IMI-NFG Course on Processing in Glass

Spring 2015

(available online www.lehigh.edu/imi)

Lecture 9: Annealing and Tempering

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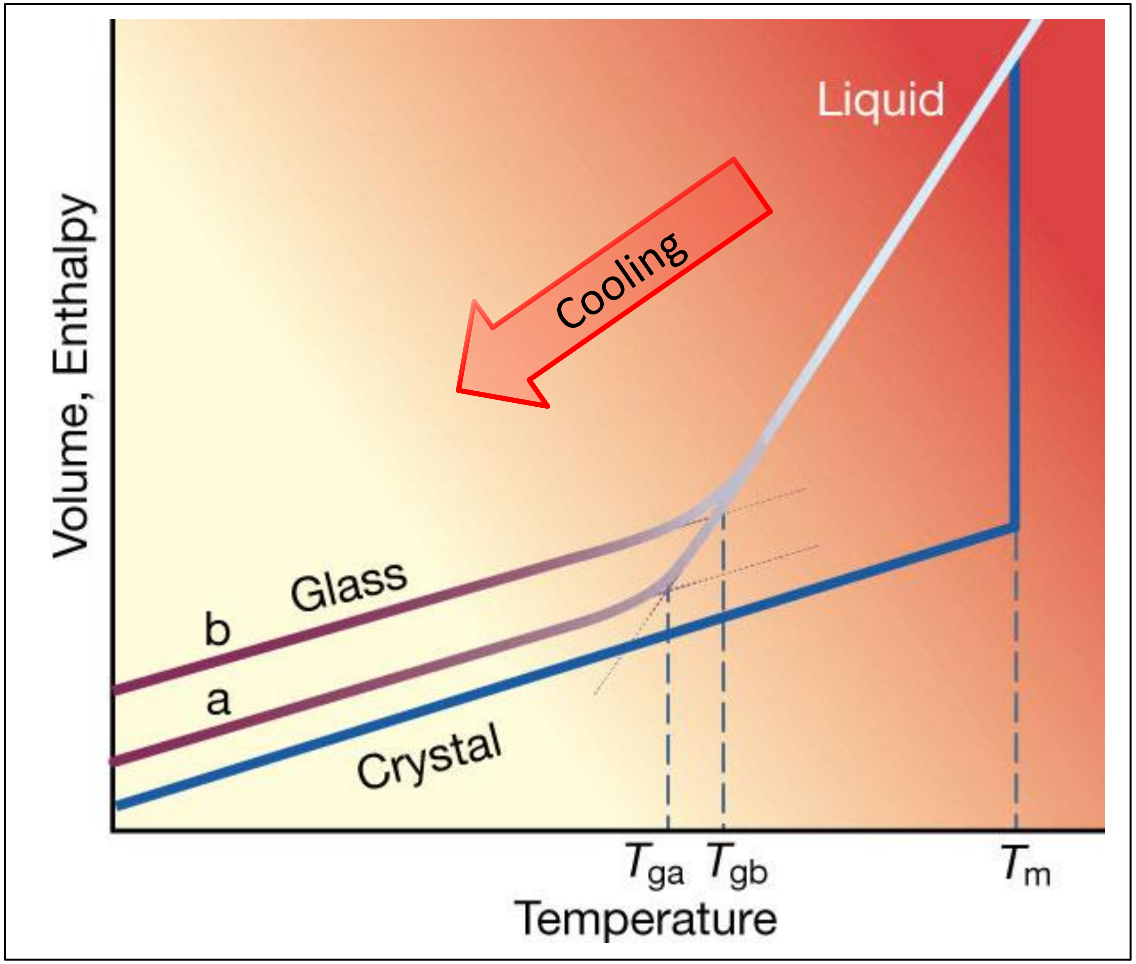
Outline of this lecture

1. **Annealing of glass**
   - Introduction - Principles
   - Annealing in industrial glass production
2. **Tempering**
   - Principles
   - Tempering in industrial glass production
   - Tempered vs. Heat strengthened glass

Introduction

Just a word on glass science – The glassy state



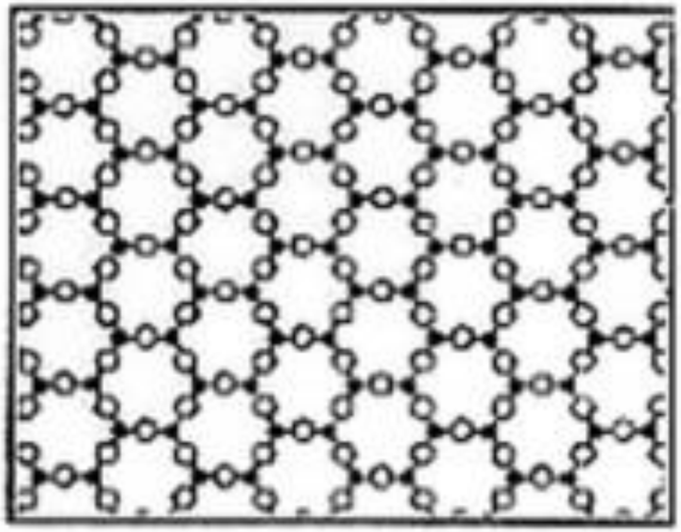
A: slower cooling rate, T_{ga}

B: faster cooling rate, T_{gb}

From P. Debenedetti and F. Stillinger, "*Supercooled liquids and the glass transition*", Nature 410, 259-267(March 2001)

Introduction

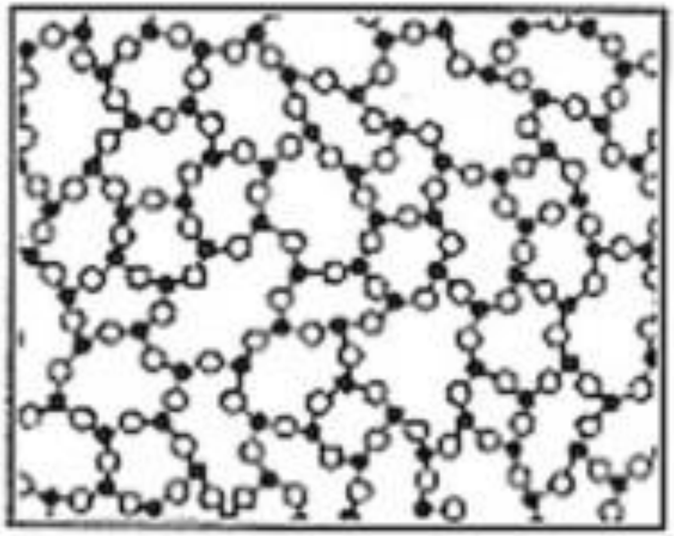
Just a word on glass science – The glassy state



Crystal
(e.g. quartz)

⇩

Ordered structure



Glass
(e.g. silica glass)

⇩

Disordered structure
(liquid-like)

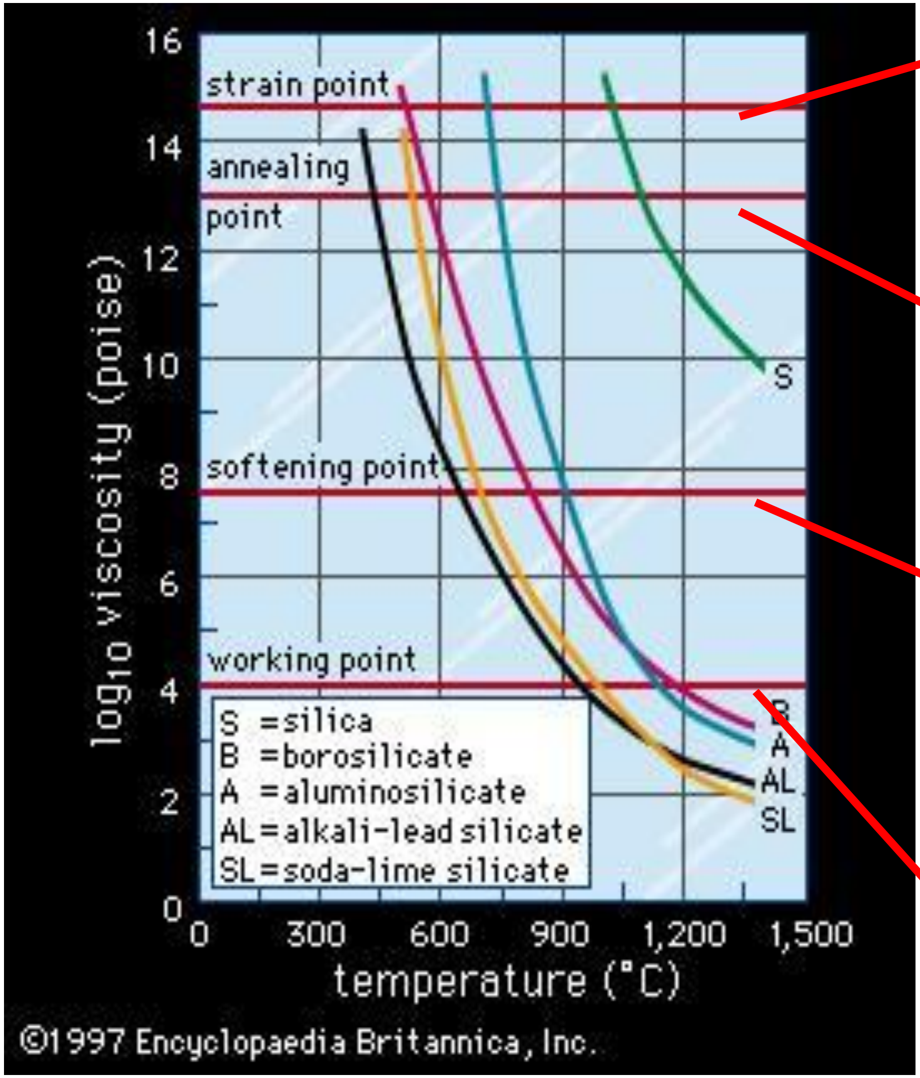
Introduction

- **Rapid cooling** of the melt is necessary to obtain a glass (avoid crystallization)
- This rapid cooling will generate **constraints** within the glass, which will are detrimental for the mechanical properties
- This constraints can be **relaxed by careful thermal treatment**
- This relaxation of constraints is called **annealing** of the glass
- **Good annealing** is extremely important to produce good commercial glasses and for their durability
- **Non-annealed** or poorly annealed glasses will be subject to **low resistance** to cracks/failure under small thermal or mechanical shocks

Annealing

- All along the cooling process, the **viscosity** of the glass increases, from a low-viscosity melt, to a rigid material with a higher viscosity
- A certain "degree of freedom" is necessary for the glass to relax the constraints caused by the rapid cooling (re-arrangements in the glass structure)
- **Good annealing** can only be obtained in a relatively **narrow range of temperatures** (thus of viscosity)
- For a good annealing of the constraints, the viscosity of the glass should be:
  - ✓ Not too high (constraints cannot be released anymore)
  - ✓ Not too low (the glass will not retain its shape)

Characteristic temperatures vs. viscosity



Source: http://www.britannica.com

- **Strain point**

$\eta = 10^{14.5}$ Poise ($10^{13.5}$ Pa.s)

Internal stresses are relieved in ~ 15 h

- **Annealing point**

$\eta = 10^{13.4}$ Poise ($10^{12.4}$ Pa.s)

Internal stresses are relieved in ~ 15 min

- **Softening point**

$\eta = 10^{7.65}$ Poise ($10^{6.65}$ Pa.s)

Glass deforms under its own weight at a rate of 1mm/min

- **Working point**

$\eta = 10^{4}$ Poise (10^{3} Pa.s)

Annealing point and stress point

Annealing point $\eta = 10^{12.4}$ Pa·s

- At this temperature, the internal thermal stresses present in the glass are relieved by **viscous relaxation** within 15 minutes. In order to relieve a glass product from its internal stresses the glass has to be heated to just above the annealing point and subsequently cooled down slowly.

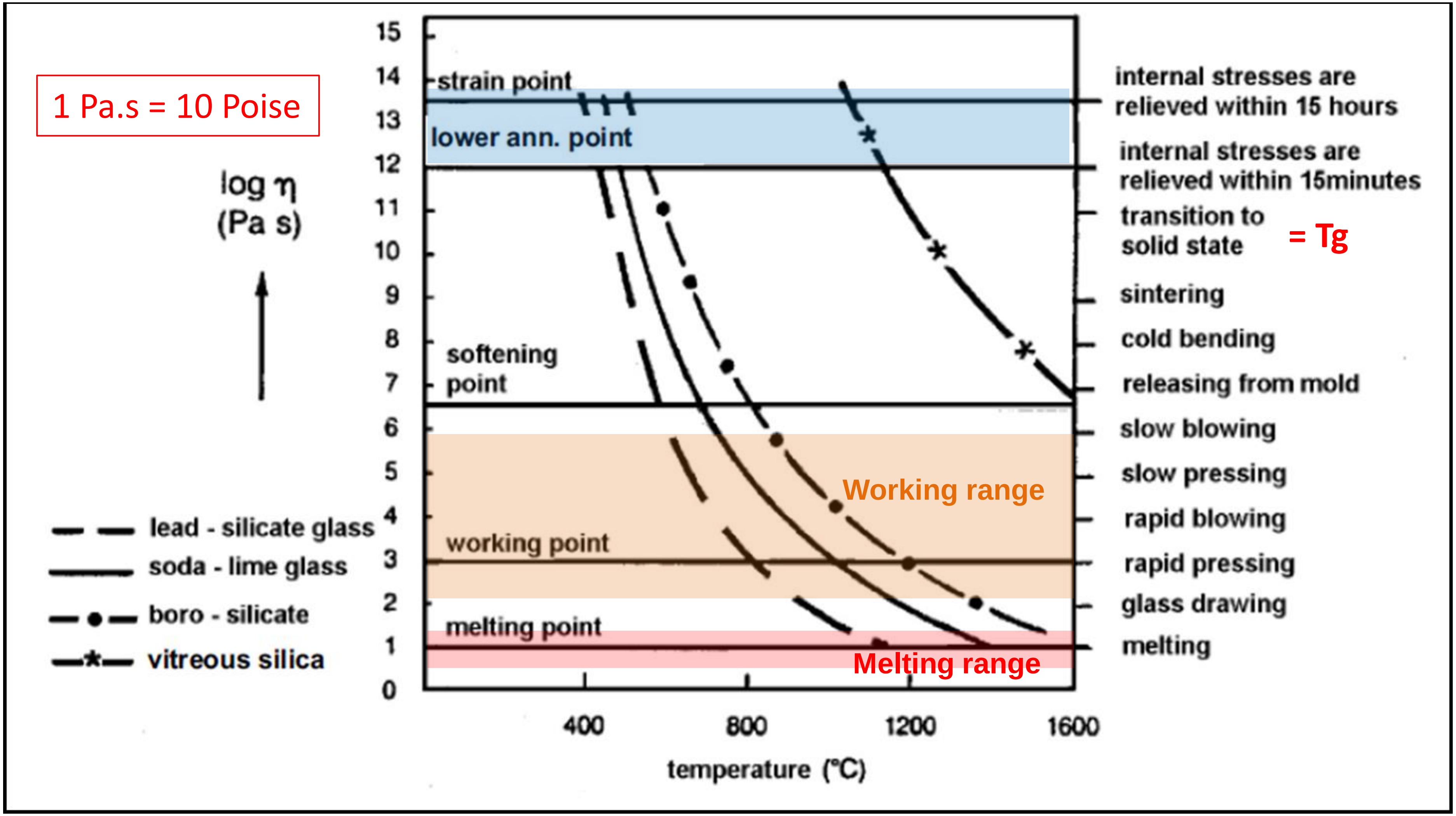
Strain point $\eta = 10^{13.5}$ Pa·s.

