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Closing the loop: using production testing and field failure analysis to build high-reliability solar panels

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ABSTRACT

Savvy solar panel manufacturers understand that wringing excess costs from every stage of the value chain is simply the price of admission to today's crowded market. They also know that reliability and quality are not only critical for delivering on a 25-year warranty promise, but also drive the true cost of energy over the lifetime of the system. This factor is becoming increasingly apparent, especially in industrial- and utility-scale solar projects, as they age and the power output of many lower quality systems begins to degrade to unexpected levels. Many of those systems used UL or IEC certifications as a proxy for good reliability. Unfortunately, UL and IEC certifications are primarily concerned with user safety, and are not rigorous enough to ensure trouble-free operation throughout the system lifetime. High reliability and quality require testing and manufacturing methods that go far beyond the certification tests.

Introduction

This article encapsulates what SunPower has learned from six years of producing silicon solar panels and from over a decade of fielding and maintaining systems with solar panels from more than a dozen different manufacturers in rooftop systems and solar farms. The closed-loop learning system described allows a manufacturer to turn the data collected from field failure analysis and each stage of testing into actionable information for improving both its panel design and manufacturing processes.

The closed-loop learning methodology

Today's solar panels are complex assemblies of metal, glass, plastic, semiconductors and adhesives that must deliver a 25-year warranty life (and usually a 30- to 40-year useful service life) in harsh rooftop environments, a task which can challenge even simple asphalt roofing materials. Building photovoltaic panels to this level of reliability requires a disciplined approach to taming the numerous subtle and not-so-subtle failure modes which arise from the thermal, mechanical, chemical, solar and electrical interactions that occur during their exposure to the elements.

The manufacturing environment is another complex factor in the reliability equation. Even subtle changes in a design or its materials and manufacturing processes can produce big changes in the end-product's reliability. In order to capture and correlate these changes with their effects on reliability, a rigorous quality control methodology has been developed that closely couples the design and supply chain management processes with qualification and production testing. In addition, a closed-loop learning process has been implemented that enhances traditional design and manufacturing quality control methodologies with a feedback loop that uses real-world data to constantly retune the quality cycle.

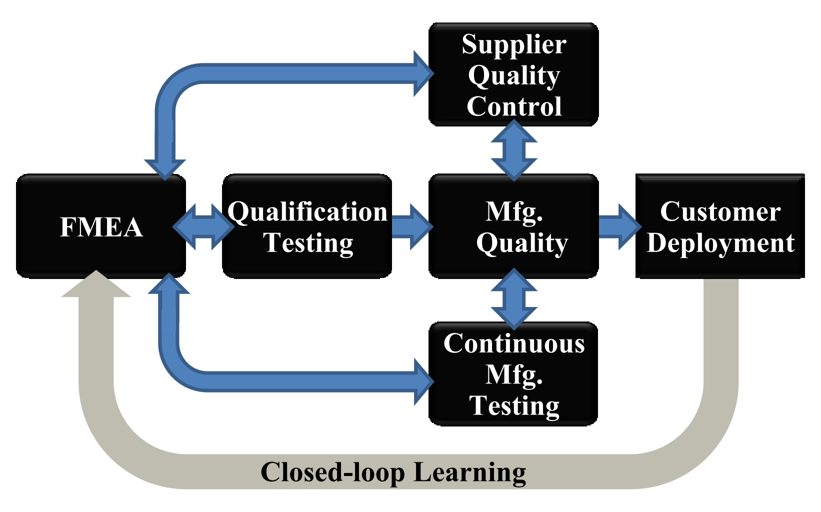


Figure 1. Adding closed-loop learning to the traditional quality control methodology.

The FMEA block

As with most modern QC systems, SunPower's process is built around a failure modes and effects analysis (FMEA) element, illustrated in Fig. 1. FMEA's function is to provide a rank-ordered list of all the known failure modes and their causal stresses that are the foundation of the design for reliability process. It also provides inputs for the qualification tests which will determine if the design of a new product or a product or process modification meets the functional and reliability requirements.

