Dynamic stress tests on PV modules – derivation of extended stress scenarios

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ABSTRACT

With current state-of-the-art PV module tests stipulating only a static mechanical load test in accordance with IEC 61215 and IEC 61646 standards, hardly any fatigue stressing is carried out on cells, cell connectors or rigid component parts such as the glass or framing. This paper presents research on dynamic load testing of PV modules and discusses reliability aspects of these essential requirements that must be considered in future standardization work.

Introduction

On the basis of the current situation of standards, PV modules demonstrate a relatively good mechanical behaviour under the applied loads that are well defined within the IEC type approval tests from IEC 61215/61646 and the safety tests from IEC 61730-2 [1]. A 2011 internal extension of these tests carried out at TÜV Rheinland indicated a failure rate in the mechanical load (ML) test of 12.6% from a set of more than 12,000 c-Si modules (between 2005 and 2010) that had failed the certification processes.

In the type-approval testing, the ML test (IEC 61215 10.16 [2]) is applied to a single PV module out of a set of 10 modules under realistic mounting conditions such as those recommended by the manufacturer. "The purpose of this test is to determine the ability of the module to withstand wind, snow, static or ice loads" [2] – this means external environmental mechanical stresses equivalent to a total load of 2400Pa (or 5400Pa if desired by the manufacturer) impacting vertically on the surface of the module. The ML test is the only stress test which determines the resistivity of the modules with regard to tensile or compressive forces induced only by mechanical forces to simulate wind or snow.

Prior to the ML test, IEC 61215/61646 stipulates that a damp-heat test at 85°C and 85% relative humidity (RH) be conducted on the same module. The module is evaluated by means of its electrical power and isolation characteristics before and after the test, as well as by the presence of any major visual defects that may occur due to the load application. According to this definition, the ML test has to be declared a static load test, since each type of load lasts for three hours, with force directions being varied for one hour between loads. A total load application of six hours is prescribed.

IEC 61215/61646 states that the pressure loads correspond to a real wind velocity of approximately 130km/h [2]. Eurocode EN1991-1-4 (for the calculations of wind actions on structures), for instance, implies aerodynamic load factors that have to be introduced into basic load assumptions. Examples of dynamic wind influences are blast vibrations due to oscillation elements (caused by changing blasts), or curl-stimulated crosswise vibrations such as galloping, judder and rain/wind-induced vibrations. The multiplication of the dynamic factors leads to a 'quasi-static' procedure, so that resonance swinging, caused by gusts, is also covered by this [3]. Unfortunately, neither the Eurocodes nor the national amendments (DIN 1055-4 in Germany, for instance) imply any conclusions on the frequency of occurrence of wind gusts. This would help to estimate how many times theoretically wind-forced pressure accumulations in front of or behind a PV module could be expected for a 25-year exposure. On the basis of these findings, a calculation of the relevant load amplitudes can be applied; however, the derivation of appropriate load sequences and times for a realistic ML test is lacking.

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As regards oscillating or alternating forces, dynamic (thermo-)mechanical loads address many more different requirements in the field than static loads. Because of the set-up of the modules, these loads may induce internal mechanical stresses at electrical joints or adhesives or, having relevance to the durability of single homogeneous materials, fatigue cracking of the cells or connectors. Research has indicated typical frequencies of around 11Hz to 12Hz as resonance frequencies [4]. In addition, module oscillations in the range of 12Hz to 35Hz caused by surface excitations have been measured as a result of alternating wind forces, but with relatively small deflections of 1.5mm to 3.6mm [5]. Similar resonances could be reproduced in the laboratory from excitation by a loudspeaker. Assmuss et al. proved that free-standing modules can oscillate in their resonance frequencies, the most common being 28Hz [5]. Nevertheless, a 25-year prediction of the feasible amount of wind gusts and accumulated power densities on relevant spectra (or resonance frequencies) is not available.

The question that now remains is how to define an appropriate laboratory testing method which enables a sufficient forecast of the behaviour of PV modules under the influence of alternating mechanical, thermomechanical and vibrating loads.

