SOLAR HEATING & COOLING PROGRAMME
INTERNATIONAL ENERGY AGENCY

TASK 27

Performance of Solar Facade Components

Performance, durability and sustainability

of advanced windows and solar components for building envelopes

Final Report

Subtask B: Durability

PROJECT B2:

Durability and reliability assessment of switchable materials and devices

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PROJECT B2: "Durability and reliability assessment of switchable materials and devices (chromogenics)"

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1. Introduction

The originally stated objective of this project was "to assess the durability and reliability, under service conditions, of a variety of switchable materials and devices including those containing electrochromic, gasochromic, and/or thermotropic layers. Such materials may have application for both building facades and solar thermal collector systems."

Although chromogenic materials of different types have been investigated for several decades now, prototypes of switchable windows in architectural dimensions (> 0.5 m2) have been produced in limited quantities only within the last ten years. With the installation of such glazing in demonstration buildings becoming a reality, the task of assessing their durability and reliability has taken on new urgency.

At the same time, the need (and the feasibility) of testing complete switchable window systems is being increasingly recognised. A complete system to actively control the light and energy transmittance through a window consists not only of the glazing unit, incorporating electrochromic, gasochromic or polymer-dispersed liquid crystal materials, but also a supply unit to provide electric power or gas, and a control unit. As the systems become more mature, the supply and control units are becoming more sophisticated, so that they may be programmed to avoid conditions known to be harmful to operation, such as high voltage spikes or switching when the glazing temperature is extremely high. When this is part of the system concept, then a complete system may perform better than its components tested individually. From the potential user's viewpoint, it is also the performance of the complete system over its lifetime which is of primary interest.

Within Project B2 of IEA Task 27, on the "Durability and reliability assessment of switchable materials and devices (chromogenics)", the joint work has reflected this shift in interest from materials and components to complete systems. The approach taken has been to adapt the general durability methodology of Project B1 [Carlsson, 2003] to specific chromogenic requirements, define and carry out accelerated ageing tests, monitor the performance of samples in outdoor tests, and compare the results of accelerated and outdoor testing as far as this is possible with the data currently available.

This report consists of a presentation of the scientific work carried out in this project, appendices with an overview of the durability test procedure adapted for use with chromogenic glazing, relevant standards identified and technical facilities used by the project group, and a summary of the administrative project details.

2. Adaptation of general durability test procedures from project B1 to chromogenic glazing systems.

Drawing on the experience gained by manufacturing companies and research institutes that had investigated durability issues, the participants specified the end-user requirements and the resulting functional properties needed, and identified critical factors of environmental stress which could cause degradation and failure [Czanderna et al, 1999; Tracy et al, 1999; Appendix I to this article, Table A].

The end-user's requirements for performance were identified by B2 participants as being:

- high solar gain when heating is required, low solar gain when cooling is required
- "sufficiently" high or low visible transmittance, depending on lighting conditions and user requirements
- acceptable switching times - on the order of minutes
- good thermal insulation
- acceptable power consumption
- 20 years service lifetime
- acceptable appearance

Each of these requirements could clearly be discussed in more detail than is possible in this paper, but a few comments can be made. The effect of different values for the technical glazing properties (visible transmittance = Tvis, total solar energy transmittance = solar heat gain coefficient = g value, thermal transmittance = U value) on the performance in buildings is currently being investigated with building energy simulations within the project A2 on "Chromogenic Glazing". An example of the state of the art concerning the power consumption relative to the glazing area is given in [Platzer, 2003], namely 0.5 Whm-2 for one complete switching cycling for electrochromic glazing. The service lifetime is the only characteristic that is quantified in the list above, but is based more on general expectations than any detailed statistical analysis of building product lifetimes or the wide range of possible operating and environmental conditions. Concerning "acceptable appearance", one aspect is homogeneity over the glazing area, which was seen to be more important in the steady states than during the switching processes. Existing specifications for the spatial homogeneity of laminated glass could be taken as a guide here [DIN EN ISO 12543-6, 1998].

The main quantities describing the severity of environmental stress expected under operational conditions were initially characterised as given in the following list. The values in parentheses were added as more information became available.

- Outdoor air temperatures between -20 °C and 45 °C (48 °C in Arizona or California, [Czanderna, 2003])
- Outer pane temperatures between -20 °C and ~80°C (–30ºC to 90ºC (centre-of-glass), [ASTM draft E GGG, 2003])
- Solar radiation intensity between 0 and 1100 Wm-2 (1200 Wm-2, [ASTM draft E GGG, 2003])
- Solar UV radiation intensity between 0 and 50 Wm-2 (60 Wm-2, s. section 4.1 and [Zerlaut, 2002])
- Large thermal gradients between shaded and unshaded areas of glazing
- High relative humidity
- Mechanical loads as for conventional glazing (wind, snow, structural, thermal shock/stress)

Based on the general requirements for performance, a list of critical functional properties for chromogenic glazing was prepared, which is to be found in Appendix I, Table B. The test methods for evaluating these properties, which are also listed, were fairly obvious; what was less obvious was the effect that a change in these properties would have on the glazing performance in a building. Two different approaches to set performance benchmarks are documented in the appendix.

One is again to draw on the building simulation expertise within Task 27 and carry out parameter sensitivity studies, e.g. to characterise the effect of the ratio of maximum to minimum g value (SHGC or TSET) on the total energy demand in the reference office defined in Project A1, and compare the results to good solar control or low-e glazing. In other cases, such as the assessment of appearance or the resistance to mechanical loads, it is considered adequate to apply existing standards for conventional glazing. A list of relevant international and national standards which was collated by B2 participants is given in Appendix II.

The identified possible damage failure modes include the glazing remaining constantly bleached or coloured, switching becoming unacceptably slow, the switching range decreasing, the appearance becoming inhomogeneous (critical in ”steady state”, less critical during switching), the upper and lower transmittance values shifting, delamination, haze, blur, yellowing and colour shifts.

Finally, in designing the initial series of accelerated ageing tests, experience was pooled regarding the most critical factors that can lead to degradation; elevated temperatures (particularly for the glazing in the coloured state), UV radiation, sudden spatial or temporal temperature gradients, air leakage into glazed unit, high humidity, condensation, inappropriate control strategies, switching frequency, prolonged periods without switching and mechanical deformation. A selection of potential degradation indicators and degradation factors that could be applied in accelerated ageing tests are also documented in Appendix I, Table C.

Based on these estimates and information, an initial series of accelerated ageing tests was defined with the conditions specified in section 3.1. At the same time, long-term outdoor exposure tests were started, which provided further information on the conditions experienced by the samples in the field. These results are presented in section 4.

3. Accelerated Ageing Tests

3.1 Test Conditions

A number of accelerated ageing tests for chromogenic glazing has been defined during the duration of IEA Task 27, in the U.S.A. as ASTM standards or drafts, and in Europe as exploratory tests within the EU-funded SWIFT project. In the first eight tests of Table 1, the samples cycle continuously between the bleached and coloured states, and are subjected to different temperature and/or radiation conditions. These eight tests are ordered according to the severity of the temperature and radiation loads.

Clearly, the ASTM tests and the SWIFT tests differ significantly in the specified number of cycles. If the criterion is the number of cycles expected during a 20-year lifetime, 3600 is probably too low (less than one cycle per two days). However, 50000 cycles, corresponding to more than 6 cycles per day, is almost certainly too high. The experience of one industrial partner with chromogenic windows installed in offices was that they were switched for one or two cycles per day, or even less frequently. This corresponds with surveys of office workers, which indicated that in most cases, lighting conditions were changed (by switching on lights or operating mechanical blinds) only when the occupant entered the room in the morning and afternoon, or if there were disturbing glare.