In a traditional FMEA, the failure mode list uses theoretical modeling and design test data (accelerated life and long-term testing) as its primary inputs. Closed-loop learning adds information that includes performance data and failure analysis results collected from operational customer sites. As will be discussed later, this long-term field data provide a critical feedback loop to further improve overall quality.

Constructing the FMEA

Specifications and functional requirements

In order to build an FMEA, one must start with a design concept, as well as a set of clearly articulated functional and reliability specifications. The latter lists all the functions that the product must deliver. For example, the defining functional requirements for a PV module backsheet might include the following:

- The design must provide electrical isolation between the back of the module and solar cells at 1000V.

Functional Requirement	Failure Mode	Effects of failure	Severity	Causes / Mechanisms of failure	Occurrence	Current design: Prevent / Detect	Detectability	RPN
Electrical isolation	J-box detaches from backsheet	Loss in power, increased leakage current, safety issue	10	RTV loses adhesion to backsheet due to surface properties	2	Test j-box and backsheet interlayer adhesion under hot-spot condition on cell on top of j-box with and without weights; test j-box and backsheet adhesion in high-temp and humidity environments	2	40
	Dielectric degradation	Leakage current, safety issue	10	Hot-spot creates burns on backsheet (insufficient temp resistance)	2	Heat soak at various temperatures to determine activation energy	2	40
				Moisture degrades insulating layer (hydrolytic embrittlement)	3	Damp heat testing; check for cracks and increased wet leakage current	1	30
				Growth of pinholes or increased conduction through pinholes	1	Wet leakage current test and optical inspection of backsheet surface as laminated, and post accelerated tests (e.g. DH, HF, TC)	1	10
				Acetic acid from EVA attacks backsheet	1	Test for various acid resistance of backsheet layers	1	10
	Dielectric separation (backsheet layers separate)	Leakage current, safety issue	10	Propagation of slit inside j-box where ribbons exit	2	DH2000, TC200	1	20
				Internal physical puncture	4	Wet leakage current test post various accelerated tests	1	40
				UV attacks individual layers or adhesives	1	Wet leakage current test post UV exposure (equivalent dose for 25 years)	1	10
				Bubbles, loss of interlayer adhesion	5	High-temperature test with and without hanging weight	1	50
Reflectivity	Colour changes	Power loss	3	UV attacks individual layers	3	UV exposure, Combined UV/DH exposure, outdoor exposure	2	18

Table 1. Excerpt of backsheet FMEA.

- The design must reflect more than 80% of irradiance incident on the cell-side surface.
- The design must shrink less than 0.5% during the lamination process along any dimension.

The FMEA also includes reliability specifications, a subset of the functional specifications, with detailed reliability requirements. Continuing with the backsheet example, some typical reliability requirements might include these prerequisites:

- The design must maintain a continuous electrical barrier (no cracks) with 99% likelihood after 25 years in each climate with cells that are at 1000V.
- The design must not bubble or delaminate with 99% likelihood after 25 years in each climate with cells that are at or below 110°C during times of peak irradiance.

It should be noted that the FMEA's effectiveness depends on a clearly defined design concept that allows the requirements to be assessed against a concrete product design. For example, acquiring a good understanding of the interlayer adhesion performance of a backsheet, for example, requires a design that includes precise specifications of the materials, processes and adhesives used to build it.

Once the design and its attendant list of specifications are complete, the FMEA can be developed. Using these inputs, a group of subject matter experts brainstorms to create a prioritized list of all the possible ways a product might fail. This process is captured on a FMEA chart, as illustrated in the excerpt shown in Table 1 that deals with the electrical isolation requirements for the example backsheet that was discussed earlier.

A scoring system is used to create the prioritized list using the following criteria:

- The severity is the economic and safety impact when the failure does occur.
- The frequency is chance that the failure actually occurs.
- The detectability is the chance that the failure mode can be averted by detection and prevention before it reaches the customer (where a low score means high detectability).

