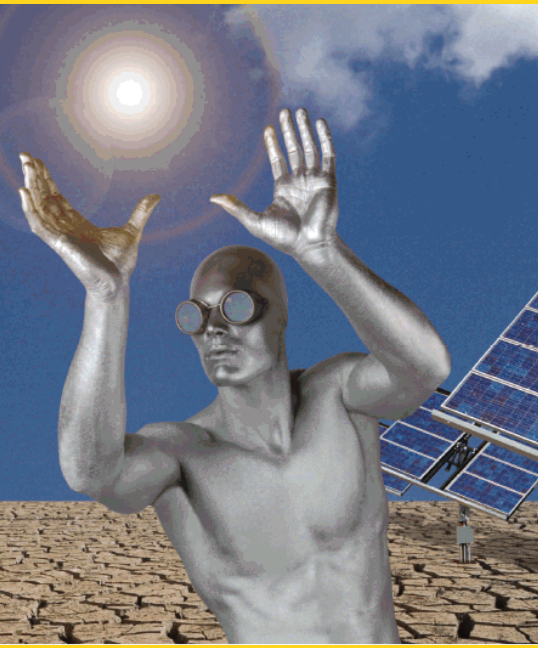
White Paper



Photovoltaic Module Weather Durability & Reliability

Will my module last outdoors?

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Executive Summary

The Issue

Most manufacturers of solar modules guarantee the minimum performance of their modules for 20 to 25 years, and 30 year warranties have been introduced. The warranty typically guarantees that the modules will perform to at least 90% capacity in the first ten years and to at least 80% in the remaining 15 years. Even though the hardware warranty may be shorter, the economics are based on the longer term.

Under most general accounting practices, manufacturers are obliged to set up reserves for the expected volume of claims under the performance warranties. The result is that the capital tied up in the reserves is no longer available for investment. However, reserves mostly cover only some of the liabilities that arise in the event of a loss – serial losses often affect several production years. A single serial loss could be sufficient to threaten a module manufacturer's existence and market position.

The Problem

Early life failures resulting from design flaws, materials or processing issues are often apparent during the first few years in service. The requisite design qualification and approval tests such as IEC 61215 for crystalline silicon and IEC 61646 for thin films are relatively short accelerated tests which attempt to discover these early "infant mortality" issues. Safety tests, such as UL 1703/IEC 61730, are performed only on new modules and tell little about safety performance after long-term field exposure.

More importantly, many module failures and performance losses are the result of gradual accumulated damage resulting from long-term outdoor exposure in harsh environments, referred to as "*weathering*". Many of these processes occur on relatively long time scales and the various degradation processes may be chemical, electrochemical, thermal or mechanical in nature. These are initiated or accelerated by the combined stresses of the service environment, in particular solar radiation, temperature and moisture, and other stresses such as salt air.

Current Practice

Weatherability testing has been successfully relied upon by industries such as automotive, building products, polymers, paints and protective coatings for over 90 years. Much has been learned about materials degradation and proper accelerated weathering approaches in that time. Weathering tests for longer term degradation are very different from the "infant mortality" stress tests that are used in the IEC standards, even when run for longer periods of time.

The Atlas Solution

Atlas, the recognized global leader in weatherability testing, has developed **Atlas 25^PLUS^**, a comprehensive, multi-dimensional, environmental weatherability program for PV modules. A complement to the IEC "infant mortality" tests, this one-year program delivers the weathering stresses representative of long-term outdoor exposure otherwise unattainable without lengthy real-time testing. Independent 3rd party data from **Atlas 25^PLUS^** supports your product R&D and cost reduction efforts, supports your warranty and performance claims, and provides validation to financial stakeholders at all levels.

Business Challenge

Importance of PV Module Economic Performance

Apart from government financial credits and incentives, the economics of photovoltaic (PV) systems of all sizes is based on their reliability to deliver the rated power over their expected service lifetime. Financial penalties result when modules prematurely fail during the hardware repair or replace limited warranty period (typically 1 – 10 years), when unanticipated service or maintenance is required, or when power delivery falls to unacceptable levels. Today, this performance warranty is frequently >90% of rated power after 10 years and >80% after 20 or 25 years although 30 year guarantees have now appeared with 40 years being anticipated soon.