On this basis, it is suggested that 15000 cycles would be a more suitable limit. However, it may be more appropriate to choose a still lower number of cycles, so that the total testing time remains with acceptable limits, but the duration of the cycling period is long enough to ensure cycling between at least e.g. 80 % of the maximum transmittance switching range. It is probable that 4000 cycles between transmittance values of e.g. 60 % and 12 % (O.D. 0.22 to 0.92) represents a greater stress to the active material in the chromogenic unit than 8000 cycles between 40 % and 17 % (O.D. 0.4 to 0.75).

Investigations by one industrial partner have indicated the importance of using samples of different areas for the cycling tests. A minimum area of 400 mm x 400 mm was recommended (preferably 600 mm x 600 mm), although a longer time is needed for one complete cycle than with smaller samples.
This is because the number of cycles successfully completed by larger samples was found to be larger than that for smaller samples which were otherwise identical in composition, i.e. the smaller samples did not adequately represent the performance of the larger ones.

Table 1: Summary of conditions for accelerated ageing tests of architectural chromogenic glazing systems. For ASTM tests, the conditions are as specified in the relevant standards and drafts. For SWIFT tests, the conditions used in the first exploratory series of tests are documented.

Test designation	Type	Sample area	Sample temperature	Radiation	Max. no. of cycles
SWIFT 3	continuous switching, 60 (40) minute cycle	400 mm x 400 mm	5 °C	none	3,600
SWIFT 1	continuous switching, 40-minute cycle	400 mm x 400 mm	room temperature (23 °C± 3 °C)	none	3,600
ASTM E2241-02	continuous switching, cycling period for initial PTR of 5:1 at 22 °C	min. area 254 mm x 254 mm: consideration of 355 mm x 505 mm recommended	22 °C ± 2°C	none	50,000
SWIFT 2 (sample C)	continuous switching, 40-minute cycle	400 mm x 400 mm	45-65°C	1000 Wm^{-2}	3,600
SWIFT 2 (sample B)	continuous switching, 40-minute cycle	400 mm x 400 mm	1 h at 100°C, 2400 h at 55-85°C (coloured)	1000 Wm^{-2}	3,600
SWIFT 2 (sample A)	continuous switching, 40-minute cycle	400 mm x 400 mm	17 h at 100°C, 450 h at 80°C, 1200 h at 50-65°C	1000 Wm^{-2}	3,600
ASTM E2240-02	continuous switching, cycling period for initial PTR of 5:1 at 22°C	min. area 254 mm x 254 mm: consideration of 355 mm x 505 mm recommended	90 °C	none	50,000
ASTM E2141-02	continuous switching, cycling period for initial PTR of 5:1 at 22°C	minimum area: 254 mm x 254 mm	70 °C - 105 °C; 90 °C recommended in ASTM Draft E GGG	UV and solar	50,000
SWIFT 4	thermal cycling, chromogenic unit in coloured state, (connected to supply and control units)	400 mm x 400 mm	56 temperature cycles between -18°C and 53°C over 4 weeks, 7 weeks at 58°C,	none	N/A - sample constantly coloured

For the tests involving chromogenic switching and constant temperature and/or solar radiation loads, the SWIFT project participants have formulated recommendations for further development resulting from the experience gained with the tests SWIFT 1, 2 and 3. These are:

- Before the first optical measurement, make some full cycles (around 10 between maximum and minimum transmittance), to be sure that the switching has become reproducible. Before testing, laboratories should determine the transmittance range and the cycling time needed to switch between the maximum and minimum at room temperature.
- Observe a fixed sequence during the characterisation process.
- Test in climatic chambers at the temperatures 23°, 40°C and 65°C without solar radiation (this is the recommendation for the next series of tests, a future series may include a temperature below freezing point).
- Test in climatic chamber at 25°C air temperature and with solar radiation (1 kWm-2)

The two climatic cycling tests in Table 1 apply similar temperature and relative humidity profiles to existing standards such as prEN 1279-2, which was specified to test the durability of the seal in conventional insulating glazing units. In accordance with the aim of testing the complete system, the scientists in the SWIFT project propose that the coloured glazing unit remain connected to the supply and control units during the test, although the latter need not be subjected to the test conditions if they are to be installed indoors.

The thermal shock test, "SWIFT 5", originally used the conditions specified in prEN 12975-2 for the external shock test of solar collectors, which is intended to simulate the effect of a summer thunderstorm. Reduction of the water temperature to 15 °C is suggested, to increase the temperature gradient to the glazing surface.

Extending the scope of this overview slightly, tests used for electrochromic car sunroofs include those from ECE R43 - 2 hours exposure in an oven at 100°C, and 100 hours exposure to a mercury vapour lamp - and from ANSI Z26.1 - 2 hours immersion in boiling water [Schütt et al, 2002; Fanton, 2003].

3.2 Choice of degradation indicator

In accordance with the end-user's expectations of a switchable window, transmittance is the primary characteristic which is measured in all the tests of Table 1. The visible transmittance, obtained from integrating spectral measurements or using luxmeter readings, has the advantage that it is well known as a specification for architectural glazing. The ratio of the visible transmittance in the bleached state to that in the coloured state, the photopic transmittance ratio (PTR), is used in the ASTM standards. The transmittance values in both states are measured and recorded in the test report, together with the PTR value. The test is terminated if the PTR becomes less than 4:1 or the visible transmittance in the bleached state falls below 50 %. If this happens before the samples have been cycled 50,000 times, they "fail the durability test" [ASTM E2241-02]. These absolute criteria imply that a chromogenic window system is functional only while these criteria are met, which does not apply generally.

As an alternative, the SWIFT tests have not defined a fixed termination point, but simply record the separate values for the visible transmittance in the bleached and coloured states, as these are the values needed when the effect of possible degradation on building energy performance or visual comfort are to be assessed. The potential user can then decide whether these values are appropriate for the location and application intended.

In either case, further discussion is needed to define when the transmittance measurement should be made. It has often been observed that the switching rate becomes slower during accelerated ageing tests, so a measure needs to be found for an "acceptable" switching rate and thus the appropriate time to wait between measurements to quantify the coloured and bleached "steady states". Some suggestions on methods to quantify the switching rate are made in Section 4.5 in connection with the outdoor measurement series. A method similar to that illustrated in fig. 10 was also applied in the SWIFT tests 1, 2 and 3 to quantify the switching rate.

A human observer is a good detector of spatial inhomogeneity, and all tests include recording of visual observations as part of the report. If the effect needs to be presented quantitatively, transmittance measurements at different positions, as proposed in ASTM draft E UUU, provide a better basis than processing of digital camera images.

4. Outdoor testing

To extend the basis of experience for judging the appropriateness of the accelerated ageing tests, some results of outdoor measurements on chromogenic glazing system prototypes are presented here.

4.1 Meteorological results

Measurements were made at two different sites with three different types of samples within the EU-funded SWIFT project. Samples of types A, B and C were exposed at the Fraunhofer Institute for Solar Energy Systems in Freiburg, Germany (48°00' N, 7°51' E, altitude: 269 m). The measurement period is from 1st December, 2001 to 31st August, 2003. To allow comparison with long-term annual measurements, the meteorological measurements are analysed over two 12-month periods, 1.12.01-30.11.02 and 1.9.02-31.8.03. The radiation exposure falling within the three months in common represents less than 20 % of the total exposure for the first year, so that the 12-month periods can be treated as largely independent, particularly as they include values from two different summers.

Samples of types A and B were exposed at the Centre Scientifique et Technique du Bâtiment (CSTB) in Grenoble, France (45°11' N, 5°43' E, altitude: 212 m). Again, results from two 12-month periods are presented, 1.1.02-31.12.02 and 1.9.02-31.8.03.

