Glass in buildings

Breakage – the influence of nickel sulfide

CENTRE FOR
WINDOW AND
CLADDING
TECHNOLOGY

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1st edition

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1st edition

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FOREWORD

Due to its exciting possibilities and versatility the use of glass in buildings has been at a high level for a number of years and the glazed proportion of buildings continues to increase. Fully-glazed exterior walls became commonplace in commercial buildings during the 1980s and during the 1990s ventilated facades grew in popularity, increasing the number of layers of glass in facades. Large areas of space are now covered with glazed roofing. Inside buildings the amount of glass used in barriers, floors, ceilings and partitioning is also significant. Much of this consumption of glass has been achieved by exploiting the strength of thermally toughened glass in combination with its classification as a safety glazing material.

Glass may break in service for a number of reasons, which are discussed in this guide. Glass in different conditions of heat treatment breaks in different characteristic ways. The notable characteristic of toughened glass is that breakage involves the sudden release of stored energy and shattering into small particles. In addition to the common causes of glass breakage, toughened glass can also be caused to shatter by discrete inclusions of nickel sulfide within the body of the glass. These inclusions occur rarely and arise from occasional contamination of the raw materials with minute quantities of nickel.

This guide covers the measures taken to avoid nickel sulfide inclusions in float glass, together with the estimated rate of its occurrence, heat-soaking to reduce the risk of critical inclusions in toughened glass and estimates of the residual risk of inclusions in heat-soaked thermally toughened glass.

The CWCT prepared this guide because the volume of toughened glass currently in buildings has recently made nickel sulfide-induced failure of glass the subject of widespread discussion and it recognised that there was a lack of up-to-date information in the public domain. The contributing sub-group comprised members of the CWCT with relevant experience in the processing, specification and use of architectural glass. The guide aims to present information and considered opinion from a cross section of the industry that will aid those involved in the construction and use of buildings to assess the risks and benefits of toughened glass. Some of the information is by its nature statistical and its use in practice will require qualified engineering judgement.

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1 OVERVIEW

This chapter presents a simple introduction to glass and nickel sulfide; the following chapters describe glass and nickel sulfide in more detail.

1.1 Advances in the use of glass

The use of glass in buildings is increasing with the now-routine construction of large glazing screens, glass roofs and curtain walls. With care glass can be used as a structural material. Guidance on the structural use of glass is given in ‘Structural use of glass in buildings’, IStructE 1999.

The increased use of glass has come about because of the flexibility available when using glass to control:

- Visual impact
- Daylighting
- Solar gain
- Acoustics
- Energy usage

Hand-in-hand with the ever-expanding list of applications, technical developments have allowed the production and use of larger panes of glass of higher quality and better visual appearance.

The basic form of glass is called annealed, which is defined in BS 952: Part 1 as

‘Glass that has been subjected to controlled cooling to reduce the presence of residual stresses thus allowing easy cutting. It is ordinary glass which includes float glass, sheet glass, patterned glass and wired glass and is independent of the glass composition.’

There are numerous different types of glass, many with their own specialist uses. Glass used in buildings is mostly soda lime silicate glass and most is produced using the float process. However, borosilicate glass is sometimes used in applications where enhanced fire resistance is required.

1.2 Glass manufacture, properties and failure characteristics

Glass is produced from bulk natural materials. These materials are processed to a high standard but naturally occurring minerals inevitably contain a low level of impurities. In some glasses other materials are deliberately added to give the glass a different property, for example if the finished product is to have a body tint.

In mechanical terms glass is theoretically very strong, stronger even than steel. Unfortunately the surface of a piece of glass is covered with microscopic flaws, which significantly lowers its strength. For the majority of applications however the strength of annealed glass is still sufficient to withstand ordinary design loads, and it is widely used. For applications that demand greater strength manufacturers have developed heat-strengthened and toughened glasses. For applications that demand safety manufacturers have developed laminated, safety wired and toughened glass. Safety glasses have modified mechanical properties that improve their post-failure performance (all are intended to fail safely, but not all are stronger than the same thickness of monolithic glass).

There are several ways in which glass can be over-stressed, including impact, thermal stress and simple mechanical overload. The risk of glass failure is increased if the edges of a pane of glass are poorly cut or damaged during installation. (Appendix A describes glass failures). The majority of glass failures have always tended to be due to impact, often deliberately caused. However, breakages also occur as a result of latent defects or natural catastrophe.

Failure of glass is an emotive subject; many people associate glass failure with sharp-edged dagger-like shards that readily lacerate people. However, whilst annealed glass does fail in this way its use is well understood, and if properly designed, handled and installed a pane of annealed glass does not present any particular hazard to human safety. The worst accidents involving annealed glass in buildings, those in which an individual accidentally impacts a pane, may be due to carelessness and disregard for personal safety. The Building Regulations, (England and Wales), Approved Document N, now addresses this issue.

