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Accelerated Lifetime Testing of Module Level Power Electronics for Long-Term Reliability

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***Abstract* — This work has applied a suite of long-term reliability ALTs (accelerated lifetime tests) to a variety of MLPE devices (module level power electronics such as microinverters and optimizers) from five different manufacturers. This data set is one of first (only [3] is reported for reliability testing in the literature) as well as the largest experimental set in literature, both in sample size (5 manufacturers including both DC/DC and DC/AC units) as well as number of experiments (6 different experimental conditions) for MLPE devices. The accelerated stress tests (thermal cycling test per IEC 61215 profile, damp heat test per IEC 61215 profile and static temperature tests at 100, and 125°C) under powered and unpowered conditions.**

Included in these experiments are the first experimental data regarding damp heat and grid transient testing as well as the longest term (>9 month) testing of MLPE units reported in literature for thermal cycling and high temperature operating life. Additionally, this work is the first to show *in situ* power measurements as well as periodic efficiency measurements over length of experimental tests, demonstrating whether certain tests result in long-term degradation or immediate catastrophic failures.

The result of this testing demonstrates the robustness of MLPE units to several environmental stressors. The fact that relatively few MLPE units have failed at this amount of long-term testing, while the majority of PV modules fail long before 3,000 hours of damp heat testing, points to robust MLPE devices that can exhibit long lifetimes and may outlive PV modules in the field under normal usage conditions.

***Index Terms* — photovoltaics, accelerated life test, module level power electronics, MLPE, reliability, microinverter, optimizer**

I. Introduction

In order to make photovoltaics (PV) cost-competitive with traditional energy sources, economies of scale have been guiding inverter design increasingly towards small, modular, module-level power electronics (MLPE). MLPE (also known colloquially as AC modules), such as microinverters (MI) and DC power optimizers (DCO), are power electronic devices integrated or attached with the module so that there is one power-conditioning unit per module. This sort of power handling topology offers numerous advantages on the system level such as reduced power handling of components, partial shading gains, and piecemeal failure of the array via distributed architectures.

However, MLPEs suffer from a number of distinct disadvantages compared to more traditional centralized inverter configurations. First, depending on installation configuration (especially the proximity to the PV module), they can be subjected to more extreme environments (*e.g.* temperature cycling) during the day than a centralized inverter [4] (with little or no active cooling), resulting in a negative impact on reliability. Additionally, since MLPE units are, in many cases, sold paired with PV panels (and future direction points towards total incorporation into the module frame or module laminate itself), customers are demanding unit lifetimes and warranties similar to that of PV modules (~25 years).

Offering a 25-year warranty for a power-handling device in a cost-competitive environment is challenging. Therefore, the statistical reliability of each device and the extension of unit lifetime are of critical importance to the continued implementation of this type of PV solution. Unlike more mature technologies (*e.g.* c-Si PV modules), the MLPE market segment is relatively nascent (large-scale implementation of MLPE units has been occurring for less than ten years) and therefore does not have long-term usage data or reliability testing that exists in many other industries. While the majority of MLPE studies have focused on performance [5], there is a distinct lack of large-scale, test to failure reliability studies (*e.g.* [3] only conducted testing for 1000 hours units from a single manufacturer). The majority of MLPE reliability studies determine mean time between failure (MTBF) of MLPE units using MIL-HDBK-217 equations [6] to determine failure rates [7]. Unfortunately, MTBF only describes the large-population statistics of random failures during normal operational life of the units (*i.e.* the "floor" of the bathtub curve) and does not elucidate time to end-of-life of devices.

The 25-year lifetimes demanded by customers is an ambitious goal for a power handling unit and standardized reliability testing and long-term lifetime tests are needed to verify that MLPEs will last their claimed 25-year field lifetimes as well as elucidate statistics and failure mechanisms related to MLPE end-of-life. The objective of this work is to apply a suite of standard reliability accelerated lifetime tests (ALTs) to MLPE devices in a technology- and vendor-neutral manner to study intrinsic failure mechanisms/mode associated with unit end-of-life. With the implementation of industry wide standard reliability tests, the confidence of system operators, integrators, manufacturers, and financiers is increased, decreasing the cost of financing, warranty claims, and maintenance of solar installations.

II. Accelerated Life Tests

MLPE devices are complicated power handling devices with a wide variety of topologies, control schemes, and components. Each unit or component may have unique failure mechanisms depending on its specific electro-thermal environment. A simple component, such as a capacitor, has several failure mechanisms for each environmental stressor (voltage, temperature, current ripple, *etc.*). Therefore, the number of failure mechanisms in a unit composed of hundreds of components can easily number in the thousands. Specifically targeting and quantifying each failure mechanisms quickly becomes intractable for a wide variety of topologies and technologies.

The suite of long-term reliability tests that are presented in this work represent stress conditions prevalent in field use conditions and were identified through a Failure Modes and Effects Analysis (FMEA) of MLPE units as well as an anonymous survey of MLPE manufacturers [8]. This information was used to identify the most critical components and failure mechnisms prevalent in MLPE units in the industry and the tests which exacerbate relevant environmental stressors (**Error! Reference source not found.**).

Table 1. Environmental stressors and failure mechanisms for test tracks in this reliability testing protocol.