As the average temperature and total radiation values in Tables 2 and 3 indicate, the second year included an unusually hot and dry summer, resulting in the high frequency of high radiation values evident in figures 1(b), 2(b), 3(b) and 4(b). During August 2003, an air temperature of 40.2 °C was recorded by the official meteorological station in Freiburg, the highest air temperature observed since official recording began [Deutscher Wetterdienst, 2003].

Table 2: Measured and long-term average meteorological parameters at Freiburg, Germany. (Sources: Fraunhofer ISE and Deutscher Wetterdienst respectively)

Quantity	Measurement period 1.12.01-30.11.02	Measurement period 1.9.02-31.8.03	Long-term value for specified period
Average annual air temperature [°C]	12.5	13.6	10.7 (1961-1990)
min., max. air temp. [°C] (5-min. averages)	-11.3 39.5	-10.1 41.8	
Annual total of global solar radiation exposure, horizontal [$kWhm^{-2}$]	1090.1	1218.7	1132.6 (1981-2000)
Annual total of global solar radiation exposure, south, 45° [$kWhm^{-2}$]	1248.8	1409.1	
Annual total of global UVA radiation exposure, south, 45° [$kWhm^{-2}$]	58.3	65.2	
Max. global solar radiation intensity, south, 45° [Wm^{-2}]	1241	1221	
Max. global UVA radiation intensity, south, 45° [Wm^{-2}]	61.0	59.7	

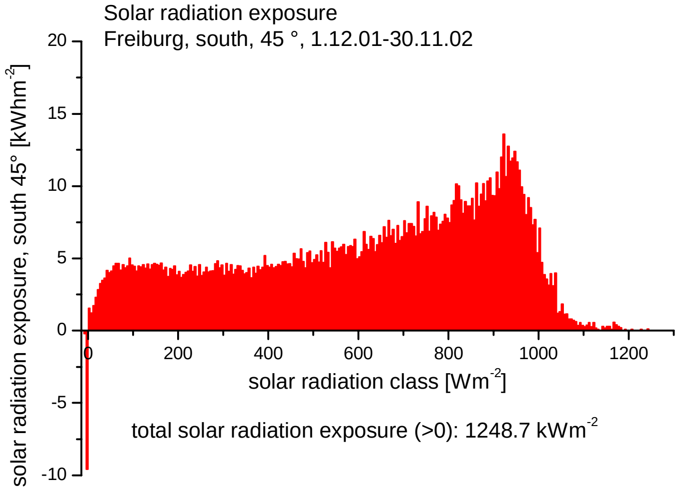


Fig. 1: Global solar radiation distribution on a 45°-tilted, south-oriented plane in Freiburg, 1.12.01-30.11.02

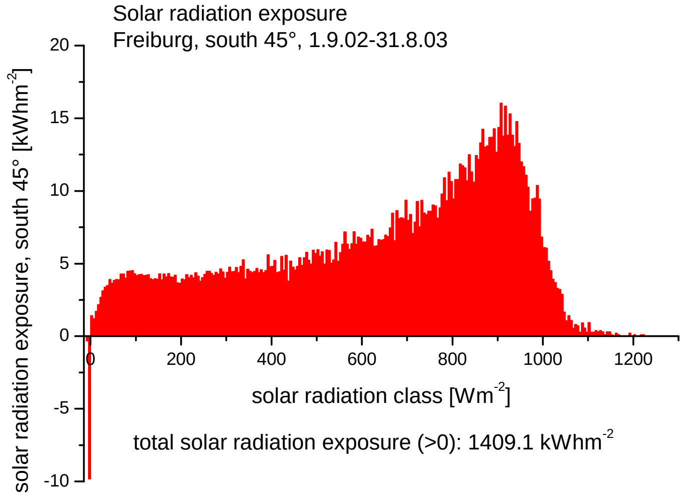


Fig. 2: Global solar radiation distribution on a 45°-tilted, south-oriented plane in Freiburg, 1.9.02-31.8.03

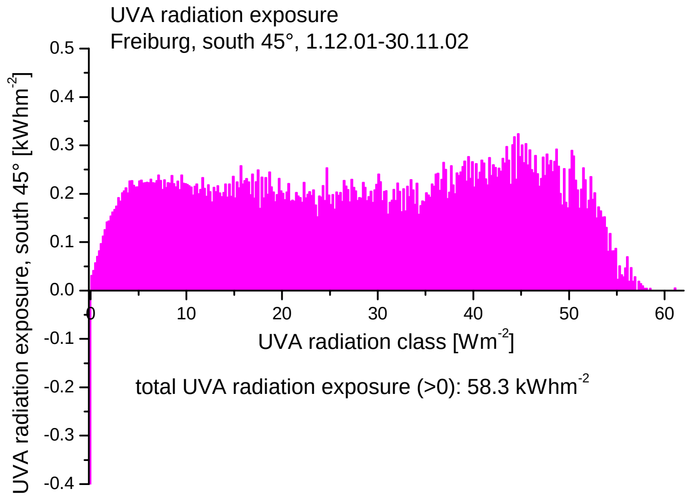


Fig. 3: Global UVA radiation distribution on a 45°-tilted, south-oriented plane in Freiburg, 1.12.01-30.11.02

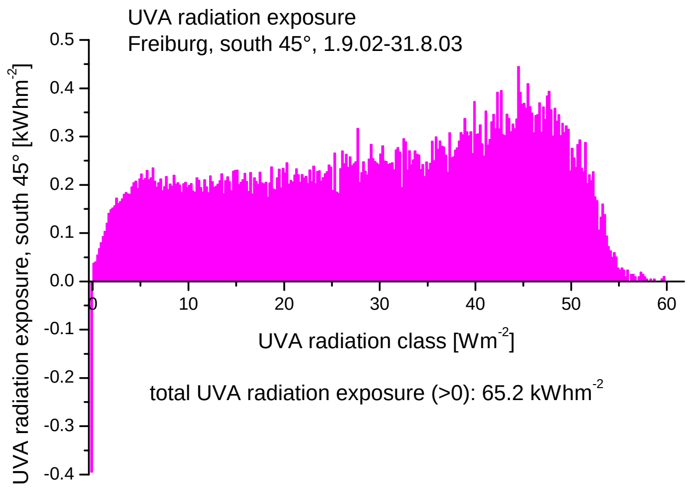


Fig. 4. Global UVA radiation distribution on a 45°-tilted, south-oriented plane in Freiburg, 1.9.02-31.8.03

Table 3: Measured and long-term average meteorological parameters at Grenoble, France. (Sources: CSTB and Deutscher Wetterdienst respectively).

Quantity	Measurement period 1.1.02-31.12.02	Measurement period 1.9.02-31.8.03	Long-term value for specified period
Average annual air temperature [°C]	12.7	14.0	11.8 (1997-2002)
min., max. air temp. [°C]		-7.8 ≥37.6	
Annual total of global solar radiation exposure, horizontal [$kWhm^{-2}$]	1243.9	1323.9	
Annual total of global solar radiation exposure, south, 45° [$kWhm^{-2}$]	1367.7	1435.0	
Annual total of global UV radiation exposure, south, 45° [$kWhm^{-2}$]	46.8	43.4	

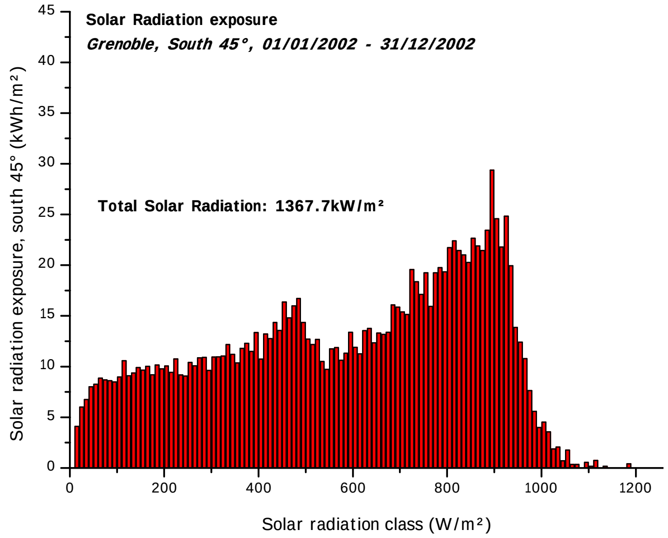


Fig. 5: Global solar radiation distribution on a 45°-tilted, south-oriented plane in Grenoble, 1.1.02-31.12.02