Thermally toughened soda lime silicate glass, which is classed as a fail-safe glass (properly toughened glass always meets Class A of BS 6206) produces small fragments (called dice) rather than sharp-edged shards. Failure of toughened glass, whilst sudden and often accompanied by a loud ‘crack’ or ‘bang’, is not explosive, as frequently described by the press. When toughened glass fails the fragments of glass may remain together and fall as clumps until they impact a hard surface.

For glass in a vertical position the fragments are often held in place until some external force dislodges them from the frame. In the case of impact it is the impacting object that can dislodge the glass (the impacting object may present the greatest threat to human health and safety in many cases).

After toughened glass has failed it may remain in a frame for several days, if vertical, or may fall under the influence of gravity if sloping. Fractured vertical glazing may be dislodged by wind loading or by thermally induced movement and should normally be removed within 24 hours. Gravity may also cause the collapse of glass that is only fixed by local clamps or bolted connections. In no circumstance apart from impact does the failure of glass impart significant translational energy to the glass fragments.

Rightly or wrongly, failure allegedly induced by nickel sulfide inclusions is sometimes considered by lawyers to indicate defective glass and there have been a number of disputes and legal cases.

1.3 So why is nickel sulfide an issue?

Nickel sulfide is one of the causes of failure of toughened glass.

Nickel sulfide has its origin in the impurities that are present in the basic ingredients used to manufacture glass. The presence of nickel sulfide in a batch of glass is variable, and significant quantities of glass may contain no nickel sulfide to speak of. Conversely an occasional batch of glass may contain a relatively high proportion of nickel sulfide. It should be noted that nickel sulfide was first identified as a cause of spontaneous toughened glass failure in the early 1960s. Growing understanding of the problem, particularly during the 1990s, has led manufacturers to take great steps to eliminate this particular impurity. In particular metal alloys that contain nickel (typically stainless steels) have been eliminated from the manufacturing process.

Nickel sulfide is present from the initial production process, i.e. all of the glass which comes off the end of a float tank may contain nickel sulfide, just as it contains all of the other impurities that were present in the basic ingredients. However, nickel sulfide does not become a potential problem in glass until the glass is thermally processed to produce toughened or heat-strengthened glass.

In this document heat-strengthened glass is defined according to the European Standard BS EN1863. In the USA heat strengthening is defined in such a way that high strength glass is close to toughened glass in its properties; nickel sulfide failure is more likely in some heat-strengthened glass manufactured to USA standards rather than to European standards.

When nickel sulfide impurities are present they are in the form of small crystals. However, there are different crystalline forms of nickel sulfide, each stable within a different range of temperatures.

During manufacture of annealed glass nickel sulfide crystals are produced. During the thermal toughening process glass is heated and then quenched, to generate locked-in stresses which have the effect of strengthening the glass. However, during this process any nickel sulfide crystals present undergo a phase change, into a high-temperature-stable form known as α-NiS. The problem is that the α-NiS crystal is more dense than the β-NiS crystal, and so occupies a lower volume (about 4% less). The softened form of the glass at the high toughening temperatures allows the glass to contract around the shrunken α-NiS crystal. When the glass is quenched the sudden cooling is rapid enough to harden the glass around the crystal, but too rapid for the crystal to change back into its β-NiS form.

The nickel sulfide crystal must revert to its low temperature form, but can only do so slowly. As it does so it must expand, and it is this expansion against the hard glass that generates the stresses that cause the glass to fail. The change of state of a nickel sulfide crystal is both temperature and time dependent, occurring more slowly at lower temperatures. However, the crystal is only likely to cause a failure if it is large enough to generate significant stress and is in the tensile core of the toughened glass, Chapter 3. Crystals capable of causing a failure are called critical inclusions.

In context, a single float plant produces about 6000 kilometres of glass in a year, in a continuous ribbon three metres wide and in a range of thicknesses. Up to half of this glass is for the architectural glass market. If the average pane of glass is, say, 1 m^2 in area then 18 million panes of glass are produced each year. Only a small proportion of this glass is thermally toughened, but even so tens of thousands of panes of toughened glass are put into buildings each year in the UK. The number of probable nickel sulfide failures is by comparison extremely small.

The actual rate of occurrence of nickel sulfide is clearly very low. However, for large areas of glass or glass used in sensitive areas a risk analysis should be carried out as described in Chapter 6, as even a single nickel sulfide induced failure could pose a threat to health and safety.

1.4 Heat-soaking

Toughened glass has been used since the 1930s. Nickel sulfide was first identified as a mechanism for toughened glass failure in the early 1960s. Processes of heat-soaking were first developed as a means of reducing the incidence of nickel sulfide failures during the 60s. These have been further developed and will culminate in the publication of a European Standard.

Heat-soaking is a process applied to thermally toughened soda lime silicate glass, to induce failure of those panes that contain critical nickel sulfide impurities. According to the major glass manufacturers the residual statistical rate of occurrence can be reduced to less than 1 critical inclusion per 400 tonnes of heat-soaked toughened glass if the glass is manufactured according to the draft European Standard prEN 14179.

