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PHOTOVOLTAIC CONCENTRATOR MODULE RELIABILITY: FAILURE MODES AND QUALIFICATION

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Introduction

In the early 1980s, three first-generation photovoltaic (PV) concentrator systems were installed in Saudi Arabia, Phoenix, and Dallas. The systems in Phoenix and Saudia Arabia used passively cooled point-focus modules built by Martin Marietta, and the one in Dallas used actively cooled line-focus modules made by ENTECH (formerly E-Systems) [1,2,3]. Although some problems were encountered, especially with poor-quality solder bonds in the point-focus modules, the modules in these systems performed remarkably well for first-generation technology. (Additional problems with the balance-of-system components occurred, decreasing the overall reliability of the systems, but that subject is beyond the scope of this paper.)

Despite the success of the early module technology, there are still some concerns about the long-term reliability of PV concentrator modules. There are several reasons for this. First, energy-cost calculations generally assume a 20- to 30-year life in the field; the field experience with the first-generation systems is on the order of 6 to 9 years, considerably less than 30 years [4]. Second, relatively few (compared to flat-plate modules) concentrator modules have been deployed in the field, due mostly to the fact that the economics of concentrators are geared toward larger power markets that have not yet materialized. Third, concentrator module design has evolved and changed substantially since the first generation systems were installed. Most of these new designs have not been installed in fielded systems. And finally, although a lot of the reliability work on flat-plate modules applies to concentrator modules as well, there are some reliability issues with concentrator module designs that are different from those of flat-plate module designs.

The purpose of this paper is to discuss the current issues of interest in PV concentrator module reliability. Before describing in detail the reliability concerns about PV concentrator modules, it should be emphasized that, with proper design and attention to quality control, there is nothing to prevent concentrator modules from being as reliable as crystalline-silicon flat-plate modules have proven to be. Concentrator modules tested outdoors, as well as in the first-generation systems, have generally been reliable, and no degradation in cell output has been observed. Also, although they are not included in this paper, there are a few items currently of concern with the

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reliability of other PV module technologies that are not issues with PV concentrator technology, such as the stability of amorphous-silicon efficiencies and concerns about EVA encapsulation [5,6].

Differences in Reliability Concerns Between Concentrator and Flat-Plate Modules

The biggest difference, from a reliability standpoint, between concentrator modules and flat-plate modules is that concentrators have a much larger volume. This large volume means that concentrator modules cannot be hermetically sealed; that is, vents must be provided to equalize the pressure as the temperature changes. Vents allow air of different relative humidities to enter the modules, and, as the temperature changes, moisture condenses onto the interior surfaces of the modules. Any exposed electrical circuits inside the modules are therefore subject to contact with water, which provides paths for leakage currents and/or short-circuits. This situation, besides being potentially detrimental to reliability, also raises safety issues. Newer concentrator designs are addressing moisture intrusion by encapsulating the electrical circuits inside the modules.

Another difference between concentrator and flat-plate modules relates to heat transfer considerations. Having areas of concentrated sunlight means that there is a smaller area in which to remove a given amount of heat. Designing for heat removal, whether by passive or active means, would not be too difficult for PV concentrator modules except that the design is complicated by the conflicting requirement of high-voltage electrical isolation. Generally a metal heat sink of some sort (either a separate heat fin or a metal module housing) is used to keep the cells cool. This exposed metal piece must be grounded and therefore electrically isolated from the cell string. This leads to electrically isolating layers between the cell string and exposed ground that are often very thin to promote good heat transfer. This thinness can create reliability problems with the electrical isolation between the cell string and the heat sink, especially under wet conditions.

Both flat-plate and concentrator module designs must account for differential thermal expansion, but the main areas and materials of concern are different for the two technologies. The two major areas of concern in concentrators are the cell string with its associated relatively large-area solder bonds and the seal between the lens and the housing, which may join metal and plastic over a length of several feet.

Other significant differences between concentrators and flat plates include the possibility for off-track charring in the interior of concentrator modules, which must be accounted for in the module design, and possible differences in hot-spot response.

Failure Modes

Probably the most common source of problems with concentrator module reliability is moisture intrusion. Failures due to moisture intrusion can be put into three categories. The first is a temporary decrease in power due to a short circuit; when the water dries, power is restored. The power decrease is generally due to low-voltage short circuits across individual cell assemblies or cell strings within a module or modules. The second category of failure causes permanent damage and can occur when water causes a destructive short or arc. The most likely place for this to happen is between a cell string and ground. Moisture intrusion can also create permanent open-circuit failures if water gets into a solder crack and freezes. The third type of failure due to moisture intrusion is caused by long-term degradation, such as corrosion. Examples of this type of failure include degraded cell metallization and deteriorated optical properties.

Modules under test both in the field and during qualification testing have exhibited several types of failures resulting from moisture intrusion. These include short circuits between cell strings and ground and between terminals and ground, high ground-fault currents which prevent the inverter from switching on, modules filling with water, corrosion, and degraded optics. The decrease in energy production of a system due to these failures is dependent on both the system configuration and the location of the failure. It can range from small short-term losses from individual cell assemblies to the entire system being shut down for a day or more after a rain storm.

