
**Glass in building — Vacuum insulating
glass —**

Part 3:
**Test methods for evaluation of
performance under temperature
differences**

Verre dans la construction — Vitrage isolant à lame de vide —

*Partie 3: Méthodes d'essai pour l'évaluation des performances en cas
de différences de température*

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Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

The procedures used to develop this document and those intended for its further maintenance are described in the ISO/IEC Directives, Part 1. In particular, the different approval criteria needed for the different types of ISO documents should be noted. This document was drafted in accordance with the editorial rules of the ISO/IEC Directives, Part 2 (see www.iso.org/directives).

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For an explanation of the voluntary nature of standards, the meaning of ISO specific terms and expressions related to conformity assessment, as well as information about ISO's adherence to the World Trade Organization (WTO) principles in the Technical Barriers to Trade (TBT), see www.iso.org/iso/foreword.html.

This document was prepared by Technical Committee ISO/TC 160, *Glass in building*, Subcommittee SC 1, *Product considerations*.

A list of all parts in the ISO 19916 series can be found on the ISO website.

Any feedback or questions on this document should be directed to the user's national standards body. A complete listing of these bodies can be found at www.iso.org/members.html.

Glass in building — Vacuum insulating glass —

Part 3: Test methods for evaluation of performance under temperature differences

1 Scope

This document specifies test methods for evaluation of performance of vacuum insulating glass samples with rigid edge seal when subjected to temperature differences between the glass sheets.

This document is not applicable to vacuum insulating glass samples with flexible edge seal.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 19916-1, *Glass in building — Vacuum insulating glass — Part 1: Basic specification of products and evaluation methods for thermal and sound insulating performance*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in ISO 19916-1 and the following apply.

ISO and IEC maintain terminology databases for use in standardization at the following addresses:

- ISO Online browsing platform: available at <https://www.iso.org/obp>
- IEC Electropedia: available at <https://www.electropedia.org/>

3.1

heat transfer control board

board placed in a test chamber for reducing air flow around the vacuum insulating glass specimen

3.2

rigid edge seal

edge seal that prevents lateral relative movement between the glass sheets at the edge of the sheets where the seal is formed, made from a rigid material such as glass or metal

3.3

flexible edge seal

edge seal structure allowing lateral movement between the two glass sheets

4 Test method

4.1 Principle

The evaluation of performance of a vacuum insulating glass specimen when subjected to a temperature difference shall be performed in the following way:

- a) the test conditions should ensure that a well-defined and reproducible temperature is established in all regions of specimen;
- b) stresses in the vacuum insulating glass specimen induced by the testing procedure from sources other than the temperature difference should be as small as possible.

In order to satisfy these criteria:

- the specimen should be surrounded on each side by air at well-defined temperatures, and
- the specimen shall be oriented vertically; this effectively eliminates stresses due to bending under gravitational forces.

NOTE Heat transfer on the glass surfaces and the glass edge constraint can have a significant influence on the stress induced in the glass sheets of vacuum insulating glass under temperature differences. A detailed study of this is given in [Annex B](#).

4.2 Test specimens

4.2.1 Number of specimens

Three vacuum insulating glass specimens shall be submitted for testing.

4.2.2 Size of specimens

Each test specimen shall measure no less than 300 mm in width and 300 mm in height and no more than 850 mm in width and 850 mm in height. Size of specimens shall be determined so that distance between edge of the test specimen and inside wall of chamber is no less than 100 mm.

4.2.3 Design of specimens

In the following, a product range shall consist of specimens having the same edge seal structure and material.

The specimen design with the lowest *U*-value in the product range shall be selected for the test. If there are multiple designs with different thickness, one design shall be selected with the following process.

The specimen design with the minimum total nominal thickness in the product range shall be selected for the test. If the selected design has different nominal thicknesses for the two glass sheets, the thicker glass sheet shall face the hot side of the apparatus. If there is more than one specimen design of glass thickness in the product range with the minimum total nominal thickness, the specimen to be tested shall be the one for which the nominal thicknesses of the glass sheets differ the least.

EXAMPLE 1 For a product range with thickness in mm of 3 + 3, 3 + 5 and 5 + 5, only 3 + 3 is tested.

EXAMPLE 2 For a product range with thickness in mm of 3 + 5 and 5 + 5, only 3 + 5 is tested. The glass sheet with 5 mm thickness faces to the hot side of the apparatus.

EXAMPLE 3 For a product range with thickness in mm of 3 + 5, 4 + 4 and 5 + 5, only 4 + 4 is tested.

4.3 Apparatus

The usual laboratory apparatus and, in particular, the following.

4.3.1 Temperature chamber, in which air temperature in a room can be controlled [see [Figure 1, a](#)] or in which air temperature in two rooms divided by the specimen and the frame can be controlled [see [Figure 1, b](#)].

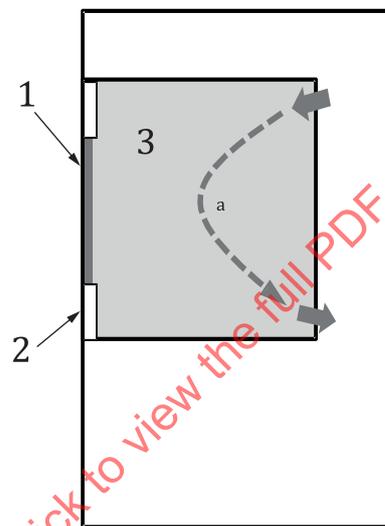
4.3.2 Frame for specimen installation, consisting of frame and insulating board [see [Figure 1, c](#)].

