White Paper

Photovoltaic Module Weather Durability & Reliability Testing

Will your module last outdoors?

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ATLAS MATERIAL TESTING SOLUTIONS

AMETEK MEASUREMENT & CALIBRATION TECHNOLOGIES

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Executive Summary

The Issues

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 10 years and to at least 80% in the following 10-15 years. Even though the hardware warranty may be shorter, project economics are based on the long term. Manufacturers are obliged to set up reserves for the expected volume of claims under the performance warranties, tying up capital. A module warranty only covers part of the replacement costs and is only as viable as the company behind it. Increasingly, investors are demanding demonstrable long term module reliability and performance, a.k.a., "bankability", in addition to IEC certification.

The Problem

Early life failures resulting from design flaws, materials or processing issues are often apparent from startup to 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. These qualification tests, while necessary, are now generally acknowledged to be non-predictive of long term durability and reliability. 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.

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, electrical, thermal or mechanical in nature. These are either 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, wind and snow.

Current Practice

Weatherability testing has been successfully relied upon by industries such as automotive, building products, plastics, paints and protective coatings for over 100 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 qualification tests, even when they are extended to longer periods. These differences are often not understood by PV reliability engineers experienced in the semiconductor device industry where testing for long-term weather resistance is unheard of.

The Atlas Solution

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

Business Challenge

Importance of PV Module Economic Performance

Apart from Feed In Tariffs and other financial 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.

The 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, financing of PV systems ("bankability"), system insurers and reinsurers, EPC and O&M companies, and end users.

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, formerly with BP Solar and now with NREL, 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.

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

[2] A. 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.

The U.S. Department of Energy's National Renewable Energy (NREL) PV module reliability group maintains an on-line document of known reliability/degradation issues for PV modules, by technology.

"General reliability issues across all PV technologies include:

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:** Interlayer 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 are either caused or influenced by outdoor weather exposure

The majority of these issues are either 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.

[3] N. Bosco, 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

A common misconception is since PV has a track record dating from the 1970's, that module reliability is now a given. Also, that early problems, such as encapsulant yellowing or TCO corrosion, are now all resolved. However, since *circa* 2005, silicon wafer thickness has been greatly reduced, new lower cost materials have emerged, and other changes have been introduced making today's c-Si modules very different from previous designs. And non-crystalline silicon PV technologies have different failure modes where prior silicon history isn't useful.

Reliability engineering is primarily concerned with outright failure and their statistical measurements. The methodology requires large numbers of samples, preferably of production units. Durability testing looks more at how and why a product degrades and uses limited test specimens representative of the design.

Testing techniques such as highly accelerated life testing (HALT) are widely employed in reliability (failure) analysis in many industries and largely derived from the semiconductor device industry. These form the basis of the current IEC 61215/61646 PV module qualification tests.

Gregg K. Hobb[4] notes several key limitations of HALT which are often overlooked:

- 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

HALT testing works best for accelerating single cause and effect degradation modes, and may not be capable of inducing or accelerating chemical or electrical degradation mechanisms.

Durability testing, however, evaluates the negative influences of outdoor environmental stresses (known as *weathering*) and life and performance. It usually uses smaller numbers of modules as statistical methods are not as applicable. Key factors for investigation include:

- mechanisms of degradation and root cause analysis
- rate of property changes
- time-stress dependency
- stress-stress interactions
- simultaneous and sequential degradation process
- modeling and estimating useful service life

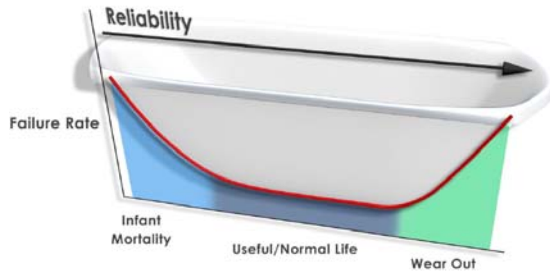
"HALT does not attempt to simulate the field environment - only seeks to find design and process flaws by any means possible".

G.K. Hobbs
Originator of HALT/HASS testing methodology

[4]G. Hobbs,"Accelerated Reliability Engineering : HALT and HASS", Wiley, 2000.

Durability, Reliability and the Bathtub Curve

The classic "bathtub reliability curve" describes failure rate as a function of in-service life and consists of three distinct phases. Early life failures, referred to as "infant mortality," typically occur out-of-box into the first 1–2 years of a module's life. These may result from fundamental design flaws or from materials or manufacturing issues. They are what is specifically addressed in the IEC design type qualification tests. Short-term HALT-type testing is subject to the limitations which Hobbs addresses.

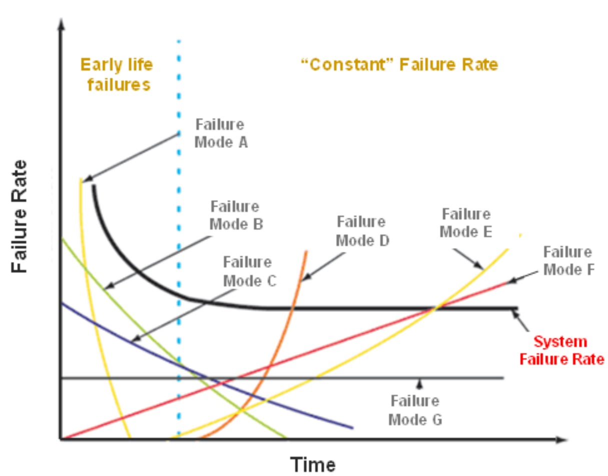


Durability testing, including weathering, instead focuses on the longer term useful life period. This is where the time-dependent repeated application of combined environmental stresses, delivered in their natural short (daily) and long-term (seasonal) cycles, causes degradation and accumulates damage.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

As multiple simultaneous or sequential degradation mechanisms may be at work in outdoor exposures, failure often is the result of accumulated damage that HALT does not adequately address. For example, an elastomeric module edge seal may become brittle from UV or thermal degradation leading to moisture ingress. This produces internal corrosion of the transparent conducting oxide (TCO) layer or silver paste which is visible as module discoloration. These result in high series resistance leading to hotspots and possible arcing and electrical failure.

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

Module failure often results from the effects of multiple climate stresses and degradation modes



IEC Qualification Tests

IEC Design Type Qualification Tests

Photovoltaic module designs must be tested in accordance to IEC 61215 for mono and polycrystalline silicon and to IEC 61646 for thin film technologies. It is important to note several aspects of these protocols (the test parameters are in the IEC documents):

- No single module goes through all exposure tests
- The test parameters (temperature, humidity, etc.) are more extreme than, and not representative of, any real climate (such as 85°C/85% relative humidity)
- 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 UV preconditioning equivalent to about 3 months of outdoor exposure)
- PV modules are not operating normally under light bias or electrical load during most exposures; most exposure tests are in the dark.

The IEC qualification tests 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 do serve as a minimum commercial requirement to weed out truly inferior products. To be commercially viable, a qualification test must be designed to "pass" most modules.

These tests, while useful for forcing some potential failure modes, do not provide natural weathering stress combinations. Extending the IEC tests, or applying them in different combinations or sequences -- as has been proposed by some -- does not produce an acceptable or predictive weather durability test.