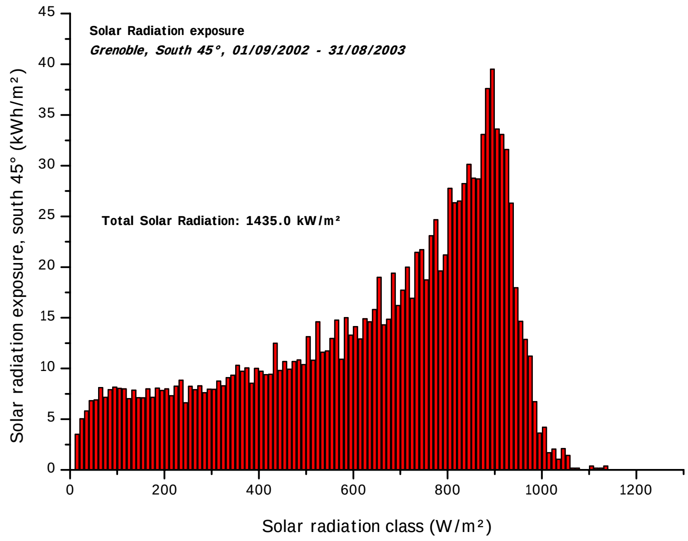


Fig. 6: Global solar radiation distribution on a 45°-tilted, south-oriented plane in Grenoble, 1.9.02-31.8.03

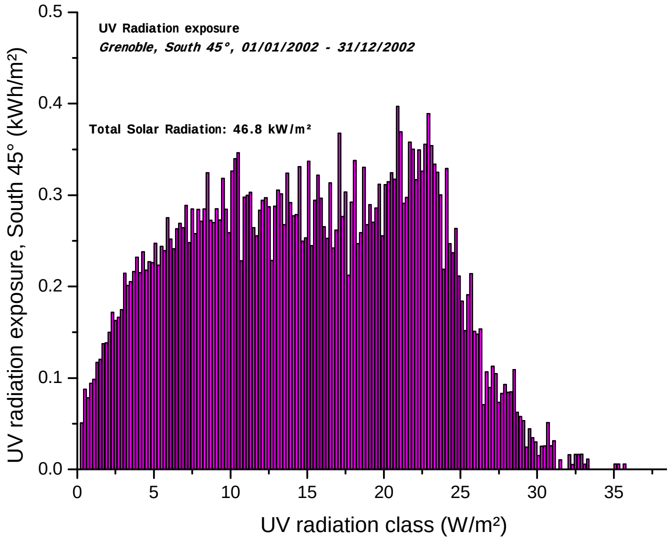


Fig. 7: Global UVA radiation distribution on a 45°-tilted, south-oriented plane in Grenoble, 1.1.02-31.12.02

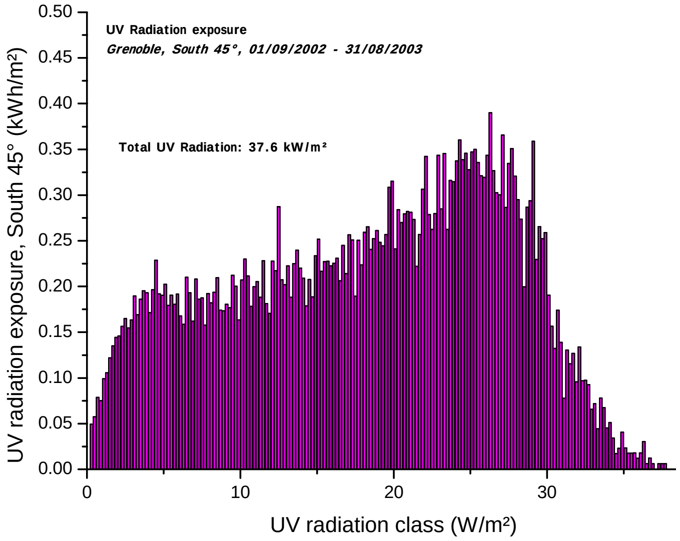


Fig. 8: Global UVA radiation distribution on a 45°-tilted, south-oriented plane in Grenoble, 1.9.02-31.8.03

4.2 Test Stand

At both test sites, the chromogenic glazing system prototypes were exposed outdoors in a test stand which is tilted 45 ° and orientated due south (fig. 5). The total glazing area for each type of sample, each represented by two IGU's, was 1.08 m2. The glazing is cycled twice a day during the daylight hours. In addition to standard meteorological data, the glazing surface temperature, the UV radiation, solar radiation and daylight incident on the plane parallel to the glazing are monitored continuously. The visible transmittance is used as the performance parameter, and is monitored with luxmeters located outside and behind the glazing units. As the solar incidence angle varies throughout the day and year, the transmittance values originally calculated from the measured luxmeter ratios reflect the angular dependence of the glazing transmittance. The transmittance values presented here from Freiburg were subsequently corrected to the values for near-normal incidence on the basis of laboratory measurements [Wilson et al, 2002]. To reduce extrapolation errors, the transmittance values used for analysis were restricted to those measured with angles of incidence less than 65° and reference illuminance values exceeding 4500 lux. The transmittance values from Grenoble still include the variation due to the angle of incidence.

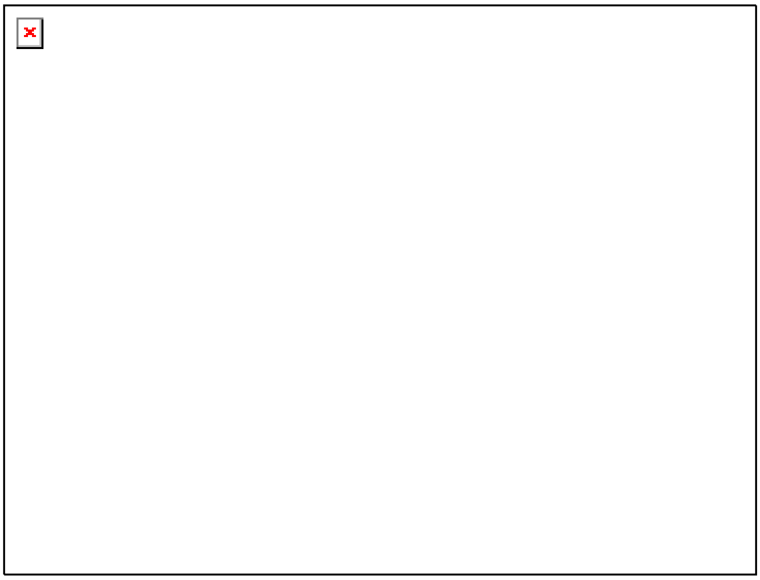


Fig. 9: View of the test box in Freiburg (back absorber plate removed for better visibility). Each of the four chromogenic IGU's shown has an area of 895 mm x 590 mm.

4.3 Extreme glazing temperatures

A summary of the temperatures measured in Freiburg of the external glazing surfaces with a shielded Pt100 probe is given in table 3. The peak temperatures for samples B and C, 68.7°C and 76.3°C respectively, were measured at midday on 12th August, 2003, when the air temperature exceeded 38°C, and the solar radiation intensity in the glazing plane ranged from 925 to 880 Wm-2. The air temperature behind the glazing during the same period was between 51 and 52.5 °C.