The product of these values constitutes the risk priority number (RPN), which is used to prioritize what must be tested to qualify the product.

To enable a thorough qualification test plan (QTP), the FMEA must have thorough coverage over the possible field failure mechanisms and the combinations of stresses that cause them. The three primary approaches used by the subject matter experts are discussed in the following three sections: field experience, highly accelerated life testing, and theoretical understanding.

Figure 2. Front-contact-cell modules after a multistress simulator test. Solder flux residue along the interconnect ribbon caused delamination bubbles (left), while lay-up tape outgassing caused backsheet bubbling (right).

Field experience

Field experience is a critical element for identifying real design failure modes [1]. Historic failure data are used to set the initial conditions of the FMEA. To be most effective, an analysis must be performed on each type of field failure to determine what combination of stresses caused the failure, so a test can be devised to ensure the new product does not have the same weaknesses. Once in production, the closed-loop learning methodology uses new data from field failures of the current product to adjust the FMEA's risk priorities.

Test data inputs to FMEA – HALT

The second primary input for defining the FMEA is highly accelerated life testing (HALT), which applies combinations of stresses that are related to those seen in field deployment, but considerably beyond the levels anticipated in a normal operating environment. It is not a pass/fail test, but rather a test designed to activate the same failure modes one would encounter after many years in the field, in just a few days or weeks. HALT is a remarkably effective way to reveal unanticipated failure modes, and thus to identify and mend any weak points in the product design.

A useful example of HALT can be found in the regimen used to qualify other manufacturers' modules for deployment in projects installed by SunPower. This is necessary because the company builds more projects than it can supply with its own back-contact cells, necessitating the use of modules from different manufacturers. HALT and long-term testing both play essential roles in qualifying these modules.

The HALT regimen cited in this paper consists of several mechanical, thermal, and electrical stress sequences:

A five-day exposure in a multistress simulator. The modules under test are placed in a short-circuit configuration and exposed to a 1000W/m^2 of solar spectrum and an additional 150W/m^2 UV spectrum. The exposure is conducted in a controlled environment at 60°C and 55% relative humidity. These tests are especially effective at uncovering any meltdown or discolouration of encapsulants, browning or bubbling in backsheets, adhesive breakdown, and delamination along the front interconnect ribbons [2].

Adding some margin beyond what is strictly necessary often produces a design that is more cost-effective because it is more tolerant of contamination and other process issues. In addition, a robust design's wider tolerances in deviations from target processes are more easily detected before they result in field failure. Multistress

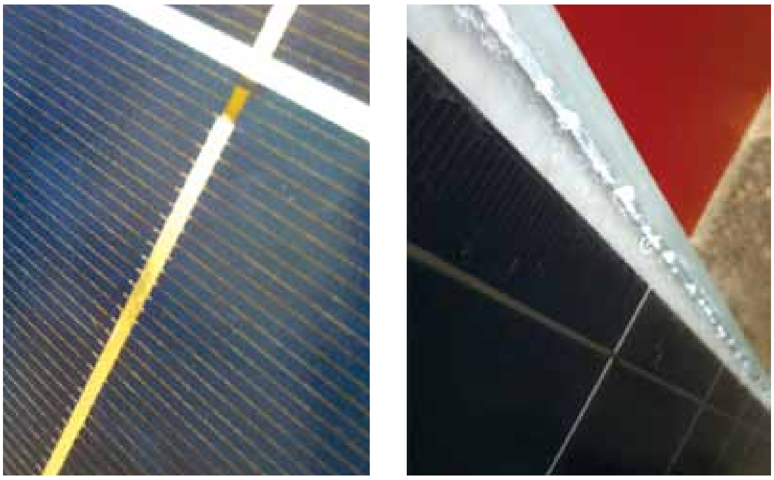


Figure 3. Following 600 hours of damp heat with voltage bias for front-contact-cell modules, corrosion can be seen on the front-contact metal (left). The right-hand picture shows the view looking down the edge of the aluminium frame that surrounds the laminate glass.

simulation testing created the front delamination on the cell shown in Fig. 2, a condition which may be due to solder flux residue. This indicates a manufacturing process control problem or a material compatibility problem and must be solved.

