PROGRESS IN THE PERFORMANCE OF TERRESTRIAL SOLAR CELL MODULES*

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ABSTRACT

Since the start of the Low Cost Solar Array (LSA) Project in 1975, approximately 400 kW of photovoltaic solar cell modules have been purchased in four separate blocks. These modules, representative of designs and manufacturing technology in the period from 1976 to the present, have been subjected to laboratory and field tests and subsequent evaluation. A review of certain figures-of-merit for the modules is useful in assessing the progress of the project in meeting a price goal of 70¢/watt in 1980 dollars and at standard test conditions. Analysis of the results of the testing program provides an assessment of the functional performance and durability of the modules and also an evaluation of the utility of the tests used in qualifying and characterizing the modules. The experience of the LSA Project in procuring, testing and evaluating these modules is given herein.

1. PROCUREMENT

As a part of the Low Cost Solar Array Project, three blocks of solar cell modules have been procured since 1976; contracts for a fourth block are currently underway. One objective of such procurements is to obtain cost and performance data which provide a measure of project success in reaching its goals. Such procurements encourage the introduction of new technology into module design and manufacture. They also make available up-to-date module designs and hardware for federally funded experiments and other applications, thereby providing a data base from which conclusions regarding durability and performance can be drawn. The block procurements are briefly described below.

With contracts starting in January of 1976, four manufacturers produced a total of 58 kW of modules for Block I. Module designs were all "off-the-shelf", and source inspection of modules was advisory only.

Commencing in July 1976 the same four contractors produced a total of 110 kW of modules for Block II. There were significant changes in the characteristics of this purchase. Module designs were developed to meet a specification which established a nominal operating voltage, an operating temperature of 60°C, a packaging envelope, and several other design features (such as redundancy) intended to enhance reliability. Source inspection to a workmanship model was performed on all modules.

At the start of 1978 five contractors began work on 216 kilowatts of Block III modules, which for the most part were delivered in late 1978 and early 1979. Module designs contained few changes from Block II. 100% source inspection was again imposed.

The design phase work for Block IV was begun in the April-July period of 1979 and involved eight contractors designing seven intermediate load modules and three residential type modules. Module design specifications included metric dimensions and several other changes.

2. DESIGN AND PERFORMANCE FEATURES

Module design has evolved in response to production, test and field experience as well as to changing application requirements. The early modules were generally intended for small battery charging applications. Block I modules came in a wide variety of sizes and used 12 to 25 solar cells. The cells were two or three inch diameter with collector patterns for non-redundant interconnects. Substrates were aluminum or epoxy fiberglass. Silicone rubber was the universal encapsulant and one module had a glass face. Block II modules were either two or four feet long but of variable width and operated at a specified voltage. Substrates were aluminum, framed polyester sheet and a molded polyester glass structure. One module used a glass superstrate to which the cell strings were laminated with polyvinyl butyral (PVB). Cell designs used collector patterns permitting

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redundant interconnects and one manufacturer put a conformal hard coating on the exposed encapsulant surface. Block III modules had the same general features with the addition of a module with a stainless steel substrate and frame, a silicone gel encapsulant, a multiply redundant solar cell contact pattern with a printed circuit and a glass face.

Block IV modules are designed with laminated encapsulation systems. Silicone is used in only one design. The top surface is usually a low iron glass which serves as a superstrate. The cells are generally formed with back surface fields; they are often nested polygons rather than circular in form. The modules are larger, more efficient and lower priced. These trends in the design are illustrated by the module packing factor, encapsulated cell efficiency, module efficiency and module price. Figures 1-4 show the range of each of these figures-of-merit for the procurements described above. There

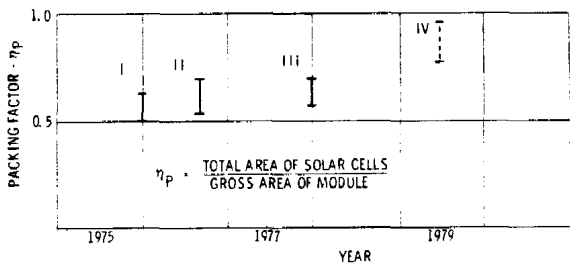

Fig. 1. Module packing factor For Block buys. Shows the fraction of total module area covered by cells.

