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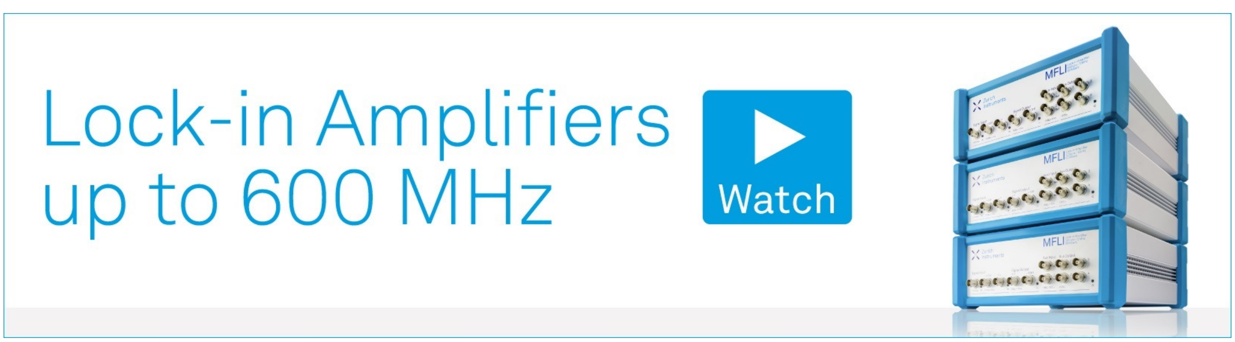

Present Status and Main Guidelines of IEC 62787: "Concentrator Photovoltaic (CPV) Solar Cells and Cell-on-Carrier (CoC) Assemblies – Qualification"

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Abstract. Qualification standards are one the driving forces for the commercialization and production of the Concentrator Photovoltaic (CPV) technology. After several years of preparation the Committee Draft of IEC 62787 has been finally submitted. The new standard IEC 62787 (Concentrator photovoltaic (CPV) solar cells and cell-on-carrier (CoC) assemblies – Qualification) fills the gap between the IEC TS 62789:2014 (Photovoltaic concentrator cell documentation) and the IEC 62108 Ed 2 (Concentrator photovoltaic (CPV) modules and assemblies - Design qualification and type approval). In the present article, apart from analyzing the objective, main guidelines, the innovative characteristics, and the life estimation from several tests of the qualification standard is also explained.

INTRODUCTION

Qualification standards are one the driving forces for the commercialization and production of the Concentrator Photovoltaic (CPV) technology because these standards are the core support in the supplier-costumer agreement. These qualification standards pursue to validate the product quality for the supplier, to ensure the product quality for the customer, and to reduce the economic risk for the investors and insurance companies involved in CPV installation.

Qualification standards based on both wide laboratory results and long track on-field failure experience are able to promote long term product life cycle [1,2,3]. Further, the tests of a standard for product qualification essentially focus on two criteria; a) only the products overcome an initial quality level will pass the qualification and b) the products passing the qualification will exhibit a high reliability for several years of lifetime. This is the goal of the new standard IEC 62787 (Concentrator photovoltaic (CPV) solar cells and cell-on-carrier (CoC) assemblies – Qualification) [4] fills the gap between the IEC TS 62789:2014 (Photovoltaic concentrator cell documentation) [5] and the IEC 62108 Ed 2 (Concentrator photovoltaic (CPV) modules and assemblies - Design qualification and type approval) [6].

After several years of preparation the Committee Draft (CD) of IEC 62787 has been finally submitted. However, due to the stagnant situation of the CPV in the last years, only a few experts have participated in the last years of preparation of IEC 62787. In the current stage of IEC 62787, when changes can be suggested by the national committees, this paper describes the most important aspects of this standard trying to promote a constructive discussion which can improve it.

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MAIN GUIDELINES OF THE IEC 62787

The standard has two separate qualification tests description for two different products, (a) one for bare solar cells, and (b) other by CoCs (cell-on-carrier). In the case of bare solar cells, the supplier shall provide solar cells on a representative carrier for developing some tests. Contrastingly, in the case of CoCs, the solar cells attached over the CoC should be previously qualified by the IEC 62787.

From the reliability perspective, the materials and devices under a combination of stressors (environmental, electrical, optical, etc.) have three types of failure rate periods (as shown in the bathtub curve of Figure 1). The tests of the IEC 62787 standard constitute a qualification gate with two different objectives,

- To avoid products with low initial quality level, that could produce infant mortality failures (IMF), due to fabrication weakness that results in failures during the first days-weeks of operation. Many of these tests are common to the qualification tests of other electronic devices.
- To avoid products that do not overcome a minimum lifetime of several years. Some Accelerated Life Tests (ALT) have been specifically designed for concentrator solar cells and CoCs in order to ensure a minimum lifetime.