The real issue then becomes, how can we guarantee 20 or more years when most current module designs and technologies have only a few years or less of field history? What predictive tools are available and what is our confidence in them? The answer has major implications for all financial stakeholders: venture capital for new product R&D; OEM warranty set-aside reserves; bank financing of PV systems; system insurers; and end users/system owners.

How can we guarantee 20 or more years when most current module designs and technologies have only a few years or less of field history?

The Need for Accelerated Tests

John H. Wohlgemuth of BP Solar describes the fundamental problem:

"Outdoor testing is a must, but it takes much too long to be of much use as a decision maker. We clearly can not wait 25 years or even a significant fraction of 25 years to introduce a new product. Therefore, we must develop and utilize accelerated tests to qualify these new products."[1]

Akira Terao, Chief Reliability Engineer for Sunpower Corporation goes further to identify some of the life-testing roadblocks:[2]

- 25 year warranty
- Ill-defined field conditions
- Harsh and varied outdoor conditions
- Materials used near their limits
- Limited acceleration factors ⇒ long tests
- Large samples, small sample sizes
- Subtle polymer chemistry
- Cumulative effects, positive feedback loops

Clearly, assessing PV module lifetime performance is not a simple task.

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[1] John H. Wohlegemuth, *et al*, "Long Term Reliability of Photovoltaic Modules", 23rd EU PVSEC Conference, 2008

[2] Akira Terao, "Modules: Remaining Reliability Challenges", Accelerated Aging and Reliaibility in PV Workshop, 2008

What Is Known?

PV Module Reliability and Durability Concerns

If a module fails to generate power it is an obvious failure and a reliability issue. However, environmental degradation such as corrosion can cause a gradual decrease in power output which is a durability issue (or more precisely, a lack of durability). Durability issues may also eventually lead to module failure.

Dr. Sarah Kurtz of the U.S. Department of Energy's National Renewable Energy (NREL) PV module reliability group maintains an on-line living document of known reliability/degradation issues for PV modules. "General reliability issues across all PV technologies are:

1. Corrosion leading to a loss of grounding
2. Quick connector reliability
3. Improper insulation leading to loss of grounding
4. Delamination
5. Glass fracture
6. Bypass diode failure
7. Moisture ingress
8. Inverter reliability"

"In addition there are issues specific to the individual technologies, to name a few:

I. **Wafer silicon:** Light-induced cell degradation, front surface soiling, effect of glass on encapsulation performance, reduced adhesion leading to corrosion and/or delamination, busbar adhesion degradation, junction box failure

II. **Thin Film Silicon:** Electrochemical corrosion of SNO_2, initial light degradation

III. **CdTe: I**nterlayer adhesion and delamination, electrochemical corrosion of SnO_2:F, shunt hot spots at scribe lines before and after stress

IV. **CIS:** Interlayer adhesion, busbar mechanical adhesion and electrical [integrity], notable sensitivity of TCO [transparent conducting oxide] to moisture, moisture ingress failure of package

V. **OPV:** Photolytic instability, moisture induced degradation, moisture ingress failure of package"[3]

The majority of these issues is either directly caused or influenced by outdoor in-service environmental exposure

The majority of these issues is either directly caused or influenced by outdoor in-service environmental exposure; therefore the need to accelerate and study the effects of weather and climate on PV durability and reliability is crucial.

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[3] Dr. Sarah Kurtz, National Renewable Energy Laboratory, "Reliability Concerns Associated With PV Modules ", www.nrel.gov/pv/performance_reliability/pdfs/failure_references.pdf.

Reliability & Durability

Reliability Engineering in Photovoltaics

Reliability engineering is a structured discipline which concerns itself primarily with absolute, discrete failures, their detection and statistical measurement such as Mean Time To Failure (MTTF), Mean Time Between Failures (MTBF), number of failures per ***n*** number of units and similar measurements. The methodology requires statistically high numbers of samples, preferably from production lots. Therefore, statistical methods cannot be used on limited R&D prototypes.

Testing techniques such as highly accelerated life testing (HALT) are widely employed in reliability (failure) analysis by PV manufacturers and other industries. Gregg K. Hobbs, the inventor of HALT and HASS (highly accelerated stress screening), points out several key limitations of HALT which are often understood:[4]

- HALT does not attempt to simulate the field environment - only seeks to find design and process flaws by any means possible.
- Intent is to determine failure modes, NOT demonstrate that a product meets specified requirements.
- Not meant to determine reliability but to improve it.
- Test environments are not directly related to real life and may be controversial.
- Time-dependent failure modes may not be revealed.
- Difficult to do on complex structures because of complex loading – FMVT (failure mode verification testing).