In the heat-soaking process, toughened glass is reheated to encourage the conversion of nickel sulfide crystals from their less stable α form to their β form. Inclusions that are sufficiently large will normally generate stresses sufficient to cause failure of the affected pane in the heat-soaking oven. This requires the process to be controlled accurately enough for the glass to attain a certain temperature for a sufficiently long period. The need for accurate control is now better understood than a few years ago and heat-soaking procedures are tending to improve in terms of reliability.

However, failure of glass in the heat-soaking oven can also occur due to other causes, for example stress concentrations at holes, regions of edge damage or over-rapid heating or cooling. The rate of failure in the heat-soaking oven is therefore not a measure of the rate of occurrence of nickel sulfide inclusions.

Note that heat-soaking is not guaranteed to remove all glass that contains critical nickel sulfide inclusions. A real risk of spontaneous breakage will remain. Thus if there is a need to eliminate all possibility of nickel sulfide inclusion induced failures, the use of toughened glass or heat-strengthened glass should be avoided.

1.5 Specification

Glass should always be specified initially on the basis of an assessment of the requirements for strength and safety. There is sometimes a choice of alternatives however, and the final choice can then be based on a consideration of cost and availability factors.

Toughened glass is commonly used where enhanced strength is required. These uses include:

- Thermal safety
- Overhead glazing
- Bolted glazing
- Glass structural members
- Insulated panel facings

Toughened glass is used for safety in:

- Door panels and adjacent glazing
- Other areas of low level glazing

In each case the specifier has to assess the risk of failure and consequences of failure before deciding whether to use heat-soaked toughened glass. The heat-soaking of toughened glass will reduce the incidence of failure due to nickel sulfide, and therefore disruption costs, and the risk of the building becoming stigmatised as unsafe. It will also give savings on maintenance and replacement costs.

Heat-soaked toughened glass is more expensive than ordinary toughened glass, due to the additional processing. However, if a risk analysis indicates that the incidence of nickel sulfide induced failure should be minimised in a given situation then heat-soaked toughened glass must be specified and used unless alternative glasses such as laminated glass are used. Prior to deciding on glass type however, it is essential to consider all relevant performance requirements and to undertake the associated risk assessments.

The specifier may try to avoid the use of toughened glass altogether but this is not always economical or even possible. The use of other glasses, such as laminated glass, may require greater thicknesses that carry a weight penalty. This may in turn be reflected in additional costs of the supporting structure, particularly for roofs, Chapter 5. Each potential glass configuration may have different breakage characteristics that also require review in a risk assessment prior to selection.

1.6 Glass failures

Glass failures that occur during the service life of a building may be due to many causes and nickel sulfide induced failure is not the dominant cause of thermally toughened glass failure (impact, usually due to vandalism, accounts for the great majority of failures). Any failure can be distressing to an owner or occupant and have an impact on the conduct of business and value of the property. All failures should be properly investigated and appropriate remedial action taken. This should be based on a full assessment of the risk presented by the remaining glass. Failure of a single pane of glass on a building is not necessarily indicative of a large or ongoing problem. Even if a single pane of glass fails and nickel sulfide is proven to be the cause it may on a small building be unlikely that further panes will fail, particularly if the glass has been correctly heat-soaked. Steps should be taken to ascertain whether, and how, the glass was heat-soaked. An assessment can then be made of the likelihood of further failures. A proper risk analysis will then identify the best course of remedial action if any.

1.7 Standardisation

European standardisation is changing the way in which glass, for use in buildings, is specified. Product standards are already available or in course of preparation that will define the various glass types, basic and processed, currently available. A list of relevant standards is given in the references.

The standard for ‘thermally toughened soda lime silicate glass’ is published. A separate product standard is in preparation for ‘heat-soaked thermally toughened soda lime silicate safety glass’. This will define the product itself, product properties and the production process including calibration of the heat-soaking oven. The product standard specifies the residual risk of breakage resulting from nickel sulfide inclusions.

All of the European Standards have a part dealing with ‘evaluation of conformity/factory production control’. This part of the standard defines how a product can meet the essential requirements of the Construction Products Directive. The product will have to be produced under a ‘system of attestation’, i.e. level of involvement of independent third party organisations, decided upon by the European Commission.

The European Standard will ensure the specified product is heat-soaked using a process with a known average statistical risk of nickel sulfide failure for large volume production.

1.8 Summary

The use of glass in buildings delivers many benefits but it can break. It can be a safe material, even post-failure, but the selection of a particular glass should be made on the basis of a thorough understanding of the material and the circumstances of its use.

An appropriate risk assessment should consider the types of glass that may be used, the risk of different forms of failure and consequences of failure. It may be appropriate to use a toughened glass. With proper specification of heat-soaked toughened glass it is possible to greatly reduce the risk of nickel sulfide induced failure.

The following chapters give guidance to the reader on a more technical level. Chapter 2 describes annealed, heat-strengthened, toughened and heat-soaked toughened glass. Chapter 3 describes the properties of nickel sulfide, and Chapter 4 describes heat-soaked toughened glass in accordance with the current knowledge of the forthcoming European product standard.

