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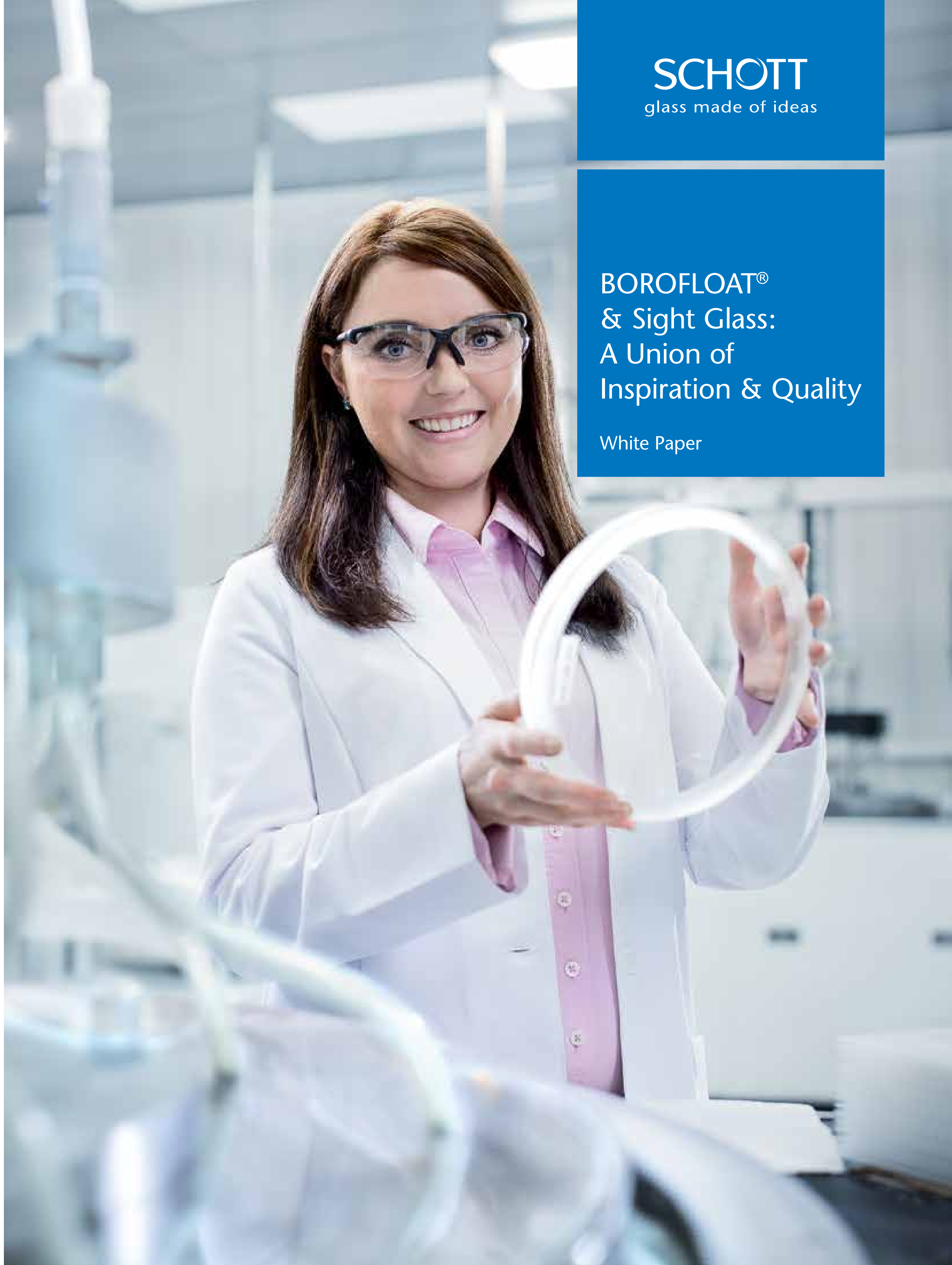

SCHOTT
glass made of ideas

BOROFLOAT® & Sight Glass: A Union of Inspiration & Quality

White Paper

BOROFLOAT® & Sight Glass: A Union of Inspiration & Quality

The performance requirements for sight glasses to monitor for instance chemical reactions in industrial reactors are extremely high. Subjected to elevated temperatures, chemical attack and high pressure, specifying the right material is critical to ensuring safety in the harshest of environments. Such environments are where BOROFLOAT® feels right at home.