4.3.3 Heat transfer control board, consisting of flat metal plate.

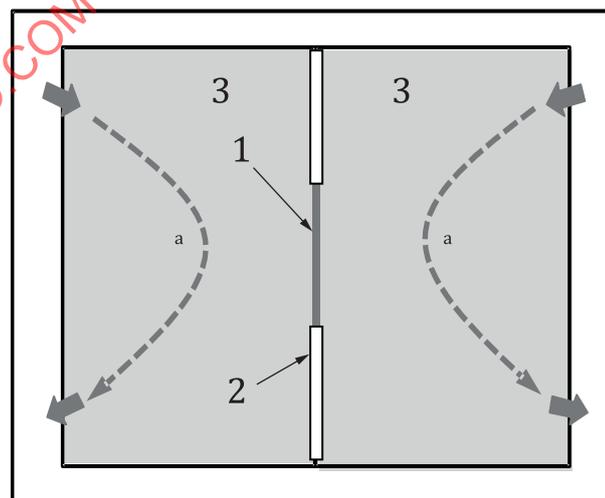
4.3.4 Thermocouples.

4.3.5 Data recorder.

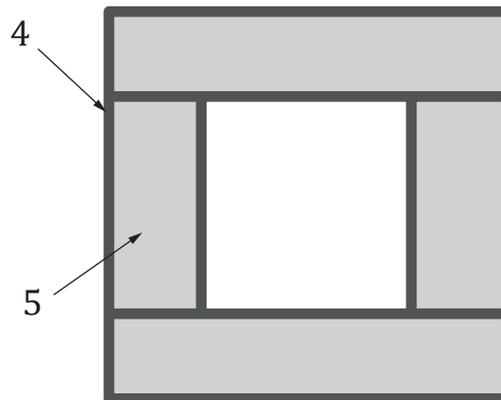
4.3.6 Adhesive tape.



a) Temperature chamber having one room



b) Temperature chamber having two rooms



c) Frame for specimen installation

Key

- 1 vacuum insulating glass specimen
- 2 frame for specimen installation
- 3 temperature controllable room
- 4 frame
- 5 insulating board
- ^a Air circulation.

Figure 1 — Examples of apparatus

4.4 Procedures

4.4.1 General

The *U*-value and the thermal resistance of each vacuum insulating glass specimen shall be determined with the method described in [4.4.2](#).

The specimen shall be prepared for the test by attaching thermocouples for temperature measurements to the surface, as shown in [4.4.3](#). The temperatures as measured by these thermocouples shall be continually recorded in a data recorder during the test.

The specimen shall be installed in the test apparatus as shown in [4.4.4](#). A heat transfer control board can be inserted between the circulating air and the surface of the specimen.

NOTE [Annex A](#) shows guidelines of the apparatus setup.

The test condition of the temperature difference to be applied to the specimen is described in [4.4.5](#).

The heat transfer coefficients on glass surfaces at the hot and cold sides shall be calculated from measured temperatures using the method described in [4.4.6](#).

If one or both of the calculated heat transfer coefficients is outside of the acceptable range defined in [4.4.7.1](#), the heat transfer control board and/or the cooling/heating system control shall be adjusted to correct the heat transfer coefficient(s) before continuing the test.

Failure criteria with the test shall be evaluated using measured temperatures as in [4.4.7.2](#).

The test procedure is shown in [Figure 2](#).

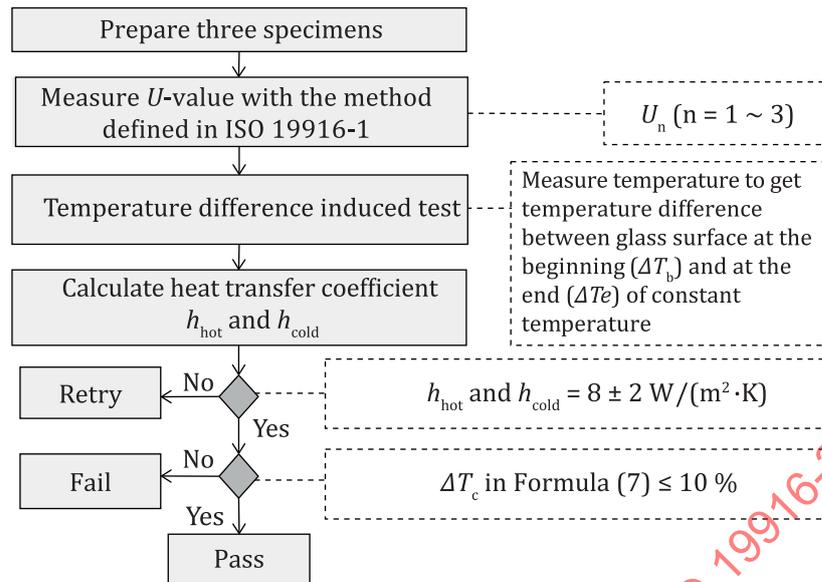


Figure 2 — Flow of test procedure

4.4.2 Measurement of U -value

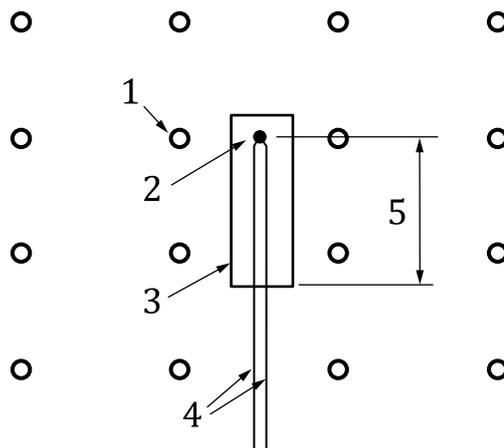
Before the specimen is installed in the apparatus, the U -value and the thermal resistance of each specimen shall be determined with the method defined in Annex A of ISO 19916-1:2018.

4.4.3 Setting of thermocouples

Thermocouples of which accuracy is guaranteed shall be placed to measure temperature at the following points. The thermocouples shall be applied on the glass and the heat transfer control board surface in such a way that the thermocouples do not change the temperature at the measuring point.

- Hot and cold side glass surface close to the centre of the specimen.
- Air temperature of hot and cold side at the point facing the centre of the specimen and at 100 mm to 200 mm from the glass surface. When the heat transfer control board is used, thermocouple shall be placed on the board at the point facing the centre of the specimen.