The lack of suitable large-scale accelerated weathering chambers to accommodate full size PV modules has previously limited testing to IEC HALT tests, or to using mini-modules in small scale accelerated weathering tests. Atlas 25$^+$ overcomes these limitations by employing large scale solar/environmental chambers (shown below) in the core accelerated weathering cycles.

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

C.Osterwald
NREL

Accelerated Testing

" . . . standard module qualification test results cannot be used to obtain or infer a product lifetime."

C.Osterwald & T. McMahon NREL

Accelerated Photovoltaic Testing

Carl Osterwald and Tom McMahon of NREL published an exhaustive and well annotated review[5] of PV module testing since 1975, leading up to the development of the IEC tests. They also note the limitations and need for improved methods, especially in the area of long-term durability testing:

"The 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."

Accelerated Weathering Testing

Formal outdoor weather exposure testing has a 100-plus year history. While necessary, the lengthy times required for real-time testing are a hindrance to developing durable products across many industries. As a result, accelerated weather testing technology, first pioneered by Atlas in 1915, has been in continuous development.

Today, both outdoor and laboratory accelerated weathering are essential to industries such as automotive, military, aerospace, building products, polymers-paints-coatings, and materials additives. These practices, however, are largely foreign to the majority of PV reliability engineers experienced in semiconductor device testing where weather testing is virtually unknown. Atlas first tested the PV modules used for the original Skylab launched in 1973. Accelerated weathering tests are extensively used at the PV materials level suppliers and research laboratories such as NREL, but until recently have not been widely performed on modules for some of the reasons cited.

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 for PV modules has a specific set of requirements, most notably:

- Full-spectrum simulation of terrestrial solar irradiance
- Control of chamber air temperature
- Monitoring of test module or reference panel temperature
- Control of relative humidity
- Simultaneous cycling of solar radiation, air temperature and relative humidity with module loaded under maximum power point conditions

While materials-level or small-scale weathering tests are usually performed at above-ambient temperatures (under steady-state or cyclic conditions), the complex multilayer laminate structure of PV modules requires a broader range of environmental parameters to simulate real climatic conditions and initiate many degradation and failure modes.

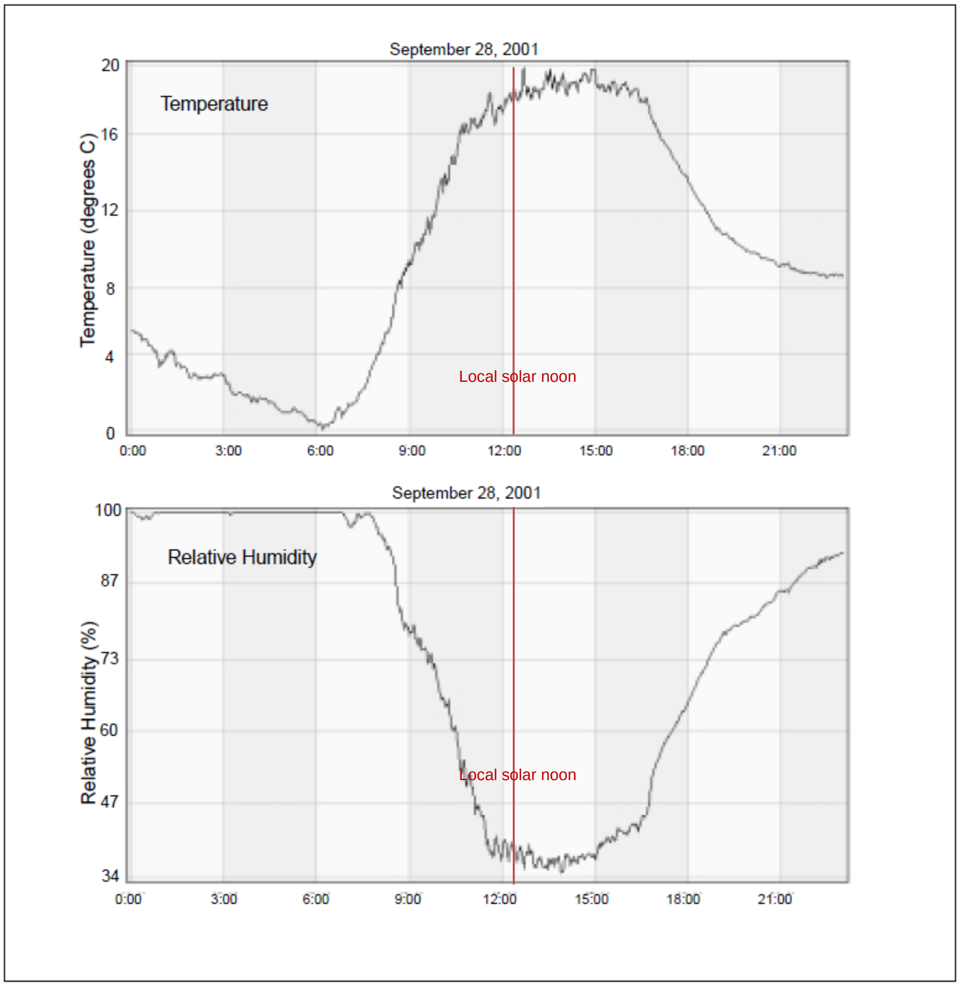
[5] C.Osterwald, T.McMahon, "History of Accelerated and Qualification Testing of Terrestrial Photovoltaic Modules: A Literature Review", Progress in Photovoltaics: Research and Applications 2009; 17:11-33, Wiley InterScience, ©2008.

Laboratory Weathering Testing of Full Size PV Modules

The three key factors of weather and climate that affect products outdoors are:

- solar radiation
- temperature
- moisture

Both the high and low limits of each as well as their dynamic cycles are important. These three key variables are not independent but rather are inextricably linked. Solar radiation and air temperature affects module temperature, and temperature affects moisture levels. As can be seen from a typical daily weather plot (Hong Kong Observatory data), as solar radiation and temperature increases, relative humidity is inversely proportional:



These large daily cycles provide thermo-mechanical tensile and compressive stresses and form a dynamic system which drives moisture permeation and condensation. These are patterns which <u>must</u> be replicated in accelerated weather testing as steady-state conditions do not exist in the real world and much degradation occurs during these transitions.

Front surface heating from the near infrared (NIR) of direct sunlight causes a temperature gradient through the module stack. This results in internal stresses and temperature profiles which are very different from those produced by heating in a typical non-solar thermal cycling chamber.

Temperatures below the dew point produce internal and external moisture condensation; temperatures below freezing introduce water expansion stress. The cycling of moisture, especially in the presence of external salts (coastal marine or alkaline desert) or internal ions (such as sodium or tin leaching from soda-lime cover glass) drive galvanic and electrochemical corrosion mechanisms and may result in ion electro-migration with current flow in an operating module. Seasonality can introduce an additional compexity of cyclic stress patterns.

Secondary factors of weather/climate may include gases and atmospheric pollutants including acid rain; industrial , agricultural and cleaning chemicals; dynamic wind and snow load; biologicals such as bird droppings, insects, mildew and other microbes; blown or retained dust/dirt and many others. These are more difficult to include or accelerate in an overall test program.

Until relatively recently the general lack of large scale accelerated environmental weathering chambers with full spectrum solar radiation capabilities, such as the Atlas XR260's at NREL (shown) has necessitated mini versus full size module testing.

The general lack of large accelerated weathering chambers has hampered the testing of full size modules.