1. Introduction

BOROFLOAT® 33 borosilicate glass can be used as sight glass or viewing window in many applications including chemical, pharmaceutical, food & beverage, off-shore drilling, nuclear, biological, mining, electrical and general manufacturing. The use of BOROFLOAT® 33 borosilicate glass for these applications can be attributed to its outstanding abilities to resist chemical attack and its exceptional thermal properties, which allow higher temperature exposures. The chemical composition of BOROFLOAT® 33 borosilicate glass is in accordance with ASTM E 438-92 (2001), Type 1, class A. In certain cases BOROFLOAT® 33 borosilicate glass can be heat strengthened to withstand even higher pressure loads. Following common international standards* this paper will discuss ways to calculate a) the sight glass thickness for given mechanical and/or thermal loads or b) mechanical and/or thermal loads for given glass thicknesses. It will further provide calculation examples and pressure charts for easy value determination.

2. Mechanical & Thermal Loads

The thickness and size of a sight glass must be determined in order to satisfactorily meet the expected pressure loads to ensure safety. Thermal stresses must also be accounted for since these will reduce the allowable mechanical stress from the pressure load. The allowable stress limit is determined by combining the mechanical and thermal loads placed upon the sight glass.

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$$S > \sigma_{mech} + \sigma_{therm}$$

S	design strength of BOROFLOAT® 33 borosilicate glass
σ_{mech}	mechanical stress
σ_{therm}	thermal stress

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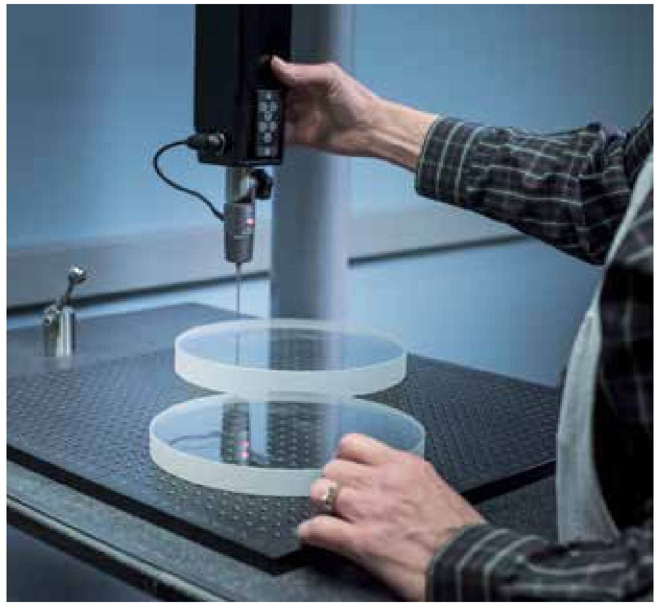


2.1 Mechanical Stress

The **mechanical stress** for a circular sight glass can be calculated per the following equation [3]:

Circular Sight Glass

2

$$\sigma_{mech} = \frac{3D^2p}{32t^2} \cdot (3+\mu)$$

D	diameter of unsupported area
t	sight glass thickness
p	applied pressure
μ	Poisson's ratio

With $\mu = 0.2$ for BOROFLOAT® 33 borosilicate glass, eq. (2) simplifies to:

3

$$\sigma_{mech} = 0.3\,\frac{D^2p}{t^2}$$

The **mechanical stress** for a rectangular sight glass can be calculated per the following equation [3]:

4

$$\sigma_{mech} = \frac{0.75 \cdot pb^2}{t^2 \cdot \left(1+1.61\,\frac{b^3}{a^3}\right)}$$

a	length of unsupported area (long side)
b	width of unsupported area (short side)
p	applied pressure

Note
Eq. (4) is related to Poisson's ratio $\mu = 0.3$ which slightly overstates the mechanical stress in BOROFLOAT® 33 borosilicate glass with its Poisson's ratio $\mu_B = 0.2$.
For a more precise value of mechanical stress σ_{mech} see calculation formulae in **appendix 1**.

One commonly referenced standard used for sight glass calculations is British Standard BS3463 „Observation and gauge glasses for pressure vessels" [1]. It provides recommended maximum working temperatures, temperature differentials and pressures and applies solely to circular sight glasses within defined dimensions.