Test	Failure Mode/Mechanism	Stressor
Thermal Cycling	solder joint cracking, AC/DC cabling, potting delamination, and power semiconductor packaging delamination	ΔT
Damp Heat	Circuit board corrosion, dendrite formation	Temperature with humidity
High Temp.	MOSFETs, capacitors, and other power handling and control componentry wear out	Time at high temperature
Grid Transient	Overvoltage/current robustness of MOSFETs, capacitors, and safety protection devices	Overvoltage/Over current

The entire testing protocol with different testing tracks is shown in Fig. 1. A total sample population of 140 units from five different manufacturers (four MIs and one DCO) was pre-characterized via visual inspection, efficiency measurement, and AC power quality testing. After pre-characterization, 20 units were set aside as control units. The remaining units were split, at 20 units per test, between Damp Heat (DH) Testing, High Temperature Operating Life (HTOL) Testing at 100 and 125°C, Thermal Cycling (TC) Testing, and Grid Transient Testing. The unit under test (UUT) voltage and power conditions were monitored continuously, with periodic re-characterization similar to pre-characterization throughout the duration of the test. All tests were planned to run until failure of the entire population with failure times recorded. After each test, failed unpotted MI units underwent root cause failure analysis to determine the final failure mode.

III. Results

Thermal Cycling

Due to their proximity to the module, MLPE units are subject to large diurnal temperature cycles. These cycles are a frequent stress condition for units in the field and introduce damage at materials interfaces due to coefficient of thermal expansion mismatch. This stress condition will determine the robustness of solder joints, AC/DC cabling, potting delamination, and power semiconductor packaging in a wide variety of technologies across the MLPE industry.

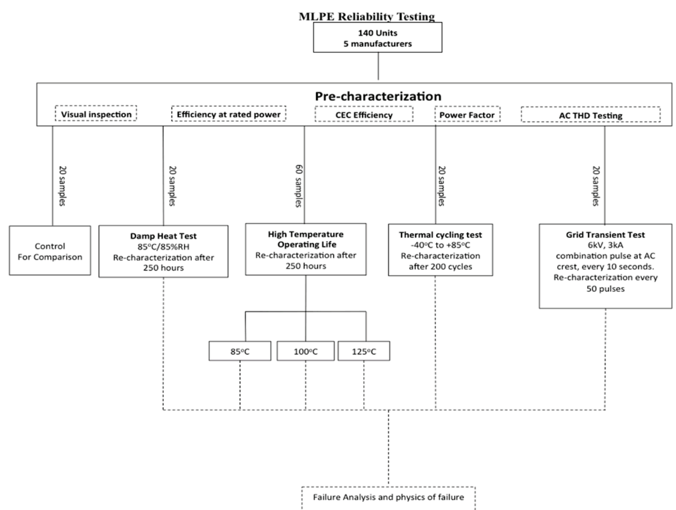

Fig. 1. Schematic for the different testing tracks for reliability testing of MLPE of different technologies and manufacturers.

Four samples per manufacturer from five manufacturers were tested for thermal cycle robustness. Two samples per manufacturer are powered (at rated power) during testing while two remain unpowered. During testing, each sample underwent thermal cycling from -40±2°C to 85°±2°C (as measured by a thermocouple attached to the UUT) with a dwell time of 10 minutes at the high and low temperatures and a ramp rate of 100°C/hr. The DC and AC voltage/current for each unit was continuously monitored for comparison to pre-stress state and to track any efficiency degradation.

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Additionally, re-characterization of efficiency and THD was carried out at room temperature after the termination of tests. The thermal cycling test is operated until units have failed (zero output power without ability to restart or degradation of greater than 20% from normal operation in MPPT, Efficiency, THD, or Power Factor).

Under powered conditions, all the MLPE units accepted DC input power for the full range of cycling. This is because the dwell time at 85°C is very short, preventing the units from entered a derate state. MLPE efficiency test results up to 836 cycles are provided in Fig. 2 below. Through the duration of the test (836 cycles lasting more than 10 months), nine of the ten powered units are operational. Only one (M3-1) of the ten powered units failed at 710 cycles.

Table 2: Final status of MLPEs after thermal cycling testing

MLPE unit	Time to failure (hours)	Powered/ Unpowered	Abnormalities
M1-1	Did Not Fail	Powered	
M1-2	Did Not Fail	Powered	
M2-1	Did Not Fail	Powered	
M2-2	Did Not Fail	Powered	
M3-1	Worked up to 710 cycles	Powered	Works under low DC Voltage (4.6 V, 7.6 A), Degraded Connectors
M3-2	Did Not Fail	Powered	
M4-1	Did Not Fail	Powered	
M4-2	Did Not Fail	Powered	
M5-1	Did Not Fail	Powered	
M5-2	Did Not Fail	Powered	
M1-3	Did Not Fail	Unpowered	
M1-4	Did Not Fail	Unpowered	
M2-3	Did Not Fail	Unpowered	
M2-4	Did Not Fail	Unpowered	
M3-3	Did Not Fail	Unpowered	
M3-4	Did Not Fail	Unpowered	
M4-3	Did Not Fail	Unpowered	
M4-4	Did Not Fail	Unpowered	
M5-3	Did Not Fail	Unpowered	
M5-4	Did Not Fail	Unpowered	