A five-day oven test. In some cases, this is used as an easier and lower-cost test that stimulates similar delamination and bubbling defects as the multistress simulator.

A 600-hour exposure to damp heat and electrical bias. The modules are placed in an 85°C environment at 85% relative humidity with a 1000V bias placed between the cells and the grounded frame. Because the high bias voltage accelerates any electrochemical corrosion or migration effects, this test is excellent for uncovering aging phenomena such as series resistance increases caused by electrolytic corrosion of metal lines or degradation of the Si-metal interface. For example, the corrosion visible on the metal of front-contact cells in Fig. 3 is responsible for causing an increase in series resistance and a decrease in efficiency. The cells' back-contact system appears to be significantly more resistant to electrolytic corrosion because most of the cell's back surface is plated with 40µm-thick copper finger conductors that have a much larger cross-sectional area.

Dynamic load testing combined with temperature cycling. Company protocol calls for 1,000 alternating cycles of mechanical pressure on each surface at ±2400Pa to simulate standard wind load, followed by four temperature cycles between -40°C and 60°C. This is very effective for investigating cell cracking [4], and the interconnect-ribbon-to-silicon wafer solder bond's ability to withstand repeated mechanical stress [5]. For front-contact cells, the copper interconnect ribbons must be soldered onto the silicon wafer at elevated temperatures. Under these conditions, the coefficient of thermal expansion mismatch between the copper and the silicon causes thermal stresses to accumulate at the interface. If not created with well-controlled processes and materials, the solder bond can be too strong, causing a phenomenon known as 'cratering,' where small cracks form in the cell underneath the ribbon or the structure becomes too weak, a condition that causes the ribbon to tear off the cell.

Sample	Tests
Backsheet sample: 6" × 6"	Moisture vapour transmission rate
	Partial discharge
	Outgassing post heat soak
	Surface morphology analysis (initial and post HF10)
	Shrinkage (at lamination conditions and during accelerated tests)
	Interlayer adhesion (as received, post lamination and HF10)
	UV exposure
Three-cell laminated coupons	Adhesion tests (to encapsulant, interlayers; j-box, labels, framing materials)
	ACL168
	UV
	HF40
	DH2000
	TC200
	Sequence B (UV/TC50/HF10)
	HF/UV combination
	Cut test (pre- and post-HF, checking for crack formation)
	High-temperature voltage stability
	Field tests
	Chemical resistance (various chemicals found in environment)
Full modules	High-temperature heat soak (check for out-gassing due to interaction with other module components)
	J-box with weights tests for creep
	HALT (see Table 2)
	HF40
	DH2000
	TC200
	Field test (in various environments, and some with additional weights on j-box)

Table 2. Backsheet qualification criteria.

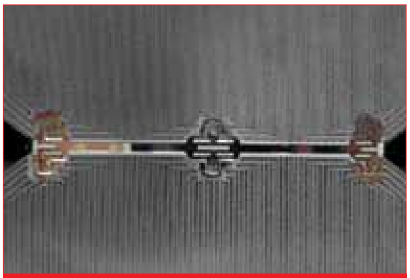


Figure 4. A strain-relieved cell interconnect between two back-contact cells. The three solder bonds on each cell, combined with the plated copper connections between those bonds on the cell, create redundancy.

Theoretical inputs to FMEA

The final element of a thorough FMEA is a sound theoretical understanding of the product's potential failure mechanisms. This is especially critical for capturing slow-moving failure modes, which may not show up in the field for many years and may not even be encountered during HALT. The only way to capture these failure modes is with lab testing, in order to understand the physics of the breakdown, guided by theoretical modelling.