Another commonly followed standard is provided by the Association of German Technical Inspection Services VdTÜV: AD 2000-Merkblatt N4: „Pressure vessels made of glass" [2]. This standard considers mechanical and thermal stresses as further explained below. Appendix 3 shows pressure charts derived when applying this standard's calculation schema to annealed and toughened BOROFLOAT® 33 borosilicate glass.

2.2 Thermal Stress

In order to determine the **thermal stress** of the sight glass, the exact temperature distribution over the entire surface of the sight glass needs to be known for all times when high temperature gradients are probable. Unfortunately this data is not always available. However, a simplified calculation can be done using the following equation (Association of German Technical Inspection Services VdTÜV: AD 2000-Merkblatt N4: Pressure vessels made of glass [2]):

5

$$\sigma_{therm} = \frac{\alpha \cdot E \cdot \Delta T}{2(1-\mu)}$$

α	Coefficient of thermal expansion (CTE)
E	Young's modulus
ΔT	Maximum temperature gradient on the sight glass
μ	Poisson's ratio

With $\alpha = 1.8 \cdot 10^{-6}$/°F, $E = 9.15$ Msi, and $\mu = 0.2$ for BOROFLOAT® 33 borosilicate glass, eq. (5) reduces to:

6

$$\sigma_{therm} = 10.5 \cdot \Delta T$$

for ΔT in °F and σ_{therm} in psi.

The advantage of eq. (6) is its simplicity. Nevertheless in some applications the thermal stress is lower than given by that equation. Besides this, mechanical stress and thermal stress do not always add up according to eq. (1), since the positions of their respective maxima do not coincide. A more realistic calculation of combined stress, mechanical and thermal, needs thorough knowledge of the spatial temperature distribution at all times and its numerical evaluation, which is beyond the scope of this paper.

The sum of mechanical and thermal stresses has to be balanced by **the design strength of the sight glass** according to eq. (1) in order to exclude breakage. Values for the design strength can be taken from British Standard BS 3463 [1] or from AD 2000-Merkblatt N4 [2]. These two standards define design strength of 7 MPa (= 1015 psi) and 6 MPa (= 870 psi), respectively. In this paper the more conservative value of 6 MPa (= 870 psi) is used.

Note
The design strength S allows for severe use conditions such as typical mechanical abrasion of the glass surface, or long term pressure load in contrast to short term pressure load, which is less critical to withstand.

In case of less severe load conditions - especially if short term pressure load is applied - the design strength may be greater than 870 psi. For recalculation of the design strength, see **appendix 2**.

If the design strength of 870 psi is not sufficient to balance the sum of mechanical and thermal stress, heat strengthening can be considered according to eq. (7) in order to increase the design strength S of the sight glass up to S_{total}:

7

$$S_{total} = S + S_{hs}$$

with heat strengthening S_{hs}.

Values for heat strengthening depend on equipment performance, temperature/time profile applied and - especially for low-thermal expansion glasses - the rapid cooling ability during the quenching step. For details and confirmation of applicable pre-stress the manufacturer of heat strengthened glass should be consulted.

As a guide for calculating sight glasses, typical **examples** (following VdTÜV: AD 2000-Merkblatt N4) are given below:

Example (1): mechanical load, circular sight glass, maximum pressure to be determined
Example (2): mechanical load, rectangular sight glass, maximum pressure to be determined
Example (3): mechanical load, toughened circular sight glass, maximum pressure to be determined
Example (4): mechanical and thermal load, toughened circular sight glass, maximum pressure to be determined

In addition to below samples, appendix 3 shows pressure charts for some typical conditions which apply to below defined sight glasses at room temperature.

- Circular sight glasses with a design strength of 870 psi for annealed glass
- Circular sight glasses with a design strength of 3000 psi (S_{hs} = 2130 psi) and 9000 psi (S_{hs} = 8130psi) for heat strengthened glass
- Square sight glasses with a design strength of 870 psi for annealed glass and 3000 psi for heat strengthened glass
- Rectangular sight glasses with side ratio 1:1.4, resp. 1:2 with a design strength of 870 psi for annealed glass and 3000 psi for heat strengthened glass

Example (1):

In the first example the maximum pressure for an annealed BOROFLOAT® 33 borosilicate glass circular sight glass at room temperature is determined.