These ALT cover first life years with a combination of infant mortality, random and wear failures that will appear mainly after several years of life, namely, as observed failure rate (OFR). ALTs are complex because there are many variables and many different working conditions depending on the location of operation and the particular design of the solar cell or CoC [7], and in this case identifying a unique "real" working condition equivalent to the non-environmental affected electronic devices is impossible. Besides, the emulation in laboratory of real working conditions presents many difficulties and it is costly. In the IEC 62787, we have carried out an integral analysis in order to avoid redundant tests with IEC 62108 Ed 2, thus reducing the time and costs of the qualification. For example, the test for UV light effect is developed for CPV modules including solar cells in the IEC 62108 Ed 2, and for that reason is not incorporated in the IEC 62787 standard.

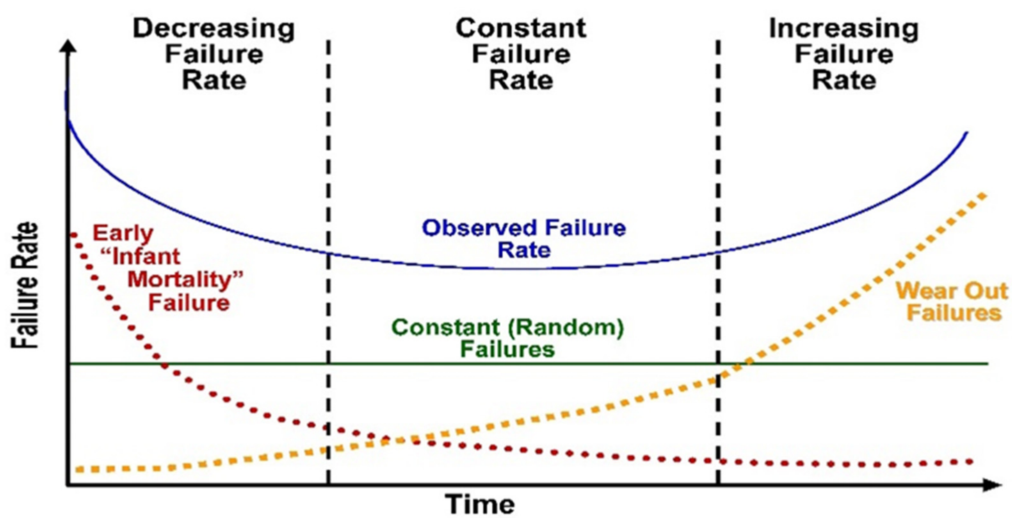

FIGURE 1. Schematics of the "bathtub curve" hazard function. The observed failure rate (OFR) (blue, upper solid line) is a combination of a decreasing hazard of early failure (IMF)(red dotted line) and an increasing hazard of wear-out failure (yellow dotted line), plus some constant hazard of random failure (green, lower solid line). Source: McSush (talk) - Bathtub_curve.jpg, Public Domain (http://bit.ly/20XKxPm).

The main objective of the proposed tests is that if a product passes the tests, it is possible to ensure that the product will have at least a minimum lifetime. In order to do that, two different types of tests are proposed:

- Tests to detect weaknesses that cause the most common early infant mortality failures (IMF). The IMF test is designed in such a way that it provokes infant failures due to possible infant weakness. If a cell or CoC does not pass an IMF test, it is not possible to ensure that a failure will not appear in the early stages of operation. Many of these tests are similar to the qualification test of other electronic devices and are related to the adhesion, wire and chip bonding, and ESD Damage Threshold (see Table 1). The origins of these tests are the military microcircuits standards (MIL-STD-883E, Department of Defense Test Method Standard Microcircuits, 1996), and their evolution and improvements by different organizations as JEDEC [8], IEC, and others, for optoelectronic semiconductor devices as IES LM-80-08 (Measuring Lumen Maintenance of Led and Light Sources), or ECSS-E-ST-20-08C Rev.1 (European Cooperation for Space Standardization - Photovoltaic assemblies and components).

- Tests oriented to ensure that bare cells and CoCs will exhibit a very low failure rate for several years of operation. These test are usually accomplished by means of ALT (see Table 1). The OFR ALT will be done with the aim of emulating the effect of the stress during several years of life in real working conditions [7]. These tests are more specific for solar cells than IMF tests, so the OFR tests are based on the degradation and failures reported in the field [9-10], the application of the ALT concept [11], and the related experiments carried out through accelerated ageing tests [12-13].