Chapter 5 discusses why toughened glass must be used in many situations. Chapter 6 highlights factors that the specifier must consider when choosing glass. Finally Chapter 7 considers the diagnosis of a nickel sulfide problem, and looks at possible remedial action.

This document concludes with three appendices and references: Appendix A reviews the common causes of glass failure, Appendix B gives data relating to the rate of occurrence of critical nickel sulfide inclusions and Appendix C lists terminology relating to glass and nickel sulfide.

2 GLASS TYPES FOR ARCHITECTURAL USE

This chapter describes annealed, heat-strengthened, toughened and heat-soaked toughened glass. This chapter is not intended to give a full definition of each glass type, but rather to describe the key characteristics of each type of glass and the differences between them.

2.1 Annealed glass

Annealed glass has been subjected to controlled cooling during production to reduce the presence of residual stresses thus allowing easy cutting. It is ordinary glass that includes float glass, sheet glass, patterned glass and wired glass.

If glass is manufactured without controlling the rate of cooling then residual stresses are developed which cause the glass to fracture unevenly when cut. Annealed glass can be cut with a clean edge simply by scoring along one surface and bending the glass over a raised edge. Annealed glass is the least expensive and most readily available type of glass.

BS EN 572-1 uses the term ‘basic’ glass, rather than annealed. That standard defines soda lime silicate glass as ‘glass having a chemical composition in the range’:

Silicon dioxide (SiO_2)	69 to 74%
Calcium oxide (CaO)	5 to 12%
Sodium oxide (Na_2O)	12 to 16%
Magnesium oxide (MgO)	0 to 6%
Aluminium oxide (Al_2O_3)	0 to 3%

The glass may also contain trace amounts of other substances. The glass could also be deliberately modified by the addition of other materials to produce a tinted glass.

Annealed glass is made by a number of processes, loosely described in BS EN 572-1:

- Float glass is glass having parallel and polished faces obtained by continuous casting and flotation on a metal bath;
- Drawn sheet glass is obtained by continuous drawing, initially vertically, of a regular thickness and with the two surfaces fire polished;
- Patterned glass is manufactured by continuous casting and rolling;
- Wired glass is glass obtained by continuous casting and rolling which has a steel mesh, welded at all intersections, incorporated in the glass. The surfaces may be either patterned or plain;
- Polished wired glass is glass having parallel and polished faces obtained by grinding and polishing the faces of wired patterned glass.

The absence of residual stresses in annealed glass means that the applied loads on the glass (i.e. wind, snow, self-weight, impact and subsequent thermal stressing) are the only sources of stress in the glass. The maximum strength of annealed glass is limited only by the tensile strength of the glass.

The theoretical tensile strength of monolithic annealed glass is very high (20,000 N/mm2). However the glass surface has myriad imperfections known as Griffith flaws (microscopic cracks and scratches). As with any flaw in a material, stress concentrations occur at the tip of the flaw and consequently weaken the glass surface. The effective tensile failure strength is substantially reduced. It depends on the type and duration of load and covers the range 5 - 120 N/mm2.

2.1.1 Breakage of annealed glass

Annealed glass generally breaks into sharp-edged shards when it fails, the shape and number of which often depend upon the cause of failure. For this reason it can be dangerous in the event of failure if pieces fall free from the glazing frame, or if a person contacts the broken pieces. However, if called for glass can be made to be stronger and/or made to fail more safely by additional processing as described below.

2.2 Heat-strengthened glass

Heat-strengthened glass is formed by re-heating annealed glass and then cooling it under controlled conditions (more rapidly than during the annealing process, but not as rapidly as for toughened glass, see 2.3). Differential rates of cooling between the surface and the core of the glass causes differential contraction, the effect of which is to generate a compressive stress in the surface layer of the glass and a balancing tensile stress in the core of the pane.

Heat-strengthened glass offers some of the strength benefits of toughened glass (described below), but it still fails in a manner similar to that of annealed glass (i.e. not safely) but at higher loads. In the UK the availability of heat-strengthened glass is limited, and it may not be possible to source panes above about 8 mm in thickness. The production of heat-strengthened glass to a required standard is more difficult and requires greater control of the oven temperature and quenching rate. As a result it is often more expensive than toughened glass.

Heat-strengthened glass is sometimes referred to as ‘partly toughened’; by varying the strengthening process it is actually possible to produce glass with fracture properties and strength anywhere between those of annealed and toughened glass.

Care must be taken that the glass is not over-strengthened to the point that the glass behaves as if toughened. The definition of heat-strengthened glass in the European Standard BS EN 1863 requires heat-strengthened glass to exhibit fracture properties similar to those of annealed glass, but with a limit on the number and size of fragments.

Whilst it is theoretically possible and there have been claims of nickel sulfide failures in heat-strengthened glass many of these may have occurred in glass that has not been properly heat-strengthened or for which production records are not available. Although nickel sulfide induced failure is theoretically possible in heat-strengthened glass it requires much larger inclusions.