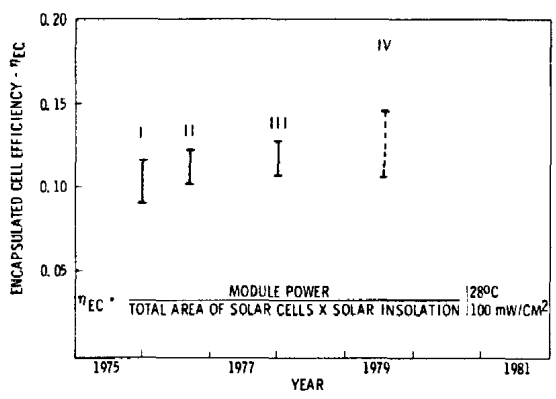

Fig. 2. Encapsulated cell efficiency for Block buys. Block IV includes modules with semi-crystalline silicon cells.

is clearly progress in all areas. The prices should only be viewed as indicators of a trend. They are derived from procurements ranging from 8 to 50 kilowatts and only reflect the prices at which the manufacturers were willing to sell. The profit or loss

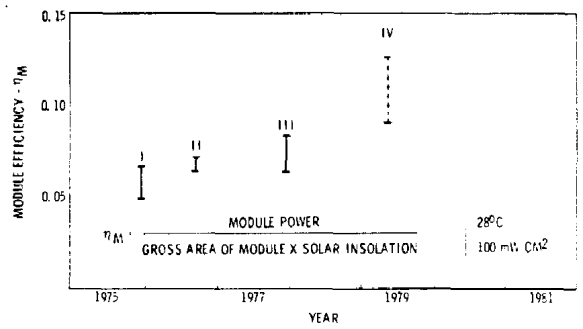

Fig. 3. Module efficiency for Block buys.

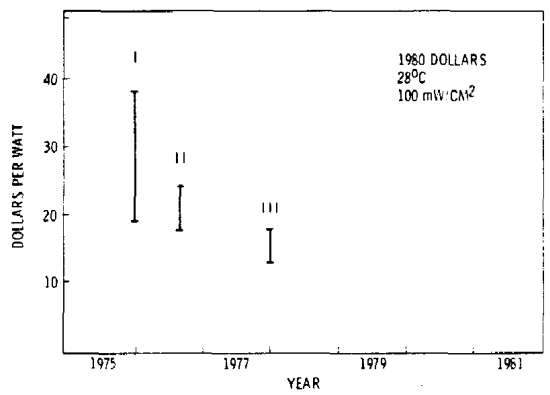

Fig. 4. Price experience in Block buys. Prices reduced to same conditions except quantity.

from these production runs is unknown. Note that Block IV data are based on preliminary requirements or manufacturers estimates; changes in these data are likely.

3. MODULE TEST AND APPLICATION EXPERIENCE

3.1 Scope

In the various phases of DOE's module and system test and application program, Block procurement modules have been subjected to a spectrum of tests and associated observations intended to determine their performance and durability. Figure 5 is a simplified flow chart for the deployment of Block Procurement modules from the manufacturers to the DOE technology development and test and application projects. Most modules, of course, go directly from the manufacturer's facility to system level field applications. During Block I-III production, a small number of modules have been diverted from the production stream to JPL for more intensive examination and subsequent environmental or field testing. The primary contributions of each of the sets of tests to module evaluation is noted on the diagram. Ideally, the results from these

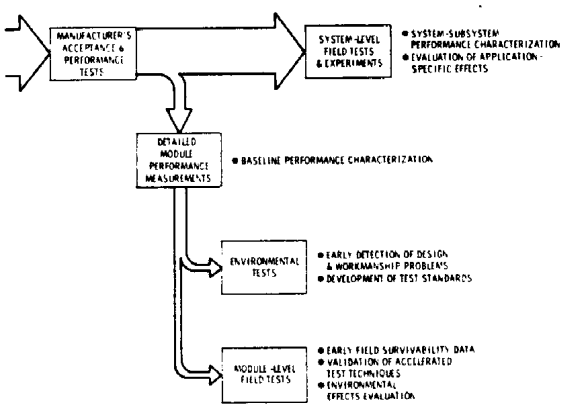

Fig. 5. Module Deployment

test activities should provide guidance for PV technology development, design, manufacture, and utilization.