Table 4: Statistics on surface glazing temperatures (Tpos1) for three chromogenic samples exposed in Freiburg.

Sample	1.12.01-31.11.02			1.9.02-31.8.03		
	average [°C]	minimum [°C]	maximum [°C]	average [°C]	minimum [°C]	maximum [°C]
A	15.0	-17.0	66.7			
B	14.3	-18.1	66.8	16.0	-17.0	68.7
C				17.2	-16.2	76.3

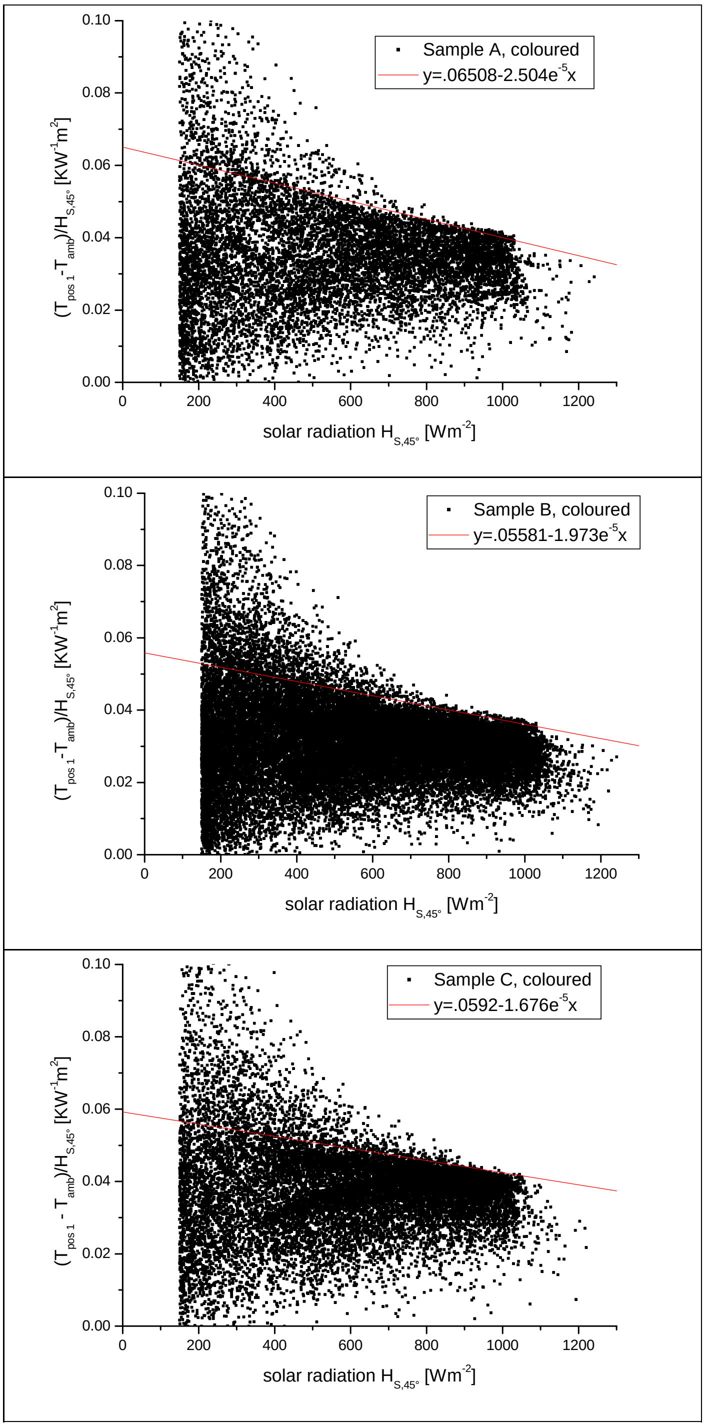


Fig. 10: Radiation-scaled temperature difference between glazing surface and air temperatures, versus global solar radiation in the glazing plane, for the three chromogenic glazing systems in the coloured state, exposed in Freiburg.

The graphs in figure 10 make use of a representation, which is commonly applied to determine the stagnation temperature of thermal solar collectors, to predict the maximum glazing temperature. The difference between the outer glazing surface temperature (T_{pos1}) and the ambient air temperature (T_{amb}) is scaled by the global solar radiation incident on the glazing plane ($H_{S,45°}$), (which is oriented south and tilted 45 ° in this case,) and plotted versus $H_{S,45°}$.

Low measured values of the solar radiation can occur under a variety of conditions, ranging from completely overcast skies to clear skies at times when the angle of incidence is very large, resulting in very different amounts of radiation absorbed in the glazing, so there is a wide scatter in the corresponding y-values in the graph.

However, high values radiation can occur only when the sky is essentially clear and the angle of incidence is small, so that the amount of radiation absorbed by the glazing for a given incident value does not vary as widely. The points at the top of the distribution at higher radiation levels are those where the absorbed radiation is greatest and other thermal loss mechanisms, such as convection due to wind, are least.

By extrapolating the manually positioned red line along the top of the distribution to higher radiation values, the maximum temperature difference between the glazing surface and the ambient air temperature can be determined to an accuracy of 3 - 4 K. For a radiation intensity of 1200 W, this temperature difference is about 42 K for sample A, 39 K for sample B, and 47 K for sample C.

If this radiation intensity coincided with an air temperature of 40°C, glazing surface temperatures exceeding 80°C could occur.

The maximum temperature for the bleached state cannot be derived simply from similar sets of data, using the transmittance value to select the points. Such data sets inevitably include points shortly after the onset of bleaching from the (heated) coloured state, where bleaching has occurred more quickly than the glass pane could cool down, i.e. radiative equilibrium had not yet been reached for the bleached state.

4.4 Temperature gradients

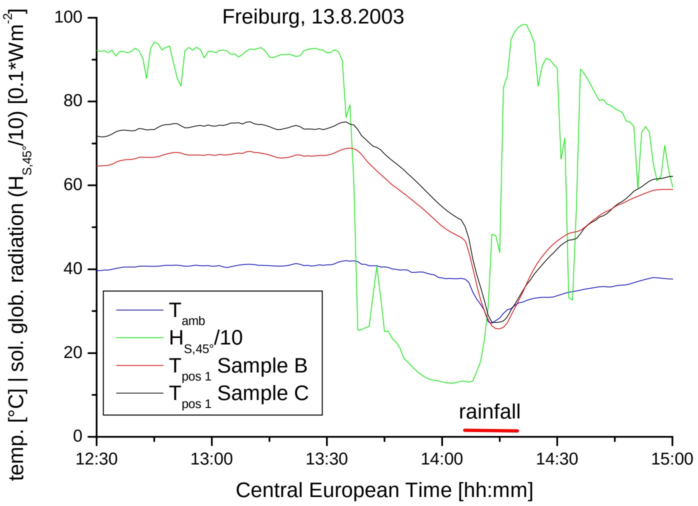


Fig. 11: Meteorological data and glazing surface temperatures during a summer thunderstorm in Freiburg