Even though units continue to operate, different manufacturers' units show differing amounts of degradation in efficiency during the extent to testing ranging from 1% (M4-1 and 2) to 7.3% (M5-1 and 2) as seen in Fig. 2. This degradation and power output is due to coefficient of thermal expansion (CTE) mismatch between disparate components. The two main causes of degradation are between the potting compound with high CTE and electronics with low CTE as well as solder joint fatigue. In both of these cases, cyclic thermal stress cause mechanical stress due to the differences in CTE coefficient between materials. This eventually causes cracks to form in materials. When these cracks form in metals, the normally low resistance metal increases, causing resistive losses in the unit to go up. These resistive losses decrease the efficiency of the unit. Different manufacturers use different formulations of potting compounds which results in different stresses under cyclic temperatures and different degradation profiles.

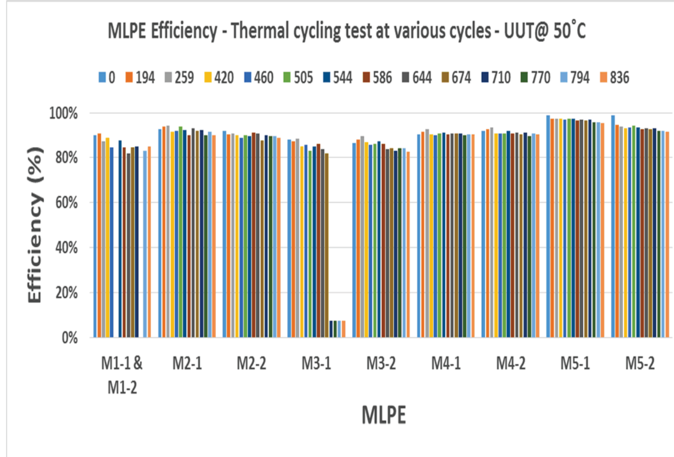

Fig. 3 MLPE efficiency at 50°C UUT after thermal cycling for 836 cycles.

It should be noted that after identifying thermal cycling issues with MLPE manufacturers, many of them stated that, in response to the issue, they had reformulated their potting compounds in order to mitigate or eliminate this failure mechanism and long-term degradation. Although CTE mismatch can never be completely abated, especially with regards to solder joints, the fact that manufacturers are aware of the issue and actively working towards solving it indicates that future generations of MLPEs will be even more robust to cyclic thermal stresses, both in regards to overall lifetime as well as efficiency degradation.

All electrical circuits which have different materials exhibit degradation due to cyclin thermal stresses leading to electro/mechanical degradation. PV modules exhibit degradation on the order of what have been seen in MLPE units in this work. Fig. 3 shows the efficiency degradations of MLPE units compared with similar cycling thermal testing of modules in [2]. The MLPE units in this work, only one of which failed, show similar rates of degradation as modules

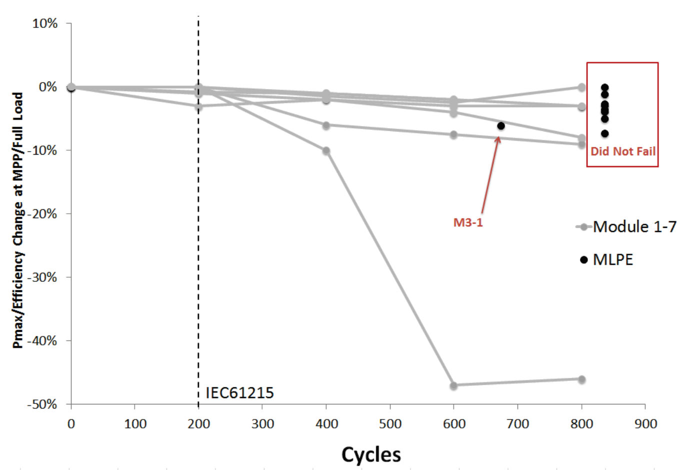

Fig. 2 MLPE and Module power output change as a function of thermal cycles. Module data
taken from [2].

over 800+ cycles. *If* the acceleration factors for modules and MLPEs are similar, this would indicate MLPE units that *may* be as robust to cycling thermal stress as the corresponding modules.

Additionally, since even the earliest failure was much longer (710 cycles) than the 200 cycles normally applied in IEC61215 testing, applying IEC61215 qualification testing to the MLPE units may be insufficient to weed-out the tail distribution of poorly operating devices from the bulk normally operating devices.

Damp Heat

Humidity is a common stress condition for power handling electronics. MLPE units in humid environments will develop corrosion as well as dendritic growth as water bridges connections on the circuit board. This stress condition highlights reliability of circuit boards and potting components. Damp heat testing was carried out for four units from five manufacturers.

Each unit to test underwent pre-characterization before any stress condition for efficiency and power quality (PF, THD, etc). Four samples per manufacturer from five manufacturers were tested. Each sample underwent damp heat stressing at 85±5% relative humidity and 85±2$_{o}$C (as measured by a thermocouple attached to the DUT) until failure (zero output power without ability to restart or degradation of greater than 20% from normal operation in MPPT, Efficiency, THD, or Power Factor). Two samples per manufacturer were powered during testing while two remained unpowered. The DC and AC voltage/current for each unit were continuously monitored for comparison to pre-stress state and to track any unit degradation. The damp heat testing was operated for >5,300 hours (>7 months).