Photo courtesy of NREL

However, not only are the thermal and mechanical stresses altered in small samples, but important electrical characteristics may not be scalable to the full size product, and mini-modules usually are not representative of the normal production process.

Although no single test or chamber can deliver all of the primary and secondary natural stresses which may be encountered, sequencing other tests with full-spectrum solar/environmental cycling accelerated weathering chambers provides the best available tool for producing meaningful results to understand a module's long term durability and identify areas for improvement.

Atlas 25^+ Test Program

Overview: Atlas 25^+ PV Module Durability Testing

Given the critical industry need and the lack of module-suitable accelerated weathering methodologies, Atlas has drawn on over 95 years of weather testing experience, with more than 25 of them in PV and solar materials. This led to the development of the Atlas 25^+ PV Module Durability Testing Program. Unlike IEC type design qualification tests which target early-life failures, Atlas 25^+ delivers the longer-term effects of weather and climate that modules will experience in service to provide critical lifetime and performance data to support manufacturer's claims.

While it is known that some specific module degradation and failure modes, such as solder or interconnect disbondment and silicon cell microcracking, can be forced by extending the IEC TC-200 thermal cycling test (+80°C to -40°C), the IEC HALT tests, as a whole, still cannot reproduce the actual module ageing mechanisms resulting from accumulated long term weather stresses. Though useful for minimum qualification purposes, as is now recommended by Solar America Board of Codes and Standards, they do not serve to demonstrate service life. Along with field testing, Atlas 25^+ provides the longer term focus which complements the IEC tests to provide a more comprehensive and useful testing program.

Extending IEC tests or combining them in novel sequences does not produce a weathering test.

An important key element of Atlas 25^+ is that, whenever under solar radiation (sun or simulated), all modules are electrically operating under resistive load at the calculated maximum power point. This realistically stresses a module both thermally and electrically as it would be in service. It is not logical to test a PV module in the dark or to artificially bias it with a power supply when its sole purpose is to generate electricity in sunlight.

However, realize that extending or combining IEC qualification tests in novel combinations or sequences, as proposed by some not familiar with accepted weathering test methodology, does <u>not</u> produce a true weathering test.
A basic comparison (table shown below) of IEC qualification tests with Atlas 25^+ tests highlights the key differences such as the specific weather stress combinations.

Use-induced stresses as well as extrinsic environmental stresses should be considered, however a differentiation must be made between module versus string/array characteristics.

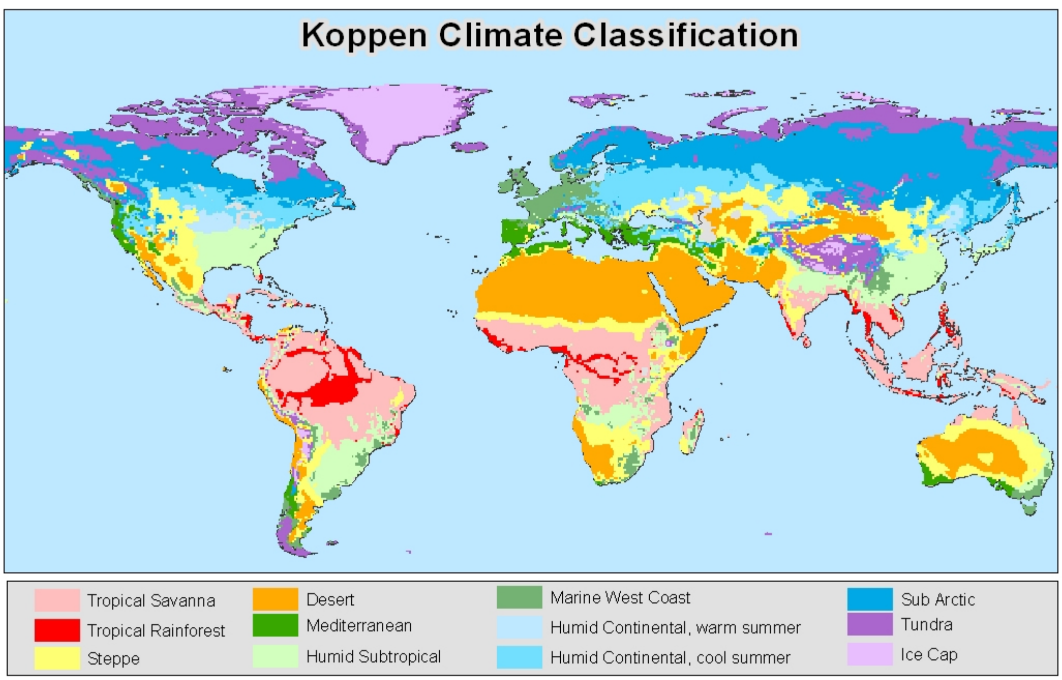
Design qualification "environmental" tests	Weathering test approaches
Intent: Accelerated tests to screen for major materials, design and manufacturing flaws which may result in premature (infant mortality) failures. Tests focus on specific common early-life failure modes.	Intent: Accelerated environmental durability tests to reproduce likely field failures and estimate service life. Tests target failures resulting for the accumulated damage of long term outdoor exposure and simultaneous stresses.
Climate Stresses (limited stress combinations): 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 other environmental stresses. Modules under solar load operational 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. Conditions sometimes controversial (e.g., 85° C at 85% RH	Stress levels based on climate-derived conditions: Multiple simultaneous stresses delivered in short and long term cycles and at levels more representative of nature. Specific climate conditions (e.g., hot/arid, hot/wet. freeze/thaw.. Possibility of "boundary condition" global combination but with less specific climate predictive ability. Other test microclimate stresses to consider: Coastal/Marine salt; Alpine/Snow Load; Urban Industrial pollution; Agricultural Chemicals; Dust-Dirt-Sand'; Acid Rain; Mildew & biological effects among others.
No long term outdoor exposure. IEC cautions about shortness of test; most tests are chamber-based with limited stress combinations	Combination of lab accelerated and outdoor exposures in key benchmark climates (e.g., Arizona, Florida, Northern)
Few cycles but under very severe conditions: Designed to stress for infant mortality failures; may induce failures which will not occur in service	Higher number of diurnal cycles under climate more climate-derived conditions designed to stress to longer term environmental effects
Modules mostly 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 follow chamber temperature; no solar differential heating effects	Modules primarily under full spectrum solar load (natural or SolarSim) for differential heating and solar load effects. Max module temperature typically < 90°C
Corrosion Testing: Limited to Damp-Heat test; separate corrosion IEC test	Salt Spray and Condensing Humidity tests combined or alternated with other lab weathering or outdoor exposures

Core Concepts of Atlas 25+

Clearly, nature does not alter the way it delivers weather and climate based on your module. Therefore, Atlas 25+ is designed to deliver the key combined weather and climate stresses, at near the levels found in nature, in both short-term daily and longer term seasonal cycles. This approach treats your module like a "black box" in terms of the applied external environment and is therefore fairly independent of specific PV technology or module design and materials.

Drawing on Atlas' data and experience, three specific PV service environments have been identified as most damaging: hot-arid desert, hot-wet tropical/subtropical and temperate freeze/thaw. Modules designed for specific deployment, such as utility-scale systems in desert locations such as Southwestern USA or Middle-East, may optionally be tested to one (or more) of these specific climate simulations.

