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Integration of energy smart materials in non-residential buildings

Switch2Save

Lightweight switchable smart solutions for energy saving large windows and glass facades

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= Deliverable D6.1 =

Improved testing methodology and characterisation procedures for long-term performance assessment of EC/TC windows

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Executive Summary

Deliverable 6.1 concludes Task 6.1 - *Develop novel testing methodologies for long-term performance assessment including durability and service life* (months 7-42) of the Switch2Save project. The background to this task is the need for a tailor-made and manageable durability testing approach for the novel technical solutions developed in Switch2Save. In particular, a set of procedures had to be found that makes it possible to measure the fatigue of a thermochromic (TC) component for the first time in an electrochromic (EC)/thermochromic (TC) tandem product. Besides, it should offer the possibility of taking into account the geographical location and deliver results quickly in order to be able to identify acceleration factors during the course of the project, i.e., in a relatively short period.

Based on a comprehensive analysis of existing standards and scientific literature as well as recommendations from the *International Energy Agency* IEA, a durability testing concept is proposed that is deemed appropriate for the novel dynamic glazing solutions pursued in Switch2Save. In addition, the proposed test plan is manageable and feasible in terms of efforts and duration of execution. It includes a screening test part and a calendar life/long-term operation test part, which are carried out one after the other. If a product variant passes the long-term operation tests, this variant is subjected to further tests that are relevant with regard to a later certification of the smart window product.

The improved testing methodology has been in use since April 2021 (month 19) and yielded first results for a new setpoint EC (1st generation) product. This is part of Task 6.5 - *Execution of accelerated long-term performance and durability testing on Switch2Save solutions*, which will be continued with further product configurations over the next months.

Partners involved: ChromoGenics AB (CMG), Fraunhofer Institute for Silicate Research (ISC), Fraunhofer Institute for Organic Electronics, Electron Beam and Plasma Technology (FEP), National Technical University of Athens (NTUA), University of Western Bohemia (UWB).

Abbreviations

1G/2G	1st/2nd generation (product)
AM	Air mass
ASTM	American Society for Testing and Materials
BBT	Black Body Temperature
CE	*Conformité Européenne*
DoA	Description of Action (part of the European Commission Grant Agreement)
DSR	Dynamic Switching Range
EC	Electrochromic
EMCC	European Materials Characterisation Council
IEA	International Energy Agency
IGU	Insulated Glass Unit
IR	Infrared
ISO	International Organization for Standardization
M	(Project) month
PTR	Photopic transmittance ratio
SWIFT	Switchable Facade Technology (project)
T	Temperature
τ_h	Photopic Transmittance in clear state, i.e. high transmittance
τ_l	Photopic Transmittance in dark state, i.e. low transmittance
TC	Thermochromic
UV	Ultraviolet
w/	with
w/o	without
WPx	Work package x

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1. Introduction and basic considerations

Deliverable D6.1 concerns the preparation of a novel testing methodology and corresponding characterisation procedures for the long-term performance assessment of electrochromic/thermochromic (EC/TC) windows. This is necessary in order to assess the long-term durability of the smart insulating glass units (IGU) developed in the frame of the Switch2Save project. The EC and TC cells developed in WP2 and WP3, respectively, are integrated on a single glass pane (IGU) in the frame of WP4. This combination of EC/TC cells in an IGU necessitates the development of realistic and reliable testing methodologies that overcome the current testing limitations and allow the long-term performance assessment of the new IGUs within the time frame of the project. Considering the above, D6.1 provides a methodological tool for the testing of the project results, but also sets the basis for improvements in the currently used long-term durability assessment of combined EC and TC windows.

The deliverable is part of WP6 - *Component level long-term performance & durability assessment* and concludes Task 6.1 - *Develop novel testing methodologies for long-term performance assessment including durability and service life*). Task 6.5 - *Execution of accelerated long-term performance and durability testing on Switch2Save solutions* will be implemented based on D6.1. Partners that have participated to D6.1 are CMG, FhG-FEP, FhG-ISC, NTUA, and UWB.