The high temperature of the test can affect different units differently, as manufacturers customize their temperature protection and derating methods. For example, M1 units were found to stop accepting the input dc power whenever the ambient chamber temperature is above 70°C – therefore, all four M1 should be considered being stressed only at 85$_{o}$C/85%RH under unpowered conditions. All other manufacturers' (M2 through M5) samples accepted the input DC power and operated normally under the ambient temperature and humidity conditions of the chamber. In addition to instantaneous input/output current/voltage measurements, the damp heat testing was briefly stopped every 250 hours and the chamber was allowed to cool down to close to room temperature so that all 10 powered samples could be removed and their functionalities and efficiencies recorded.

Efficiency results for the damp heat test after 5,380 hours are shown in Fig. 4. The temperature of one of the M1 units was used as the UUT (unit under test) temperature.

The units under test exhibited rather small (<5%) changes in efficiency over test lifetime. As the margin of error for an efficiency measurement is a few percent (~±2%), the deviations in efficiency during the length of the test shown in Fig. 4 are within the error of efficiency measurement. Additionally, the changes in efficiency are not consistent. Therefore, if there is long term unit degradation, it is a slight secondary effect. This is to be expected if the relevant failure mechanisms are component wearout (especially capacitors), which would have little effect on power output.

Damp heat was a much more damaging test to the units with four of the power units failing during testing. MLPE time-to-failure (TTF) table for powered and unpowered units after 5,380 hours of damp heat chamber testing is provided in Table 3.

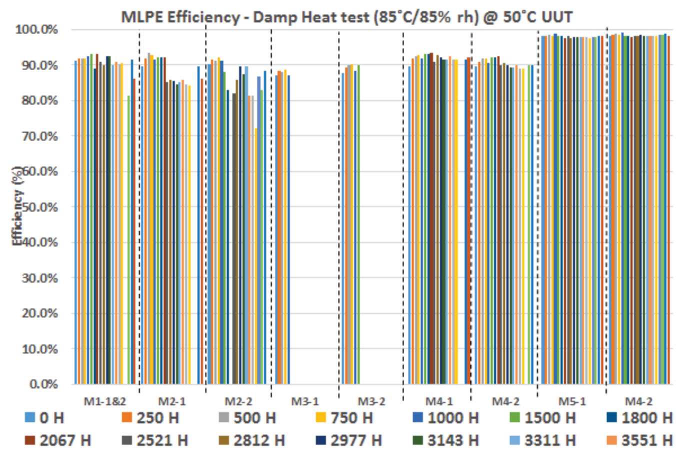

Fig. 4 MLPE Efficiency at different times during damp heat testing

The failure of all units occurred suddenly with no precursor degradation (example in Fig. 5). The failed units were analyzed and the interiors of the failed units were compared with pristine devices. It was evident from corrosion markers on the potting material that the units allowed moisture ingress into the potting material during testing. This ingress of moisture most likely caused failure due to dendritic growth on the PCB, eventually resulting in a short circuit and permanent unit failure.

In addition to corrosion by-products in and around the pottant, several packaging and connector issues became apparent in a variety of units. Although these issues did not

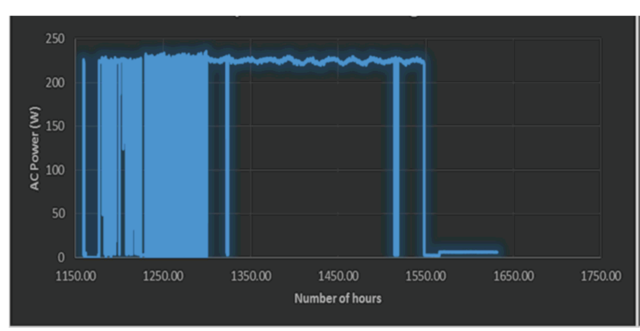

Fig. 5 Failed M3-1 unit#1 failed catastrophically with no degradation signatures at 1550 hours of testing

cause failure (this work only considered the power handling stage, although connector/housing issues could retroactively be considered a failure since they would most likely result in a warranty claim in the field), they are disconcerting since they occurred a temperatures (85°C) which should be well below the limits of the polymers used in the construction of the units. Damage in the test, which was not considered a failure ranged from cracked casing in the M5 units to screw corrosion in passive M1 units. Units from Manufacturer 3 had AC connectors that were found to have become brittle after long hours of damp heat exposure. Multiple connectors were broken while passive units were tested for failure. This was not apparent from the powered units because those units are not moved and connected/disconnected repeatedly from the characterization equipment. This indicates that a connect/disconnect testing protocol should be included with MLPE device testing.