However, a single "Global Composite" derived pseudo-climate is based on an amalgam of the set of boundary conditions of these three climates. This is used as the standard default Atlas 25+ parameters, although testing to any of the three specific climates is possible. The composite approach is applicable for products which may be used globally as shown in the Köppen-Geiger climate classification map:



World climate data is derived from scientific databases as well as Atlas' Worldwide Exposure Network test sites. "Average" climate data is reconciled with high/low boundary conditions to derive test cycle parameters. This is further compounded with seasonal variation patterns to provide more representative and predictive exposure profiles. For example, one-fourth of the "Global Composite" cycles include a higher-latitude Temperate winter freeze/thaw cycle. This annual seasonality is simulated by alternating the Spring/Summer/Autumn cycle with Winter condition content.

Atlas 25^{+} Weathering Exposures

Atlas 25^{+} acknowledges the need to balance time-under-test with providing sufficient stresses representative of long module service life and the limits of reliable acceleration. Therefore, **Atlas 25^{+} Standard** and **Atlas 25^{+} Premium** each take 12 months to perform; raw interim measurement data is provided at specified intervals during testing.

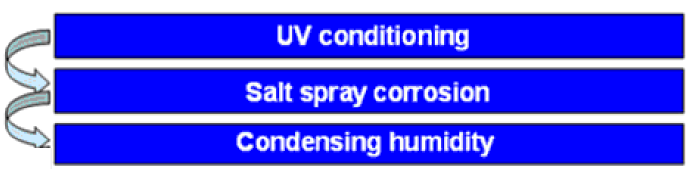
An abbreviated 6-month **Atlas 25^{+} Basic** is offered which is limited to the highest-acceleration tests; this primarily provides data for module design and materials R&D rather than for predictive module performance. Atlas 25^{+} Standard and Atlas 25^{+} Premium are recommended for production modules. Flow charts of these programs are provided in Annexes A1, A2 and A3.

A minimum of three modules are exposed in the Atlas 25^{+} Standard program. One module each is exposed on a 2-axis solar tracker near Miami, Florida, and Phoenix, Arizona. The third undergoes the primary Atlas 25^{+} accelerated aging protocol. Initial, final and interim measurements are as shown in the above mentioned Annexes.

Atlas 25^{+} Premium adds two additional outdoor static module exposures, one in the Florida Keys (coastal marine corrosion) and one in Prescott, Arizona (high altitude/snow load), for a total of four specific outdoor exposure climates.

Whenever under sun or solar simulation all modules are exposed operationally “live” under resistive load at the maximum power point (P_{max}). This is an important stress for electrochemical corrosion, cell hot spots, bypass diode failure, etc. The outdoor 2-axis tracking exposures provide some acceleration of two key critically harsh climates (hot-arid and hot-wet) as well as exposure to normal stresses such as rain, wind load and dust/dirt. The two additional outdoor modules in Atlas 25^{+} Premium further test to important secondary climate conditions where specific degradation or failure associated with coastal or high altitude conditions may occur.

The third, or “laboratory”, module in Atlas 25^{+} Standard, undergoes a number of tests; the initial ten week exposure sequence is:



where

- UV-A and UV-B ultraviolet light exposure provides an initial dose of UV to start photodegradation processes, particularly of polymeric materials (encapsulants, sealants, potting compounds, cables, junction-boxes, topsheets, backsheets, coatings, etc.) and other UV sensitive materials

- Salt fog exposure tests for coastal, marine and alkaline desert corrosion of electrical connectors, frame components, micro-inverters, and also tests module package integrity.

- Condensing humidity test (100%RH) for moisture ingress into module package, frame, junction box, electrical connectors, etc., and removes salt remaining from the salt fog test.

This laboratory module then continues with the alternating core solar/environmental chamber accelerated weathering cycles:

- Accelerated weathering chamber testing with cyclic full-spectrum **S**olar radiation, **T**emperature and **H**umidity (STH). Parameters are climate derived from boundary conditions of service use in one (or more) of the three main climate tracks. The "Global Composite" serves as the normal (default) parameter set. The upper limit keeps module front surface temperature < 95°C during solar load while electrically operating under MPPT loaded conditions.

- Accelerated weathering chamber cycles of **S**olar, **T**emperature and **H**umidity with **F**reeze/thaw (STH/F) conditions (except in the wet-moist subtropical/tropical climate track). Freezing conditions comprise approximately 25% of the 1,450 total "Global Composite"cycles.

As modules age they may become increasingly more sensitive to natural cyclic environmental stresses. The alternating patterns in the chamber expose modules to a large, but realistic, range of conditions in both daily and seasonal patterns as would outdoor service. Full-spectrum solar load provides more realistic thermal stresses than does dark environmental chamber cycling. Solar load may also initiate photodegradation mechanisms and results in important electrical stresses as the module generates current.

Another key aspect of Atlas 25^+ is the relatively fast cycle times of the two exposure conditions. This rapid cycling provides increased thermo-mechanical stress and increases the test acceleration factor. These alternating chamber cycling tests are performed for 100 days to provide both daily and seasonally adjusted patterns.

The program then continues with the "laboratory" module undergoing:

- Outdoor 2-axis solar tracking in Arizona for 70 days during peak summertime temperatures and solar radiation (May 1 through September 30).

- Atlas 25^+ Premium (Annex A2) adds an additional 30-day non-cycling solar chamber exposure for the laboratory module; this is under continuous sun at elevated temperature and low humidity to simulate extended hot-arid desert operation in addition to the 10-week peak summer outdoor tracking exposure.

- Additional extended outdoor Arizona 2-axis solar tracking under MPPT loading for the balance of the year to obtain maximum possible module irradiation and real-world stresses.

Test cycles and temperatures were designed and tested to target maximum module surface temperatures <95°C under full spectrum solar radiation. Due to the size of most full sized PV modules, only one module normally goes through the full test sequence. However, four smaller-sized mini-modules may be optionally substituted for a full size module for R&D purposes rather than for normal life performance testing.

Measurements and reports

Inspections and measurements are conducted at specified intervals (see Annexes A1, A2, A3) to characterize module performance and check for problems. Initial and final relative I-V curve measurements on all modules are taken under our large-area 1,000 W/m^2 steady-state solar simulator (Class BBA). Alternatively, when internationally recognized Certified Body certification to Atlas 25^+ is required, a “flasher” I-V curve tracer (Class AAA) is used for the initial and final I-V measurements and power loss determinations. All interim I-V curves are taken outdoors on days >1000 W/m^2 or under the steady state simulator.

Visual inspections, I-V measurements, digital photographs, electroluminescence (EL) imaging, wet leakage current and digital infrared (IR) thermographic imaging are taken as described in Annexes A1, A2, and A3.

Inspection and measurement data is provided as developed during the exposure sequence 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 25^+ testing.

As each module manufacturer makes their own determination as to what constitutes acceptable durability, reliability and performance, Atlas 25^+ provides no absolute pass/fail criteria other than all modules must complete the test without early termination due to catastrophic failure (no output) or potential safety issues. However the test does provide data which manufacturers may use to provide further evidence of their claims of durability and/or performance.

For those requiring a module certification to Atlas 25^+, internationally recognized certification can be provided by Atlas’ independent Certified Body partner. Certification is only provided for tested full size production models. Contact Atlas for certification details.