2.3 Thermally toughened glass

Thermally toughened glass is formed by heating and then rapidly cooling (quenching, but in a controlled manner) annealed glass. Differential rates of cooling between the surface and the core of the glass causes differential contraction, the effect of which is to generate a compressive stress in the surface layer of the glass and a balancing tensile stress in the core of the pane. The locked-in compressive stresses at the surface of the glass prevent the surface flaws from propagating until the compressive stresses are completely overcome and sufficient tensile stress is generated to overcome the basic strength of the glass.

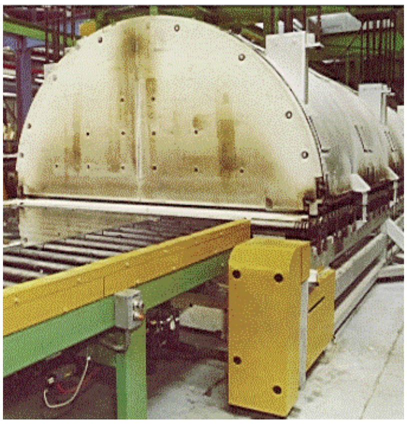

Fig 1 ***Toughening oven***

The tensile stresses in the core of a pane of thermally toughened glass are the reason why the glass fails as it does. The tensile stresses are normally contained by the balancing surface compressive stresses. If the compressive layer is breached by a crack then the energy contained in the core, as a tensile stress, is sufficient to cause rapid propagation of multiple cracks throughout the glass. This results in the pane shattering into numerous small pieces of glass known as dice.

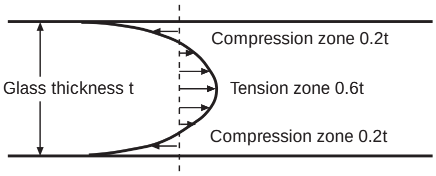

Fig 2 ***Stress distribution in toughened glass***

As a rule of thumb each surface compressive layer is 1/5 of the glass thickness, and the core tensile zone is 3/5 of the thickness. In a 6 mm thick pane the surface compressive layer is approximately 1.2 mm thick. Interestingly it is possible to damage the edge of a piece of toughened glass, but providing the damage does not penetrate the compressive layer the glass will not fail immediately. However, the strength of the glass may be significantly reduced by such damage, and it is not wise to use toughened glass that has been damaged. Many contractors fail to spot edge damage however, and the design of many framing systems does not allow damaged edges to be inspected once the glass is installed. The nature of the failure of thermally toughened glass is such that proving edge damage after failure is often impossible. However, if the pane is held in place by the framing system there will be a tell-tale pattern of cracks radiating away from the edge of the pane at the point where the damage occurred.

It is also possible to strengthen glass by chemical means. In chemical strengthening the glass is immersed in a bath of molten potassium nitrate, which causes the sodium atoms near the surface of the glass to be replaced with larger potassium atoms. This generates a compressive stress at the surface, but the compressive layer is very much thinner and the tensile stress in the core of the glass is very low, when compared to thermally toughened glass. Chemically strengthened glass for use in buildings should comply with EN 12337. The performance of chemically strengthened glass is not directly equivalent to that of thermally toughened glass. It is not a safety glass.

Importantly glass cannot be cut after thermal toughening (it would fail instantly as the compressive layer was penetrated) and all cutting, drilling and shaping have to be completed before toughening. Irregular shaped pieces of glass and even simple round holes will modify the pattern of compressive stress in the surface of the glass and corresponding tensile stresses. The edges of toughened glass panes are generally arrised before toughening - this reduces imperfections and features in the edge that might otherwise cause failure during the toughening process.

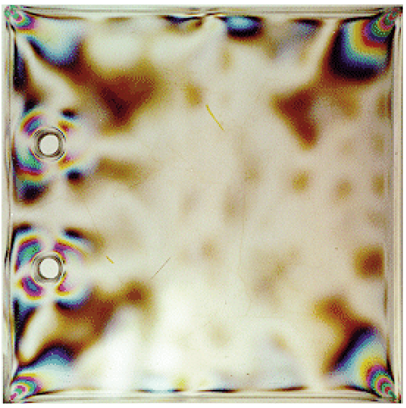

Fig 3 ***Stresses in toughened drilled glass***

The maximum size of glass sheet that can be toughened is governed by the size of toughening oven available. Most toughening ovens can handle sheets up to 2100mm wide. The larger ovens can generally toughen sheets up to 2400mm wide. Beyond this size there are a few ovens that can toughen larger sheets but these are not readily available. As a rule increasing the sheet size required reduces the number of suppliers. The designer who tries to use the largest panes may find problems with availability and delivery time (and the cost might be even higher if the glass processor knows that his oven is the only one that can handle that size of glass).

2.3.1 Breakage of toughened glass

Toughened glass that achieves an appropriate particle count on breaking, or does not break, can be regarded as a Class 'A' safety glass as it will pass the requirements of BS 6206.