Good examples of critically important but slow-moving failure modes that are best understood using theoretical analysis occur in the metal interconnect and solder bonds between cells in a module. Fatigue-induced interconnect failures have proven to be one of the two most frequent field failure modes for traditional front-contact-cell modules, information that was used to design the interconnect structure for back-contact cells in 2004. The original design included an in-plane strain relief scheme, which initial validation tests indicated would survive 10,000 mechanical cycles and 20 thermal cycles with no failures and a power degradation of less than 3%.

However, subsequent testing revealed that solder bond failure could occur in extended thermal cycling, leading to a loss in fill-factor of ~8% at ~500 cycles. The failure mechanism was found to be cracking, which resulted from heterogeneous coarsening of the solder microstructure.

As a result, the interconnect was redesigned to reduce stress on the solder bonds by increasing the compliance of the interconnect, and work was done to model the failure mechanism.

Production processes were altered to use a higher compliance interconnect (as shown in Fig. 4) and an SnAg solder after testing showed that the combination cut the fill-factor loss to < 2% in 700 thermal cycles [6]. Additional information was then sought to quantify the acceleration factors of the solder joints to be able to predict product life [7,8]. Subsequent testing revealed that there were zero failed joints in 2,300 thermal cycles, significantly more than required for 25 years in a harsh climate.

Qualification testing

Once a solid FMEA is completed, a product test plan is developed. For example, the first line of the backsheet FMEA concerns possible detachment of the junction-box from the backsheet caused by a loss of adhesion of the RTV or backsheet interlayer adhesion. Since its RPN number is high enough to cause concern, a test must be derived to determine whether the product meets the specifications, which involves building a series of modules and coupons that have junction-boxes attached to backsheets with RTV. These are put into field testing with the cells above the j-boxes shaded to induce operating temperatures from hot cells.

These qualification tests can be pass/fail if the relevant acceleration factors are known, or they can require an equivalent or better performance compared to a known high-reliability baseline. In most cases, the tests are extended to produce failures with the aim of learning how this happens.

Long-term testing

Certification-type tests can form the basis for long-term testing, simply by extending the tests to when failure happens. Fig. 5 shows SunPower modules in the extended length versions of the standard certification tests and indicates no runaway failure modes, only slow degradation as a result of the accumulated stresses. Note that these tests are similar to HALT, but the stresses are gentler. For qualification tests to produce meaningful results, it is necessary to run them until failures occur. These extended tests are also repeated periodically as part of the ongoing reliability testing (ORT) for manufacturing.

Field testing

Field testing should always be started immediately and carried out simultaneously in different climates (hot and humid, hot and dry, temperate, urban, rural, coastal, etc.) on full-size modules. These deployments must be monitored and visited regularly to look for any new developments since any significant problem means the product has serious flaws.

An example that highlights of the value of field testing occurred during a failed qualification attempt for a new encapsulant. Coupon-size prototypes had shown no problems in lab tests, so full-sized modules using the same materials were put through field testing for prolonged exposure to various climates. The field tests were the first to show delamination at the encapsulant/glass interface. These defects did not occur during coupon testing, although they also did occur subsequently in damp-heat testing of full-size modules.

This particular example underscores that certification tests are not generally sufficient for qualifying a product design because they are only designed to indicate a reasonable level of initial product quality and safety, and are not meant to indicate product lifetime [9]. Almost all commercial modules that have experienced problems in the field were designs which passed certification testing.

