THE BLOCK PROGRAM APPROACH TO PHOTOVOLTAIC MODULE DEVELOPMENT*

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ABSTRACT

A series of photovoltaic module development activities, designated Blocks I through V, used increasingly refined requirements together with extensive testing and failure analysis to assist industry in developing the most advanced modules possible. The block program approach is described and the design details are given for all modules developed, highlighting the blockwise improvements. The success of this approach is demonstrated by the fact that most design details of the Block V modules have been adopted internationally. Instrumental to this success have been the steady improvements in design and test specifications that have guided module development. The experience gained since development of the Block V specification is being incorporated into a Block VI Design and Test Specification, which includes upgraded and revised application-specific requirements. Highlights of this Block VI specification are also described.

INTRODUCTION

In 1975 the National Photovoltaics Program initiated research on PV materials, processes, components and systems with the goal of developing photovoltaics as a viable alternative energy option. One instrument organized to pursue this program was the Flat-Plate Solar Array Project (FSA) at the Jet Propulsion Laboratory (JPL). The FSA Project, in consideration of the need for an objective method of evaluating progress towards this goal, conceived the idea of embarking on a series of photovoltaic module development programs. In these programs the development would be performed by industry and the performance evaluation of the modules would be performed by JPL. In preparation for each of these development programs, JPL prepared a design and test specification and a statement of work, both of which were instrumental in inducing the proposers to make maximum use of the latest PV technology.

For each development program several parallel contracts were issued to provide for alternative approaches. Furthermore, each contractor was encouraged to continue work on his approach until he had successfully passed the qualification tests or had abandoned the proposed design.

These development programs served two functions. First, they were an effective method of transferring the technology developed under the national program to the industries that must make use of them if the goal were to be met. Second, they produced practical modules whose performance evaluation under a formal set of qualification tests enabled identification of the research problems to be solved to continue progress toward the goals.

THE BLOCK PROGRAM APPROACH

The sequence of events that typify the block program approach are:

(1) JPL prepares design and test specification.

(2) JPL conducts competitive procurement culminating in award of parallel contracts.

(3) Contractor performs module design.

(4) JPL conducts design review.

(5) Contractor manufactures 10 modules.

(6) JPL performs module qualification tests (and failure analysis, as applicable).

(7) Contractor modifies design and/or processing procedure to correct problems revealed by qualification tests.

(8) JPL conducts design review.

(9) Contractor manufactures 10 modules.

(10) JPL performs module qualification tests (and failure analysis, as applicable).

(11) Contractor modifies design and/or processing as necessary and supplies modules for retest.

(12) JPL completes final testing.

(13) JPL prepares and issues User Handbook [1, 2, 3, and 4], describing construction details

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and performance of successful module design by each contractor.

The principal ingredients responsible for the success of this approach are the competitive procurement, the JPL design and test specification and the continuous cooperative interaction between JPL and the contractor. The competitive procurement provides incentive to incorporate the latest technology. The design and test specification identifies the design improvements needed to improve performance, as revealed by the results of prior qualification test results (from the preceding block), field experience and project research. The interaction between JPL and the contractor is the means for applying all available technical resources to the guidance of the design and the solution of the problems. Not the least part of this interaction is the provision that JPL qualification tests and failure analysis provide the vehicle for unearthing and correcting flaws, rather than merely identifying success or failure.

RESULTS OF THE BLOCK APPROACH

The block approach has been applied to a series of five development programs designated consecutively as Blocks I through V and spanning the period 1975 to 1985. The mechanical and electrical characteristics of the resulting 26 modules are given in Tables 1, 2 and 3 and a photographic example of one module in each block appears in Figure 1. The variety of design features within each block reflects, inclusively, the applicable state of the art at the time of procurement. However, despite this variety there is a degree of commonality among the modules within each block that reveals a stepwise evolution from the common features of one block to those of the succeeding block. This evolution is illustrated in Table 4, which lists a single, representative set of characteristics for each block. A set does not constitute a description of a specific module because each feature is individually chosen for being most representative of that block and most indicative of design evolution. It should also be explained that the representative Block III characteristics do not materially differ from those of Block II because the Block III procurements were for large production orders (30 to 50 kW each) of essentially Block II technology, rather than for a development program.