The recently published European Standard for 'thermally toughened soda lime silicate safety glass' (EN 12150) defines the product by means of the following:

- A fragmentation test; for 6mm glass this is a minimum of 40 particles in a 50mm x 50mm square,

- A 4-point bending strength test

And, if the product is claimed to give protection in the case of accidental human impact:

- A classification in accordance with prEN 12600. This will give toughened glass a different performance classification, when compared with BS 6206, as it looks at first breakage as well as safe breakage characteristics.

When thermally toughened soda lime silicate safety glass breaks an individual fragment is fairly small and relatively light. However, fragments can clump together and form larger pieces. This is more likely to occur if breakage is internally induced (for instance by nickel sulfide). This issue is discussed further in Chapter 6.

A broken vertical pane may remain in its frame unless dislodged by the wind, thermally induced bowing, human interference or freezing water. Bolted glass however has no frame, and often has little to support it if it breaks. Sloping panes are highly likely to fall, even if framed, soon after they break.

Fig 4 ***Failure of vertical toughened glass***

2.4 Heat-soaked thermally toughened glass

Heat-soaking is a further stage in the glass production process by which thermally toughened glass is re-heated and then held at a high temperature. The intention of this process is to accelerate nickel sulfide inclusion conversion, so that nickel sulfide inclusions revert to their β state in the heat-soaking oven rather than on the building. Proper heat-soaking significantly reduces the incidence of nickel sulfide failure, but does not otherwise change the physical properties of the glass (it is as strong as thermally toughened glass and fails in the same way).

If the specifier is certain that toughened glass must be used, and has carried out a risk assessment which indicates that the risk of spontaneous failure resulting from nickel sulfide inclusions should be minimised then heat-soaked toughened glass should be specified.

Note that heat-soaking does not guarantee the elimination of all critical nickel sulfide inclusions. If failure is unacceptable then a different design may be necessary to enable the use of a configuration that does not incorporate toughened glass.

The heat-soaking process is described in more detail in Chapter 4.

2.5 Laminated glass

Laminated glass is formed by bonding together two or more panes of glass using a plastic interlayer. Any of the above forms of glass may be used, in any combination. A common interlayer material is poly-vinyl-butyral (PVB), which is used in multiples of 0.38 mm thickness. A thicker interlayer may help to reduce the risk of projectile penetration on impact.

Glass is laminated for the purpose of:

- Keeping the glass in place should a pane of glass break,
- Reducing the likelihood of penetration (for security or safety reasons),
- Improving acoustic properties;
- Giving decorative effects.

Laminated annealed-annealed glass breaks into shards having sharp edges, but these are held together by the interlayer. Different interlayer materials and thicknesses have different effects upon performance.

Toughened glass in a laminate will fracture into small dice. The use of only toughened glass in a laminate will produce a glass that is flexible post-failure, if both sheets fail, although the glass dice remain attached to the laminate. The CWCT does not recommend use of laminated toughened-toughened glass in sloping overhead situations where the post-failure flexibility of the broken laminated glass could present a hazard.

The use of annealed or heat-strengthened glass with toughened glass in a laminated glass will give the glass greater integrity post-failure.

Laminated glass is only slightly weaker than a single pane of the same thickness and type of glass but will deflect more under long-term loads. Under short-term loads it behaves as monolithic glass in terms of both strength and deflection.

3 NICKEL SULFIDE INCLUSIONS

3.1 Introduction

All glass contains impurities that arise from the raw ingredients and sometimes from equipment used during the manufacturing process. One of these impurities is nickel sulfide.

Steps have been taken by the glass manufacturers to reduce the incidence of nickel sulfide, since the significance of nickel sulfide was discovered in the early 1960s. This principally consists of efforts to remove nickel from the process. Whilst nickel may be found in the raw materials it is also likely to be found in processing machinery which is made from stainless steels containing nickel. The glass manufacturers have eliminated the deliberate use of stainless steel but manufacturers have reports of tracing a sudden nickel sulfide outbreak to the unintentional use of stainless steel tools during raw material extraction or transportation.

Just 0.1 gramme of nickel will produce 50,000 nickel sulfide inclusions of 100 micron diameter, each sufficient to cause a pane of thermally toughened glass to shatter spontaneously (Bordeaux and Kasper 1997). The fact that such wholesale failure of toughened glass does not occur reflects the glass producers' efforts to eliminate nickel sulfide from the process. The rate of occurrence of critical inclusions is claimed to be between one per 4 tonnes and one per thirteen tonnes of glass by the European glass manufacturers. In practice one critical inclusion in four tonnes equates to one failure per 265 m^2 of 6 mm thick glass (Appendix B presents figures for other rates of occurrence and glass thickness').

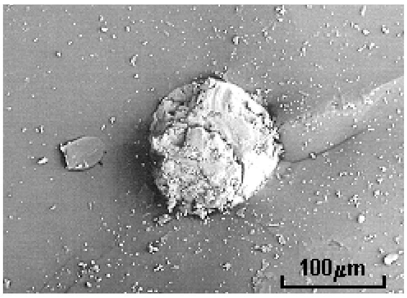

Fig 5 ***A nickel sulfide inclusion viewed under a scanning electron microscope***

3.2 The chemistry of nickel sulfide

Nickel sulfide as it is found in glass is not composed purely of nickel and sulfur but also contains a small amount of iron. A paper by Kasper (1999) suggests that scanning electron microscope analysis of nickel sulfide inclusions gave a mean composition of $Ni_{0.99}Fe_{0.01}S_{1.00}$, i.e. 99 parts nickel and 1 part iron to 100 parts sulfur. Importantly the iron was found to slow the rate at which nickel sulfide inclusions change state.

