

The Glass Tempering Handbook

Understanding
the Glass Tempering Process

by

Jonathan Barr



Artistically Tempered Glass (Peter Schlossman USA)

Forward

By Bob Spindler

Vice President, Technical Services Cardinal Glass Industries (Retired)

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“Jonathan Barr is a recognized Tempering Glass Consultant. His expertise in glass tempering technology and resolving glass tempering problems is second to none. As a reviewer to his book on Glass Tempering, I am amazed that no one in the past has put together a book on this subject that not only details the theories and technology of tempering glass, but also some of the problems associated with tempering glass. Jonathan’s book is a tremendous resource for Companies that temper glass (including but not limited to Management, Tempering line supervisors, etc.) or anyone interested in the technology of glass tempering. Jonathan explains the simple process of heating glass and quenching it, to produce tempered or heat strengthened glass, is not an over complicated process. However, to meet aesthetic concerns and break safe requirements, there is a lot of technology required. In the past, some people have thought that tempering glass is more of an art than a science. The production personnel have many variables to consider on a daily basis i.e., glass thickness, throughput speed, quench air temperature, furnace operating conditions, aesthetics, break safe requirements, etc. Jonathan’s book presents a realistic review of the technology of tempering glass and with his knowledge that he has put into this book, he has helped in making glass tempering more of a science than an art.”

Jonathan is available for consulting on tempered glass problems and both 'on-site' and remote training for tempering furnace operators.

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About the Author

Jonathan Barr is a qualified Electrical Engineer and worked for 20 years with Glasstech as their Electrical Engineer being involved with trouble-shooting tempering systems around the world. Jonathan retired from Glasstech as General Manager in 2003 and continued to travel extensively as an independent consultant on glass tempering systems..

He was initially trained by the RAF as an electronic systems engineer on aircraft automatic flight controls. He served 25 years and for 4 years was stationed by the RAF at Smiths Industries to work on the world's first commercial automatic landing system. Later he was the Engineering Officer on a missile site in Germany and as a result of work he carried out there he was posted to a research establishment working with civilian scientists on the Rapier missile system.

The information in this book is a result of his observation, analysis and diagnosis of the tempering problems he has seen in the last 30 years.

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Introduction to Thermally Tempering Glass

This book aims to demystify the process of thermally tempering glass. Whether tempering large architectural panels, automotive glasses, or small highly stressed industrial glasses, the basic tempering process is the same – heat the glass to a temperature above its *Transition Point*, where it becomes plastic, keep it optically flat (or form it to a shape if required) then cool it at a controlled rate to a temperature below the *Strain Point* so there is a temperature difference between the surfaces and the central plane of the glass as it becomes solid again. The differential contractions between the surface and the central plane will introduce the final stress into the glass as it cools down to ambient temperature.

To understand what is happening as the glass heats and cools it is necessary to look at the viscosity and expansion of glass at temperature, and how these features are exploited in order to temper glass.

This book will cover:

1. The constituents of glass and the fact that the mix percentages can affect the final tempering stresses.
2. How to temper a piece of glass.
3. The mechanical and thermal effects that can cause distortions in the glass and how to minimise them.
4. The critical points in the process.

Brief History of Tempered Glass

Deliberately tempered glass was first patented in June/July 1874 by the Frenchman Francois Royer de la Bastie but not developed until the early 1900s and the first patent for a process to produce tempered glass is said to be held by Rudolf Seiden, an Austrian chemist who emigrated to the United States in 1935. Prior to this time the only documented use of deliberately tempered glass was the production of Prince Rupert Drops which were novelty items. Back in the early 1600s a German in Mecklenburg discovered that if he dropped molten glass into a bucket of cold water he produced tadpole shaped pieces of glass that were unbreakable until the tail was fractured. When the tail was broken the tadpole of glass then disappeared, as if by magic, in a cloud of dust.

How these were made was kept a secret and they were sold as novelties throughout Europe.

In 1660 Prince Rupert, Duke of Bavaria, gave some to King Charles II, who in turn gave them to the Royal Society for further investigation and they discovered that the 'drops' were in fact molten glass that had been stressed by dropping into cold water. The resultant temperature differences present in the glass as it became solid produced very high

compressive stress in the surface and high tensile stress in the core of the glass. When the tail was fractured a shock wave, followed by a fracture front, travelled through the glass breaking it completely into extremely small particles.

Tempered Glass in 1625

Prince Rupert's Drops

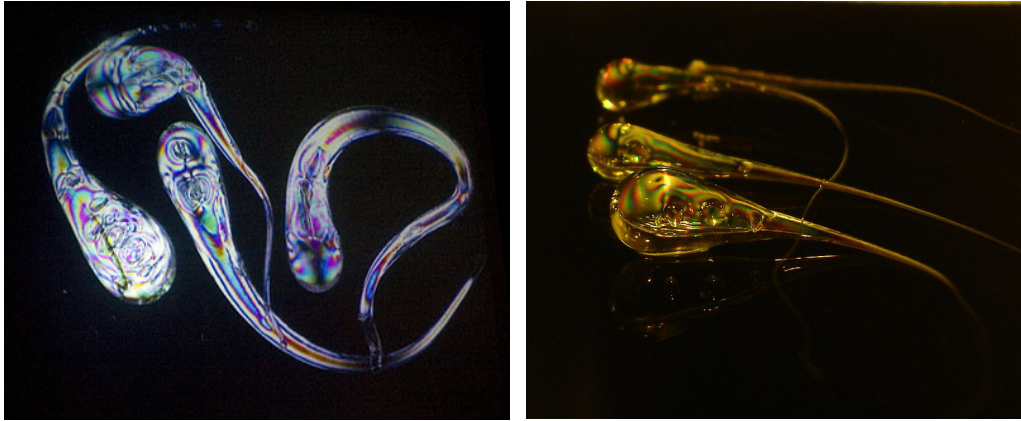


Illustration 1: Prince Rupert Drops

Illustration 1 shows Prince Rupert's drops viewed under polarising filters that highlight the internal stresses in the glass.

There is a very good video on YouTube by 'Smarter Every Day':- [Prince Rupert Drops](#) showing the manufacture, and filmed at 130,000 frames per second, the destruction of Prince Rupert Drops. It is very worthwhile viewing, just click on the link above to watch it.

In the 1940's, Henry Ford started using tempered glass for the side and rear windows of his automobiles and its use in vehicles became common place in the 1950's. Architectural tempered glass started to become popular in the 1960's as the benefits of the stronger, safer glass became more widely known.

Glass: Basic Properties

Clear glass is not completely transparent, a 6mm-thick piece of clear float glass will capture around 13-percent of light within the visible spectrum, allowing 87-percent of the visible light to pass through it. However, as the wave-length of light moves away from the visible range the transmission changes, and for many frequencies glass is quite opaque. Glass is relatively transparent to short wave infra-red but opaque to long-wave infra-red.

Raw float glass is very strong when in compression – it can easily withstand 1034MPa (150,000psi). In other words, it is extremely difficult (almost impossible) to break glass when it is in compression.

Theoretically, glass with a perfect surface (no micro-flaws) can also withstand about 1034MPa (150,000 psi) tensile stress. However, in practice, glass is relatively weak when in tension and can only take 25 - 34MPa (4000 to 5000psi) of tensile stress before it fails due to micro-flaws in the surface migrating into and through the glass.

When glass is tempered, all the outer surfaces, including the edges of the glass, are put into compression. The inner portion of the glass will naturally go into tension, so that all the forces are balanced, but because the 'surfaces' of the tension layer are inside the glass it should not have any micro-cracks, unless there is an impurity or air-bubble present, and therefore the tension layer should not fail.

This makes tempered glass very difficult to break compared to raw glass and it is generally considered to be 4 to 5 times stronger than raw glass.

Understanding Glass

To understand the process of tempering glass it is necessary to understand a little about the expansion and viscosity of glass at temperature, so let's take a quick look at the float glass manufacturing process.

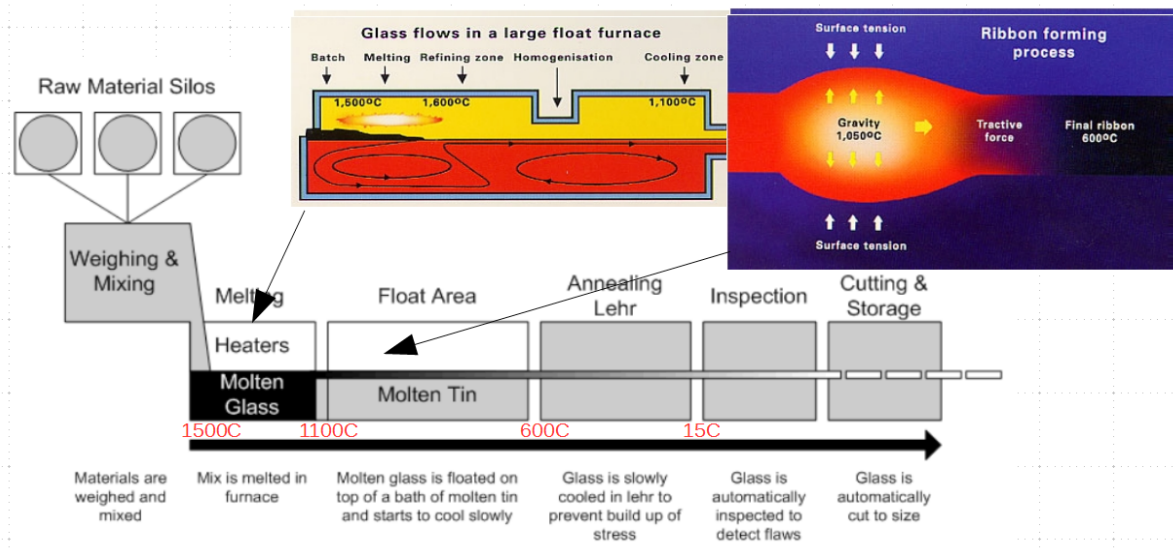


Illustration 2: The Float Glass Process

Manufacture of Glass

Glass is made by melting certain chemicals together which then form into a clear solid as it cools down.

Illustration 2 above shows a schematic diagram of the float process for making glass. This process was invented by Pilkington and has been licensed to most glass manufacturers. To the left are the raw material silos containing the basic constituents of modern glass, these are weighed and mixed (it is then called the *batch*) in the ratios of approximately 72% Silica, 13% Soda Ash, 12% Limestone plus a small amount of Feldspar and fed into the furnace where they are melted at around 1510°C, homogenised and allowed to cool down to around 1100°C.

Silica (sand) – is the major ingredient in glass.

Soda Ash – acts as a flux and is added to help melting.

Limestone – makes the glass durable & insoluble.

Feldspar – acts as a flux and also gives the glass good weather resistance.

Glass can be tinted (coloured) by adding small amounts of metallic oxides to the existing ingredients. For example, the addition of iron oxide produces a green glass. Bronze and grey are produced by the addition of selenium and nickel oxide.

The molten homogenised glass, having been cooled to around 1100°C, is then floated off onto a molten *tin bath*. If the molten glass was allowed to settle (pool) naturally, gravity tries to flatten it out, and surface tension opposes the force of gravity. The result of these two opposing forces is that the molten glass thickness would be about 6mm. Therefore the speed at which the glass is drawn out of the hearth and down the *tin bath* is adjusted by *Top Knurl Wheels*, also known as top rollers, and the resultant ribbon is also either pulled or squeezed as it travels on the tin to control the final thickness. (See illustration 3).

For glass thinner than 6mm the top rollers have a positive slew angle to stretch the glass, and for glass thicker than 6mm the top rollers are slewed with a negative angle to squeeze the glass.

The top rollers work in pairs and for 2 to 12mm glass there are normally 5 to 6 pairs. For glass thinner than 2mm and glass thicker than 15mm there can be up to 20 pairs of top rollers needed to control the thickness accurately.

The *top knurl wheels* indent into the glass ribbon leaving a thick roll of glass at the edges of the ribbon. This uneven (waste) portion of the glass ribbon is cut off as it leaves the annealing lehr and added back into the furnace by an underground conveyor.

Tin Bath

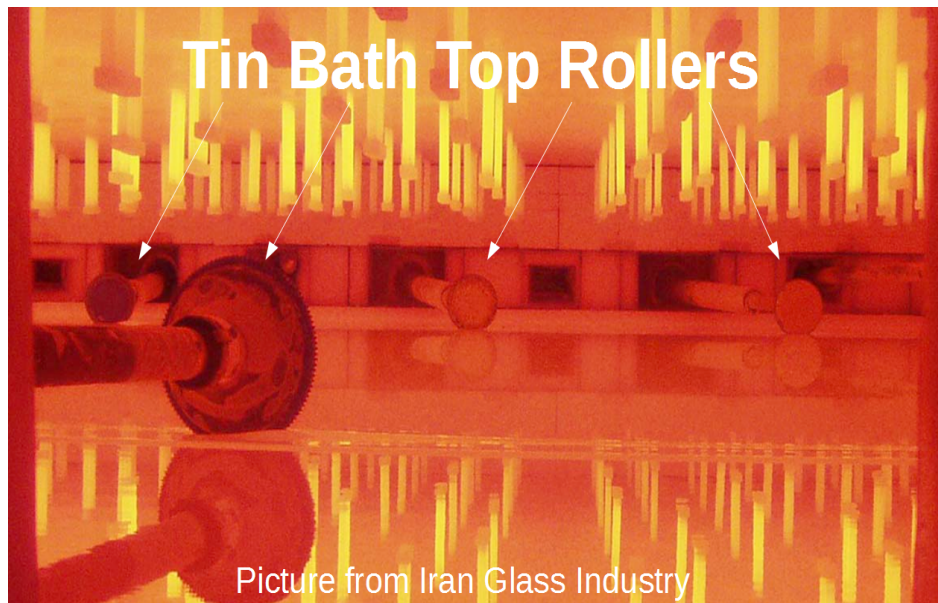


Illustration 3: Inside The Tin Bath

Molten tin is ideal as a medium to float the glass onto because tin melts at around 232°C and doesn't boil until 2270°C . However, tin oxidises easily so the atmosphere in the tin bath is controlled with a high percentage of nitrogen mixed with hydrogen. The glass is cooled as it travels down the 60m long bath so that when it leaves the bath it is nearly solid at around 600°C . The semi-solid ribbon of glass is raised off the tin by *lift-off* rollers and, on some float lines, a little SO_2 gas is injected to help reduce damage to the lower surface of the glass by the rollers, it is then transported down the annealing lehr on a ceramic roll bed. The annealing lehr accurately controls the rate of cooling of the glass ribbon to reduce temperature differences within the glass as it becomes solid and, therefore, reduce any stresses in the glass to an absolute minimum. Once it becomes solid if the cooling rate is too high there is a risk of cracking the glass. The tin-bath is typically about 60m long. It contains around 200 tons of pure molten tin at an average temperature of 800°C (1475°F). A series of adjustable (in speed and angle) *top knurl wheels* stretch or compress and control the speed of the ribbon to control the final glass thickness. The entry temperature to the tin bath is 1100°C and the exit temperature is 600°C .

It is interesting that the natural thickness of the ribbon is around 6mm because it has been found that 6mm glass is without doubt the easiest thickness to process in a tempering line.

The question is, what is the difference between the top and bottom surfaces of the float glass?

The bottom surface is a damaged surface (micro flaws) because it has been in contact with the *lift-off* roller and annealing lehr rollers.

How can you tell the difference between the two surfaces?

The lower surface (the tin side) will fluoresce when illuminated with an ultraviolet light.

Why do we need to know?

When processing tempered glass to a standard that requires it to be subjected to a ball-drop test, (e.g. a car sun-roof) it is advantageous to process the glass in a tempering furnace with the tin-side in contact with the roll bed. This means that there is one surface that has never been in contact with a roll bed and is therefore completely undamaged (providing that the pre-processing equipment has not contacted the air-side of the float glass). The ball is then dropped onto the tin-side and the bending of the glass by the force of the impact means that it is the undamaged surface that is stretched. This undamaged surface is less likely to fail, because there are virtually no micro-cracks present. The damaged surface will be compressed by the impact, which will simply close up the micro-cracks.

Properties of Expansion and Viscosity of Glass with Increasing Temperature

The properties of *expansion* and *viscosity* are critical to the tempering process so let us take a look at what happens to the glass as it is heated.

Expansion of Glass

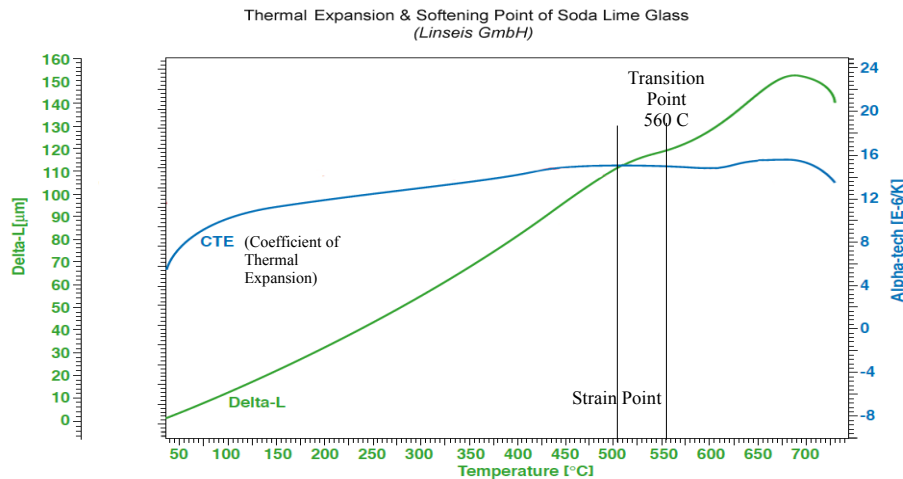


Illustration 4: Expansion Coefficient of Soda Lime Glass

The coefficient of thermal expansion of glass (shown by the blue line in the Linseis GmbH graph above) increases from around $6 \times 10^{-6}/^{\circ}\text{C}$ to around $13 \times 10^{-6}/^{\circ}\text{C}$ as the temperature increases, the green line shows the actual expansion of the glass. Therefore a one-metre long glass will grow by about 8 to 9mm as it heats up from ambient temperature to 600°C .

Note that there is a slight kink in the graph at around 510°C which is the first point of interest in tempering glass. This is called the *Strain Point* of soda-lime glass. Below this temperature the glass is considered to be solid (in its elastic state). Above the *Strain Point* is a point called the *Annealing Point* at around 550°C which is where any stresses in the glass will start to relieve. The *Transition Point* occurs next at around 560°C and above this temperature any stresses in the glass will relieve very quickly as the glass enters its plastic state.

Strain and Stress

Strain is a condition that is induced into a solid when the length of the solid is changed from its normal length by stretching or compressing. The value of *stress* is then calculated by multiplying the *strain* by *Young's Modulus* from illustration 6. So, as an example, an 80 degree difference in the temperatures of the surfaces compared to the centre inside the glass during heating in a furnace would cause the surfaces to expand more than the centre and stretch the centre by about 0.822mm in a 1000mm long glass. The centre plane of the glass would therefore experience a tension stress of around 56MPa as shown in illustration 5.

Strain and Stress

Stretched

$$\text{Strain} = \frac{L_0 - L_1}{L_0} \quad (\text{Tension})$$

$$\text{Strain} = \frac{(1000 - 1000.822)}{1000} = -0.000822$$

$$\text{Stress} = \text{Strain} \times \text{Young's Modulus}$$

$$\text{Stress} = -0.000822 \times 68.5 \times 10^9 = -56 \text{ MPa (8122psi) Tension}$$

Illustration 5: Calculation of Strain and Stress

Young's Modulus is actually affected by the percentage mix of the glass batch, see the example in illustration 6 taken from Wikipedia, which for window glass is generally accepted to be approximately 72GPa which means that different types of glass will produce different stress levels for the same temperature difference. Because *Young's Modulus* affects the final tempered stress levels, furnace operators should be aware that glass from different suppliers may well need small changes to the tempering system parameters to achieve a satisfactory result.

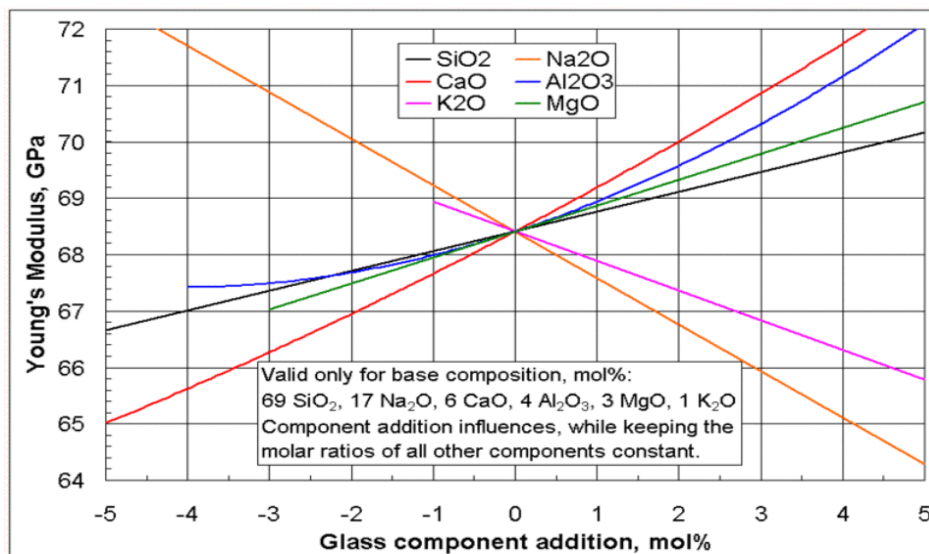


Illustration 6: *Young's Modulus - Changes with Batch Mix*

Illustration: 7 shows the stress induced into 4mm glass as it is heated and then cooled **before** it reaches the *Strain Point*. The top trace shows the glass on the load table with no temperature difference through the thickness of the glass. The second trace shows the situation 18 seconds after entering the furnace where the surfaces have heated over 65 degrees more than the centre and the expansion of these surfaces cause stretching of the central (cooler) plane of the glass. This causes compression in the surfaces and tension in the middle of the glass. This is similar, but to a lesser degree, to tempered glass and because of the compression in the surfaces the glass is very strong. This explains why we can put a cold glass into a red hot furnace and it survives.

The third trace shows that after 90 seconds the surface temperature is about 480°C (below the *Strain Point*) and the difference in temperature between surface and centre has reduced because the rate of heating of the surfaces has reduced (the exponential curve effect, which will be explained later), allowing the centre temperature to catch up.

If the glass (which is still solid and in its elastic state) is now removed from the furnace and the surfaces rapidly cooled they will contract more when compared to the centre of the glass and therefore they will go into tension. The tension will cause any micro-flaws to run into and through the glass and break it.

Stress due to Temperature

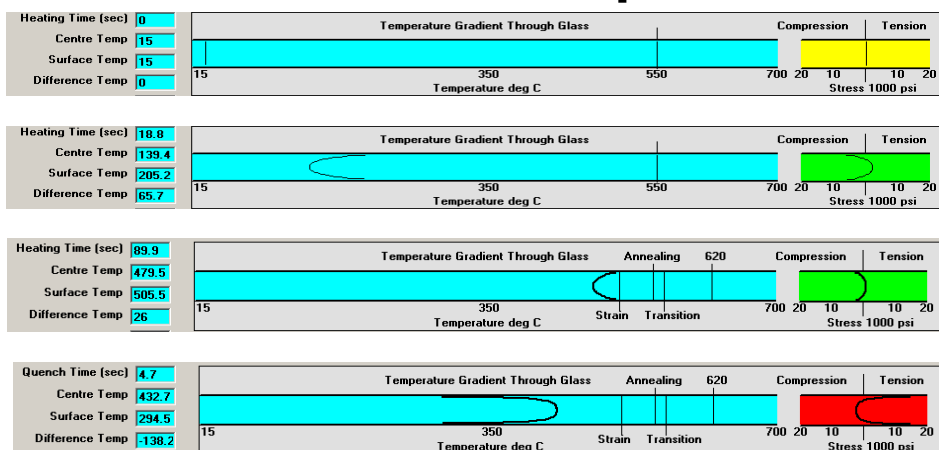


Illustration 7: *Stress Due To Expansion & Contraction in the Elastic State*

Properties of Glass above the Transition Temperature

As the temperature of glass is increased above the *Strain Point* and past the *Transition Point* the glass starts to soften i.e. the viscosity of the glass reduces to a level where stresses can start to relieve and the glass enters a plastic state. In the plastic state any solid can be distorted by a force and the distortion will remain in place, unlike in its elastic state when it will return to its original shape after the force is removed.