Completion of Atlas 25^+ without any module catastrophic failure (no output) or termination for safety reasons entitles the manufacturer use of the **Atlas 25^+ Tested** Mark for the specific module type tested**.**

ATLAS TESTED 25+

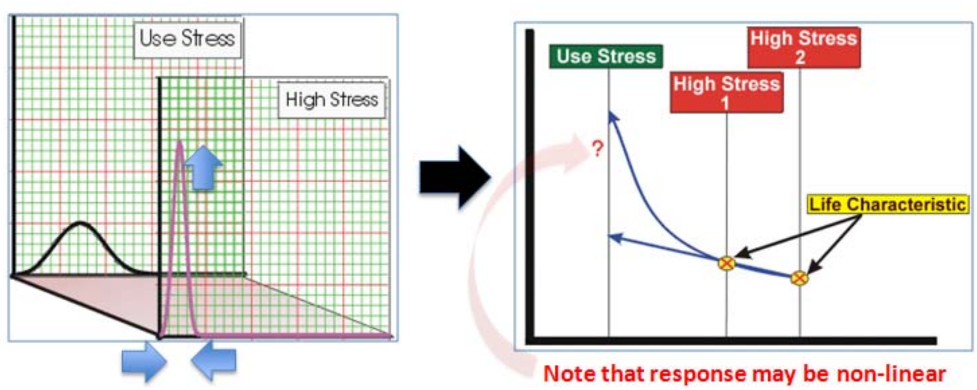
Atlas 25+ Correlation and Acceleration

Acceleration and Correlation

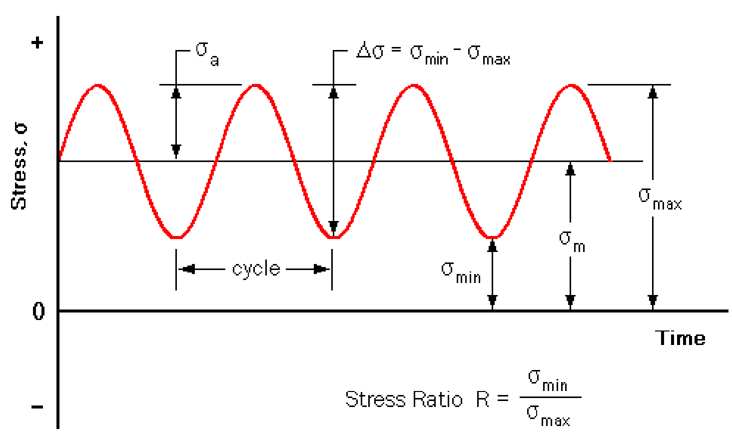
Accelerated Life Testing (ALT) test methodology is normally predicated on first being able to reproduce a specific degradation or failure mode without altering it (correlation); and, second, to produce that result in less than real-time acceleration).

Degradation and failure may result when an applied stress exceeds material or product strength. This may be a one-time catastrophic event, the result of cyclic fatigue, or a gradual decline in requisite properties due to ageing mechanisms.

The basic testing principle is to apply a stress at higher levels (steady-state, ramping or cyclic) in less time than the actual environment, then extrapolate the data to derive performance or life at the normal stress level or time:



In practice, the choice of stress, how to apply it, and at what level(s) is critical. With cyclic stress application, for example, test acceleration results from both the stress amplitude and the rate of change. These must both be considered in test design and in modeling test acceleration:



For simple, single-stress induced mechanisms, this can be relatively direct, provided cause-and-effect correlation can be demonstrated. This is often the case for mechanical wear out. With multiple stress mechanisms typical of weathering where there are stress interaction effects, calculating test acceleration factors can be extremely challenging.

The classical Accelerated Life Testing approach requires a detailed understanding of the failure modes and the stresses which produce it. In reality PV modules degrade or fail in many ways and may involve multiple mechanisms and stresses which may interact. These may neither be fully identified nor understood.

Often, sequential or multiple simultaneous ageing mechanisms are at work. In PV, several are specifically related to electrical performance such as increased shunt or series resistance and hot spots. These may have multiple root causes. Couple this with a constantly changing end use environment with multiple climate possibilities and the task becomes daunting. This is evidenced by both the inability of current IEC tests to predict long term module ageing and the difficulty establishing consensus on materials and module level durability testing within the standards setting bodies.

Atlas 25+ is designed as an advanced accelerated weather aging protocol for modules. Correlation to real world performance requires validation with real-time long-term exposure data for each specific module design and bill of materials. "Acceleration factors" for any single accelerated test are highly variable and are dependent on materials, product design, manufacturing method, degradation mechanisms and many other factors.

There are no "universal" correlation or acceleration factors in testing.

Both correlation and acceleration are also specific to each module property and degradation or failure mode. Acceleration factors and test correlation cannot be absolutely predicted without validation by the requisite long-term outdoor exposure data for the specific module design. In many cases activation energies for mechanisms must be known As these are data which usually do not exist, there is a requirement to for to model and extrapolate the limited accelerated test data.

The core Atlas 25+ accelerated weathering chamber exposures are designed to simulate the key climate stresses such that each core weathering chamber cycle provides stresses calculated to be the equivalent of a minimum of 2 to 5 days outdoors for some commonly identified degradation and failure modes (Annex B). This is based on multiple modeling tools such as Arrhenius, Coffin-Manson, Peck and others. Additional acceleration is provided by the UV, condensing humidity, corrosion and solar tracking exposures such that the entire Atlas 25+ program delivers exposure equivalents calculated to be in excess of 10 years real time, with specific degradation mechanisms each being more or less accelerated from this value.

An explanation of Arrhenius modeling for thermal effects appears in "*An Arrhenius approach to estimating organic photovoltaic module weathering acceleration factors*[6]." Addtional models are described in "*A Review of Accelerated Test Models*[7]."

[6]O.Haillant, D.Dumbleton, A.Zielnik, "An Arrhenius approach to estimating organic photovoltaic module weathering acceleration factors", Solar Energy Materials and Solar Cells, February, 2011.

[7]L.Escobar, W.Q.Meeker, "Review of Accelerated Test Models" Statistical Science, 2006 Vol.21, No.4, 552–77.

Effective temperature climate modeling is further described in "*Theoretical Estimation of Acceleration Factors for Temperature Dependent Processes*[8]" and "*Realistic test approaches provide accurate LED-lifetime numbers*[9]". A table of some common PV module failure modes and applicable modeling tools appears in Annex B[10].

It should be noted that while models may be useful for interpreting accelerated test data, no current model can predict the complex weather ageing behavior of a complete PV module, nor absolutely predict service lifetime. Atlas 25+ can provide useful information regarding failure modes, longer term ageing issues and indications of power loss. Atlas 25+ has provided valuable failure and degradation data across PV technologies and has generated defects which have been seen in the field. This includes weathering defects in module models which have received certification under IEC 61215/61646 qualifications tests.

***Atlas 25+ has produced degradation and failures in modules which passed the IEC tests*.**

The name **Atlas 25+** is derived from Atlas' over 25 years experience in durability testing PV materials and modules. It is also serves as a differentiator to symbolize testing beyond IEC basic qualification testing and address the longer term 25 year and beyond service life expectation. It is presently the most comprehensive single test program within Atlas' extensive product testing portfolio. This fact attests to the complexity of testing PV modules which require performing in extremely severe environments for a time equivalent to a human generation.

Extending the duration of the core aspects (e.g., chamber tests) of Atlas 25+ is optionally available. This increases the confidence level and extends test acceleration expectations beyond the nominal ten year equivalent (however this remains failure mode and module dependent).

