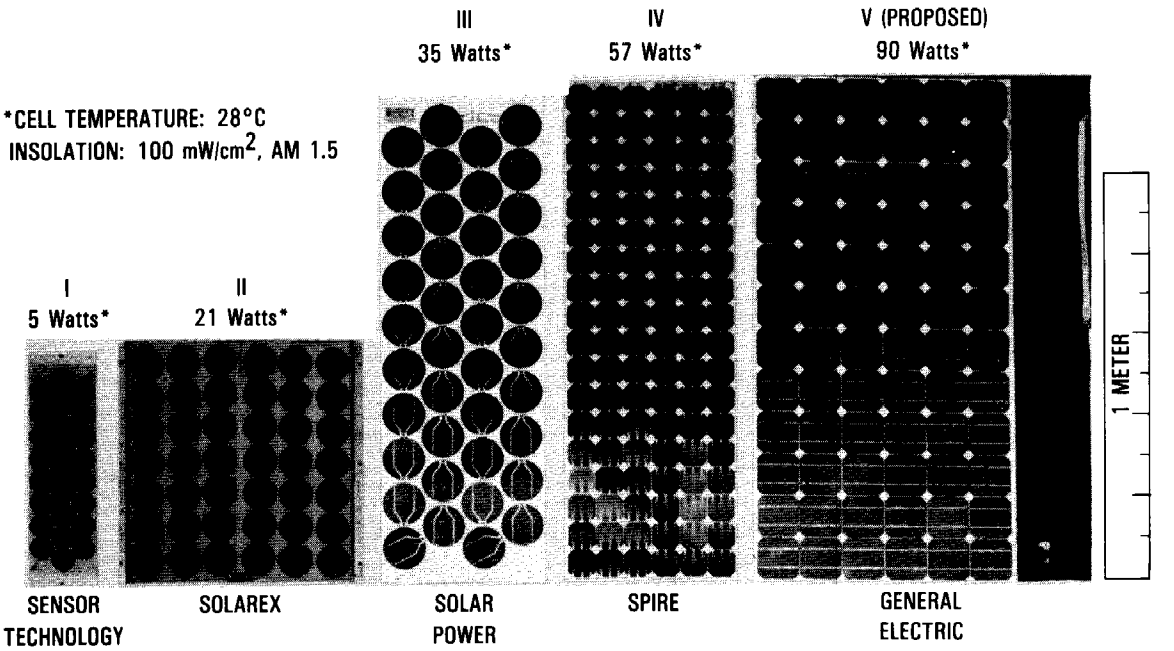

Fig. 1. Examples of Block Procurement Modules

Addressing trends in design for electrical reliability, the early modules were subject to catastrophic failure caused by even one crack in a single cell. Cracks can result from many causes (5), including defective cells, module handling, hail impact, and thermal stress from environment or from overheating caused by shadowing on a cell. Manufacturers have improved cell reliability by redesigning collector and grid patterns, by attention to crystal plane orientation and by providing additional care in processing and inspection to prevent or reject crack-prone cells. At the module level, manufacturers were encouraged, via the Block procurements to introduce design protection against this failure mode. The recommended fault-tolerance measures, listed in Table 1, are parallel cell strings, interconnect redundancy and by-pass diodes.

Of these measures only interconnect redundancy appeared in Blocks II and III. Furthermore, it was in a very limited form involving a parallel pair of interconnections close together on the cell circumference. In Blocks IV and V a major advancement was made wherein two or three interconnects were soldered at many points broadly distributed over the cell. Parallel cell strings were common techniques in Blocks IV and V. This circuitry and the interconnect redundancy provide modules in which cell cracks should not usually cause module failure. The by-pass diodes, which appeared in Block IV and V designs, mitigate against module failure and/or array failure, depending on circuit location.

Regarding trends in module structure, Table 1 shows that modules in the first three Blocks were typically encapsulated by casting silicone rubber onto a rigid, pan-type substrate that supported the cell circuitry. The silicone rubber served also as the top cover. In Blocks IV and V the favored construction consists of lamination of the circuitry in thermoplastic or thermosetting material between glass as a superstrate and a flexible sheet (0.1 to 0.2 mm thick) as a bottom cover.