- Below this temperature relieving the internal stresses is practically impossible (at the strain point it may last about 15 hours)
- Between the annealing and the strain point glass products should be cooled down gradually, slowly and uniformly in order to avoid the formation of internal stresses, due to temperature gradients

Temperature profile and stresses

- Stresses acquired during cooling and remaining from temperatures above the **strain point** are **permanent stresses** (unless annealed)
- Stresses acquired during cooling below the strain point are considered **temporary stresses** (but can still lead to failure in case of a too important thermal shock)
- The goal of the **annealing process** is to **relieve the permanent stresses** created by the fast cooling below the strain point which occurred during the forming process of the glass
- To avoid creation of permanent stresses, the cooling of the glass should be slow in the temperature (viscosity) range between the annealing point and the strain point

Viscosity – Temperature profile of glasses

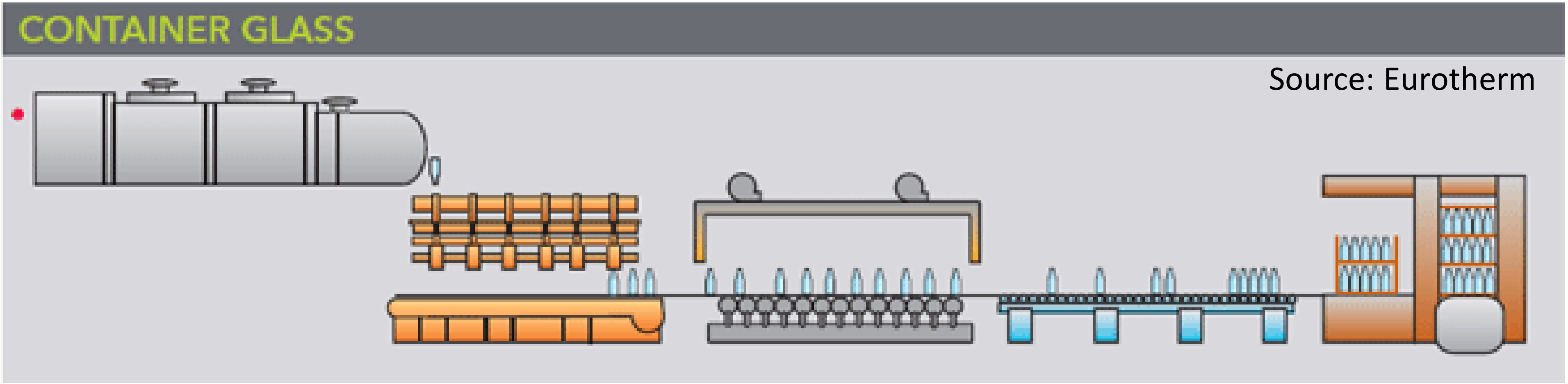


In blue: Critical temperature range for annealing

Annealing in continuous glass furnaces

- Right after the forming process (e.g. molding for container glasses), a rigid glass article is obtained
- The article did not experience a homogeneous cooling and a lot of stresses are generated
- To reduce these stresses, the articles are brought to a temperature-controlled kiln, or **Lehr**, for annealing
- The process from the forming of the article to the annealing Lehr is **continuous**, the articles are conveyed on belts or rollers
- The **temperature profile** in the lehr must be **controlled** for an efficient annealing
- After annealing (at the end of the lehr), the articles are continuously conveyed to further processing steps (coatings, cutting,…)

Example: forming of glass bottles

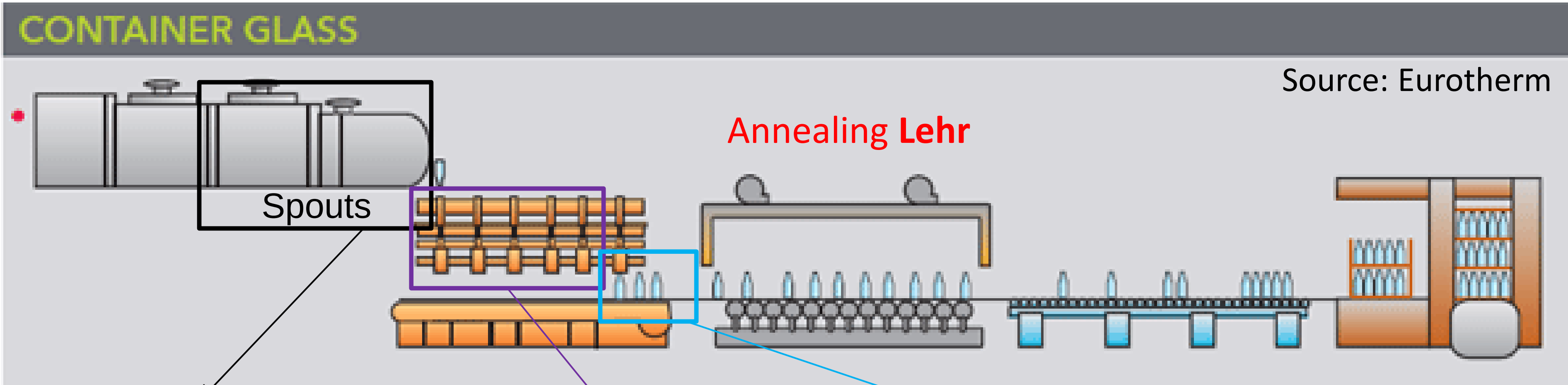


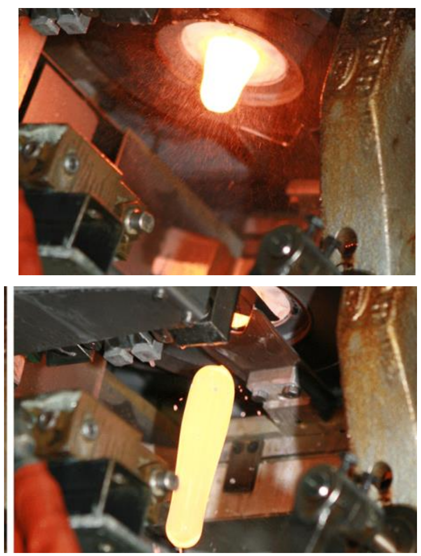
Melting tank
Melting, fining, conditioning of the glass melt

Forming
In this example, molding of glass bottles

Annealing, coatings, post-processing…

Example: forming of glass bottles





Source: BDF Industries

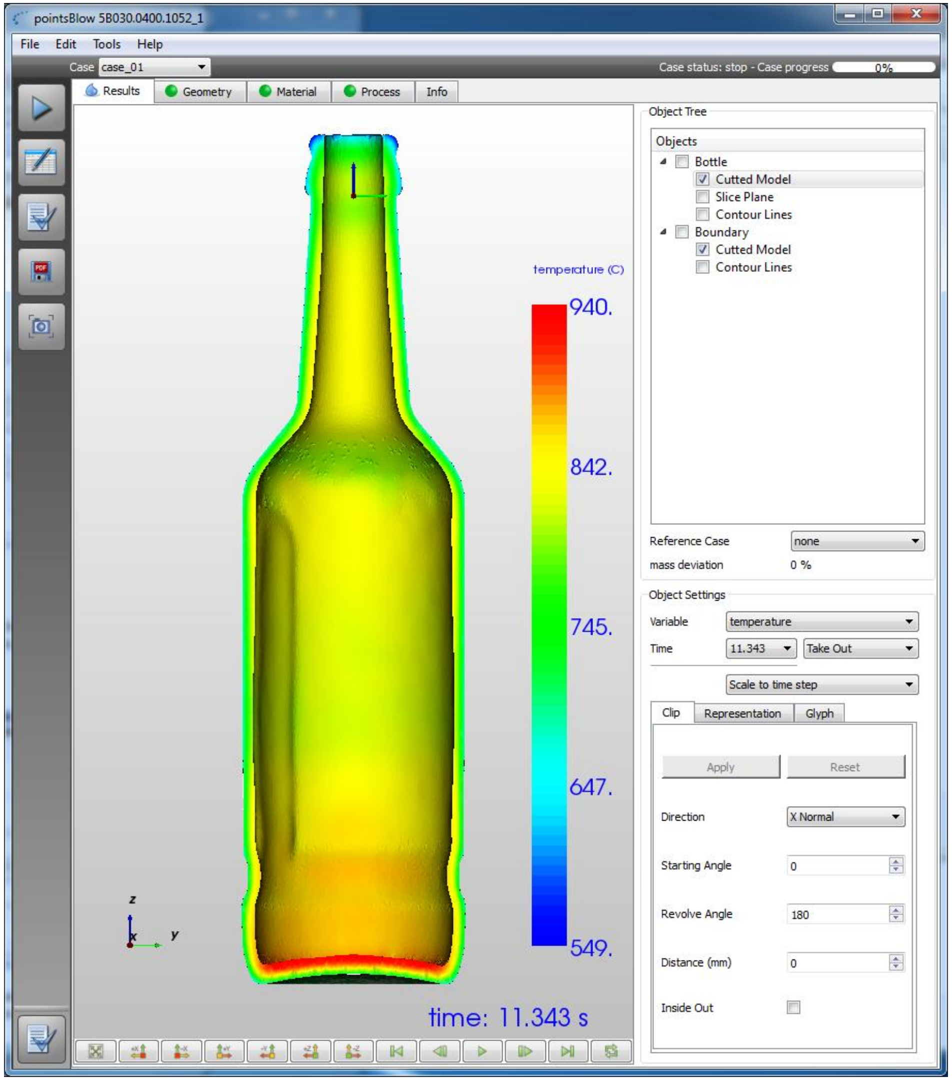
Molding

"Solid" glass

Conveying Belt

Further cooling during conveying

Temperature distribution right after forming



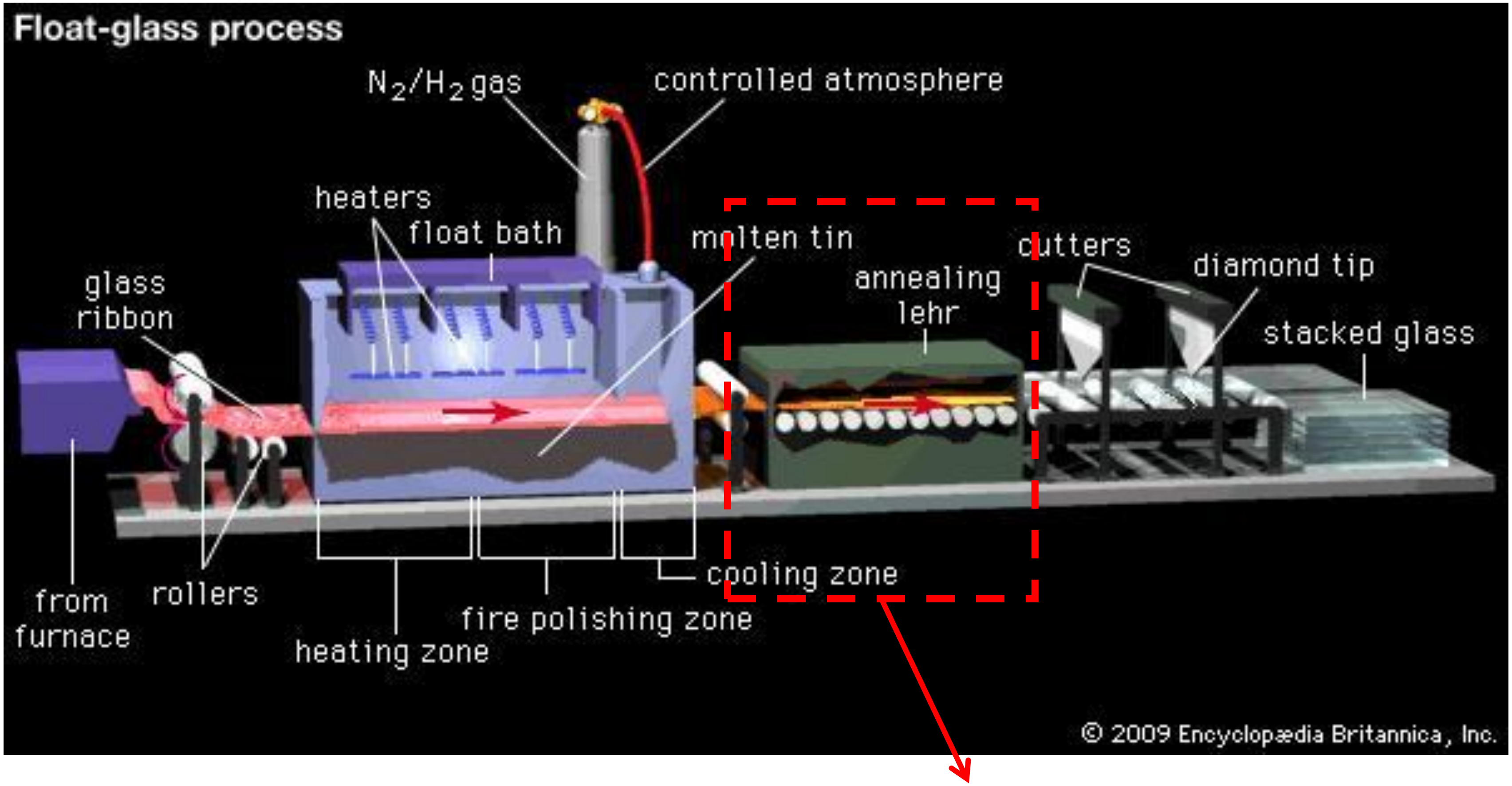
- Right after forming (and before annealing), the temperature distribution is not uniform throughout the glass article

- Different parts cooled down at different rates, which can result in constraints and residual stresses

Source: NOGRID, www.nogrid.com/index.php/en/product/nogrid-points-blow1

Industrial annealing Lehr

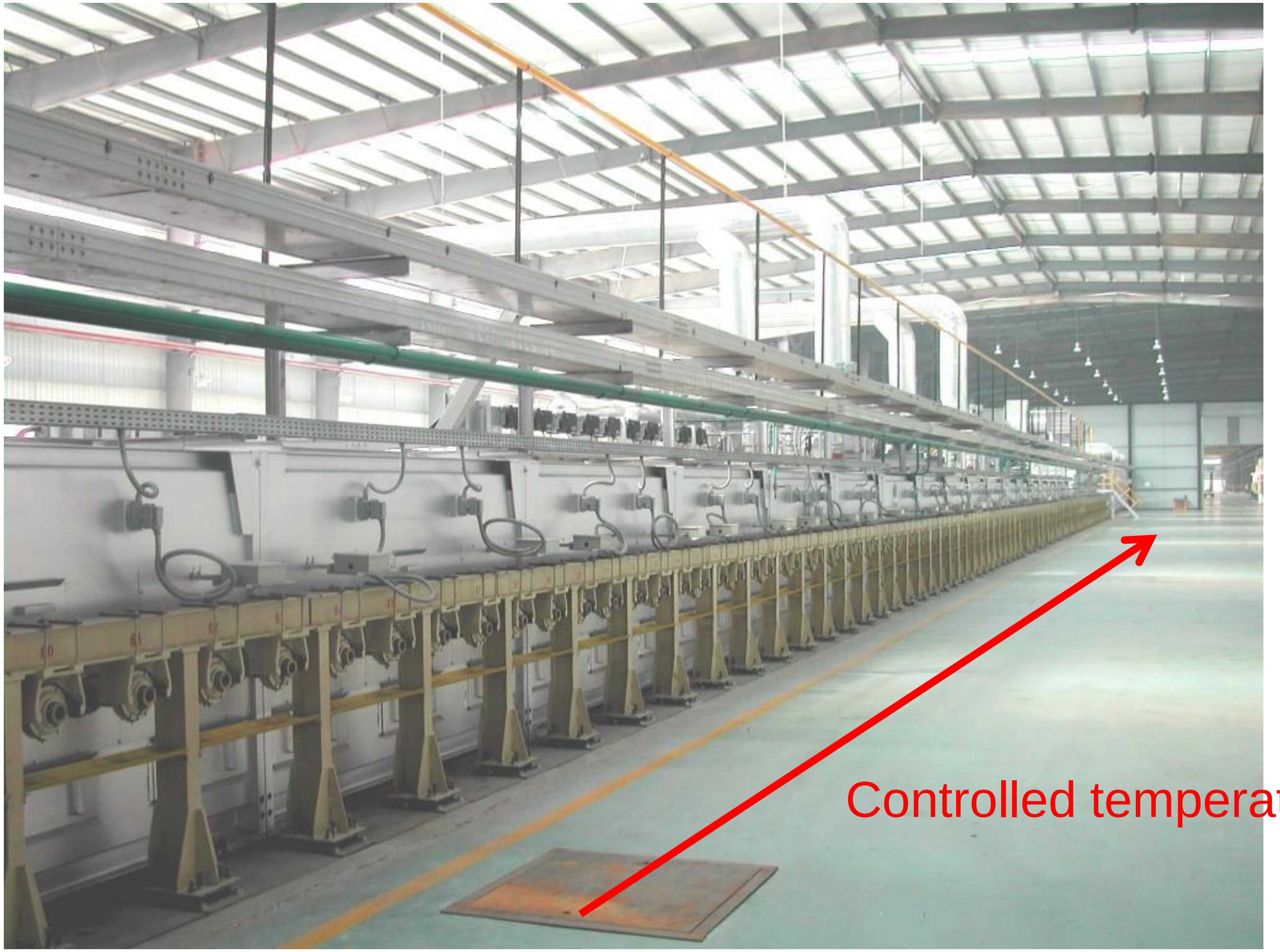
Illustration of the continuous process for flat glass