According to the Description of Action (DoA), the task of the group was to review any available durability testing methods and develop a test matrix incl. novel testing strategies for the envisaged technical Switch2Save solutions for smart architectural glazing, i.e.,

- the concretely envisaged tungsten oxide / nickel oxide-based EC film architectures incl. hybrid-enabled approaches derived therefrom;
- (TC)/EC multilayer setups and
- Vanadium oxide / zirconium oxide TC film technology and layer stack design.

In three successive technical meetings in the course of project months M8-M12, the WP6 team discussed and narrowed down durability testing methods that were considered necessary and useful - and at which point in time in the project own/internal testing methods including methods developed earlier on can be taken into account. This exercise eventually led to a streamlined and customized testing methodology and test plan that were presented in the M18 meeting (10-11 March 2021) and the first Review Meeting (18 May 2021).

The task group plans to develop further the methodology once first findings and results from the execution of the work plan (i.e., Task 6.5) are available, the ultimate goal being a unique combination of accelerated ageing with outdoor testing, including evaluation of intermittent testing scenarios and, where possible, rejuvenation techniques.

2. Overall Durability Test Strategy and Preliminary Remarks

The window product (during its service life) can be exposed to some or all different aging factors such as extremely low and high temperatures, UV radiation, long-term operation, deep cycling and high cycling frequency, or no operation at all (at rest). Therefore, it is of high importance to structure the durability testing in an optimal way in order to ensure that the real lifetime of the chromogenic material/product is assessed.

Switch2Save proposes a multi-step durability testing matrix that covers different aspects of the product service life. It allows to evaluate the durability of the material and product already during technological development.

The following indicates the rationale for the chosen test package:

- Screening test A_65°C_100%/120%:[1] This test is extremely accelerated (includes all aging factors; temperature, higher cycling frequency, deep cycles and higher voltage) and is used to simply select the best set-point/material that is able to withstand long durability test periods (up to 10 weeks).
- Short-term operation “SO_x_80% (-20°C & 85°C)_200 cycles”: The window product could be exposed for such extreme temperatures for only some hours/year, therefore, operation under these conditions should be put to a reasonable level.
- Long-term operation “LO_x_80% (room temperature & 65°C)_3000 cycles”: The product service life of the window is estimated on the basis of an assumed maximum of one cycle/day, which corresponds to 3000 cycles for a service life of 10 years.
- Calendar Life “CaL_UV”: This test aims to explore what would happen to a window that is exposed to environmental factors, but not cycled. To accelerate storage time, simulated solar (UV) radiation is used.

[1] Percentage of transmittance range (dynamic switching range); see also Table 1

3. Results and Discussion

3.1. Preparative work on available, required, and optional tests standards and procedures

In a first step, the Switch2Save consortium examined the methods available at their facilities. Existing standards and procedures were reviewed, analysed and compiled to a comprehensive map for parameter comparison, including expired or withdrawn standards, revisions, recommendations of the *International Energy Agency IEA*, and relevant European project results. Where applicable - scientific publications were taken into account, in particular with respect to TC fatigue testing. There is a large number of potentially relevant standards and procedures for windows in general and for EC windows in particular, some of which have significantly different test parameters or different scope. For efficiency reasons, the group has focused on methods linked to the chromogenic (switchable) functions. The table was revised and consolidated continuously during WP6.

As for the international standardization efforts, there have been two main activity routes so far, i.e. ASTM/ISO[2] and SWIFT/IEA[3]. The ASTM/ISO route aimed to testify ultimate durability and a lifetime of 20+ years. The SWIFT/IEA route strove for appropriate and meaningful testing scenarios according to findings of the SWIFT project and IEA recommendations. The IEA's ultimate goal was to adapt generic durability test procedures to chromogenic glazing systems, based on end-user requirements specified and the resulting functional properties needed (after having identified critical factors of environmental stress, which could cause degradation and failure). The primary interest of potential users is to assess the performance of the complete system – incl. sophisticated control units to avoid harmful operation conditions over its lifetime. Such complete system may perform better than its components tested individually. Moreover, the IEA made some important statements in their Task 27 - Final Report B2 [3]:

- The ASTM and SWIFT tests differ significantly in the specified number of cycles. If the criterion is the number of cycles expected during a 20-year lifetime, 50 k cycles, as demanded by ASTM, is almost certainly too high. Rather, according to an industrial partner with chromogenic windows installed in offices, one or two cycles per day (or even less frequently) is a meaningful assumption.
- It may be more appropriate to choose a still lower number of cycles, so that the total testing time remains within acceptable limits, but the duration of the cycling period is long enough to ensure cycling between at least e.g. 80% of the maximum dynamic switching range (DSR).
- Using the photopic transmittance ratio (PTR) to define a switching range as it is suggested in ASTM and ISO standards, is not considered appropriate, because electrochromic products can widely differ in PTR. Rather, a maximum dynamic switching range DSR (DSR = τ_h-τ_l) should be used and a certain percentage, e.g. 80% of the DSR, be defined.
- Demanding a test to be rated "failed" when the photopic transmission ratio (PTR = τ_h/ τ_l) drops below 4 is useless for products with an initial PTR lower than 4. In any case, such fixed termination points are not considered useful, as potential users should decide whether transmittance values are still appropriate for the location & application intended.
- It is probable that 4000 cycles between transmittance values of e.g. 60% and 12% represents a greater stress to the active material in the chromogenic unit than 8000 cycles between 40% and 17%.

The Switch2Save consortium agreed to ground their methodology on IEA recommendations.

Since 2017, there is a dedicated ISO standard test in place exclusively for EC glazing (ISO 18543). Apart from the fact that this standard does not foresee any TC function to be tested; for a later certification, only those tests are relevant that are established for laminated glass and laminated safety glass (i.e., ISO 12543). The ISO 12543 series

[2] ASTM: American Society for Testing and Materials; ISO: International Organization for Standardization, in Geneva, CH.

[3] SWIFT: Switchable Facade Technology (2000-2003), 5th Framework Programme EU project, Grant No. ENK6-CT-1999-00012; Fraunhofer ISE (CO) & 11 partners; IEA: International Energy Agency, Cooperation platform headquartered in Paris, FR. c/o Solar Heating & Cooling Programme, Task 27 Solar Building Facade Components, Subtask B: Durability.

also comprises a UV test and thermal stress tests. There are many certified bodies to perform ISO 12543 testing, while as of August 2021 there was no facility found to perform a durability test according to ISO 18543 in Europe.

The task group proposed to focus first on the optical properties (incl. IR-optical) on component level as the thermal and mechanical performance would rather be determined by the window frame and the Insulating Glass Unit (IGU) configuration [note: this holds true except for the g-value (Total Solar Energy Transmittance)]. The industrial partners in the project stated that later CE certification is extremely important, which is why this task was also to provide an idea about any issues that could possibly hamper certification. Some possible subcontractors were discussed.

The task partners with Fraunhofer ISC in lead suggested pursuing the following approach:

1. Clarify on tests necessary to assess EC and TC performance and identify gaps in existing methodology and standards, especially for IGUs (gap analysis);
2. Create a customized and appropriate test plan (and adapt it if necessary or useful);
3. Run testing campaigns according to test plan (→ Task 6.5);
4. Determine acceleration factors (→ Task 6.5);
5. Perform tests necessary to support receiving certification under current conditions (tentatively).

3.2. Durability testing approach

After diligent review of existing durability testing methods for (smart) windows, literature study, compilation of necessary data, teleconferences to discuss data & information, and in-depth analysis of irradiation characteristics, the task group developed the following rationale on how to proceed towards an appropriate testing scenario for the envisaged Switch2Save solution(s).

3.2.1. Gap analysis

- A dedicated procedure is proposed for TC glazing, in particular for TC fatigue testing at sample level. This must be adopted from scientific literature. Apart from that, established tests for laminated glass (ISO 12543) shall be applied. In doing so, the thermal effect of the TC coatings must be taken into account (metallic state reflects heat above threshold temperature).
- Testing at higher temperatures is pointless if the glass - upon UV-exposure in the test chamber – would heat up to temperatures that would never be achieved in real life, not even in southern Europe or other hot climate zones.
- The time consuming nature of durability tests should be considered – is there a trade-off between significance and duration of a test?
- The geographical location of the Switch2Save demo buildings in Uppsala and Athens incl. the corresponding air mass (AM)/insolation levels needs to be considered. Comparing insolation levels, two years of exposure in Phoenix, Arizona, USA correspond to five years of exposure in Stockholm, Sweden.
- A strategy to derive acceleration factors is to be created, also comprising literature studies for reasons of available time. This shall be used to finalise the durability testing methodology.