Dynamic load tests in accordance with EN 12211 and EN12179

In 2007 and 2008 TÜV Rheinland carried out a series of dynamic load tests based on tests for windows and façades. Within the European research project 'Performance' [6], sub-group 6 dealt mainly with adapted testing and standardization situations. Because one major deficiency identified in the test sequence for the estimation of load behaviour was a dynamic load test, research on formulating relevant wind load tests was conducted. As EN 12210 and EN 12179 are benchmark tests for windows and façades, varying pressure and tensile loads form the criteria in characterizing these products in terms of their ability to withstand wind loads while retaining their functions (opening/closing the window, no deformations etc.) [7–9].

Transferring these requirements to PV modules, retaining functions for PV relates to the capability of a product to remain static in the frame, safety of the glass, fixings within the frames, avoidance of permanent deformations of the module construction, coping with minor power loss due to cell cracks or disconnections of electrical joints, etc. According to these standards the specimen has to be mounted

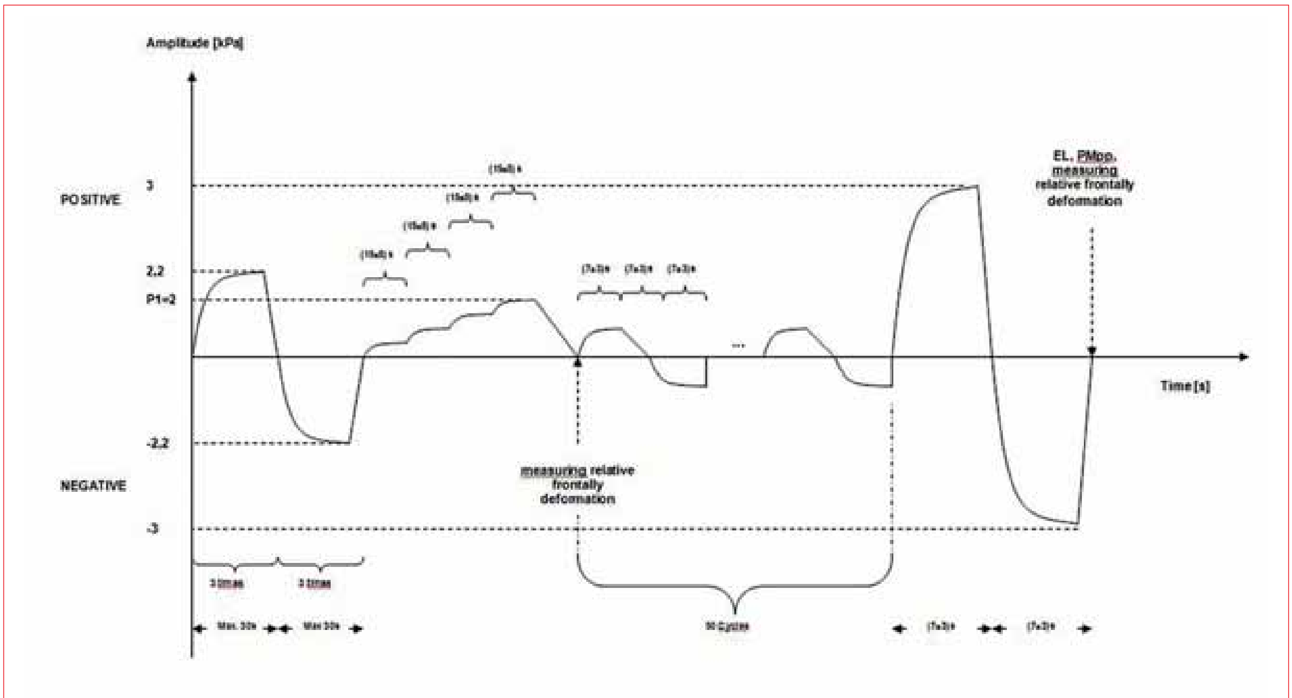

Figure 1. Combined dynamic mechanical stress tests in accordance with EN 12211 and EN 12179 for research test series, carried out at TÜV Rheinland.

in a pressure chamber with sealed edges. In order to include the characterization of a frame under specific dynamic loads as well, a free bending of the module is allowed by adapting the same load frequencies and cycles, amplitudes and measurement methods for determining the deformation.