Table 4 shows that over all five Blocks, the module area has increased more than tenfold, the quantity of cells increased about sixfold, cell size increased, cell configuration changed from round to shaped, and the packing factor increased about 60%. These mechanical changes are the principal reason that module power has increased from about 8W to about 117W and module efficiency has increased from about 5.8% to about 10.6%. Some of these changes are evident from the module examples shown in Figure 1.

The Block I features (Table 4) that predominantly limit power are the small 0.1 m^2 area, and the poor 0.54 packing factor, which limited the module efficiency to 5.8%. The only other directly contributing factor is encapsulated cell efficiency of 10.6%; however, perusal across the table shows about 12.3% cell efficiency in Block V, only a 16% improvement from Block I.

Table 1. Module Mechanical 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]	47J254977GI-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	ARCO SOLAR	004-014168-2	0.745	1.221	0.610	12.0	↓	TED/PET/TED[e]	↓	↓	ALUM.	J-BOX	0.90
	G.E.[a]	47E258449G2-A	0.776	1.226	0.633	13.6	↓	TED/PET/AL/TED[d,e]	↓	↓	NONE	FLAT CABLE	0.90
	MSEC[a]	Ra-180-12-D	2.154	1.791	1.203	29.5	↓	PET/AL/TED[e]	↓	↓	↓	J-BOX	0.89
	SOLAREX	C-120-10A	1.331	1.391	0.957	23.6	↓	PET/MYLAR/TED[e]	↓	↓	↓	PLUG-IN	0.88
	SPIRE[a]	058-0008-B	0.875	1.134	0.595	7.3	↓	TEDLAR	↓	↓	↓	PLUG-IN	0.76

[a] RESIDENTIAL MODULE
[b] EXPOSED AREA
[c] OVERALL DIMENSION
[d] PLUS SHINGLE MATERIAL
[e] PET = POLYESTER FILM, POLYTHYLENE TEREPHTHALATE

Table 2. Module Cell and Circuit Characteristics

	MANUFACTURER	MODEL NO.	CELL					CIRCUIT			
			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	ARCO SOLAR	004-014168-2	72	97 x 97	QUASI-SQUARE	CZ	N/P	12	6	3	1
	G.E.^{a}	47E258449G2-A	72	100 x 100	QUASI-SQUARE	CZ	N/P	36	2	34	3
	MSEC^a	Ra-180-12-D	432	95 x 48	RECTANGULAR	EFG	N/P	36	12	2	1
	SOLAREX	C-120-10A	117	101 x 101	RECTANGULAR	SEMI-XTL	N/P	13	9	–	1
	SPIRE^a	058-0008-B	72	91 x 91	QUASI-SQUARE	CZ	N/P-P+	36	2	2	3

NOTE: ^{a}RESIDENTIAL MODULE

Cell efficiency is very important because cell cost is the major driver of module cost. Nonetheless, 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 quasi-square or rectangular rather than round, thereby permitting close spacing. An additional increase in the packing factor has resulted from reducing the ratio of frame area to active module area, an outcome of the increased module area.

In summary, 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 dollar-per-watt cost of manufacture and reduction in field-site labor costs. 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.

Addressing improvements in 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, including defective cells, module handling, hail impact, thermal differential stresses, or from hot-spot heating caused by shadowing on a cell. Manufacturers have improved cell reliability by redesigning collector and grid patterns for increased numbers of cell attachment points, 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 4, are parallel cell strings, interconnect redundancy and by-pass diodes.

Table 3. 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	MSP43D40-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	56
	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
			AT 100 mW/cm^2, AM 1.5, 25°C CELL TEMP.								AT 100 mW/cm^2 AM 1.5, NOCT[b]								
V	ARCO SOLAR	004-014168-2	84.1	5.82	14.5	7.16	15.9	0.74	11.3	12.6	75.0	5.20	14.4	6.56	16.1	0.71	10.1	11.2	49
	G.E.[a]	47E258449G2-A	81.7	17.0	4.81	20.9	5.65	0.69	10.5	11.7	65.4	13.3	4.92	17.7	5.69	0.65	8.4	9.3	65
	MSEC[a]	Ra-180-12-D	185.	15.3	12.1	18.9	13.3	0.74	8.4	9.4	165.	13.2	12.5	17.9	13.7	0.67	7.5	8.4	48
	SOLAREX	C-120-10A	139.	5.84	23.8	7.47	26.7	0.70	10.3	11.7	123.	5.18	23.7	6.79	27.2	0.67	9.1	10.3	48
	SPIRE[a]	058-0008-B	70.7	16.1	4.39	20.7	4.79	0.71	10.1	13.3	62.7	14.5	4.32	18.9	4.84	0.69	9.0	11.8	47[d]

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

None of these measures appeared in Block I and 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 the modern modules with excellent tolerance to cracked cells. The by-pass diodes, which appeared in Block IV and V designs, mitigate against module open circuits and hot-spot heating.