Supplier quality

In order for a product based on a qualified design to perform in a predictable, reliable manner, its input materials must be well-specified and held within those

specifications continuously. To accomplish this, supplier qualification and supplier continuous monitoring programs have been employed, which are defined in four stages:

- Stage 1 is internal to the company, in which requirements are clarified and a sourcing strategy is determined. Key requirements are part of the output of the qualification process.
- Stage 2 involves contacting likely suppliers, setting expectations, and developing joint plans.
- Stage 3 is where the primary suppliers go through a 'PSC audit' to evaluate how they are doing along the three most important dimensions:
  - Prevention: extent of employee training, usage of statistical process control, FMEAs, and a formal corrective and preventive actions (CAPA) methodology, as well as their own reliability and supplier quality programs.
  - Standardized/simplified/scalable: evaluation of business processes to make sure they are of high quality, with the change notification process of particular importance.
  - Customer satisfaction: customer surveys, responsiveness to customer issues, etc.
- Stage 4 builds a strong partnership to deliver high-quality products at a large scale. Regular self-assessments with periodic reviews and validation as well as improvement plans are implemented. Such rigor is absolutely necessary for ensuring a consistently high-quality product.

This testing is generally accomplished with a mix of vendor tests (with shared reports) and periodic inspections of incoming material. Table 3 shows a partial list of the incoming materials testing done as part of a regular sampling program. It is critically important to require that absolutely no formulation or design changes be made to the qualified components without requalification.

Material	Measurement
Encapsulant	Gel test, pull test, temperature soak test
Backsheet	Peel test, temperature soak test
Diodes	Leakage current test
Connectors	Production test (wiring fitness, crimping, pull test)
Frame	Mechanical load test, frame pull test
Label	Tape test, IPA test

Table 3. Examples of incoming materials audits.

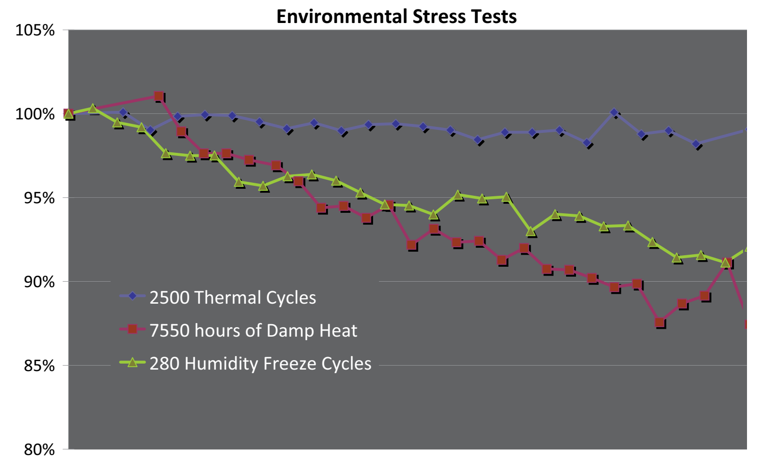


Figure 5. Extended testing of power output for back-contact-cell modules, which pass insulation resistance testing after more than 7× the certification standard in DH, 12× in TC, and 28× in HF.

Separate qualification of each of a vendor's different manufacturing sites is a subtle but critical issue, even when the component being purchased is the same part number. In one instance, a backsheet supplier was bringing up a new manufacturing facility, and the material produced during small pilot runs passed accelerated testing results that exceeded the IEC61215 testing requirements [10] and also passed the customer's internal qualification. This changed when the supplier ramped up to full production, and incoming inspection tests showed the backsheets from the new facility displayed weaker interlayer adhesion than the material received during the qualification testing. This revealed an inconsistency in material quality from the new facility that the supplier then corrected.

Manufacturing quality

The quality system

Consistent manufacturing is an essential part of achieving and maintaining the quality necessary to meet the reliability requirements of PV cells and modules. SPC, total quality management, and six sigma are among the general systems which can help attain and maintain quality in manufacturing. All these methodologies emphasize one main point: quality must be built into the product and cannot be audited into the product.

Since most PV modules must meet the 25-year warranty period as a baseline requirement, minimizing problems that might remain hidden for a decade or more is also essential. This is why SunPower borrowed heavily from the rigorous manufacturing quality procedures developed by the semiconductor industry. The original system was based heavily on the methodology used by Cypress Semiconductor (the majority investor in the company from 2002 to 2008) and later refined to better match the requirements of photovoltaic manufacturing. The key elements of the system include systematized business processes for all developments and changes; coordinated product, process, and equipment development procedures with six levels of control; quality and continuous improvement mentality; and variability and waste reduction.