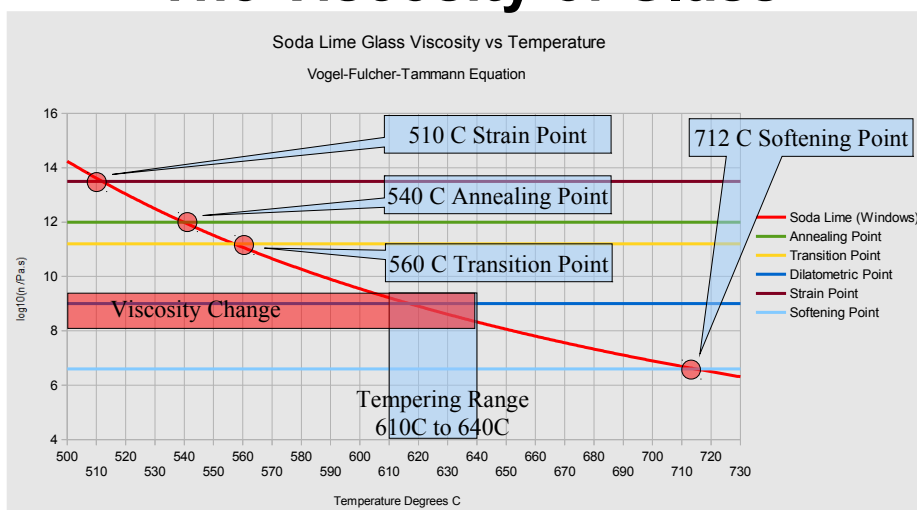
$\log_{10}(\eta, \text{Pa}\cdot\text{s})$	$\log_{10}(\eta, \text{P})$	Description
1	2	Melting Point (glass melt homogenization and fining)
3	4	Working Point (pressing, blowing, gob forming)
4	5	Flow Point
6.6	7.6	Littleton Softening Point (Glass deforms visibly under its own weight. Standard procedures ASTM C338, ISO 7884-3)
8-10	9-11	Dilatometric Softening Point, T_d , depending on load ^[2]
10.5	11.5	Deformation Point (Glass deforms under its own weight on the μm -scale within a few hours.)
11-12.3	12-13.3	Glass Transition Temperature, T_g
12	13	Annealing Point (Stress is relieved within several minutes.)
13.5	14.5	Strain Point (Stress is relieved within several hours.)

When glass is heated right up to its *Littleton Softening Point* a block of glass will distort under its own weight and the temperature required is approximately 712°C as shown in illustration 8.

Viscosity

The viscosity of the glass reduces as it is heated up and, above the *Transition Point*, it can overcome the problem that is seen if the glass was cooled before it reached a high enough temperature. The higher the temperature the more the molecules vibrate and the less rigid the glass becomes. There are defined points for the stiffness of a material, and illustration 8 below shows the *viscosity curve* for normal soda-lime glass versus temperature.

The Viscosity of Glass



If the glass is heated to above the *Transition Point* (defined as the point where any stress in the glass will quickly dissipate) it is found that the glass can be quenched without it breaking. This is because the soft surfaces (they are like plasticine) can be stretched about the central mass of the glass as long as their temperature is above the *Transition Point*. Although the surfaces are cooler than the centre, and therefore should be shorter, they are in fact at the same length as the hotter centre plane of the glass.

Illustration 8: Viscosity of Glass 500°C to 730°C

The reason for the need to go well above the *Transition Point* is to give time for this temperature difference to be set in the glass without causing any significant stress. However, the higher the temperature, the softer the glass becomes and it is therefore more prone to distortion. As the temperature difference is being set by the quench air extracting heat energy from the surfaces, they are being cooled and will start to enter their solid state as the temperature drops down through the *Transition Point*. Therefore, the higher the starting temperature the easier it is to set the temperature difference before the glass starts to solidify.

The temperature difference then needs to be maintained while the entire thickness of the glass is cooled to below the *Strain Point* where it becomes solid. Now that the glass is solid, with a temperature difference, as it cools down to ambient temperature and normalises throughout the thickness, the hotter parts of the glass (centre plane) will contract more than the cooler parts (surfaces). The result of this asymmetric contraction is that the surfaces will go into compression and the centre plane will go into tension. Because the border between compression and tension is buried inside the glass it means that the 'surface' of the tension layer is effectively a perfect surface (no micro flaws) and can easily withstand the high tensile forces of around 34 to 48MPa (5000 to 7000psi). The tensile force is approximately half the value of the compressive (surface) force for reasons explained later in the book.

As outlined above, to give the tempering process time to cool and stretch the surfaces in the quench before they become too cool to be stretched, the glass needs to be exiting the furnace at well above the *Transition Point* but not so hot as to cause it to be too soft and therefore easily distorted. This requirement defines the working range of temperature for tempering architectural glass and is typically around 610 to 640°C depending on glass thickness and it lies across the *Dilatometric Softening Point*. The glass only needs to go to a higher temperature to make it softer if it is required to be formed, for example automotive side and rear windows or curved architectural glasses. In these cases the exit temperature of the glass is in the region 640 to 660°C.

Note that the change in viscosity (shown in red in illustration 8) is an order of magnitude for a temperature change of just 30 degrees. Therefore, processing glass slightly hotter than necessary will result in considerably increased distortion in the finished product.

Small changes in the percentage ratio of the chemical mix of the glass will affect the actual viscosity at a given temperature (illustration 9). For example:

Window glass = 73% SiO₂ + 14% Na₂O gives a Transition temperature of 564°C.

Container glass = 74% SiO₂ + 13% Na₂O gives a Transition temperature of 573°C.

Borosilicate (Pyrex) = 80% SiO₂ + 13% Boric oxide + 4% sodium oxide and 3% aluminium oxide gives a Transition temperature of 610°C and a softening temperature of 820°C

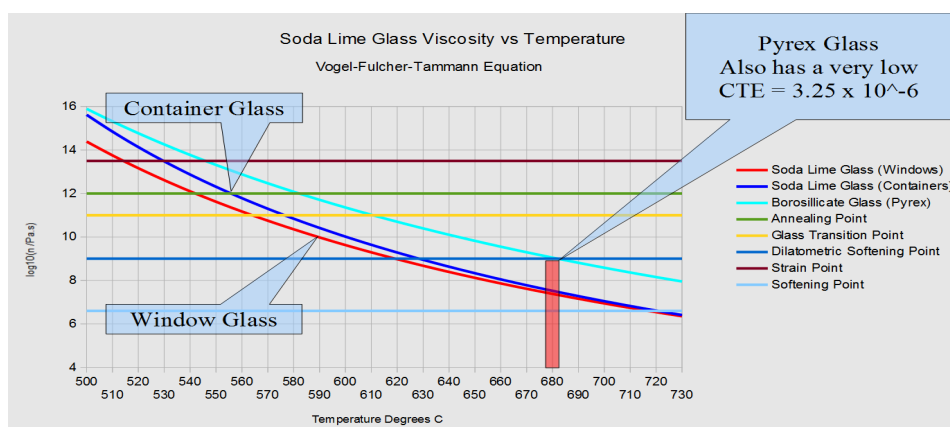


Illustration 9: Glass Viscosity vs Temperature

So again, furnace operators should be aware that glass from different suppliers may well need small changes to the tempering system parameters to achieve a satisfactory tempered result.

Note: Thin Borosilicate glass cannot be tempered in a normal tempering furnace because it requires very high temperatures and even then, due to the very low coefficient of expansion of the glass, the temperature difference that can be achieved by a conventional air quench is insufficient to cause high stress levels in the finished glass.

The Viscosity of Glass

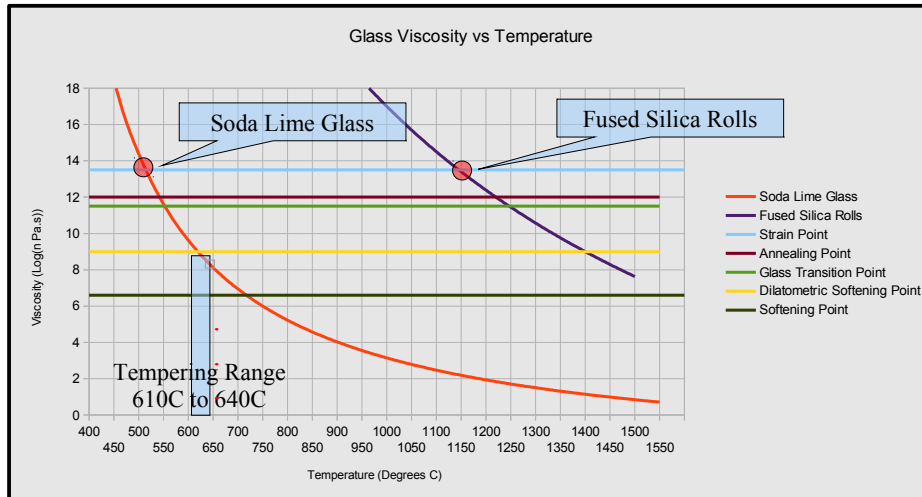


Illustration 10: Viscosity of Glass and Fused Silica Rolls

Before leaving the subject of viscosity it should be noted that the viscosity of fused silica rolls used in tempering systems is such that their *Strain Point* is around 1150°C (as shown in illustration 10) and therefore even if a roll bed is stationary at full furnace temperature the fused silica rolls will not sag or be damaged. Also, because of their very low coefficient of expansion, even at 700°C they can survive the application of cold water which has been used on many occasions to try and spring off glass particles stuck to them as a result of a glass exploding inside the furnace. The glass particles contract but the rolls do not, so the probability is that the glass particles will spring off the roll.

Strength of Tempered Glass

The strength of glass is usually measured by bending the glass until it fails and recording the force that was required to break it. For building glass this is called a *four point bending test* and is called up in the European standard EN 1288-3. A surface compression level of 90 MPa (13,200 psi) in the glass is required to pass the test.

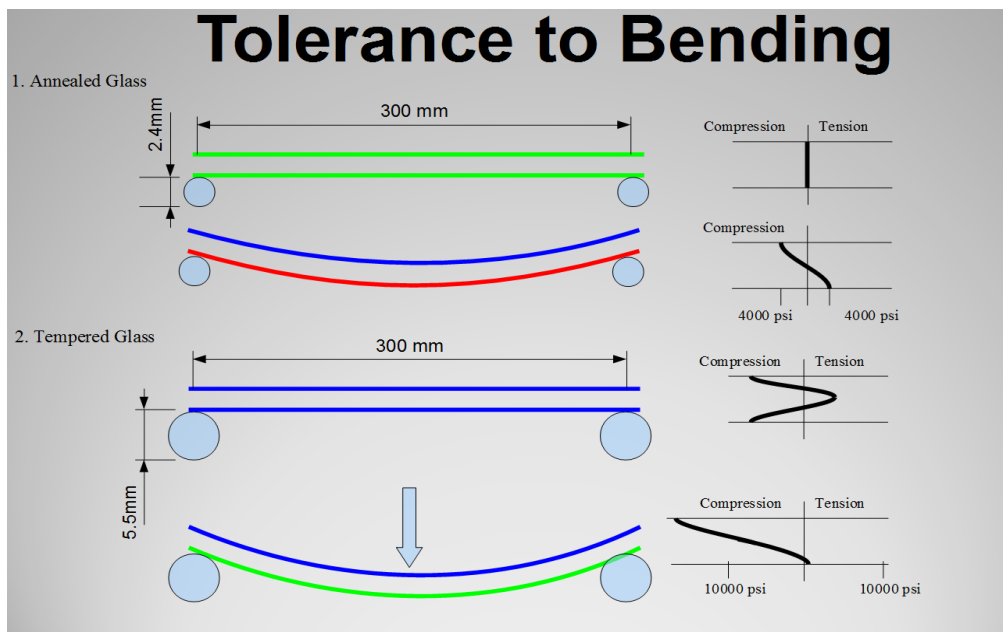


Illustration 11: Tolerance to Bending

Illustration 11 shows that for an annealed glass of 300mm length only 2.4mm depth of bend is required to put the lower surface of the glass into tension of about 27.6 MPa (4000 psi) which is probably sufficient for the glass to fail. For a tempered glass the surfaces are in compression so the same size glass can be bent to a depth of 5.5mm before the lower surface compression is simply reduced to zero and the glass should not break.

Therefore tempered glass has a higher wind loading capability than annealed glass. It also can be hit by a blunt object without breaking. Because the stress in tempered glass is a result of differential contraction due to temperature differences in the glass as it became solid it has a higher resistance to fire and heat shock applied to one surface because that surface will be expanded by the temperature of the hot object, which simply reduces the compression in the other surface (similar to bending the glass). Information from Cardinal Glass USA indicates that thermal stress in glass can cause a fracture due to the temperature difference between the edge of the glass hidden in the frame, and the glass that sees the sunlight at the frame/glass interface. Depending on the quality of the edge, clean cut annealed glass can withstand approximately a 4 to 5°C temperature difference. Heat strengthened glass can withstand a 38°C difference and tempered glass approximately 200°C.

Importance of Raw Glass Quality

The quality of the raw glass cannot be emphasised enough. Here are a few of the possible problems that can be caused by the raw glass when considering the tempering process.

Incorrectly Annealed. If the glass has not been correctly annealed during the float process, residual stresses will be present in the glass. These stresses will mean that when the glass is cut it will not break-out cleanly, and when the glass edges are abraded or polished it will tend to chip and not leave a clean smooth edge. These chips and flaws will act as stress raisers during the tempering process and can risk taking the transient stresses beyond what the glass can withstand, causing breakage both in the furnace and the quench.

Impurities. (Bubbles, inclusions, knots, scratches, cracks). If there are impurities present, especially in the tension layer after tempering there is a risk that the glass will fail catastrophically later. This is especially true of Nickel Sulfide particles which can occur when Nickel rich contaminants come into contact with Sulphur. The problem of Nickel Sulfide particles, and what can be done to reduce this risk, will be discussed later in the book.

Thickness Variation. Drawline defects generally consist of cylindrical thickness variations whose axes extend longitudinally, i.e., in the direction of the draw, or in other words, in the direction that the glass ribbon travels as it emerges from the melting tank and passes over the float bath. When drawline defects include elongated inhomogeneities within the glass, they are sometimes called strings, striae or ream.

Any variation in thickness, either sheet to sheet or within a sheet, will cause non uniform temperatures during heating of the glass. It will be seen later that non uniformity of heating can cause distortion and poor break pattern in the finished glass.

Low Emissivity Coated Glass

Emissivity is the ratio of energy radiated by a particular material compared to energy radiated by a black body at the same temperature. A true black body would have an $\epsilon = 1$ while any real object would have $\epsilon < 1$. Emissivity is a dimensionless quantity. For example an emissivity of 0.84 means that 84% of energy is radiated and 16% of energy is retained.

Ordinary glass has an emissivity of 0.84 and this can be reduced by coating the surface of the glass with a thin metallic coating which will better reflect energy to which it is subjected. For high efficiency glazing one surface of the glass is coated so that it reflects infra-red radiation to help either, keep the building warm in cold climates, or to reduce the solar heating effect in hot countries. In either case it makes the glass more difficult to heat in a furnace in readiness prior to tempering.

Glasses are usually coated by one of two methods, either in the float process, called Pyrolytic (Hard Coat), or after the float process by sputtering very thin layers of silver oxides onto one surface (Soft Coat).

Hard coated *low emissivity* glasses are not particularly efficient having a surface emissivity of around 0.3 compared to the normal 0.84. However the coating is robust and these glasses can be readily processed in a standard tempering furnace fitted with a simple compressed air aspiration system to aid heating of the upper (coated) surface of the glass.

Soft coated glasses are an order of magnitude more efficient in that they typically have surface emissivities in the region of 0.03. However the coating is very fragile and easily damaged. The temperable versions of these glasses usually have a sacrificial layer on top of the coating which will protect the layers below, but will burn off during the tempering process. Processing these glasses in a radiant heater requires a very efficient forced air convection system to heat the coated surface by conduction from a hot air mass because the very low emissivity surface reflects infra-red radiation.

Variations of coating thickness, robustness or uniform coverage will cause non uniform heating of the glass resulting in deformation of the glass or visible damage to the coating.

Note: Any coated glass should be run with the coating side up to avoid damaging the coating by contact with the rolls.

Cutting

The property of poor strength of glass in tension is exploited in the cutting of glass. Glass is cut by putting a slight flaw in the surface of the glass (usually with a diamond wheel) then bending the glass so that the flawed surface goes into tension. The flaw will then run cleanly through the glass in a straight line if there are no stresses in the glass (illustration 12).

If too high a wheel pressure is used, or the use of an incorrect wheel angle for the glass thickness, there will be a risk of a bad cut and breakout (see illustration 13). The subsequent edge-working of the glass may not remove all the flaws introduced by the cutting. This in turn will lead to increased breakage during quenching.

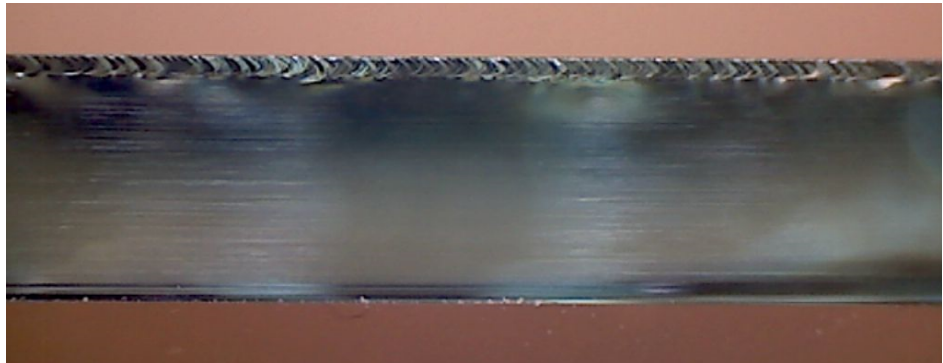


Illustration 12: Example of Good Cut and Breakout

Edge Working

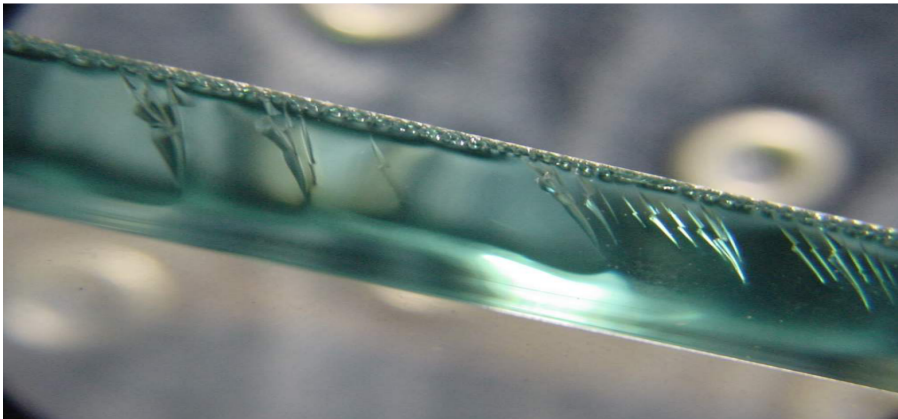


Illustration 13: Bad Cutting (Sharks Teeth)

The purpose of grinding or polishing the edges of the glass before tempering is to remove all sharp edges, chips and flaws from the glass. Any sharp edge will act as a stress raiser and is similar to the effect of a sharp angle in, for example, a shelf bracket where the point of failure, if the bracket is overloaded, will usually be in the sharp corner because that is where the stress is concentrated (see illustration 14). (Picture courtesy of hawkridgesys.com)

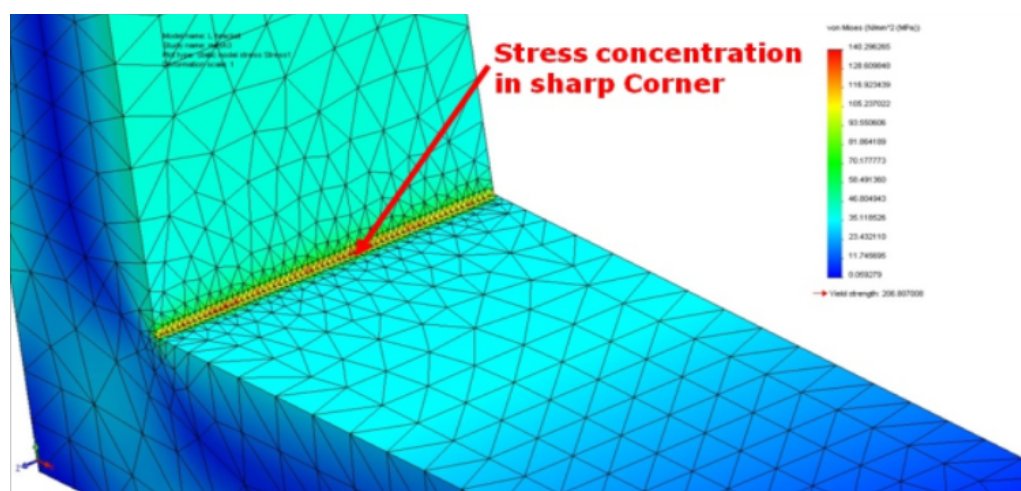


Illustration 14: Concentration of Stress in Sharp Corner

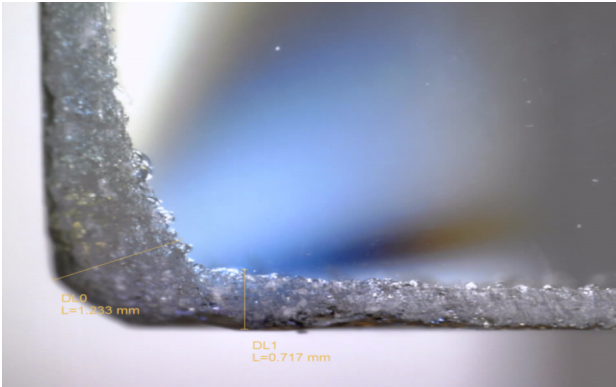
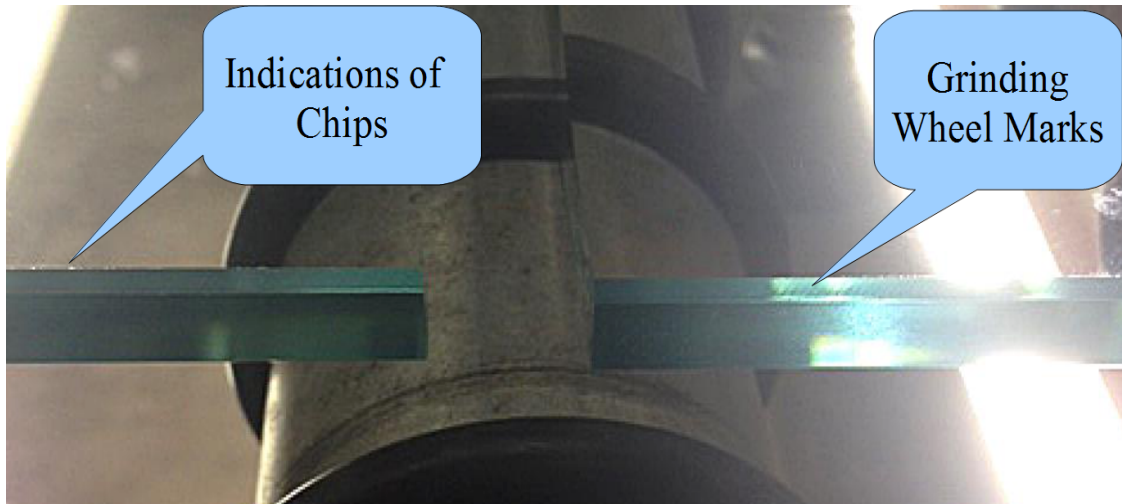


Illustration 15: Poor Edgework Example



Illustration 16: Good Edgework Example



The above picture shows a 12mm glass that cracked in the quench because of slight chips in the edge of the polishing. Glint from the chips and wheel marks can be clearly seen. Slowing down the speed and reducing the pressure of the polishing wheels stopped the chips and subsequent quench breakages.

Arrising (seaming) the glass edges is carried out by abrasive belts. The best system is where the belts are wet as this helps keep the glass edge cool and avoids overheating the edge which can produce fractures that will cause problems later in the quenching. In either case, wet or dry, the belts should be changed regularly to make sure they are not worn or producing flaws at the glass edge.