Table 3. Final status of MLPEs after damp heat testing

MLPE unit	Time to failure (hours)	Powered/ Unpowered	Abnormalities
M1-1	No failure	Powered	
M1-2	No failure	Powered	
M2-1	No failure	Powered	
M2-2	4369 - 4876	Powered	Nonfunctional at Ambient Conditions
M3-1	1240	Powered	Works only low power (40V, 2.9 A)
M3-2	1550	Powered	
M4-1	No failure	Powered	
M4-2	4369 - 4876	Powered	Nonfunctional at Ambient Conditions
M5-1	No failure	Powered	Cracked case, otherwise functional
M5-2	No failure	Powered	Cracked case, otherwise functional
M1-3	No failure	Unpowered	
M1-4	No failure	Unpowered	
M2-3	No failure	Unpowered	
M2-4	No failure	Unpowered	
M3-1	No failure	Unpowered	
M3-2	No failure	Unpowered	
M4-1	No failure	Unpowered	Broken Connector, otherwise functional
M4-2	No failure	Unpowered	
M5-1	No failure	Unpowered	Cracked case, otherwise functional
M5-2	No failure	Unpowered	

Damp heat testing is traditionally very damaging to power electronics devices. Although half the powered units failed during this testing regime, they did not exhibit large decreases in power output. Fig. 6 shows the normalized power output of seven Si PV modules [1] with the MLPE results obtained here. Compared to the modules, the MLPE units show relatively small power degradation over the length of the test. However, it is known that damp heat testing on PV modules over accelerates certain failure mechanisms that are not seen

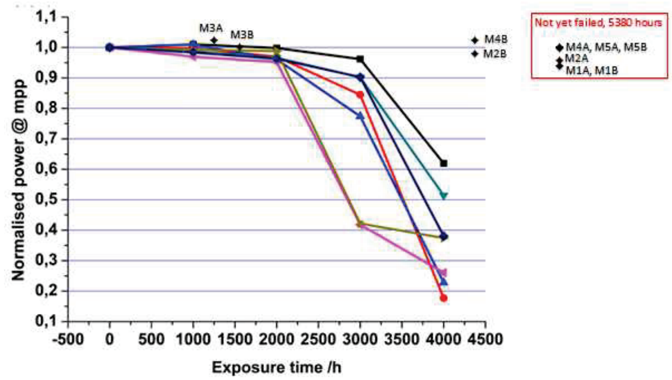

Fig. 6. Relative power at MPP of 7 different c-Si modules after DH testing (data from [1]) compared to full load testing of MLPE units (normalized efficiency)

in fielded units. Since the failure mechanisms are different and the PV failure mechanisms are over-excited, a true apples-to-apples comparison between lifetimes of modules and MLPE is not possible without further testing. Although certain failure mechanisms (of the hundreds or thousands that are present) in MLPEs are also over-accelerated by damp heat exposure and are likely over-represented failure mechanisms in these tests, further testing must be carried out on the specific failure mechanisms to make more direct comparisons and determine overall unit lifetime.

High Temperature Operating Life (125°C)

High temperature is a primary wearout mechanism for electronic components. MLPE units in high temperature environments will see higher component failures of silicon devices and other passive components. This stress condition highlights reliability of MOSFETs, capacitors, and other power handling and control componentry.

For testing, each sample underwent high temperature stressing while at 125oC as measured by a thermocouple attached to the UUT. The DC and AC voltage/current for each unit was continuously monitored for comparison to pre-stress state and to track any unit degradation. Ten samples were powered (two per manufacturer; five manufacturers) and another set of ten samples were unpowered (two per manufacturer; five manufacturers). Units were removed every 250 hours for re-characterization and comparison to pre-stress state. This approach was repeated for environmental chambers at 100oC.

All samples derated and stopped accepting power around 125 °C, although the specific set point of the derating behavior varied from manufacturer to manufacturer. Units from manufacturer M1 and M2 stopped accepting input power once the UUT reached 85-90 °C. M4 began derating behavior around 90-100 °C and M5 units stopped operating around 100-105 °C. No units accepted input power under the 125 °C UUT temperature test condition.

In addition to continuous monitoring of input/output current/voltage, testing was briefly stopped once a week to

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allow the chamber to cool to around 50°C for the purposes of measuring the functionalities and efficiencies of all 10 powered samples.

MLPE efficiency test results up to 3,694 hrs of 125 °C exposure was provided as shown in Fig. 7. All chamber tests (damp heat, thermal cycling and all three static temperatures) were terminated on December 30, 2015. It is to be noted that the 125°C static temperature test for the M3 units were started only in late November, 2015 due to unavailability of the test samples (unlike other units which were started about six months earlier). All four M3 units were introduced in the chamber when all other manufacturers' units have already gone through 3166 hours of stress and hence were subjected to only 528 hours with no failures observed (see the green and blue data in Fig. 7).

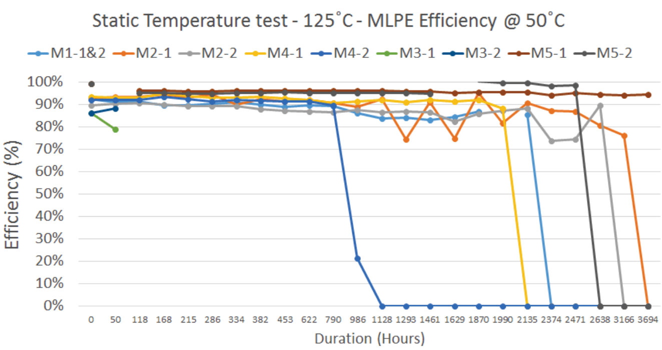

Fig. 7. Static 125°C test results of the powered units after maintaining at 50°C at rated input power

MLPE time to failure table for powered and unpowered units for the 125°C test is provided Table 4. Powered M-1&2, powered M2-1&2, powered M4-1&2, and powered M5-2 (unit M5-1 did not fail) were determined to be failed after cooling down to 50°C as shown in the table. It is to be noted that M3 units were put into test only for 528 hours.