3.2.2. Testing strategy

- Methods and facilities that already exist in the consortium shall primarily be employed, also to save resources. These procedures go back to IEA recommendations to a large part.
- No testing according to standards that are to be complied with for regular, non-chromogenic glazing anyway (e.g. IGU seal tightness, impact testing). Tests required for certification and not falling in the above category shall eventually be performed (i.e., ISO 1279).

- Adapt procedure proposed by Long et al. in 2019[4] for TC fatigue testing => 1st step to test TC functionality.
- For thermal cycling incl. humidity testing the task group will cling to DIN EN ISO 1279-2 (general laminated safety glass testing).
- For EC cycle tests w/o simulated solar radiation, existing procedures utilizing a dynamic switching range of 80% will be adopted that take into account both SWIFT/IEA recommendations for EC glazing.
- For tests w/ simulated solar radiation load according to ISO 12543-4 shall be performed, because it is an established standard with a manageable test duration (2000 h).
- Atmospheric testing will be performed with laminated or sealed specimens only.
- Thermal shock testing is not considered useful at this stage.

3.2.3. Test plan

Switch2Save pursues two generations of Smart Window products, i.e., 1G and 2G; the first being endowed with an EC function only, the latter showing combined EC and TC function. The 1G variants will presumably comprise an EC layer stack with improved bright state transmittance as well as two hybrid-enabled high-contrast product configurations. The double functional 2G variants shall be based on these products.

The test plan provides for a screening test applying all known acceleration factors (temperature, voltage, frequency, high DSR) followed by cycling tests w/ and w/o radiation exposure. The screening test matrix is based on data and experience from CMG installations and several internal durability studies, especially in terms of number of cycles and temperature. Thermal stress and fatigue testing should then take place afterwards. The following table breaks down the main parameters for the individual test methods. Unless indicated otherwise, laminated glass samples 290 x 270 mm^2 in size will be tested.

[4] Shiwei Long et al., *Application-oriented VO_2 thermochromic coatings with composite structures: Optimized optical performance and robust fatigue properties,* Solar Energy Materials and Solar Cells 189 (2019) 138–148.

Table 1. Parameters of the Switch2Save test plan for 1st and 2nd generation product configurations.

1G & 2G	SCREENING Test to be passed before entering full test campaign	
Reference	A_65°C_100% OR _120%	
Type	**Screening**	
T	65 °C	
Cycles	Not defined as no. of cycles is used as an optimisation parameter	
DSR	100 % OR 120 %[5]	
1G	**EC Cycling @ constant temperature, w/o solar radiation load**	
Reference	SO_x_80%	LO_x_80%
Type	**Short-term cycling tests (optional)**	**Long-term cycling tests**
T	(-20°C) & (+85°C)	RT & (+65°C)
Cycles	100	3.000
DSR	80%	80%
1G & 2G	**Solar radiation load w/ & w/o EC cycling**	
Reference	ISO 12543-4	RL/LO_UV+BBT 70°C_80% (IGU 290 x 270 mm²)
Type	**Calendar**	**Real life test – similar to ISO 18543**
T	(45 ± 5) °C	BBT 70 °C
Cycles	n/a	3.000
DSR	n/a	80%
Radiation	1 sun (Xe, 51.6 W/m² @ 300-400 nm) – possibility to adapt for geographical location/insolation levels	
1G & 2G	**Thermal cycling and fatigue**	
Reference	DIN EN ISO 1279-2	LO_x-PTR2 adapted according to Long et al., 2019
Type	**Thermal cycling**	**TC fatigue (2G only)**
T	(-18 °C ⇆ +53 °C) over 4 w; (+58 °C) @ 95% rH for 7 w	(+25 °C) ⇆ (+65 °C) [10.000 cycles] @ 60% rH
Sample area	(502 ± 2) mm x (352 ± 2) mm	to be specified

Approval criteria to pass the tests:

1. **Transmittance:**

   The samples must fulfil the DSR defined. Accepted degradation after 10 years in tinted state is maximum 2.5% units. In bright state, maximum 5% units as long as the total degradation does not exceed 5% units.