Quality audits

The quality audit is an important part of achieving and maintaining the consistent manufacture of a high-reliability product. This is most effective if done by people who are outside of a manufacturing unit, such as those working in an independent quality organization.

An audit of workers' adherence to the manufacturing specifications serves both to

Figure 6. Fielded modules with silicone contamination on glass surface show four stripes.

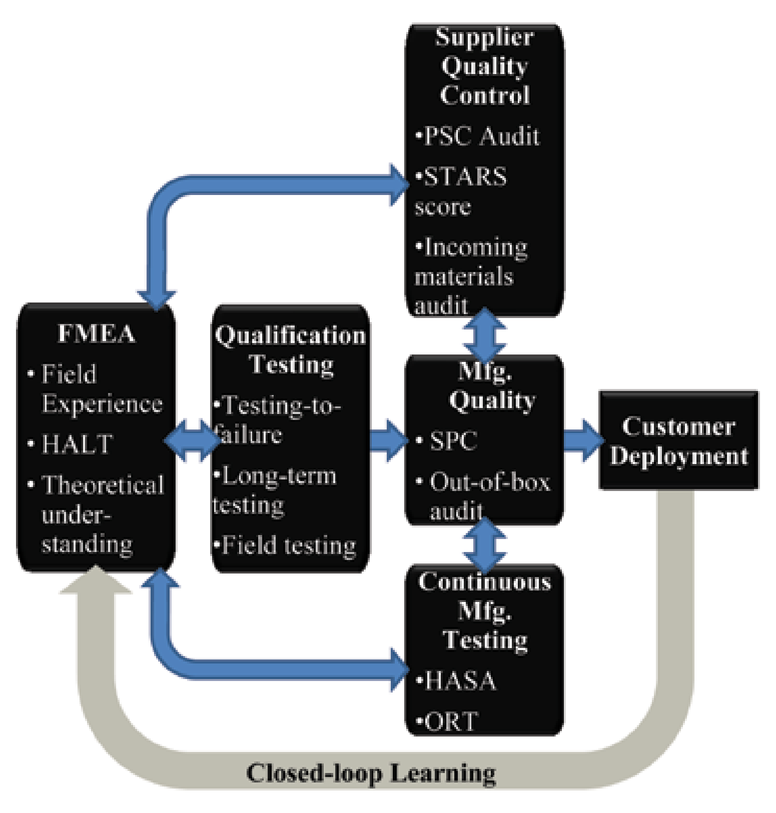


Figure 7. The primary methodologies discussed in each process area.

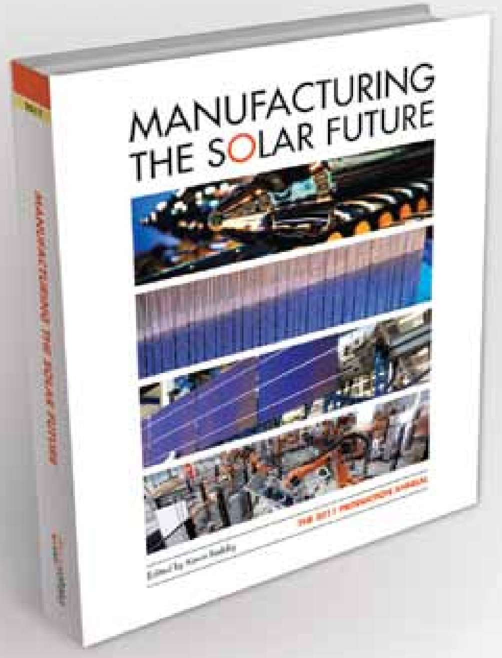
instil the proper mentality on the line and to catch breeches. The mentality must be to follow the specifications to the letter, or else to change the specifications with any proposed specification change handled only through the structured business process.