Regarding improvements in module structure, Table 4 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.

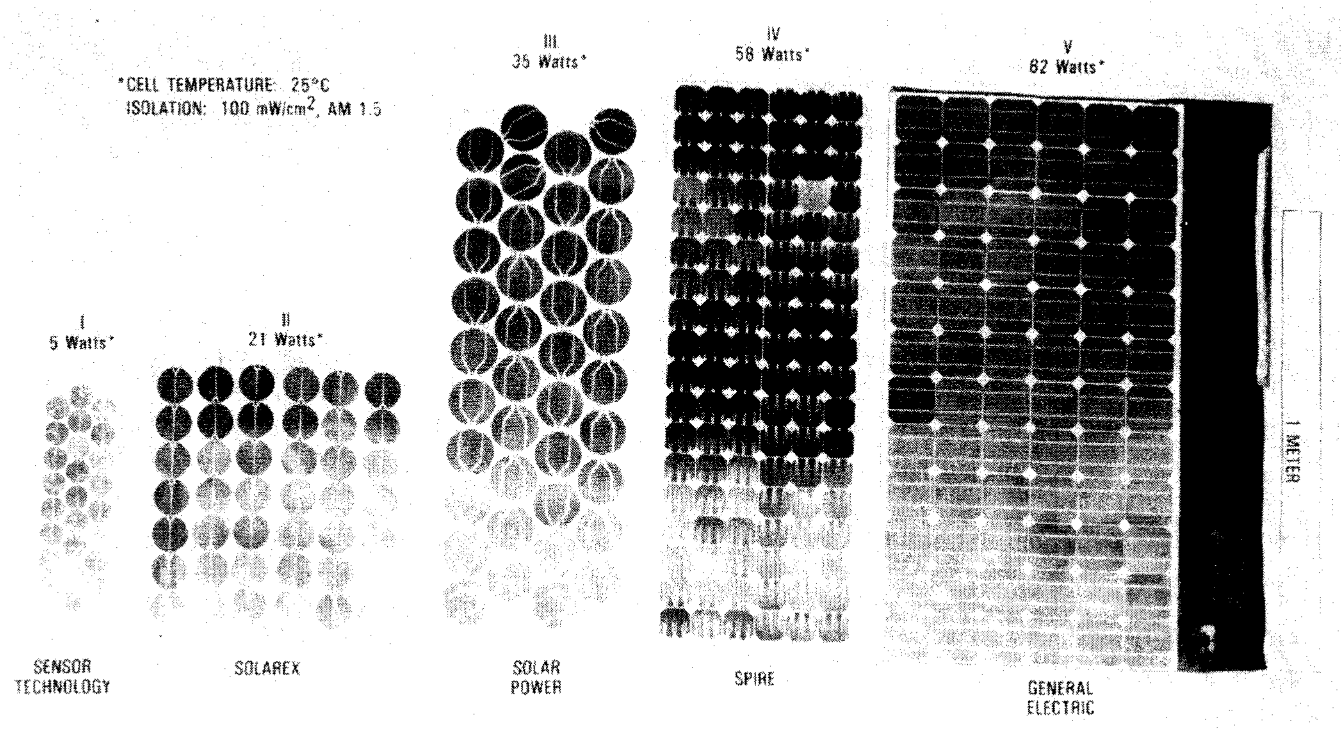
The cast silicone rubber encapsulant, as a top surface, offered inadequate protection against cell fracture caused by hail impact, accumulated dirt that did not wash off well under rain or even with cleaning maintenance, was excessively subject to delamination under field conditions, and required difficult and costly processing. 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 provides superior protection to the circuitry and is less expensive than PVB. The tempered glass is highly resistant to hail, thermal stresses and to soiling, and it becomes the circuit carrier during lamination; therefore, the only additional component needed is a thin bottom sheet for voltage isolation. 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 polyester, sometimes sandwiching a sheet of aluminum foil.