The Tempering Process.

The tempering process is a very simple process, just heat the glass up to well above the *transition temperature*, maintain the glass optically flat, or form it to a shape if required, then uniformly cool it so that the temperatures of the top and bottom surfaces are equal, and lower than the temperature at the centre plane of the glass, as it cools to below the *strain temperature*, then cool it down to ambient temperature.

That is the 'sum total' of what a good tempering system does!

However, the following has to be achieved in order to obtain good quality tempered glass:

- Very uniform temperature in the glass as it exits the furnace and enters the quench.

- Temperature well above the *Transition Point* (567°C)

- Temperature well below the *Softening Point* (710°C)

- Keep the glass optically flat whilst soft (or form it if required)

- Transfer it to a quench without losing too much temperature

- Uniformly cool it at a controlled rate to the *Transition Point* (567°C)

- Maintain the cooling rate until well below the *Strain Point* (510°C)

- Cool it down to a handling temperature.

The Importance of a Trained Operator

Variations in glass thickness (4mm glass is usually down around 3.85mm) and glass composition (Glaverbel glass is a white low iron glass compared to a Pilkington float glass which is greener) means that they will heat at slightly different rates, and provide different stress levels for the same temperature differences. The operator will need to trim the 'theoretical' conditions to suit the actual glasses being processed. The quality of edge-work will also affect the losses in the quench, in that poor edge work will need to be processed at higher temperatures in order to survive the transient stresses in the quench. So having an operator that fully understands the tempering process is necessary to achieve the maximum output from the system.

Heating The Glass

When a cold glass is put into a hot furnace the **rate of heat energy** that the glass absorbs is proportional to the **difference in temperature** between the furnace and the glass. As the glass heats up, the temperature difference reduces so the energy transfer rate reduces. This produces a heating curve which is exponential. The great thing about an exponential curve is that the shape of the curve is known, it does not alter if the aiming point is constant, and any point along the curve can be easily calculated. The curve is plotted mathematically by the formula $y = (1 - e^{-k})$ and is shown by the red line in illustration 17.

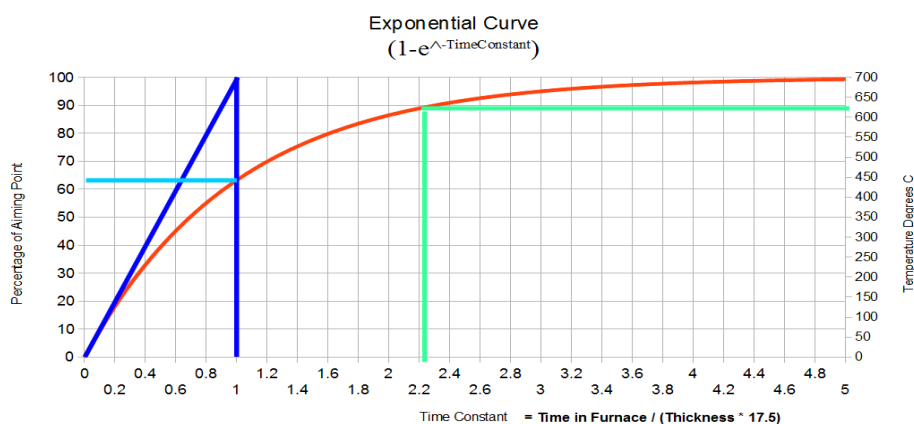


Illustration 17: Exponential Heating Curve

If the initial heating rate is projected by a straight line to the aiming (furnace) temperature, and a vertical line is dropped from this point to the time (x) axis (dark blue lines), the point at which it intersects the axis is known as the *time constant* ($k = 1$) and the temperature value (y axis) at this time (light blue line) will always be 63.2% of the aiming value. (See illustration 17).

When the value of k equals 5 (five time constants) the temperature will be 99.3% of the aiming temperature.

It will be seen later how this information can be used to help decide the furnace parameters when trying to process difficult glasses, for example, large square thin glasses that will tend to go bi-stable on normal furnace settings.

The *time constant* is equal to the time in the furnace divided by the glass thickness and then divided by a number applicable to the type of furnace and glass. For a radiant furnace processing clear glass this number is about 17.6.

Time constant (k) = Time in furnace (seconds) / (Glass thickness (mm) x 17.6 (radiant furnace))

As a body tinted glass absorbs radiation faster than a clear glass, the number is about 16.

A hard coated glass in a radiation furnace does not absorb the radiation well, therefore the number is about 25.

For a full convection furnace processing either clear or coated glass the number is about 12.5.

Example: Using the graph above, the green lines show that to exit **any** thickness of glass at around 625°C from **any** type of furnace set to 700°C we require a time constant of about 2.22.

Rearranging the formula to give: Time in Furnace = Time Constant x Glass Thickness x 17.6

For 4mm glass: Time in Furnace = 2.22 x 4 x 17.6 = 156 seconds

For 10mm glass = 2.22 x 10 x 17.6 = 390 seconds

For 4mm glass in a full forced convection furnace:

Time in furnace = 2.22 x 4 x 12.5 = 111 seconds. So an FCH furnace would normally be run at a lower temperature of around 680°C, to give 120 seconds heating time for 4mm glass

However, the really useful information from this graph is that it illustrates that the longer the glass is in the furnace, the slower the rate of heating, and therefore the greater the chance of a glass being uniformly heated. If the furnace is set to, say, 630°C and the glass left in for 5 time constants (350 seconds for 4mm glass) it would guarantee that the glass would be $630 \times 99.3\% = 625^\circ\text{C}$.

An alternative way of using this information is to find the temperature of the glass at any time from the following equation, or for the rate of heating as it leaves the furnace (make T_{start} = the exit temperature and time = 1 second)

$$T_{\text{Glass}} = (T_{\text{furnace}} - T_{\text{start}}) \times (1 - e^{-k}) + T_{\text{start}}$$

Where $k = \text{Time in furnace (seconds)} / (\text{Glass thickness (mm)} \times 17.6 \text{ (for a radiant furnace) or } 12.5 \text{ (for a convection furnace)})$

Worked Examples (4mm glass, 160 seconds heating, 700°C radiant furnace, 15°C ambient temperature):

Exit Temperature: $T_{\text{glass}} = (700 - 15) \times (1 - 2.71828^{-(160 / 4 \text{ mm} / 17.6)}) + 15 = 629.4 \text{ degrees C}$

Rate at Exit: $T_{\text{rate}} = (700 - 629) \times (1 - 2.71828^{-(1 / 4 \text{ mm} / 17.6)}) + 0 = 1.0014 \text{ degrees C / second}$

By dropping the furnace temperature to 665°C and exiting at 620°C after 188 seconds the rate of heating is reduced to just 0.635 deg/sec which would give a much better chance of uniformly heated glass for a loss of just 20% production.

However, it is important to remember that a furnace has a significant thermal mass and therefore an inertia against quickly altering its temperature. If an operator calls up a different temperature profile, then at least half an hour should be allowed for the furnace to stabilise at the new temperature before starting production on the new settings. For this reason operators should be discouraged from using different temperature profiles to process different glasses. The operator should simply adjust heating time, aspirator pressures (or hot fan speeds) and quench pressures. Remember, any cold object put into a hot chamber will eventually heat up to that chamber's temperature, so playing with the temperature profile for different glasses can be counter productive. If it is found absolutely necessary to produce some (difficult) glasses with a different furnace temperature, efforts should be made to batch the glasses arriving at the furnace to give extended runs on the different settings to avoid problems with instability in the heater.

It is also very important that the furnace temperature (the aiming point for the glass temperature) is constant and does not drop significantly when a load of cold glass is put into it. For this reason a powerful heater with significant thermal inertia is beneficial compared to a lightweight furnace with marginal installed power (see Appendix A).

What is Happening to the Glass as it is Heated

Energy absorption

When the glass enters the furnace it absorbs energy from the furnace chamber in three ways.

1. Infrared radiation at the surface of the glass, and a little way into the glass.
2. Conduction on the bottom glass surface where it is in contact with the ceramic rolls.
3. Conduction from the air mass inside the furnace if it is being forcibly directed onto the glass surfaces from:
 - a. Compressed air aspirators augmenting the heating in a standard radiation furnace.
 - b. Air recirculation fans driving the air mass in a forced convection furnace.

The inside of the furnace at a constant temperature can be considered as a *black body* radiant chamber and as such the frequency of the radiation is determined by the temperature. Using *Wien's Displacement Law* (which effectively states that the wavelength multiplied by the temperature in Kelvin, equals a constant of 2897µm K) the wavelength can be calculated from $\lambda T = 2897 \mu\text{m K}$ or $\lambda = 2897/T$

For a stable furnace at 700°C (973°K) the wavelength is therefore approximately 2.977µm (2977nm).

From the transmission graph below it can be seen that soda-lime glass absorbs this wavelength quite well, in other words the infra-red energy at furnace temperatures does not pass through, or into the middle of the glass.

Note: Infrared energy from the sun is at a much higher frequency (typically 498nm) because the source temperature is around 5778 K and it will therefore pass through the glass, which is why you can sense the temperature of sunlight through a car or house window. This also explains why a greenhouse works so well, the high frequency infra-red from sunlight passes through the glass and heats the components inside the greenhouse which in turn re-radiate infra-red energy at a much lower frequency which does not then pass back out through the glass.

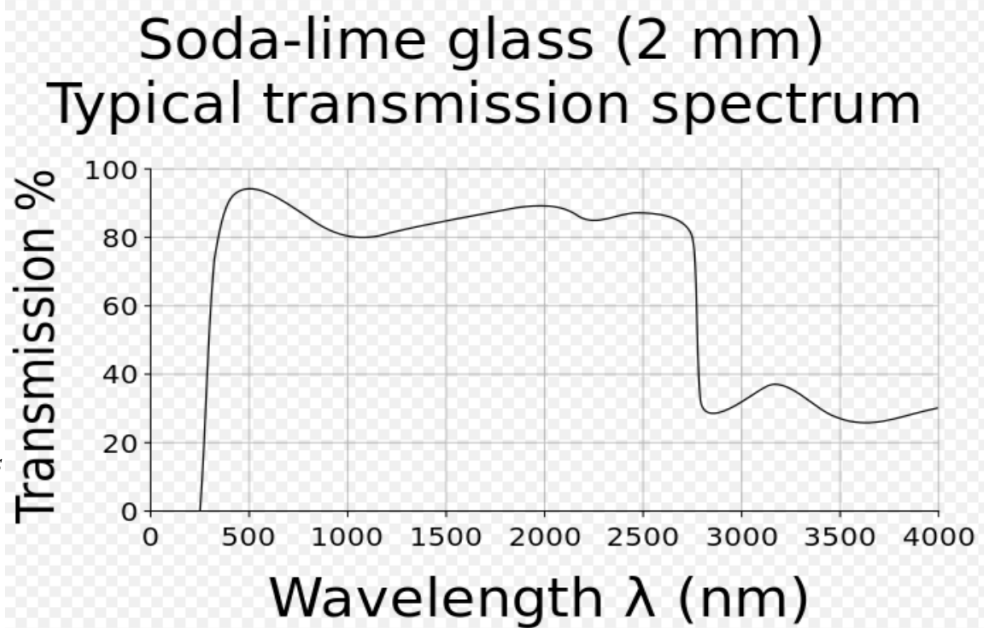


Illustration 18: Glass Transmission Spectrum (source Wikipedia)

Initially when the glass enters the furnace the surfaces will become considerably hotter than the middle, due to the absorption of the IR radiation at and just inside the surfaces. Therefore, the middle of the glass will really only heat up by conduction of the heat from the surfaces.

Note: With solar panel manufacturers requiring glass that is very transparent to solar energy for maximum efficiency from the panel, there is now an abundance of low iron and water-white glasses which do not absorb the furnace IR as well as 'normal' glasses. The time in the furnace has to be extended for these glasses to be at the correct temperature for quenching. Also the coefficient of expansion may be reduced so increase in the quench pressures may be required.

Stress in glass during Heating & Quenching

Illustration 19 to the right shows the temperature and stress situation just 21 seconds into heating 4mm glass. The surfaces are at 219.5°C and the middle is at 155.2°C (a temperature difference of 64.3°C). This temperature difference creates a total stress in the glass of around 47MPa (compressive stress in the surfaces and tension stress in the centre) similar to, but lower than, the finished tempering stresses.

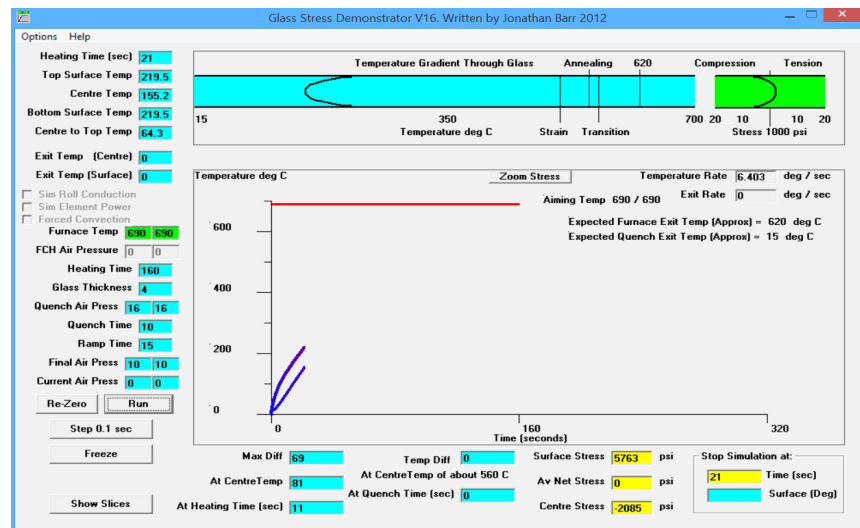


Illustration 19: 4mm Glass Heating after just 21 seconds

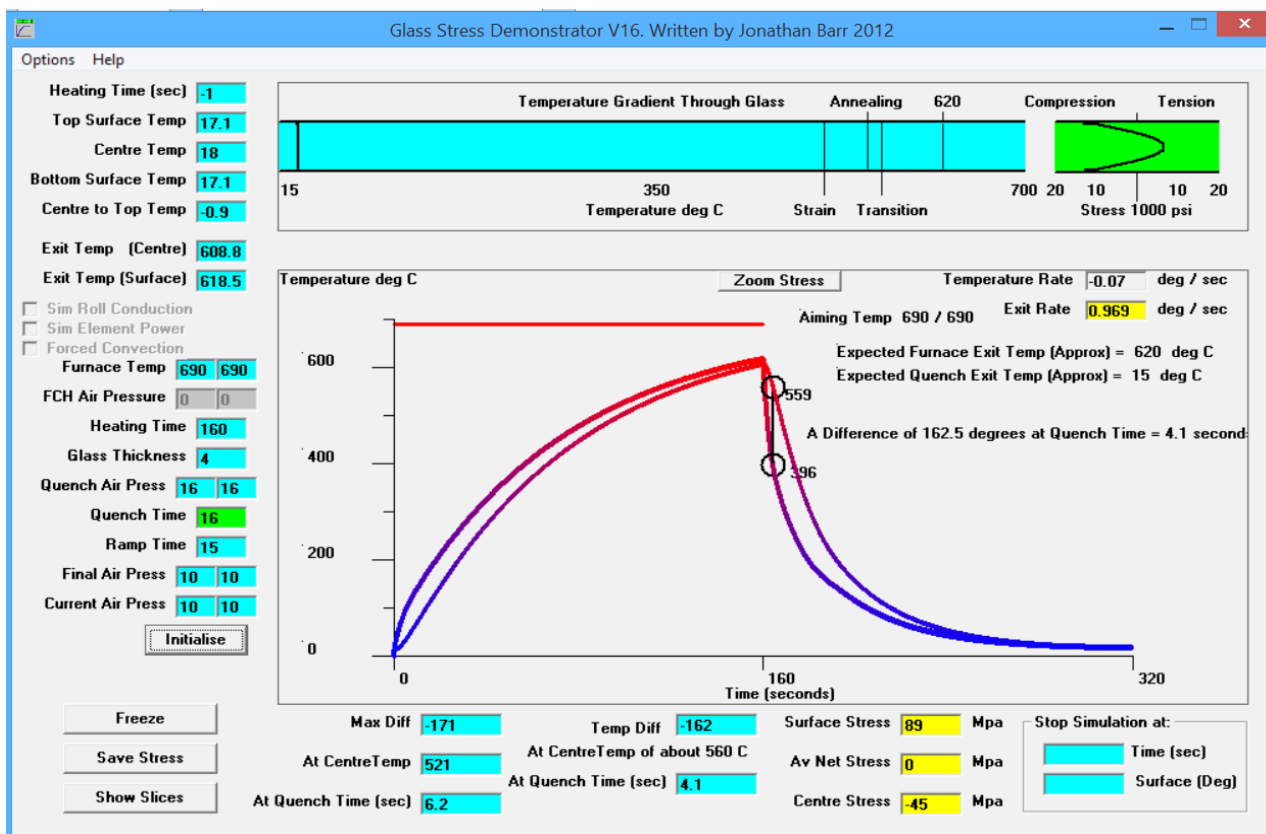


Illustration 20: 4mm Glass Full Heating and Quenching Cycle

Illustration 20 shows graphically the full heating and quenching cycle, and how the centre temperature lags the surface temperature. Note that at the exit from the furnace the centre of the glass was almost 10 degrees cooler than the surfaces and this difference has to be overcome by the quenching. The faster you heat the glass the greater this difference would be and the more difficult it is for the quenching to achieve the correct temperature difference before the glass becomes solid. Note that when the centre temperature passed down through the *Transition Temperature* 560°C, the difference was 162.5°C but that the maximum difference between surfaces and centre occurred at 521°C, 6.2 seconds into the quenching so, to ensure that the glass is well below the *Strain Temperature* before reducing the quench pressure to a cooling pressure, it is necessary to set a safe quench time to guarantee that the glass temperature is well below *Strain Temperature* and there is no creeping of the stress in the glass.

Generally in the process conditions we tend to set a safe quench time and here a good 'Rule of Thumb' is:

Quench Time = Glass Thickness ^{1.8} e.g.

For 4mm glass Quench Time = 4 ^{1.8} = 12 seconds

For 6mm glass Quench Time = 6 ^{1.8} = 25 seconds

For 10mm glass Quench Time = 10 ^{1.8} = 63 seconds

For 15mm glass Quench Time = 15 ^{1.8} = 131 seconds

If you don't have a calculator handy, squaring the glass thickness is acceptable. (e.g. 100 seconds for 10mm glass).

The temperature gradient in the glass, and the stress it causes during heating and quenching is shown below.

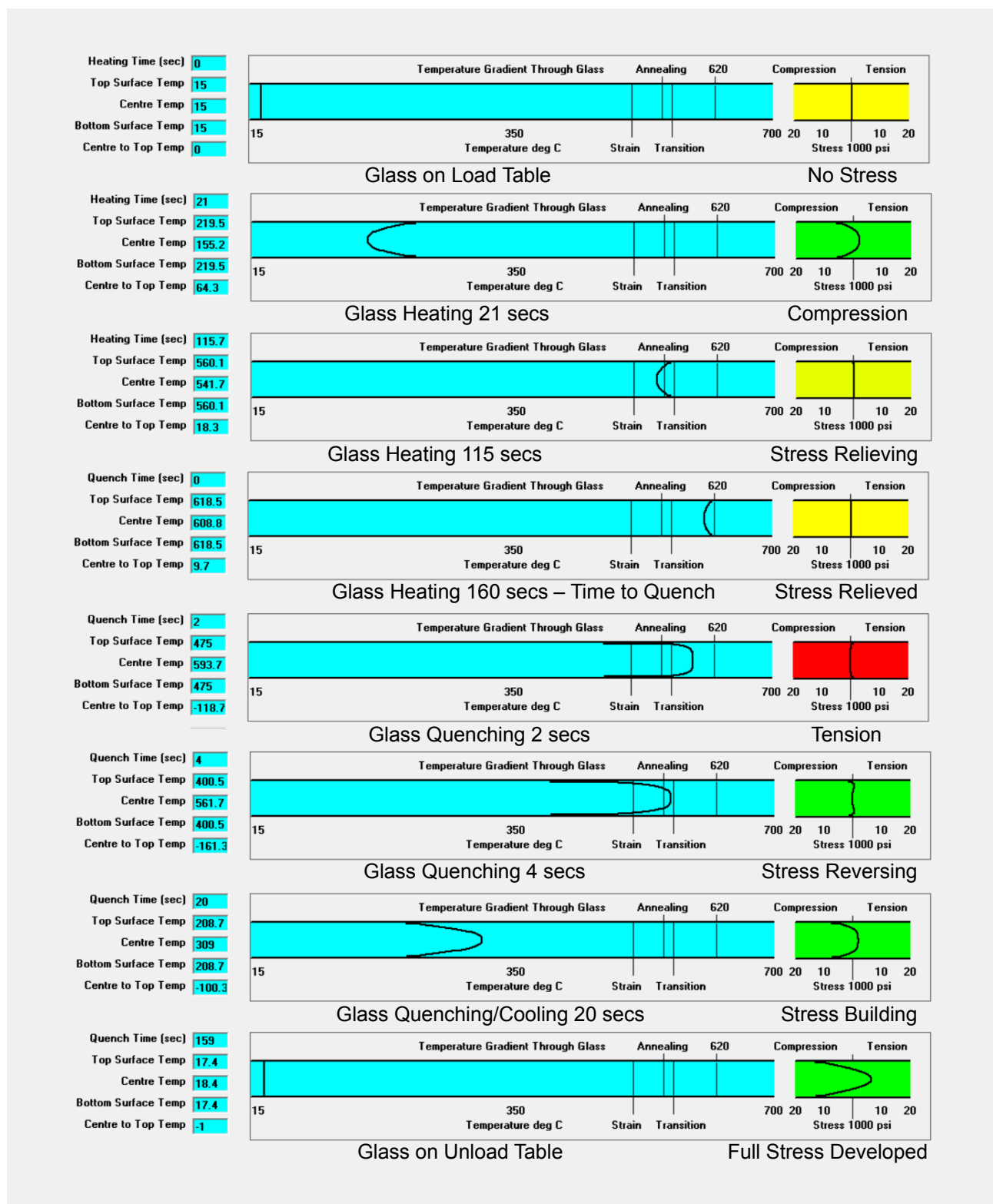


Illustration 21: 4mm Glass Heating & Quenching Sequence

See next page for the description of the above sequence.

Illustration 21 shows the heating and quenching sequence for 4mm glass. Starting from the top trace:

<u>Heating Time</u>	<u>Glass Condition</u>
0	Raw glass on the load table - no stress in the glass.
21	Surfaces expanding faster than the centre – compression in surfaces, tension in the centre.
115.7	As the glass continues heating, the rate of heating reduces (Exponential Curve Illustration 17) and the transient stresses will therefore reduce as the centre temperature catches up with the surfaces. When the surface temperatures go above the annealing temperature the compressive stresses relieve. However the centre is still solid and the tension stress in this centre layer will pull the surfaces, resulting in a slight loss of glass dimension.
<u>Quench Time</u>	<u>Glass Condition</u>
0	Glass is about to enter the quench. All of the glass is well above the transition temperature so there are no stresses remaining in the glass. However, there is a slight difference in temperature between the surfaces and the centre of around 10 degrees.
2	The surfaces are being rapidly cooled by the quench air. They want to contract but the main body of the glass won't let them and so the surfaces are stretched. They are cooler than the centre (and should therefore be shorter) but they are the same length as the centre of the glass. Because they are being stretched as they become solid, the surfaces go into tension and any surface or edge-working flaws will run into the glass and may crack it into large pieces. This is the dangerous time in the quench and the cooler the glass is exited from the furnace (for best optical quality) the greater the transient tension stresses are. This means that the edge-working has to be absolutely first class for the glass to survive. If the central area of the glass is too cool <i>chill cracks</i> can be pulled into the glass which, to the eye, may disappear later as the compressive stresses build up in the surfaces and close the cracks, but in reality they are still there and this is now a weakness in the glass.
4	The stresses now reverse and the surfaces start going into compression.
20	The stresses now increase towards their final value and if any cracks have been pulled into the tension layer at the 2 second point, the glass is likely to explode into small pieces like a normal break pattern as the stresses increase.
159	Glass on the unload table, the temperature is normal throughout the thickness and the full tempering stresses have developed.