As part of the quality audit, an 'out-of-box audit' needs to be regularly performed, using a random sampling of products that have been packed for shipment. In addition to the quality of the packaging, documentation, product cleanliness, and visual defects, the audit compares the panel's actual electrical performance with performance recorded during manufacturing tests.

Continuous manufacturing reliability testing

Continuous testing ensures that the quality of the product does not change over time. The testing plan derives directly from the (regularly updated) FMEA and falls into two categories:

- A highly accelerated stress audit (HASA) detects any material defects or manufacturing problems that have escaped the supplier quality and manufacturing SPC hurdles. The HASA tests exercise important degradation mechanisms determined from the earlier steps in the product design process (HALT, historical data, theoretical understanding, and FMEAs from the product design and the process designs). They must have a fast turnaround time and be well-structured with clear pass/fail criteria that non-experts can interpret.
- An ongoing reliability testing (ORT) continues to validate the baseline



reliability of the product. These tests are longer with lower stresses, smaller sampling sizes, and provide a general indication that the baseline reliability of the product is not changing.

Closed-loop learning from the field

When used properly, field failures provide invaluable information about the causal stresses a product encounters and how it degrades under real-world conditions. A thorough and thoughtful failure analysis provides critical feedback that can be used to strengthen the FMEA and associated testing of future products. The following incidents illustrate a few of the failure modes caught during field tests that helped improve the test plans currently in use.

An episode involving glass-surface contamination shows how a seemingly insignificant change in manufacturing process can have a surprising effect. For a short period in 2007, a modification was made to the cooling racks for modules coming out of the laminator that used a different insulating cloth to protect the hot modules from being scratched while they cooled. This new cloth, however, turned out to contain silicone oil, which gave the glass a different contact angle with water. While undetected in the factory, it created uneven soiling under field conditions. This problem was discovered fairly quickly but it required significant investment in a nine-step cerium oxide cleaning process to clean all modules deployed at customer installations to the proper specification.

This incident shows the value of fully vetting every process change. Instead of the isopropyl alcohol used in earlier tests, an outgoing water spray inspection for non-washable stains is used, which mimics panel washing practices deployed in the field. Additionally, all manufacturing accessories that have any physical contact with modules are included in the list of materials to be controlled as part of production.

A final problem illustrates how the same closed-loop process uses information from final testing to generate new standard test plans and update FMEAs. In 2009, a new wire/connector pair was undergoing its final qualification test when the humidity-freeze cycling sequence revealed a wet insulation resistance failure. This was traced to a sizing mismatch between the cable and connector that resulted in a broken sealing ring in the connector. Although the original problem was caught and corrected before any products reached the field, it resulted in a continued investigation which revealed that even dimensionally compatible cables are subject to failures. These discoveries led to a new qualification test to compare lifetimes of a population of cable/connector pairs with cycles of humidity-freeze.

Conclusion

A complete design-for-reliability process illustrates a methodology for producing solar modules that meet the dual challenges of the industry-standard 25-year warranty and a highly price-sensitive market. The methodology incorporates QA processes that bridge organizational boundaries and multiple information feedback paths to help it cope with the rapid materials and process changes common to modern manufacturing operations.

As shown in Fig. 7, the FMEA uses inputs from field experience, HALT, and theoretical understanding to generate the criteria for the thorough qualification testing needed to deliver a high-reliability product design. Subsequent feedback from qualification testing, production testing, and supplier quality control testing identify new potential failure modes for possible inclusion in the FMEA and to reweight existing ones.

As part of an ongoing commitment to quality, a closed-loop learning process has been added that channels information from field failures in customer deployments back into the FMEA. The inclusion of closed-loop learning in the quality cycle gives the manufacturing process it supports more intelligence and adaptability to the inevitable changes in design, process, and supply chain, allowing the capability to deliver products that go beyond basic certification to meet or exceed today's stringent reliability requirements in a consistent and cost-effective manner.

Acknowledgment

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