Some other important failure modes in PV concentrator modules result from differences in thermal expansion coefficients. In particular, the solder bonds that connect the cells are susceptible to fatigue. Each cell typically carries a current on the order of 10 Amps, so the interconnects (usually copper) must be robust enough to carry the current. The coefficient of thermal expansion for silicon is much smaller than that of copper, so the joints between the interconnects and the cells must be designed to minimize stress on the solder bonds. The solder bonds joining cells to copper heat spreaders (if used) or other substrates must also be designed carefully to minimize the effect of differences in coefficients of thermal expansion.

If a metal housing is used with a plastic lens (as is frequently done), the difference in coefficient of thermal expansion between the metal and plastic must be accounted for in the design of the lens seal. If the seal is too weak, it will not survive thermal cycling. If the seal is too rigid, it will not allow relative movement between the lens and housing, and the lens will buckle.

Other types of failures are less frequently encountered, but are worth mentioning. The materials in the module must be able to withstand long-term ultraviolet (UV) light exposure. Some recent module tests have resulted in degraded or cracked lens seals, material embrittlement, and discoloration of glass secondary optical elements. The discolored glass secondaries ultimately cracked when they became dark enough to absorb significant amounts of light. Off-track concentrated sunlight can char materials (such as encapsulants or polymeric insulation) if the module is not properly designed. Improper design also occasionally results in lenses being pulled out of modules by high winds and failures due to hot-spot heating. And finally, no discussion of concentrator failure modes is complete without mentioning the importance of quality control during manufacture.

Current Issues in the Qualification of Concentrator Modules

Sandia has developed and published qualification specifications for PV concentrator modules [7,8]. The purpose of the tests is to screen new designs and new production runs for susceptibility to known failure mechanisms; however, there is insufficient information correlating accelerated testing with field exposure to establish field lifetimes. The tests include ultraviolet radiation testing of materials, characterization of electrical performance, checks to assure safety and structural integrity of modules, and accelerated environmental aging or cycling. They are modelled after the Jet Propulsion Laboratories (JPL) Block V qualification specifications for flat plate modules [9]. In addition to testing complete modules, separate tests are conducted on cell assemblies and receiver sections because the receivers experience a more severe environment than the rest of the module.

The specifications are currently being revised to incorporate the latest information on failure mechanisms and the relationships between accelerated tests and field reliability. The major changes include an increase in the number of thermal cycles required for receiver assemblies and the addition of a wet insulation-resistance test.

The most critical components of a PV concentrator module are the cell assemblies. The cell assemblies, or receivers, collect the light transmitted by the module optics and convert it to electricity. Degradation of the cell assembly, in particular degraded or broken solder bonds, causes a corresponding decrease in electrical output as the resistance in the circuit increases. Complete breakdown of the cell assembly can result in loss of the solar cell altogether. Poorly designed cell assemblies can damage or break the cells.

In addition to being critical to module output, cell assemblies also see the most severe environment of any module component. Since the cell assemblies are exposed to concentrated sunlight, they undergo considerable thermal cycling as the sun rises and sets and the temperature of the assemblies changes from night-time ambient to 60°C or more. Thirty years encompass nearly 11,000 daily cycles. Intermittent clouds add additional thermal cycles.

Because cell assemblies are so crucial to module output and because they see the most severe environment, qualification of PV cell assemblies receives considerable attention in Sandia's reliability work. Tremendous progress has been made in this area: five years ago very few cell assemblies survived the accelerated 250-cycle qualification test; now most survive 1000 cycles. Our understanding of the correlation between field life and accelerated testing has also improved [10,11]. Accordingly, the revised qualification specifications will require survival of a minimum of 800 accelerated thermal cycles for cell assemblies and receiver sections; the current specifications require only 250 cycles. The cycling frequency may also be decreased, but this requirement must be balanced against the need to complete the test in a reasonable amount of time.

Testing in the field and in environmental chambers has established that moisture intrusion, especially condensation, must be addressed in the qualification of PV concentrator modules. This is important both for reliability and for personnel safety. Under contract to Sandia, JPL is developing a trial-use procedure for a wet insulation-resistance test. The test will be performed at 500 Vdc in each polarity. The interior surfaces of the module will be sprayed with water that contains a wetting agent, and the insulation resistance between the cell string and ground (or other appropriate locations) will be measured with a suitable high-impedance ohmmeter. This requirement may allow only one polarity (the circuit or ground) to be exposed inside a module and could have a significant impact on future concentrator module designs. The latest concentrator modules are already being designed to pass this test [12].

A number of other less consequential changes to the qualification specifications are also being considered, such as increasing the number of modules required for testing, adjusting the allowable degradation levels, adjusting thermal cycling temperatures and frequencies for complete modules, and specifying tests for optical components, terminal robustness, and bypass diodes.

Summary

Despite the reliability concerns discussed above, all of the problems can be solved with proper design, manufacturing, and quality control; none of the problems require technical breakthroughs for solution. The reliability issues for concentrators are comparable in nature to many issues of concern in other PV technologies. Concentrator cell technology has proven to be very reliable, with no degradation in cell outputs observed in fielded modules.

In certain climates, concentrators still offer potential for producing PV-generated electricity at lower cost per kWh than flat-plate modules [13,14]. Concentrator modules use much less cell material than other PV options and do not require extremely sophisticated production facilities, making their production attractive to developing areas of the world. Most concentrator modules require two-axis tracking and accept only the direct-normal component of the incident sunlight, but these factors are offset by module efficiencies that are generally higher than those of other PV technologies.

The references below give more comprehensive discussions of the topics addressed in this paper. In addition to the references called out in the text, some papers on cell assembly design and quality control for concentrator module manufacturers are also included [15,16,17].

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