The cast silicone rubber encapsulant, as a top surface, offered inadequate protection against humidity and against cell fracture caused by hail impact; and it accumulated dirt that did not wash off well under rain or even with cleaning maintenance. For these reasons and because of lower-cost projections, manufacturers changed to encapsulation by means of lamination of the cells onto a tempered-glass superstrate, using polyvinyl butyral (PVB) encapsulant in Block IV and ethylene vinyl acetate (EVA) in Block V. EVA appears to provide superior protection to the circuitry and is expected to be less expensive than PVB. The tempered glass is highly resistant to hail and to soiling, and becomes the circuit carrier during lamination; therefore, the only additional component needed is a thin bottom sheet for protection against moisture. The bottom sheet was typically a Tedlar sheet in Block IV. In Block V the bottom sheet was more commonly a lamination of sheets of Tedlar and/or polyethylene, sandwiching a sheet of aluminum foil.

3. MODULE STATE OF THE ART

The foregoing description of module trends was presented in terms of trends for each characteristic, with the description for that characteristic being chosen by the degree to which it represents the specific Block and reveals the dominant trends. The state of the art at any one point in module design is more completely portrayed by examining overall module designs and the range of key characteristics. For Blocks I through IV this portrayal will take the form, in each case, of a description of one specific module followed by identification of the most advanced features within the Block, if they differ from the example module. For Block V more extensive data will be covered. This will be followed by a graphical treatment of the key characteristics of modules in all five Blocks.

The Block I Sensor Technology module (Fig. 1) is made of cast silicone rubber on a rigid substrate, with 25 round 50-mm cells and a 0.51 packing factor, producing 5 W at 4.8% efficiency. The Block I cell size ranged to 87 mm, packing factor to 0.61, power to 13 W and efficiency to 6.5%. One module had a glass top cover.

The Block II Solarex module is made of cast silicone rubber on a rigid substrate, with 42 round 76-mm cells (slightly cropped on one side) having redundant interconnects at the cell edge and a 0.56 packing factor. This design produces 21 W at 6.0% efficiency. The Block II cell size ranged to 102 mm, cell quantity to 120, packing factor to 0.69, power to 34 W and efficiency to 7.4%. One module had a hard conformal top coat of silicone rubber to reduce soiling. Another module was laminated with PVB encapsulant on a glass superstrate with a transparent Mylar bottom cover, and it had three parallel cell strings.

The Block III Solar Power module is made of cast silicone rubber (with a hard top coat) on a rigid substrate. It has 40 round 102-mm cells, with redundant interconnects at the cell edge, and a 0.69 packing factor, producing 35 W at 7.7% efficiency. The Block III cell quantity ranged to 48, and efficiency to 8.4%. Two modules had glass top surfaces: one was a laminated module with PVB encapsulant and a Tedlar back cover, and the other used a silicone gel encapsulant and incorporated six interconnections distributed around the cell periphery and four parallel cell strings.

The Block IV Spire module is laminated with EVA encapsulant on a glass superstrate and has a bottom cover made of a thin sheet of a Mylar/aluminum lamination. It has 108 quasi-square, 64 x 64 mm cells having three interconnections along one side and a 0.85 packing factor, producing 57 W at 11.4% efficiency. The Block IV cell size ranged to 100 x 100 mm, cell quantity to 136, packing factor to 0.87, and power to 85 W. Design advancements in some other Block IV modules include the use of a three-layer back laminate (Tedlar/aluminum/Tedlar), three redundant interconnects (each soldered continuously across the entire cell), the use of six parallel cell strings, and integral encapsulation of 36 by-pass diodes. One manufacturer provided semicrystalline cells with wrap-around cell contacts. Block IV also introduced the shingle module concept, for direct roof-top mounting in residential service.

The General Electric module in Fig. 1 is of their proposed Block V design. It happens to be a residential module (shingle type), not a pre-requisite for Block V. It is laminated with EVA encapsulant, on a glass superstrate and has a laminated Tedlar/polyethylene/aluminum/Tedlar bottom cover (backed up by the shingle structure). It has 72 quasi-square 100 x 100 mm cells, having two continuous interconnects across the entire cell surface, and a 0.90 packing factor, producing 90 W at 11.5% efficiency. To put this design into the Block V perspective, refer to the Block V data in Tables 2, 3, and 4, which list characteristics of all Block module designs. The largest cell measures 100 x 150 mm (Solarex semicrystalline). The smallest cells are 51 x 102-mm Mobil Tyco edge-defined film-fed growth (EFG) cells (the first appearance of non-sawed sheet material in the program). Of these EFG cells, 352 are used to implement the largest module with greatest power output, 176 W. Maximum cell efficiency, in the Spire design, is estimated at 14.1%, with maximum module efficiency of 11.6%. Module construction details show all modules being laminated with EVA and having a superstrate of glass and bottom covers usually of multilayer laminates. One exception is the RCA design, which has a glass substrate. Fault-tolerance measures in the form of highly redundant interconnects (not shown in the tables), parallel cell strings (up to 12) and by-pass diodes are almost standard in these designs.