THE BLOCK V MODULES

The above discussion refers to the Block V modules only in terms of the representative characteristics listed in Table 4. Since these modules represent the current state of the art it is appropriate to describe them in more detail.

Figure 2 is a photographic view of the five Block V modules. The obvious common characteristics of these modules, is large size, which reaches 2.15 square meters in one case. The General Electric module is a roof-shingle design, for use

Figure 1. Examples of Block I Through Block V



in residential applications. The three modules on the left are made of single crystal cells; the Solarex module uses semi-crystal cells; the Mobil Solar module uses edge-defined film-fed (EFG) ribbon cells, grown by the Mobil Nonegon Process.

From Table 1, Module Mechanical Characteristics, it can be seen that all the designs have converged to the glass/Ethylene-Vinyl-Acetate (EVA)/plastic-film configuration. All have high packing factor, except for the Spire module. However, the lower packing factor in that case was the result of an early cost trade-off that is no

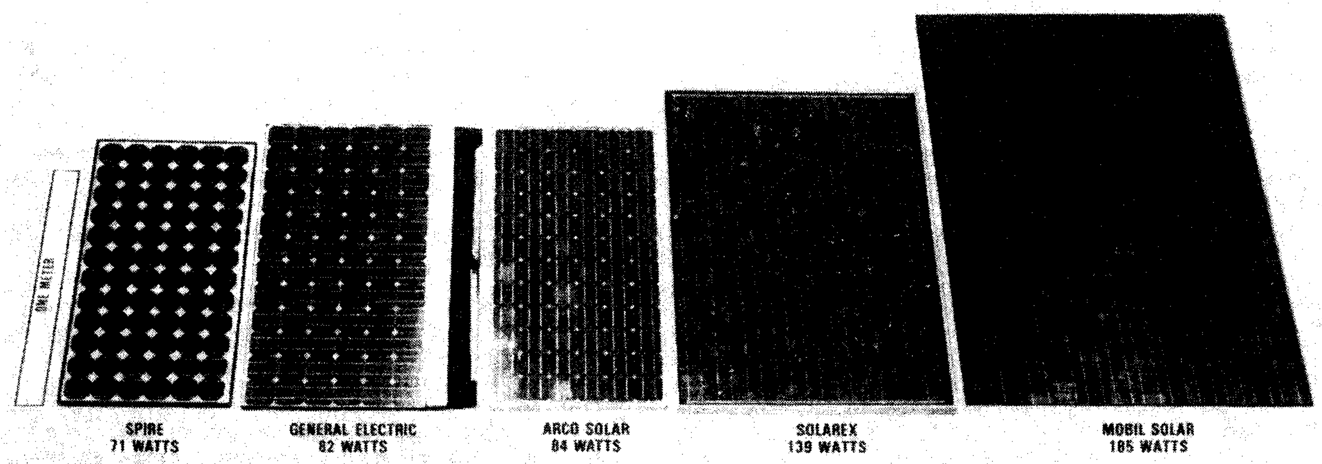
Table 4. Representative Characteristics of Block Modules

	I	II	III	IV	V
AREA (m^2)	0.1	0.4	0.3	0.6	1.1
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	117
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
FAULT TOLERANCE					
PARALLEL CELL STRINGS	NONE	NONE	NONE	3	6
INTERCONNECT REDUNDANCY	NONE	MINOR	MINOR	MUCH	MUCH
BY-PASS DIODES	NO	NO	NO	YES	YES
PACKING FACTOR	0.54	0.60	0.65	0.78	0.89
NOCT[a]	43	44	48	48	48
PERFORMANCE AT 28°C CELL TEMP.[b]					
POWER, MAX. (W)	8	24	26	54	112
MODULE EFFICIENCY (%)	5.8	6.7	7.4	9.1	10.6
ENCAPSULATED CELL EFFICIENCY (%)	10.6	11.2	11.5	11.8	12.3

[a] NOMINAL OPERATING CELL TEMPERATURE: CELL TEMPERATURE IN OPEN-CIRCUITED MODULE EXPOSED TO 80 mW/cm² INSOLATION IN AMBIENT OF 20°C, 1 m/s WIND VELOCITY.

[b] AT 100 mW/cm², AM 1.5 INSOLATION.