As a result, a combined testing method (of EN 12210 and 12179) was developed by performing a test sequence which includes the application of various dynamic loads, as shown in Fig. 1. The load amplitudes for each test unit are appropriately lower than the ones specified in IEC 61215, but higher frequencies and alternating changes in load are involved. The pressure and tensile amplitudes of the applied loads were chosen to be those for the highest window class from the classification standard EN 12210: P1 is defined as 2kPa; P2, which provides the load for the 50 load

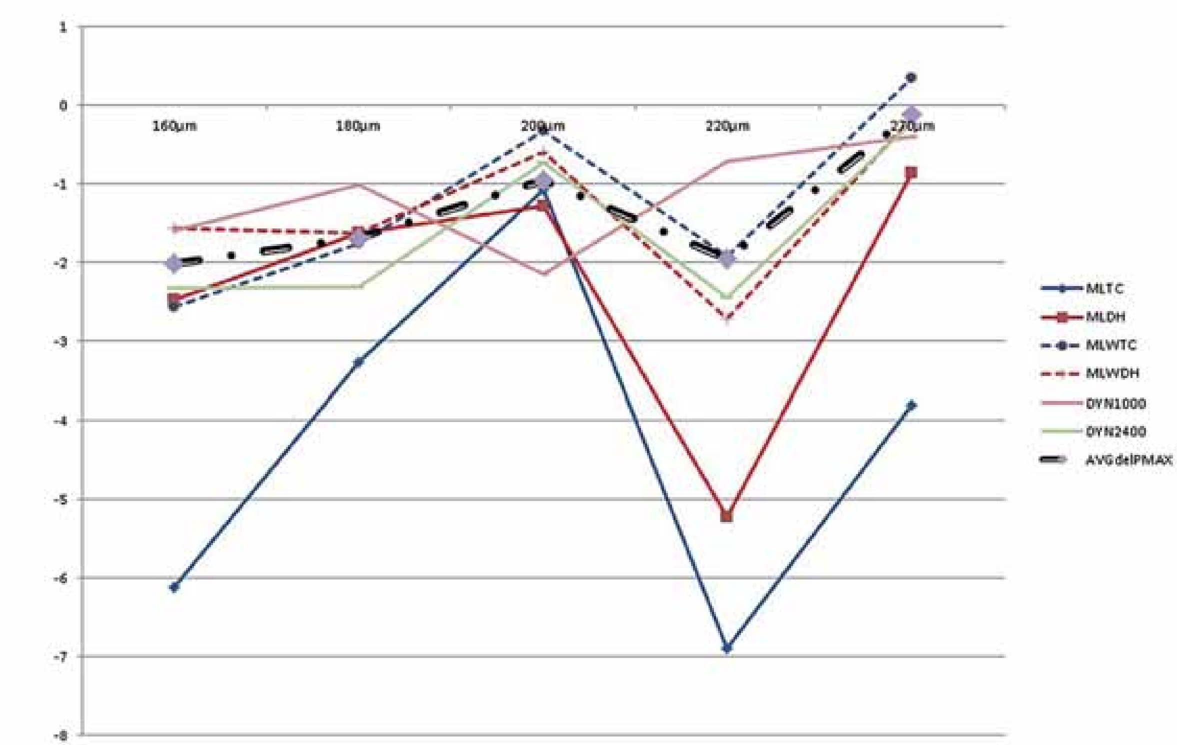

Figure 2. Electrical power measurements after and between static loads with thermomechanical and damp-heat stress testing, compared to dynamic load tests. The increase in the power loss is also clearly defined by TC tests.

cycles directly in the middle of the entire sequence, is set at 1kPa. A final 'safety test' with an excessive load of 3kPa simulates strong wind gusts at intervals of 21±9 sec per half cycle.

The single load peaks are within the limits specified in EN 12210 and, therefore, indicate a high degree of safety in terms of wind gusts with reference to EN 1055-4. A set of four standard polycrystalline glass/foil PV modules with aluminium frames, identical in construction, were exposed to these combined dynamic loads and to the regular IEC static-test loads. Electrical power loss measurements for modules exposed to the static load were about –0.2%; for the dynamic load test, marginal losses were also measured to be about –0.1%. In total, all modules still retained sufficient power-producing capability, and the degradation measurements were all within the measurement uncertainty of the flashlight simulator system. The requirements from the standard benchmark classes were able to be fulfilled. Since all lasting mechanical deformations were below 3mm, the highest window class could be applied to the tested modules – a very helpful result from a building-integrated PV (BIPV) perspective.