Source: http://www.britannica.com

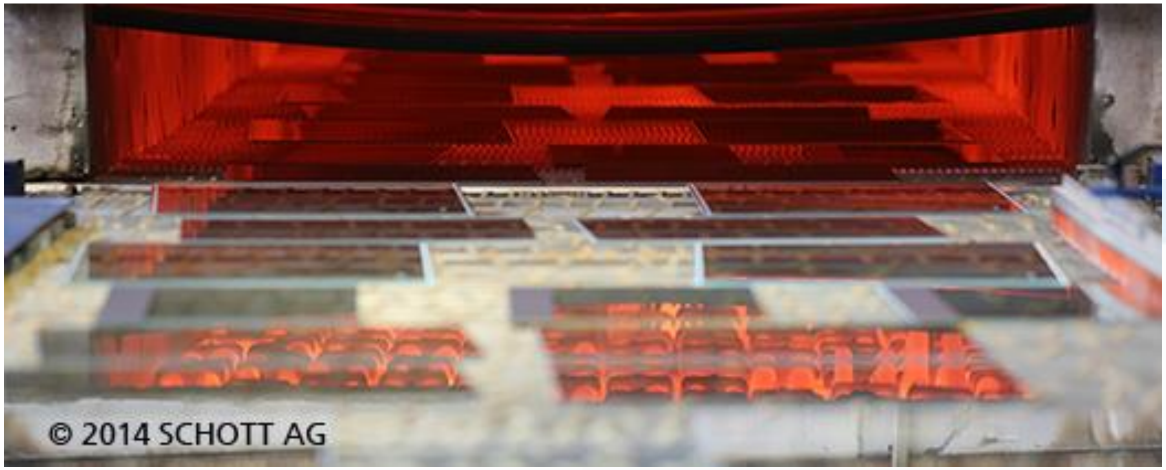
Controlled temperature profile

Industrial annealing Lehr



Source: http://newhudson.com/

Industrial annealing Lehr



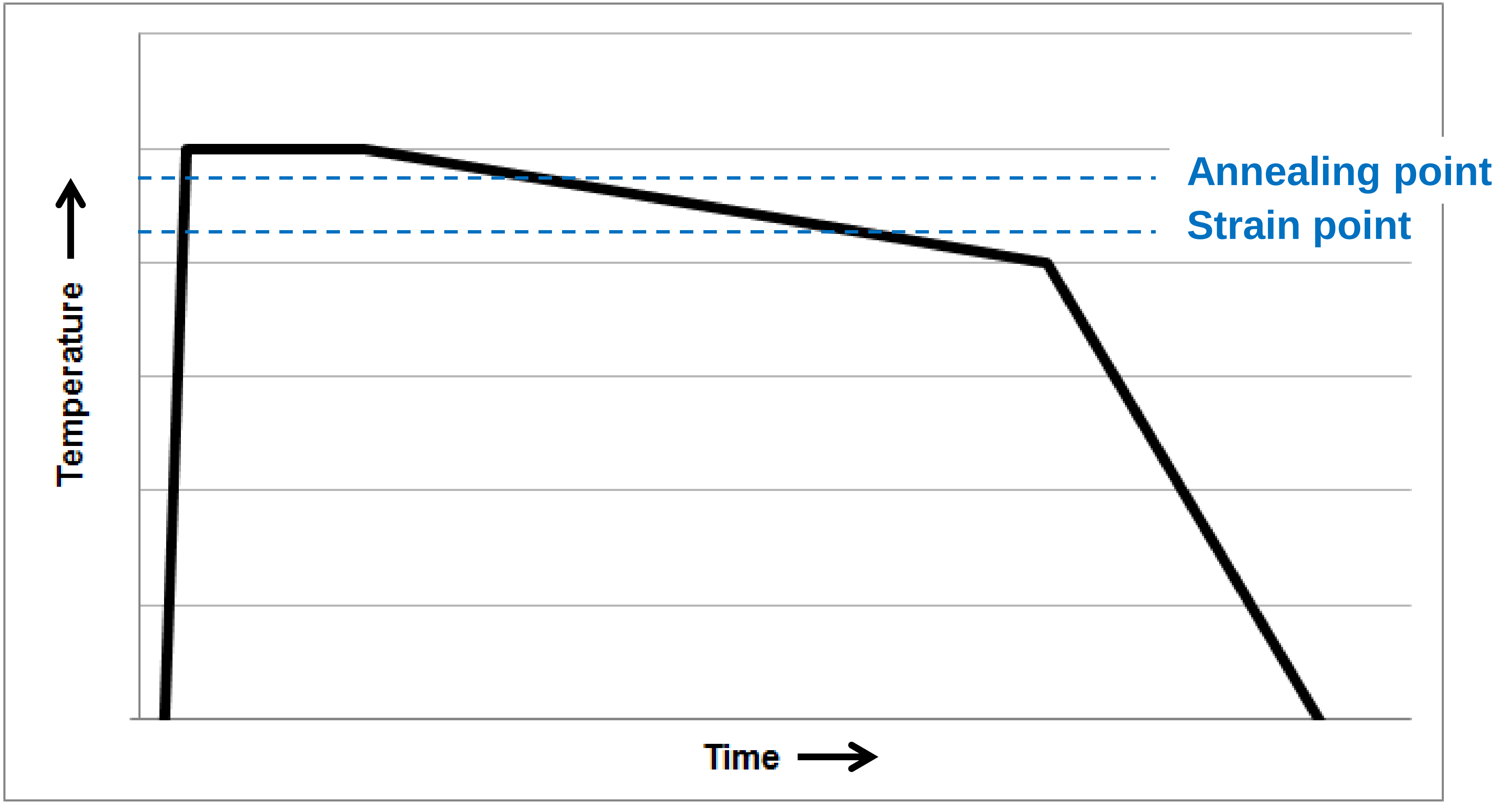
Industrial annealing Lehr

- The **viscosity-temperature profile** for a glass depends on its **composition**
- Thus, the **annealing point** and **strain point** depend on the type of glass produced
- Different articles with **different shapes** (e.g. bottles, tubes, plates…) and **different characteristics** (e.g. thickness, diameter, …) will have **different thermal behavior**
- All these parameters have to be taken into account when designing the annealing lehr
- The goal for an annealing lehr: it should be as short as possible while guaranteeing an efficient annealing
- Equations exist to calculate the best temperature profile for the lehr

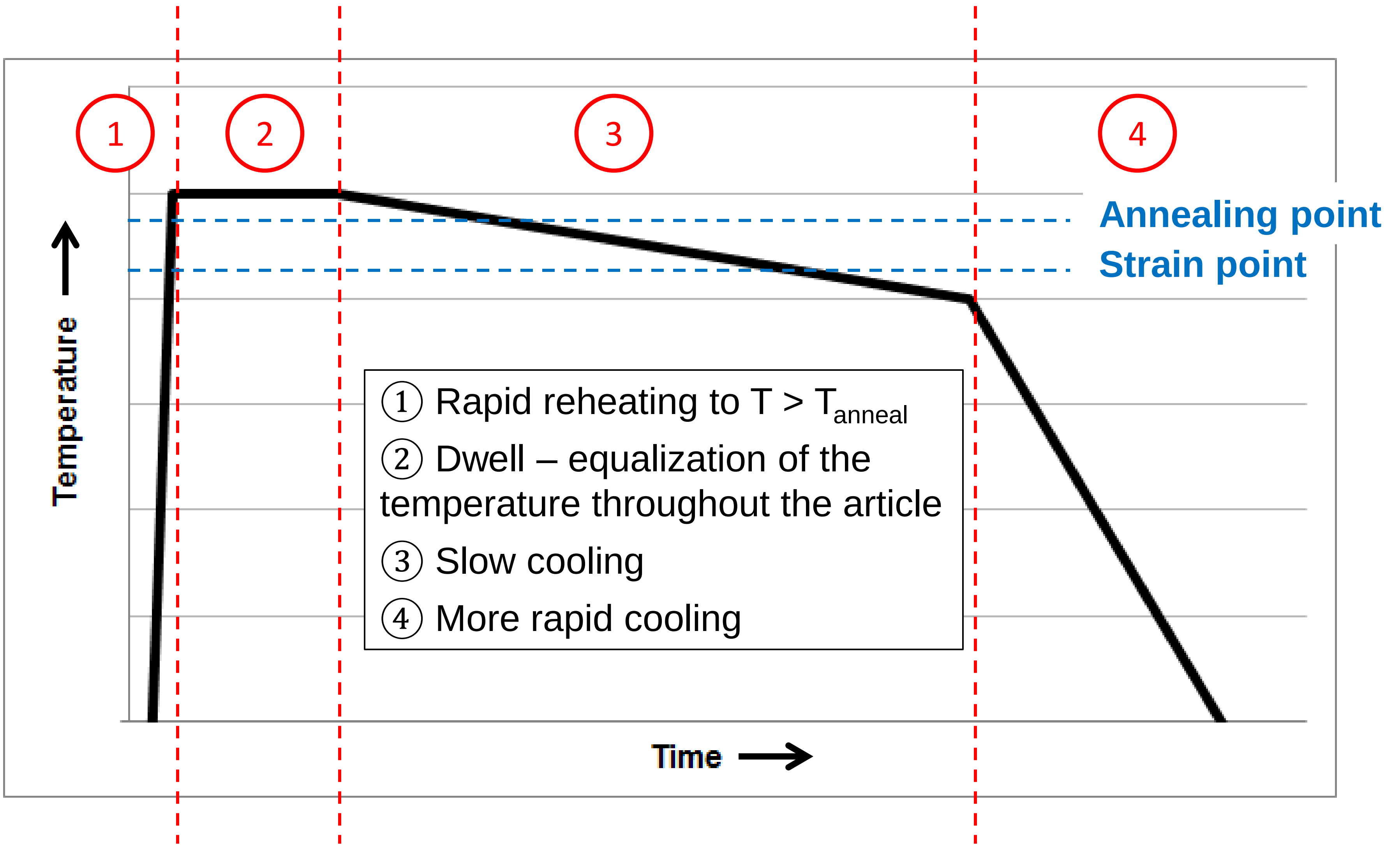
Temperature profiles and stresses in glass

- During cooling of glass, **internal temperature gradients** develop, depending on **cooling rate** & **internal thermal equalization** within the glass
- The internal temperature gradients will eventually lead to **stresses**
- The stress in the glass can be calculated from the cooling rate, properties of the glass and shape of the article
- In return, the “best” cooling rate can be calculated for a maximum allowable residual stress in the glass article
- Keep in mind: the goal of (industrial) annealing is to minimize the stresses in the glass article in a duration as short as possible (annealing = heating = energy consumption = costs)

Temperature profile in annealing Lehr



Temperature profile in annealing Lehr



Temperature profiles and stresses in glass

The relation for cooling rate h from above the annealing point to below strain point and generated permanent thermal stress is given by:

$$\sigma = \frac{E \cdot \alpha_{ex}}{1-\mu} \cdot \frac{\rho \cdot c_p}{\lambda} \cdot h \cdot d^2 \cdot b \quad [Pa]$$

	h	= cooling rate	[K/s]
Article characteristics	d	= characteristic dimension	[m]
	b	= shape factor	[-]
Glass characteristics	λ	= thermal conductivity	[W/(m·K)]
	ρ	= density	[kg/m^3]
	c_p	= specific heat	[J/(kg·K)]
	α_{ex}	= thermal expansion coefficient	[K^{-1}]
	E	= Young's modulus	[Pa]
	μ	= Poisson's ratio	[-]

Temperature profiles and stresses in glass

We have

$$\sigma = \boxed{\frac{E \cdot \alpha_{ex}}{1-\mu} \cdot \frac{\rho \cdot c_p}{\lambda}} \cdot h \cdot d^2 \cdot b \quad [Pa]$$

= M

With

$$M = \frac{E \cdot \alpha_{ex}}{1-\mu} \cdot \frac{\rho \cdot c_p}{\lambda}$$ in $MPa \cdot s \cdot K^{-1} \cdot m^{-2}$

Thus

$$\sigma = M.h.d^2.b \quad \Longrightarrow \quad \boxed{h = \frac{\sigma}{M.d^2.b}}$$

(σ in MPa) *(h in K/s)*

Glass characteristics

Survey of the expansion coefficient α_{ex} of some familiar glass types

	$\alpha_{ex\ 0\text{-}300°C}$ [K^{-1}]	T_g [^oC]
Soda-lime-silica glass	92×10^{-7}	520-580
Pyrex borosilicate	33×10^{-7}	565
E-glass	60×10^{-7}	670
Vycor (97 SiO_2, 3 B_2O_3)	8×10^{-7}	910
Vitreous Silica	5×10^{-7}	1100

For a soda-lime-silica glass, the factor M is equal to 1.2×10^6 $MPa.s.K^{-1}.m^{-2}$ which gives:

$$\sigma = 1.2 \times 10^6\ h.d^2.b\ [MPa] \text{ with d in m and } \sigma \text{ in MPa}$$

Characteristic dimensions and shape factor

$$\sigma = M.h.d^2.b$$

With d: characteristic dimension
b: shape factor

Characteristic dimension "d "

d = thickness for one-sided cooled plate

d = 0.5 thickness for double-sided cooled plate

d = radius for spheres and cylinders

d = √(d.L) for pots and bottles with wall thickness d and bottom thickness L

d = L for pots and bottles with thick bottoms (L = bottom thickness)

Characteristic dimensions and shape factor

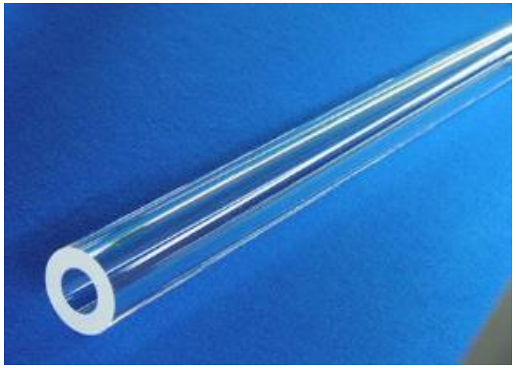
$$\sigma = M.h.d^2.b$$

With d: characteristic dimension
b: shape factor

Shape factor "b "

b = 0.336 for flat plates

b = 0.126 for massive cylinders



b = 0.066 for spheres

b = 0.3 for hollow products

Example annealing (cooling) rate

When a maximal permanent stress of 1 MPa is permitted after cooling, the limit for the cooling rate h for a glass with M = 0.8 $MPa \cdot s \cdot K^{-1} \cdot m^{-2}$ becomes:

$$h \leq \frac{1}{0.8x10^{6}.d^{2}.b} \quad [K/s]$$

$$h = \frac{\sigma}{M.d^{2}.b}$$

h ≤ 6 K/min. for 10 mm plate glass cooled double-sided

h ≤ 36 K/min. for 4 mm plate glass cooled double-sided

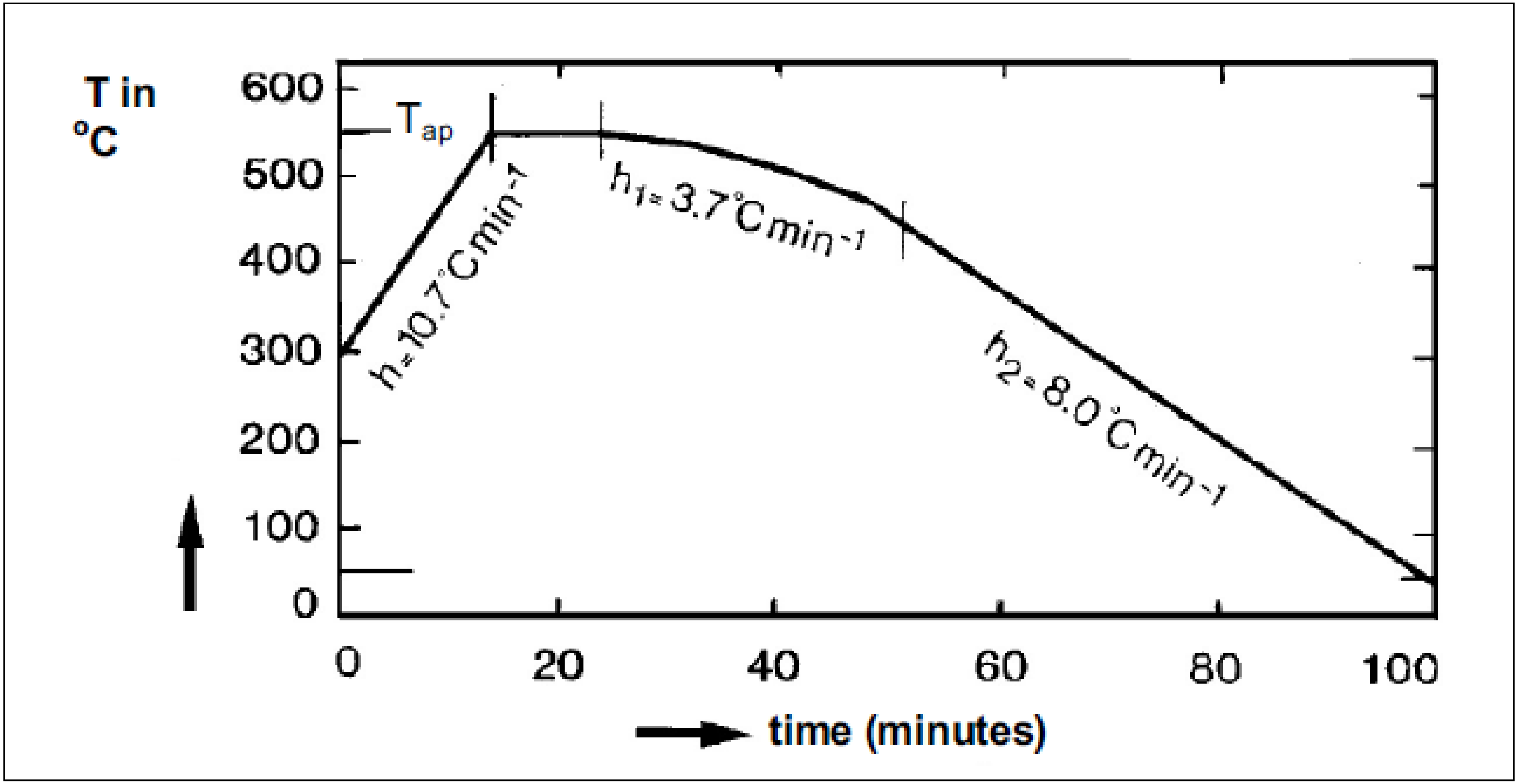
h ≤ 36 K/min. for 2 mm hollow glass cooled one-sided

Example annealing (cooling) rate

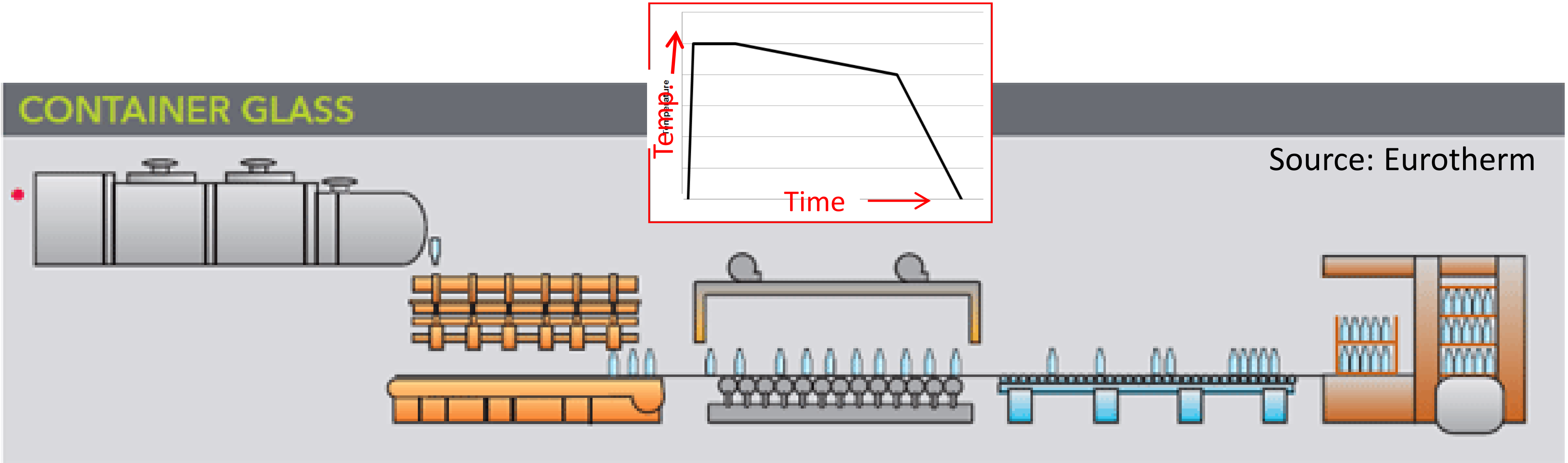
- The **cooling rate** h must be maintained (should not exceed the above given limits) in the critical annealing range between $\boldsymbol{T_{ap}}$ **and** $\boldsymbol{T_{str}}$, because this is the determining range for the build-up of a permanent stress.
- Below this range a faster cooling rate is allowed, because this will cause only a temporary stress
- However fracture or crack formation during cooling, caused by too large value of ΔT still to be prevented
- The limitations on the cooling rates will determine the needed length and temperature profiles in the annealing lehr
- As an example: the annealing range for soda-lime-silica glass is about 20-30^{o}C (± 515 - 545^{o}C).