2. **Optical quality** (evaluated by trained eye in one test series with 6 devices 25 x 25 cm² in size):

   - All defects 0-1 mm in size are allowed.
   - Defects 1-3 mm in size, one defect is allowed.
   - No clusters are allowed. A cluster is defined as 4 or more defects within a distance of 20 cm from each other, i.e., there is a maximum number of allowed defects in a 25 x 25 cm2 device, even though the defects are <1 mm in size.

3. **Statistics:**

   For an approved series of tested devices, at least 5 of 6 devices should be approved according to the specified criteria (for ISO tests, this is 3 of 4 devices/samples).

[5] The screening test has no upper limit for approval. Rather, the material is chosen that survives the longest without defects and still fulfils the required DSR defined for S2S project (32-75%),

Figure 1 shows a flow chart comprising all tests envisaged including their chronological sequence.

The full campaign test plan is divided into a screening part (dark yellow coloured box) and a calendar life/long-term operation part (orange/green coloured boxes in the middle of the chart), which are carried out one after the other. If the long-term operation evaluation is rated positive, tests shall be carried out with regard to later certification (orange/blue coloured boxes on the right hand side of the chart). TC fatigue is only performed on 2G samples. Further, optional short tests may be used as required (grey coloured box), requiring a certain amount of development, though.

After the preparations in months 19 to 20 had been completed, the first test campaign could be started in month 21 (June 2021; Task 6.5). The duration of the campaign is estimated to be 4 months; first interim results are available and are currently being evaluated. Parallel to this first campaign, a second one is about to be started with a hybrid-enabled configuration.