The diameter of thermocouple wire should be no more than 0,25 mm. The thermocouples should thermally contact the glass and the board surface for no less than 20 mm in length, using thin adhesive plastic tape having emissivity close to that of the surface. Metallic tape should not be used. The tip of the thermocouple on the glass should be positioned at the mid-point between two pillars and the contacting thermocouple wires should be located along a line mid-way between two adjacent rows of pillars. An example is shown in [Figure 3](#).



Key

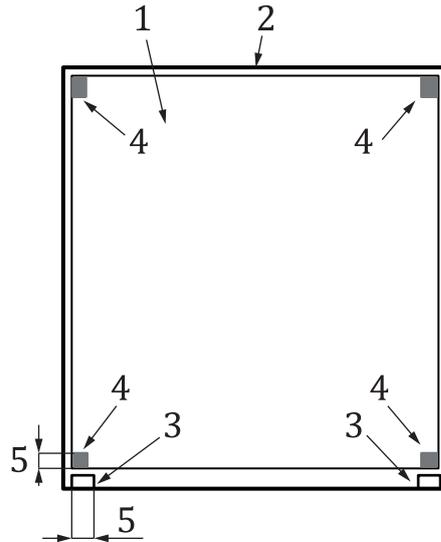
- 1 pillar
- 2 tip of thermocouple
- 3 plastic adhesive tape
- 4 thermocouple wire
- 5 no less than 20 mm

Figure 3 — Example for setting a thermocouple on a glass surface

4.4.4 Installation of specimens

Place a specimen vertically at the opening of the test apparatus, taking care that significant stress is not induced in the specimen by the method of fastening. In particular, all four edges shall be free to bend during the test.

EXAMPLE The specimen is placed on two setting blocks at the bottom corners and fixed at four corners. The setting blocks and fixing materials contact the specimen for a distance of no more than 30 mm from the corner of the specimen. A diagram of the fixing structure is shown in [Figure 4](#).

**Key**

- 1 vacuum insulating glass specimen
- 2 frame of the apparatus
- 3 setting block
- 4 fixing material
- 5 maximum 30 mm

Figure 4 — Example for fixing structure of the specimen

The gap between the specimen edge and the frame is sealed with a soft material, such as adhesive tape, in order to stop air flow through the gap.

NOTE The edge constraints affect stress in the specimen. This document specifies the test method with no edge constraint condition in order that test results obtained in different laboratories are comparable.

4.4.5 Temperature profile

Air temperature at both sides of the specimen shall be controlled at constant temperature. Temperature difference of the hot side and cold side glass surfaces ΔT_{VIG} shall be at no less than the value calculated with [Formula \(1\)](#), which is derived from condition of circumstance that air-to-air temperature difference is 40 °C and heat transfer coefficients are 8 W/(m²·K) and 23 W/(m²·K) on both side of surfaces.

NOTE 8 W/(m²·K) and 23 W/(m²·K) are the respective values of the reference internal and external heat transfer coefficients in ISO 10292.

$$\Delta T_{VIG} \geq 40 \times R / (0,168 + R) \quad (1)$$

where

ΔT_{VIG} is the temperature difference of the hot side and cold side of the glass surfaces, in °C;

R is the thermal resistance of the specimen, in m²·K/W.

The temperature difference of the hot side and cold side glass surfaces ΔT_{VIG} shall be controlled within ±5 % range around average value during the steady-state temperature condition for at least 1 h.

4.4.6 Determination of heat transfer coefficient

The heat transfer coefficient at the centre of the specimen on the hot and cold sides shall be calculated with [Formulae \(2\)](#) and [\(3\)](#):

$$h_{\text{hot}} = (\Delta T_2 / \Delta T_1) / R \quad (2)$$

$$h_{\text{cold}} = (\Delta T_2 / \Delta T_3) / R \quad (3)$$

where

- h_{hot} is the heat transfer coefficient on the hot surface of the specimen, in W/(m²·K);
- h_{cold} is the heat transfer coefficient on the cold surface of the specimen, in W/(m²·K);
- ΔT_1 is the average value, under steady-state temperature condition, of the temperature difference between hot side air and hot side glass surface in °C, or the average value of temperature difference between the board and the hot side glass surface in °C when the heat transfer control board is used on the hot side;
- ΔT_2 is the average value, under steady-state temperature condition, of the temperature difference between hot side glass surface and cold side glass surface, in °C;
- ΔT_3 is the average value, under steady-state temperature condition, of the temperature difference between cold side air and cold side glass surface in °C, or the average value of temperature difference between the board and the cold side glass surface in °C when the heat transfer control board is used on the cold side.

NOTE The heat flow through the specimen Q , in W/m², can be calculated as shown below:

$$Q = \Delta T_1 / (1 / h_{\text{hot}}) \quad (4)$$

$$Q = \Delta T_2 / R \quad (5)$$

$$Q = \Delta T_3 / (1 / h_{\text{cold}}) \quad (6)$$

[Formulae \(2\)](#) and [\(3\)](#) can be derived from [Formulae \(4\)](#), [\(5\)](#) and [\(6\)](#).

4.4.7 Requirements

4.4.7.1 Heat transfer coefficient

The calculated heat transfer coefficient on the hot surface of the specimen h_{hot} and heat transfer coefficient on the cold surface of the specimen h_{cold} shall be 8,0 W/(m²·K) ± 2,0 W/(m²·K).

NOTE The value 8,0 W/(m²·K) is selected as a free convection condition as used in Formula (13) of ISO 10292:1994. The range ± 2,0 W/(m²·K) is to account for variations in the measurement.