Dynamic and thermomechanical loads

On the basis of the findings of the EN 12211/12179 dynamic load tests, the varying load test unit of 50 cycles, with a total time of around 14–30 sec for each cycle, was the focus of further research to serve as a rudimentary tool for indicating possible fatigue behaviour. Although single micro-cracks could be induced by alternating loads, no major or electrically relevant losses, in terms of power or isolation, were caused. This time, 20 polycrystalline PV modules of two different types were exposed in a similar set-up to just ML tests and the aforementioned dynamic load test unit, but using up to 2000 cycles. In addition, further stresses from environmental exposure were included by using the IEC-established thermal-cycling (TC) and damp-heat (DH) tests. As a further interesting aspect, five different cell thicknesses were used.

After the specimen had undergone ML tests combined with subsequent environmental tests, the dynamic load tests were conducted individually without additional thermal or humidity stresses. The goal was to estimate whether any correlation could be found between the cracking behaviour of the cells and the corresponding power loss and cell thicknesses, or whether single dynamic load tests with oscillating forces are capable of providing similar stresses to the combined ML and TC test or the combined ML and DH test from IEC 61215. For practical use, the test sequences are abbreviated as follows: ML(IEC)+TC200(IEC) = MLTC; ML(IEC)+DH(IEC)=MLDH; dynamic loads of ±1000Pa = DYN1000; dynamic loads of ±2400Pa = DYN2400.

Fig. 2 shows the accumulated power losses at ΔP_{MAX} over the range of all tested

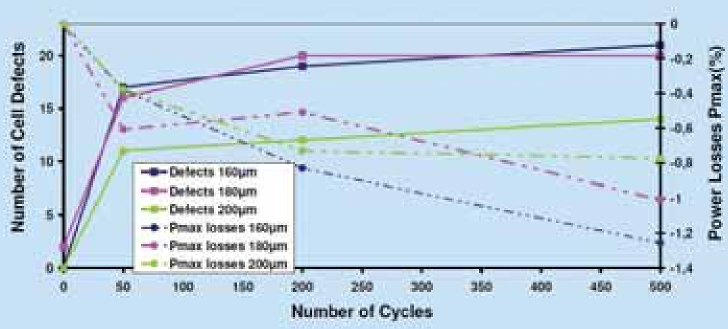

Figure 3. Correlation, for different cell thicknesses, of power losses at P_{MAX} with the number of cell defects.

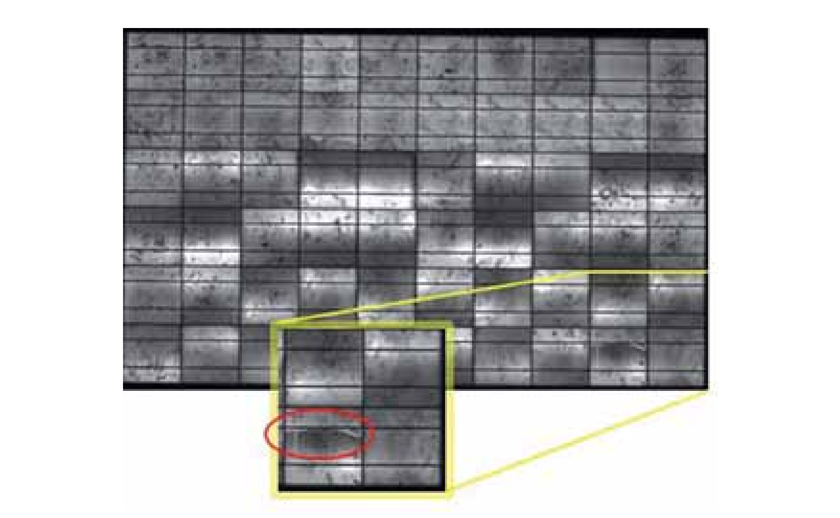

Figure 4. Highlighted cell with a micro-crack in a prepared module, resulting in meandering busbar interruptions.