The range of expected key characteristics in Block V as compared to prior Blocks is shown graphically in Figs. 2 through 5. Fig. 2 shows that power has been increasing overall even though Fig. 3 shows the extreme values of cell efficiency decreasing as well as increasing. A significant factor in the down trend is the introduction of semicrystalline and EFG cells in the attempt to reduce the cell cost. Fig. 4 shows that the packing factor has contributed to the continuous rise of power. However, there still is a wide range of module efficiencies (Fig. 5), and we seem to have reached an upper limit for the immediate future.

The above advancements in the state of the art have accompanied a reduction in module cost as indicated in Fig. 6, which illustrates the JPL

TABLE 2. MODULE PHYSICAL CHARACTERISTICS

	MANUFACTURER	MODEL NO.	AREA[b] (m^2)	LENGTH (m)[c]	WIDTH (m)[c]	MASS (kg)	SUPERSTRATE OR TOP COVER	SUBSTRATE OR BOTTOM COVER	ENCAPSULANT	ENCAPSULANT METHOD	FRAME	ELECTRICAL CONNECTIONS	PACKING FACTOR
I	SENSOR TECH.	V-13-AT	0.097	0.57	0.17	1.3	RTV-615	ALUMINUM	RTV-615	CASTING	NONE	TERMINALS	0.51
	SOLAREX	785	0.133	0.51	0.26	1.1	SYLGARD 184	NEMA-G10 BOARD	SYLGARD 184			PIGTAILS	0.61
	SOLAR POWER	E-10-229-1.5	0.229	0.61	0.37	2.6	D.C. R4-3117	NEMA-G10 BOARD	SYLGARD 184			J-BOX/CABLE	0.57
	SPECTROLAB	060513-8	0.080	0.66	0.12	1.6	GLASS	ALUMINUM	RTV-615			TERMINALS	0.49
II	SENSOR TECH.	20-10-1452-J	0.168	0.582	0.289	1.5	RTV-615	ALUMINUM	RTV-615			TERMINALS	0.64
	SOLAREX	A-0221-D	0.335	0.579	0.579	4.1	SYLGARD 184	NEMA-G10 BOARD	SYLGARD 184		ALUM.	J-BOX	0.56
	SOLAR POWER	E-10008-C	0.454	1.168	0.389	7.6	D.C. XL-2577	GFR POLYESTER BOARD	SYLGARD 184		NONE	J-BOX	0.69
	SPECTROLAB	022962-G	0.453	1.168	0.388	6.1	GLASS	MYLAR	PVB	LAMINATION	ALUM.	PLUG-IN	0.52
III	ARCO SOLAR	10699-C	0.270	1.168	0.231	3.7		TEDLAR	PVB	LAMINATION	ALUM.	TERMINALS	0.69
	MOTOROLA	P-0170-770-J	0.340	0.583	0.583	6.6		STAINLESS STEEL	D.C. Q3-6527A	CASTING	ST. STEEL		0.65
	SENSOR TECH.	20-10-1646	0.166	0.582	0.286	3.7	RTV-615	ALUMINUM	RTV-615		NONE		0.65
	SOLAREX	A-0221-G	0.335	0.579	0.579	4.4	SYLGARD 184	NEMA-G10 BOARD	SYLGARD 184		ALUM.	J-BOX	0.56
	SOLAR POWER	E-10008-F	0.454	1.168	0.389	7.4	D.C. R4-3117	GFR POLYESTER BOARD	SYLGARD 184		NONE		0.69
IV	ARCO SOLAR	012110-E	0.372	1.219	0.305	5.2	GLASS	TED/ST/TED	PVB	LAMINATION	ALUM.		0.76
	ASEC	60-3062-F	0.834	1.198	0.696	13.5		TEDLAR	PVB		ALUM.	PIGTAILS	0.74
	G.E.[a]	47J254977G1-C	0.196	0.818	0.669	4.0		MEAD PAN-L-BOARD	G.E. SCS2402		NONE	FLAT-CABLE	0.76
	MOTOROLA	MSP43D40-G	0.426	1.198	0.356	5.8		TED/AL/TED	PVB		ST. STEEL	J-BOX	0.76
	PHOTOWATT	ML-1961-D	0.532	1.199	0.444	7.4		TED/AL/TED	PVB		ALUM.	PLUG-IN	0.62
	SOLAREX	580-BT-L-C	0.762	1.200	0.635	13.9		TEDLAR	EVA		ALUM.	PIGTAILS	0.85
	SOLAREX[a]	580-BT-R-C	0.749	1.193	0.628	11.2		TEDLAR			NONE	PIGTAILS	0.87
	SPIRE	058-0007-A	0.504	1.200	0.417	7.8		MYLAR-AL-COAT			ST. STEEL	PLUG-IN	0.85
V[e]	ARCO SOLAR	013185-A	0.74	1.22	0.61	11		TED/PET/AL/TED[f]			ALUM.	PLUG-IN	0.72
	G.E.[a]	47E258449G	0.78	1.85	0.81	12		TED/PET/AL/TED[d,f]			NONE	FLAT CABLE	0.90
	MOBIL TYCO[a]	17A	2.02	1.68	1.20	26		PET/AL/TED[f]				J-BOX	0.91
	RCA	8681501	1.44	1.22	1.18	23		GLASS				PLUG-IN	0.75
	SOLAREX	SX-1560	1.32	1.38	0.96	24		POLYETHYLENE/TED					0.89
	SPIRE[a]	058-0008	0.67	1.13	0.59	7		TEDLAR					0.82