4.4.7.2 Proportional change in the temperature difference

The proportional change in the temperature difference at the hot and cold sides of the specimen from the beginning to the end of the steady-state temperature condition ΔT_c , in %, shall be calculated using [Formula \(7\)](#).

$$\Delta T_c = 100 \times |\Delta T_e - \Delta T_b| / \Delta T_b \quad (7)$$

where

ΔT_b is the temperature difference between the hot and cold sides of the glass surface at the beginning of the steady-state temperature condition at the test, in °C;

ΔT_e is the temperature difference between the hot and cold sides of the glass surface at the end of the steady-state temperature condition at the test, in °C.

If the calculated value of ΔT_c during the test of one or more of the test specimens exceeds 10 %, the relevant set of specimens shall fail the test. Breakage due to laboratory handling is not considered as test failure. Specimens broken due to laboratory handling shall be replaced and the measurement shall be repeated.

NOTE The most likely failure mode under this test is mechanical failure leading to loss of vacuum. This is detectable as a significant decrease in the temperature difference across the test specimen.

5 Test report

The test report shall contain the following items:

- a) the international Standard used (including year of publication);
- b) identification of the specimens:
 - specimen description (e.g. manufacturer's name, product name or other reference),
 - length (mm),
 - width (mm), and
 - nominal thickness (mm);
- c) description of the test apparatus, including:
 - manufacturer's name and model, if using a commercially-available apparatus,
 - inside dimensions of the chamber, i.e. height, width and depth (mm), and
 - dimensions and material of the heat transfer control board located inside the chamber, if used (mm);
- d) measurement and calculation results of
 - the U -value [$W/(m^2 \cdot K)$] and thermal resistance [$m^2 \cdot K / W$] of each specimen,
 - the average, the minimum and the maximum temperature difference (°C) between the hot side and the cold side glass surfaces during the steady-state part of the test,
 - the calculated heat transfer coefficient [$W/(m^2 \cdot K)$] on the hot side glass surface h_{hot} and the cold side of the glass surface h_{cold} , and
 - the calculated proportional change of the temperature difference of the hot and the cold side of each specimen at the beginning and the end of the steady-state temperature condition ΔT_c (%);
- e) the evaluation result: pass or fail of the tests;
- f) any deviations from this document which may have affected the result;
- g) the date of the test.

Annex A (informative)

Guideline for the test apparatus

A.1 General

This annex provides guidelines to make the test conditions suitable for the requirements in this document.

Circulating air within the chamber can lead to a large heat transfer coefficient at the surface of the specimen. This heat transfer coefficient can be controlled by inserting a heat transfer control board between the circulating air and the specimen so that air does not directly flow against the vacuum insulating glass specimen.

A.2 Guidelines

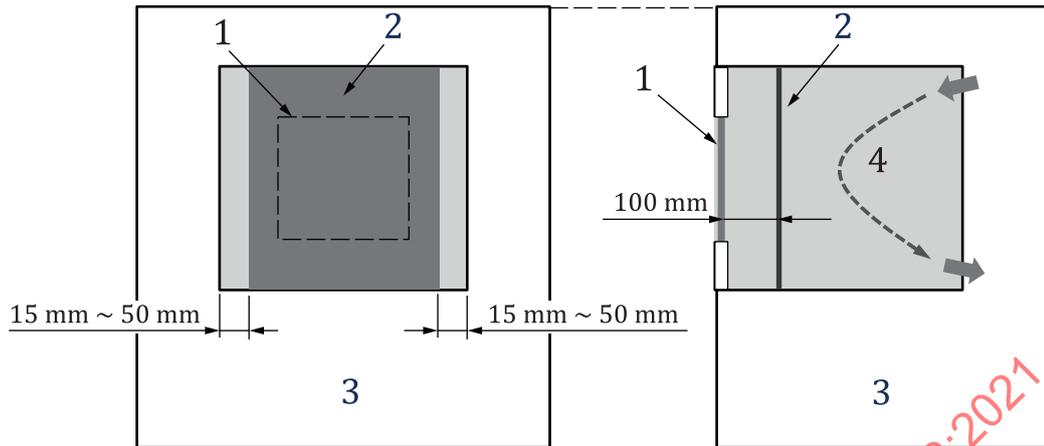
A.2.1 Option 1

The heat transfer control board allows a small amount of forced convection at the surface of the specimen.

The dimensions of the heat transfer control board depend on the nature of the forced convection within the chamber. For example, in case that circulating air flows from top to bottom, the board should be sealed against the inside surfaces of the apparatus at the top and bottom so that the air does not flow easily into the space between the board and the specimen. There should be gaps between the board and the chamber on both sides.

A possible dimension would be a heat transfer control board having 15 mm to 50 mm gap between the chamber wall and around 100 mm distant from the vacuum insulating glass specimen surface. An example of the apparatus is shown in [Figure A.1](#).

The board should be painted black on the surface facing to the specimen so that radiative heat transfer is enhanced.

**Key**

- 1 vacuum insulating glass specimen
- 2 heat transfer control board
- 3 cooling or heating chamber
- 4 air circulation

Figure A.1 — Example of option 1

A.2.2 Option 2

For an apparatus in which there is negligible forced air flow at the surface of the specimen and sufficient natural convective heat transfer is established at this surface, the heat transfer board is not necessary.