In 125°C testing, issues with cracked and degraded cabling became apparent. Although these issues did not cause failure (this project only considered the power handling stage, although connector/housing issues could retroactively be considered a failure since they would most likely result in a warranty claim in the field), they are disconcerting since cabling issues, especially on the AC-side of the unit, can lead to safety issues while in the field. However, 125°C is an extremely stressful test for polymeric materials and is at or near their maximum operating point of the constituent polymers for cabling/connectors. Damage in the test, which was not considered a failure, ranged from embrittled and cracked cabling with insulation leakage in M4 units to cable fraying at the entrance to the unit body in M2.

High Temperature Operating Life (100°C)

In the static temperature 100 °C testing, ten samples were powered (two per manufacturer; four manufacturers) and another set of 10 samples were unpowered (2 per manufacturer; four manufacturers). As with the 125°C testing, the units from different manufacturers exhibited a range of derating temperatures. All samples except M5 units stopped accepting power at the 100 °C chamber temperature. In addition to continuous monitoring of input/output current/voltage, the testing was paused weekly and the chamber was allowed to cool down to 50 °C so that functionalities and efficiencies of all powered samples could be measured.

Table 4. Time-to-failure (TTF) of MLPE units in static temperature 125°C test

MLPE unit	Time to failure (hours)	Powered/ Unpowered	Abnormalities
M1-1	1870 - 1990	Powered	COD (comm. device) trip
M1-2	2135 - 2374	Powered	
M2-1	3166 - 3694	Powered	Embrittled, cracked wires
M2-2	2638 - 3166	Powered	Embrittled, cracked wires
M3-1	Did Not Fail	Powered	
M3-2	Did Not Fail	Powered	
M4-1	1870 - 1990	Powered	Embrittled, cracked wires, encapsulant leakage
M4-2	791 - 986	Powered	Embrittled, cracked wires, encapsulant leakage
M5-1	Did Not Fail	Powered	
M5-2	2471 - 2638	Powered	
M1-3	Did Not Fail	Unpowered	
M1-4	Did Not Fail	Unpowered	
M2-3	Did Not Fail	Unpowered	Embrittled, cracked wires
M2-4	Did Not Fail	Unpowered	Embrittled, cracked wires
M3-3	Did Not Fail	Unpowered	Embrittled, cracked wires, encapsulant leakage
M3-4	Did Not Fail	Unpowered	Slightly cracked connectors, encapsulant leakage
M4-3	Did Not Fail	Unpowered	
M4-4	Did Not Fail	Unpowered	
M5-3	Did Not Fail	Unpowered	
M5-4	Did Not Fail	Unpowered	

As with the 125°C testing, it is to be noted that the 100°C static temperature test for the M3 Bridge units was started late due to unavailability of the test. All the four M3 units were introduced in the chamber when all other manufacturers' units have already gone through 2963 hours of stress; hence the M3 were subjected to only 798 hours of 100°C with no failures were observed (see the green and blue data points in Figure 27). MLPE efficiency test results up to 3,491 hours of 100 °C exposure is provided in Fig. 8

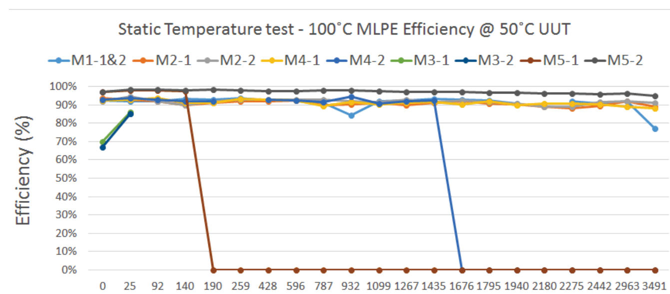

Fig. 8. Static 100°C test results of the powered units after maintaining at 50°C at rated input power

MLPE time to failure table for powered and unpowered units for the 100°C test is provided Table 11. It is to be noted that two units failed during the extent of testing (3491 hours), M5-1 (at 752 hours, which is most likely due to a manufacturing issue and is not a true end-of-life time) and M4-1 at approximately 1500 hours. It is also to be noted that M3 units were put into test only for 798 hours.