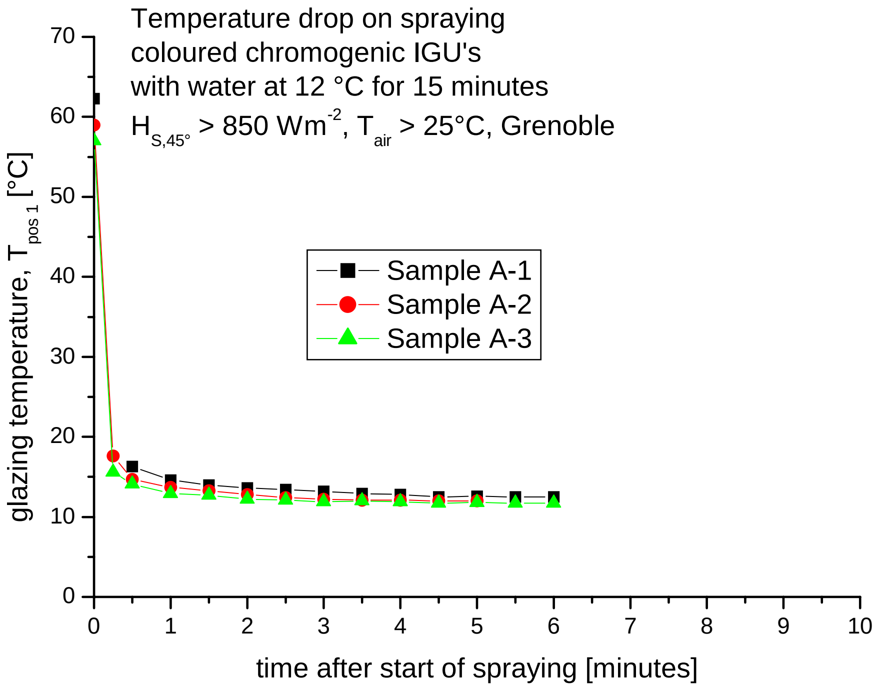


Fig. 12: Glazing surface temperatures during the thermal shock test (Table 1, SWIFT 5) in Grenoble

Not only the question of the maximum possible glazing temperature is of interest, but also that of large temperature gradients. On analysing the data for Freiburg from 1.12.2001 to 31.08.2003, the largest cooling rates for Samples B and C and for the ambient air temperature were all found to occur on 13th August, 2003.

As can be seen in fig. 7, the solar global radiation in the glazing plane exceeded 900 Wm-2 and the air temperature was about 40 °C (!) until the early afternoon, when clouds gathered, reducing the solar radiation to a minimum of 128 Wm-2. This caused a marked decrease in the surface glazing temperature of both samples, but the temperature drop became even faster during a period of rainfall.

The maximum cooling rate, calculated as the difference between consecutive 1-minute average values, was -3.9 K/minute for sample B and -5.0 K/minute for sample C.

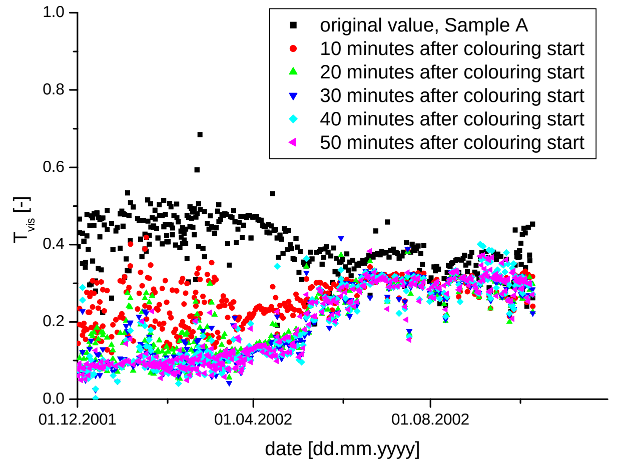
The highest heating rate for sample C in the complete measurement series was also measured on this day, namely 1.6 K/minute, which is significantly lower in absolute value than the cooling rate. At the same time, the heating rate for sample B was 2.0 K/minute. The highest heating rate determined for sample B during the reporting period was 2.3 K/minute on 23rd March, 2002, still significantly lower than the highest cooling rates. Pt100 resistance thermometers were used for these measurements.

By comparison, fig. 8 shows the temperatures measured with a thermocouple on the glazing surface during the thermal shock test conducted on three samples of type A in Grenoble according to the specifications of SWIFT 5, except that the water temperature was 12 °C. The maximum cooling rate was measured there during the initial 15 s after the onset of water spraying, and exceeded -160 K/minute.

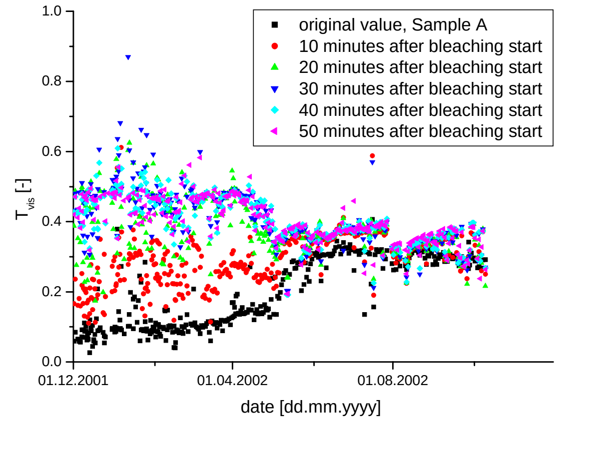
This is more than an order of magnitude greater than the maximum values determined from the outdoor measurements, indicating that the specified test conditions should be adequate. The water temperature specification could well be increased to 15 °C, so that the test could often be conducted using mains water rather than needing an additional thermostat.

It should also be mentioned that both the samples B and C presented in fig. 7, and the samples A, B and C subjected to the SWIFT 5 test, survived the thermal shock without any mechanical damage or degradation in the switching properties.

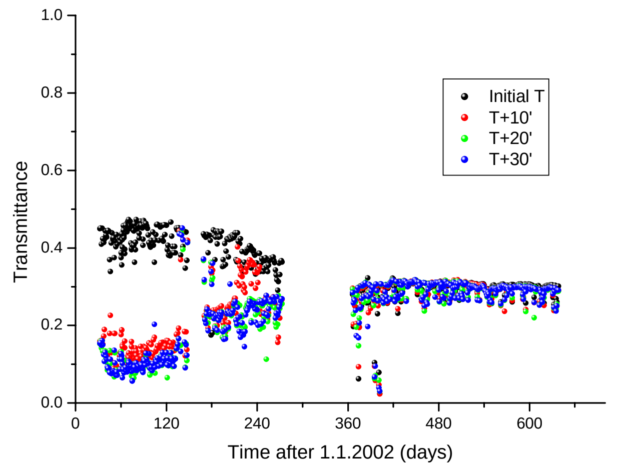
4.5 Evolution of transmittance and switching rates with time



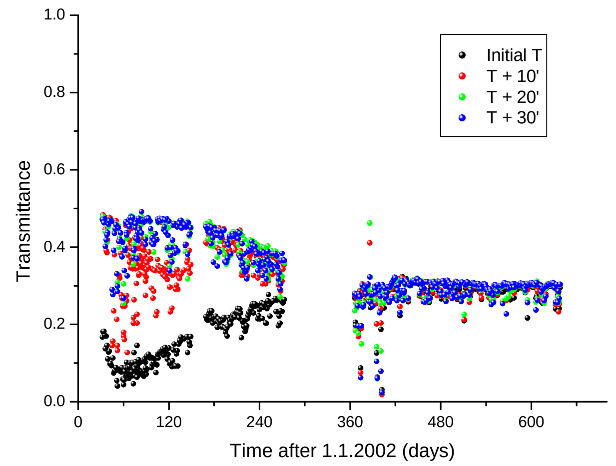
Sample A during colouring, Freiburg, 1.12.01-10.10.02