Annex B (informative)

Stress induced in the glass sheets of vacuum insulating glass under temperature differences

B.1 General

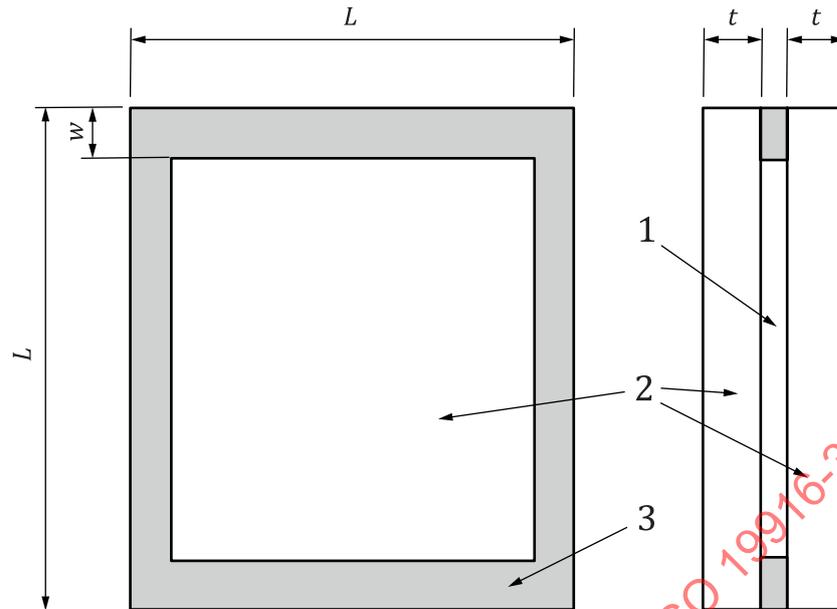
A temperature difference across a vacuum insulating glass specimen causes the hot glass sheet to expand relative to the cold sheet. The rigid edge seal prevents relative movement of the sheets at the edges. This produces mechanical stresses in the sheets and causes the structure to bend. These stresses can be analysed using analytic and finite element modelling methods. This Annex presents results of the nature and magnitude of the stresses obtained with both these modelling approaches and discusses the different physical mechanisms that affect them. The results of the modelling approaches were validated through systematic measurements performed on VIG units exposed to a well-defined thermal load.

B.2 Modelling conditions

The temperature difference across a vacuum insulating glass is established in the modelling configurations by locating the specimen between a hot environment at temperature T_H and a cold environment at temperature T_C . The heat transfer coefficients between the hot and cold environments and the corresponding glass surfaces are h_1 and h_2 respectively. Heat transfer between the hot and cold environments beyond the vacuum insulating glass is prevented by a surrounding thermally insulating baffle.

The configuration used to apply the thermal difference across a VIG unit should establish a stress distribution over the glass panes that is close to that which would be observed in a typical window installation. Primarily, this means that the heat transfer processes at the glass, on the hot and cold sides, should at least be a combination of heat flow due to natural convection and radiation. There is sometimes an extra convective component in practical installations due to forced air flow (wind) on the cold side. However, in the practical test specified in this document, it is convenient to use equal heat transfer coefficients on both glass sheets, to within an acceptable limit (that is, $8,0 \pm 2,0 \text{ W}/(\text{m}^2\cdot\text{K})$). This reduces the complexity in the setup and reduces possible inconsistent outcomes between tests. As discussed in the following sections, choice of the heat transfer coefficients can, by a significant margin, affect stress levels. Nevertheless, the variations in stress (including the origin of the stress components) are well understood and can be well predicted through analytical solutions.

[Figure B.1](#) is a schematic diagram of a vacuum insulating glass specimen defining symbols for the parameters used in this Annex.

**Key**

- t glass thickness (mm)
- L specimen size (mm)
- w width of edge seal (mm)
- 1 vacuum layer
- 2 glass sheets
- 3 edge seal

Figure B.1 — Schematic diagram of a vacuum insulating glass specimen

As is conventional, the surfaces of the glass sheets are denoted Surface 1 to 4 from the cold side to the hot side. Compressive stress is written as negative and tensile stress as positive.

The numerical results of modelling presented in this Annex are for an unconstrained vacuum insulating glass specimen having properties given in [Table B.1](#), under the thermal conditions given in [Table B.2](#).

NOTE In both [Tables B.1](#) and [B.2](#), parameters that are denoted * are varied in some of the data presented below.

Table B.1 — Details of specimen modelled

Glass thickness t (mm)	3*
Specimen size $L \times L$ (mm \times mm)	350 \times 350*
Width of edge seal w (mm)	4
Thickness of edge seal (mm)	0,2
Pillar separation (mm)	40
Pillar diameter (mm)	0,5
Corrected emissivity of low E coating	0,03
Glass-to-glass specimen conductance h_v [$W/(m^2 \cdot K)$]	0,46
Coefficient of thermal expansion of glass α ($1/^\circ C$)	9×10^{-6}
Young's modulus of glass E (GPa)	70
Poisson's ratio of glass μ	0,21

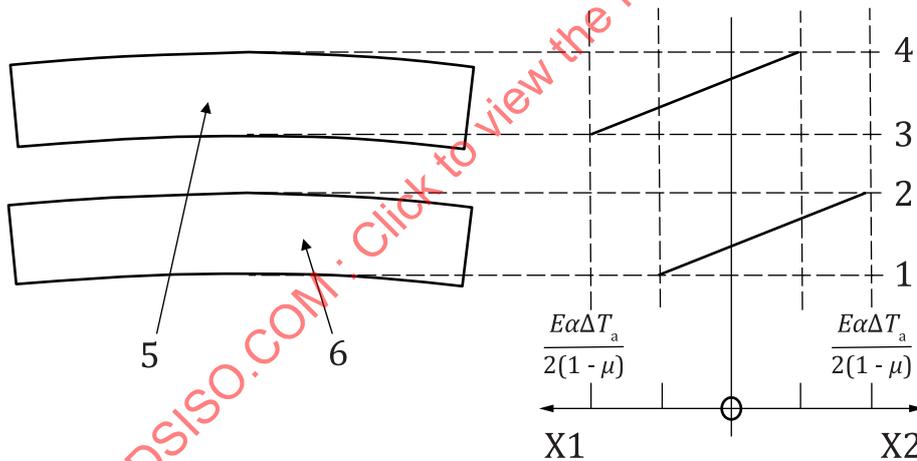
Table B.2 — Thermal conditions for modelling

Heat transfer coefficient, hot side h_1 [W/(m ² ·K)]	8
Heat transfer coefficient, cold side h_2 [W/(m ² ·K)]	20*
Air temperature, hot side T_H (°C)	20
Air temperature, cold side T_C (°C)	10*

B.3 Basic analytic model

Reasonable estimates of the magnitude of the temperature-induced stresses and the associated bending in vacuum insulating glass can be obtained using an analytic model.^[2] In its most basic form, the model assumes that both glass sheets have the same thickness t , the temperature of each glass sheet is uniform, the mean temperature of the vacuum insulating glass is T_m , and the average temperature difference between the glass sheets is ΔT_a . In the model, it is assumed that each sheet bends into a spherical shape, and that the stresses due to bending at the mid-plane of each sheet are zero. These conditions are appropriate for small amounts of bending, and this bending mode is conventionally referred to as linear bending.