Like many crystalline materials nickel sulfide can exist in different crystal forms. At low (room) temperatures the stable form is the rhombohedral form conventionally designated as β-NiS. At the higher temperature associated with the toughening oven nickel sulfide is stable as a hexagonal form designated as α-NiS. The transition between the forms is not instantaneous however - there is a time-temperature dependent relationship for the conversion, and the conversion occurs gradually throughout the inclusion, so that at any given time and temperature there can be a mix of β-NiS and α-NiS.

3.3 The physics of nickel sulfide

Any piece of annealed glass could contain nickel sulfide inclusions, which are of no consequence while the glass remains annealed. However, when annealed glass is re-heated during the thermal toughening or heat-strengthening process the glass reaches a high enough temperature of sufficient duration to convert the NiS into its α state. Then, when the glass is rapidly quenched to induce surface stresses there is insufficient time for the inclusions to revert to their β state. The process of conversion to their β state will take place at room temperature but at a slow rate.

The low-temperature β-NiS has a looser crystal structure (i.e. is less dense) and occupies a volume about 4% greater than the high-temperature α-NiS crystal. During the heating part of the toughening or heat-strengthening process the glass passes its softening temperature and is able to contract around the shrinking inclusion. When the glass is quenched it hardens rapidly, and the glass is solidified around the smaller α-NiS inclusion. Any change of state of the NiS cannot now be accompanied by a change in volume, and so the inclusion presses on the glass to generate a stress concentration. It is this stress concentration which causes the glass to break.

The magnitude of the stress concentration depends upon the size of the inclusion and the central tensile stress in the glass around the inclusion. A formula for the critical diameter of a spherical inclusion (Bordeaux and Kasper 1997) is:

$$D_C = \frac{\pi K^2_{IC}}{3.55 P_0^{0.5} \sigma_0^{1.5}}$$

K_{1C} is the stress intensity factor and is a constant (0.76 $m^{0.5}$MPa). P_0 accounts for differences in thermal expansion coefficient of the NiS and the glass and is also a constant (615 MPa). The critical diameter D_C is therefore inversely proportional to a power of the glass residual stress σ_0.

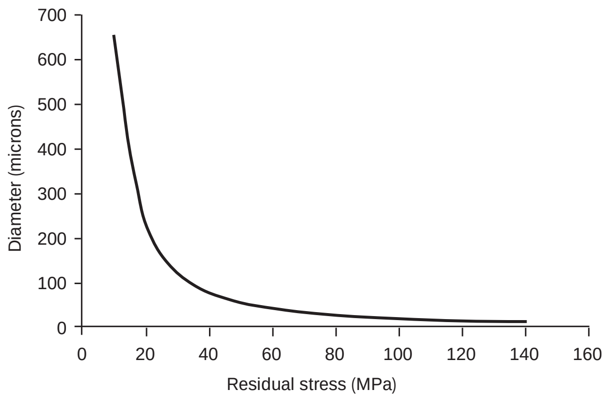

Fig 6 ***Relationship between critical diameter and surface stress (Bordeaux and Kaspar, 1997)***

Annealed glass has no residual stress (σ_0=0) and so an inclusion would have to be infinitely large to cause failure (therefore nickel sulfide is not a problem in annealed glass). For a thermally toughened glass with a residual tensile stress of 50 MPa the critical diameter is 58 microns. Bordeaux and Kasper (1997) report measurements on 250 inclusions that have caused failure of toughened glass, and found an average diameter of around 200 microns. A similar paper by Kikuta and Sakai (1999) gives a mean diameter of 150 microns. Theoretically an inclusion could cause failure of heat-strengthened glass if large enough; again Bordeaux and Kasper calculate that an inclusion would have to be at least 160 microns in diameter to cause failure in a heat-strengthened glass with 25 MPa residual stresses. Nickel sulfide failures are known to have occurred in heat-strengthened glass with nickel sulfide inclusions of 230 microns diameter. Nickel sulfide induced failure of heat-strengthened glass occurs less often as nickel sulfide inclusions of sufficiently large size are less likely to form in the basic glass.

The relationship between inclusion critical diameter and induced stress is also important in dictating where the inclusion needs to be to cause failure. As discussed previously the stress distribution in a piece of toughened glass ranges from tension at the core of the glass to compression at the surfaces. A smaller inclusion can cause failure in the tensile core of the glass, whilst a larger inclusion is needed where the stresses are lower. Nickel sulfide crystals in the surface compression zone do not cause failure and are not critical inclusions. Bordeaux and Kasper have plotted the distribution of the inclusions against normalised glass thickness and have found that the majority of failures occur with inclusions located in the central 40% of the glass.