Atlas 25+ produces accelerated-weather-aged modules which, should they exhibit generally recognized early indicators of known failure modes (e.g, cell micocracks, delamination, discoloration, hot spots, corrosion, power loss, etc,) that the module may have future problems and not live up to lifetime claims or expectations.

The absence of these early indicators in Atlas 25+ accelerated testing provides the manufacturer and stakeholders with currently the best available assurance, apart from decades-long field testing, that the product is durable and expected to survive and produce in the environment.

Modules aged in Atlas 25+ are subsequently available for additional performance testing such as repeating the IEC test qualification or safety tests as well as providing accelerated-aged modules for forensic analysis.

[8] O.Haillant, D.Dumbleton, "Theoretical Estimation of Acceleration Factors for Temperature Dependent Processes", www.interpv.net, 2010.

[9] O.Haillant, "Realistic test approaches provide accurate LED-lifetime numbers", Electronic Design News, May 18, 2011.

[10] D. Das, Ph.D., "Presentation: Technology Advances to Improve Reliability –A Broad View", Center for Advanced Life Cycle Engineering (CALCE), University of Maryland, 2011.

Summary

Value of Atlas 25^{+}

Atlas 25^{+} is the only weathering-specific testing 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 exposure risks product failure with its subsequent financial impact as well as potential safety liability. And additional independent test data is increasingly being demanded by financial stakeholders to address bankability issues.

Can you or your stakeholders answer the question "Will my module last outdoors" with your current testing?

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

Atlas Intellectual Property

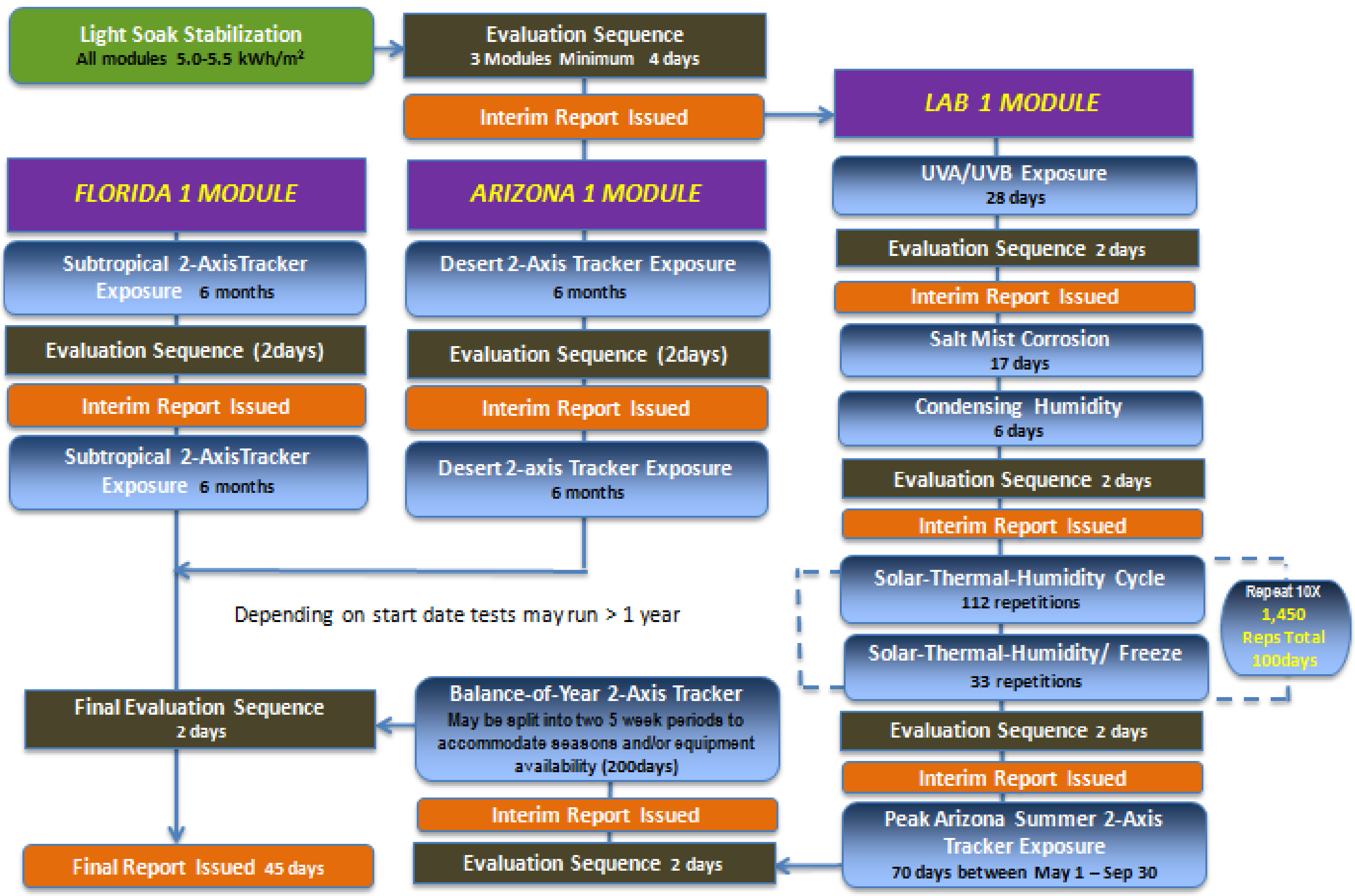
Atlas 25^+ IP

Atlas 25^+ was developed using Atlas proprietary data, knowledge and highly specialized testing equipment over many years. Thus, the specific test conditions, equipment requirements and related program details are the exclusive intellectual property of Atlas Material Testing Technology LLC. This information is not disclosed except under a duly executed confidentiality Non-Disclosure Agreement (NDA). This NDA is part of the Atlas 25^+ testing contract and test specifics are reported in the Atlas 25^+ reports or, alternatively, with a separately executed NDA as part of the sales disclosure process.

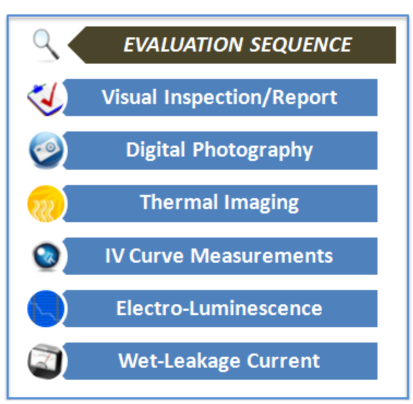
Atlas 25^+ and key program elements are available under license to qualified organizations.

Please contact Atlas Material Testing Technology LLC for additional details.