Unsupported diameter	D=5 inch
Thickness	t= ¾ inch
Design strength	S=870 psi = maximum allowable stress σ_{mech}

From eq. (3) (calculation for a circular sight glass) the maximum pressure p is:

8

$$p = \sigma_{mech} \cdot \frac{t^2}{0.3 \cdot D^2}$$

For this example, a maximum pressure of 65 psi is determined. (The same result may be derived from the **pressure chart** in appendix 3.)

Comment
When selecting glass from the table of available glass thicknesses please consider the panel thickness tolerance and refer to the lowest resulting glass thickness for an added factor of safety.

Example (2):

In the second example, the maximum pressure for an annealed BOROFLOAT® 33 borosilicate glass rectangular sight glass at room temperature is determined.

Unsupported length	a=8 inch
Unsupported width	b= 4 inch
Thickness	t= ¾ inch
Design strength	S= 870 psi =maximum allowable stress σ_{mech}

From eq. (4) (calculation for a rectangular sight glass) the maximum pressure p is:

9

$$p = \sigma_{mech} \cdot \frac{t^2 \cdot \left(1 + 1.61 \frac{b^3}{a^3}\right)}{0.75 \cdot b^2}$$

Applying this equation, a maxmimum pressure of 49 psi is determined. (The same result may be derived from the **pressure chart** in appendix 3.)

Example (3):

In the third example the maximum pressure for a high pressure toughened BOROFLOAT® 33 borosilicate glass circular sight glass at room temperature is determined.

Unsupported diameter	D=5 inch
Unsupported width	t= ¾ inch
Thickness	S_{hs} = 8130 psi
Design strength	S_{total} = 870+8130= 9000 psi =maximum allowable stress σ_{mech}

Applying eq. (8) (example 1), **a maximum pressure of 675 psi** is determined. (The same result may be derived from the **pressure chart** in appendix 3.)

Example (4):

In the fourth example the maximum pressure for a high pressure toughened BOROFLOAT® 33 borosilicate glass circular sight glass at 500 °F (260 ° C) is determined.

Unsupported diameter	D=5 inch
Thickness	t= ¾ inch
Temperature	T = 500 °F (260 ° C)
Difference in temp.	ΔT= 430 °F (238.9 K) (vs. room temperature 70 °F (21.1 °C))
Heat strengthening	S_{hs} = 8130 psi
Design strength	S_{total} = 870+8130 = 9000 psi =maximum allowable stress $\sigma_{mech} + \sigma_{term}$

From eq. (6) the thermal stress equals σ_{therm} = 10.5 · 430 °F = 4515 psi. Regarding the total design strength of S_{total} = 9000 psi and the thermal stress σ_{therm} = 4515 psi, the mechanical stress is limited to 4485 psi.

Using eq. (8) and inserting σ_{mech} = 4485 psi, a maximum pressure of 336 psi is determined.

Literature
[1] BS 3463: Observation and gauge glasses for pressure vessels
[2] AD 2000-Merkblatt N4: Pressure vessels made of glass, Published by German Technical Inspection Agency VdTÜV
[3] Roark, R. J.: Formulas for Stress & Strain, p. 194, McGraw Hill New York, Toronto, London, 3rd Edition 1954
[4] Drouven, G. (Bayer AG): Application-technical information 199/78
[5] G. Exner: Permissible bending stress in glass components under continuous loading. Glastech. Ber. 56 (1983) Nr. 11, S. 299-312

Appendix 1: mechanical stress in rectangular sight glasses: full calculus

The values derived from eq. (4) are related to Poisson's ratio $\mu = 0.3$ which slightly overrates the mechanical stress in BOROFLOAT® 33 borosilicate glass with its Poisson's ratio $\mu_B = 0.2$. For a more precise value of mechanical stress σ_{mech} this calculus may be used [4].

Step 1: defining normalized values

Normalized pressure:

$$p^* = \frac{p}{E} \cdot \left(\frac{a}{t}\right)^4 \quad \text{(A1)}$$

Normalized deflection:

$$f^* = \frac{f}{t} \quad \text{(A2)}$$

Normalized mech. stress:

$$\sigma^* = \frac{\sigma}{E} \cdot \left(\frac{b}{t}\right)^2 \quad \text{(A3)}$$

Side ratios:

$$e = \frac{a}{b} \quad \text{(A4)}$$

With: p = applied pressure, E = Young's modulus, f = deflection, t = thickness. a and b denote the length and width