The characterization and environmental testing of Block procurement modules has been described in Reference 1. Module-level field tests are described in References 2 and 3. Test and Application Project array results have been given in References 4 and 5. The deployment of Block modules to these projects is shown in Table 1. It should be noted that

Table 1

kW PER BLOCK	I	II	III
APPLICATIONS & EXPERIMENTS			
° NASA/LeRC			
Indian Village	0.3	4	
Remote Weather, Radio, etc.	2		0.5
° MIT/LL			
Residence(s)		7	14
Radio Station			15
Mead, Neb.		28	
Natural Bridges		20	80
Misc.	2		
° DOD			
Mt. Laguna		7	53
Battery Chargers	6		
Radar	8		
Telephone & Radio	3		
FIELD TEST SITES			
° NASA/LeRC	13		20
° NASA/JPL	0.3	8	0.5
° MIT/LL	5	4	
° Sandia		4	

the time required for fielding of the larger systems has resulted in a significant lag between the time of module manufacture and the time when system-level field results are available. Laboratory testing and small-scale field testing at the module level therefore are critical for early detection of potential problems.

3.2 Observational and Diagnostic Techniques

The measurement of module power output, important both in establishing initial performance and in detecting changes caused by the service environment, depends on adequate instrumentation, appropriate measurement standards, and care in their application. Instrumentation for in-situ (outdoor) module performance measurements has suffered from both a lack of accuracy and a lack of portability. Correction of data to standard test conditions requires compensation for cell temperature, insolation level, and input spectral content. LSA has adopted the interim measurement standards contained in Reference 6, which specify the use a Large-Area Pulsed Solar Simulator (LAPSS) illumination source. Field measurements are corrected to standard conditions using modified Sandstrom equations.

Visual inspections have been the primary means of determining the physical condition of tested modules. Efforts have been made to reduce the subjectivity of inspections by categorizing visual defects and standardizing nomenclature. Field inspections, in particular, are carried out under difficult conditions of lighting, environment, and physical access. A continuing need exists for correlation of visual appearance with life-limiting degradation modes, and for the development of more sophisticated non-visual observational tools.

The preceding techniques are useful first order checks on the functional and physical condition of modules. Investigations into the cause of module degradation induced by environmental test or field service require the use of sophisticated diagnostic tools, including both non-destructive and destructive tests. The methodology and equipment for such problem/failure analysis is described in Reference 7. Laser scanning, optical microscopy, scanning electron microscopy, materials analysis, illuminated and non-illuminated performance analysis, and corona discharge equipment are the most commonly used techniques for problem/failure analysis.

3.3 Results

A unifying mechanism for the evaluation and comparison of results from Block procurement module tests and applications is the Problem/Failure Report (P/FR) and Analysis system described in Reference 1. This system provides a procedure for reporting and analyzing module problems occurring in test or in applications, and for making the findings of such investigations known to the module manufacturers to enable them to improve the performance and reliability of their product. In general, a P/FR is initiated for any observed condition which either potentially or actually causes the failure of a module to perform satisfactorily.

Since the implementation of this system in 1976, nearly 1000 P/FR's have been filed, about 2/3 of which have now been analyzed and closed with recommendations for corrective action. Figure 6 summarizes the results of these analyses for the more common problems experienced by Block modules in environmental and field tests.

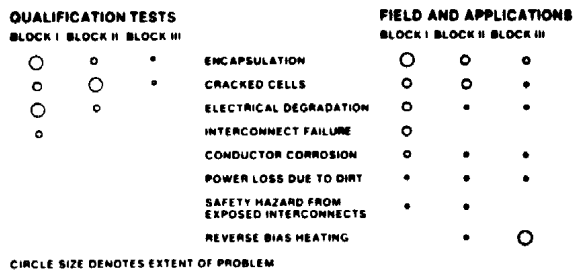

Fig. 6. Frequency of occurrence of failures

Silicone rubber encapsulants have frequently experienced a loss of adhesion and subsequent delamination and moisture ingress. This problem has been controlled but never really eliminated on later module designs.

Cracked cells are the most common cause of random module degradation and electrical failure. This problem has been experienced to some extent by all manufacturers, and is of concern in production, handling and shipping, and field use. Diurnal thermo-mechanical stresses (temperature cycling) are the external factor of most importance, but module packaging design and cell flaws induced in manufacture have also been shown to be critical. Most cell cracks do not lead immediately to module power reduction. If the contacts remain intact, the individual pieces of the broken cell continue to deliver power.

Interconnect failures were a common problem on early module designs. Temperature cycling led to fatigue fractures on cell-to-cell metal interconnects with resultant open circuiting. This failure mode has been virtually eliminated on later modules through the use of stress relief loops and similar design techniques.

Corrosion of electrical termination hardware, lead wires, buss bars, interconnects, and cell contacts has been observed as a more-or-less random occurrence, especially in field service. With the notable exception of hardware corrosion in marine environments, such attack of circuit elements has usually been the result of interactions with contaminants within the encapsulant remaining from manufacture (e.g., solder flux). Conductor corrosion has not usually led to significant power loss.