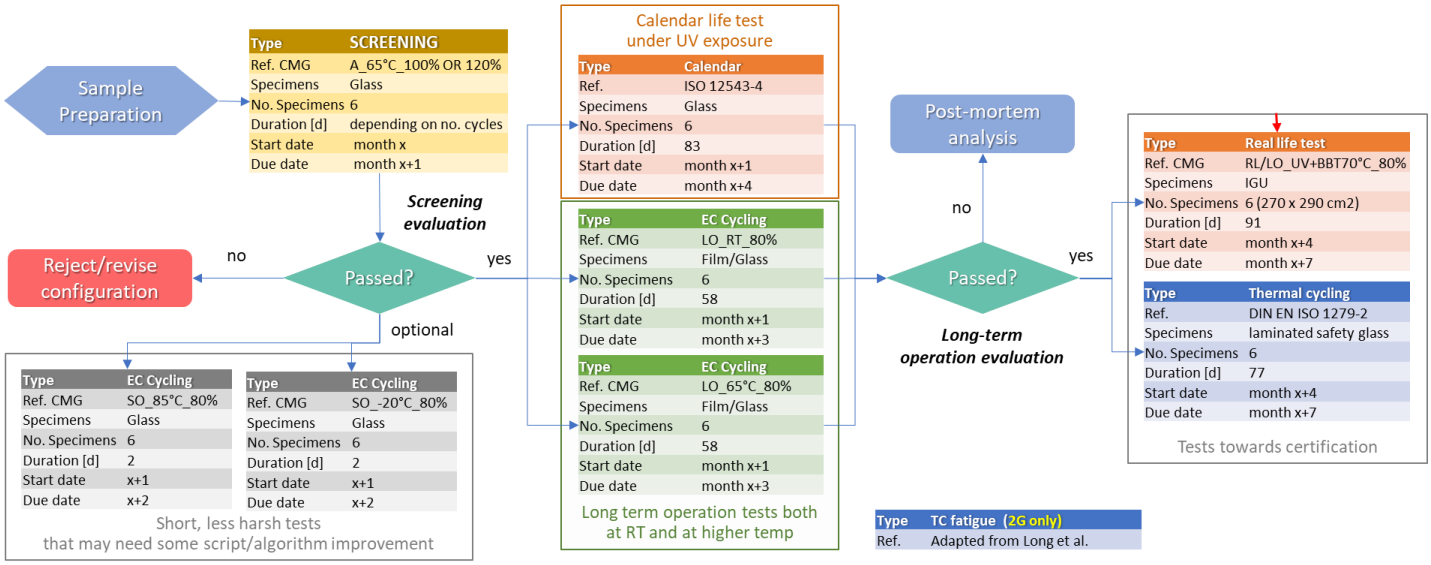

Figure 1. Flow chart of the Switch2Save test plan (version 1).

3.2.4. Improvements in durability testing methodology

A considerable methodological improvement is achieved with the new test procedure. Many years of knowledge from a well-known European manufacturer of switchable glazing, from development, production and use, have been incorporated. Against this background, the previously known methods were questioned and a test plan was developed that a) is suitable for EC / TC glazing, b) takes into account aspects of economic efficiency and technical feasibility, and c) includes recommendations of the IEA based on user behaviour.

In the following, it is highlighted what the task group modified/added with respect to current testing methods and procedures:

- Opposed to the outdated concept of a given photopic transmission range with fixed termination points, a dynamic transmission switching range (DSR) is introduced as a new, more useful criterion allowing many different chemistries and configurations to be tested.
- In terms of response time and switching frequency, a more manageable, more economical process is introduced that also better maps real-life behaviour. Test durations that are too long and cannot be handled in a technical development are thus avoided without reducing the meaningfulness of the tests.
- Unrealistic cycling conditions that do not reflect actual user behaviour are avoided.

- A proposal is made as to how TC glazing (and EC/TC tandem configurations) can be tested and TC fatigue behaviour be assessed in a meaningful way.[6]
- The proposed test concept is also significantly more economical than previous methods. It consists of three successive phases that take into account the level of technological maturity during development. This saves resources and time.

[6] There are methods for evaluating the thermal stability of a window (including thermal stress). However, these are not suitable for measuring TC fatigue, i.e., the fatigue behaviour of the TC layer itself, which is caused by repeated switching.

4. Conclusions

An improved durability testing methodology is proposed that is deemed appropriate for the novel dynamic glazing solutions developed in Switch2Save. It features a new dynamic transmission switching range concept (DSR), avoids unrealistic cycling conditions and allows for shorter test durations without sacrificing the meaningfulness of the tests. The proposed concept appears more economical than previous methods as it saves time. More specifically, the test time is reduced from 7 to 3 months. This is particularly important in materials development where quick feedback is required after each technological iteration cycle.

The new methodology has been in use since April 2021 (month 19) and yielded first results for a new setpoint EC product that are currently evaluated (testing campaign #1, Task 6.5).

Shortly, further testing campaigns will be started with (hybrid-enabled) EC or TC product configurations. Such new variants are intended to be pre-selected by means of the proposed screening test. *Vice versa*, screening results can be used effectively and efficiently to accelerate material and process optimization in EC / TC product development.

It is expected that valuable insights can be gained concerning temperature evolution in EC/TC glazing. How the temperature of (tinted) EC and TC coatings develops during exposure is of most importance for the design of future test procedures as large thermal expansion stresses, local overheating, and other issues may arise.[7]

The chosen practical approach is intended to be continued in the context of Task 6.5 and finally used to determine “acceleration factors”, i.e., a correlation between calendar life and accelerated aging. First considerations have already been made concerning the acceleration factors temperature and voltage range. This activity is running.

Any findings that could be of interest with regard to the standardization efforts of the European Commission will be communicated to the *European Materials Characterization Council* (EMCC). The EMCC may be approached when substantial gaps in testing methodology have been identified and adapted (or even new) methods can be proposed.

5. Degree of Progress

Degree of fulfilment of the task activities: 100%

6. Dissemination Level

Public

[7] TC coatings represent low-e coatings with emissivity modulation; the effect of such modulation on the components of a switchable window has not yet been demonstrated.