Another critical aspect of HALT testing is that correlation does not prove causation. In other words, just because you obtain a result (change or failure) in a HALT test that seems to match that from the real time field use doesn't prove it was caused by the same mechanisms. Cause and effect must be proven.

Further, HALT testing works best for accelerating physical degradation modes and may be incapable of accelerating chemistry-induced degradation.

Durability testing on the other hand, when applied to studying the degrading influences of outdoor environmental stresses (known as ***weathering***) is a highly specialized interdisciplinary science that is concerned with:

- routes to failure (mechanisms)
- rates of property change (performance)
- time-stress dependency
- stress-stress interactions (synergy)
- simultaneous and sequential degradation process

These concerns may affect critical performance properties or lead to outright failure; evaluating the effects of various climates on product performance and life is a core aspect of product weatherability assessment.

> ***"HALT does not attempt to simulate the field environment - only seeks to find design and process flaws by any means possible".***
>
> ***- Gregg K. Hobbs***
> ***Inventor of HALT testing***

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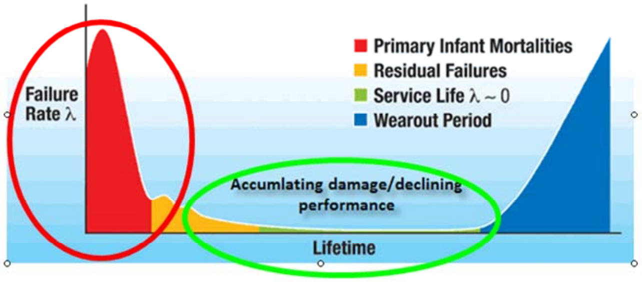
[4] Gregg K. Hobbs, "Accelerated Reliability Engineering: HALT & HASS", John Wiley & Sons

Durability, Reliability and the Bathtub Curve

Another way of considering *durability* v. *reliability* and *HALT* v. *weathering* is through the classic "bathtub reliability curve" describing failure rate as a function of in-service life. Early-life failures, referred to as "infant mortality," typically occur out of box into the first 1–2 years of a product's life. These may result from fundamental design flaws but also from materials or processing issues. Remember, short-term HALT-type testing is subject to the limitations Hobbs addresses.

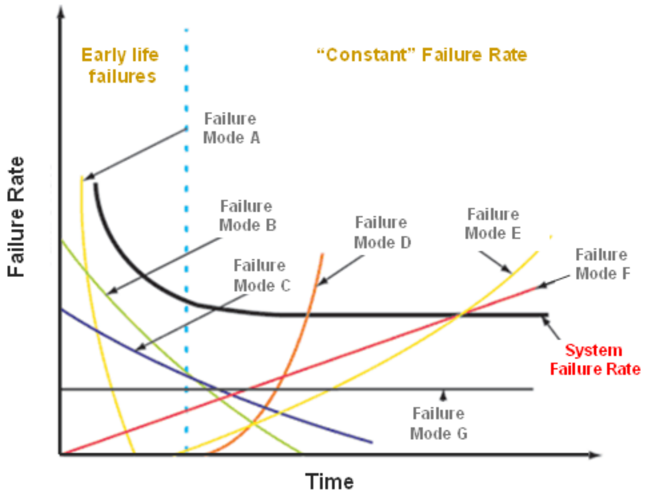


Durability (*weathering*) testing focuses instead on the longer term in-service period. This is the period where the time-dependent repeated application of combined environmental stresses, delivered in their natural short and long-term cycles, causes degradation and accumulates damage which causes wear-out and eventual failure. In this accumulated damage model no single stress-relaxation event will cause failure, but the accumulated damage resulting from long-term exposure will lead to decreasing performance and eventual failure.

As multiple simultaneous and/or sequential degradation mechanisms may be at work in long-term exposure, failure often is the result of prior events (accumulated damage) that HALT does not adequately address. For example, an elastomeric or polymeric module edge seal may become brittle from UV and thermal degradation leading to moisture ingress producing internal corrosion of the transparent conducting oxide (TCO) layer visible as module discoloration resulting in electrical failure.