The thicker the glass, the less IR energy reaches the centre of the glass so for example 10mm glass will see very large temperature differences between the surfaces and the centre of the glass of around 124°C after 45 seconds and these will create transient stress levels almost equal to the final tempering stresses. As a result of these stresses, if there is a flaw present in the glass, or a corner is damaged during heating, a 10mm (or thicker) glass may break in the furnace and the resultant break pattern (particles) will look as though the glass was tempered.

Also, with thick glass the cooling time is usually insufficient for the temperature of the central region to get right down to ambient temperature. This means that the final stresses will not have completely developed at the unload table and if a glass is deliberately broken to check the break pattern, the glass will have a slightly more open break pattern than if it is left for a while to completely cool down.

Why the glass is bigger if tempered once

Because the surfaces were stretched during the first 2 seconds in the quench the finished glass will actually be bigger than the original raw glass when it was on the load table. Typically there will be a 0.6 to 0.7mm increase in the size of a 1000mm long glass.

Most architectural glass processors will not be aware of this small increase in size but producers of highly stressed industrial glasses, where the manufacturers size tolerances are very tight, will be aware of this problem and will be cutting the raw glass slightly undersize to cater for the growth during tempering.

Why the glass is smaller if tempered a second time

If the glass is processed a second time, it already has the full tempering stress in the glass when it enters the furnace. When the surfaces reach the transition temperature and become plastic, the very high tensile stress in the centre of the glass will pull the glass and squash the surfaces so the glass reduces in size. Although in the quench the surfaces are stretched once again, it is not to the same extent as the squashing during heating. When the glass is back down to ambient temperature a 1000mm long glass will be just over 1mm shorter than when it was put on the load table. This reduction in size will occur every time the glass is re-tempered.

Tests run for me by Ian Hendricks of Cardinal Glass Chehalis Washington USA gave the following results on a 1199.00 mm long 3.1mm thick glass tempered to only 10,000 psi (solar panel back panel). It grew to 1199.77 mm on the first tempering run, and then shrank to 1199.1 mm when re-tempered. Had it been run again it would have reduced in size to about 1198.4 mm. At higher tempering stress levels the initial increase and subsequent reductions in the size would be greater.

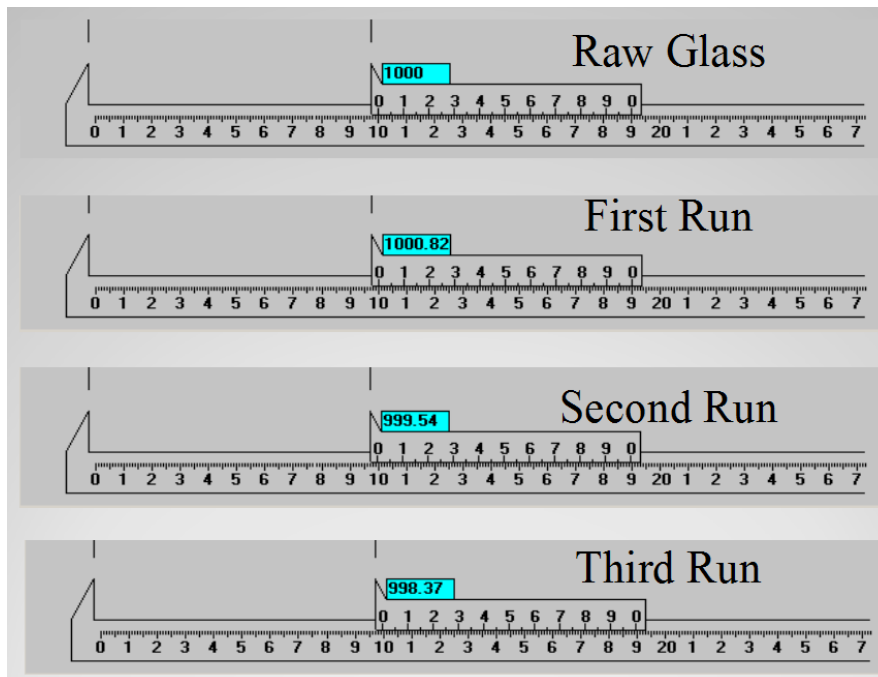
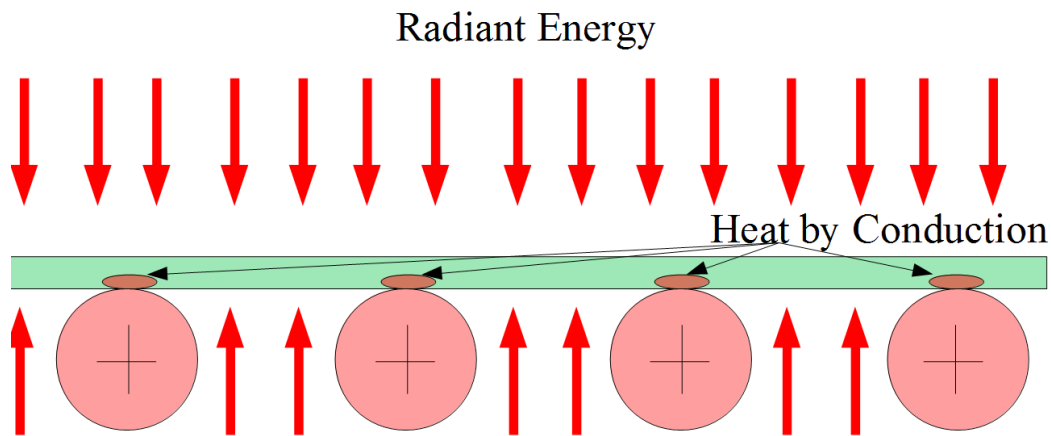


Illustration 22: Examples of Typical Glass Dimension Changes due to Tempering

Re-tempering a glass (maybe because the bow was out of tolerance) means that the transient stresses during heating will add to the existing tempered stresses and therefore there is a danger that the glass will explode in the furnace. For 3 to 6mm glasses the risk is relatively low, but the risk increases with glass thickness. Therefore production management have to weigh up the relative costs of re-cutting a fresh glass versus the cost of stopping and cleaning the furnace if a re-run glass does explode inside the heater.

Problems with obtaining uniform heating

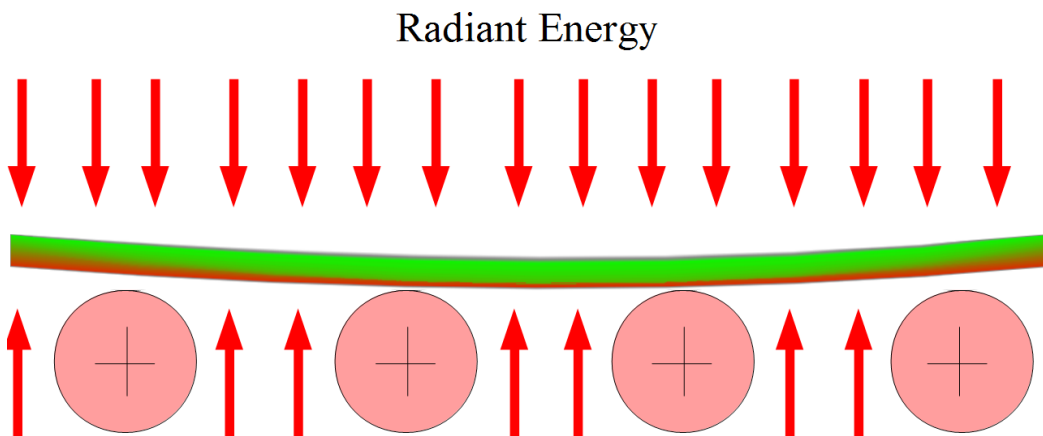
Referring to illustration 21 it can be seen that the temperature difference between surface and centre will cause the surfaces to expand more and go into compression making the glass very strong. However, if extra heat goes into the bottom surface by conduction from the rolls (illustration 23) it means that the lower surface will heat up and expand more quickly than the top surface and therefore become longer. The longer, lower, surface of the glass means that the glass will tend to go into a water holding bow condition (illustration 24). This in turn will concentrate the whole weight of the glass into the central area and can result in point loading (crush) damage to the bottom surface, usually seen as a white haze mark. In severe cases it can result in deformation of the contact area and is seen as an optical defect when objects are viewed through the glass at an acute angle and it is referred to as a *lensing* effect.



Radiant Energy

Illustration 23: Asymmetric Heating

Automotive side windows are checked very closely for this lensing defect to ensure it is not present before being fitted to a vehicle.



Radiant Energy

Illustration 24: Bowing in Furnace

This asymmetric heating is exacerbated when low emissivity coated glass is being processed because the infrared energy is being reflected away by the coated surface. In order to overcome this condition, and the effect of heat by conduction from the rollers, it is necessary to augment the heat input into the upper surface of the glass. This is achieved by forcing the hot furnace air into contact with the surface of the glass by driving it either with compressed air aspirators, or by hot gas fans. The hot air mass coming into contact with the glass will conduct extra heat into the glass. However, because of the temperature (700°C) the air is very thin and does not have much mass (air at 15°C weighs 1.224 Kg/m³ but air at 700°C only weighs 0.362 Kg/m³) so as soon as the air hits the glass it loses temperature and has to be removed and replaced with fresh hot furnace air. Typically, the weight of the air mass that hits the glass surfaces during the heating cycle in a full forced convection heater is about 8 times the weight of the glass, and is provided by fans generating a pressure around 75dPa

Furthermore, using cold compressed air to move the furnace air onto the glass means that the mixed air that hits the glass is not at full furnace temperature (illustration 25), so it is counter productive to use cold compressed air aspirators for longer than about 2/3rds of the heating cycle. Hot (pre-heated) compressed air aspirators and hot gas fans can be used throughout the heating cycle.

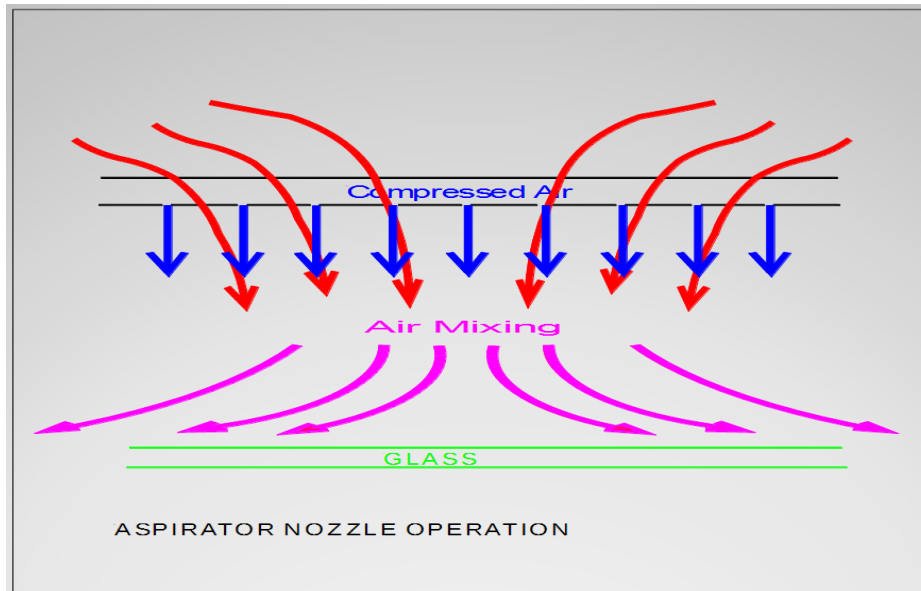
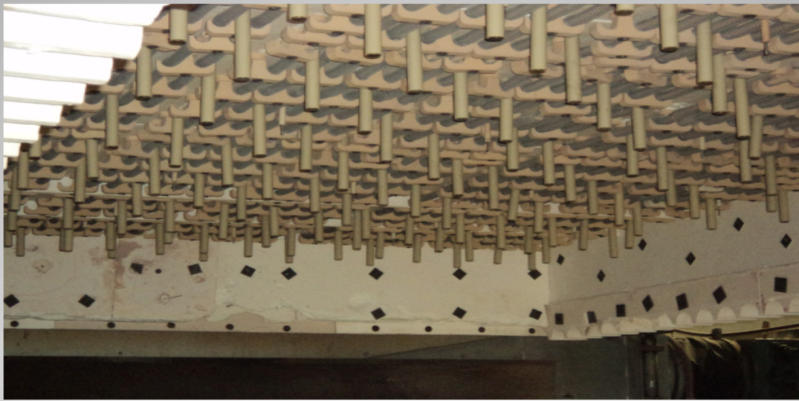


Illustration 25: Cold Compressed Air Aspiration

Smart Air Convection



Glaston 'Vortex Pro' Computer Controlled Aspiration

Illustration 26: Glaston Vortex Pro

There are now smart aspiration systems available which, using a row of closely spaced sensors at the load table, measure the individual glasses in the load as they enter the furnace. This load is then tracked as it oscillates inside the furnace and individual aspirator nozzles are computer controlled with the required pressure and fired as necessary to heat parts of individual glasses. An example of the Glaston smart aspirator system is shown in illustration 26.

A scanning IR camera at the interface between the furnace and the quench is required so that the operator can confirm that the settings are correct and that the glass load has been uniformly heated.

Illustration 27 shows how useful scanning IR cameras are to display badly heated glass loads as they exit the furnace and the picture indicates quite clearly where adjustments to the heating profile are required.

Forced Air Convection

There are two basic methods of heating by forced convection.

One is using gas burners to heat the air, and the other is by blowing the air over electric elements and then on to the glass.

Illustration 28 shows the inlet of a hot-fan located inside the furnace with the outlet feeding a chamber on top of fins. Each fin contains an electric element so the air is heated just before it leaves the fin and is directed onto the glass surface. Illustration 29 shows inside a typical gas fired furnace where the air heated by a flame, and the air is then used to heat the fins before being directed onto the glass surface. In this case the air is losing temperature as it passes down the length of the fin, and in a side-feed fin the temperature at the far end of the fin will be lower than at the entrance to the fin. The advantage of both these configurations is that there is no direct element radiation to the glass, and both systems will heat the glass at a high rate of approximately 30 seconds per mm of glass thickness.

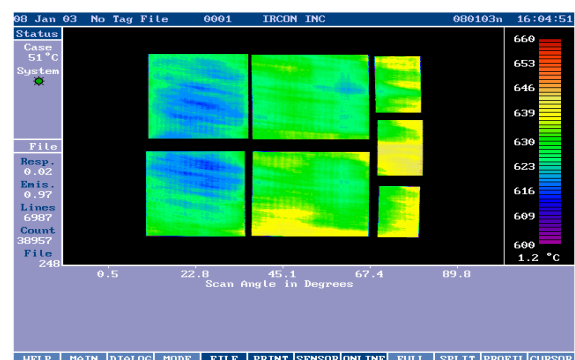


Illustration 27: Picture from a scanning IR camera of a bed of hot glass.

In an electric system, the temperature distribution across the width of the furnace is much better than a gas fired system because the fins are aligned with the direction of glass travel and each fin electrical element is individually controlled. However, the advantage of a gas system is that a much higher power density can be installed compared to an electric system and it is therefore more capable of sustaining continuous full-bed loading. Appendix A shows the instantaneous load on the system when a glass load enters the furnace is very high.



Illustration 28: Electrically Heated Forced Convection



Illustration 29: Typical Gas Fired Forced Convection

A further problem with uniformly heating coated glass is that because the cut edges of the glass are surfaces, and are uncoated, they will absorb more IR radiation than the coated surface area and the periphery of the glass will therefore become hotter (illustration 30). Because the top edges of the coated side are hotter, the net effect of the higher temperature difference between top and bottom at the edges of the glass means that after quenching the edges will tend to curl up giving a 'picture frame' effect around the glass.

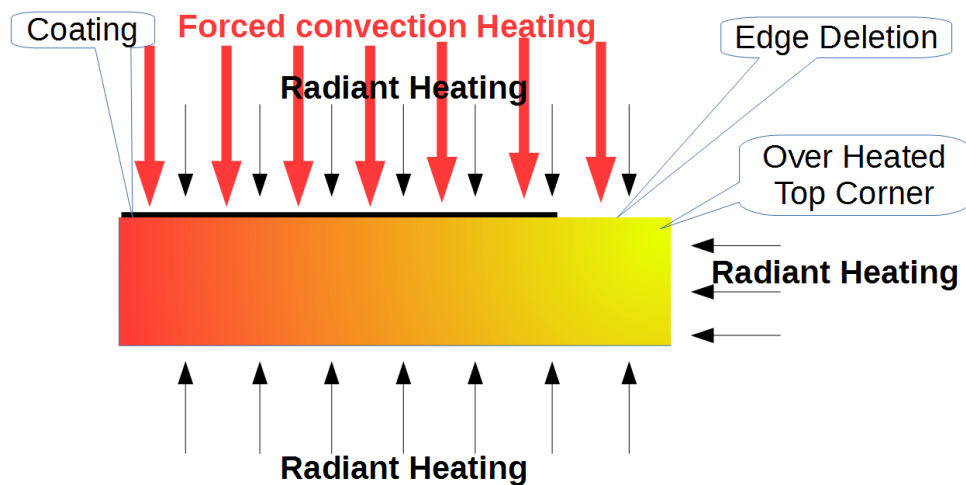


Illustration 30: Non Uniform Heating of Coated Glass

In a batch type of furnace, where the glass oscillates backwards and forwards while heating, the leading and trailing edges are travelling over freshly heated rolls and will become hotter than the central area because the central area of the glass never sees freshly heated rolls. Also, the edges of the glass are surfaces and will absorb infra-red energy so they will become hotter than the central area. The resultant of all this asymmetric heating means that the periphery of the glass will become hotter and therefore, because of expansion, longer than the centre. This extra length has to go somewhere, so the edges will bow into an arc in order to lose the extra length. The bow will actually be in opposite directions on adjacent edges of the glass and it will therefore form a *saddle bow* shape (illustration 31).

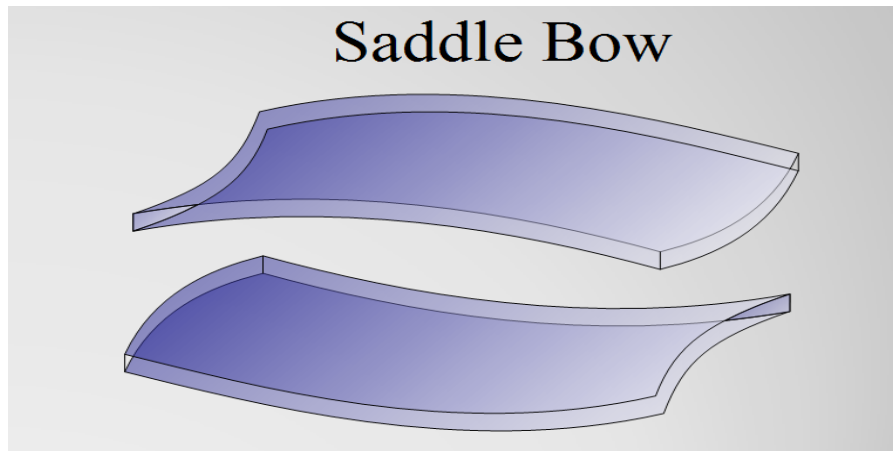


Illustration 31: Saddle Bow

The shape is unstable and in thin glass (3 to 5mm) the edges can easily flip into the opposite direction of bow. If the glass is viewed in the furnace in this condition it can appear a bit like a manta ray moving about on the roll bed. The resultant point loading on the edges of the glass against the rolls can cause marking and, in severe cases, chipping in the middle sections of the lower edges.

Problems heating thick glass

When a large bed of thick glass (10mm and above) enters the furnace, because of the mass of the load, the temperature of the furnace will reduce more than with a load of thinner glass. The PID loops in the temperature control system will start to ramp up the element power levels which, in turn, will radiate at a higher temperature. After about 50 to 60 seconds, depending on the PID loop settings, the elements will be firing at 100% producing a very intense radiation which will hit the surfaces of the glass. The direct radiation from the lower elements in the furnace is shaded by protective floor pans and the ceramic roll bed, and this means that the bottom surface of the glass does not see the same level of intense radiation that the top surface is seeing. The result is that the top surface will heat and expand faster than the lower surface causing the glass to go into a water shedding bow condition. All the weight of the glass is now concentrated out towards the corners which can cause marking and, if the bow is really severe, the corners of the glass will bang into the rolls which can cause chipping (illustration 32). Because of the high stress levels in the glass (compression in the surface and tension in the middle) this chipping can cause flaws to enter the tension layer and the glass can fail inside the furnace with a break pattern that looks like tempered glass.

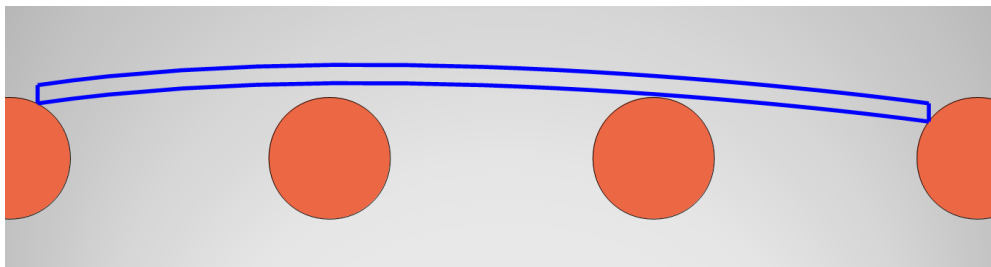


Illustration 32: Cause of Chipped Corners

Different furnace manufactures use various ways of trying to prevent this condition arising and they include:

Shielding the bottom of the upper thermocouples so that the cold glass is not sensed by the thermocouple and this gives a more gentle power response to the elements (the lower thermocouples should not be shielded as they are required to monitor and hopefully maintain the ceramic roll bed temperature constant).

Software to limit the maximum power to the upper elements in the early stages of the heating cycle before raising the limit slowly and allowing the furnace to recover temperature well before the next load enters.

Shielding the upper elements with steel cups to provide a lower frequency (less intense) re-radiated radiation to the glass. Illustration 33 shows the upper section of a Tamglass furnace with the upper elements hidden behind steel plates.

Using Ni-Chrome ribbon elements instead of Kanthal elements because at 100% power Ni-Chrome elements radiate at only about 870°C and Kanthal elements radiate at around 1100°C.



Illustration 33: Upper Elements Shaded by Steel Cups

When processing thick glass, to compensate for the initial roll conduction followed by the upper elements firing hard, the pressure and time setting for aspirators is not easy. Typically a short burst of pressure during index into the furnace and the first oscillation is all that is required as the upper elements will then assist the upper surface heating. However, using the old Mk1 eyeball and looking into the furnace through an open entrance door for the first few minutes or so will usually ascertain if the settings are correct or not. The final check is of course the finished glass on the unload table not showing any visible signs of marking or damage.

Thick glass, oscillating in the heater, will extract significant heat from the rolls. The central area of the roll bed, where the glass covers it continuously, will end up cooler than the entrance and exit areas where the rolls also receive radiation from the upper elements as the glass oscillates clear of the rolls. This results in a cooler central area of the glass and chill cracks can be pulled in the glass when it is stretched during the early part of quenching if it is not hot enough.

Problems with Quenching the Glass

In order to set the temperature difference in the glass while it is in its plastic state (above the *transition temperature*) it is necessary to extract the heat from the surfaces a lot faster than the centre plane of the glass can lose its temperature. This is achieved by blowing cold air at the glass which will conduct the heat away from the surfaces.

Because the centre plane of thin glass will lose its heat much more quickly than with thick glass, thin glass requires a much higher rate of surface cooling than thick glass. In fact the ratio of quench air pressure to glass thickness is approximately proportional to the inverse cube of the difference in thickness (illustration 69). Note from the graph that for 15mm glass and thicker, virtually no air cooling is required because the rate at which the surfaces radiate the heat away is sufficient to set the required temperature difference in the glass before it cools below the *transition temperature*. The only reason to use any air on glass of 15mm or thicker is to control the final bow in the glass and help keep the quench heads cool.

When quenching, the forced air cooling is assisting the natural radiation from the surfaces, and because a low-E coated glass surface has a lower emissivity than an uncoated surface it will not radiate as efficiently. This means that a higher rate of forced cooling (quench air pressure) is required on the coated surface for it to be at the same temperature as the uncoated surface as the main body of the glass passes down through the *Strain Point* and becomes solid.

With thin glass (3mm & 4mm) the large volume of high velocity air can cause the glasses to be flipped or even lifted off the quench rolls if the upper to lower nozzle alignment is not perfect.