Temperature profile in annealing Lehr

Example: annealing curve for tube glass, 10 cm diam. & 1 cm wall thickness



Example: forming of glass bottles



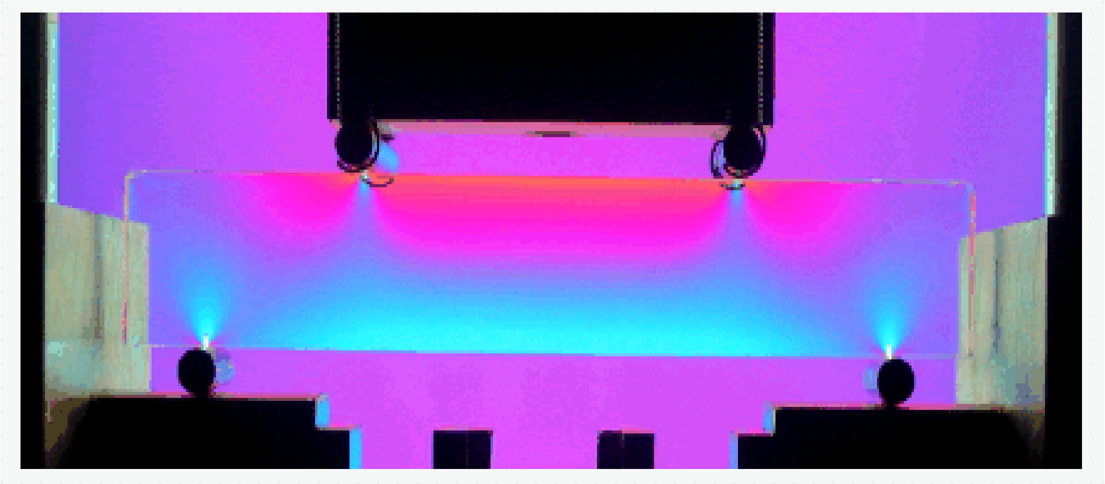
- At the exit of the annealing lehr, the glass article is (continuously) conveyed to further steps, including coatings, cutting, inspection…

Inspection – residual stresses in the glass

- Perfect glass is **optically isotropic, i**ts refractive index is the same in all directions
- **Mechanical stresses** causes deformations in the glass that lead to (local) **changes in the refractive index** within the material
- A difference in the refractive index within the glass article will lead to **birefringence**
- This birefringence can be analyzed and quantified with a **polarimeter** (or polariscope), in which the angle of rotation of the polarization direction of linearly polarized light passing through the sample is determined
- Thus, polariscopes can be used to determine the presence of residual stresses within the glass article
- Automated devices based on this principle are used in the glass industry for systematic inspection of the articles produced

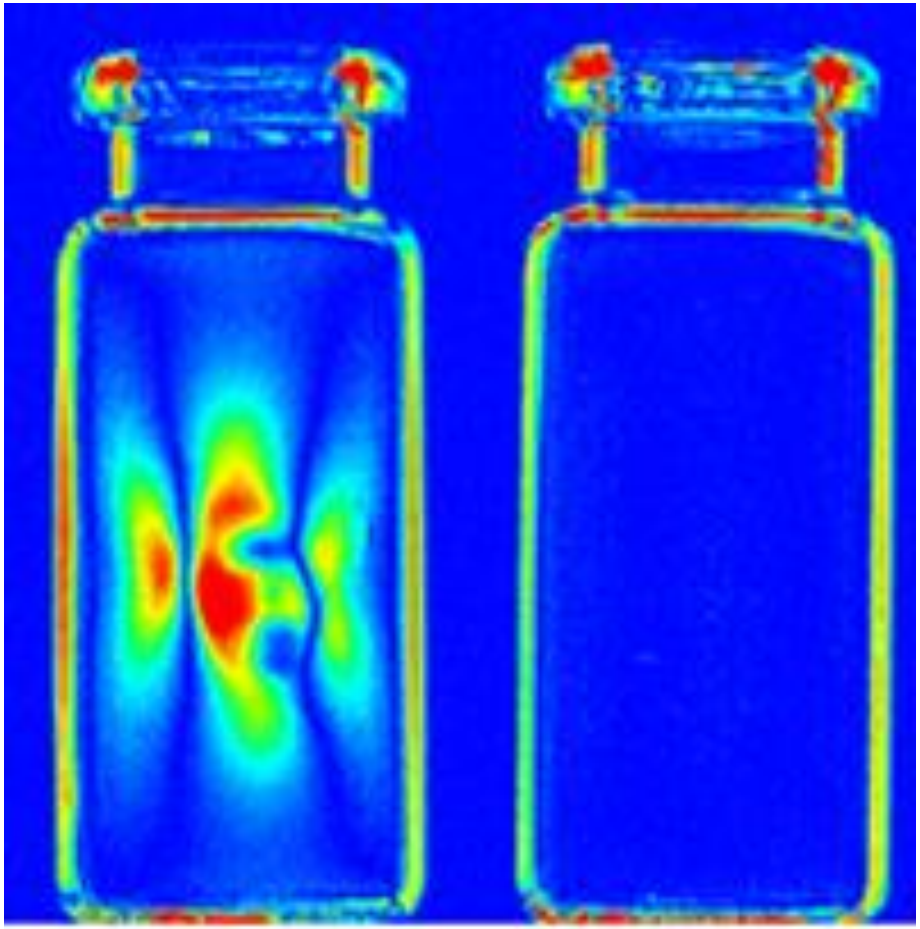
Polariscopes and stresses in glass

Example of polariscope



Example of stress distribution in glass
(university Erlangen, Germany

Polariscopes and stresses in glass



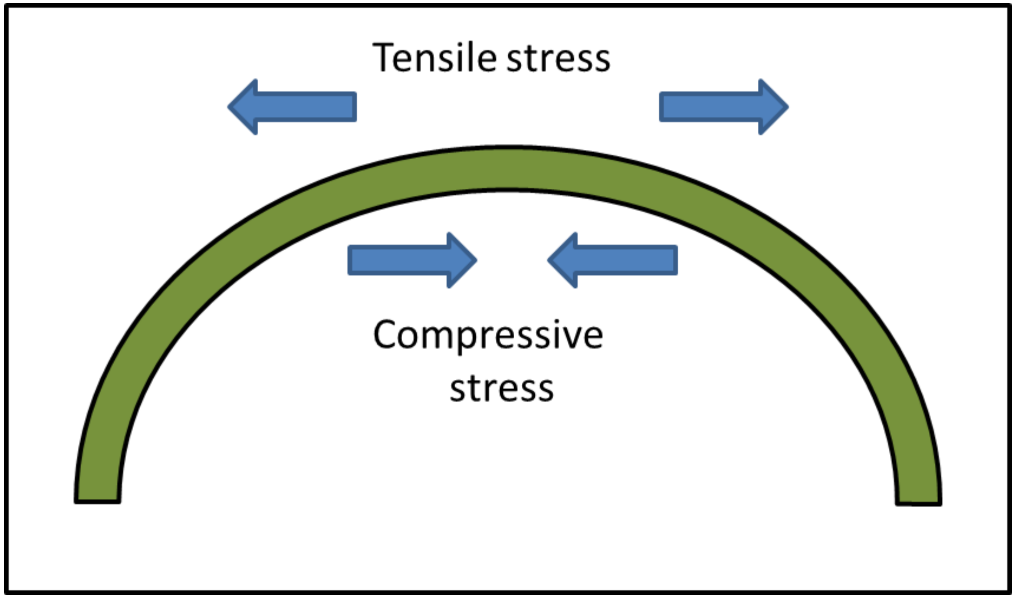
http://www.vision-systems.com

- Articles with a too high amount of residual stress (e.g. jar on the left of the picture) are rejected (automatic process)
- The rejected product are (often) collected and re-injected in the furnace as raw material (internal cullet)

Tempering

Introduction – what is tempered glass?

- Glass is stronger in compression than is tension (compressive strength ~10 times higher than tensile strength)
- Glass failure almost invariably originates from flaws at the surface (stress multipliers for local tensile stresses)
- A compressive stress at the surface of the glass can thus increase glass strength



Introduction – what is tempered glass?

- Tempered glass is a glass that has been subjected to an **additional heat treatment after annealing** in order to increase its mechanical strength
- The tempering process lies on the **controlled creation of permanent stresses** in the glass
- The surface is under compressive stress while the core is under tensile stress
- Tempered glass can be as much as **4 to 5 times stronger than annealed glass** (without tempering)
- When fracturing, tempered glass breaks into small fragments. It is often referred to as "**safety glass**"

Introduction – what is tempered glass?

- Tempering of glass is mostly applied to articles with relatively simple geometries, e.g. windows, windshields…
- The tempering process involves **reheating of the glass** article to a critical temperature (typically above 600-650°C) and **subsequent rapid cooling** of the surface to create a desired **stress profile** within the material
- NB: tempering of the glass is performed on an already well annealed glass
- The following slides will illustrate the principle of tempering for a flat glass plate

Principle – Tempering of glass

- **t_0**: Temperature T > Tg

Uniform temperature throughout the sample

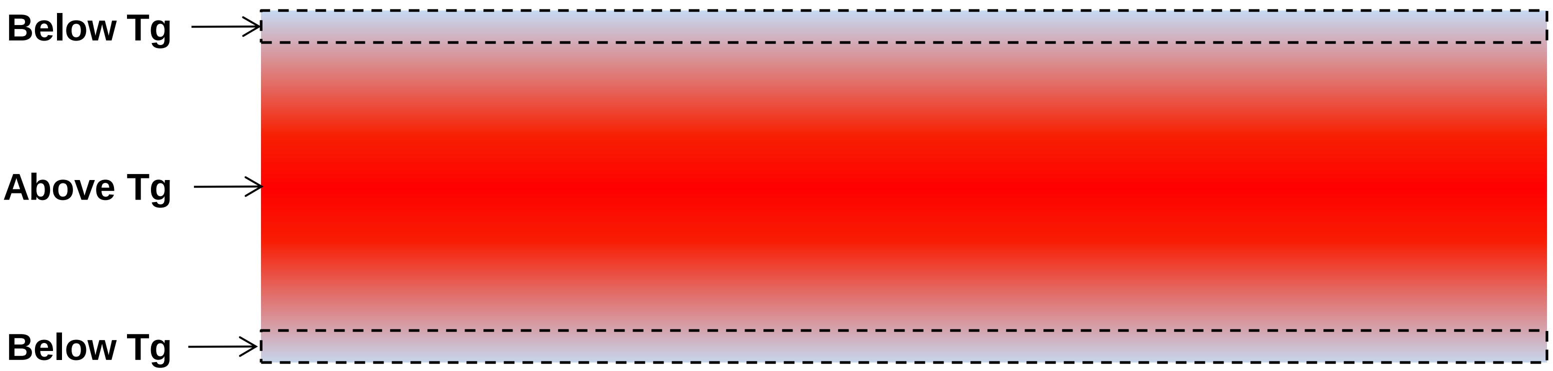
NB: The temperature T_0 (at t_0) should not be too high to avoid deformation of the glass plate

Principle – Tempering of glass

- **t_1: surface** of the glass piece **cooled down rapidly to a T < Tg**

Surface temperature below Tg => “frozen”

Core still above Tg, relaxing under viscous flow



At t_1: Surface tries to shrink while the inner part acts as a counterforce:

$\Rightarrow$ *Surface under tensile stress*
$\Rightarrow$ *Inner part under compressive stress*

Principle – Tempering of glass

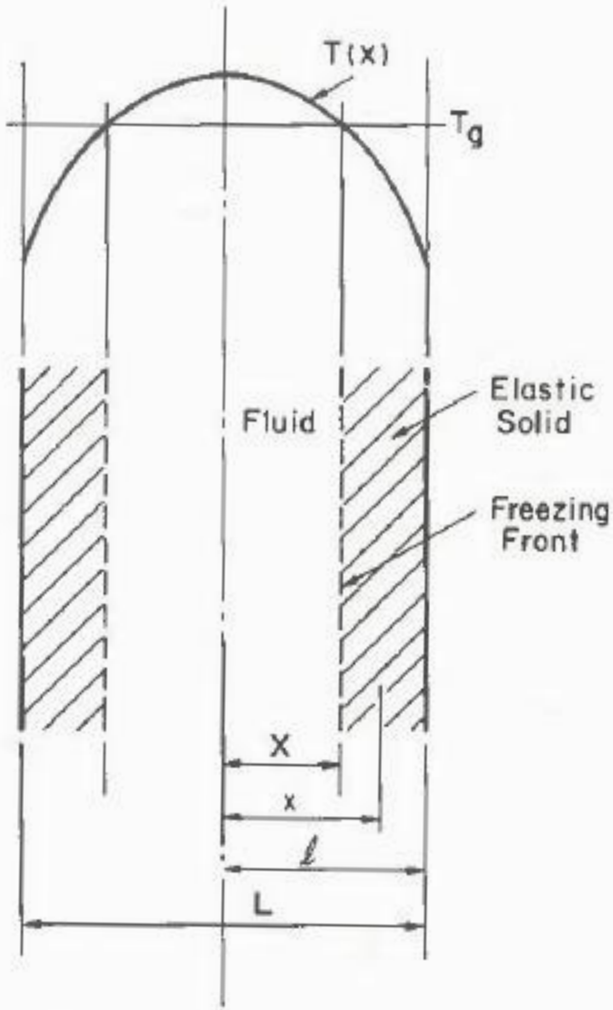
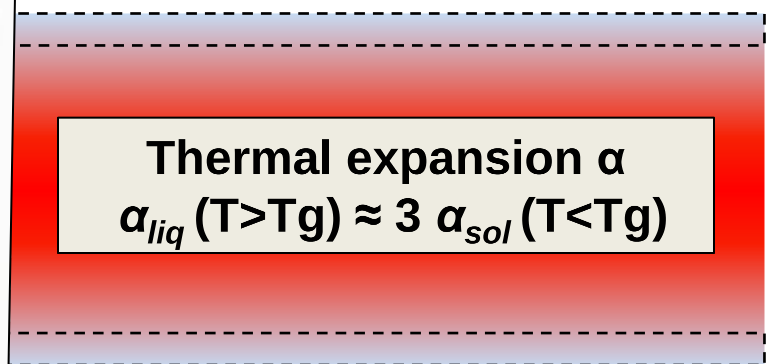


FIG. 15. The "instant freezing" model.

cooled down rapidly to a T < Tg

ure below Tg => "frozen"

relaxing under viscous flow



From R. Gardon, "*Thermal tempering of glass*", in "Glass: Science and Technology, Vol.5, Elasticity and Strength in Glasses", Ed. D. Uhlmann and N. Kreidl, Ac. Press, 1980