Figure 2. The Block V Modules



longer valid; Spire has since produced a design with 0.90 packing factor, on another JPL contract.

Table 2, Module Cell and Circuit Characteristics, shows the large cell quantities used in the modules, the large cell sizes (except for the ribbon cells) and the fact that all of the cells are rectangular, or nearly so. Parallel circuit strings are the rule, both for array reliability and, in most cases, to avoid string lengths that necessitate bypass diodes at substring intervals to prevent back-bias caused hot-spot failures.

The data in Table 3, Module Electrical Performance, was measured on a single sample of each module. Power values are high, ranging from 71 to 185 watts. Current values range up to 23.8 A, resulting from the large number of parallel cells. The efficiencies are almost uniformly good, the ribbon module being lowest. The efficiency values for the Solarex modules and cells are particularly noteworthy because they represent an increase in encapsulated cell efficiency and module cell efficiency at 25°C from about 8% and 10%, respectively, 2 1/2 years ago, to approximately 10% and 12% today (In clarification of the module efficiency calculations, the value used for module area includes an allowance for borders, based on the dimensions of the mounting system suggested by the contractor.).

Symbolic of the advances in Block V relative to Block I is the increase in module power output from about 8 W to as much as 185 W, the addition of semi-crystalline and ribbon cells to the original single-crystalline cells, and the elimination of failures due to cracked cells, fatigued interconnects, hail impact and back-bias induced hot spots.

BLOCK VI SPECIFICATION HIGHLIGHTS

The steady improvements in design and test specifications that have guided the module development have been instrumental to the success of the block program approach. Since 1975, the requirements within the documents have undergone significant evolutionary changes through frequent assessment of module design and performance results from the closed-loop (interactive) specification development process. Table 5 summarizes the chronology of these specifications and their intended application.

Table 5. Prior JPL Block Module Specifications

JPL Document No.	Application	Date Issued
5-342	Block I	June 1975
5-342-1, Rev. B	Block II	December 1976
5-342-1, Rev. C	Block III	May 1977
5101-16, Rev. A	Block IV Intermed. Load	November 1978
5101-83	Block IV Residential	November 1978
5101-161	Block V Intermed. Load	February 1981
5101-162	Block V Residential	February 1981

Since publication of the Block V specifications in 1981 [5 and 6], a wide selection of solar cell and module performance data have been generated from endurance testing, including long-term accelerated environmental exposure and exploratory tests characterizing anticipated or known failure mechanisms. Module assessments from these sources along with performance data of fielded modules from previous block procurements and JPL's qualification testing have been used to upgrade existing design and test specification procedures. In addition, simplification of procedures and elimination of less useful tests based on past performance history, have been used to reduce qualification test costs.

These recent changes together with the need for a generic specification, combining the requirements of low-voltage small-remote residential, intermediate-load and central-station arrays into one document, has resulted in the ongoing development of a Block VI Design and Test Specification. The Block VI Specification is to emphasize module performance rather than geometrical or aesthetic considerations so as to allow one to select appropriate design and test requirements based on the application. Discussions of several anticipated additions and refinements are given in the following paragraphs.

Global Air Mass 1.5 Measurement Conditions

Over the past few years interest has increased in adopting a reference solar spectrum which more accurately matches the spectral distribution of a typical clear-sky day, including the blue-sky diffuse component. The previous AM1.5 direct spectrum was chosen for its compatibility with standard reference-cell calibration procedures, which utilized precision normal-incidence radiometers that only view the direct component of the sun and exclude the blue sky light. Although the differences between the direct and global spectra are small (1%) for a broad-band device such as crystalline-silicon, they can result in large ($>15\%$) differences with narrow-band devices such as amorphous-silicon. Consistent with the international movement to the AM1.5 global spectrum, that spectrum has been adopted in the Block VI specification.

New NOCT Test Procedure

A module's Nominal Operating Call Temperature (NOCT) has proven to be an effective figure-of-merit of its thermal design performance as well as a useful numerical parameter for predicting field operating temperatures and annual electrical energy production. The previous test procedure, included in Blocks IV and V, has undergone gradual refinement and upgrading to improve the speed and accuracy of its NOCT determinations. A recent study [7] has identified that observed scatter in NOCT test values is attributable to secondary environmental factors that were not controlled. These include sky radiation, ground reflection and emission, test angle, and transient wind effects.