A further problem is due to the air flow slowing right down (to near stationary) between the lower glass surface and where the glass contacts the quench rollers. In 1738 Bernoulli discovered that in a fluid stream the total pressure was constant and consisted of a static pressure and a dynamic pressure $P_{\text{total}} = P_{\text{static}} + P_{\text{dynamic}}$

The dynamic pressure is $P_{\text{dynamic}} = 0.5 \times \rho \times \text{velocity}^2$ so when the velocity of the air jet reduces, the dynamic pressure reduces to the square of the velocity drop. This means that to keep the total pressure constant, the static pressure increases proportional to the square of the velocity drop and this increase in static air pressure below the glass will tend to lift thin glass off the roll bed. Most manufacturers have some form of blocking (roll mimic) in the upper quench heads to mimic the effect of the quench rolls in an attempt to keep the glass on the roll bed. GT Lambert tell me that on a couple of 3mm systems they even had a set of driven rolls mounted above the glass in the quench to give perfect aerodynamic symmetry.

The best design of the roll mimic is such that air can escape between the mimic and the side of the fin (shown in **Green**) but that it has an inverted 'V' profile as shown below.

The theory is that the inverted 'V' traps some of the air travelling off the glass (shown in **RED**) and slows it down to zero. This reduction of velocity (Dynamic Pressure) increases the Static Pressure (shown in **Blue**) and helps hold the glass down against the quench roller.

Another problem in very wide quenches is that the air release from the central area is not as good as in the areas near the edges of the quench. If the air cannot release cleanly then there is a resistance to the fresh air issuing from the nozzles and the cooling effect will be reduced, leading to non-uniform quenching of large sheets and possible distortion and poor break pattern in the central area of the glass if it is subsequently broken.

Different Types of Quench Characteristics

There are many different types of quenches but all of them set a temperature difference in the glass by extracting heat from the glass surface using an air mass driven into contact with the glass.

The air is directed onto the glass by nozzles which can vary from complex 'Trumpet Tubes' to simple holes punched into sheet steel. Air issuing from any type of hole or proper nozzle requires time/distance for the jet of air to stabilise into a smooth (efficient) stream of air. Generally, the distance required is between 6 and 8 nozzle diameters and this is almost regardless of the diameter or smoothness of the internal bore of the nozzle (see illustration 34)

This distance (determined by the nozzle diameter) is what determines the operating distance of the quench head from the glass. For the older style quench heads, with large nozzle diameters (6 to 8mm), this means that the heads operate around 50mm from the glass surface giving plenty of room to view the glass during quenching and get a breaker pole in to clear broken glass. Personally I prefer this type of quench as it is more robust for factory conditions and relatively insensitive to small errors in the operating distance from the glass.

The best type I ever worked with was a Glasstech 'trumpet tube' quench. It operated about 48mm from glass surface and had tubes angled 22 degrees upstream and downstream. The yield was extremely good and it was excellent at producing glass to automotive and the French (SNCF) railway standards. The only disadvantage of this quench was the cost of manufacturing it.

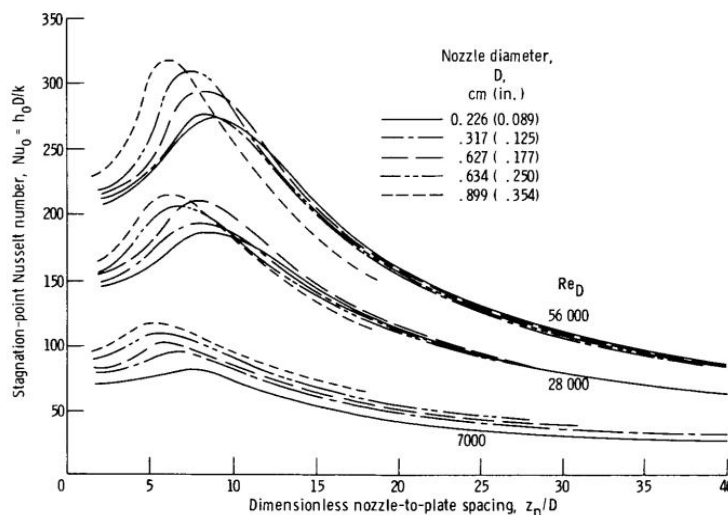
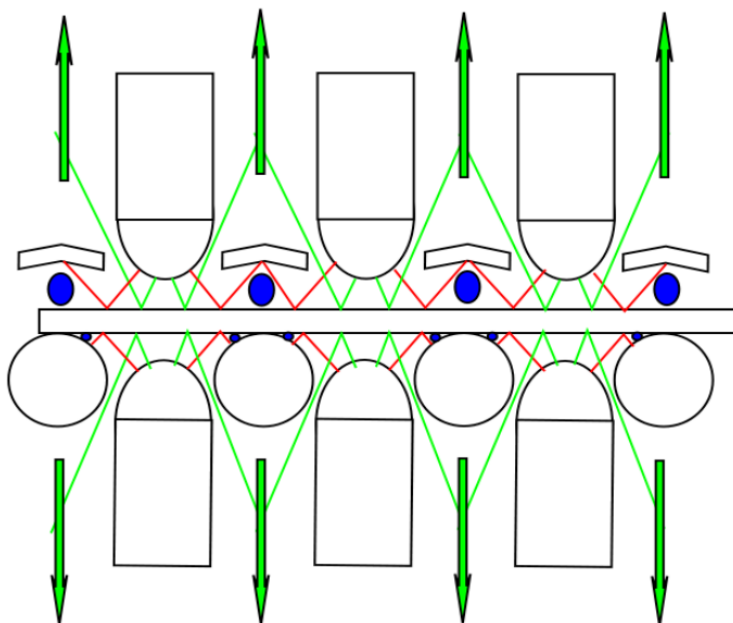


Figure 3. - Correlation of heat-transfer coefficient at stagnation point of a jet. (From ref. 16.)

Illustration 34: Nozzle Efficiency versus Distance

The newer, 'Hi Efficiency' quenches have many small holes punched into sheet steel formed into a curve. Because of the small diameter holes they have to operate very close to the glass, typically 10mm away from the surface in order to be efficient. This means that the upper head must be adjusted up and down for different glass thicknesses, and there is no room to see into the quench, and when glass does break the upper head must be lifted clear in order to access and clear the broken glass.

Additionally, the fins are quite broad and reduce the clearance between the quench rolls and the fins causing broken glass to become trapped until the lower head is dropped down. Any slight error in head height becomes a significant percentage of the operating distance, and when processing thick glass (8mm & 10mm) to heat strengthened standards the very low airflow through the head and close proximity to the hot glass causes the centre of the upper heads to distort downwards into the glass.

A further disadvantage with the close proximity heads is that with 3mm glass the rear glasses in a load (on an oscillating furnace) will be prone to breaking. This is due to the fact that when the trailing glasses leave the furnace they only travel a very short distance before stopping for the conveyor reversal. As they stop they are still very hot and the very intense cooling directly adjacent to the nozzles alongside the areas not being cooled rapidly (because of the gap between the fins) causes large differential contraction rates which will result in the glass cracking. The glasses at the front of the load will have cooled considerably while they travelled down the quench and are not subjected to these same transient stresses as the rear of the load when the load stops to reverse.

The large gap between fins also means that they are not suitable for processing 3mm glass to automotive standards which requires a uniform dot matrix pattern of high stress points to be formed in the glass during the first seconds of quench.

As may be surmised from the above statements, I am not a fan of these 'High Efficiency' quench heads, however, they are very efficient, taking around half the power compared to the old types of quenches.

Development of Stress in the Glass

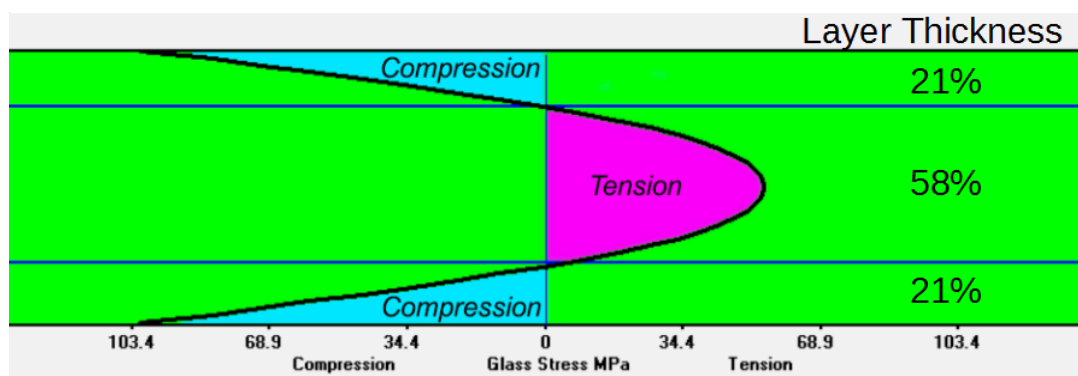


Illustration 35: Profile of Stress in Tempered Glass

The stress imparted into the glass during the tempering process is a result of the stretching of the surfaces during the first stages of quenching and the differential contraction due to the non-uniform temperature through the thickness of the glass as it cooled down through the *strain point*. Initially in the quenching, the surfaces are being cooled rapidly compared to the centre of the glass and the temperature gradient through the thickness approximates to a parabolic curve. As the glass solidifies and then cools down to ambient temperature the contraction of the hot centre (compared to the cooler surfaces) will try and compress the surfaces. The surfaces will resist this contraction and in turn cause the centre to go into tension. These two opposing forces will balance each other and therefore the area of the tension layer will equal the two areas of the compression layers (see illustration 35). Due to the parabolic shape of the curve, this results in the surface compressive forces being approximately twice the value of the centre tension stress.

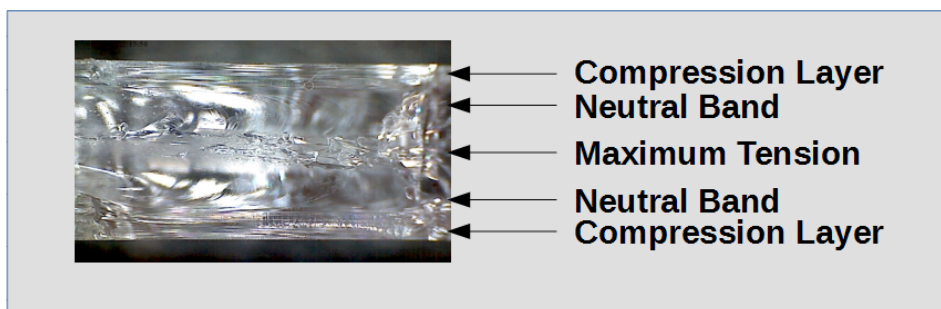


Illustration 36: Cross Section Through Tempered Glass Particle

The 'surfaces' of the tension layer are buried within the glass at a depth of approximately one sixth of the glass thickness. This 'surface' is a perfect surface in that there are no micro-cracks present and therefore the glass should not fail even though the tension far exceeds the level that would normally break raw glass.

However, if a flaw is introduced into this tension layer (by a centre punch, Nickel Sulfide particle, inclusion, etc.) the tension force will cause the glass to fail as discussed below.

Failure of Tempered Glass

When a flaw is introduced into the tension layer the stress in the glass releases a shock wave that radiates out from the point of the flaw. A shock wave in a solid will travel at a very high speed called V_{shear}

$$V_{\text{shear}} = \sqrt{(\text{Shear Modulus of glass} / \text{Density of glass})} = \sqrt{(28.7 \text{ Gpa} / 2500 \text{ Kg/m}^3)} = 3387 \text{ m/sec}$$

Cracks will accelerate and try to follow the shock wave radiating out from the failure point, but high speed photography (watch the YouTube by 'Smarter Every Day':- [Prince Rupert Drops](#) video) has shown that as the crack speed reaches approximately half of the V_{shear} speed the cracks bifurcate. In doing so energy is taken and the crack speed reduces because the cracks are forming new surfaces. The tension stress in the glass accelerates the crack again, and then again at half V_{shear} speed the cracks bifurcate once more. The higher the tension stress in the glass, the faster the cracks accelerate and the earlier the bifurcation occurs, resulting in smaller particles so the fracture front average speed of about 1680 m/sec is around half of V_{shear} . The pictures below (*courtesy of Stan Joehlin Inc.*) show the resultant fracture pattern of two different stress levels. In the 9800 psi picture it can be seen that the cracks have travelled a long way before reaching half V_{shear} and bifurcating.

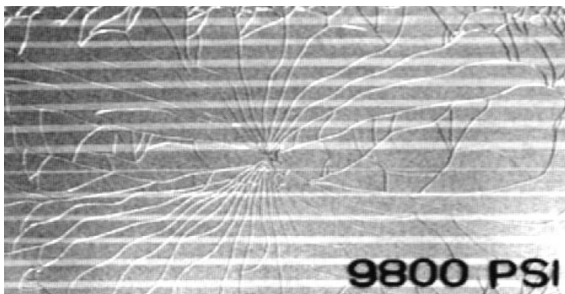


Illustration 38: Break Pattern at 9800 psi

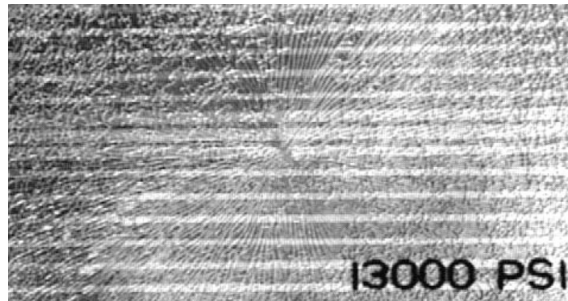


Illustration 37: Break Pattern at 13000 psi

The phenomenon of the crack being accelerated by the tension stress (and not the compressive stress) explains why chemically toughened glass does not break into small pieces (a break pattern) when it is broken and is therefore not considered a safety product. With chemically toughened glass the glass is immersed in a hot potassium salt bath and potassium ions are infused into the surface crowding it. The result of this crowding is to cause high compressive stresses in a very thin surface layer of the glass. This puts the centre into tension, but because of the thin depth, the two areas of surface compression are very small and the tension force needed to balance the compression force is very low (illustration 39) This very low tension is insufficient to accelerate cracks to a speed where bifurcation occurs and the glass therefore breaks like raw glass.

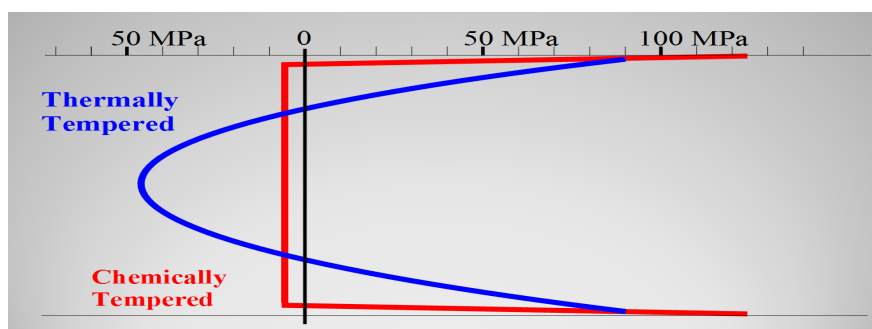


Illustration 39: Stress in Thermally & Chemically Toughened Glass

Test Breaking a Tempered Glass

The European Standard (EN 12150) defines the size of glass that has to be tested as 360mm x 1100mm. It is tested by fracturing it with a centre punch 13mm in and halfway down the long edge.

This size has been chosen because the aspect ratio of the glass will cause two areas of larger particles to occur if the stress in the glass is marginal to produce the minimum pass level of 40 particles in a square 5cm x 5cm. The reason for these two areas is as follows.

Illustration 40 shows the shock wave (travelling at 3387m/s) reflecting off the far inside edge of the glass after about 1.6 milliseconds.

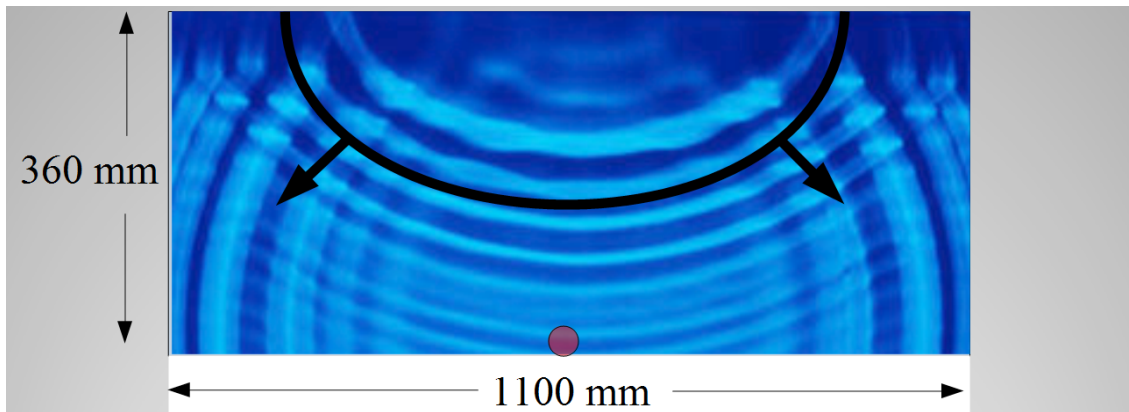


Illustration 40: Shock Wave Reflecting Off Far Inside Edge (3387m/sec)

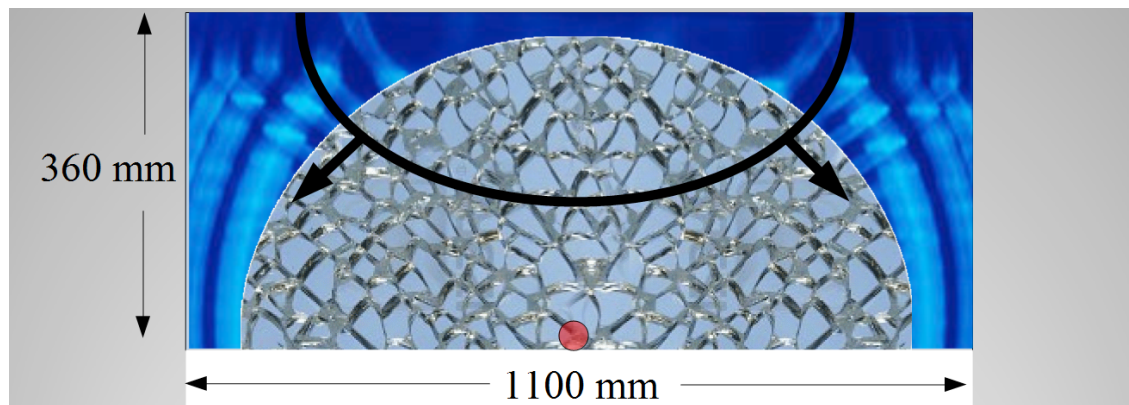


Illustration 41: Fracture Front Radiating Outwards (1680 m/sec)

Illustration 41 shows the travel of the fracture front after about 1.6 milliseconds (half the speed of the shock wave).

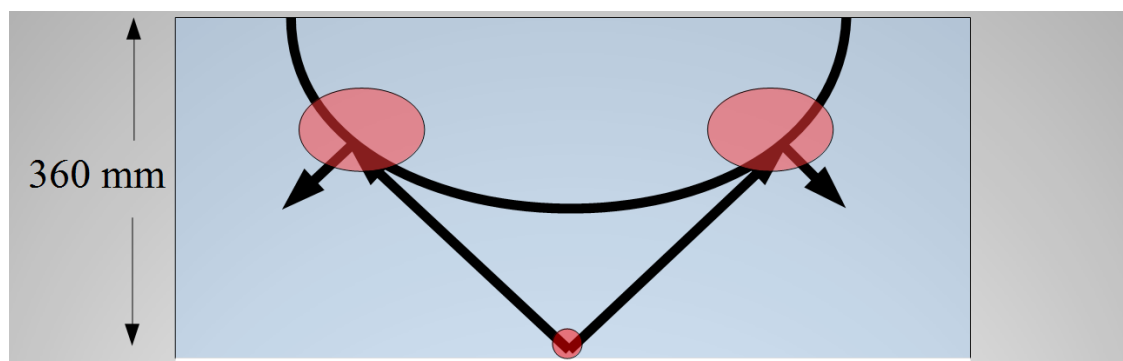


Illustration 42: Interaction between Shock Wave and Fracture Front

Illustration 42 shows that the shock wave travel direction is 90 degrees to the direction of the fracture front when the two meet. This interaction modifies the way the fracture front develops and if the tension stress in the glass is not high

enough to accelerate the crack quickly through the shock wave, the resultant break pattern will open up in the area where these two forces meet.

If a glass is broken from the corner, this shock-wave/fracture-front interaction at 90 degrees does not occur and the break pattern should be very uniform even at marginal stress levels. Breaking the glass from a corner will therefore show any problems with the heating or quenching process because the resultant break pattern is entirely due to the stresses in the glass, so if a non uniform pattern is observed when the glass is broken from a corner, then it is due to either non-uniform heating or non-uniform quenching producing variations in the stress levels in the glass.

Glass Testing by Double Tyre Impactor & 4 Point Bend Tester.

If sample glasses pass the centre punch test described above, then full size patio door glasses (1938mm x 876mm) are subjected to the 'Double Tyre Impactor' test called up by EN 12600 (illustration 43).

In this test the glass is clamped in a frame and the double tyre impactor is swung into the glass. To pass the test, either the glass must not break or, if it does, it must break 'safely'.

Note: The equivalent American safety standard is ANSI Z-97 and in place of the 'Double Tyre Impactor' a 100 pound leather clad lead shot bag is swung into the glass simulating a child's head impacting the glass at 15mph.

'Safely' is defined as the ten largest particles weighing less than 645 cm² (10 in²) of the original glass material.



Illustration 43: Double Tyre Impactor Test Rig

AX Building Glass Tester



Illustration 44: 4 Point Glass Tester

The failure mode of the glass in these tests is very different from the centre punch test because in the Double Tyre Impactor test, the weight swinging into the glass distorts the glass into a bow. The surface of the glass away from the weight becomes stretched and goes into tension. If the tension is sufficient for the surface micro cracks to migrate into the glass, then the glass will fail.

The fact that one surface has gone into tension (the other surface will have increased slightly in compressive stress) means that the centre tension layer in the region of the impact (which is what will accelerate the cracks) will have altered and the particle size will not be the same as those obtained from the centre punch test.

Similarly, for building glass, there is another destructive test called up by EN 1288-3 and it is called the 4 Point Bend Test (illustration 44). Here the glass is supported on 4 points and then bent under load until it fails. The force required to break the glass is recorded by the testing rig. In order to pass the test the tempered glass needs to have at least 90 MPa (13200 psi) surface compression.

Heat Strengthened Glass and Fire Rated Glass

When a fully tempered glass fails, the particle count is more than 40 particles in a square 50mm x 50mm. The European standard for Heat Strengthened glass is that there should be no particles that can fall out of a frame, so all cracks should go to the edge of the glass. The picture to the right shows a glass that is heat strengthened to USA standards but would fail the European standards because there are islands that could fall out.



Illustration 45: Heat Strengthened Glass (USA)

To get the lower levels of stress of around 48MPa (7000 psi) compared to a fully tempered glass requires a reduction in the quench pressure used. Typically about 2/10ths of the normal tempering pressure is required (see illustration 47). However small variations in quench pressure or glass exit temperature will cause significant changes in the final stress level, and the thicker the glass the more difficult it is to control. It is not normal for glass thicker than 10mm to be processed to Heat Strengthened standards.

For a Fire Rated tempered glass, for example Superlite 1XL and Pyroswiss which have 20 minute ratings, the glass must be tempered to very high stress levels of around 138 MPa (20,000 psi) and the resultant break pattern will be 200+ particles in a 50mm x 50mm square. To achieve these levels of compression in the surface requires extremely high rates of quenching so the transient stresses in the first few seconds of quenching will be extremely high and the glass must have all edges fully polished as glass with arised edges would simply breakup in the quench.



Illustration 46: Fire Rated (Super Tempered) Glass

The illustration 47 shows the amount the quench pressure needs to be changed from normal to increase or decrease the stress in the glass. For example processing 6mm super tempered glass to 138MPa requires about 4.5 times the normal 6mm quench pressure, which would be higher than normal (full temper) 4mm pressures!