Principle – Tempering of glass

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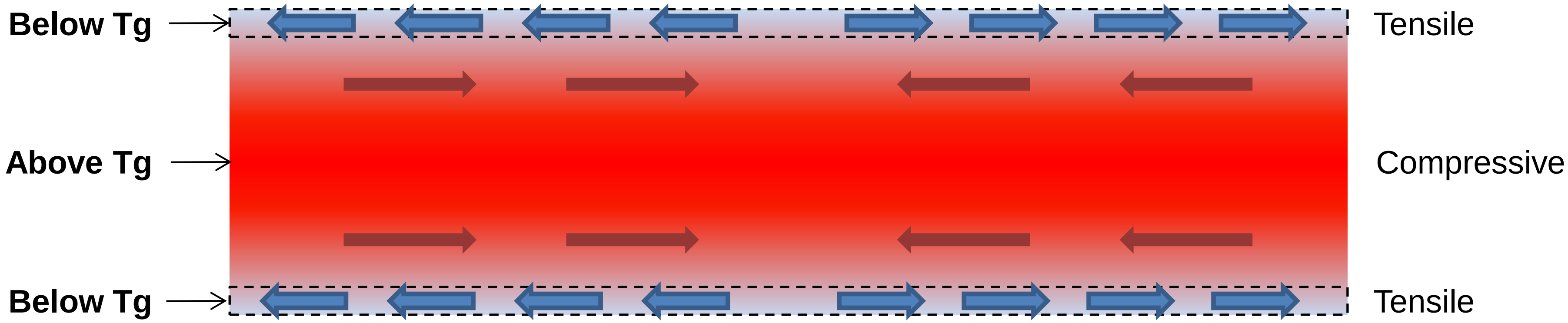


At t_1: Surface tries to shrink while the inner part acts as a counterforce:

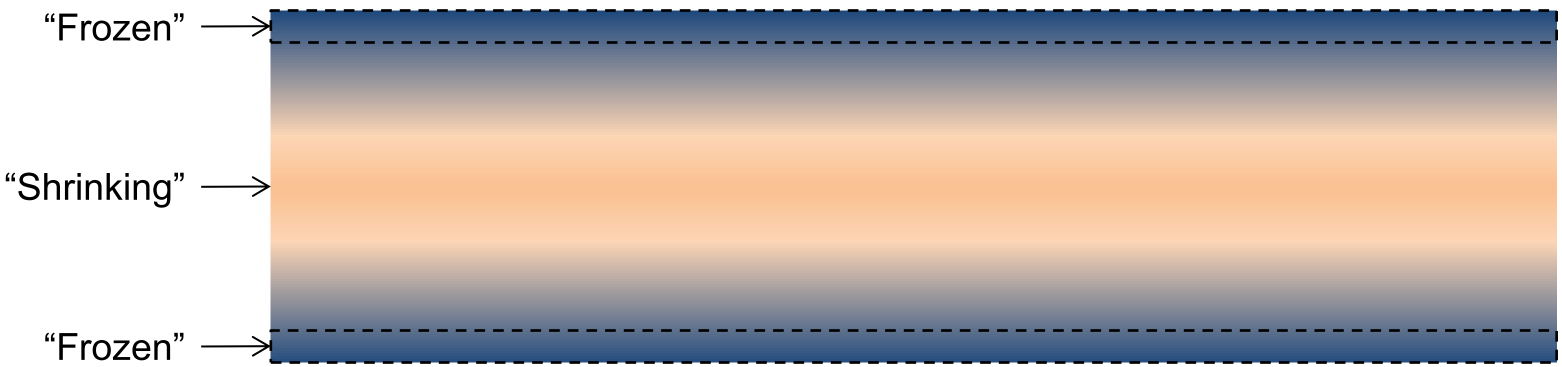
$\Rightarrow$ *Surface under tensile stress*

$\Rightarrow$ *Inner part under compressive stress*

Principle – Tempering of glass

- t_2: **further cooling**, inner part cooled down to a temperature T < Tg

Inner part of the glass piece contracting (“shrinking”)
Surface temperature already “frozen”, shrinking less



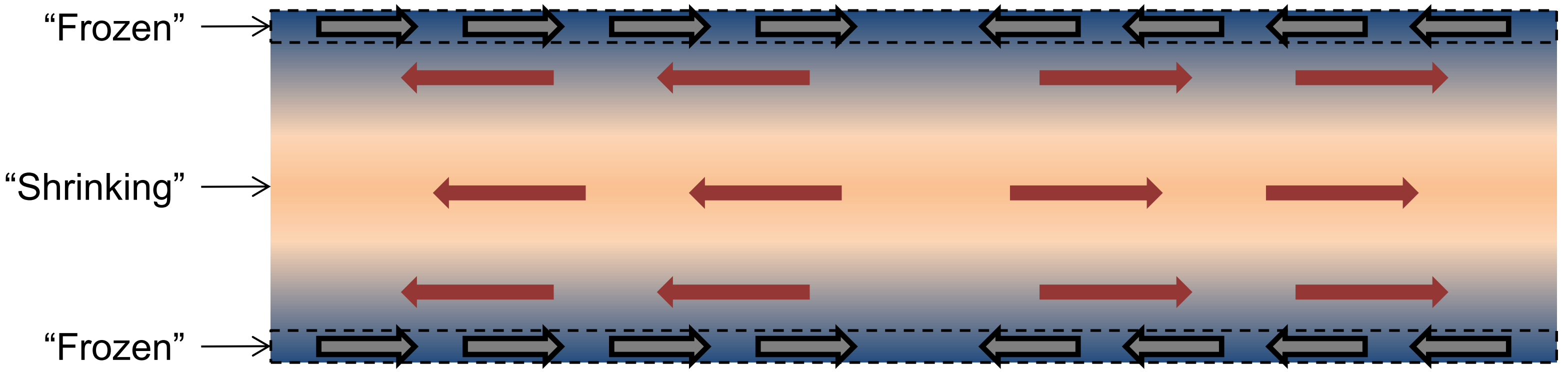
At t_2: Inner part tries to shrink while the surface acts as a counterforce:

$\Rightarrow$ *Surface under compressive stress*
$\Rightarrow$ *Inner part under tensile stress*

Principle – Tempering of glass

- t_2: **further cooling**, inner part cooled down to a temperature T < Tg

Inner part of the glass piece contracting (“shrinking”)
Surface temperature already “frozen”, shrinking less



At t_2: Inner part tries to shrink while the surface acts as a counterforce:

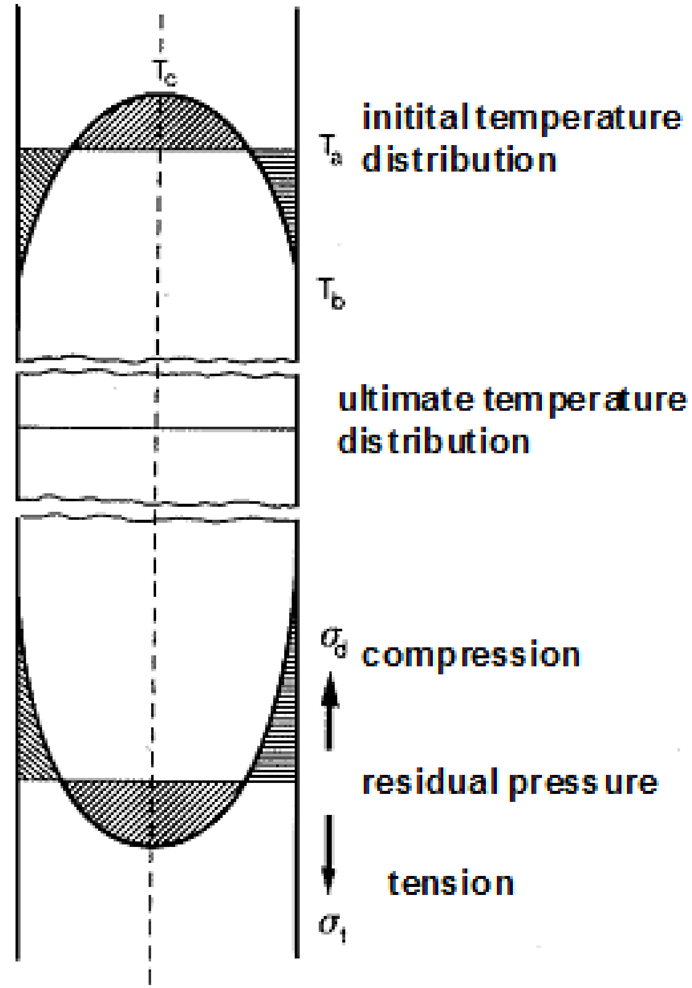
$\Rightarrow$ *Surface under compressive stress*

$\Rightarrow$ *Inner part under tensile stress*

Principle – Tempering of glass

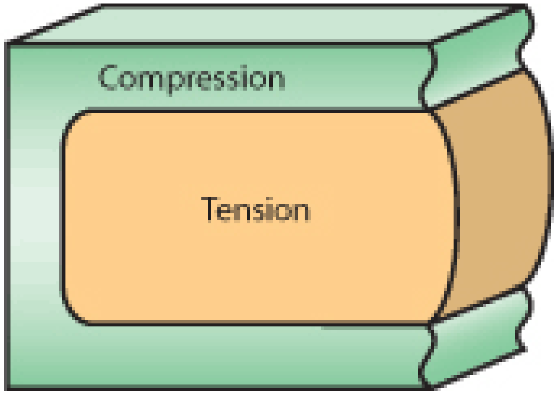
t_1: Surface in tension and core in compression

t_2: Surface in compression and core in tension



Principle – Tempering of glass

- After further cooling, the glass article is left with a permanent stress profile with:
  - ✓ Surface in compressive stress
  - ✓ Core in tensile stress

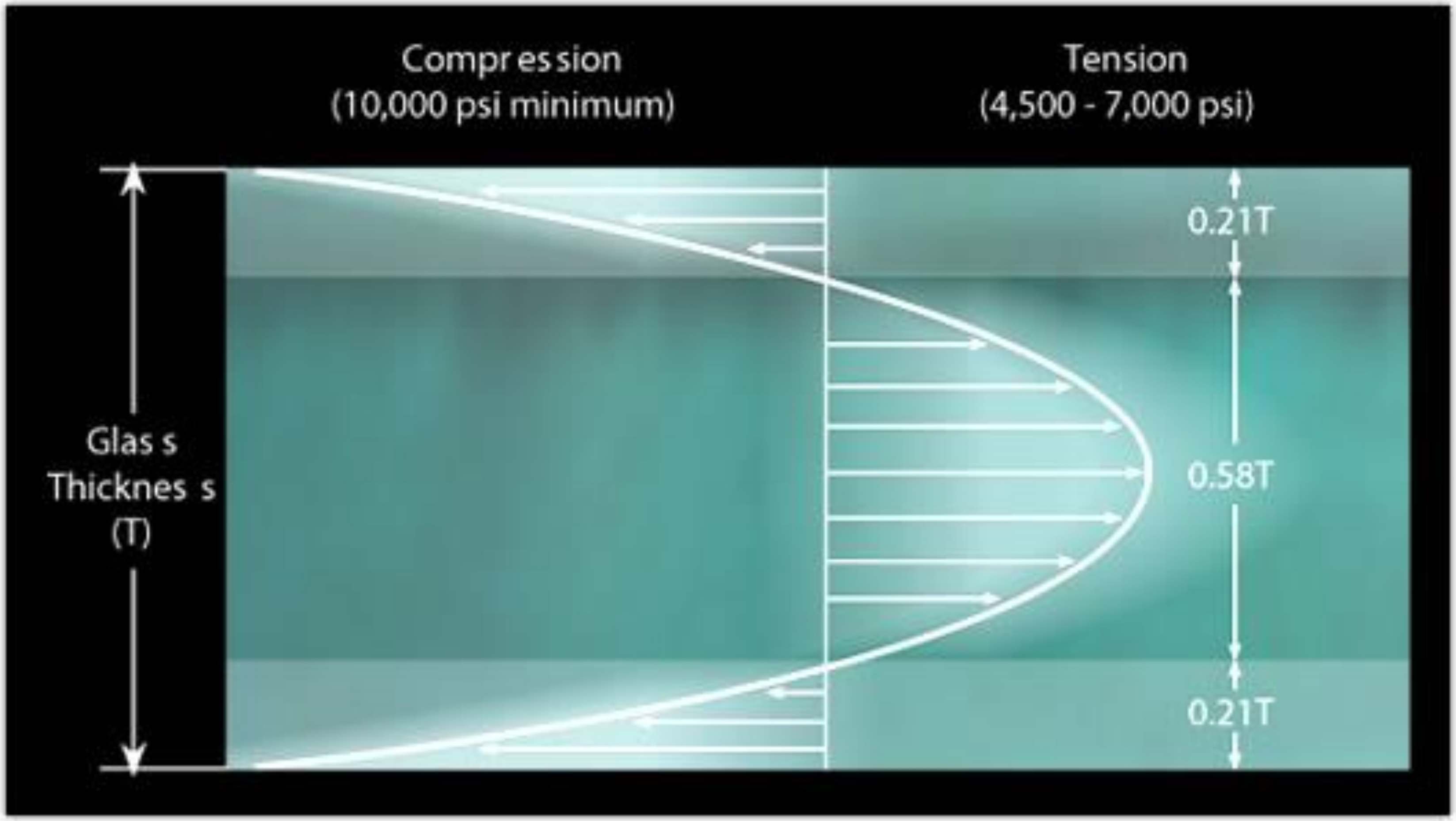


- For a crack to propagate from the surface of the glass article, it must overcome the usable strength of the material + the extra compressive force at the surface
- For this reason, tempered glass is more resistant to failure than a glass which is simply annealed (without compressive layer at the surface)

Picture from: http://www.na.en.sunguardglass.com

Principle – Tempering of glass

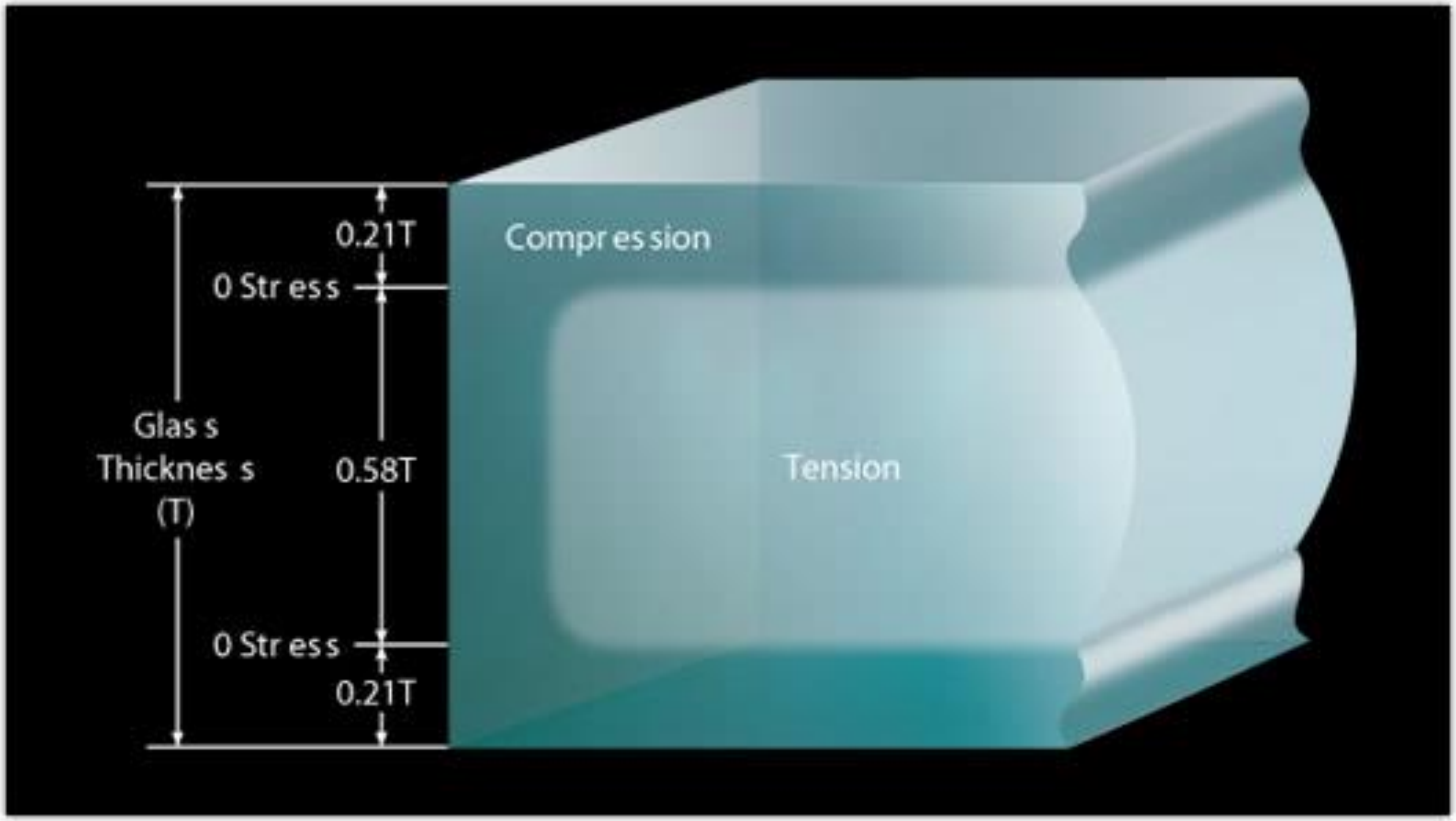
Example stress distribution in solar (flat) glass