For this simple case, the model predicts that the external surface of the hot sheet (surface 4) experiences tensile stresses of magnitude $+E\alpha\Delta T_a / 4(1 - \mu)$, and the internal surface of this sheet (surface 3) experiences compressive stresses of twice the magnitude. Stresses of the same magnitude, but in the opposite sense, exist on surfaces 1 and 2 of the cold glass sheet respectively. These stresses are illustrated in [Figure B.2](#).



- Key**
- X1 compressive stress
 - X2 tensile stress
 - 1 surface 1
 - 2 surface 2
 - 3 surface 3
 - 4 surface 4
 - 5 hot glass sheet
 - 6 cold glass sheet

Figure B.2 — Stresses in the glass sheets calculated from the basic analytic model

B.4 Extensions to analytic model

B.4.1 General

The basic analytic model can be extended to include the influence of several additional physical effects in a vacuum insulating glass subjected to a temperature difference.

B.4.2 Stiffness of the edge seal

The edge region is twice as thick as either glass sheet and stiffens the structure, reducing the bending. The extended analytic model shows that, for a square specimen of side L , an edge seal of width w reduces the magnitude of the centre-of-glazing stresses on surfaces 1 and 4 from the values predicted by the simple analytic model by the factor $[1 - 6w(1 - \mu)/L]$. The stiffening effect of the edge seal does not affect the stresses on surfaces 2 and 3. The stiffening effect of the edge seal reduces the edge stresses by the factor $[1 - 2w(1 - \mu)/L]$. For a 350 mm square vacuum insulating glass specimen with a 4 mm wide edge seal, this represents a reduction in the centre-of-glazing stresses on surfaces 1 and 4 by about 5 %. The corresponding reduction of the edge stresses is approximately 2 %.

B.4.3 Stresses in the edge region

In the extended analytic model, the bending stresses at the edge seal are estimated by assuming that the edge region is a solid beam of glass of thickness $2t$ bent into a circular shape of the same radius of curvature as that of the glazing remote from the edge. In this approximation, the edge stresses are unidirectional parallel to the edges, in the same sense as the external surface stresses remote from the edge, and larger in magnitude by the factor $3(1 - \mu)$. For soda lime silicate float glass, this factor is approximately 2,4.

B.4.4 Non-uniformities in the temperatures of the glass sheets

The bonded edge region represents a thermal short circuit between the two glass sheets, causing the temperature difference between the glass sheets close to the edges to be very small. A simple one-dimensional analysis^[3] shows that the temperatures of the glass sheets change approximately exponentially from the value at the edge to the centre-of-glazing values. The temperature non-uniformities of the glass sheets in the vicinity of the edges reduce the average temperature difference between the glass sheets. The effect of these temperature non-uniformities on the bending and the associated stresses can be included in the analytic model by using a value of ΔT_a calculated as the difference between the average temperatures of each glass sheet.

B.4.5 Hoop stresses

If the heat transfer coefficients on each side of the vacuum insulating glass are different, or if the vacuum insulating glass has glass sheets of different thickness (referred to as asymmetric vacuum insulating glass and discussed in the next subclause), the mean temperature of the glazing T_m can be different from the temperature of the edge T_e . In such a situation, additional stresses, referred to in this document as hoop stresses, exist in the edge region of the vacuum insulating glass. The hoop stresses are uniform through the thickness of the bonded edge seal and are parallel to the edges of the vacuum insulating glass. Hoop stresses are tensile if $T_e < T_m$, and have magnitude $E \alpha (T_m - T_e)$. For soda lime silicate float glass, the magnitude of the hoop stresses (in MPa) is $\sim 0,6(T_m - T_e)$.

B.4.6 Vacuum insulating glass with glass sheets of unequal thickness (asymmetric vacuum insulating glass)

The analytic model has been extended to determine the stresses in asymmetric vacuum insulating glass having glass sheets of unequal thickness t_H and t_C on the hot and cold side respectively. [Table B.3](#) gives expressions for the stresses on the surfaces of the vacuum insulating glass remote from the edges, and at the edges, as calculated with the extended analytic model.

Table B.3 — Temperature-induced stresses on the four surfaces and the edges of a vacuum insulating glass with glass sheets of different thicknesses t_H and t_C

Surface 1	$-\frac{E\alpha\Delta T_a}{(1-\mu)} \times \frac{t_H(2t_C^3 - t_H^3 + 3t_H t_C^2)}{(t_H + t_C)^4}$
Surface 2	$+\frac{E\alpha\Delta T_a}{(1-\mu)} \times \frac{t_H(4t_C^3 + t_H^3 + 3t_H t_C^2)}{(t_H + t_C)^4}$
Surface 3	$-\frac{E\alpha\Delta T_a}{(1-\mu)} \times \frac{t_C(4t_H^3 + t_C^3 + 3t_H^2 t_C)}{(t_H + t_C)^4}$
Surface 4	$+\frac{E\alpha\Delta T_a}{(1-\mu)} \times \frac{t_C(2t_H^3 - t_C^3 + 3t_H^2 t_C)}{(t_H + t_C)^4}$
Surface 1 at edge	$-3\frac{E\alpha\Delta T_a}{(1-\mu)} \times \frac{t_H t_C}{(t_H + t_C)^2}$
Surface 4 at edge	$+3\frac{E\alpha\Delta T_a}{(1-\mu)} \times \frac{t_H t_C}{(t_H + t_C)^2}$

B.4.7 Combination of different effects

In a practical vacuum insulating glass subjected to a temperature difference, most or all of the above effects are present. In the extended analytic model, the combined influence of these several effects is determined simply by applying all of the relevant corrections to the quantities obtained from the basic analytic model. For example, the effect of edge stiffness on the stresses in asymmetric vacuum insulating glass is calculated by multiplying the terms in [Table B.3](#) by the factors in [B.4.2](#).