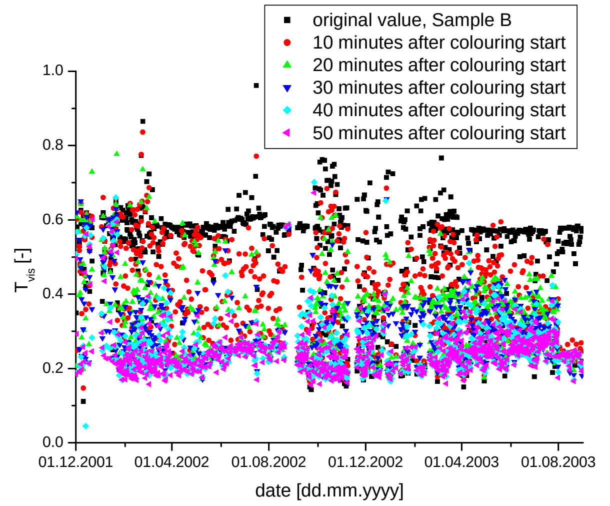
Sample A during bleaching, Freiburg, 1.12.01-10.10.02



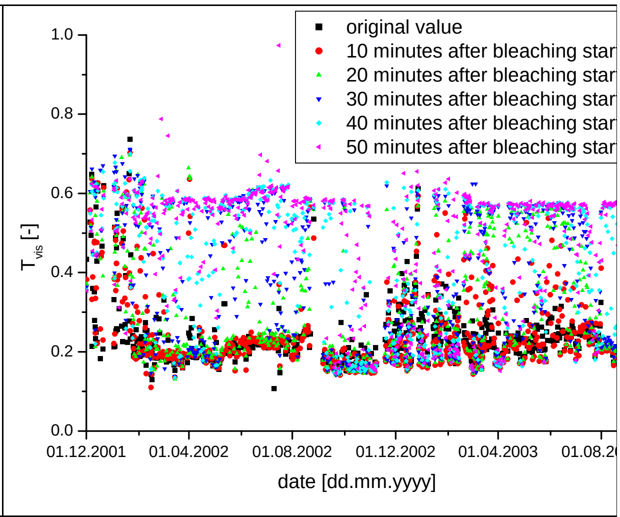
Sample A during colouring, Grenoble, 1.1.02-30.09.03



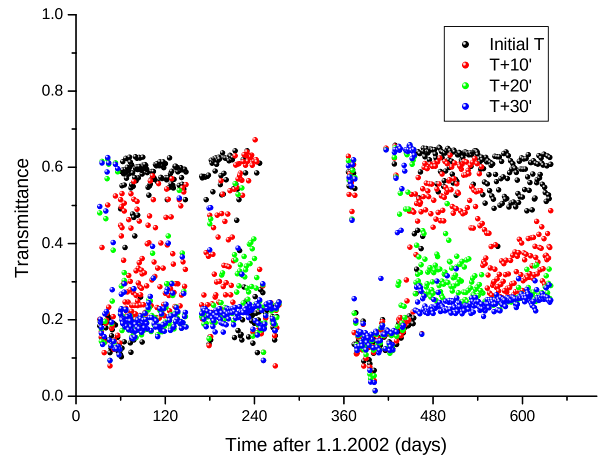
Sample A during bleaching, Grenole, 1.1.02-30.09.03



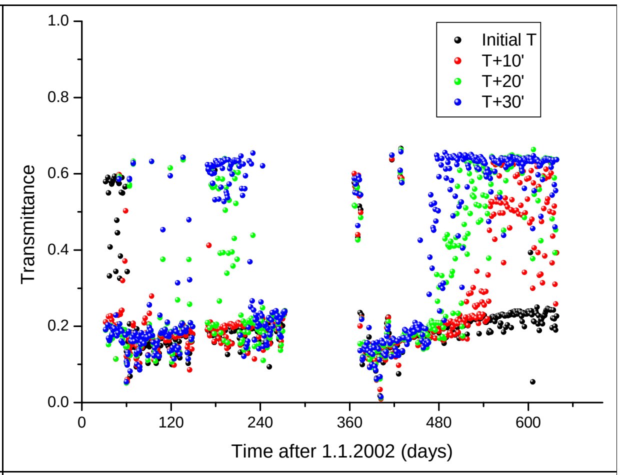
Sample B during colouring, Freiburg, 1.12.01-31.8.03



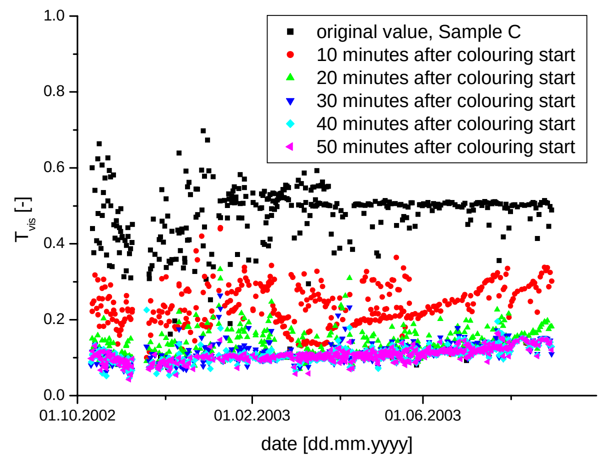
Sample B during bleaching, Freiburg, 1.12.01-31.8.03



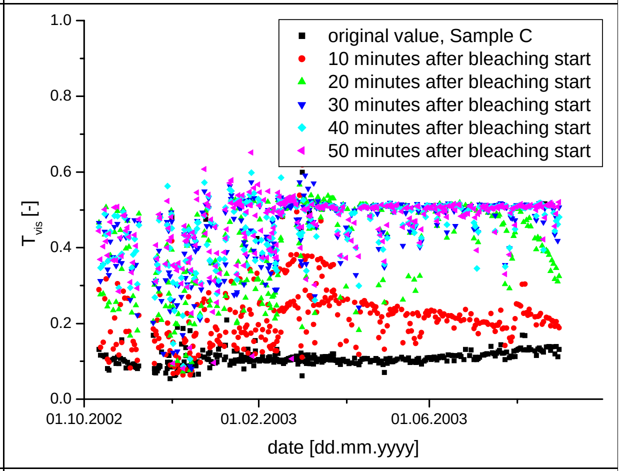
Sample B during colouring, Grenoble, 1.1.02-30.09.03