[a]RESIDENTIAL MODULE
[b]EXPOSED AREA
[c]OVERALL DIMENSION
[d]PLUS SHINGLE MATERIAL
[e]PROPOSED
[f]PET - POLYESTER FILM, POLYETHYLENE TEREPHTHALATE

TABLE 3. MODULE CELL AND CIRCUIT CHARACTERISTICS

			CELL					CIRCUIT			
	MANUFACTURER	MODEL NO.	QNTY	SIZE (mm)	SHAPE	BASE MATL	JUNCTION	SERIES CELLS	PARALLEL CELLS	CROSS TIES	BY-PASS DIODES
I	SENSOR TECH.	V-13-AT	25	50 DIA	ROUND	CZ	N/P	25	–	–	–
	SOLAREX	785	18	76 DIA			N/P	18	–	–	–
	SOLAR POWER	E-10-229-1.5	22	87 DIA			P/N	22	–	–	–
	SPECTROLAB	060513-8	20	50 DIA			N/P	20	–	–	–
II	SENSOR TECH.	20-10-1452-J	44	56 DIA				44	–	–	–
	SOLAREX	A-0221-D	42	76 DIA				42	–	–	–
	SOLAR POWER	E-10008-C	40	102 DIA			P/N	40	–	–	–
	SPECTROLAB	022962-G	120	50 DIA			N/P	40	3	–	–
III	ARCO SOLAR	10699-C	41	76 DIA				41	–	–	–
	MOTOROLA	P-0170-770-J	48	76 DIA				12	4	11	–
	SENSOR TECH.	20-10-1646	44	56 DIA				44	–	–	–
	SOLAREX	A-0221-G	42	76 DIA	ROUND W/1 FLAT			42	–	–	–
	SOLAR POWER	E-10008-F	40	102 DIA	ROUND		P/N	40	–	–	–
IV	ARCO SOLAR	012110-E	35	103 DIA	ROUND W/2 FLATS		N/P	35	–	–	1
	ASEC	60-3062-F	136	76 DIA	ROUND			34	4	5	1
	G.E.[a]	47J254977G1-C	19	100 DIA	ROUND W/1 FLAT			19	–	–	–
	MOTOROLA	MSP43D40-G	33	100 x 100	QUASI-SQUARE		N/P P^+	33	–	–	–
	PHOTOWATT	ML-1961-D	72	76 DIA	ROUND			12	6	–	–
	SOLAREX	580-BT-L-C	72	95 x 95	SQUARE	SEMI-XTL		36	2	35	36
	SOLAREX[a]	580-BT-R-C	72	95 x 95	SQUARE	SEMI-XTL		12	6	11	12
	SPIRE	058-0007-A	108	64 x 64	QUASI-SQUARE	CZ		36	3	11	2
V[b]	ARCO SOLAR	013185-A	66	103 DIA	ROUND W/2 FLATS		N/P	11	6	–	NONE
	G.E.[a]	47E258449G	72	100 x 100	QUASI-SQUARE		N/P P^+	36	2	2	3
	MOBIL TYCO[a]	17A	352	51 x 102	RECTANGULAR	EFG	N/P P^+	44	8	3	4
	RCA	8681500	144	100 DIA	ROUND W/4 FLATS	CZ	N/P	12	12	5	1
	SOLAREX	SX-1560	78	100 x 150	RECTANGULAR	SEMI-XTL	N/P P^+	39	2	2	3
	SPIRE[a]	058-0008	72	91 x 91	QUASI-SQUARE	CZ	N^+/P P^+	36	2	5	3