These overlapping and/or sequential degradation modes (illustrated below) can interact to produce module failure. Basic HALT tests cannot reproduce the complex stress interactions of the real-world environment as illustrated below:

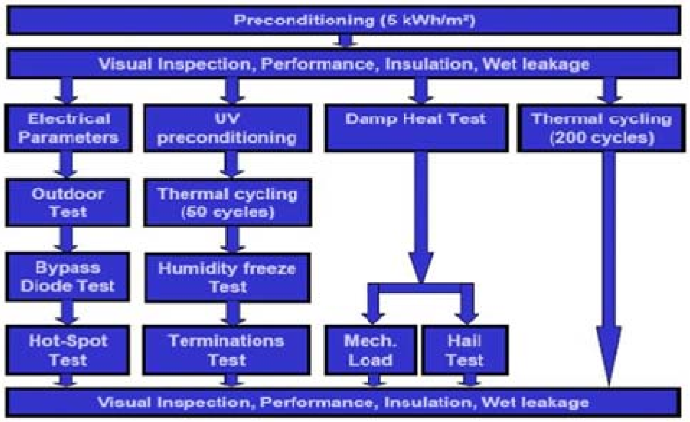
Module failure often results from the interaction of multiple climate stresses and complex action modes which basic HALT tests cannot reproduce.



IEC Qualification Tests

IEC Design Type Qualification Tests

Photovoltaic module designs must be tested in accordance to IEC 61215 for wafer based silicon and to IEC 61646 for thin film technologies. A summary of the key environmental-related tests within the larger IEC 61215 regimen (IEC 61646 is similar) is shown:



It is important to note several aspects of this protocol (the exact test parameters are in the IEC documents):

- No single module goes through the full complement of environmental tests
- No simultaneous solar radiation, temperature and humidity stresses as outdoors
- The test parameters (temperature, humidity, etc.) are more extreme than and not representative of any real climate
- No test (except for a short outdoor exposure) is under full solar radiation
- Chamber tests do not combine solar radiation, temperature, and humidity as in nature
- Short test durations and low cycle counts (e.g., 200 thermal cycles or 1,000 hours damp heat each take only about 6 weeks to run)
- PV modules are not electrically active (light bias) during exposure

The IEC qualification tests are HALT-type tests which focus on short-term "infant mortality" resulting from design, materials and processing defects. They do not imply any longer term life or climate-specific performance but only serve as a minimum commercial requirement.

It is important to note that extending these tests to longer durations or additional cycles, while useful for forcing and identifying some potential failure modes (subject to Hobbs' limitations), do not provide the predictive natural weathering stresses required in weathering testing. The previous lack of suitable large-scale accelerated weathering chambers to accommodate full size PV modules has largely limited testing to this inadequate approach or to using non-representative mini-module samples in conventional weathering tests. **Atlas 25$^{\text{PLUS}}$** overcomes these limitations. As you can see, neither HALT nor IEC tests are suitable for producing weathering effects.

"… the relatively short tests in the qualification standards do not and cannot provide lifetime data …"

- ***Carl Osterwald NREL and ASTM E44***

Accelerated Testing

Accelerated Photovoltaic Testing

Carl Osterwald and Tom McMahon of NREL published an exhaustive and well annotated review of PV module testing since 1975 leading up to the development of the IEC and related tests. They note the limitations and the need for improved methods, especially in the area of long-term durability testing: "The intent and history of these qualification tests, provided in this review, shows that standard module qualification test results cannot be used to obtain or infer a product lifetime. Closely related subjects also discussed include: other limitations of qualification testing, definitions of module lifetime, module product certification, and accelerated life testing."[5]

Accelerated Weathering Testing

Formal outdoor weather exposure testing has a hundred year history. While necessary, the lengthy times required for real-time testing are a hindrance to new product development and introduction for all long-lived products. As a result, accelerated weather testing, pioneered by Atlas in 1915, has been in continuous development for 95 years. Today, both accelerated outdoor and laboratory accelerated weathering are essential in industries such as automotive, military, aerospace, building products, polymers-paints-coatings, and materials science. They have been widely applied to solar energy materials and products since Atlas first tested the PV modules used for the original Skylab launched in 1973 and are used by materials suppliers, PV manufacturers and laboratories such as NREL.