Sample B during bleaching, Grenoble, 1.1.02-30.09.03



Sample C during colouring, Freiburg, 10.10.02-31.8.03

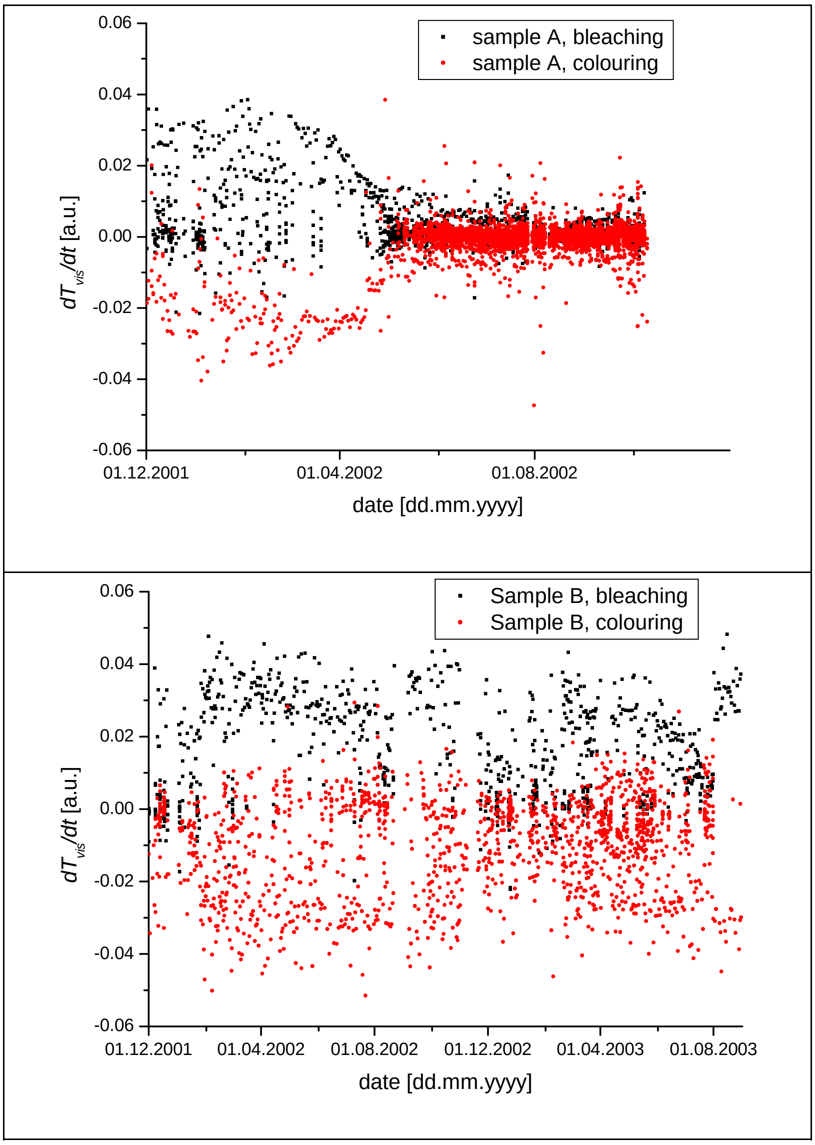


Sample C during bleaching, Freiburg, 10.10.02-31.8.03

Fig. 13: Transmittance values at 10-minute intervals after the beginning of colouring or bleaching for the chromogenic glazing samples A, B and C, exposed outdoors in Freiburg and Grenoble

Figure 13 gives a representation of each switching process by showing the transmittance value at different times after the start of bleaching or colouring processes. Despite filtering the data to remove points corresponding to the lowest light levels and highest incidence angles, the prevalence of low light levels and high incidence angles clearly reduces the accuracy of the transmittance values determined in winter, causing wider scatter of the points then. However, qualitative trends can be recognised, including the similarity in behaviour shown at the two different sites for samples of type A or B. Figure 9 allows some estimation of the switching rate, as the greater the difference in transmittance value between the original value and that 10 minutes after the start of switching, the faster is the switching process.

Figure 10 represents a different attempt to quantify the switching rate for the samples. To obtain the points shown in fig. 10, switching rates were determined from the difference between successive 5-minute averages of the transmittance values. Only those rates corresponding to the "central band" of transmittance values, where the switching rate is usually highest, are displayed. Although this selection method means that some switching processes may not be represented at all, and some may be represented by several points, the distribution of the points and the evolution of the outer envelope of the points indicate general trends in the switching speed.



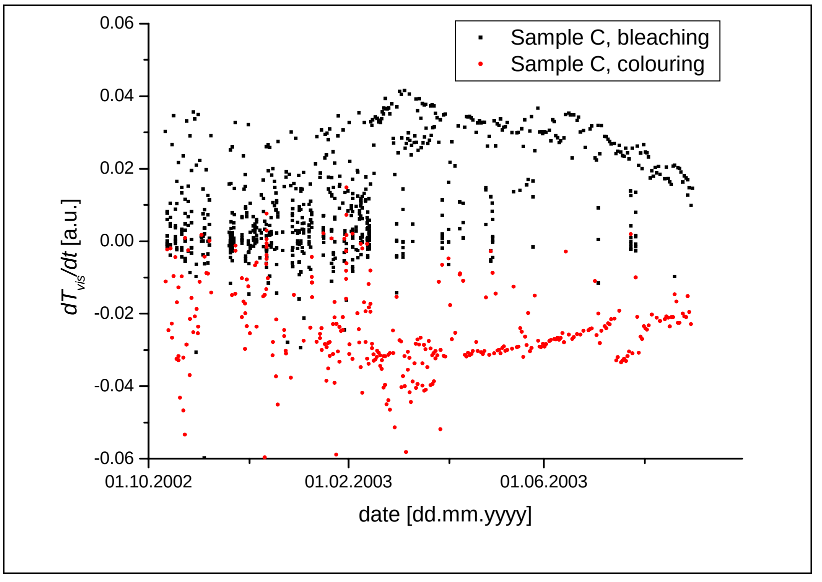


Fig. 14: Change over time of switching rates (black - bleaching; red - colouring) in arbitrary but identical units for samples A, B and C, exposed outdoors in Freiburg.

5. Discussion

On the basis of the graphs for sample A at both sites in figures 9 and 10, it is clear that the transmittance values for the coloured and bleached states have converged and the switching rate has decreased so much that the chromogenic glazing system has failed. This agrees qualitatively with the results from the accelerated SWIFT tests 1 and 3. However, the high-temperature accelerated test, SWIFT 2, on this sample did not reveal the same type of marked degradation as had been seen in the outdoor test after high temperatures in spring and summer.

By contrast, the SWIFT 2 test caused catastrophic failure of samples B and C, although the outdoor performance is quite good. This raises the question of an appropriate temperature and radiation level for the accelerated ageing test. Obviously, the temperature should not be so high that the activation energy threshold for new degradation mechanisms is exceeded. However, even if a temperature is chosen which is lower than the peak which can be experienced in outdoor exposure, it can be questioned whether the continuous cumulative load on the switching system only accelerates degradation or whether it enables a sequence of mechanism steps that would be terminated and may even reverse during the nocturnal conditions of natural exposure.

In choosing testing conditions for architectural chromogenic glazing systems, there may be a case for distinguishing the requirements according to the application. For example, safety standards differentiate between vertical and overhead glazing - for absorptive glazing such as coloured chromogenic glazing, the difference in maximum possible incident solar radiation intensity could be significant.

Similarly, a classification according to climatic zones, as is the case for energy rating systems, could also be considered. Finally, the flexibility associated with the control unit, which is an integral part of a chromogenic glazing system, means that precautionary measures can be taken to prevent the glazing from reaching a temperature known to be harmful. A test specifying a higher temperature then may become irrelevant.

6. Further steps in the durability methodology

Quantitative benchmarks to define passing or failure of these tests have not yet been suggested within Project B2, as the effect of changes in the indicators on the performance of the installed architectural glazing has not been investigated sufficiently. This aspect is on the agenda for Project A2, which has been extended by one year.

As development of the complete chromogenic glazing systems was proceeding in parallel with the test series, variations within the sample sets make it impossible to predict long-term durability of the products quantitatively on the basis of the tests 1, 2 and 3 conducted during Project B2. However, the results already gained demonstrate the general validity of the approach taken, which should be repeated in future, taking into account the modifications suggested above, when the production process has passed the prototype stage.

7. Conclusion

After the general methodology for durability testing had been adapted to the specific characteristics of chromogenic glazing, one series of accelerated ageing tests and outdoor exposure was completed.

Comparison of the results from indoor and outdoor testing raised questions on the appropriate choice of temperature and radiation loads, switching cycle duration and number of cycles in current and proposed accelerated ageing tests.

The visible transmittance in the bleached and coloured states, the b* colour co-ordinate in the L*a*b* system and the rate of change of the visible transmittance were identified as useful indicators for both accelerated and natural durability tests.

Valuable information is documented for reference purposes on the maximum glazing surface temperatures and rapid temperature changes experienced during outdoor exposure.

The questions of quantifying switching rates, and taking account of changing switching rates in the determination of "steady-state" transmittance values, were also addressed.

Definitive answers to these questions will require further time-consuming accelerated ageing and natural exposure tests, and careful analysis and comparison of their results.

It was not possible to carry out this initially planned work with the time, financial and personal resources available to Project B2, as they decreased markedly during its duration due to the withdrawal of several key participants.

Nevertheless, it is hoped that the results presented here will provide a good basis for continuation of the work when circumstances become more favourable.

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