NOTE: [a]RESIDENTIAL MODULE
[b]PROPOSED

TABLE 4. MODULE PERFORMANCE CHARACTERISTICS

			SAMPLE PERFORMANCE																
			AT 100 mW/cm^2, AM 1.5, 28°C CELL TEMP.								AT 100 mW/cm^2, AM 1.5, NOCT[b]								
	MANUFACTURER	MODEL NO.	P_{max} (W)	$V_{P_{max}}$ (V)	$I_{P_{max}}$ (A)	V_{oc} (V)	I_{sc} (A)	FILL FACTOR	MODULE EFF. (%)	CELL EFF.[c] (%)	P_{max} (W)	$V_{P_{max}}$ (V)	$I_{P_{max}}$ (A)	V_{oc} (V)	I_{sc} (A)	FILL FACTOR	MODULE EFF. (%)	CELL EFF.[c] (%)	NOCT[b] (°C)
I	SENSOR TECH.	V-13-AT	4.7	9.8	0.48	DATA NOT AVAILABLE			4.8	9.4	DATA NOT AVAILABLE								39
	SOLAREX	785	8.7	7.0	1.24				6.5	10.6									48
	SOLAR POWER	E-10-229-1.5	13.2	9.6	1.38				5.8	10.2									49
	SPECTROLAB	060513-8	4.7	9.4	0.50				5.9	12.0									35
II	SENSOR TECH.	20-10-1452-J	11.4	20.7	0.55	24.8	0.60	0.77	6.8	10.6	10.4	18.7	0.56	23.4	0.59	0.75	6.3	9.6	43
	SOLAREX	A-0221-D	20.5	18.0	1.14	24.3	1.43	0.59	6.0	10.7	18.7	16.3	1.15	22.4	1.44	0.58	5.5	9.8	47
	SOLAR POWER	E-10008-C	33.8	18.0	1.88	23.5	1.98	0.73	7.4	10.7	31.3	16.6	1.89	22.0	1.98	0.72	6.9	9.7	46
	SPECTROLAB	022962-G	30.0	18.2	1.65	23.0	1.86	0.70	6.6	12.7	28.5	17.3	1.65	21.9	1.88	0.69	6.3	11.7	41
III	ARCO SOLAR	10699-C	22.8	18.2	1.25	23.3	1.38	0.71	8.4	12.2	20.6	16.5	1.25	22.0	1.40	0.67	7.6	11.0	50
	MOTOROLA	P-0170-770-J	26.2	5.9	4.45	7.1	4.82	0.76	7.7	11.8	23.6	5.3	4.45	6.6	4.88	0.73	7.0	10.8	53
	SENSOR TECH.	20-10-1646	11.3	20.2	0.56	24.6	0.62	0.74	6.8	10.5	10.2	18.6	0.55	23.0	0.62	0.72	6.1	9.4	43
	SOLAREX	A-0221-G	21.7	17.8	1.22	23.7	1.40	0.65	6.5	11.6	19.7	16.4	1.20	22.1	1.41	0.63	5.8	10.4	46
	SOLAR POWER	E-10008-F	34.8	18.3	1.90	23.6	1.97	0.75	7.7	11.2	32.2	17.2	1.87	22.0	1.98	0.74	7.1	10.3	46
IV	ARCO SOLAR	012110-E	35.7	16.6	2.15	21.0	2.42	0.70	9.6	12.6	32.4	15.0	2.16	19.6	2.42	0.68	8.7	11.4	46
	ASEC	60-3062-F	84.6	16.5	5.11	20.2	5.40	0.78	10.1	13.6	77.4	15.0	5.16	19.2	5.45	0.74	9.3	12.6	47
	G.E.[a]	47J254977GI-C	18.8	8.5	2.21	11.0	2.53	0.68	9.6	12.6	15.3	7.1	2.16	9.6	2.53	0.63	7.8	10.3	58
	MOTOROLA	MSP43040-G	37.3	16.2	2.30	19.5	2.50	0.76	8.8	11.6	34.3	15.1	2.27	18.4	2.52	0.74	8.1	10.6	49
	PHOTOWATT	ML-1961-D	38.6	5.68	6.79	6.98	7.58	0.73	7.2	11.6	34.9	5.10	6.84	6.5	7.62	0.70	6.6	10.6	47
	SOLAREX	580-BT-L-C	62.6	16.1	3.90	19.6	4.50	0.71	8.2	9.6	57.3	14.4	3.98	18.1	4.58	0.69	7.5	8.8	49
	SOLAREX[a]	580-BT-R-C	60.8	5.31	11.4	6.60	13.2	0.69	8.1	9.3	54.5	4.70	11.6	6.2	13.3	0.66	7.3	8.4	49[a]
	SPIRE	058-0007-A	57.0	16.2	3.52	20.3	3.64	0.77	11.4	13.6	50.8	14.2	3.58	18.6	3.67	0.74	10.1	11.9	49
			ESTIMATED PERFORMANCE																
			AT 100 mW/cm^2, AM 1.5, 28°C CELL TEMP.								AT 80 mW/cm^2 AM 1.5, NOCT[b]								
V[e]	ARCO SOLAR	013185-A	72	5.2	13.8	6.5	15.0	0.74	9.7	13.5	50	4.8	10.3	6.0	11.8	0.71	8.4	11.7	48
	G.E.[a]	47E258449G	90	17.3	5.2	21.8	5.76	0.72	11.5	12.8	58	14.3	4.0	17.9	4.64	0.69	9.2	10.2	61
	MOBIL TYCO[a]	17A	176	19.2	10.7	24.6	10.7	0.67	8.7	9.6	126	17.5	7.2	22.3	8.8	0.64	7.8	8.6	47
	RCA	8681501	114	5.5	20.6	6.8	22.5	0.74	8.0	10.7	86	5.3	16.3	6.5	18.0	0.74	7.5	10.0	42
	SOLAREX	SX-1560	108	17.6	6.14	21.8	6.60	0.75	8.2	9.2	77	15.4	5.0	20.0	5.13	0.75	7.3	8.2	49
	SPIRE[a]	058-0008	78	17.5	4.46	21.0	4.64	0.80	11.6	14.1	54	15.0	3.6	18.9	3.76	0.78	10.1	12.3	49