Source: http://www.cardinalst.com/products/solartemp/

Principle – Tempering of glass

Example stress distribution in solar (flat) glass

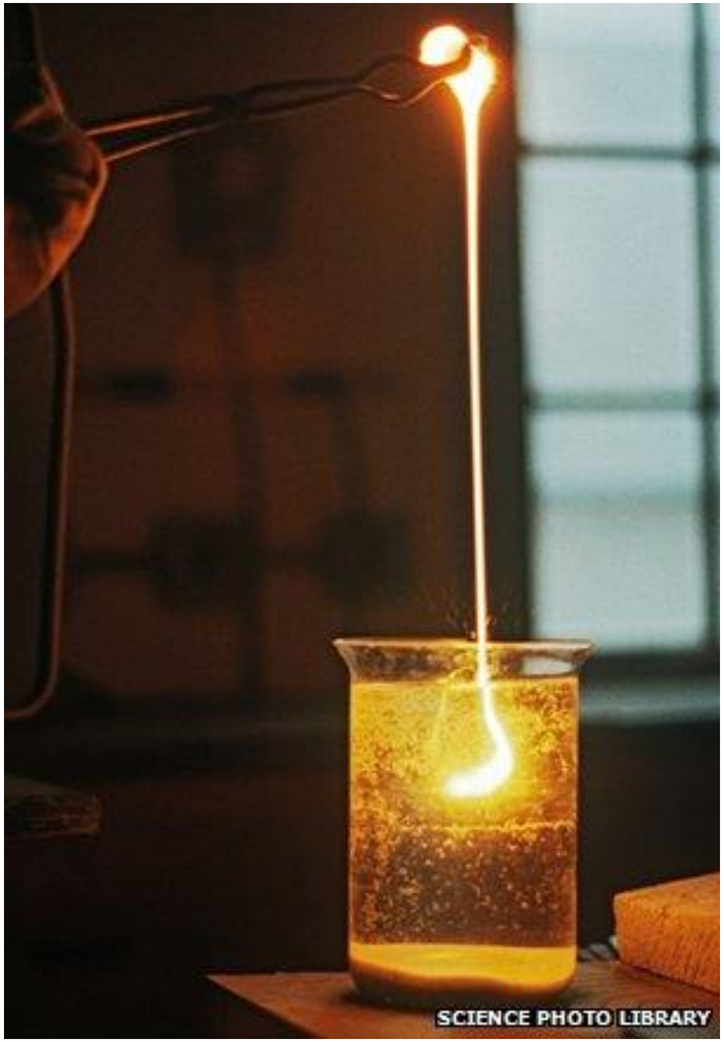


Source: http://www.cardinalst.com/products/solartemp/

Fracture pattern of tempered glass

Source: http://www.graysci.com/chapter-seven/shattering-the-strongest-glass/

Illustration – Prince Rupert's drops



Taken from: www.bbc.co.uk

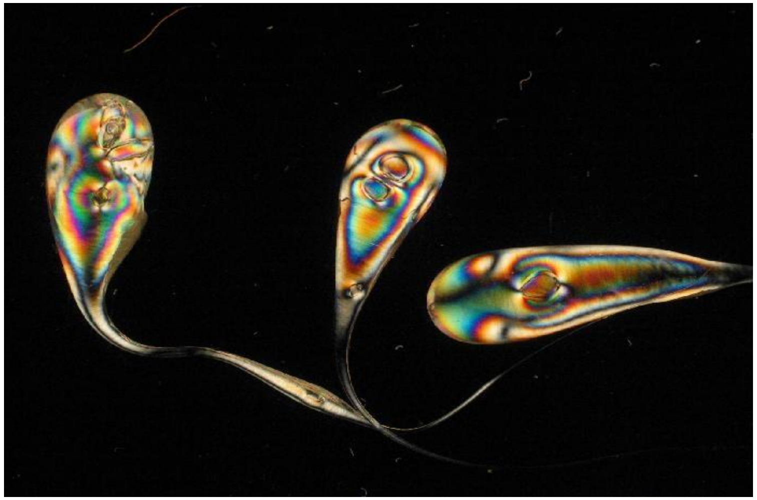


Illustration – Prince Rupert's drops

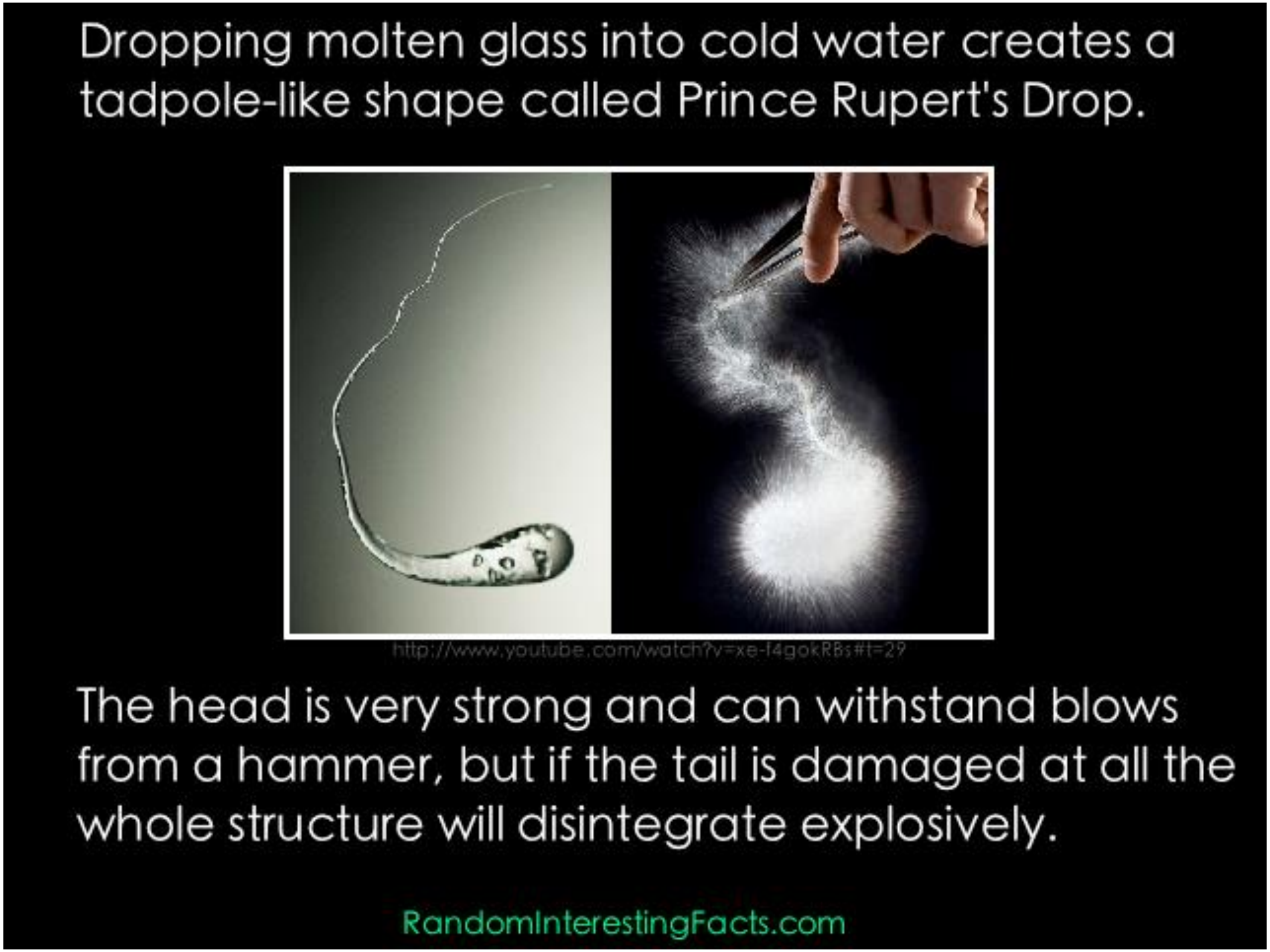
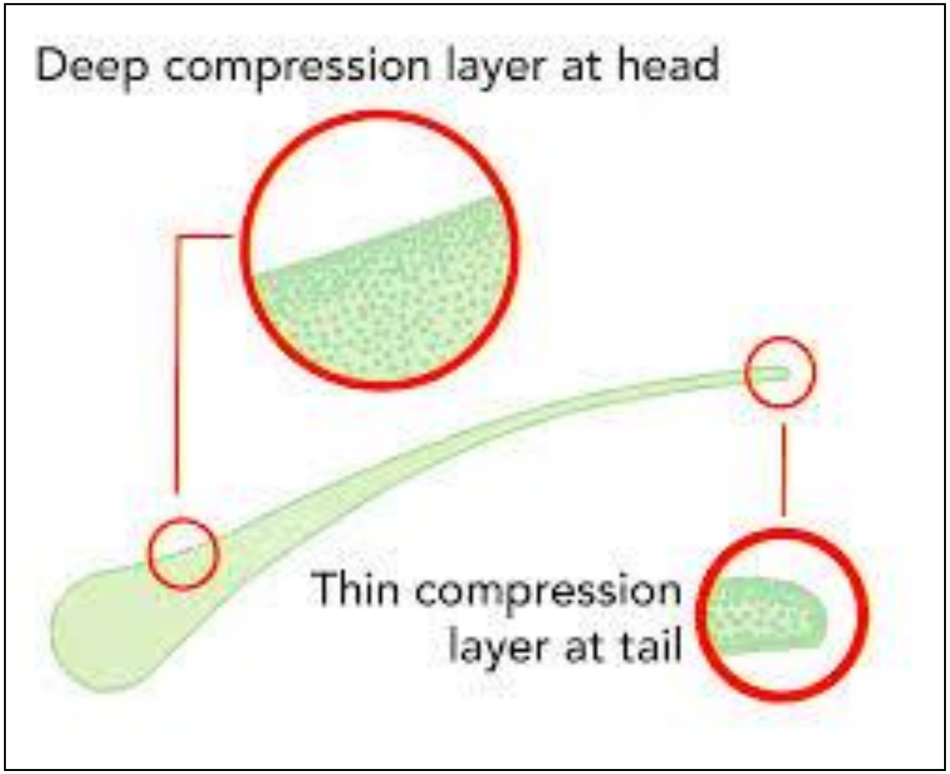


Illustration – Prince Rupert's drops

- What does it mean?



Pictures © Smarter everyday

Illustration – Prince Rupert's drops

- When damaging the tail => creation of a flaw which propagates to the core, in tensile stress
- All the strain energy stored in the glass (stress-strain relationship) is released, leading to the catastrophic failure of the glass article
- This is similar to what is observed in tempered glass

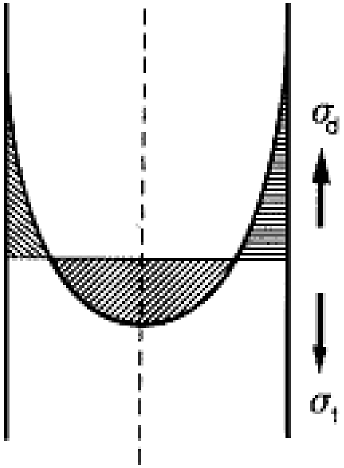
≈

- More on Prince Rupert's drops? Check out these videos:
  - ✓ Video "Smarter everyday - Mystery of Prince Rupert's Drop at 130,000 fps"
  - ✓ Video "Corning- The glass Age, Part 2: Strong, Durable Glass "

Important parameters for glass tempering

- Permanent stress profile generated σ_p

$$\sigma_p = \frac{\alpha . E . \Delta T_{MS}}{1-\mu} = \frac{\alpha . E}{1-\mu}\, x\, \left(1+\frac{2\lambda}{hd}\right)^{-1} x\, T_E$$



With:

Glass characteristics

- α = thermal expansion coefficient [K^{-1}]
- E = Young's modulus [MPa]
- μ = Poisson's ratio
- λ = thermal conductivity [$W/m^2.K$]

Process related

- h = heat transfer coefficient [$W/m^2.K$]
- $\Delta T_{MS} = T_M - T_S$ = Temp. middleplane – Temp. surface [K]
- T_E = "freezing temperature" ≈ Tg [K]
- d = thickness of the glass plate [m]

Thermal history in a tempered glass plate

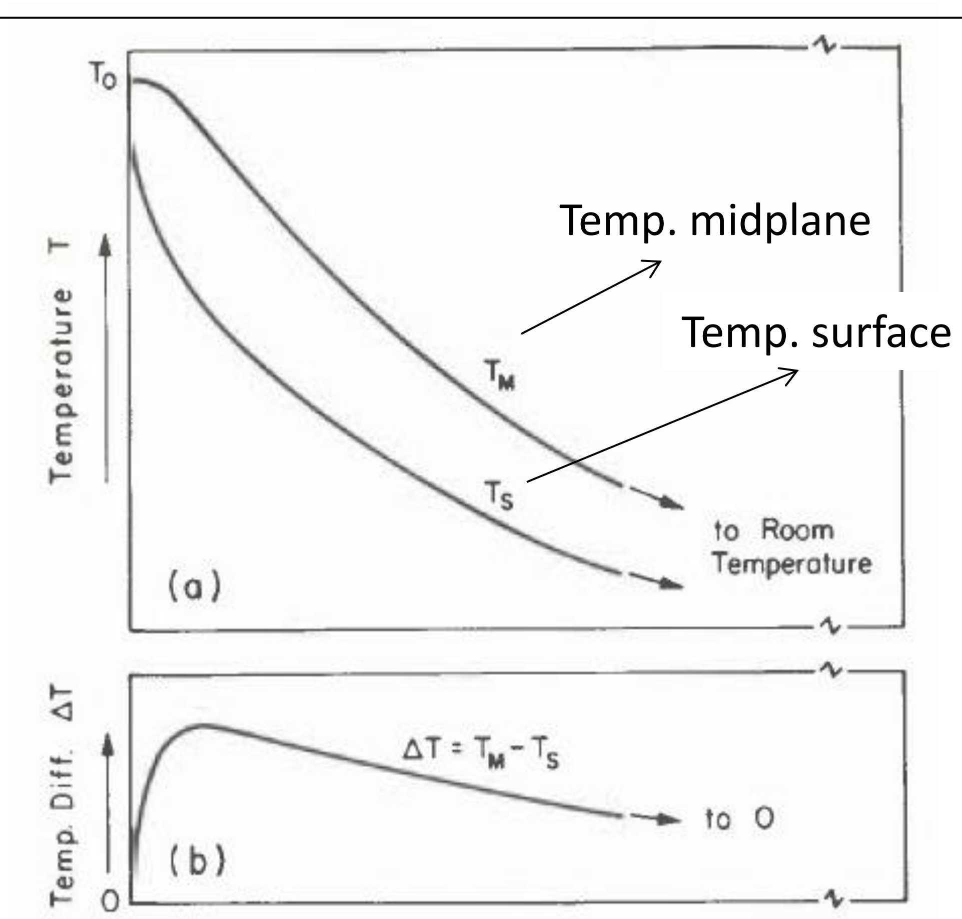


FIG. 12. Schematic temperature- and stress-histories during the tempering of a glass plate.

Adapted from R. Gardon, "*Thermal tempering of glass*", in "Glass: Science and Technology, Vol.5, Elasticity and Strength in Glasses", Ed. D. Uhlmann and N. Kreidl, Ac. Press, 1980

Effect of glass thickness

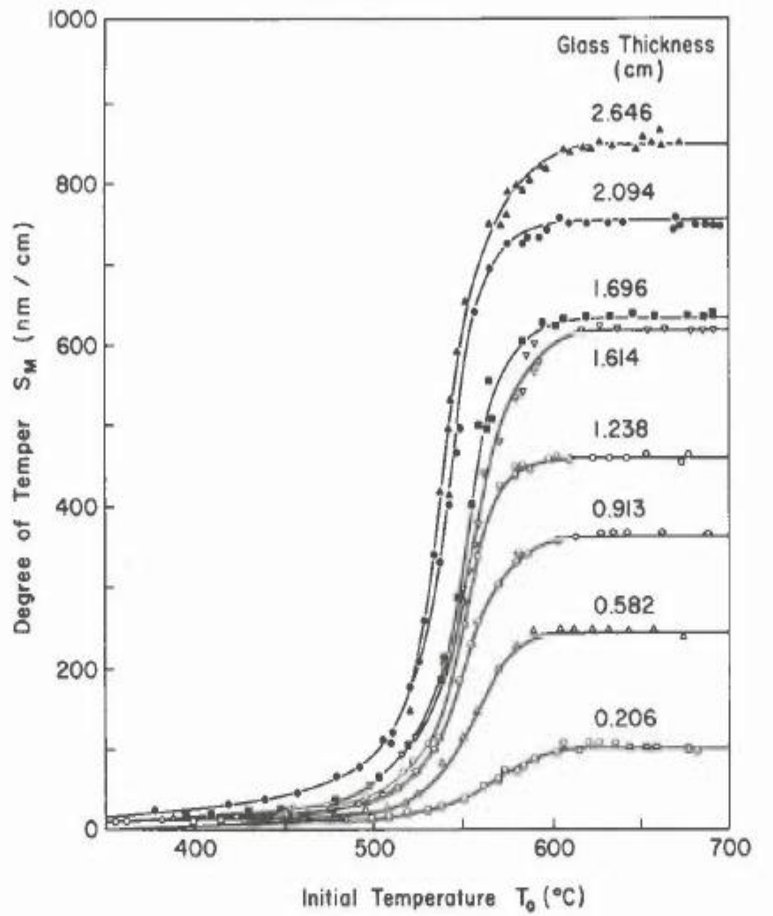


FIG. 6. Degree of temper as function of glass thickness and initial temperature. Natural convection cooling (Bartenev, 1949).