The primary cause of array power loss in the field seen to date is the reduction in cell illumination caused by airborne dirt deposited on the module surface. Reference 8 surveys the effect of this phenomenon, noting that power reductions of 10-30% are common. Glass is much less affected than softer encapsulants, such as silicone rubber. No satisfactory way of reproducing field soiling conditions in the laboratory has yet been devised.

A minor problem to date, but one which must be resolved in future applications, is that of exposed live circuit elements. Interconnect penetration of encapsulant is occasionally seen in the field, with obvious potential for personnel shock hazard. Improved encapsulation is ameliorating this problem, but safety standards are needed.

Cell string shorting, for safety purposes or by action of bypass diodes, leads to a situation in which one or more cells function as the load for the remainder of the cells in the string. For badly mismatched cells, this circumstance can even occur at normal operating currents. The cell or cells in a string will operate in reverse voltage bias, and severe overheating can occur. In addition to the power loss caused by this condition, subsequent encapsulant and cell damage can lead to catastrophic module failures. The severity of this problem is highly dependent on cell and module design and manufacture, being worst for those modules with cells of high shunt resistance, packaging with poor thermal conductance, and poorly matched cell outputs. This problem, while not common, can lead to chronic module failures and premature array degradation for some module types.

Despite the impression which the foregoing recitation of failure modes may convey, the overall field experience with Block modules has been very good. Failure rates have not exceeded 2% per year for Block II-III under JPL individual module field testing. Performance of modules in the applications experiments has been even better - failure rates have typically been less than 1% per year. Reverse bias heating effects have caused serious problems on one applications experiment, however, where 25% of the modules show power output below 75% of original levels (4).

4. CONCLUSIONS AND RECOMMENDATIONS

The design and production experience for Blocks I-IV clearly indicates continuous improvement in electrical performance, consistency and quality of product, and suitability for larger scale, higher voltage systems. Design, test, and quality specifications have been expanded to accommodate more rigorous applications requirements, while setting

price goals which call for continuous reductions in manufacturing costs. The Block manufacturers have shown remarkable success in simultaneously achieving price, performance, and durability goals. The improvements shown during Block I-III came mainly as a result of mastering and gradually improving the design and production techniques initially in use. The Block IV designs contain some significant departures from past practices in an effort to exploit lower-cost technologies; the success of these innovations will be tested over the coming months, but the industry has demonstrated a willingness to take developmental risks to achieve a more competitive product.

The Block procurements have not realized the potentials of automated mass production. Rather, these procurements have been more on the order of pilot production runs, with some attendant "learning curve" problems and lack of process controls. Module rejection rates have therefore been high - on the order of 20% - and there is a clear need for attention to further improvements in product uniformity and production yields.

Reference cells, calibrated by Lewis Research Center and later by JPL, have been used to establish uniform electrical measurement standards between manufacturers and module users. The time required for fabrication and calibration, and continuing concerns about calibration accuracy, spectral match of reference cells to manufactured products, applicability of normal incidence calibrations to field conditions, and various other problems have caused difficulties throughout these procurements. Basic developmental work is needed which will lead to the establishment and maintenance of measurement standards which are accepted and employed throughout the industry.

Correlation of environmental test results with field experience indicates that the series of qualification tests used to date are valuable in screening for potential problems. Modules which do well in environmental test also generally do well in service. Several parameters affecting lifetime or performance in the field have not been successfully duplicated in the laboratory, however. Soiling, UV, and cell back-bias are known stresses of importance which should be incorporated in future qualification testing. Long term weathering, with attendant erosion and corrosion, may never be successfully simulated in accelerated testing. Certain application-specific effects such as those associated with installation and maintenance can only be evaluated in actual use. Field tests at both module and system level will therefore continue to be important in the final assessment of serviceability.

The systematic evaluation and correlation of test and field problem/failure data is essential in the feedback to manufacturers and technologists which results in continuous upgrading of commercial products. Establishing and maintaining a system for providing such feedback does not come naturally in a rapidly expanding technology with as many participants as the DOE's photovoltaics program. We learn as much from our failures as our successes, however, and emplacing problem/failure reporting and analysis provisions as an integral part of the applications experiments and demonstrations program will provide this needed data.

Experience to date has revealed no fundamental technical barriers to achieving DOE's goals for terrestrial photovoltaics. The program is now entering a phase of intensive field experimentation. Proper application of this learning experience should establish photovoltaics as a reliable energy source for the markets which emerge as the price comes down.

5. REFERENCES

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