NOTES: [a]RESIDENTIAL MODULE
[b]NOMINAL OPERATING CELL TEMPERATURE: CELL TEMPERATURE IN OPEN-CIRCUITED MODULE EXPOSED TO 80 mW/cm^2 INSOLATION IN AMBIENT OF 20°C, 1 m/s WIND VELOCITY
[c]ENCAPSULATED CELL
[d]RACK-MOUNTED
[e]PROPOSED

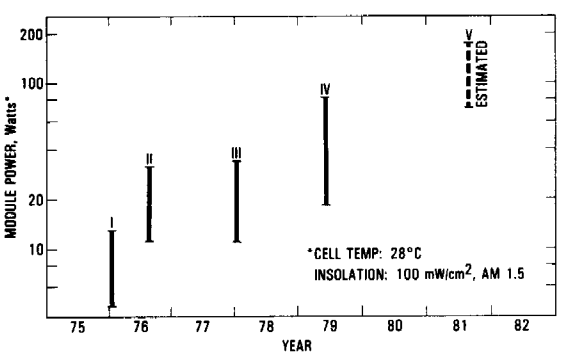

Fig. 2. Module Power Trend

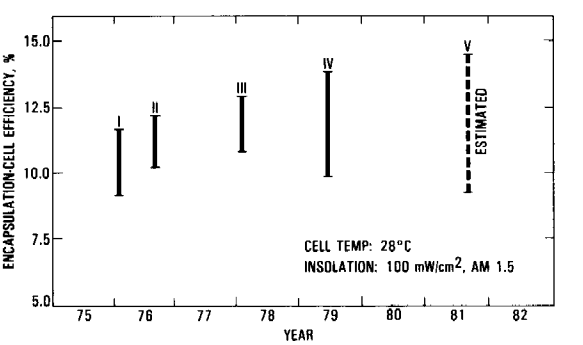

Fig. 3. Cell-Efficiency Trend

experience in constant 1980 dollars. This cost reduction was not fortuitous because the original project goal, now modified by national policy, was specifically the reduction of module cost. For each Block the vertical bar shows the range of cost data, and the dot locates the average value. The Block I, II, and III data are derived from purchases of 40, 127, and 259 kW of module power (referenced to 28°C cell temperature). The Block IV data are drawn from a JPL-designed computer simulation, provided by the contractors and is based on 1-MW purchases. At present there is no provision for projecting Block V module costs.