Laboratory-accelerated weathering is a specialized form of Accelerated Environmental Testing (AET). While oven aging, UV exposure or thermal-cycling chambers are various forms of AET, laboratory accelerated weathering has a specific set of minimum requirements, notably:

- Full-spectrum simulation of terrestrial solar radiation (AM1 to AM1.5)
- Control of chamber air temperature
- Monitoring of test specimen or reference panel temperature
- Control of relative humidity
- Simultaneous cycling of solar Irradiance, air temperature and relative humidity

While materials-level or small-scale product tests are usually performed at above-ambient temperatures (under steady-state or cycling conditions), the complex multi-layer laminate structure of PV modules requires a wider range of environmental control to simulate real climatic conditions.

> ***"Reliability is easy . . . lifetime is not."***
>
> ***Akira Terao - Sunpower Corp.***

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[5] *History of Accelerated and Qualification Testing of Terrestrial Photovoltaic Modules: A Literature Review*, ©2008, http://www.nrel.gov/pv/performance_reliability/pdfs/osterwald_pip_review_2008.pdf

Weathering Testing of Full Scale PV Modules

Due to module size and the prior lack of suitably large accelerated weathering devices, apart from real-time outdoor testing the best approach has utilized small (typically 1-cell) "mini-module" test specimens in standard-sized commercial weathering instruments. This "mini" test approach has several key limitations.

First, mini-module test specimens typically do not go through normal production equipment. Secondly, their down-sizing produces mechanical stresses such as those resulting from thermal expansion; these may be very different than that of full sized modules. Third, most standard accelerated weathering instruments for small samples lack the full cycle temperature ranges (especially at the low end) that modules will encounter. And finally, no standard or custom accelerated weathering chamber can deliver all of the natural stresses which are likely to be encountered, such as salt air corrosion in combination with temperature, humidity and solar cycling.

As a result, Atlas has pioneered new state-of-the-art accelerated weathering chambers such as the XR360™ and SolarClimatic 2000 to expose full size PV modules which is a cornerstone of **Atlas 25**$^{\text{PLUS}}$ testing.

Atlas 25^{PLUS} Program

Atlas 25^{Plus} PV Module Durability

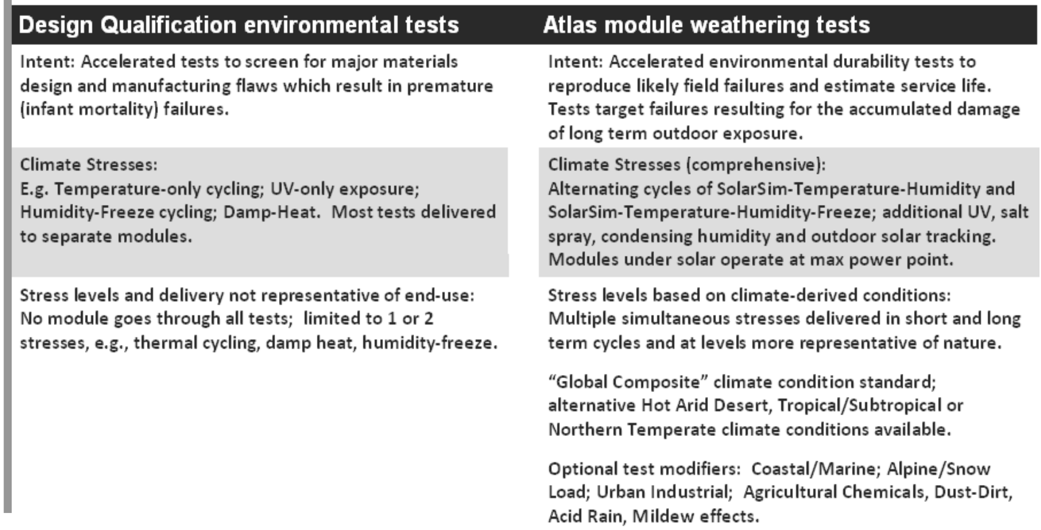
Given the critical industry need and the lack of module-suitable accelerated weathering methodologies, Atlas has drawn on 90 plus years of weather testing experience, with more than 25 of them in PV and solar materials, to develop the **Atlas 25^{PLUS}** PV Module Durability Testing Program. Unlike IEC type design qualification tests which target early-life failures, **Atlas 25^{PLUS}** targets the long-term effects of weather and climate that modules will experience in service to provide critical lifetime and performance data to support manufacturer's claims.