If a bare solar cell or CoC pass both types of tests, one can assume that it will not have the most common infant failures and it will have a minimum lifetime. Table 1 shows the classification of tests related to IMF and OFR. IMF tests are well-known procedures, also applied to other electronic device areas, while the OFR tests are customized for CPV applications, including outdoor operation, high temperature, current injection, etc.

The tests to ensure bare solar cell and CoC lifetime will be done to emulate the effect of the stress during several years in nominal working conditions. These tests are based on ALT [3,11-13] and they have to provoke the same failures that appear in real operation conditions but in a short period of time (because of the acceleration factor). For this purpose, during ALT an overstress over a given performance condition is applied in combination with the emulated non-overstressed functional real operation. The selection of the most suitable ALT depends on the conditions, which upon the application of the stress enhances the main failures mechanisms that appear in real operation. As bare solar cells and CoCs are subjected from nominal conditions to high stresses such as temperature, thermal cycles, full spectrum illumination, and current, all these stresses must be taken into consideration (see Table 1).

TABLE 1. Table presents the test for bare solar cells and CoCs included in the IEC62787, classified by failure types: IMF related tests and OFR related tests.

Failure Types	Test Name IEC 62787 (bare solar cell)	Test Name IEC 72787 (CoC)
IMF (Early life)	ESD Damage Threshold Front and Back Metal Adhesion Solderability High Temperature Storage	ESD Damage Threshold Wire/Ribbon Bond Strength Die Adhesion Connectors shear strength Bypass Diode (if present) shear strength High Temperature Storage
OFR (First years of life)	High temperature with current injection Thermal Cycling Low Level Light Biased Damp heat Illumination	High temperature with current injection Thermal Cycling

However, to extrapolate the results from ALT to real operation in a solar cell or CoC has a major difficulty because real operation of a solar cell or CoC is not unique as it undergoes changes depending on the environmental conditions (ambient temperature and irradiance among others) [7]. Nevertheless, the target of the qualification tests is not to evaluate the lifetime of the product but to assure a minimum lifetime, and all these considerations have been taken into account while designing the tests.

Another important consideration is the significance of the sample size test. In the case of this standard, the election of sample size is biased by (i) the difficulty of test development, (ii) the cost, and (iii) the insurance of an Acceptable Quality Limit adequate (AQL) of the product population. This AQL is defined on the standard IEC 61193-2:2007, and a pass criterion of zero failures has been selected in each test [14]. The specific protocol to pass the standard in case of some failures during tests is developed in section “7 Pass criteria” of the standard [4]. The combination of information regarding both the sample test size significance and the estimation of real life time equivalent of an ALT OFR test becomes a powerful tool.

A final remark is the specific characterization methods for measuring the performance of bare solar cells and CoCs subjected to qualification tests for identifying failure modes that appear in laboratory tests or real operation.

These methods are (a) visuals inspection, (b) dark and light I-V measurement, (c) thermal resistance measurement, (d) X-ray and Scanning Acoustic Microscope (SAM), and (e) optionally Electroluminescence mapping (EL). Generally, the basis of this characterization is to pass several criteria, but the most common one is the illumination power degradation criteria, which should be < 5% before and after the test.

LIFE ESTIMATION FROM QUALIFICATION TESTS (OFR)

An example of the equivalent life time estimation of one OFR ALT test of the IEC 62787 is the "High temperature with current injection test" for CoCs with a duration of 400 h (t_{ALT}) at 130ºC (T_{ALT}) and alternatively 2500 h (t_{ALT}) at 110ºC (T_{ALT}),. in both cases with simultaneous current injection of 0.5 I_{sc} (where I_{sc} is achieved at the maximum concentration specified by the manufacturer). Life dependence of electronics devices with temperature are assumed to follow an Arrhenius law and therefore AF depends on E_A, T_{real} and T_{ALT} [3,7,11-13].

$$AF = \frac{t_{T_{real}}}{t_{T_{ALT}}} = \frac{exp\left(\frac{E_A}{k_B T_{real}}\right)}{exp\left(\frac{E_A}{k_B T_{ALT}}\right)} = exp\left(\frac{E_A}{k_B}\left(\frac{1}{T_{real}} - \frac{1}{T_{ALT}}\right)\right) \quad (1)$$

From equation (1), where k_B is the Boltzmann constant, and E_A the activation energy of the main failure cause occurring at the temperature ALT. Furthermore, E_A identifies the acceleration of time reliability parameters (Mean Time to Failure) when the temperature of ALT test is over the real temperature.