4. QUALIFICATION TEST EVOLUTION

An economically viable life for a photovoltaic module seems to be about 20 yr. To ensure pertinent, timely evaluation of new designs, a

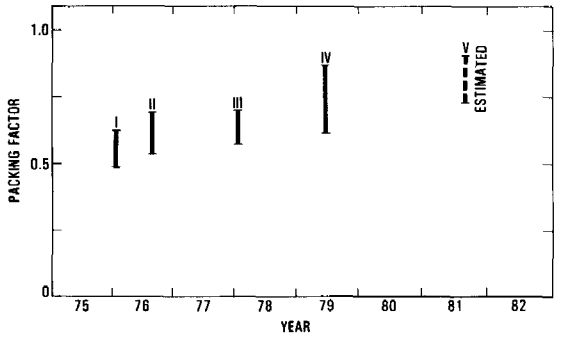

Fig. 4. Packing Factor Trend

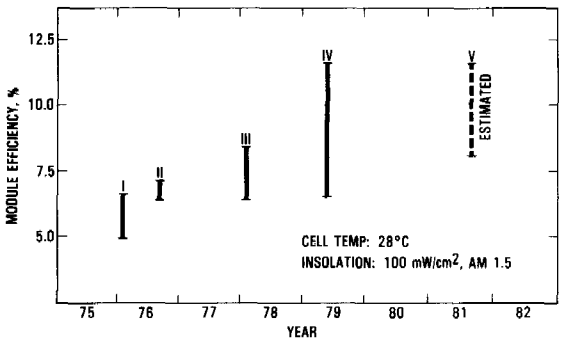

Fig. 5. Module Efficiency Trend

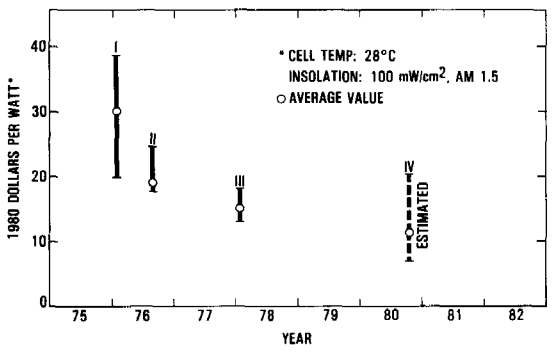

Fig. 6. Module Cost Trend

short-term simulation of the long-term field exposure is essential. For this simulation a set of accelerated life tests, designated "Qualification Tests", has been developed and refined throughout the Block procurement program (6). Qualification of a module, in the project lexicon, means that a small number of modules (less than 10) of a specific design have been shown capable of withstanding the stresses of the test program without more than 5% power degradation, without failure of a high-voltage-breakdown test, and without visible degradation exceeding pre-selected criteria. Qualification, therefore, is a reasonably good indication of the design potential; it is not a good indication of the probability of adequate subsequent process control.

Development of a set of qualification tests that truly simulates field exposure is a task that evolves continuously as new failure modes are discovered and as better correlation is developed between field degradation rates and qualification-test degradation rates. Discovery of failure modes has come from qualification tests, from the FSA Project field-test program and from the deployment of Block modules in the U.S. Department of Energy (DOE) test and applications program. Correlation of degradation rates is the subject of current FSA Project experimental investigations.

The evolution of qualification testing to date is evident from Table 5. The Block I tests, a "best guess", consisted only of 100 temperature cycles and a humidity soak. In Block II the number of thermal cycles was dropped to 50 because it was observed that thermal stress failures during the 100-cycle test always occurred before 50 cycles. The humidity soak was changed to a standard humidity test (i.e., with temperature cycling). A mechanical cyclic loading test was added to allow for wind and other mechanical loads. A twist test was added to simulate distortion in mounting structures. Also, a 1500-V voltage isolation test was added with the optimistic assumption that it would assure against breakdown in series-connected modules providing a nominal system voltage of 250 V.

In Block IV the mechanical loading cycles were increased from 100 to 10,000 to permit detection of fatigue failures. An alternate to this test was introduced, for residential shingle modules, consisting of a 2-h application of air flow to provide uplift pressure. Another new test, hail impact was introduced because of field experience with this failure mode. The voltage isolation test value was raised to 2000 V (except for residential modules). This increase followed more rigorous guidelines from Underwriters Laboratory, which require a 2000-V test value for a nominal system voltage of 250 V. The 1500-V value, for residential modules, is adequate for approximately 125 V system nominal.

For Block V the thermal cycles have been increased to 200 (for part of the sample) to detect cell interconnect fatigue, following appearance of interconnect failures in the field. The humidity test is expanded to 10 cycles with temperature cycling between -40°C and +85°C. (Within each cycle at least 20 h is spent at 85°C, 85% relative humidity.) This increase in test rigor was influenced by standard semiconductor usage and by gradual accumulation of evidence that module degradation in the field was not being predicted by the results of the prior humidity test.