Atlas 25^{PLUS} leverages the key research findings on degradation across all photovoltaic technologies as well as advanced weathering testing techniques. Atlas has developed new accelerated weathering instruments, such as the XR360™ large-scale weathering chamber, to expose full size modules.

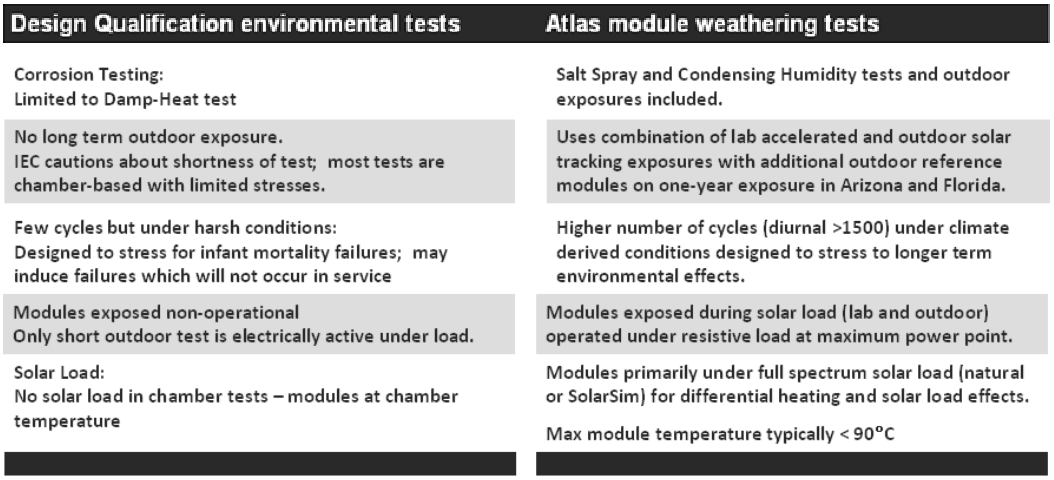
Atlas 25^{PLUS} does not duplicate the IEC or similar tests. **Atlas 25^{PLUS}** does generate independent third-party data for manufacturers to both improve product reliability and performance and provide best-available assurance to financial stakeholders.

Atlas 25^{PLUS} neither duplicates nor replaces IEC qualification testing, but rather is an essential complement to help answer the question, "Will my module last outdoors?"

A comparison of "qualification testing" and **Atlas 25^{PLUS}** illustrates the essential differences:



Design Qualification environmental tests	Atlas module weathering tests
Intent: Accelerated tests to screen for major materials design and manufacturing flaws which result in premature (infant mortality) failures.	Intent: Accelerated environmental durability tests to reproduce likely field failures and estimate service life. Tests target failures resulting for the accumulated damage of long term outdoor exposure.
Climate Stresses: E.g. Temperature-only cycling; UV-only exposure; Humidity-Freeze cycling; Damp-Heat. Most tests delivered to separate modules.	Climate Stresses (comprehensive): Alternating cycles of SolarSim-Temperature-Humidity and SolarSim-Temperature-Humidity-Freeze; additional UV, salt spray, condensing humidity and outdoor solar tracking. Modules under solar operate at max power point.
Stress levels and delivery not representative of end-use: No module goes through all tests; limited to 1 or 2 stresses, e.g., thermal cycling, damp heat, humidity-freeze.	Stress levels based on climate-derived conditions: Multiple simultaneous stresses delivered in short and long term cycles and at levels more representative of nature.
	"Global Composite" climate condition standard; alternative Hot Arid Desert, Tropical/Subtropical or Northern Temperate climate conditions available.
	Optional test modifiers: Coastal/Marine; Alpine/Snow Load; Urban Industrial; Agricultural Chemicals, Dust-Dirt, Acid Rain, Mildew effects.