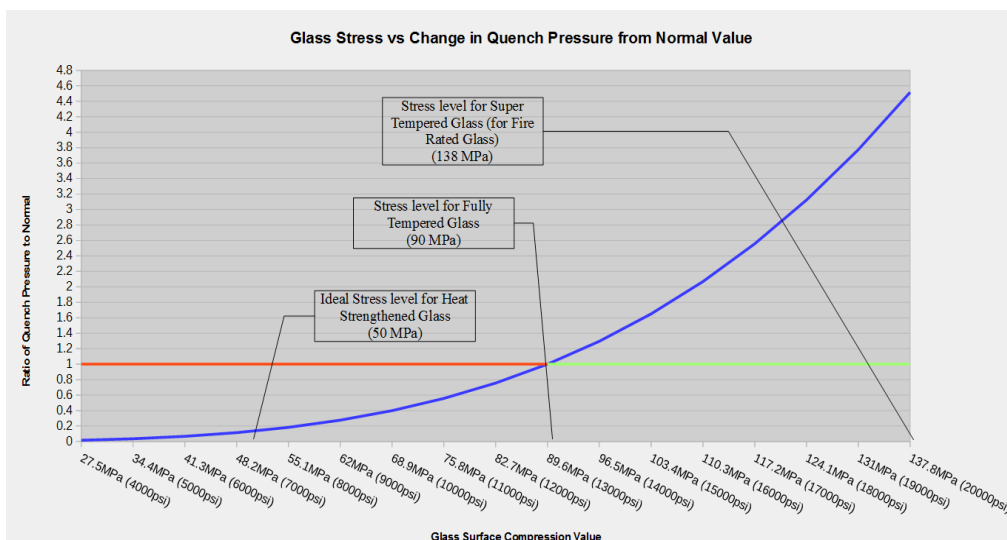


Illustration 47: Glass Stress versus Quench Pressure Change

Glass Marking

Glass can be damaged with spot marking by the ceramic rolls in the furnace if they are not clean, and a dimple type 'orange peel' marking can be caused by excessively hot rolls, especially with thick glass. White haze marking can occur in the middle area and out at the corners if the weight of the glass is concentrated in an area by thermal bowing during heating and can be particularly bad immediately after a roll wash. Keeping the glass flat during heating will reduce or eliminate white haze and the use of Sulphur Dioxide (SO_2) can also help reduce the level of this type of marking.

Sulphur Dioxide (SO_2) Gas

The basic recommendation is to avoid using SO_2 unless absolutely necessary. SO_2 oxides easily and becomes SO_3 and works by combining with the Sodium (Na) in the surface of the glass to produce a form of Sodium Sulfate (NaSO_3) which condenses onto the roll. It is liquid at furnace temperatures and therefore provides a form of lubrication between the glass and the roll. However, when a furnace is cooled down, the Sodium Sulfate solidifies and unfortunately it has a coefficient of expansion far greater than the ceramic rolls. This means that if a lot of SO_2 has been used in production, any large spots of Sodium Sulfate that may have formed will contract and can crumble the surface of the rolls. So if any spots are seen to be forming on the rolls they should be gently washed off at the earliest opportunity with plain hot (70°C) water, and not scraped off with a sharp blade!

The effectiveness of SO_2 will be reduced if the float line has used this gas at the lift-off roll point at the end of the tin bath. The reduction in effectiveness is because some of the Sodium in the glass surface has already been leached out. It should also be noted that pumping the gas into an empty furnace is of no benefit because there is no Sodium to react with to produce the Sulfate. Additionally, when the oxidised SO_2 (SO_3) mixes with moisture (H_2O) it produces H_2SO_4 which is Sulphuric Acid. This means that if there is a leak of SO_2 and you breathe it in, the 'smelling salts' effect you experience is actually the gas reacting to the moisture in your nasal passages producing Sulphuric Acid!

Nickel Sulfide Particles (NiS)

Nickel Sulfide particles are really bad news for tempered glass. They can form in the float process when a nickel rich contaminate, such as stainless steel, comes into contact with sulphur. Modern float lines are now very clean and do not use fuel oil as an energy source, instead they use natural gas. So the sulphur is probably provided from the Sodium Sulphate they add to the batch as a fining agent to help remove small air bubbles from the molten glass and prevent scum formation.

The particle that forms is usually very small, around 100 to 200 microns, so it is very difficult to see on visual inspection of the glass. The problem is that NiS has two phases (states), a hot alpha-phase and, below 380°C , a cold beta-phase, and in the alpha-phase the particle is smaller than when in the beta-phase. In the float line process after drawing the glass off the tin bath the glass is very slowly cooled in the annealing lehr and this gives time for the particle to transform from its alpha-phase to its beta-phase, and it does not cause any problems in annealed glass. In the tempering process the glass is heated up to around 620°C and the particle transforms into the alpha-phase. In the quench the glass is chilled very rapidly and this traps the particle in its alpha-phase.

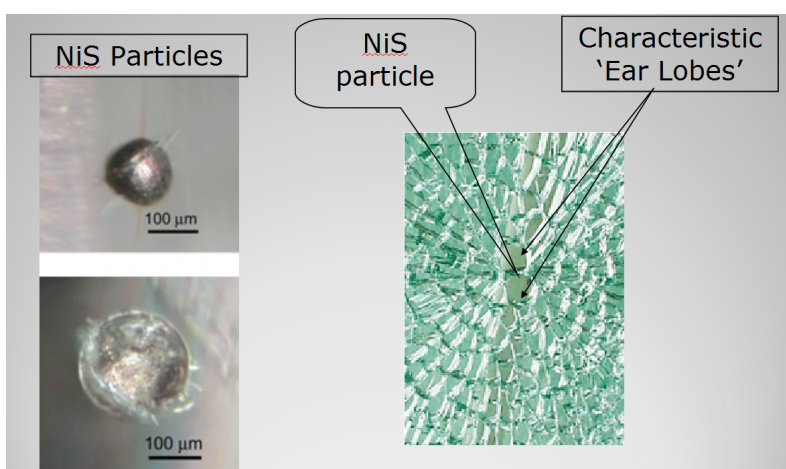


Illustration 48: Nickel Sulfide Particles and Resulting Break Pattern

However, **the particle cannot survive in this alpha-phase and it must, and will, return to its beta-phase at some time in the future.** In returning to its beta-phase it will increase in size by about 2 to 4% and this expansion will cause micro flaws in the glass (shown in the left hand picture in illustration 48). If these flaws occur in the tension layer of tempered glass then the glass will spontaneously fail without any warning. This occurrence can happen at any time, it may take hours, or days or even years for the particle to revert to its cold state **but it will revert.**

Illustration 48 shows typical particles and the break pattern that results if the glass fails because of the particle. Note the characteristic 'ear lobes' that will always appear either side of the origin of failure.

These 'ear lobes' are 2 – 6 sided particles which if taken apart the NiS stone can be seen in one of these particles.

Illustration 49 shows a window glass that failed but remained in place and the same 'ear lobes' can be clearly seen.

Glass failures from Nickel Sulfide particles are relatively rare these days due to the cleanliness of modern float lines but they can be virtually eliminated from getting into service by 'Heat Soaking' the glass after tempering.

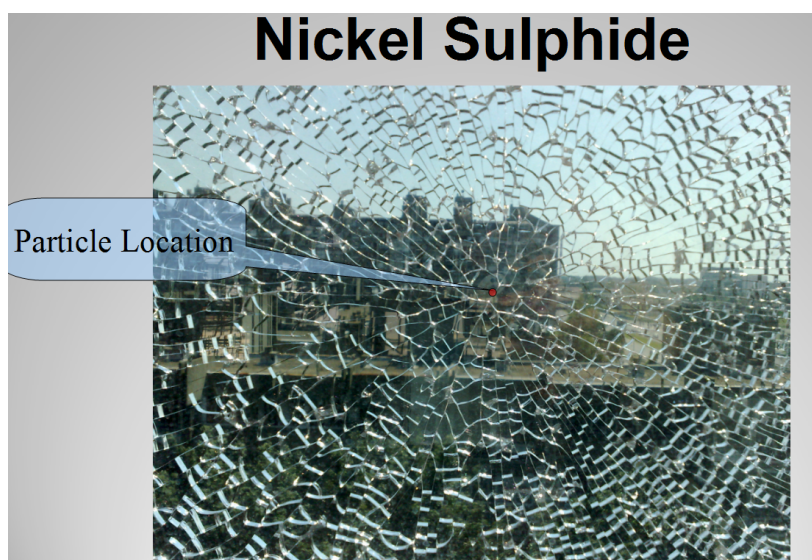


Illustration 49: Window Glass Broken by Nickel Sulfide Particle

Heat Soaking Tempered Glass (EN 14179)

The process of 'Heat Soaking' tempered glass is to reheat the glass to a temperature of 290°C and maintain that temperature for at least 2 hours after the last piece of the glass load in the Heat Soak oven has reached 290°C. This accelerates the phase change of any Nickel Sulfide particles that may be present, and if the particle was in the tension layer the glass will fail in the Heat Soak oven and not make it out into an installation. This process has been successful in significantly reducing the potential of glasses failing in the future. Glasses that survive the Heat Soak test either have no Nickel Sulfide particle present, or the particle is so small as to not cause a problem, or the particle resides in the compressive layer and again it should not present a problem in the future. However, research by A Kasper and quoted by Asahi Glass, indicates that less than 1 break in 10,000 panes of glass is expected to occur after a Heat Soak of 2 hours so Heat Soaking is not a complete guarantee of zero failures.

Glass Distortion due to Process Conditions

Providing the system is mechanically set up correctly and all elements and aspirators are working, any distortion seen in the processed glass is due to the way the glass was heated or quenched, or was subjected to extraneous draughts as it entered the quench, because if it is uniformly heated and uniformly quenched it will be perfectly flat (or shaped). The only exception to this is roll wave and end-kink.

Roll Wave & End-kink

Roll wave and end-kink distortion only happen in the last few moments of heating when the glass is very soft and pliable. End-kink is due to the leading and trailing edges of the glass being unsupported as they leave one roll and travel to the next roll because the unsupported weight will cause the edge to bend down. The speed of the roller bed and the pitch of the roll bed will affect the amount of end-kink seen, high speed and a close pitch roll bed will usually produce less noticeable end-kink. Roll wave is caused by ceramic rolls that have a high TIR (total indicated run-out) so that the out-of-true portion of the roll pushes the glass up causing a high point every time the roll rotates. The peak to peak distance of the wave in the glass is therefore equal to the circumference of the bad roll (illustration 50). With both end-kink and roll wave, the hotter the glass, the lower the viscosity and therefore the easier it is to distort the glass from its optically flat condition. Processing the glass very cool will reduce the end-kink, and the effect of any bad rolls, but the transient stresses in the first few seconds of quenching will increase the probability of the glass breaking in the quench. Remember from illustration 8 that just 30 degrees increase in temperature is equal to an order of magnitude reduction in the viscosity of the glass, so processing the glass hotter, maybe to obtain less breakage because of poor edge-work, will result in an increased yield in the quench, but at the expense of optical quality as can be seen in illustration 51.

Lisec have developed a tempering system that transports the glass on an air-bed and therefore claim that it is completely free of any roll wave or end-kink. It is also claimed to be able to temper very thin glass – 2mm to EN 12150 standard.

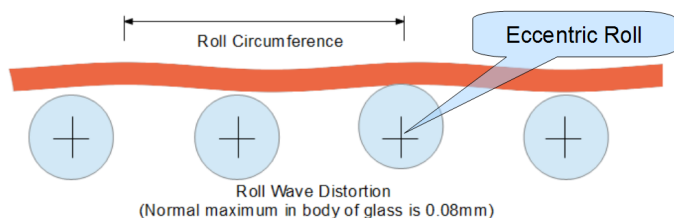


Illustration 50: Roll Wave Distortion



Illustration 51: Roll Wave Distortion in Architectural Glass installed in a Building

Bowed Glass (Stable)

Glass that is bowed in a stable 'water shedding' or 'water holding' bow after being quenched is caused by the fact that the upper and lower surfaces were not at the same temperature when the glass became solid in the quench. The hotter surface will contract more than the cooler surface as they cool down to ambient temperature and the shorter surface will pull the glass into a bow. The reason for the imbalance in temperature is immaterial because the correction is to increase the rate of cooling on the hotter surface so that it is at the same temperature as the cooler surface when the glass cools down through the *Transition* and *Strain* temperatures and becomes solid.

'Blow into the Bow' is a saying used by some operators to remember which way to adjust the upper and lower quench air balance.

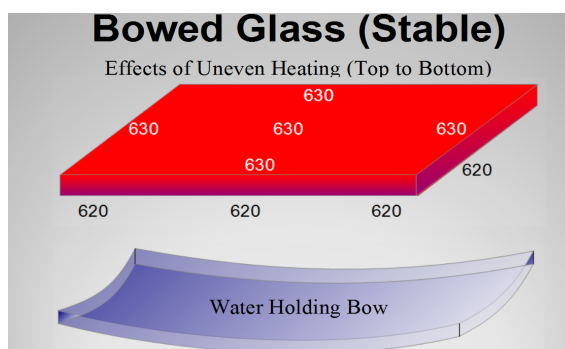


Illustration 52: Bowed Glass

'S' Shaped Bow

If there is 'blowback' from the quench towards the furnace when the glass enters the quench the resultant bow after optimum quench air balance adjustment will be an 'S' bow down the long edge. The sequence is that the air pressure build up above and below the glass does not start until the glass is part way into the quench. On the lower surface of the glass the air is blocked from travelling upstream by the quench rolls, but on the upper surface there is no restriction so the air is free to travel upstream chilling the top surface of the glass as it leaves the furnace and before it gets into the quench. The leading edge of the glass is not affected but the operator doesn't notice this and just observes a 'water

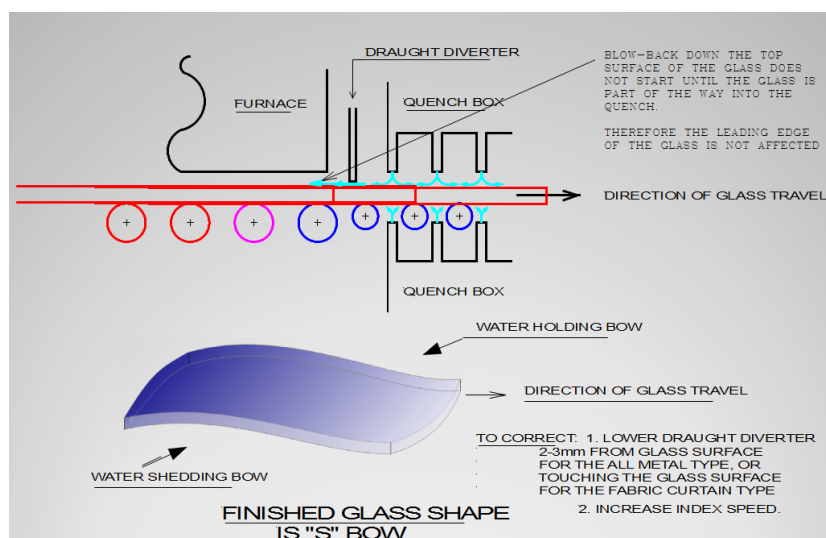


Illustration 53: 'S' Bow in Long Thin Glasses

shedding' bow on the finished glass. He reduces the upper quench air pressure (or increases the lower air pressure) to correct the observed bow. On subsequent glasses, the leading edge does not now have sufficient top pressure, the blowback gives sufficient cooling for flatness in the centre section and the top surface trailing edge still has too much cooling. The resultant shape is an 'S' bend which is **always** water holding at the leading edge and water shedding at the trailing edge of the glass. The only way to correct this problem is to reduce the blowback from the quench using some form of draught diverter on the upstream face of the upper quench box located very close (about 2mm) to the upper surface of the glass (illustration 53).

Bowed Glass (Unstable)

Unstable bowed glass is caused by a non-uniform distribution of temperature in the glass as it cooled down through the *Transition* and *Strain* temperatures and became solid (illustration 54). As in the stable bow condition, once the glass is solid, the hotter regions will contract more than the cooler areas. The problem becomes worse with thin glass (3mm & 4mm) as the size increases and the glass shape aspect ratio approaches unity (square). Long narrow glasses will not exhibit these effects.

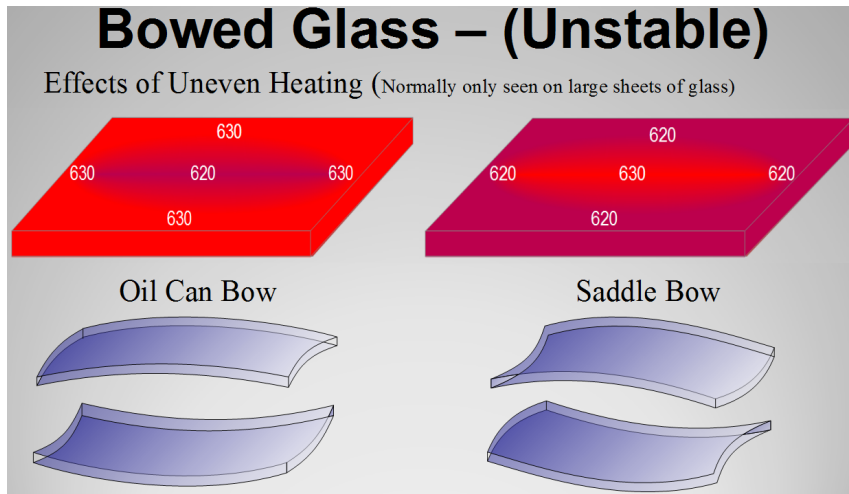


Illustration 54: Unstable Bowed Glass

directions resulting in a saddle shape. The edge bow direction can be flipped to the opposite direction and so again, the condition is not stable and the glass will have a very loose feel to it if it is placed vertically on an edge and a corner is shaken by hand.

The 'oil-can' bow is the more usual condition that is seen due to the centre of the roll bed cooling with successive loads combined with the edges of the glass absorbing infra-red radiation resulting in non-uniform glass heating in the furnace. If there are only one or two difficult size glasses to be run in a day the bow can be eliminated by running the glasses into a furnace that has been idling for a while, for example after a coffee or lunch break, the glasses will come out flat without any bi-stability because the roll bed will be at a uniform temperature. If there is a considerable number of these difficult size glasses to be run then there is no option but to reduce the furnace temperature and run an extended heating time to soak the glasses to a more uniform temperature.

The 'saddle' bow condition is not so normal and is usually associated with poor air release from the centre of the quench causing a hot central area during quenching. Here there is little option but to try and run the glass at the edge of the load area and hope that the problem is solved. If that doesn't work then it may be a heating related problem in which case reducing the furnace temperature and increasing the heating time may help.

Good Quality Glass

Good quality glass can be achieved by careful attention to edge-work, cleanliness, straightness and good TIR of the ceramic roll bed together with running the glass as cool as possible as can be seen in illustration 55.

This is actually a picture of 6mm Antillio coated glass run at a low furnace temperature on a Glasstech gas fired Forced Convection furnace used by Saint Gobain in at their Sas Van Gent factory located in Holland. They specialise in very high quality reflective glass for buildings.



Illustration 55: High Quality Fully Tempered 6mm Glass

Automotive Tempered Glass

Tempering glass to automotive standards means that when a glass fails, in addition to the minimum particle count, there is also a maximum particle count and a requirement that there are no splines over 75mm. To achieve this the nozzle array in the quench should be very uniform and closely spaced. With a spherically shaped glass, i.e. a car rear window or sun-roof, the quench heads are usually manufactured to the shape of the glass to maintain correct nozzle-to-glass distance, and the glass itself is supported on a peripheral ring.

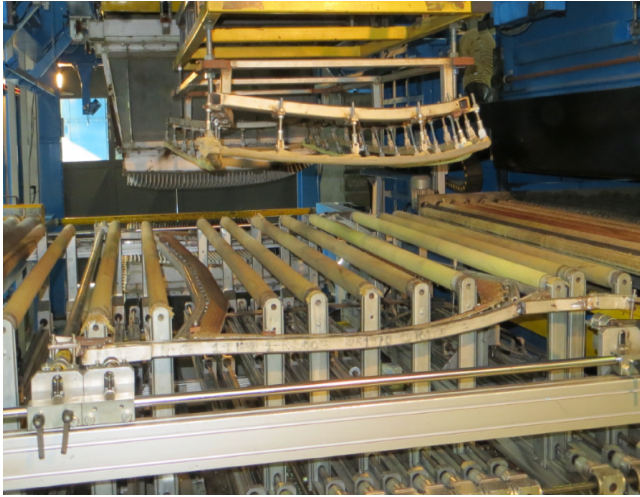


Illustration 56: Typical Automotive Glass External Press Bender

Illustration 56 shows a typical automotive glass 'External Press Bender' with the peripheral ring waiting below the roll bed for the glass. When the glass is above the ring the ring is lifted up and takes the glass up onto the upper mold to press the glass periphery to the correct shape. After pressing, the ring carries the glass into the shaped quench (see illustration 57).

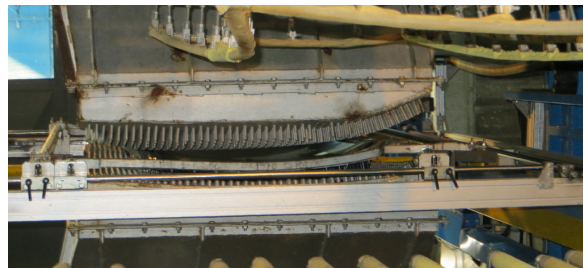


Illustration 57: Shaped Quench

Because the ring is supporting the edge of the glass it interferes with the cooling jets of air from the lower quench box and there is a danger that the edge of the glass will not be correctly tempered. In this case the low compression at the edge allows the tension layer to get very close to the edge of the glass and it is then susceptible to failure from a slight knock to the edge of the glass, or by distortion of the glass by the supporting frame.

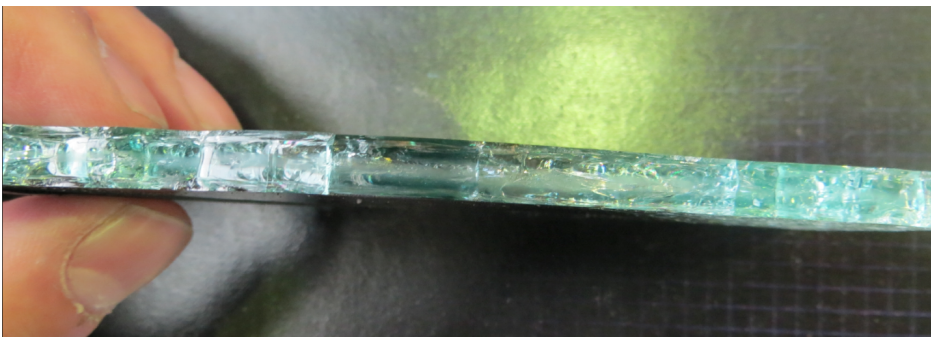


Illustration 58: Glass Fragment from the Edge of a Failed Auto Glass

In illustration 58 it can be seen that the milky white line which denotes the line of maximum tension in the glass is not central between the upper and lower surfaces. It is slightly lower than centre, indicating a lower compressive stress in the lower surface where it had been supported by the quench ring.

Illustration 59 shows a glass supported by a Kevlar covered peripheral quench ring, where the amount of overlap of the glass on the ring is considered to be excessive.



Illustration 59: Excessive Edge Support of Automotive Glass

Where the quench ring interferes with the quench air it can cause the neutral band to get very close to the edge of the glass, and this will cause the glass to be very weak at this point and susceptible to failure if the edge is knocked.

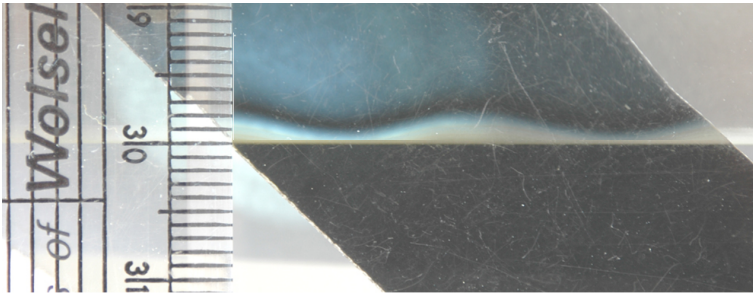


Illustration 60: Neutral Band Not Parallel to Glass Edge

Illustration 60 shows a tempered glass viewed between two pieces of polaroid film. The wavy black line is the neutral band and it is wandering very close to the edge of the glass because of poor tempering stresses due to interference by the quench ring.