TABLE 5. EVOLUTION OF QUALIFICATION TESTS

	I	II	III	IV	V	NOTES
THERMAL CYCLING						
RANGE (°C)	-40 to +90	-40 to +90	→	→	→	
CYCLES	100	50	→	→	200	
HUMIDITY CYCLING						
RELATIVE HUMIDITY (%)	90	→	→	→	85	
TEMP. RANGE (°C)	+70*	-23 to +40	→	→	-40 to +85	*NO CYCLING, +70°C
CYCLES	–	5	→	→	10	CONSTANT FOR 168 h
MECHANICAL CYCLIC LOADING*						*EXCLUDING SHINGLE
PRESSURE (kPa)	–	±2.4	→	→	→	MODULES
CYCLES	–	100	→	10,000	→	
WIND RESISTANCE (kPa)*	–	–	–	1.7	→	*SHINGLE MODULES ONLY
TWISTED MOUNTING (mm/m)	–	20	→	→	→	
HAIL IMPACT						
SIZE (mm)	–	–	–	20	25.4	
TERMINAL VELOCITY (m/s)	–	–	–	20.1	23.2	
IMPACTS	–	–	–	9	10	
HOT-SPOT ENDURANCE (h)	–	–	–	–	100	
ELECTRICAL ISOLATION (V)	–	1500	→	2000*	3000*	*1500 FOR RESIDENTIAL MODULES

The Block V hail impact test is more rigorous in both hailstone size and terminal velocity, in accord with newer data on field environment. A hot spot endurance test is introduced, again responding to field failures, to test for module deterioration due to cell heating caused by cell failure or partial module shadowing; and the voltage isolation value was increased to 3000 V, to allow for system operation at 500 V, nominal, in non-residential applications.

This continuous evolution of qualification tests has directly influenced module development, as can be seen by the module design trends shown in Sections 2 and 3 above. Additional module improvements may be expected as the qualification tests continue to be refined, based on additional field experience and on the results of experimental tests to improve correlation between the qualification-test environment and field exposure.

5. FIELD TEST EVOLUTION

Early in the course of the Block procurements, the FSA Project initiated a field-test program. As modules from the Block procurements became available they were installed at the field sites. Their electrical performance and physical condition were checked periodically over 4-1/2 yr. The modules were loaded individually; they were not connected into arrays. The program provided an endurance test of the modules that produced data on relative failure rates. Analysis of data on 389 modules at three sites (7) showed that Block I failures occurred almost immediately and rose at almost a constant rate to about 13% (out of 225 modules) in 56 mo. Block II modules did not start failing for about 6 mo., but the number of failures then climbed rather rapidly to about 12% (out of 116 modules) in 54 mo. In contrast, 48 Block III modules have been in the field for periods up to 36 mo without any failures. An alternate indication of Block III reliability appears in data from the DOE test and applications program (8). Of 5,724 Block III modules that were in the field for periods of 1 to 4 1/2 yr, 3.6% had failed as of October 1981.

The endurance tests have been useful, but, because of the pace of module development the test results were reported in many cases after the designs were obsolete. Furthermore, because the modules were not connected into operating systems, some failure modes were not detected until they appeared in the DOE test and applications program, long after modules were available for the FSA field tests. Thus, the program could not provide the rapid response needed to influence designs as they were developing. Therefore, a new plan evolved to shift from the collection of endurance data to early detection and analysis of fundamental problems. Toward this objective (and because of reduced funding) most of the endurance sites have been closed-down and the Block IV modules are being configured into loaded arrays, representative of true operational systems. A data collection system has been added that can measure loaded array performance and loaded individual module performance almost simultaneously. Data measurement techniques are being refined to improve accuracy as a means of reducing the time before module degradation is detected. By these means, combined with the use of new techniques of documenting baseline module condition and with a plan for immediate detailed investigation of questionable module performance or physical condition, it is expected that the field-test program will provide more timely support to module development.

6. CONCLUSIONS AND RECOMMENDATIONS

During the past six years, modules have developed from rudimentary battery chargers to candidate components of megawatt power generating stations. This change has been due to a concerted program of development of materials, of design techniques and of test methods. Additional improvements are being pursued in cells, encapsulants, module packaging and in components suitable for automated module production. Design techniques and test methods are now mature enough to provide sophisticated support to the introduction of these improvements for the purpose of obtaining the low initial cost and the long life needed for photovoltaic power to assume a major role in energy generation.

7. ACKNOWLEDGMENT

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