Figure 5. Affected cell crack with smouldering and arcing along the defect.

modules along with the corresponding cell thicknesses. The individual points indicate the final measurement after the complete test sequences. The combined ML and TC tests subsequently carried out prove to have the highest impact compared to the other test sequences. The main impact on the average power loss for each cell thickness, therefore, depends largely on the results from MLTC. A stronger effect of MLTC, due to thermo-mechanical stresses on thinner wafers, is not clearly defined.

TC, however, exhibits a high degree of damage to cells and busbars, as Fig. 2 demonstrates. The figure shows a direct comparison of static and dynamic load tests without extended tests using the simulated environmental impacts TC and DH. Here, MLWTC stands for ML without TC; similarly, MLWDH is ML without DH.

In these particular measurements, although DYN1000 induces far lower stresses than those caused by DYN2400, the latter leads to almost the same degradation results in comparison to regular ML. In 2008 Wolgemuth et al. [10] worked out that the breakage behaviour of thin crystalline cells is obviously more severe when environmental stress tests, such as 50 thermal cycling (–40°C...+85°C) and 10 humidity freeze cycles, are carried out subsequent to dynamic loads, than for single dynamic loads.

For thinner cell thicknesses, the power losses caused by the application of ±1000Pa correlate very well with the number of cell defects, as determined by electroluminescence for each number of

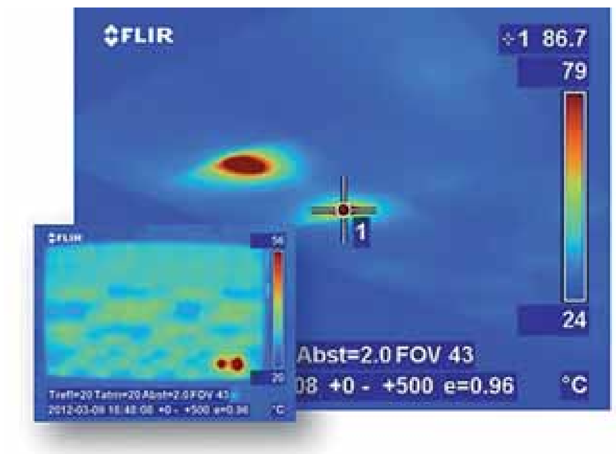

Figure 6. Hot spots at the cell connectors, caused by higher series resistances from the cell crack and high current load.

cycles. Between 200 and 500 load cycles, the number of cell defects reaches a saturation level (see Fig. 3).

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In conclusion, the dynamic mechanical loads based on the European standards EN 12211/12179 establish a solid basis for generating the same electrical degradation in modules as the IEC ML test. The higher the load amplitudes chosen, with reference to actual peaks induced by wind gusts, the more severe the damage expected. Indeed, the number of load cycles also plays a certain role, since the number of cell cracks can increase as the number of alternating loads changes.

Reliability and safety issues

A test sequence is at present being developed (in a current German research project concerning the evaluation of fire issues with PV systems) for estimating the risk of PV modules causing electric arcs under accelerated stress. To understand the progression of a degradation process at soldering joints or cell connectors, a combined testing sequence is currently applied to a variety of modules. The objective is to reproduce similar conditions in the modules to those that have already led to single smouldered joints detected in modules in operation in the field. In addition, a forward bias of 1.2–2 times the I_{sc} condition of the modules is applied to achieve a higher temperature in the electrical circuit.

Under the influence of the forward-bias potential, hot spots can be identified at positions where series resistances are higher. By using modules for these tests that have already shown severe hot-spot damage at soldering joints between the cells, even electric arcing in three modules could be induced under the influence of dynamic loads and an intentionally applied forward bias. In one non-aged module containing polycrystalline cells, each connected by two busbars, a meandering course of current was induced by intentionally interrupting the cell interconnectors in an alternating pattern. One cell revealed a cell crack alongside the front busbar. Under an applied forward bias of $1.2 \times I_{sc}$ and dynamic loads of ±2400Pa, the current was forced to run entirely along the cell crack. As a result, with each positive or negative stroke, tiny flashes were created, producing smouldering and burn-through of the backsheet. (Further results will be presented at the IEEE PVSEC in Austin in 2012.)

One result to come out of recent standardization work carried out on the estimation of other dynamic loads is a draft standard (IEC 62759-1) for testing related to transportation issues of PV modules and module stacks, which has been developed under the lead of WG 2 from IEC TC 82.