Considering a solar cell real operation temperature on CoC of 85 ºC (T_{real}) and an average operation of 5.0 hours day as real condition, with the considerations over the influence between location and solar cell temperature, as explained in [7], and using a range of typical activation energies from 0.7 to 1.5 eV, it is possible to evaluate the equivalent time at nominal conditions of both qualification test conditions. The value of 0.7 eV is the standard one in low power silicon semiconductor devices and is a common value used when there is no information about E_A. The upper limit value of 1.5 eV is the highest of all our temperature ALT experiments with current injection over CPV CoC [13]. Furthermore, other relevant values are: the 0.9 eV that it is common for other III-V optoelectronic devices with similar temperature and density current stress conditions [3], and roughly 1 eV resulted in other CPV III-V solar cells temperature ALT [12].

The results of the tests with the previous considerations are (see Figure 2):

- Considering that the experimental results of temperature ALT for CPV III-V solar cells [12] and CoCs [13] will result in an activation energy ranging probably 0.9-1.5 eV [3,12,13], the equivalent lifetime from equation (1) lies between 6 and 33 years.
- The test duration namely, 400h and 2500h, has been elected for obtaining a life time almost equivalent for the whole activation energy range. The election of one of two possible test condition is usually decided by the supplier, depending on the limited continuous working maximum temperature allowed by the combination of materials used in the CoC. The test at 130ºC is more rapid and cheap, but is not suitable for all type of carrier materials, because an excessive ALT temperature can produce fake failures in the test that would never occurred in CoCs real operation.

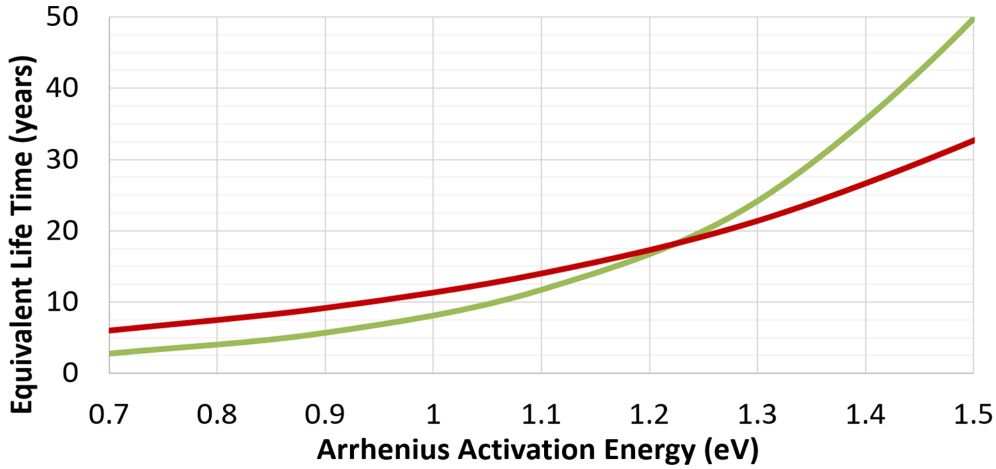

FIGURE 2. Estimated equivalent lifetime for CoCs, if the product pass this test, vs. activation energy for the test "High temperature with current injection test" (green line 400 hours at 130 ºC and alternatively red line 2500 h at 110 ºC with 0.5 Isc current injection) considering a CoC operation temperature of 85 ºC.

These estimations based on equation (1) and Figure 2 for temperature ALT, can be developed for other test types with the adequate equivalent model between real and ALT condition, but it is not ever simple. As we have mentioned that the objective of the related OFR tests is to cover the maximum spectrum of real conditions stresses types that could unleash failures in real working condition. For that, the ideal functional condition in ALT is the illumination, but it is not possible or is very expensive to combine the illumination real working condition with additional overstress parameters such as humidity, high temperature or thermal cycling. For that, in some cases, the qualification standard uses current injection to emulate the working condition.

In the present study, we identified the following objectives of the OFR tests and the lifetime accelerated models [9]:

- The high temperature with current injection test should reveal failures driven by the high working temperature of the solar cells and the CoC materials, and the estimation lifetime can be evaluated, by using the Arrhenius model. Furthermore, the need for 20 samples and zero failures for passing the test assumes an exigent AQL equal to 0.65% of the population. Furthermore, the product population only passes the test if the percentage of failed products is under 0.65%.
- For Thermal Cycling test, the purpose is to determine the solar cells and CoCs ability to withstand thermal mismatch, fatigue, and other stress caused by rapid, non-uniform or repeated changes of temperature. The testing of the bare solar cell is carried out without a current injection, whereas the CoCs is tested with the current injection. Its acceleration model is related to the Coffin Masson model [10,11].
- The purpose of the Light Biased Damp Heat test is to identify the weakness of the bare solar cells that are affected by the moisture together with the addition of light. In this test, five solar cells over representative carrier are tested at 65ºC/65% HR at 150 suns for 500 hours. In this case, the acceleration model assumes the combination of temperature and humidity models.
- The Illumination test is an ALT that applies real broad-spectrum light at maximum specified concentration ratio and an open circuit condition at high temperature (120 ºC for bare solar cells) by a short period of time (200 h). The goal is to reveal failures that appear in real operation conditions under high radiation and high environmental temperature condition, and for that, the adequate model to estimate lifetime is the Arrhenius law.