The new test methodology defines allowable values for these secondary factors and measures the module's temperature relative to that of a calibrated reference plate with a known NOCT value. Since the module and reference plate are subjected to the same environment, the temperature difference between the module (cell) and plate surface is approximately constant.

The NOCT value is obtained by summing the calibrated-plate NOCT temperature and the average differential module-cell-to-plate temperature over a selected time interval. The new methodology simplifies NOCT determinations by not requiring sophisticated wind and solar irradiance information and by allowing a broader test window. Additionally, the NOCT test is more accurate, since relative temperature values between modules (cell) and plate temperature are monitored simultaneously and can be known within 0.5°C.

Design Criteria and Test Procedure for Bypass Diodes

Bypass diodes are frequently used to limit the detrimental effects of array shadowing and internal open-circuit module failures. Since diodes are required to perform their function occasionally or continuously over the life of the array, an important consideration is their long-term reliability. Important parameters influencing by-pass diode reliability include derating of the diode characteristics, adequacy of the heat-sink design and the expected worst-case field thermal environments.

A recent study, addressed to the development of a methodology for assessing the design adequacy and reliability of bypass diodes [8], identified the predominant failure mechanisms in diodes as being strongly temperature-dependent. Design criteria were established addressing the adequacy of diode heat sinking by limiting diode junction temperatures to: (1) the manufacturer's maximum allowable operating temperature under worst-case PV field thermal conditions, and (2) a derated temperature, 50°C below the manufacturer's maximum, for prolonged periods of high operating temperature (see Table 6).

Table 6. Diode Design Criteria

Diode Type	Maximum Allowable Junction Temperature	Derated Temperature for Long-Term Reliability
p-n	175°C	125°C
Schottky	125°C	75°C
Applicable Field Conditions	100 mW/cm^2	100 mW/cm^2
	40°C	40°C
	1.5 I_{sc}	1.0 I_{sc}

The rating criteria and the corresponding test method developed are applicable to diodes mounted either integrally to or externally to module assemblies. Test results have shown that the derated, long-life temperature is the more difficult design criterion. The design criteria and test procedures have proven useful in assessing diode reliability, configuring heat sinks and selecting reliable diodes.

New Ultraviolet Exposure Test

Inspections of modules fielded for the last few years utilizing polymeric films for either back or front cover materials have revealed shrinkage and cracking due to UV exposure. These observations have encouraged renewed photothermal aging studies to characterize degradation parameters and aging rates and to develop a photothermal qualification test. Results from this ongoing study will be used to recommend a UV exposure test procedure for the Block VI Specification.

Electrochemical Stress Test

Electrochemical corrosion of metallized grids of solar cells was initially observed on mini-modules exposed to 85°C/85% RH environments in the Wyle long-term endurance tests [9 and 10]. Subsequent testing has subjected mini-modules with a variety of cell metallizations, encapsulants and back-cover materials to electrical stresses including positive and negative polarity voltage biasing up to 500 V dc. These tests have characterized this degradation mechanism over a range of environmental exposures [11]. Electrochemical degradation is accelerated greatest in high temperature and high humidity environments and is directly proportional to electrical stress. Consequently, this type of degradation is of particular concern for central station applications where maximum array voltages are 250-300 Vdc relative to ground. Consideration is being given to adding electrical stresses to the Block V Humidity-Freeze test procedure to assess module sensitivity to electrochemical degradation.

Micellaneous Updates

It is also expected that the Block VI Specification will include minor improvements such as an upgraded ground continuity test with resistance and applied test current requirements, and refinements in design requirements and test procedures for electrical isolation, hot-spot and hi-pot tests. In addition, it is expected that the twisted-mounting-surface test will be eliminated, and that the hail test will be waived for module designs having 0.125-thick tempered glass front cover and a hail-size requirement below one inch in diameter.

CONCLUSIONS

The Block Program approach to photovoltaic module development has been an effective method of progressively transferring advanced photovoltaic technology into the successful design and production of commercial modules. Current evidence of this success is the fact that the Block V technology is now in common use internationally and that three of the five Block V modules, in one form or another, are now part of major PV installations. Much of the credit for this record is due to the effort that has gone into the continuous upgrading of the module design and test specifications over a ten-year period. The Block V Design and Test specifications, which have gained international acceptance and application, are now being refined and modified, incorporating research and experience during the last four years, to provide a new contribution to the field of PV module technology.

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