Table 5. Time-to-failure (TTF) of MLPE units in static temperature 100°C test

MLPE unit	Time to failure (hours)	Powered/ Unpowered	Abnormalities
M1-1	Did Not Fail	Powered	
M1-2	Did Not Fail	Powered	
M2-1	Did Not Fail	Powered	Embrittled, cracked wires
M2-2	Did Not Fail	Powered	Embrittled, cracked wires
M3-1	Did Not Fail	Powered	
M3-2	Did Not Fail	Powered	
M4-1	1435 - 1676	Powered	Insulation Leakage
M4-2	Did Not Fail	Powered	
M5-1	152	Powered	
M5-2	Did Not Fail	Powered	
M1-3	Did Not Fail	Unpowered	
M1-4	Did Not Fail	Unpowered	
M2-3	Did Not Fail	Unpowered	Embrittled, cracked wires
M2-4	Did Not Fail	Unpowered	Embrittled, cracked wires
M3-3	Did Not Fail	Unpowered	
M3-4	Did Not Fail	Unpowered	
M4-3	Did Not Fail	Unpowered	
M4-4	Did Not Fail	Unpowered	
M5-3	Did Not Fail	Unpowered	
M5-4	Did Not Fail	Unpowered	

Similar to 125oC testing, issues with cracked and degraded cabling became apparent. Again, these issues were not considered a cause of failure. However, they demonstrated cabling issues car occur lower than the maximum operating temperature of the polymer. Damage in the test, which was not considered a failure, ranged from embrittled and cracked cabling with insulation leakage in M4 units to cable fraying at the wire/body interface in M2 units .

Grid Transient Testing

Grid transients are a significant stress on power conversion systems that can lead to failure (both failure due to actuation of circuit detection devices as well as unintended failures) or unintended operational modes (e.g. damage to sensing equipment). Utility interconnected devices are required to adhere to IEEE 1547-2005 [9] and be listed to UL 1741-2010 [10] requirements. These standards primarily address inverter performance and safety or protection aspects such as power and current limits. However, their robustness to repeated AC-side transients (such as from lightning strikes) is unknown.

This stress condition highlights reliability of MOSFETs, capacitors, and safety protection devices to repeated voltage/current surges below what is necessary to actuate the safety protection devices. Voltage surges stresses high impedance componentry (MOSFET in blocking mode, transformers, etc.) while current surges stress low impedance components (filter capacitors, protection devices, etc.) if the protection circuit does not fully abate the surge from the AC side.

Powered grid transient testing for four units from five manufacturers was carried out. This test is based off of NFPA 780 and IEEE C62.45, safety tests that require devices to survive a single grid transient surge without total loss of functionality. For these evaluations, the reliability testing is focused on the ability of MLPE units to withstand repeated surges from the AC-side (such electrical transients may be present due to an unstable grid or weather events) without changes in performance. This test determines the robustness of systems to repeated grid transients, which sheds light on the lifetime of devices, especially in lightning prone areas or areas with weak grids.

Four samples per manufacturer from five manufacturers were connected to real PV and the utility. Grid transients were applied to the UUT from a combination voltage/current waveform (V=6 kV 1.2 x 50 µs, I=3 kA, 8x20 µs) applied every 10 seconds by a Haefely PIM200 Surge unit that complies with C62.41.2. The combination wave applies a 1.2 x 50 µs voltage wave across an open circuit and a 8 x 20 µs current into a short circuit. The resultant waveform is determined by the generator and the impedance of the UUT. For these tests, the value of the peak open-circuit voltage is 6 kV, and the peak short-circuit current is 3 kA.

Each unit to test undergoes pre-characterization before any stress condition for efficiency and power quality (PF, THD, etc). Units were re-characterization every 100 pulses and compared to the pre-stress state.

When pulsed, the DUT output power shows a variety of behavior from a momentary fluctuation in power output (but remains on during each pulse) to shut down and restart (after ~20s). The specific response to the pulse depends on the manufacturer. For example, M4 units showed a momentary fluctuation, but rode through the pulse while M2 units shut down and required a restart.

All units tested showed extreme robustness with respect to high current/high voltage pulses on the AC side. Even the least robust units (M4) lasted for at least 300 pulses before failure (Table XII), far more than would be seen during the lifetime of the unit under normal operation. Units from other manufacturers lasted >700 pulses.

Table 6. Pulse number where failure occurs

MLPE	Number of Pulses until Failure
M4-1	~300
M4-2	400
M4-3	500
M4-4	>700
M4-5	300

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The tested units showed no signs of degradation in CEC efficiency, voltage or current THD, or (Fig. 9) and failed in in a "safe" mode, with no misoperation, misinformation, or safety issues associated with the failure. The robustness and lack of degradation indicates that the pulse train does not propagate through to protection circuit to the power stage (at least not enough to damage the power stage until overall failure of the unit after hundreds of pulses). This indicates that the protection componentry of the units should operate in a normal manner for the duration of the unit's mission.

IV. Summary

This work has applied a suite of standard reliability ALTs to a variety of MLPE devices from different manufacturers. This data set is one of first (only [3] is reported for reliability testing in the literature) as well as the largest experimental set in literature, both in sample size (5 manufacturers including both DC/DC and DC/AC units) as well as number of experiments (6 different experimental conditions) for MLPE devices. Included in these experiments are the first experimental data regarding damp heat and grid transient testing as well as the longest term (>9 month) testing of MLPE units reported in literature for thermal cycling and high temperature operating life.