Step 2: defining auxiliary factors

$$A = \frac{19.45}{1+2.6 \cdot e^2+e^4} \quad \text{(A5)}$$

$$B = 5.22 \cdot \left(1+\frac{1}{e^2}\right)^2 \quad \text{(A6)}$$

$$C = \frac{4.58}{1+1.666 \cdot \left(e^2+\frac{1}{e^2}\right)} \quad \text{(A7)}$$

$$D = 5.141 \cdot (e^2+0.2) \quad \text{(A8)}$$

Step 3: derive deflection f*

The relation between deflection and pressure is given by eq. (A9):

$$p^* = Af^{*3}+Bf^* \quad \text{(A9)}$$

Since eq. (A9) is cubic, solutions for deflection f* are numerical in most cases.

Step 4: derive stress σ*

With deflection f*, stress can be calculated according to:

$$\sigma^* = f^* \cdot (Cf^*+D) \quad \text{(A10)}$$

Recalculating the mechanical stress σ from its normalized value σ* will be done by eq. (A3).

Note
This calculus refers to sheets of glass which are supported, not clamped. Clamped glasses lead to slightly lower stresses. Similar formulae are available for clamped glasses. Nevertheless, clamped glasses are difficult to establish in reality. Therefore and for the sake of safety this calculus for supported glasses is recommended.

Appendix 2: design strength of annealed sight glasses: full calculus

The design strength of glass for pressure vessels is defined by various standards as, e.g., BS 3463 or AD 2000-Merkblatt N4. These two standards define design strength as 7 MPa and 6 MPa, respectively. In these standards the design strength is derived from generally recognized glass strength data, measured by standardized laboratory equipment in the state as delivered, reduced by an overall safety factor.

Since this safety factor has to cover all applications irrespective of the severity of the single load condition (size of sight glass, duration of peak load), sight glass calculation may undervalue the design strength for this special purpose.
A useful tool to calculate the safety factor and the design strength of sight glasses for individual applications is given in literature [5]. This procedure comprises:

- Standardized measurement of glass bending strength (e.g. ring-on-ring test according to EN 1288-5) with its surface abraded to simulate long-term exposure
- Evaluation of the results in a statistical manner (e.g. Weibull statistics)
- Derivation of first safety factor f_A (area factor): The area factor takes into account that larger sizes are more prone to critical flaws and therefore yield lower strength
- Derivation of second safety factor f_P (probability factor): The probability factor takes into account that the strength of glass is a statistical property with certain scattering for inevitable physical reasons
- Derivation of third safety factor f_F (fatigue factor): The fatigue factor takes into account that the strength of glass is a time-dependent property. For a certain load the risk of failure increases with time

This procedure, adapted to BOROFLOAT® 33 borosilicate glass, yields an individualized design strength S_{ind} acc. to eq. (A11):

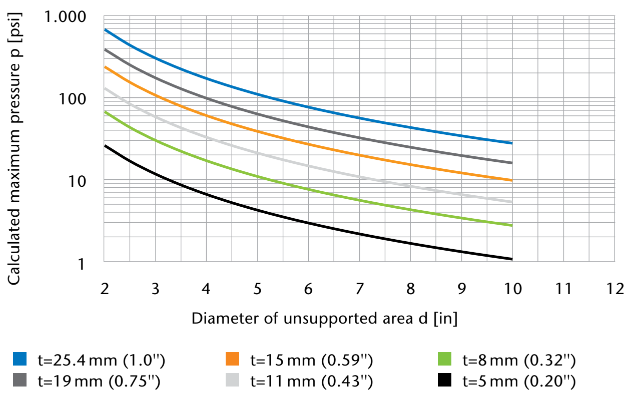
$$S_{ind} = 1140 \cdot \left(\frac{1}{\tau}\right)^{0.0333} \left(\frac{1}{A}\right)^{0.0861} \quad \text{(A11)}$$

With τ time of load at pressure p between 65 % and 100 % maximum pressure in hours, A the sight glass area in in², and individualized design strength S_{ind} in psi.