Iridescence in Tempered Glass

Preventing splines from forming when a glass breaks can be achieved by deliberately having areas of higher and lower stresses. This is because when a spline tries to form (two cracks accelerating side by side but not reaching half the V_{shear} speed, see page 32) the cracks come across an area of higher stress, they accelerate faster and bifurcate, effectively breaking the spline. The higher and lower stress levels are put into the glass by stopping the glass from moving in the quench at the start of quenching for a few tenths of a second so that the nozzle pattern generates a pattern of high stress points directly adjacent to each nozzle illustration 61.

However, because any stress in the glass will twist light, if a glass is looked at with a polarised light source the variations in the stress in the glass will twist the light differently and the high/low stress areas can be seen. As all reflected light is polarised the pattern is quite easily seen in an automotive rear window by light reflected from a nearby building (illustration 62). If polaroid sunglasses are worn the visual effect is even greater.

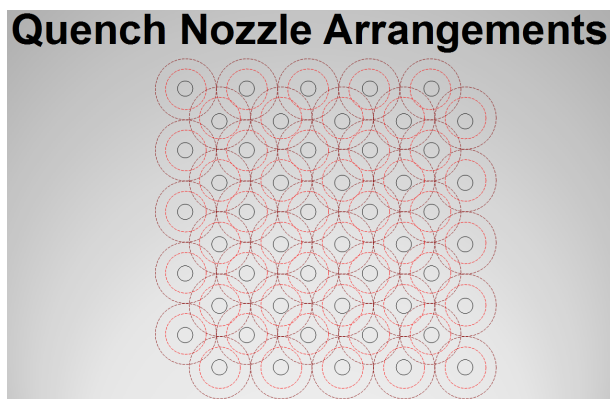


Illustration 61: Domino Pattern Nozzle Arrangement



Illustration 62: Iridescence in Automotive Glass

Iridescence can also be observed by reflected light on architectural glass, especially in bright sunny climates and with thick glass 8mm and above. The varying stress pattern in thick architectural glass is a result of many oscillations in the quench stopping at the same position before the glass temperature falls below the strain point. On each stop, as the glass reverses, the glass directly adjacent to a nozzle will receive a fraction more cooling than the areas not adjacent to the nozzles and this will build up until the glass temperature falls below the strain point. To reduce this effect the furnace operator should set a slow speed into the quench, a slow oscillation speed, and if possible set the oscillation distance to an odd number of half the distance between quench fins, or vary the oscillation distance incrementally if the software allows.

Drilled Holes in Glass

Processing glasses that have had holes drilled in them gives rise to problems during heating. The inside edges of holes are actually surfaces absorbing radiation which will therefore try and expand more than the surrounding body of the glass. This means any holes that are close to the edge of the glass will cause the area between the hole and the edge of the glass to experience a level of tension. Any chips at the edge of the hole will act as stress raisers and if the tension stress is high a crack will run.

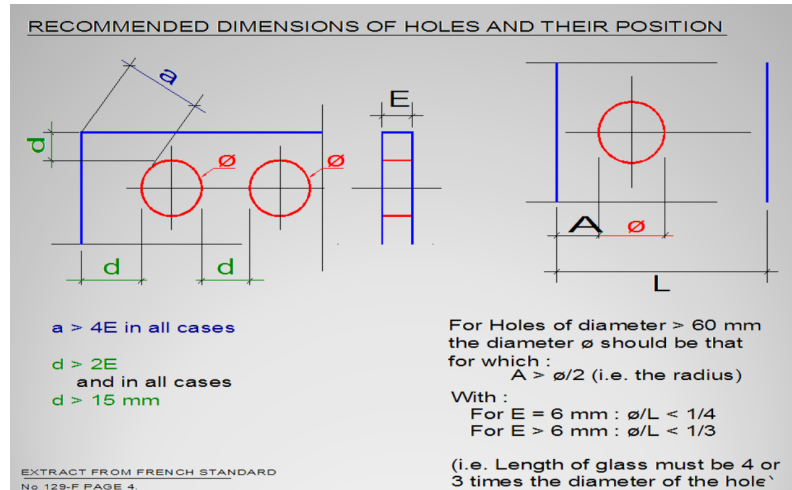
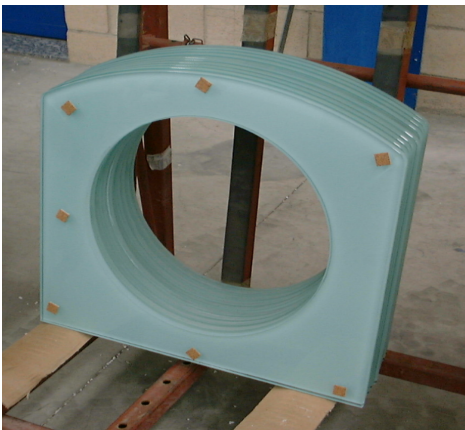


Illustration 63: Recommended Minimum Position of Holes

An example of a recommendation for the position of holes relative to the edge of the glass is shown below (taken from the French SNCF railway standard 129-F). If a hole has to be very close to the edge of a glass (maybe the hinge point on a tempered glass door for example) then a slot should be cut from the hole to the glass edge before tempering which will prevent the build up of tension during heating. The slot will not reduce the strength of the finished glass and the hinge plate should be designed to hide the cut.

A little trick to reduce the expansion of the hole during heating is to paint the inside edge of the hole with typist's Snopake correction fluid (if you can find any in this digital age) to help reflect the IR radiation. The Snopake will become powder during the heating and can be wiped off the hole after tempering.

There are of course always companies that manage to process glasses outside the recommended standards and examples of very large holes in tempered glasses are shown below.



Conclusion

It is hoped that this book has explained the factors affecting the glass tempering process, and that by understanding what is happening to the glass and why, any problems seen in the processed glass can be resolved. As stated in the beginning of the book, the glass tempering process is very simple – uniformly heat the glass to well above the *transition temperature*, keep it optically flat (or form it if required), transfer it to a quench and uniformly cool it at a controlled rate to below the *strain point*, then cool it down to ambient temperature.

Jonathan Barr

Appendix A: Effect of Glass Load on an Oscillator Type Furnace

Calculating the total energy required to heat the glass load to say 620°C from an ambient temperature of 15°C is very easy. Simply multiply the weight of the glass by the specific heat and by the temperature rise for example:

At 15°C a full load 2140mm x 3660mm (7.8324m²) of 4mm glass has a volume of 0.0313296 m³.

Multiply that by its 'Specific Weight' of 2563 kg/m³ to get the weight of the load which equals 80.297 kg.

The weight multiplied by the 'Specific Heat' (0.88 kJ/kg.K) multiplied by the temperature rise of 605°C (620°C - 15°C) gives 42750.53 Joules. There are 3600 kJ in a kWhr, so a total of 11.875 kWhrs of energy is required to heat the glass. This is heated in a time of just 160 seconds, therefore 11.875 kWhrs x 3600/160 equals an average power input of 267.19 kW into the glass. The 11.875 kWhrs divided by the glass area gives a figure of 1.516 kWhrs per square metre of glass to raise its temperature by 605°C.

To obtain the true cost of heating the glass, the heat loss from the furnace shell, the power into the conveyor drive and the cost of the compressed air to the aspirators all need to be added. Unfortunately, the energy input to the glass is not constant; when the cold glass enters the furnace the energy transfer is very high and just before exiting the furnace it is very low. Indexing the glass into the furnace at 600mm/sec it takes just over 6 seconds to get the full load into the furnace. Calculating from the 7 second point in the heating cycle, the rate of temperature rise in 1 second at 7 seconds heating time is calculated by subtracting the temperature at 6 seconds from the temperature at 7 seconds:

$$((690 - 15) \times (1 - e^{-(7/4/17.6)}) + 15) - ((690 - 15) \times (1 - e^{-(6/4/17.6)}) + 15) = 78.89 - 70.15 = 8.74 \text{ deg/sec}$$

The instantaneous load = 80.297 kg x 0.88 kJ/kg.K x 8.74 deg/sec x (3600/1 sec) / 3600 KJ/kWhr = 617.5 kW

The instantaneous load then continues to decrease as the glass heats up, and is shown in the graph below.

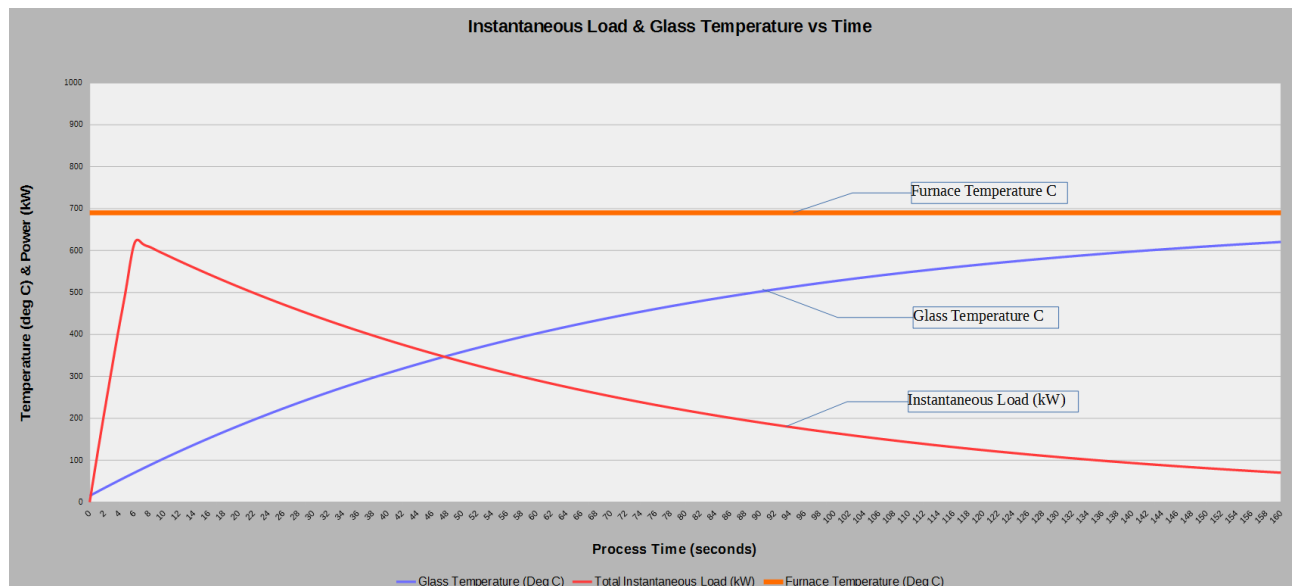


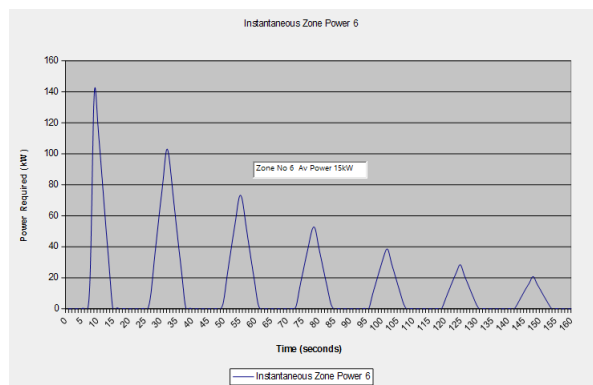
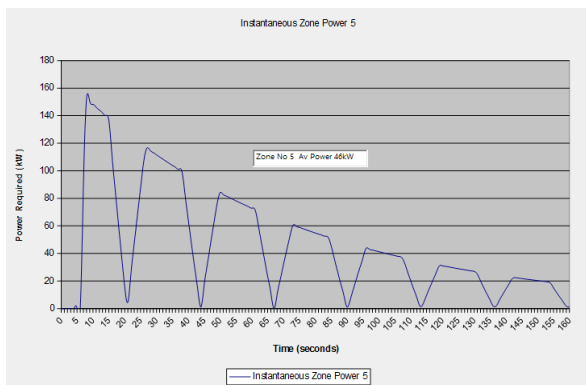
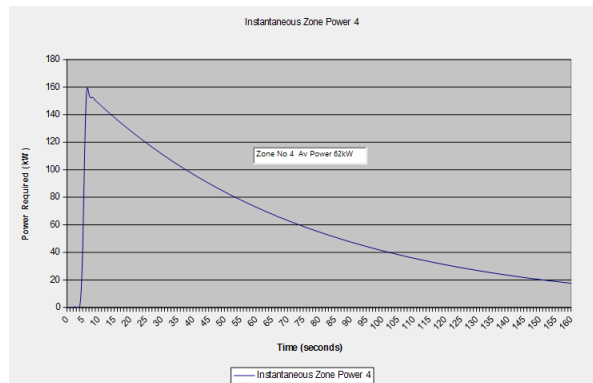
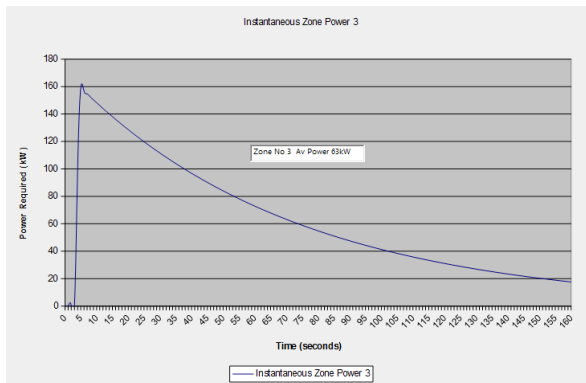
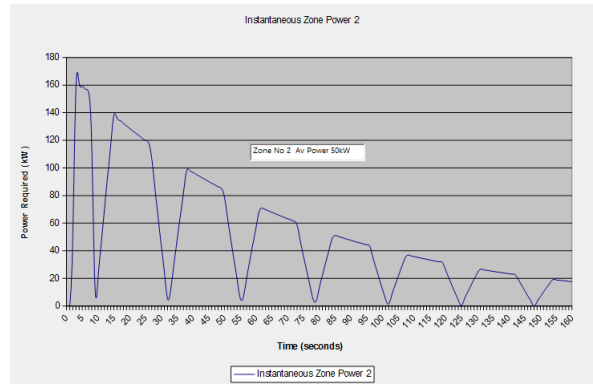
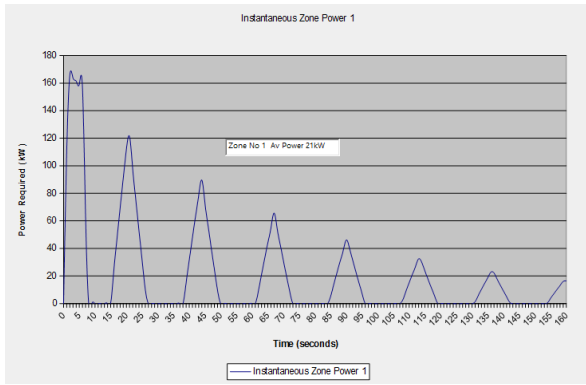
Illustration 64: Instantaneous Glass 'Heat Load' on Furnace Chamber

A further transient effect is the fact that the glass is oscillating in the furnace. As an example, with a 5.5m long heating chamber divided into 6 x 917mm long heating zones processing a 3660mm load, the instantaneous load on each section as the glass oscillates is shown in the charts on the following page.

The centre sections (3 and 4) obviously take the major portion of the energy load because the glass load never oscillates out of these areas and therefore they would normally have the highest installed power to cope with the energy requirements. Zones 1 and 6 are the lightest loaded zones due to the glass clearing out of the zone on each oscillation.

A furnace with a large thermal mass (and therefore inertia) will assist in smoothing out the element power requirement as the large thermal mass will supply the energy without dropping too much temperature. The PID temperature control loop setting, thermocouple response times and shielding the upper thermocouples from sensing the glass will also assist in preventing large swings of element power levels.

With a forced convection furnace the instantaneous load increases and peaks at about 925 kW because of the reduced heating time (30 seconds/mm), plus the energy consumed by the recirculation fans needs to be added.



Appendix B: Quench Characteristics

The business end of the quench are the nozzles which remove the heat from the glass at a controlled rate by forcing a cool air mass into contact with the glass surface. The prime mover of the force to drive the air mass onto the glass is pressure, usually derived from large centrifugal fans or on some 3mm machines, compressors. The fan output pressure can be controlled by either inlet vanes, or by the speed of the fan wheel, or a combination of the two as shown in illustration 65. Outlet dampers on fans are not usually employed as there is a danger of surging, resulting in non-stable air pressure. Inlet vanes are not a particularly efficient way of controlling the fan output, especially when very low air pressures are required. Additionally, if there is any looseness in the inlet vane linkages, setting the inlet vane control gear to a given position will not produce a repeatable output pressure.

The balance of air pressure between the upper and lower quench boxes controls the final shape (bow) in the glass. The simple way of doing this is by one fan feeding both boxes with a balance damper in the ductwork to control the relative air flow to the boxes.

A more precise, but more expensive, way is to use one fan for the upper box and one fan for the lower box. The fans are individually controlled in speed and offer a much more accurate way of controlling the relative pressures and shape of the glass.

Speed control is accomplished by either DC motors and drives, or AC motors with vector control inverters. DC drives are usually cheaper to buy than AC drives, but they do have a maintenance penalty in that the motors will need to have the commutator brushes renewed at some point in time.

For low speed operation the motors are normally fitted with blower motors to provide cooling as the internal main motor fans are insufficient at low speed to provide the necessary cooling.



Illustration 65: Single Quench Fan - IVC and Speed Controlled

Illustration 66 shows a twin fan system, one fan for each of the upper and lower quench heads.

The size of the fans depends on:

1. The area of the quench head.
2. The type of quench nozzles.
3. The minimum glass thickness to be processed.
4. The altitude of the installation above sea level.

Generally speaking, at sea level, for 4mm glass, the old style quenches (with 6 to 8mm diameter nozzles) have fans producing about 716 daPa with a flow of 7.1 m³/sec consuming 61kW for each square metre of quench area. The figures for newer high efficiency heads are 422 daPa, 4.4 m³/sec consuming about 22kW. For 2.85mm glass these figures increase to around 300kW/m² and 100 kW/m² respectively.



Illustration 66: Dual Speed Controlled Fan System

Illustrations 67 and 68 show examples of the two different types of quench nozzles. The 'high efficiency' quench is pictured in the open position, normally the fins would be about 10mm from the glass surface.

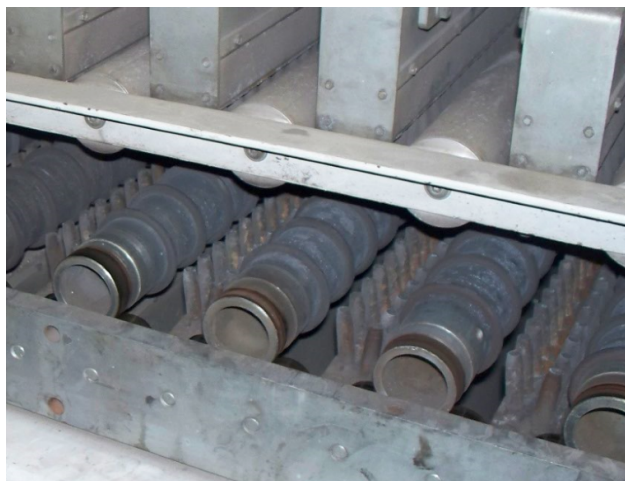


Illustration 67: Example of Older Style Quench Nozzles

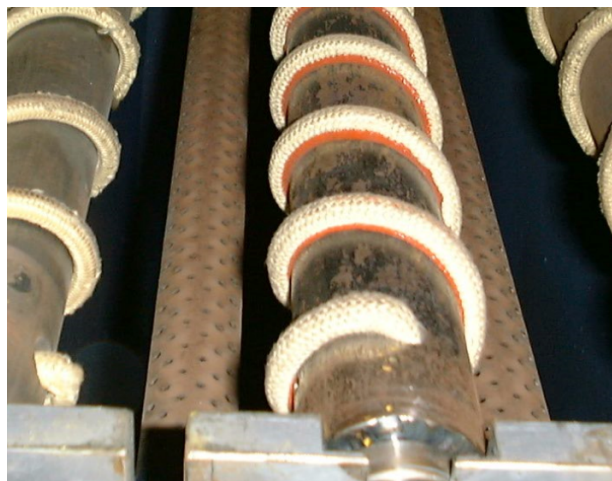


Illustration 68: Example of High Efficiency Quench Nozzles

It should be noted that the flow from a fan increases proportional to the increase in wheel speed, and the pressure increases to the square of the increase in wheel speed. The power required is proportional to the flow x pressure so increasing the speed will increase the power required by the cube of the increase. For example, doubling the speed will increase the power taken by the fan by a factor of 8.

The quench air pressure required to process glass to full tempering standard in a typical 'High Efficiency' quench is shown in illustration 69 and the pressure change is equal to the inverse cube of the change in glass thickness.

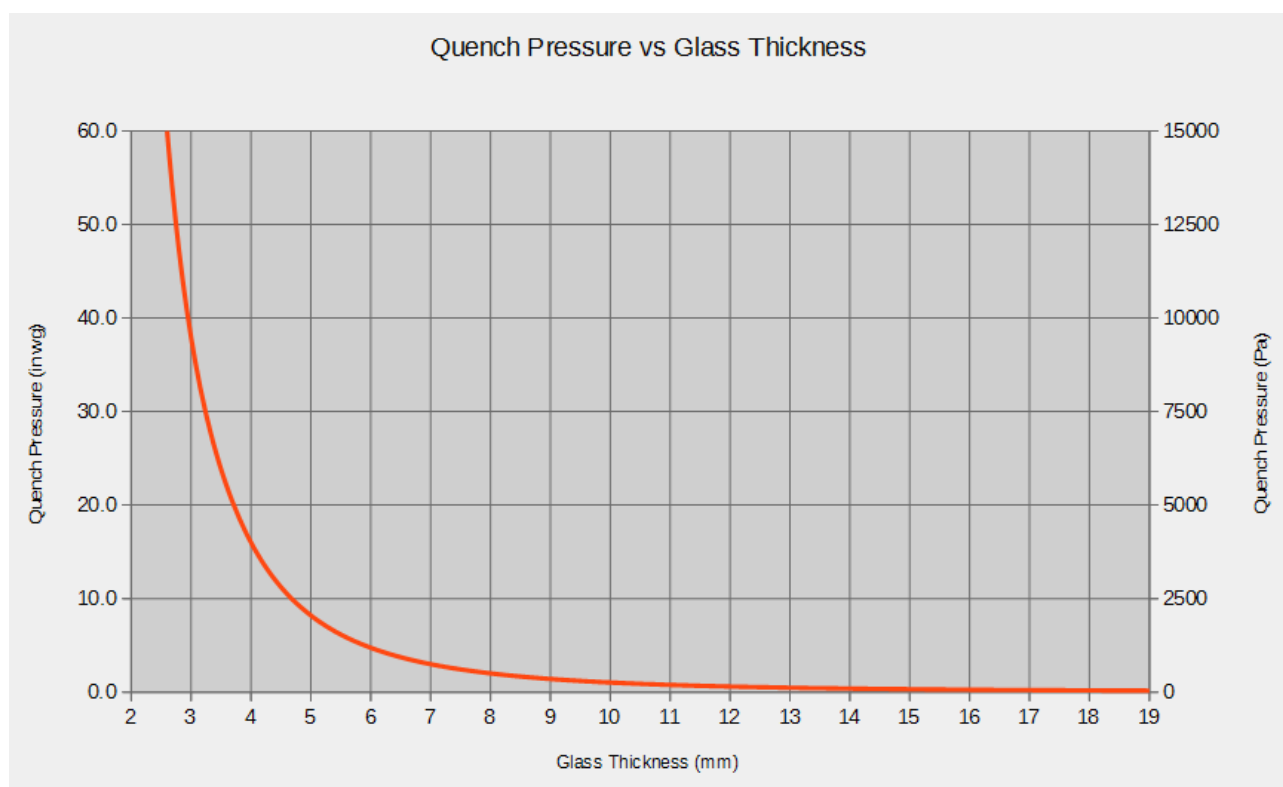


Illustration 69: Quench Pressure vs Glass Thickness (High Efficiency Quench)

For example a quench, which requires 5in wg to temper 6mm glass, the pressures for other thickness would be:

$$4\text{mm glass} = 5 \times (6/4)^3 = 16.8 \text{ in wg}$$

$$8\text{mm glass} = 5 \times (6/8)^3 = 2.1 \text{ in wg.}$$

$$10\text{mm glass} = 5 \times (6/10)^3 = 1.1 \text{ in wg}$$

$$15\text{mm glass} = 5 \times (6/15)^3 = 0.3 \text{ in wg}$$

The amount of heat removed from the glass will depend upon the mass of air per second hitting the glass. The mass is dependant upon the density of the air which will vary according to the atmospheric conditions (illustration 70). On a 'Standard' day (1013.25mbar and 15°C) the density of air is 1.224 kg/m³. On a hot (30°C) low pressure day (red dotted line) the density of the air is considerably less (about 1.134 kg/m³) and on a cold (5°C) high pressure day (blue dotted line) it is considerably higher (about 1.288 kg/m³). The required adjustment to the fan wheel speed to get the same air mass per second onto the glass is shown on the Y axis. Note: The quench pressure change, as seen on a manometer, will be in the same ratio as the speed change because the change in air density also affects the output pressure of the fan.