B.4.8 Edge constraints

In addition to being influenced by the heat transfer coefficients between the external surfaces of the glazing and the surroundings, the difference between the temperature T_e of the edge region and the mean temperature T_m of the vacuum insulating glass can be affected by the design of the frame in which the vacuum insulating glass is mounted. Mechanical constraints exerted by the frame on the vacuum insulating glass can also affect the bending and therefore the temperature-induced stresses. There are many possible frame designs. The only realistic testing configuration that would enable valid comparison of results obtained in different laboratories is therefore an unconstrained specimen. For this reason, edge constraints are assumed to be zero throughout this annex.

B.5 Numerical modelling of stresses

Several numerical modelling studies have been undertaken of the temperature-induced stresses in vacuum insulating glass.^{[4],[5]} For relatively small amounts of bending, the results obtained with finite element modelling agree well with estimates obtained using the extended analytic model. However, for large bending, such as can occur if there is a high temperature difference between the glass sheets of the vacuum insulating glass, or if the vacuum insulating glass specimen is large, the results obtained from the two modelling methods may differ significantly. These differences arise as a result of nonlinear bending. As noted above, the assumptions intrinsic to the analytic model limit its applicability to linear bending situations.

B.6 Temperature-induced stresses of most significance

The tensile stresses on the internal surface 2 of an unconstrained vacuum insulating glass specimen are approximately twice as large as the tensile stresses on the external surface 4. However, these internal

tensile stresses do not lead to fracture the glass. This is because this surface is in a highly evacuated, water-free environment, and glass is known to be very strong under such conditions. The temperature-induced stresses of most importance for causing long term failure of the glass are therefore those on Surface 4 of the glazing. These stresses are largest around the edge region. The edges are also the part of all glass sheets with the highest density of surface flaws. In terms of assessing the likelihood of failure of vacuum insulating glass under a temperature difference, the most important tensile stresses are therefore at the edges on the hot side.

B.7 Results

B.7.1 General

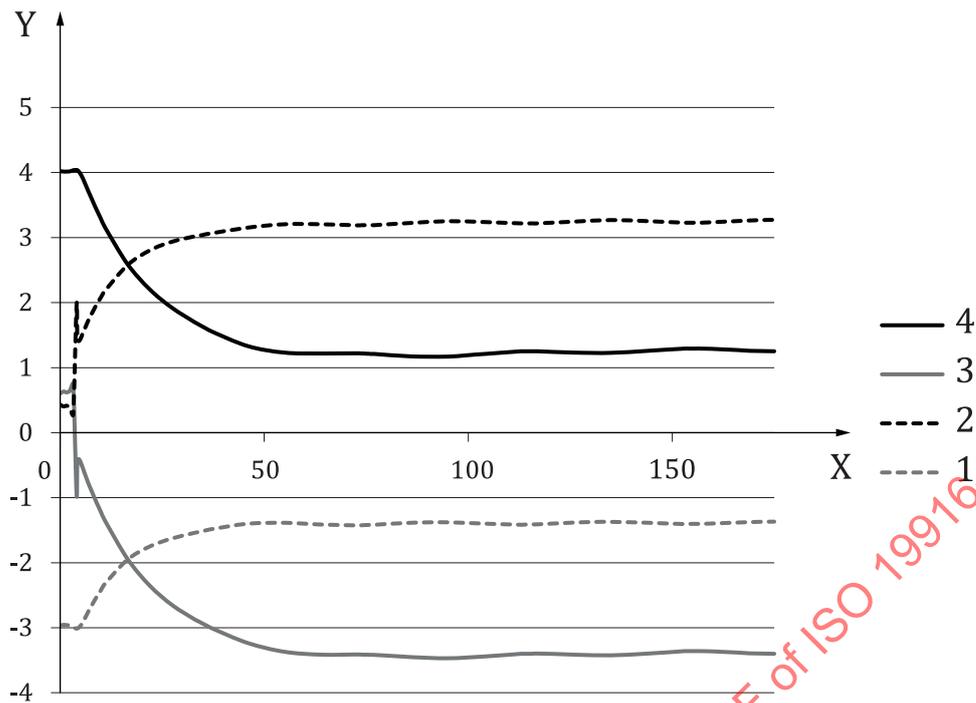
In [B.7](#), temperature-induced stress data are presented for specific vacuum insulating glass designs and testing configurations. In all cases, that data include the effects of the stiffening of the edge region, hoop stresses, and temperature non-uniformities in the glass sheets. Except where noted otherwise, all of the data are for a vacuum insulating glass specimen of properties given in [Table B.1](#), under the thermal conditions given in [Table B.2](#).

The finite element modelling stresses given in this document are along a centreline of the vacuum insulating glass specimen and are presented as a function of distance away from an outside edge of the vacuum insulating glass. The stresses are denoted S_{yy} and represent the magnitude of the stress in the direction parallel to the edge. The values presented in [B.7](#) of analytic modelling stresses remote from the edges are the magnitude of the isotropic stresses. Near the edges, the values presented for both modelling approaches are the magnitude of the unidirectional stress in this region. The finite element modelling stresses and those obtained with the analytic model are therefore equivalent.

B.7.2 Vacuum insulating glass with glass sheets of equal thickness (symmetric vacuum insulating glass)

B.7.2.1 Stresses on all four surfaces

[Figure B.3](#) shows finite element modelling results of the stresses on all four surfaces of a symmetric vacuum insulating glass with specifications given in [Table B.1](#) under the conditions given in [Table B.2](#). The magnitude of the centre-of-glazing stresses and the edge stresses agree well with those calculated with the extended analytic model.