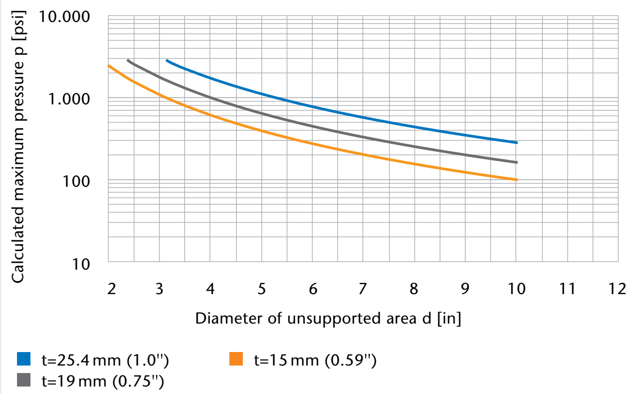
Nevertheless, if S_{ind} is calculated as less than 870 psi, the standardized design strength of 870 psi should be used.

Appendix 3:
pressure charts: circular sight glass
(following AD 2000-Merkblatt N4)

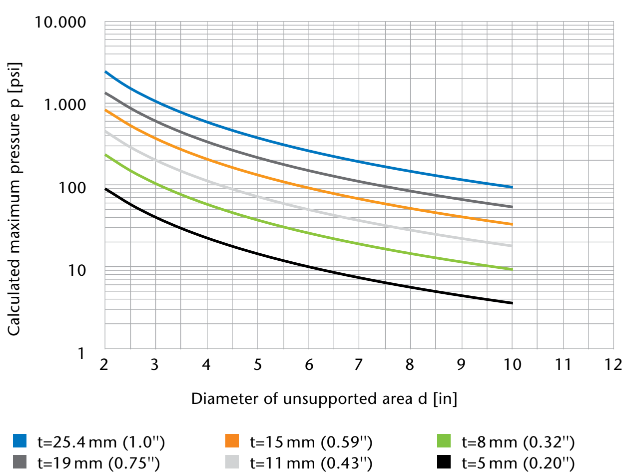
Circular sight glass at room temperature
annealed BOROFLOAT® 33 (design strength 870 psi)



Circular sight glass at room temperature
BOROFLOAT® 33 high pressure heat strengthened 8130 psi (design strength 9000 psi)

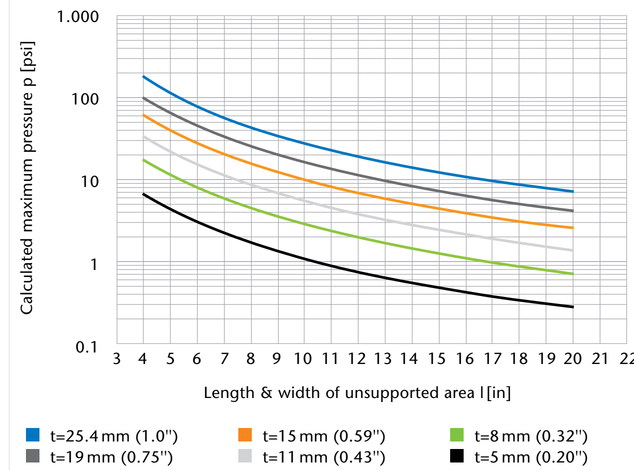


Circular sight glass at room temperature
BOROFLOAT® 33 heat strengthened 2130 psi (design strength 3000 psi)

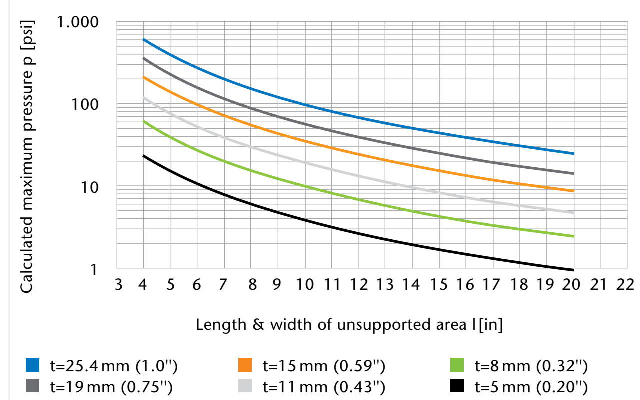


Appendix 3:
pressure charts: square sight glass
(following AD 2000-Merkblatt N4)

Square sight glass at room temperature
annealed BOROFLOAT® 33 (design strength 870 psi)