- With thicker plates, higher degrees of temper achieved (larger stress profiles)
- Above a certain temperature, a plateau is reached
- Below a certain thickness, tempering becomes inefficient

From R. Gardon, "*Thermal tempering of glass*", in "Glass: Science and Technology, Vol.5, Elasticity and Strength in Glasses", Ed. D. Uhlmann and N. Kreidl, Ac. Press, 1980

Effect of temperature and quenching coefficient

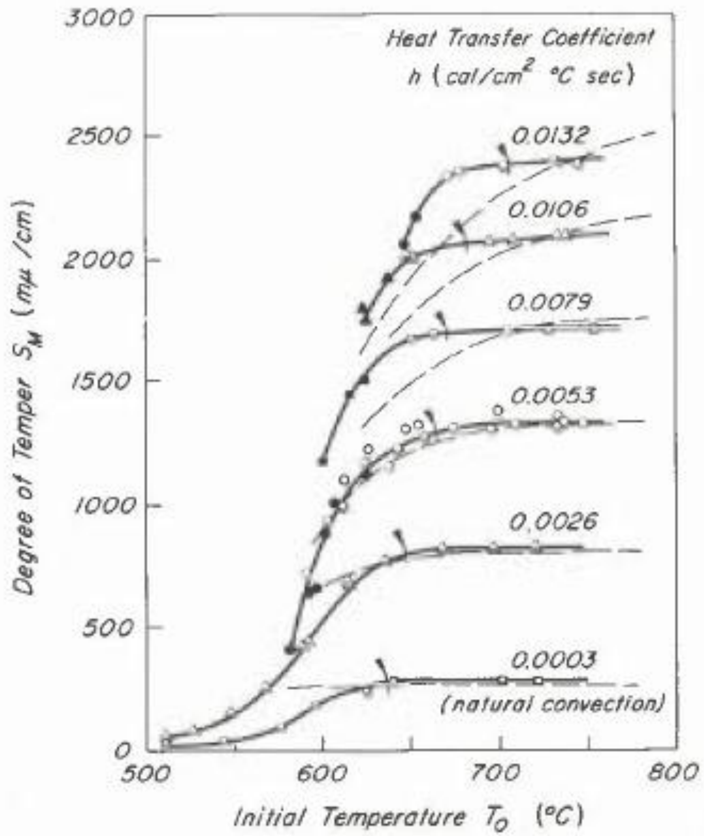


FIG. 7. Degree of temper as function of initial glass temperature and quenching coefficient. Forced convection cooling. Glass thickness, 0.61 cm. Experimental results, —○—; broken specimens, ●; calculated by Bartenev's theory ---- (Gardon, 1965a).

From R. Gardon, "*Thermal tempering of glass*", in "Glass: Science and Technology, Vol.5, Elasticity and Strength in Glasses", Ed. D. Uhlmann and N. Kreidl, Ac. Press, 1980

Examples for a glass plate of thickness = 8mm

- Initial viscosity of the glass $\eta_i = 10^8$ Pa.s

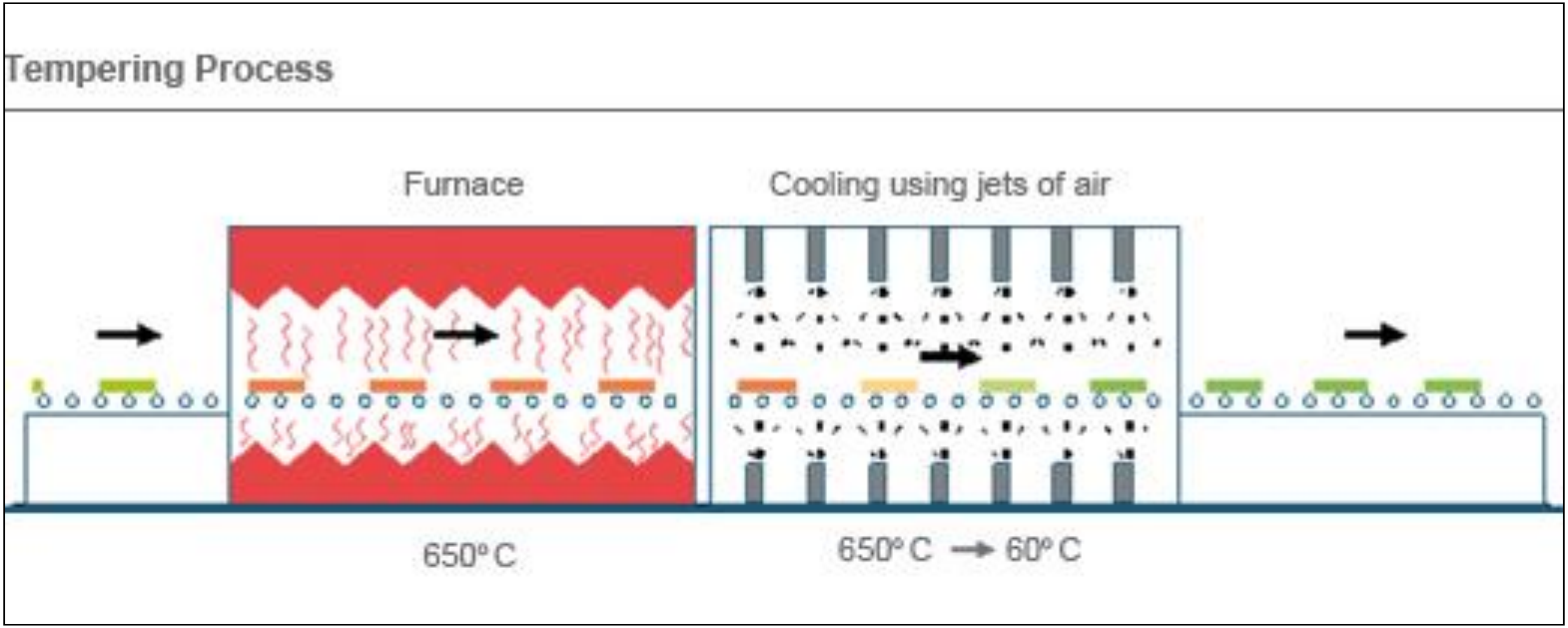
	H_{max} *($W/m^2.K$)*	**Initial temp. T_i** *(°C)*	**σ_{max} midplane** *(MPa)*	**σ_{max} surface** *(MPa)*
Soda-lime-silicate $\alpha = 9.10^{-6}$ K^{-1}	4500	650	105	235
Borosilicate $\alpha = 3.10^{-6}$ K^{-1}	>5000	730	32	70

- Initial viscosity of the glass $\eta_i = 10^9$ Pa.s

	H_{max} *($W/m^2.K$)*	**Initial temp. T_i** *(°C)*	**σ_{max} midplane** *(MPa)*	**σ_{max} surface** *(MPa)*
Soda-lime-silicate $\alpha = 9.10^{-6}$ K^{-1}	470	630	65	135
Borosilicate $\alpha = 3.10^{-6}$ K^{-1}	1500	680	25	50

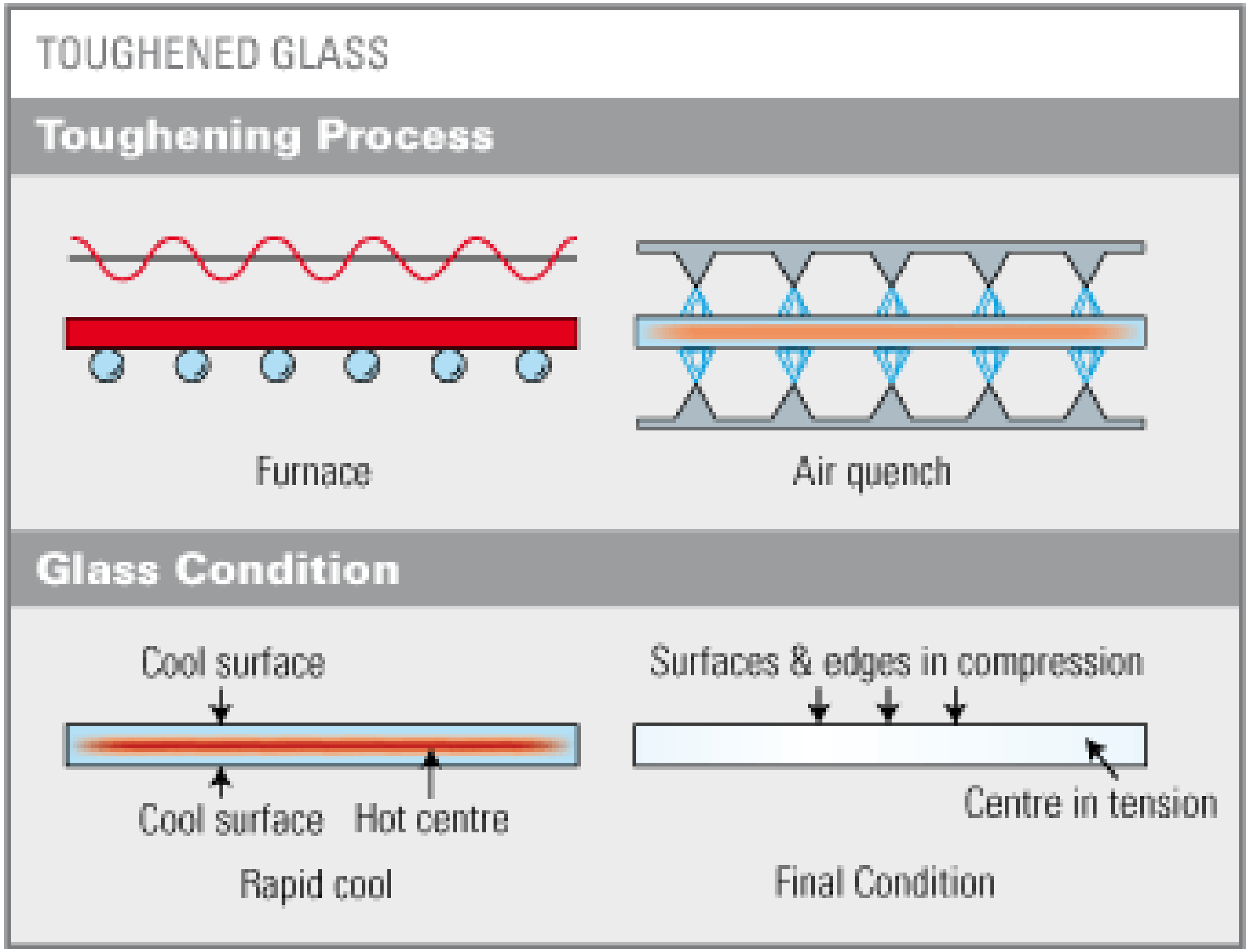
Industrial tempering of glass

Illustration of the a glass tempering unit for a soda-lime-silica glass



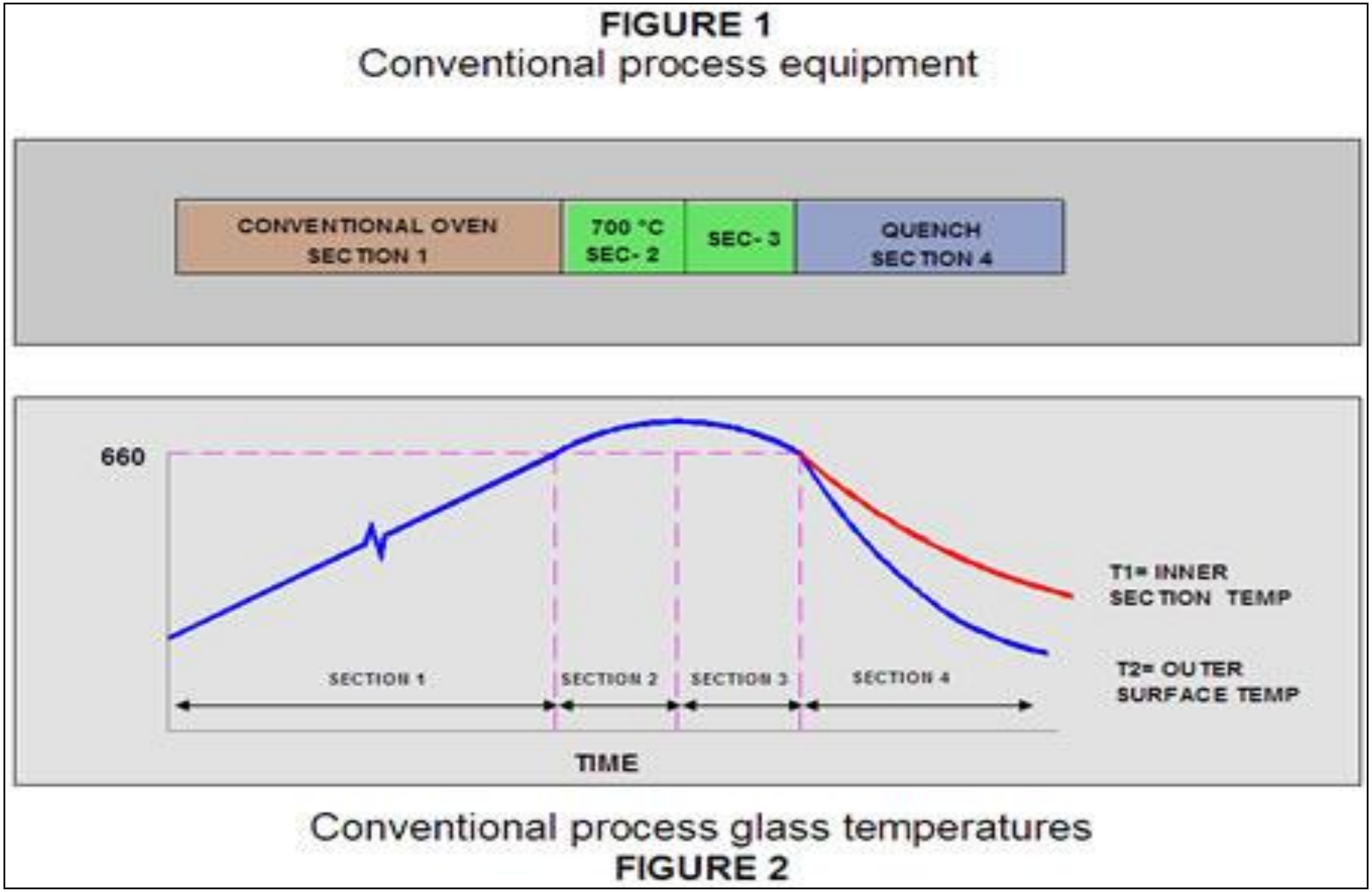
From: http://us.agc.com

Industrial tempering of glass



Source: http://www.metroglasstech.co.nz/catalogue/038.aspx

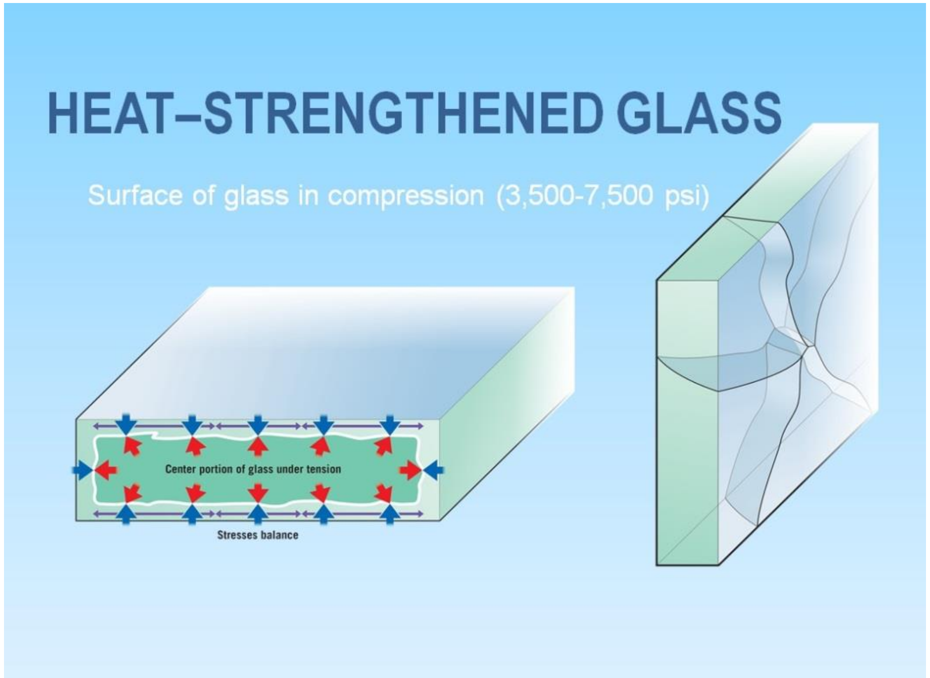
Industrial tempering of glass

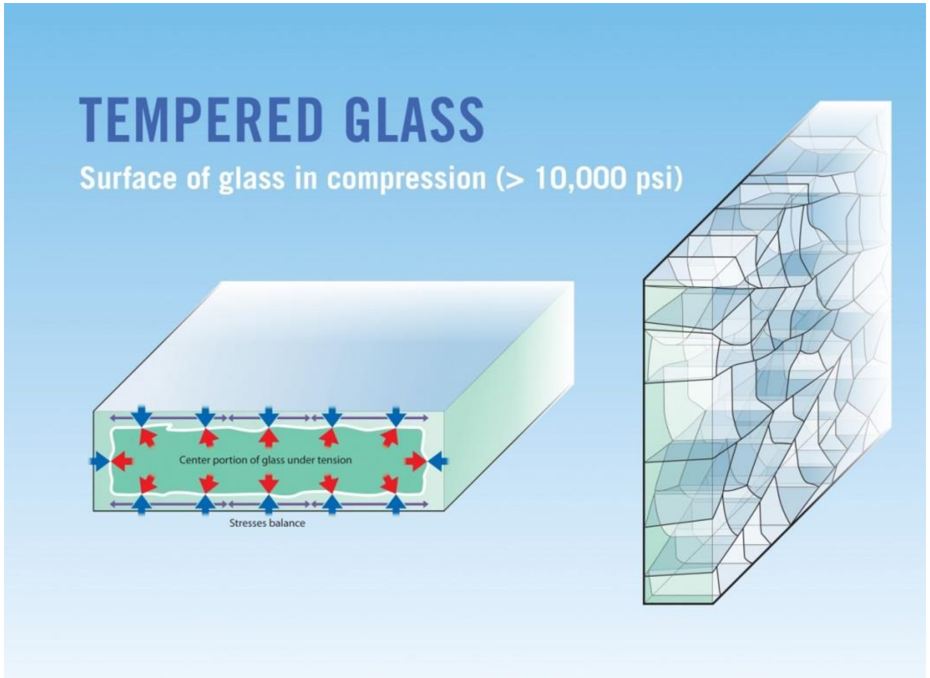


From P. Boaz "Thin glass processing with radio wave assist", www.glassonweb.com/articles/article/561/

Heat-strengthened vs tempered glass?

