PACT Module Preconditioning Protocol

Version 0.1

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1. Introduction

The purpose of this protocol is to bring metal halide perovskite (MHP) modules to a repeatable and relevant state prior to making a performance measurement. Performance measurements are made before and after a stressor has been applied to the module to quantify the degree of loss resulting from the stressor. This procedure is intended to be carried out both before and after the accelerated test

This initial protocol is designed to consider the metastability of the module across diurnal cycles, in contrast to existing standards such as IEC 61215 that only consider accumulated light (insolation) under continuous exposure. For this procedure, the period of interest is defined to be 24 hours. Shorter or longer duration metastable behaviors may exist but are not considered here. While both indoor and outdoor preconditioning are allowed in IEC 61215, this initial draft for perovskite modules only considers indoor preconditioning under well-controlled conditions. This procedure also acknowledges that the current technology readiness level (TRL) for MHP modules is such that the procedure itself could induce unintended degradation. The termination criterion is intentionally less stringent than the requirements found in IEC 61215 and is intended to become more stringent as technology improves.

2. Definitions and References

- **BPT** – Black Panel Temperature
- **IEC 61215** – defines requirements for the design qualification and type approval of terrestrial photovoltaic (PV) modules suitable for long-term operation in general open-air climates
- **IEC 60904-2** – defines requirements for solar reference devices
- **IEC 60904-9** – defines requirements for artificial light sources used to characterize PV devices
- **Module** – weatherproof package containing multiple, interconnected solar cells that can be electrically connected to an external load
- **MHP** – Metal Halide Perovskite
- **MPPT** – maximum power point tracking
- **RTD** – Resistance Temperature Device
- **Solar Simulator** – artificial light source designed to reproduce natural sunlight for the purpose of characterizing the operation of PV devices

3. Required Equipment

- **Light Source** - Continuous light source or solar simulator of Class CCC or better (BBA or better preferred). Within 30 minutes of starting each light cycle, the light source shall be capable of achieving and maintaining an irradiance between 980-1020W/m^2.
- **Module Temperature Control** – Means of maintaining elevated module temperature during preconditioning. Control may be via natural heating from the light source or by external means such as forced convection or direct contact with a heated surface[1]. The control method shall be

[1] Note: The thermal environment may be adjusted by controlling fan speed, chilled water flow, or by other similar means.

capable of maintaining module temperature to between 40°C and 60°C and must be stable to ±2°C within 30 minutes of the beginning of the light exposure period. If preconditioning is conducted in a chamber capable of holding multiple modules simultaneously, feedback for temperature control shall be via black panel temperature (BPT).

- **Dark Storage** - Dark storage may be *in situ* inside the light source or in a designated dark storage space determined to be free of stray light. If dark storage is *in situ*, the light source chamber must be capable of reducing module temperature to < 30°C in 1 hour or less and must be capable of maintaining module temperature to between 20°C and 30°C.
- **Load** - Means of maintaining the module at its maximum power point using active maximum power point tracking (MPPT) during light exposure and at an unloaded condition during dark storage. Means shall be capable of continuous operation during light exposure and shall be capable of dissipating at least 10% more power than anticipated to be produced by the test device during exposure. The MPP shall be maintained via voltage control and a simple perturb and observe routine. If the dark storage is performed *in situ*, the load circuit shall remove bias voltage and maintain an open circuit condition.
- **Voltage and Current** – Means of measuring voltage and current while the test device is under load. Measurement accuracy shall be ≤ 0.1% of the expected Isc and Voc of the test device and shall not modify the load condition during measurement.
- **Irradiance** – Means of measuring irradiance during light exposure. Means shall be a broadband (400 -1100 nm) reference device of calibrated to Working class or better and have a minimum resolution of ±5 W/m^2. The reference device shall be capable of continuous operation in the exposure environment.
- **Temperature** – Means of measuring module temperature. Means shall have a resolution of ≤ 0.5°C. It is recommended to use either a Special Limits of Error Type-T thermocouple or PT100 RTD.