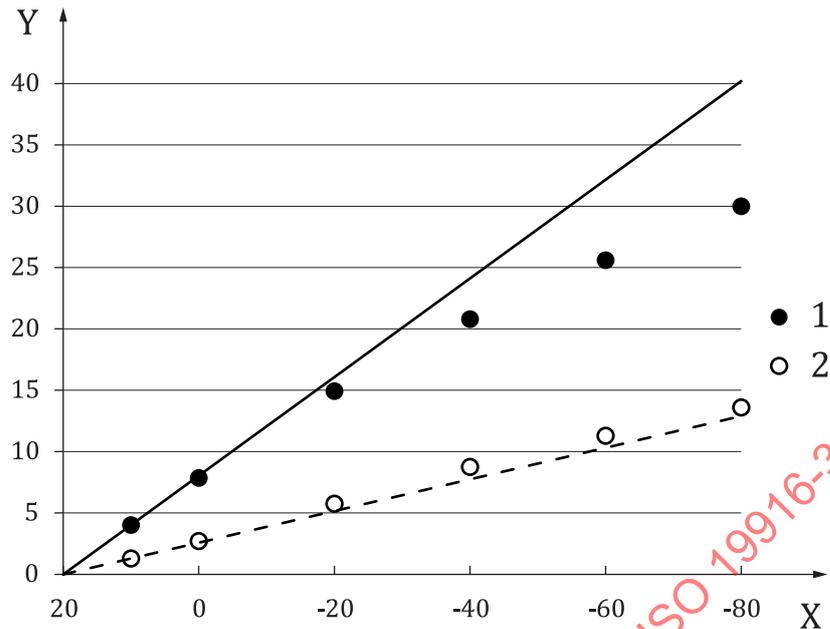
Key

- X distance from edge (mm)
- Y stress (MPa)
- 1 surface 1
- 2 surface 2
- 3 surface 3
- 4 surface 4

Figure B.3 — Finite element modelling results of stresses on all four surfaces of the vacuum insulating glass

B.7.2.2 Dependence of stresses on temperature difference

Figure B.4 shows finite element modelling data (points) for the stresses on surface 4 of a vacuum insulating glass with specifications given in Table B.1, for different cold environment temperatures. The lines on this chart are linear extrapolations of the data for small temperature differences.

**Key**

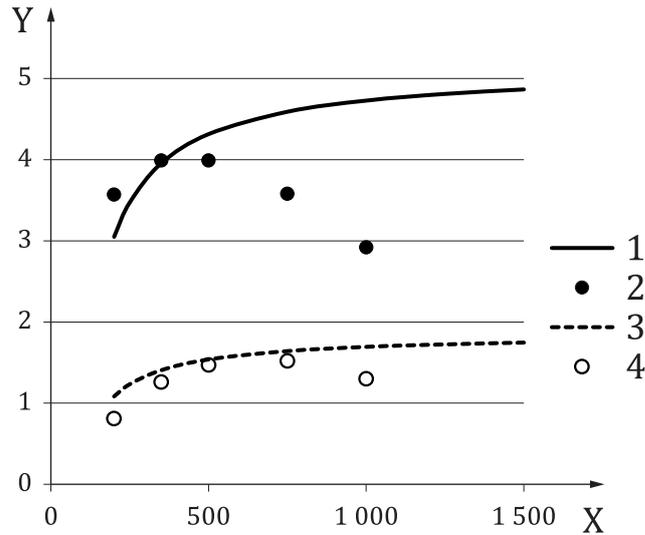
- X cold air temperature (°C)
 Y stress (MPa)
 1 edge
 2 centre of glass

Figure B.4 — Finite element modelling estimates of centre-of-glazing (C of G) and edge stresses on surface 4 of a vacuum insulating glass for different cold environment temperatures

As expected, for small air-to-air temperature differences, the stresses in the vacuum insulating glass are approximately proportional to the temperature difference. The stresses in this region agree well with results from the extended analytic model. For larger temperature differences, however, the centre-of-glazing stresses increase more than this linear dependence and the edge stresses increase less. Such effects are due to nonlinear bending of the glass sheets.

B.7.2.3 Variation of centre-of-glazing and edge stresses with lateral dimension of vacuum insulating glass

Figure B.5 shows finite element and analytic modelling data for the centre-of-glazing and edge stresses on surface 4 for square vacuum insulating glass having different lateral dimensions, with parameters otherwise as given in Tables B.1 and B.2.



Key

- X dimension of vacuum insulating glass (mm)
- Y stress (MPa)
- 1 edge, analytic
- 2 edge, FEM
- 3 centre of glass, analytic
- 4 centre of glass, FEM

Figure B.5 — Finite element and analytic modelling data of centre-of-glazing (C of G) and edge stresses on surface 4 for vacuum insulating glass of different lateral dimensions, with parameters otherwise as given in [Tables B.1](#) and [B.2](#)

The finite element modelling edge stresses do not vary monotonically with specimen size. Such effects are also associated with nonlinear bending of the sheets. Despite this qualitative inconsistency between the finite element and analytic modelling data, the stresses obtained with both approaches are reasonably close for vacuum insulating glass of size ≤ 500 mm.

The data in [Figure B.5](#) show that the linear analytic model provides good qualitative and quantitative estimates of the behaviour of vacuum insulating glass under linear bending conditions. When nonlinear bending occurs, however, data obtained with the analytic model must be interpreted with caution.

B.7.2.4 Variations in the stresses with external heat transfer coefficient on the cold side

[Figure B.6](#) shows data obtained with the extended analytic model for the edge stresses on surface 4 as a function of the heat transfer coefficient on the cold side, for several air-to-air temperature differences, with parameters otherwise as given in [Tables B.1](#) and [B.2](#).