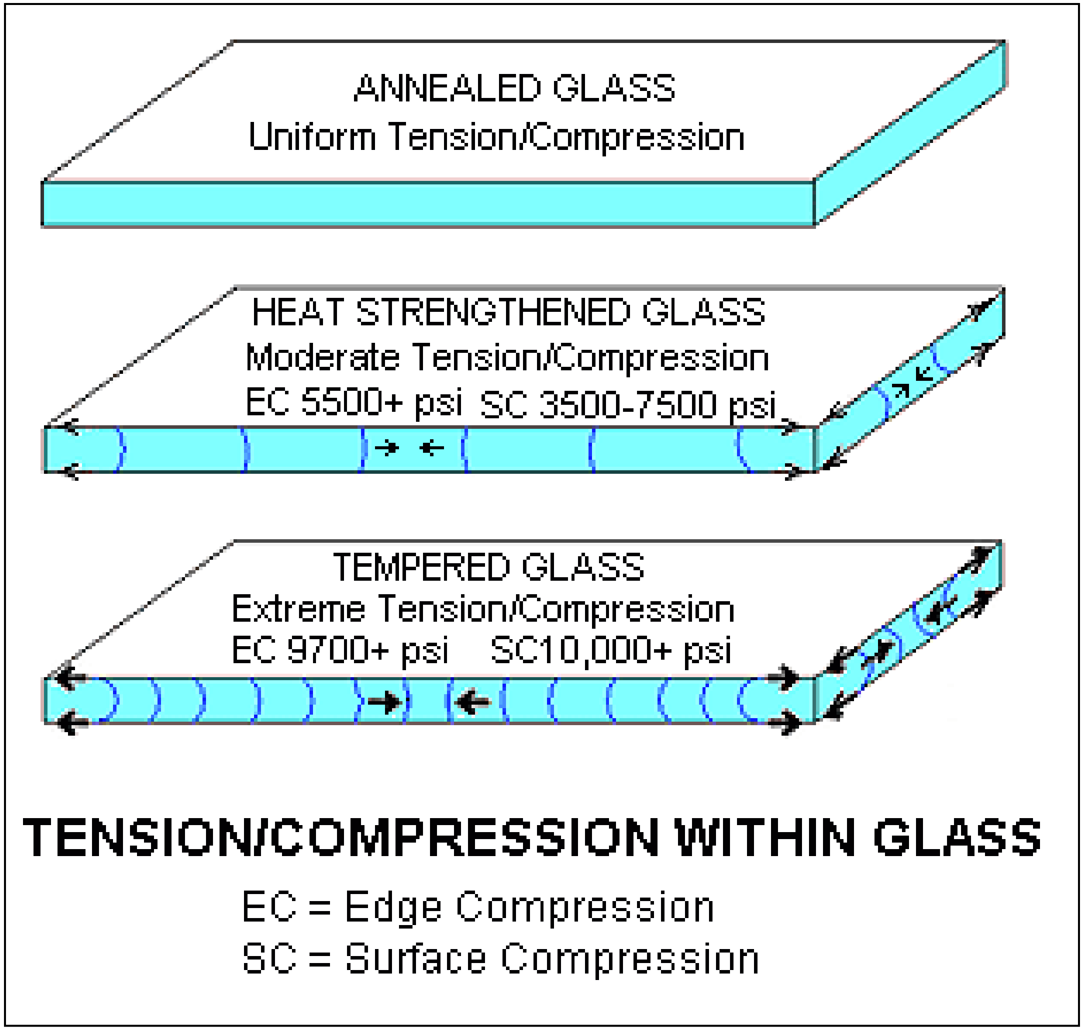
- Heat-strengthened glass: the **cooling process is slower**, which means the **compression stress is lower**
- In the end, heat-strengthened glass is approximately twice as strong as annealed glass but less strong than tempered glass





Pictures from: http://educationcenter.ppg.com

Heat-strengthened vs tempered glass?



Source: www.chicagowindowexpert.com

Processing of tempered glass

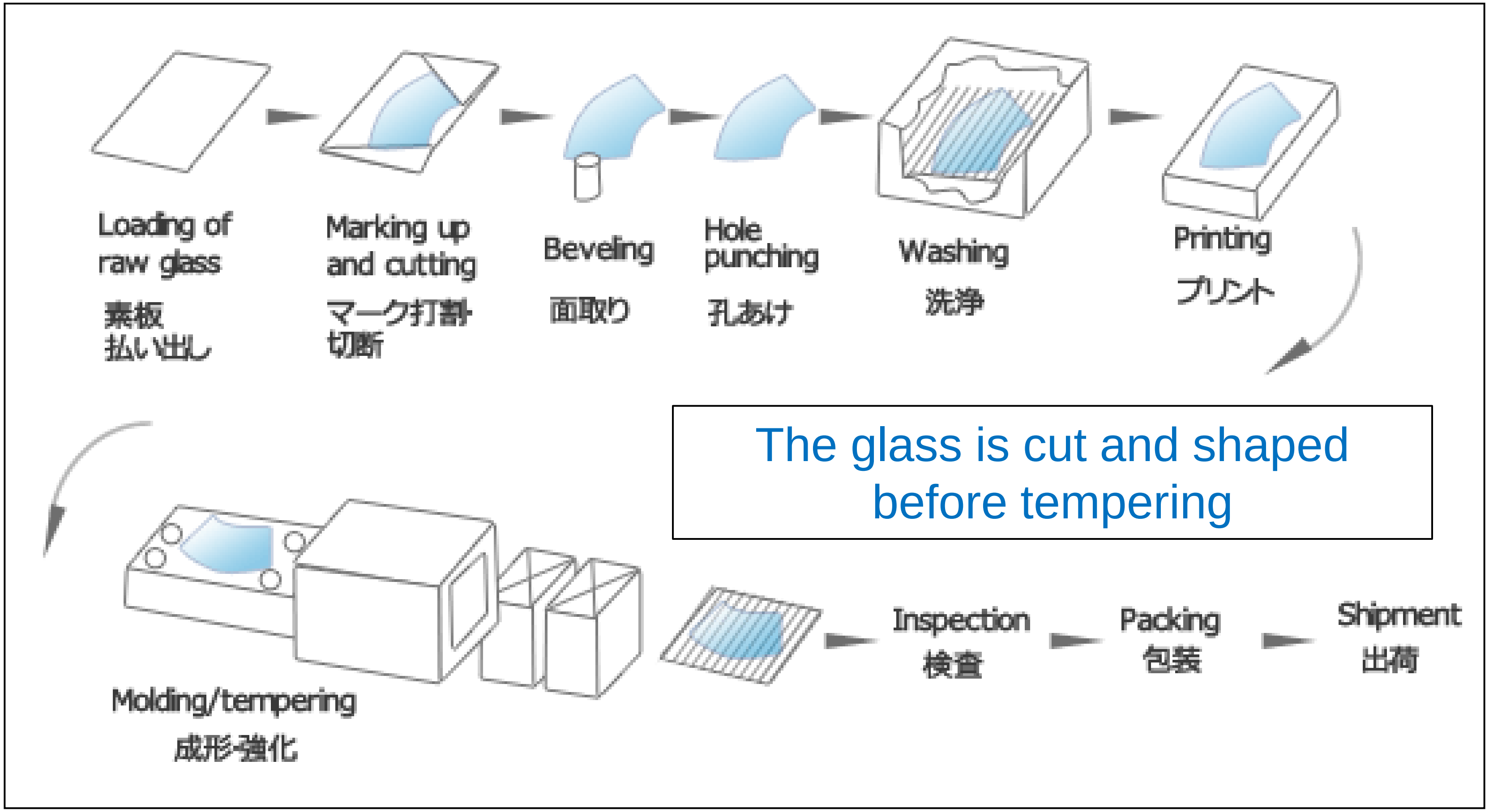
- **Tempered glass cannot be cut nor drilled!** It would lead to release of the strain energy and thus catastrophic failure of the glass
- How are the tempered glass articles made (for instance the windshields?)

http://glassdepotny.com

http://www.grandsportautobody.com

Processing of tempered glass

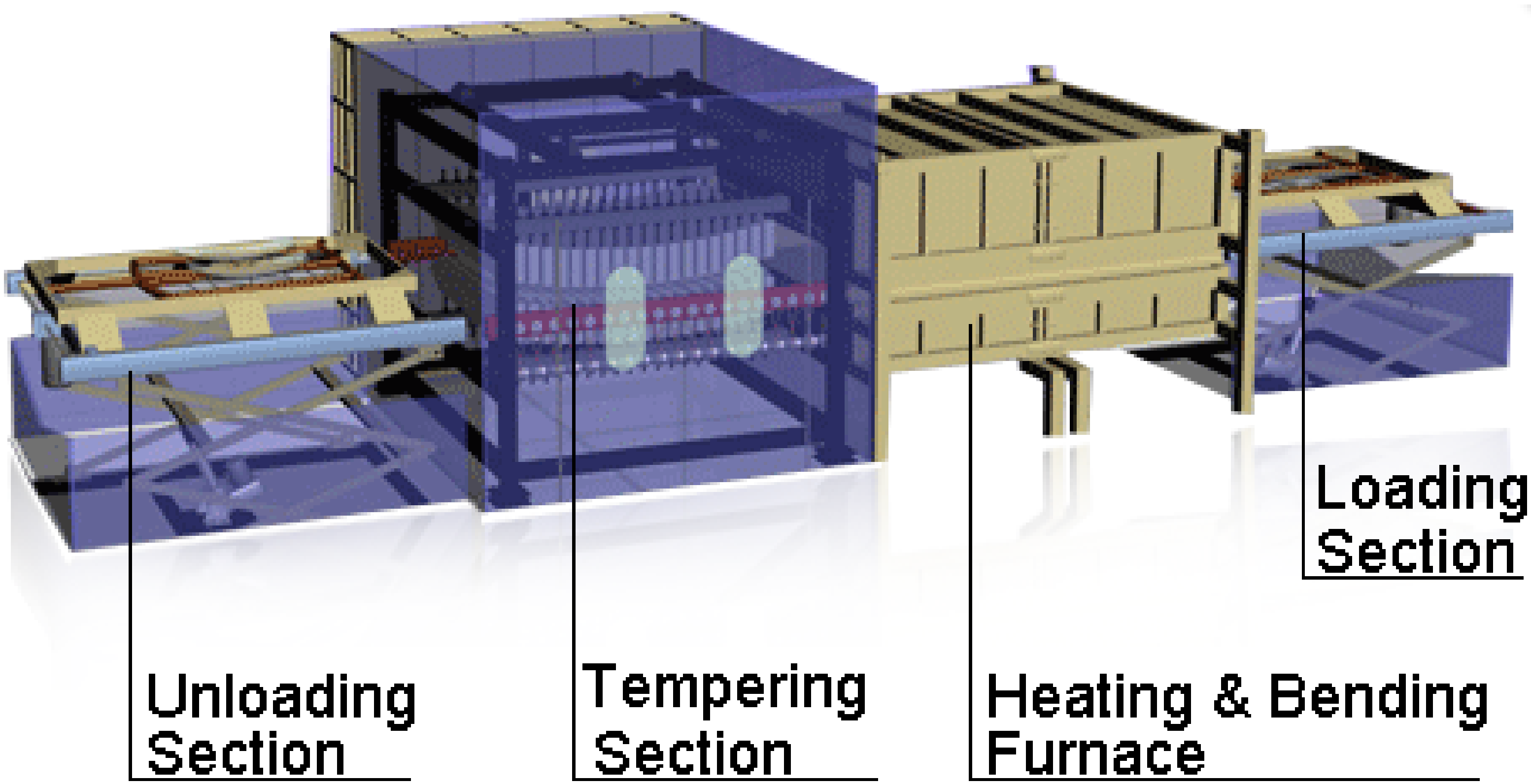
- Example of fabrication of tempered windshields



From: www.agc-automotive.com/english/products/temper.html

Industrial tempering of glass

Example of a glass tempering furnace



Picture from www.xinology.com/Glass-Processing-Equipments-Supplies-Consumables/glass-tempering/glass-tempering-furnace/feature/bending-tempering.html

Other technical considerations

- A certain thickness is necessary for obtaining an efficient strengthening of the glass by tempering
- For thin glass articles with a thickness below 2mm (typically), thermal tempering becomes much less efficient
- Also, tempering requires a uniform cooling from both sides of the glass article (e.g. both surfaces of a glass plate)
- It is thus complicated to temper glass articles with complex or uneven geometries (such as bottles)
- For these types of products, strengthening (when applied) can be performed using ion-exchange technique (chemical strengthening)

Chemical strengthening

- Chemical strengthening of glass also relies on the formation of a compressive stress on the surface, with the core in tensile stress
- The way to achieve this stress profile is however very different (ion-exchange instead of thermal treatment)
- Chemical strengthening of glass will be presented by A. Varshneya in this series of IMI-NFG lectures

Picture from: R. Gy, "*Ion exchange for glass strengthening* ", Materials Science and Engineering B 149 (2008) 159–165

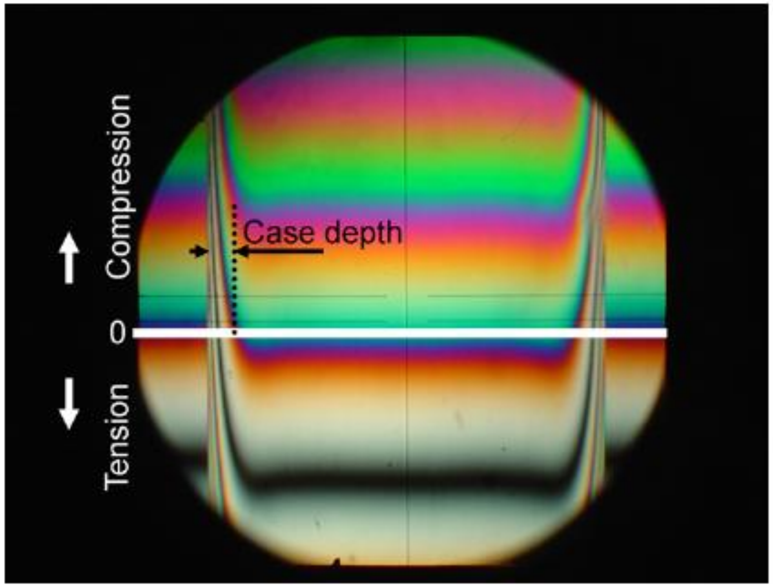


Fig. 3. Stress pattern in a chemically tempered glass: side view in a polariscope equipped with a Babinet compensator.

Conclusions – 1/2 - Annealing

- **Annealing** of the glass articles after the forming process is crucial for **relaxing the stresses** due to inhomogeneous, rapid cooling
- The annealing consists in reheating the glass above the annealing temperature and perform a **controlled, slow cooling** between the annealing point and the strain point
- The **cooling rate between T_{anneal} and T_{strain}** is crucial and will depend on the type of glass (composition) and the type of article produced (shape, thickness…)
- At industrial scale, annealing is a continuous process, and is performed in **annealing lehrs**
- The **temperature profile** in the lehr should be optimized to obtain a well-annealed product in the shortest possible time

Conclusions – 2/2 - Tempering

- **Tempering** of glass is a thermal treatment performed on annealed glasses to create **controlled** stresses in the glass
- The glass is **reheated** at a critical temperature and then **rapidly cooled**, leaving the **surface in compressive stress** and the **core in tensile stress**
- Tempered glasses can be **5 times stronger** than annealed glass
- If broken, tempered glass will shatter in small fragments (securit glass)
- Tempered glass cannot be cut or drilled, and the glass article must be shaped before the tempering process
- Tempering is **limited to relatively thick** products (> 2mm) and **relatively simple geometries** (windows, windshields…)

Home assignment

- A multiple choice questionnaire (MCQ) including questions on industrial glass annealing and tempering processes is provided with this lecture
- The MCQ will be available online on IMI's website

References and further reading

- “The glass tempering handbook” by Jonathan Barr, available online (free) at https://dl.orangedox.com/IOM4ukrFcunESCW2Yh/TheGlassTemperingHandbook.pdf

- Book “Strength of Inorganic Glass”, Ed. C. Kurkjian (Plenum, 1985)

- R. Gardon, “Thermal tempering of glass”, in “Glass: Science and Technology, Vol.5, Elasticity and Strength in Glasses”, Ed. D. Uhlmann and N. Kreidl (Academic Press, 1980)

- CelSian’s glass course e-learning trailer: https://www.youtube.com/watch?v=pID0PYsBIbQ&feature=youtu.be

Thank you for your attention

Questions ?

Visit us in Eindhoven

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