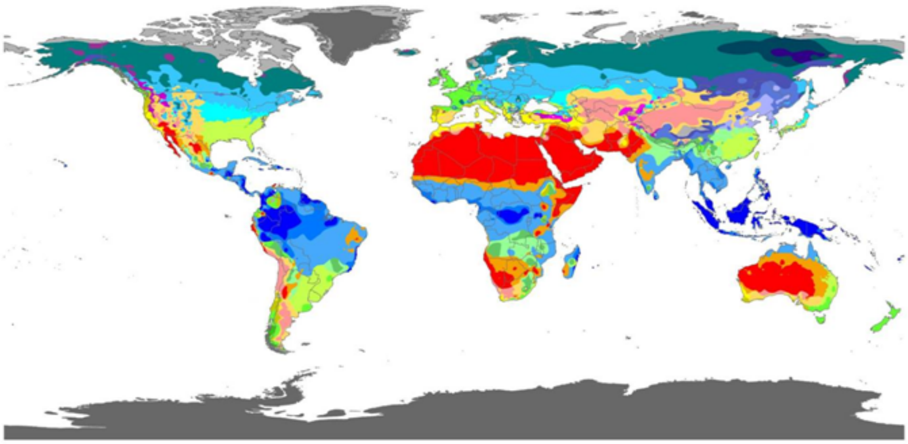
Design Qualification environmental tests	Atlas module weathering tests
Corrosion Testing: Limited to Damp-Heat test	Salt Spray and Condensing Humidity tests and outdoor exposures included.
No long term outdoor exposure. IEC cautions about shortness of test; most tests are chamber-based with limited stresses.	Uses combination of lab accelerated and outdoor solar tracking exposures with additional outdoor reference modules on one-year exposure in Arizona and Florida.
Few cycles but under harsh conditions: Designed to stress for infant mortality failures; may induce failures which will not occur in service	Higher number of cycles (diurnal >1500) under climate derived conditions designed to stress to longer term environmental effects.
Modules exposed non-operational Only short outdoor test is electrically active under load.	Modules exposed during solar load (lab and outdoor) operated under resistive load at maximum power point.
Solar Load: No solar load in chamber tests – modules at chamber temperature	Modules primarily under full spectrum solar load (natural or SolarSim) for differential heating and solar load effects. Max module temperature typically < 90°C

Core Concept of Atlas 25^{PLUS}

Nature does not change the way it delivers weather and climate based on your module. Therefore, **Atlas 25^{PLUS}** is designed to deliver the key weather and climate stresses, at the levels found in nature, in both short-term daily and longer term seasonal cycles. This approach treats your module as a "black box" and while independent of specific PV technology or design, incorporates the stresses found in nature identified as detrimental to photovoltaic modules.

Drawing on Atlas' data and experience, three specific service environments have been identified as most damaging: hot arid desert, tropical/subtropical and northern temperate. Modules designed for specific deployment, such as utility-scale systems for desert locations such as Southwest USA or Middle-East, may optionally be subjected to one or more of the specific climate simulations. A general "Global composite" climate based on the worst-case boundary conditions of these three specific harsh climates is used as the standard exposure condition for products to be used globally as shown in the Köppen-Geiger climate classification map:

World map of Köppen-Geiger climate classification



Atlas 25^{PLUS} acknowledges the need to balance time-in-test with providing sufficient stresses representative of long module service life and the limits of reliable acceleration. Therefore, **Atlas 25^{PLUS}** takes exactly one year to perform although interim measurement data is provided throughout the program.

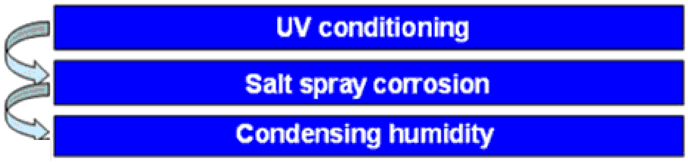
Atlas 25^{PLUS} Weathering Exposures

Three modules are exposed in the standard **Atlas 25^{PLUS}** base program. One module is exposed on a solar tracking rack at Atlas' Solar Test Center in Arizona, and a second on tracking rack in south Florida. The third undergoes the primary **Atlas 25^{PLUS}** accelerated aging protocol. Modules are backed similar to a surface roof-mount to provide elevated but realistic module temperatures.

While under sun or solar simulation, all three modules are exposed operationally "live" under resistive load for operation at the maximum power point (P$_{max}$). This is important to stress for electrochemical degradation resulting from ion migration, hot spots, bypass diode failure, etc. The outdoor tracking exposures provide some acceleration of two key critically harsh climates as well as benchmark performance data.