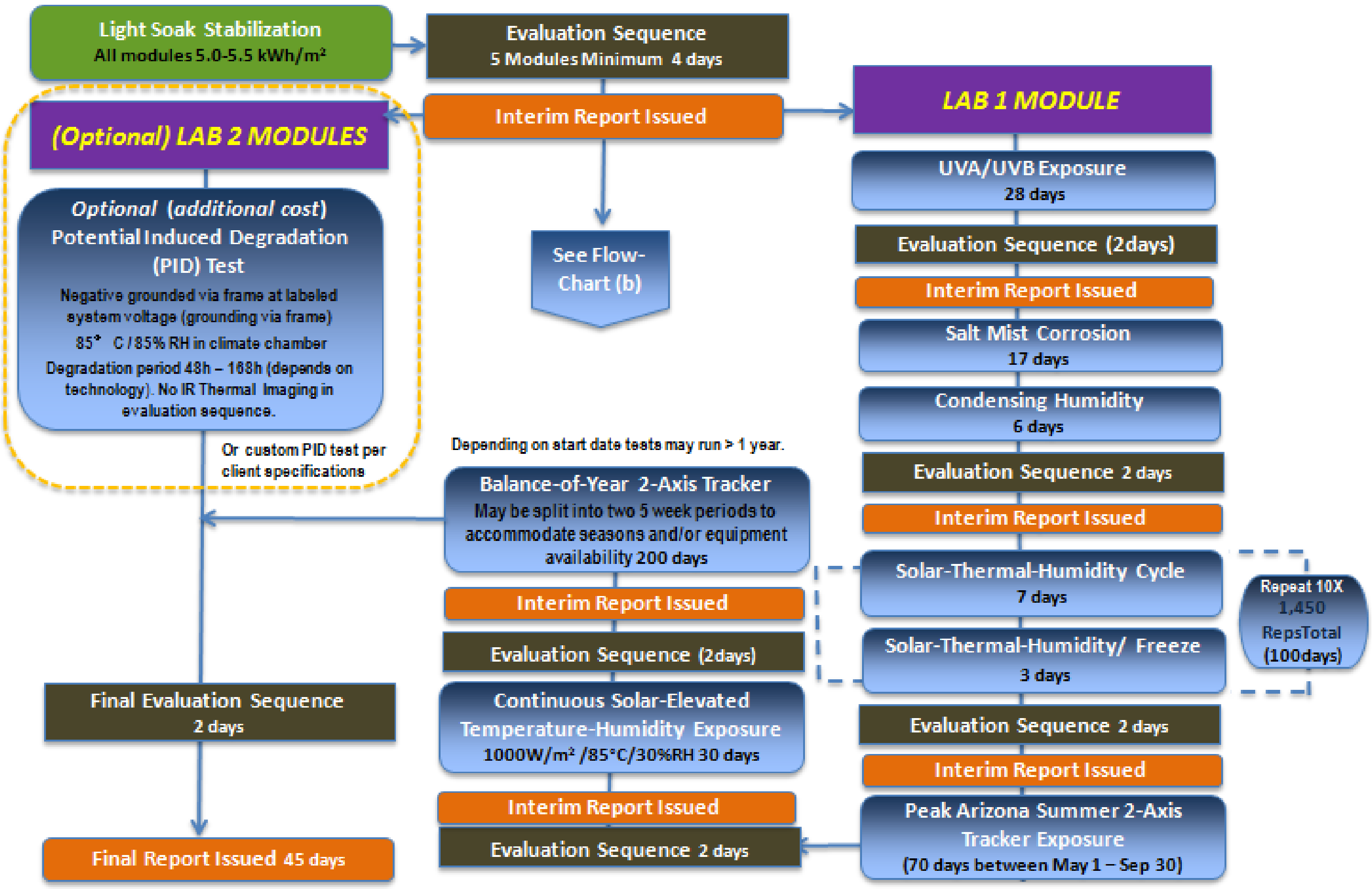
Annex A1
Atlas 25+ Standard



All Pmax determinations to be performed following washing. Final report to consolidate interim reports and provide analysis. Four test sample "mini-module" options also available instead of a standard module. Interim reports are data only and contain no analysis.



Annex A2(a)
Atlas 25+ Premium



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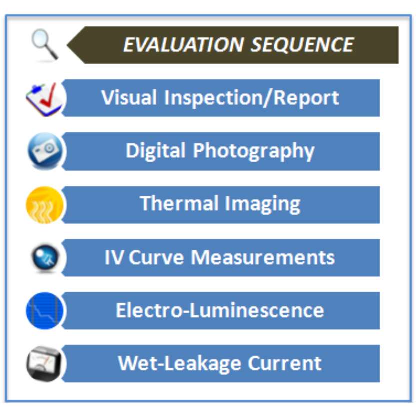
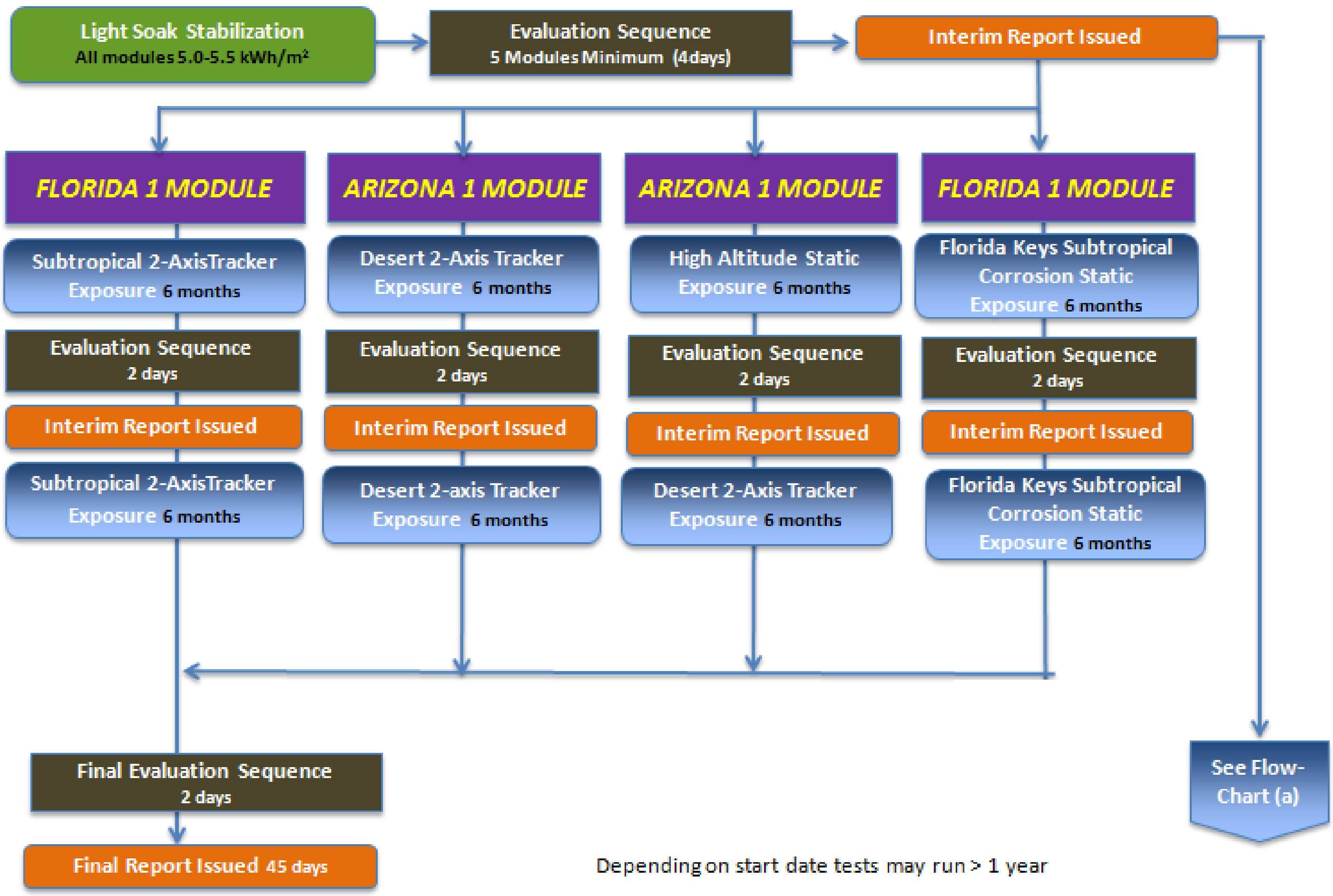