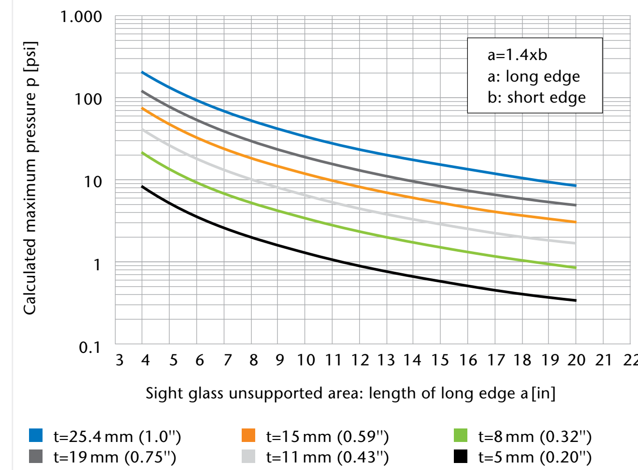


Square sight glass at room temperature
BOROFLOAT® 33 heat strengthened 2130 psi (design strength 3000 psi)

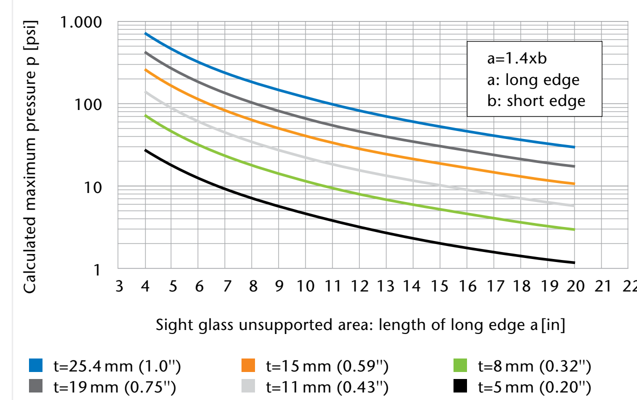


Appendix 3:
pressure charts: rectangular sight glass: side ratio 1.4 : 1
(following AD 2000-Merkblatt N4)

Rectangular sight glass at room temperature
annealed BOROFLOAT® 33 (design strength 870 psi)



Rectangular sight glass at room temperature
BOROFLOAT® 33 heat strengthened 2130 psi (design strength 3000 psi)



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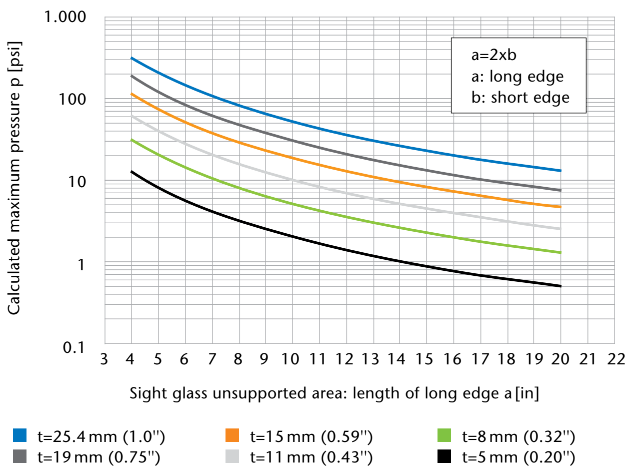
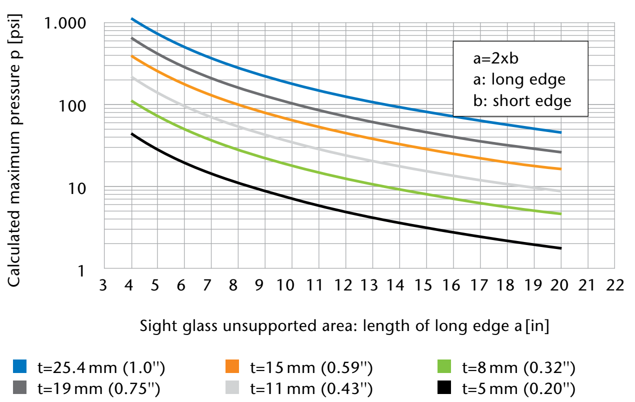
Appendix 3:
pressure charts: rectangular sight glass: side ratio 2 : 1
(following AD 2000-Merkblatt N4)

Rectangular sight glass at room temperature
annealed BOROFLOAT® 33 (design strength 870 psi)



Rectangular sight glass at room temperature
BOROFLOAT® 33 heat strengthened 2130 psi (design strength 3000 psi)



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