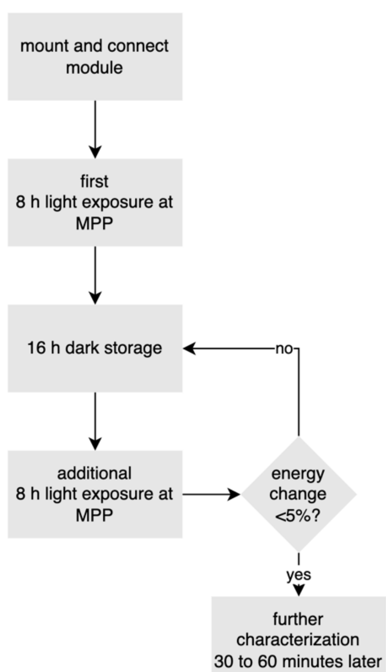

Figure 1. Test flow for preconditioning of perovskite modules

4. Light Cycling

- One full cycle shall consist of 8 hours of exposure to continuous light at elevated temperature followed by 16 hours of dark storage nominally at room temperature. The 8 hours of exposure begins at the start of the 30 minute “warm up” window specified in Section 3.
- Light exposure shall be at an irradiance of between 980–1020 W/m^2 (1000 W/m^2 preferred)
- BPT shall be maintained between 40°C and 60 °C during light exposure (50 °C preferred). BPT shall be held constant ±2°C during each 8-hour cycle and returned to the same level for subsequent cycles.
- BPT shall be maintained between 20-30°C during dark storage
- The test device shall be maintained under load during light exposure using active MPPT. Fixed power mode on an electronic load shall not be allowed.
- Initial voltage shall be V_{max}, an estimate of the voltage at maximum power from a conventional IV scan taken prior to MPP.
- A voltage step (ΔV) shall be established from V_{max}. ΔV shall be 1% of V_{max}. Voltage scan rate shall be 1 sample/second.
- The test device shall be maintained at an unloaded condition during dark storage.
- Light cycling will be repeated until the termination criterion defined below has been met and shall include no fewer than 2 cycles. If total energy continually decreases outside the bounds of the termination criterion with each cycle, light cycling shall be discontinued after 5 consecutive cycles and the device shall be designated as unstable. If the module experiences greater than 20% drop after a minimum of two consecutive cycles, preconditioning may be terminated.
- Once the termination criterion has been met, the total energy calculated as described in Section 6 shall be used to quantify device performance and determine any changes due to intermediate tests or conditions between applications of this procedure.
- Modules shall remain in the same location for each cycle and shall be returned to the same location in the simulator between subsequent applications of this procedure.

5. In-situ Measurement

- During light exposure, measure and record device current (I) and voltage (V) at consistent intervals of 15 minutes or less. The load condition shall not be changed during measurement.
- At the same interval of current and voltage measurement, irradiance (G), BPT, and module temperature (T_m) shall simultaneously be measured and recorded.
- Record the time (t) associated with each group of measurements.

6. Performance Quantification and Termination Criterion

- For each measurement interval i, calculate power (P) as the product of measured voltage and current.

$$P_i = V_i I_i$$

- Correct each calculated power to a common irradiance, e.g., 1000 W/m^2.

$$P_{i,corr} = P_i \frac{G_{ref}}{G_i}$$

Note 1: To minimize translation error, G_{ref} may be chosen as the mean or median of the measured irradiance during Preconditioning cycling. However, this reference value must be consistent between sequential exposure periods.

- Exclude all power measurements taken during the first 30 minutes of exposure.
- Calculate the total energy in Watt-hours produced by the device during each illumination interval *j*,

$$E_j = \sum_{i=1}^{n} P_{i,corr} \left(\frac{t_i - t_{i-1}}{60} \right)$$

- Preconditioning is complete when energy from two consecutive light intervals satisfies:

$$\frac{E_j - E_{j-1}}{(E_j + E_{j-1})/2} \leq x$$

  where x = 0.05. x is intended to become more stringent as MHP technology improves; future versions will target x = 0.02, consistent with thin film specific component of IEC 61215.

- E_j from the final interval in which the termination criterion is met shall be used to quantify changes in device performance between successive applications of this procedure

7. Protocol Validation

This protocol still needs to be validated before it can be adopted generally and may need to be adjusted as more experience is gained testing perovskite PV modules. PACT plans to initially test this protocol using a set of stable c-Si PV modules. These tests will allow us to determine if energy production during the light cycles is sufficiently constant with a stable PV module technology. It is unknown at present whether the temperature and light levels within the light soak chamber are sufficiently uniform from one light period to another for this test to be able to detect stability in the modules under test. It is also unknown at present whether the MPP method and parameters specified in this protocol will be applicable to a wide range of devices over a long period of operation. The MPP protocol will be updated periodically as more experience is gained.

8. Version History

- Version 0.1 – 2/24/22 Initial release

PACT

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