A higher impact on the modules' breakage behaviour can be expected from resonance frequencies that have been estimated in several crystalline modules, caused by longer-lasting vibrations. After a PV module was subjected to a sinusoidal excitation (acceleration 1g), the resonance frequency was detected from a sweep between 3.5Hz and 15Hz [11]. Fig. 7 shows the damage to a module from the resonance determination with a continuous load for 20 sec for each frequency unit. In this particular case the resonance occurred at a frequency of 11.5Hz and caused a power loss of 8%.

From a resonating material perspective, not only do wind-driven vibration phenomena act on the modules, but also transportation-induced oscillations occur during (for example, truck) transportation. The current draft (IEC 62759-1) projects these influences to complete transportation stacks or package units by applying a random noise spectrum between 5 and 200Hz on the basis of ASTM D4169 [11]. The use of a power spectral density (PSD) profile allows a correlation between power densities (in g^2/Hz) and the individually occurring frequencies. Following these and further individual transportation-specific tests on the shipping unit, environmental tests are then linked into the simulation sequence.

Two testing paths (A and B) are defined

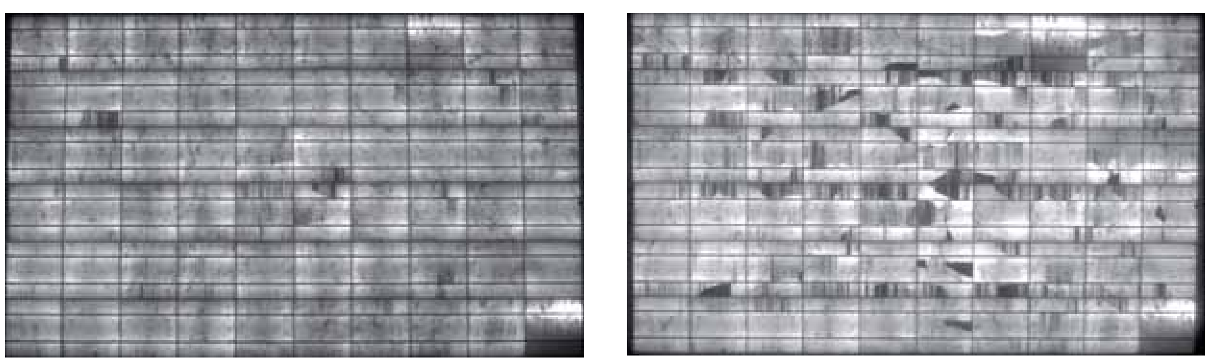

Figure 7. Comparison of EL images of a crystalline module before and after applying vibration frequencies for resonance oscillations.

for the exposure of the modules that are degraded the most from the transportation simulation in order to estimate whether cell cracks or macro damages of the specimen can contribute to a higher performance loss under environmental ageing [12]. Therefore, path A includes a single stress of 200 thermal cycles, whereas path B introduces a sequence of dynamic loads (following EN 12211, 250 cycles, 24 sec/cycle, ±1000Pa), 50 TCs, HF 10 and the regular ML test. From initial experiences, in accordance with the draft transportation-testing standard, path B indicates a stress four times higher in terms of degraded power production than the single 200-TC test for path A.

"Dynamic load tests clearly reveal a different stress potential from that indicated by static mechanical loads."

Conclusion

With reference to accelerated ageing procedures of PV modules, dynamic load tests clearly reveal a different stress potential from that indicated by static mechanical loads. Consequently, fatigue mechanisms for soldered joints or for the cells themselves can be completely determined. The constant application of a forward bias is helpful for generating a higher stress on the cell connectors, for example for addressing arcing issues. In addition, associated environmental tests aid in intensifying the stress on cell connectors [10,13].

Further stress tests will have to be carried out to obtain a more detailed insight into the behaviour of modules under the loads discussed here, to investigate whether higher frequencies and similar load amplitudes will lead to the same reported results. Testing times could be drastically reduced. Moreover, the different research results indicate that the number of load cycles when non-linear breakage behaviour of modules occurs still varies between 200 and 2000 cycles. However, a necessary comparison of adapted test series is important for determining the optimum number of load cycles to be applied, where a saturation level of damage to cells and connectors can be designated.

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