SUMMARY AND CONCLUSIONS

The present paper pursues to explain the main guidelines, and significance of more relevant tests included in the IEC 62787, whose CD has been recently submitted.

Since the standard is open for receiving modifications, an additional objective of this paper is to open the standard to as much CPV specialists as possible in order to receive suggestions that can improve the standard.

IEC 62787 tests have been designed in such a way that it ensures a minimum lifetime by means of two different type of tests: tests to avoid infant mortality failures, and tests to ensure that solar cells and CoCs have a minimum lifetime in nominal operation conditions.

As a case study, the lifetime estimation for a product that overcome the test of "High temperature with current injection" has been analyzed resulting in more than 10 years of life, assuming an activation energy over 1.0 eV, as it has been determined in previous works of temperature ALT solar cells and CoCs [12,13].

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REFERENCES

1. S. Kurtz, et al. "International quality assurance standards", NREL, Photovoltaic Module Reliability Workshop, (February 16-17, 2011).
2. Osterwald, C. R., & McMahon, T. J. "History of accelerated and qualification testing of terrestrial photovoltaic modules: A literature review". Progress in Photovoltaics: Research and Applications, (2009), 17(1), 11-33.
3. N. Nuñez, et al. "Semi-quantitative temperature accelerated life test (ALT) for the reliability qualification of concentrator solar cells and cell on carriers". Progress in Photovoltaics: Research and Applications, (2015), vol. 23, no 12, p. 1857-1866
4. IEC 62787 ED1 "Concentrator photovoltaic (CPV) solar cells and cell-on-carrier (CoC) assemblies – Qualification". https://www.iec.ch/Draft version.
5. IEC TS 62789:2014 "Photovoltaic concentrator cell documentation". https://www.iec.ch/
6. IEC 62108:2016 RLC "Concentrator photovoltaic (CPV) modules and assemblies - Design qualification and type approval". https://www.iec.ch/
7. Vazquez, M., Tamayo-Arriola, J., Orlando, V., Nuñez, N., Alburquerque, O., & Algora, C.. "Reliability of commercial triple junction concentrator solar cells under real climatic conditions and its influence on electricity cost". Progress in Photovoltaics: Research and Applications, (2017), vol. 25, no 11, p. 905-918.
8. McPherson, J. W.. "Brief history of JEDEC qualification standards for silicon technology and their applicability (?) to WBG semiconductors". In 2018 IEEE International Reliability Physics Symposium (IRPS) IEEE ,2018-March, pp. 3B-1).
9. Muller, M., Jordan, D., & Kurtz, S. "Degradation analysis of a CPV module after six years on-Sun". In AIP Conference Proceedings. AIP Publishing. (2015, September). Vol. 1679, No. 1, p. 020004.
10. Bosco, N., Sweet, C., & Kurtz, S. (2009, June). "Reliability testing the die-attach of CPV cell assemblies." 34th IEEE Photovoltaic Specialists Conference (PVSC), 2009, pp. 000917-000922.
11. Nelson, W. B.. "Accelerated testing: statistical models, test plans, and data analysis" (Vol. 344). John Wiley & Sons, (2009).
12. Nuñez, N., Gonzalez, J. R., Vazquez, M., Algora, C., & Espinet, P., "Evaluation of the reliability of high concentrator GaAs solar cells by means of temperature accelerated aging tests." Progress in Photovoltaics: Research and Applications, (2013), 21.5: 1104-1113.
13. Espinet-González, P., Algora, C., Núñez, N., Orlando, V., Vázquez, M., Bautista, J., & Araki, K., "Temperature accelerated life test on commercial concentrator III–V triple-junction solar cells and reliability analysis as a function of the operating temperature." Progress in Photovoltaics: Research and Applications, (2015), vo. 23, no 5, p. 559-569.
14. IEC 61193-2:2007 "Quality assessment systems - Part 2: Selection and use of sampling plans for inspection of electronic components and packages". https://www.iec.ch/.