Annex A2(b)
Atlas 25$^+$ Premium



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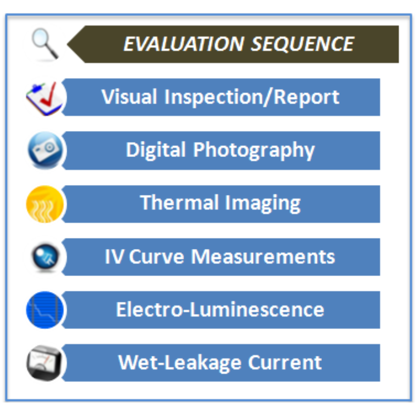
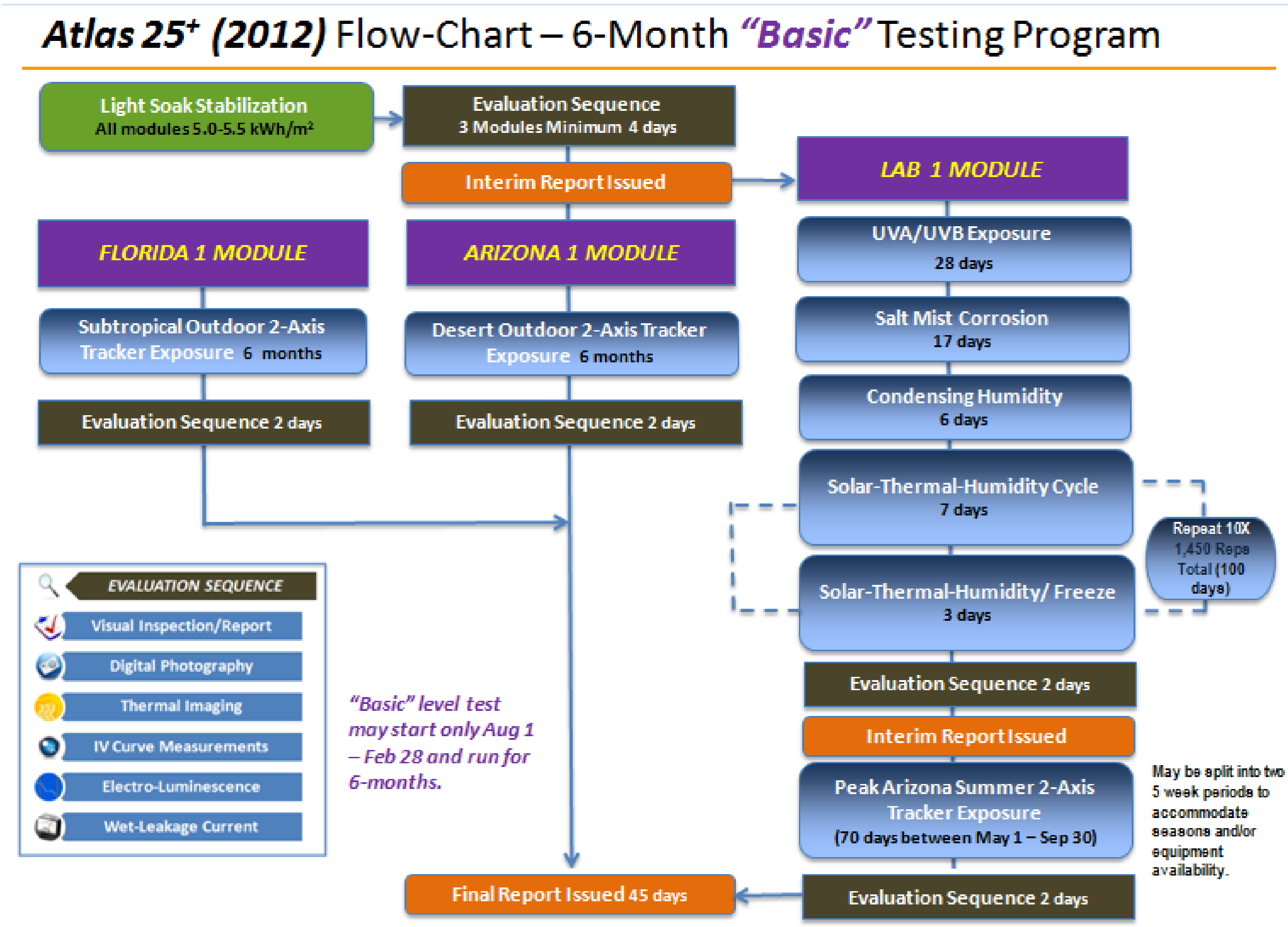


Annex A3
Atlas 25+ Basic
(Materials or Module R&D)



All Pmax determinations to be performed following washing. Final report to consolidate interim reports and provide analysis.

Annex B

Failure Mechanism Models – PV Module

Failure Mechanism	Failure Site	Failure Mode	Relevant Stresses	Environment Test	Model
Dielectric Breakdown	EVA Encapsulation	Leakage Currents	V, T	Powered Temp Aging	Eyring $V^n e^{-Ea/kT}$
UV Reaction Discoloration	EVA Encapsulation	Lower light efficiency	T, Intensity. Frequency	UV Exposure at Temp	Arrhenius Exp (-Ea/kT)
Deadhesion	Front Surface	Electrical Open	ΔT, H, ΔH	Damp heat Temp cycle	Coffin-Manson $N = C(\gamma)^n$
Deadhesion	Back Surface	Poor Heat Transfer	ΔT, H, ΔH	Damp heat Temp cycle	Coffin-Manson $N = C(\gamma)^n$
Corrosion	Front Surface Interconnects	Open Circuit Incr. Resist.	M, ΔV, T, impurities	Powered damp heat at Temp	Eyring $(V)^n(RH)^n e^{-Ea/kT}$
Fatigue Disintegration	Backsheet Lamination	Cracking	ΔT, ΔH, ΔV	Damp Heat Temp cycle	Coffin-Manson $N = C(\gamma)^n$
Fracture	Glass	Cracking	Mech Load	Mech Load	Paris Law (LEFM)
Fatigue	Edge Sealing	Cracking Voiding	ΔT,ΔH, ΔV	Damp Heat Temp cycle	Coffin-Manson $N = C(\gamma)^n$
Metal Segregation	Solder Connection	Voiding Intermetallic	T, J	Powered Temp Aging	Eyring (Black) $J^n e^{-Ea/kT}$
Fatigue	Solder or Cell Connection	Loss of connection	ΔT, ΔV	Powered Temp cycle	Coffin-Manson $N = C(\gamma)^n$

calce Center for Advanced Life Cycle Engineering 19 University of Maryland

D. Das., "Technology Advances to Improve Reliability –A Broad View", Center for Advanced Life Cycle Engineering (CALCE), University of Maryland, 2011.

White Paper

Photovoltaic Module Weather Durability and Reliability Testing

Authors: Allen F. Zielnik, Dr. David P. Dumbleton

Solar Energy Competence Center
Atlas Material Testing Technology LLC
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