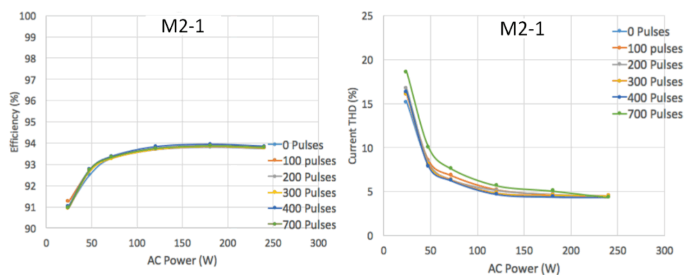

Fig. 9. (a) Efficiency (b) Current THD for M2-1 showing no degradation in energy production throughout grid transient testing

Additionally, this work is the first to show *in situ* power measurements as well as periodic efficiency measurements over length of experimental tests, demonstrating whether certain tests result in long-term degradation or immediate catastrophic failures.

The result of this testing demonstrates the robustness of MLPE units to several environmental stressors. A summary of the time to failures of these devices is shown in Table 7. These test are similar to those carried out on modules in IEC [11], which have the same microenvironment as MLPE devices. The fact that relatively few MLPE units have failed at after 3,000+ hour of testing points to robust devices that may perform for long timeframes with their attached PV modules in the field under normal usage conditions. This comparison is more valid for thermal cycling tests than damp heat due to the similarities in failure mechanisms. In damp heat testing, module failure mechanisms are over-accelerated, while it is unknown what, if any, failure mechanisms may be over-accelerated in MLPEs (it is likely at that least some of the thousands of failure mechanisms present in MLPEs are over-accelerated, although which ones and to what extent require much further study).

Table 7. Summary of failure times of MLPE devices under test

Device	Thermal Cycling	Damp Heat	Static T (100oC)	Static T (125oC)
M1-1	> 835 cycles	>5380 hr	>3491 hr	1870 hr
M1-2	> 835 cycles	>5380 hr	>3491 hr	2135 hr
M2-1	> 835 cycles	>5380 hr	>3491 hr	3166 hr
M2-2	> 835 cycles	4876 hr	>3491 hr	2638 hr
M3-1	710 cycles	1240 hr	>528 hr	>528 hr
M3-2	> 835 cycles	1550 hr	>528 hr	>528 hr
M4-1	> 835 cycles	>5380 hr	1435 hr	1870 hr
M4-2	> 835 cycles	4369 hr	>3491 hr	791 hr
M5-1	> 835 cycles	>5380 hr	152 hr	>3469 hr
M5-2	> 835 cycles	>5380 hr	>3491 hr	2471 hr

Additionally, in this work, the experimental testing has demonstrated possible weaknesses in insulation/connectors at temperatures as low as 85°C. Although the work looked at failures in regards to power handling, these connector issues are extremely problematic as they would most likely result in warranty claims. Additionally, the degradation of cabling on the AC-side connectors is troubling as it could lead to a safety condition if the cables short.

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VI. References

[1] M. Koehl, "Moisture as stress factor for PV-modules," in *Photovoltaic Specialists Conference (PVSC), 2013 IEEE 39th*, 2013, pp. 1566-1570.

[2] W. Herrmann and N. Bogdanski, "Outdoor weathering of PV modules—effects of various climates and comparison with accelerated laboratory testing," in *Photovoltaic Specialists Conference (PVSC), 2011 37th IEEE*, 2011, pp. 002305-002311.

[3] T. P. Parker, P. L. Chapman, and P. Gilchrist, "Dominant factors affecting reliability of alternating current photovoltaic modules," in *Photovoltaic Specialist Conference (PVSC), 2015 IEEE 42nd*, 2015, pp. 1-6.

[4] K. M. Armijo, B. B. Yang, D. Riley, O. Lavrova, S. Gonzalez, and H. Lomasney, "Predictive reliability

for AC photovoltaic modules based on electro-thermal phenomena," in *Photovoltaic Specialist Conference (PVSC), 2015 IEEE 42nd*, 2015, pp. 1-6.

[5] S. Krauter and J. Bendfeld, "Cost, performance, and yield comparison of eight different micro-inverters," in *Photovoltaic Specialist Conference (PVSC), 2015 IEEE 42nd*, 2015, pp. 1-4.

[6] "MIlitary Handbook: Reliability prediction of electronic equipment," in *MIL-HDBK-217F*, ed, 1991.

[7] S. Harb and R. S. Balog, "Reliability of Candidate Photovoltaic Module-Integrated-Inverter (PV-MII) Topologies—A Usage Model Approach," *Power Electronics, IEEE Transactions on,* vol. 28, pp. 3019-3027, 2013.

[8] A. Sastry, S. Kulasekaran, J. Flicker, R. Ayyanar, G. TamizhMani, J. Roy*, et al.*, "Failure modes and effect analysis of module level power electronics," in *Photovoltaic Specialist Conference (PVSC), 2015 IEEE 42nd*, 2015, pp. 1-3.

[9] IEEE, "IEEE1547: Standard for Interconnecting Distributed Resources with Electric Power Systems," in *1547-2005*, ed, 2005.

[10] U. Laboratory, "1741: Standard for Inverters, Converters, Controllers and Interconnection System Equipment for Use With Distributed Energy Resources," in *1741-2010*, ed, 2010.

[11] IEC, "61215: Crystalline silicon terrestrial photovoltaic (PV) modules. Design qualification and type approval," ed. Geneva, 2005.