The third module undergoes an initial test sequence:

- UV-A and UV-B ultraviolet light exposure; provides activation of thin film PV, Staebler-Wronski degradation for amorphous thin film silicon, light activation of inactive semiconductors and photodegradation of polymeric materials (encapsulants, sealants, potting compounds, cables, Junction-boxes, topsheets, backsheets, coatings, etc.)
- Salt fog corrosion testing; accelerates marine and alkaline desert metal corrosion including connectors, micro-inverters, etc.
- Condensing humidity tests; tests moisture ingress into PV, Junction boxes, etc.



This module then undergoes the core chamber accelerated weathering:

a) Accelerated weathering chamber testing of full-spectrum solar radiation, temperature and relative humidity cycling; parameters are climate derived
b) Accelerated weathering chamber cycles of solar, temperature and humidity under freeze/thaw conditions.

Full-spectrum solar load provides more realistic module stresses than does basic environmental chamber cycling as well as photodegradation and forward bias.

Another key aspect of **Atlas 25PLUS** is the fast cycle times of the (a) exposure (117 cycles in 7 days) followed by the (b) cycles (44 cycles in three days). This rapid cycling provides increased thermo-mechanical stress for greater acceleration. This ten day core super-cycle is then repeated for a total of 80 days to provide both daily and seasonal climate-adjusted patterns.

The program then continues with:

- Outdoor solar tracking in Arizona for 12 weeks during peak summer temperature and solar radiation (May, June, July)
- Outdoor solar tracking for balance of year (~4 months)

Test cycles and temperatures were designed and tested to target maximum module temperatures of ~85°C under full spectrum solar radiation. Due to physical size constraints given the dimensions of most "standard" full sized PV modules, one module is run through the comprehensive battery, although several smaller-sized modules may be optionally accommodated.

Measurements and reports

Inspections and measurements are conducted at intervals to characterize module performance and check for problems. Initial and 12-month final I-V curve measurements on all modules are taken under our large-scale 1,000 W/m^2 near-Class-A steady-state solar simulator. All interim I-V curves are taken outdoors on days >1000 W/m^2 unless optionally arranged.

Visual inspections, digital photographs and digital infrared (IR) thermographic images are taken at initial, final and 5 interim points. These are approximately every two months (weather permitting) for the outdoor exposures and at transition points between chamber test sequences.

Inspection and measurement data is provided as developed during the exposure permitting qualified exit points in the event of module problems or failures. A final composite report including these measurements, test site meteorological and solar radiation data as well as any findings by Atlas is provided at the end of **Atlas 25PLUS** testing.

As each module manufacturer makes their own determination as to what is acceptable durability, reliability and performance, **Atlas 25PLUS** provides no pass/fail criteria or certification, but does provide data manufacturers can use to provide evidence of their claims. Completion of the **Atlas 25PLUS** program allows the manufacturer use of the **Atlas 25PLUS** Mark**.**

What does 1 Year in Atlas 25PLUS Equal?

Atlas 25PLUS is an advanced accelerated weather aging protocol. Precise correlation to expected performance requires validation with real-time long-term exposure data for the specific module design. Specific "acceleration factors" for any accelerated test are highly variable and dependent on materials, product design, manufacturing, degradation mechanisms and other factors.

Acceleration factors and correlation cannot be absolutely predicted without the requisite long-term outdoor exposure data for the exact module, data which usually does not exist.

The core **Atlas 25^{PLUS}** accelerated laboratory exposure is designed to simulate the key climate stresses such that each cycle provides stresses equivalent to a minimum of 2 to 5 days outdoors. Additional acceleration is provided by the UV, condensing humidity, corrosion and solar tracking exposures such that the entire program delivers exposure equivalents in excess of 10 years real time.

Extending the duration of the core aspects (chamber cycles) of **Atlas 25^{PLUS}** is optionally available to increase that confidence level to an expectation of 20 years or more.

Summary

Value of Atlas 25^{PLUS}

Atlas 25^{PLUS} is the only program designed to answer the basic question of ***"Will my module last outdoors?"*** The answer to this question is crucial to new product development, to establish warranty and performance claims, and to provide assurance to financial stakeholders. Failure to understand and appropriately test for durability to in-service weather and climate risks product failure and the subsequent financial impact as well as potential safety liability. Can you answer the question of "Will my module last outdoors?"

For further information contact your local Atlas representative or contact us at **www.solar.atlas-mts.com**.

White Paper

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