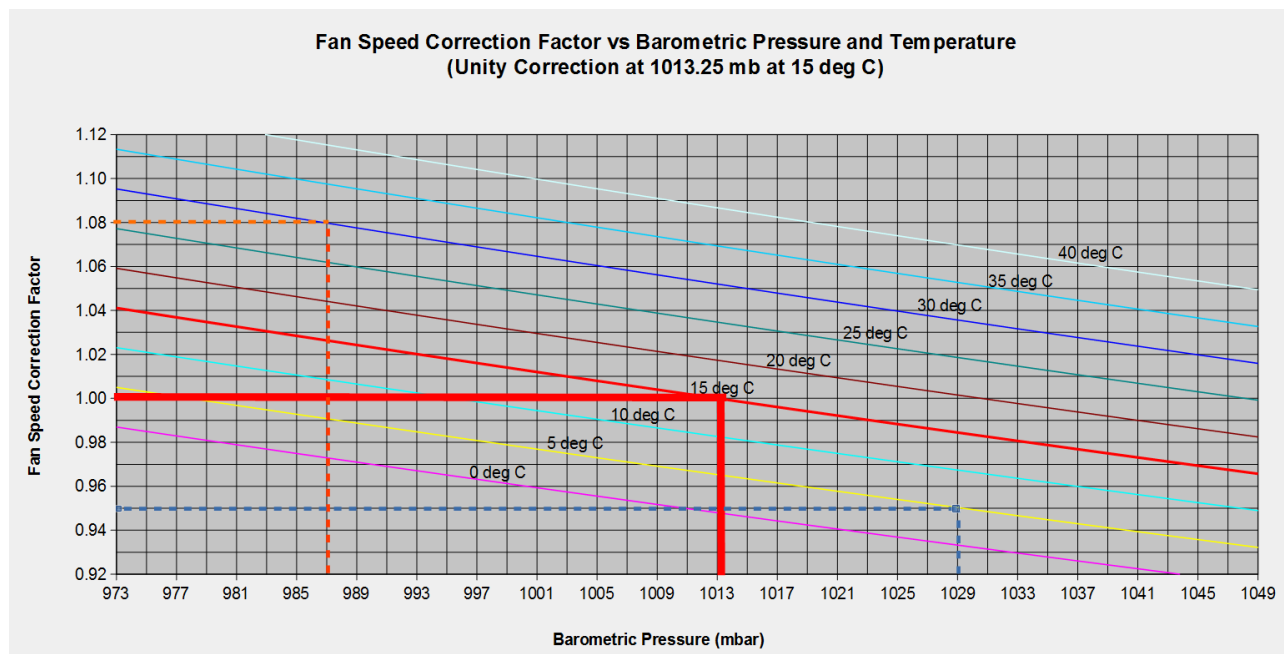


Illustration 70: Fan Speed Correction for Changes in Atmospheric Conditions

If the furnace operator is making test breaks on the glass production about every hour he will see the break pattern changing and adjust the air pressure accordingly to give the correct break pattern. This will automatically be compensating for any changes in atmospheric conditions. For example, midday production will undoubtedly use higher quench pressures than the night-shift will use at 3 o'clock in the morning.

The altitude of the production site will also determine the size and power of the fan. For example, a 4mm furnace located in Johannesburg (1753m above sea level) will have a much larger quench fan and drive than a 4mm furnace located in Cape Town (sea level).

Pressure drop between fans and quench boxes.:

Air will always flow from a high pressure to a low-pressure area at a velocity dependent upon the pressure difference. The pressure drop of the air is given by the formula:

$$P = .5 \times \text{Rho} \times V^2. \quad (\text{Where } P = \text{pressure in Pa, Rho} = \text{density in kg/m}^3, \text{ and } V = \text{velocity in m/sec.})$$

For example, if the air was flowing in the duct at 20.15 m/sec (4000 ft/min) and density (Rho) was 1.224 kg/m³, then the pressure drop would be:

$$P = .5 \times 1.224 \times 20.15^2 = 248.7 \text{ Pa, (248.7 Pa} = 1 \text{ inch water gauge.)}$$

Ductwork is normally sized by the furnace manufacturer to keep the air velocity below 20.15 m/sec so the pressure loss will be less than 248.7 Pa (1 in wg).

Appendix C: Critical Mechanical Set-up of the Tempering System

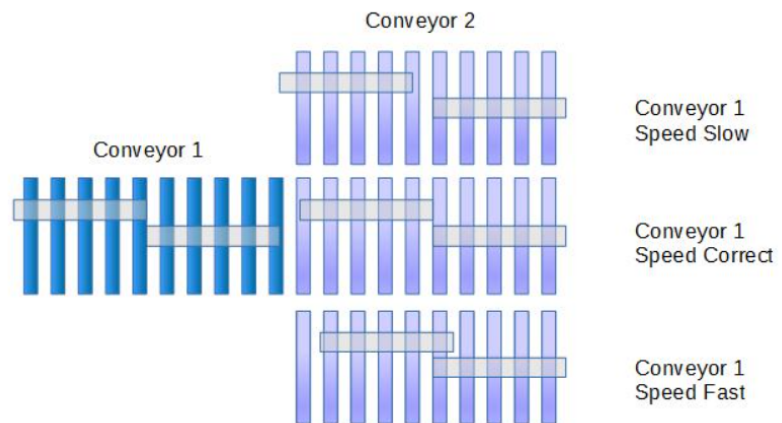
The critical areas of mechanical set-up are:

Load Table:

If this has a separate drive to the main furnace conveyor, it is very important that the roll surface speed is accurately matched to the main conveyor to prevent the gaps between glasses opening or closing as the glass load is transferred across these two conveyors and indexed into the furnace.

This speed match is very easy to check by simply loading two glasses side by side so that the leading edge of the second glass is aligned with the trailing edge of the first glass. Open the furnace roof 15 to 20mm (just enough to look into the chamber) and observe the glasses once they are in the furnace to see if the relative positions of the edges have altered. For example, if the leading edge of the second glass is now ahead of the trailing edge of the first glass it indicates that the load table drive is too fast (see picture to the right).

If the table is fitted with a ball lift-frame that drops as the table starts to index, the frame must drop absolutely level to ensure the individual glasses are not misplaced as they contact the rolls.



Heating Chamber:

Roll seals and entrance and exit doors should be a close fit to reduce drafts into, and heat loss out from, the furnace.

Conveyor movement should be smooth, especially in an oscillator type heater as the conveyor reverses.

Drive gearboxes and drive shafts should not have any backlash present.

Conveyor acceleration and deceleration values should not exceed 0.05G to ensure the glass does not skid on the ceramic rollers as this could cause scratches.

Ceramic rolls should be checked periodically to ensure they have a TIR of less than 0.127mm (5 thou) and certainly not exceeding 0.254mm (10 thou).

Ceramic rolls should be scrupulously clean and without any Sodium Sulphate build up if SO₂ gas has been used. Rolls should only be cleaned using plain hot water without any detergents or solvents. Normally nothing more abrasive than a green 'ScotchBrite' cleaning pad should be used. However, very occasionally it may be necessary to use a fine wet-and-dry paper to remove fine glass particles (fines) adhering to the rolls which in some instances can transfer to the processed glass. A quick test of the surface smoothness of a roll is to hold it at an angle of about 45 degrees and see if a chiffon scarf will slide down the roll without snagging.

The removal of these almost invisible glass fines is very important as there have been many problems reported in the USA of scratching of the finished tempered glass from window cleaners using metal blades.

The roll bed should be exactly square to the direction of travel to avoid the glass load crabbing across the furnace.

All compressed air aspirator nozzles should be clear. They can easily become blocked with lime scale from moist air if the compressed air has not been dried sufficiently.

SO₂ pipework to the furnace chamber should be leak-tight and the SO₂ bottle located in a vented enclosure outside the factory.

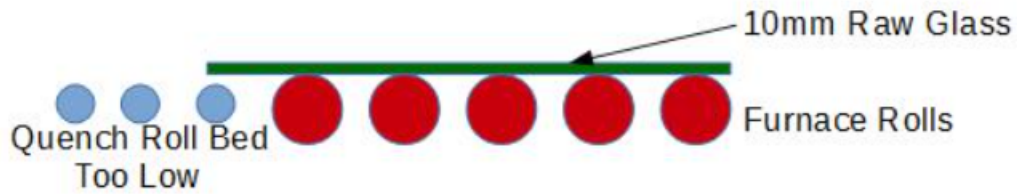
If there has been a glass breakage in the furnace the rolls should be thoroughly cleaned using a fine abrasive paper to remove glass fine stuck to the rolls.

Quench:

Like the load table, the speed of the drive must be exactly equal to the speed of the main drive and this can be checked in the same manner as the load table using two glasses.

The quench conveyor, usually Kevlar wrapped steel rolls, must be **exactly** level with the ceramic furnace rolls. If it is high a kink will appear in the glass close to the leading edge. If it is low (which can happen as the Kevlar packs down with usage) a kink will appear about 400mm back from the leading edge. The problem will be more apparent on thin glass than on thick glass..

The Quench bed height is easily checked by putting a piece of 10mm raw glass on the furnace rolls and sliding it forward over the first quench roll.



It can also be cross-checked with the system hot by putting the raw 10mm glass on the quench conveyor and sliding it back to the furnace conveyor.

If the quench rolls are not true but are banana shaped, the leading parts of glasses loaded either side of the system centreline will tend to twist outwards.

Good alignment of the quench heads (upper to lower) is very important to avoid thin glasses being flipped by the force of the air jets as they are transferred down the quench.

Roll Mimics, which are used to try and balance the lifting force from below the glass, should all be level and the same distance from the upper glass surface as they will affect the cooling rate.

Ideally the air into the quench room should be filtered to avoid glass dust being sucked into the fans and deposited onto the glass, which can then cause problems if the glass is later cleaned by a window cleaner using a metal blade. If the fan room is fitted with filters then they should be included in a service routine to be changed on a regular basis

All quench nozzles should be clear as any blocked nozzles will reduce the cooling effect at that location which can lead to shape distortion, splines and poor break pattern if the glass is later broken. Again, very easy to check. With the conveyor switched off put two glasses, one on top of the other, into the quench area to be checked. The corners should be taped to keep them together. Switch the fan(s) on at about 30% speed and shake a tablespoon or so of talcum powder in front of the inlet to the fan(s). The talcum dust will flow through the ductwork onto the stationary glasses and produce a dust pattern on the surfaces of the glass. The dust will settle where the air jet velocity becomes slow or zero.

The glasses are then carefully lifted out of the quench and the upper and lower pattern will show how well, or otherwise, the nozzles are aligned. The tape at the corners is then cut and the glasses separated. The dust pattern on the two glasses will then show if there are any blocked nozzles, illustration 71 shows a typical pattern from a quench box with blocked nozzles. The problem of blocked nozzles can be largely prevented by fitting a close mesh guard to the fan inlet to prevent insects and debris being sucked in. The previous illustration 65 on page 44 shows a fan fitted with this type of guard, and the 'drum' type design is necessary to avoid restricting the airflow and starving the fan inlet of free airflow.

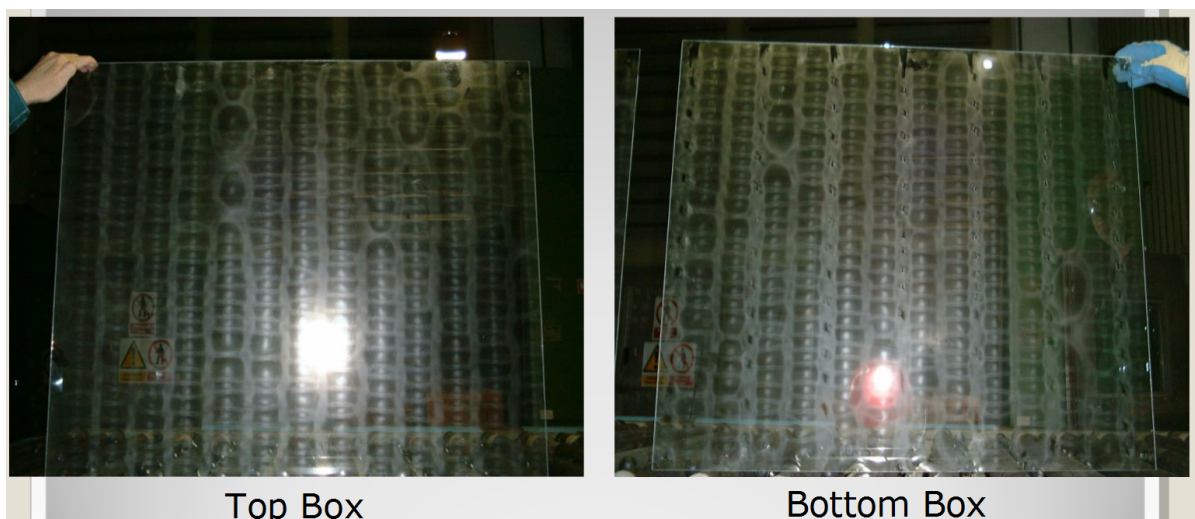
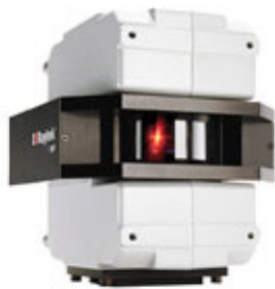


Illustration 71: Dust Pattern Check for Blocked Nozzles

Appendix D: Recommended Additional Equipment

The tempering system manufacturer simply supplies a heater and quenching unit to process glass, it is then up to the user to operate it in the best possible way to produce high quality tempered glass. To help the user there are a number of items available to help check the quality and assist the operator to make changes to obtain the best possible quality.

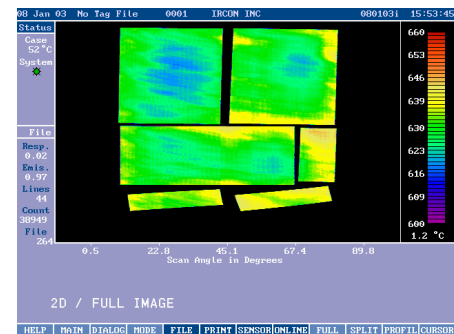
The first, and most important, item that I believe should be fitted to every tempering system is a line scanning IR camera. The camera mounted between the furnace and the quench will show the temperature profile of every piece of glass as it exits the furnace. This is the single most critical piece of information that a furnace operator can be given as it allows the operator to make accurate adjustments to the system parameters to get the most uniform heat distribution throughout the load of glass. There are expensive cameras, and there are inexpensive cameras, but a camera should definitely be fitted!



Raytek Scanning IR Camera



Optris Scanning IR Camera

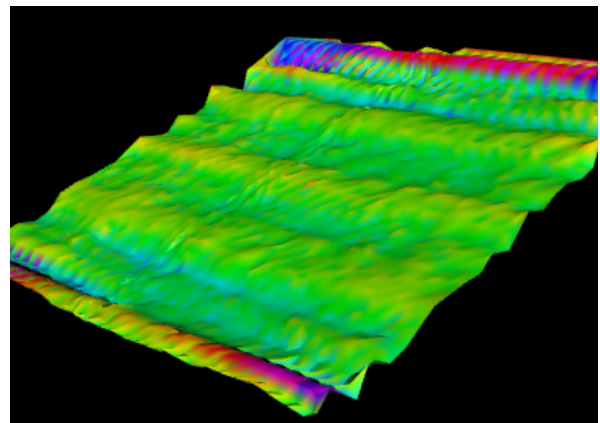


Typical Picture from a Line-Scan Camera

For continuous furnaces producing high volumes of glass parts, the need for an online distortion measurement system is absolutely critical. If a problem is not discovered until an off-line check is made on a glass, there may have been several hundred glasses through the system that are now out of specification. An on-line system such as LiteSentry alerts the operator immediately the glass quality starts to deviate from the acceptable standard, and in many cases adjustments can be made to correct the issue before the glass is totally out of specification. The system can also trigger a marker to mark any glass that is out of specification so the glass can be isolated by the unloading personnel, and not become packed with good quality glass.



LiteSentry On-Line Monitoring Equipment



LiteSentry - Picture of Distortion in Glass

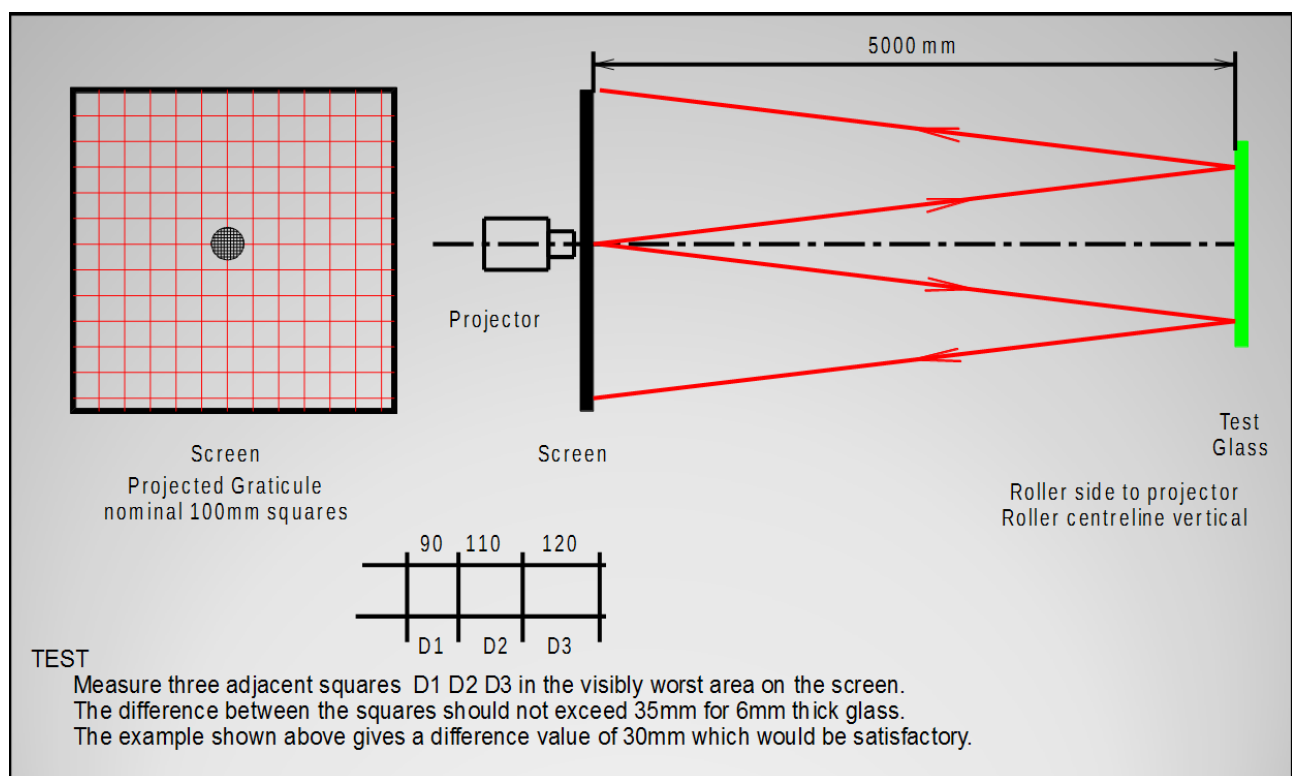
For smaller glass processors who cannot justify the cost of an on-line checking system there are a couple of low cost options. The first is a simple 'Zebra' board mounted on the downstream face of the Quench so that the operator can view the distortion as shown below. However, the check is purely subjective and one operator may say the glass is acceptable, and another may say the glass is not acceptable.

A simple way of getting a definitive measurement of distortion that will always give the same result, regardless of who makes the measurement is to project a grid onto the glass in a darkened room (preferably all walls and ceiling painted matt black). The grid is reflected back off the glass onto a screen and a measurement of adjacent squares can be taken in the worst affected area and compared to an 'in-house' standard set by the quality manager of the factory. The grid size reflected onto the screen from a perfect surface should be a nominal 100mm x 100mm square.



Zebra Board Showing Distortion

A diagram of the set-up is shown below.



Simple 'Off-Line' System to Check Distortion Seen in Reflection

Appendix E: Soda-Lime-Silica Float Glass Properties

Tinted Colours are produced by the addition of metal oxides (typically <1%). Physical properties of the glass are not changed significantly by these small additions and affect primarily only the colour, transmission and reflection.

Typical Mechanical Properties:

Young's Modulus E 72 GPa

Poisson's Ratio μ 0.23

Hardness Moh's 5-6

Annealed < 4,000 Psi (27.6 MPa)

Heat-Strengthened < 8,000 Psi (51.4 MPa)

Fully Tempered >13,000 Psi (89.6 MPa)

Coefficient of Linear Thermal Expansion (CTE) $\alpha_{25...275^{\circ}\text{C}}$ $8.3 \times 10^{-6}\text{K}^{-1}$

Specific Heat Capacity (@ 25°C) CP 0.88 KJ x (kg x K)⁻¹

Softening Point ASTM C 338 715°C

Annealing Point ASTM C 336 548°C

Strain Point ASTM C 336 511°C

Coefficient of Thermal Stress 0.62 MPa /°C

Maximum Recommended Operating Temperature

 Fully Tempered Tmax250°C

Resistance to Thermal Shock

 Annealed 38°C

 Heat Strengthened 121°C

 Fully Tempered 204°C

Typical Chemical Mix

72.6% SiO₂

13.9% Na₂O

0.6% K₂O

1.1% Al₂O₃

8.4% CaO

3.9% MgO

0.2% SO₃

0.11% Fe₂O₃

Emissivity @ 25°C = 0.84

Appendix F: Simple Spreadsheet for Calculating Time to Heat Glass

	A	B	C	D	E
1	Glass Rate of Heating				
2					
3	Ambient Temperature	15	Degrees C		
4	Furnace Temperature	690	Degrees C		
5	Glass Exit Temperature	620	Degrees C		
6	Heating Constant	17.6	Radiant Furnace		
7	Rate Time	1	seconds		
8	Glass Thickness	4	mm		
9					
10	Temperature Rise =	0.987	degrees per 1 secs		
11					
12	Time Required to 620C =	159.5	Seconds		
13					

"Time Required to "&C5&"C ="

$(C4-C5)*(1-EXP(1)^{-(C7/C8/C6)})$

$(-1*(C8*C6)*LOG(1-((C5-C3)/(C4-C3)))/LOG(EXP(1)))$

Cells:

- C3 = Ambient temperature.
- C4 = Average furnace temperature.
- C5 = Required exit temperatures.
- C6 = 26 for Hard Coated Low E in a Radiant Furnace.
= 17.6 for clear glass in a Radiant Furnace.
= 16 for a medium body tinted glass in a Radiant Furnace.
= 12.5 for any glass in a full Forced Convection Furnace.
- C7 = Time period for final rate of heating (at glass exit time) usually 1 second.
- C8 = Glass thickness in mm.
- C10 = Calculated rate of temperature rise as glass leaves furnace.
- C12 = Calculated time to reach temperature set in C5.

Example of a low temperature furnace setting:

The low temperature furnace setting below, of 665°C, shows a much reduced rate of temperature rise as the glass exits the furnace which will improve the uniformity of heating across the area and throughout the thickness of the glass. There is however a loss of 20% in production throughput due to the extended heating time.

Glass Rate of Heating				
Ambient Temperature	15	Degrees C		
Furnace Temperature	665	Degrees C		
Glass Exit Temperature	620	Degrees C		
Heating Constant	17.6	Radiant Furnace		
Rate Time	1	seconds		
Glass Thickness	4	mm		
Temperature Rise =	0.635	degrees per 1 secs		
Time Required to 620C =	188.0	Seconds		