Only impurities above a certain size will cause failure, and then only if they are in the core (tensile zone) of the glass. Inclusions that meet these criteria are known as critical inclusions.

3.4 Detection

At the present time there is no reliable, cost effective, non-destructive way to detect nickel sulfide inclusions in glass. Attempts to find them using polarised light and microscopy have failed either because they do not identify a sufficient proportion of the inclusions or because the process cannot be applied to tonnes of glass in a practical time period.

3.5 The rate of failure

Bordeaux and Kasper (1997) present data for nickel sulfide failures on a particular heavily affected building. Failures appeared immediately after construction, and over a period of 4,000 days (more than 11 years) about 180 individual pane failures occurred. Half of the failures occurred within the first 800 days or so, and the rate of failure at 4,000 days can be estimated as 1 failure per 100 days.

The relatively high number of failures described above highlights one of the concerns with nickel sulfide - clusters of failures may occur if there is a lapse in the production process and a source of contamination is missed. However, few incidences of nickel sulfide reach this scale, particularly where glass has been heat-soaked. Many cases of nickel sulfide are of the order of one or two failures per year at most.

Roof glazing and south facing glazed spandrel panels falsely appear to contain more critical nickel sulfide inclusions than glass used elsewhere, because they get warmer in use. The warmer environment accelerates the conversion of crystals so that more failures occur earlier on in the life of the building.

When considering risk it is important to consider the risk of failure over the life of the building. If there are three critical nickel sulfide inclusions in a whole roof then they may all cause failure in year two or they may cause failure at irregular intervals over 10 or 20 years. Both sequences present the same whole-life risk but the perception of risk will be higher for a building operator reviewing the situation in year two of the building’s life. Risk assessment and its bearing on glass specification is discussed in more detail in Chapter 6.

3.6 Preventing a problem

The implications of nickel sulfide depend upon the particular application, and on many factors. In the worst case nickel sulfide failure may be a hazard to the general public, for instance where glass falls on to a trafficked area. In the best situation it might only represent a nuisance and maintenance cost that the bill-payer would prefer to avoid, for instance where any broken glass is prevented from falling by a lower sheet of glass.

When nickel sulfide induced failure is not considered to pose a threat to health and safety, the decision to deal with or accept a possible problem comes down to the bottom line. The developer may wish to spend a little more money to avoid a potential problem, or the impact on whole-life costs may be too weak, see Chapter 6.

In many cases the use of toughened glass is desirable, and the use of heat-soaked toughened glass (see Chapter 4) must be specified if the risk analysis warrants this step. If an alternative glass is reasonably practicable then this option may be taken otherwise the specifier may decide that the use of ordinary thermally toughened glass will not be a problem even if nickel sulfide failures do occur. Chapter 5 discusses reasons why toughened glass might be the best or only option for glazing in a particular situation.

The best safeguard against nickel sulfide is to use alternatives to toughened glass. Where toughened glass is used the risk of failure can be reduced by using heat-soaked toughened glass. The heat-soaking process is described in Chapter 4.

4 HEAT-SOAKED TOUGHENED GLASS

4.1 Introduction

Heat-soaking can reduce the risk of failure of toughened glass due to nickel sulfide inclusions. There has long been a debate over whether heat-soaking is a process or a test. The questions should be: Is the heat-soaking done effectively? What is the residual risk of further nickel sulfide induced failure? And, does the final product have the expected properties of a thermally toughened safety glass?

The proposed European Standard for 'heat-soaked thermally toughened soda lime silicate safety glass' (prEN 14179) deals with the final product. For the product, in the future, to claim to comply with the Standard it must be manufactured using a process that has heat-soaking as an integral part. A product produced to the Standard will have a stated residual risk of nickel sulfide inclusions, i.e. 1 per 400 tonnes, and known product fragmentation, bending strength and, if appropriate, impact performance classification.

Heat-soaking is a process in which toughened glass is re-heated, maintained at a specific temperature for a specific time period and then cooled, without compromising the toughened nature of the glass. The heat-soaking process is intended to induce breakage of glass panes that include critical nickel sulfide inclusions. Over the years as more has been learnt about the nature and behaviour of nickel sulfide inclusions and the efficacy of heat-soaking processes, methods of heat-soaking have been refined to improve the rate of detection. Thus, there now tends to be a lower residual risk of breakage in use of toughened glass heat-soaked in accordance with current practice than in former times.

In the past some glass processors have heat-soaked glass by holding it at a high but reduced temperature after toughening, so called on-line heat-soaking. However, this hasn't always been successful. This report relates to off-line heat-soaking in which the glass is cooled to ambient temperature before heat-soaking. This is the practice followed by most of the glass industry, and is required by the European product standard for heat-soaked toughened glass.

4.2 The process

Heat-soaking requires thermally toughened or strengthened glass to be re-heated to encourage the unstable α-NiS crystals to revert to their low-temperature-stable β-NiS form. The objective is to force the stress concentrations that cause the glass to fail to occur in the oven.

Fig 7 ***A heat-soaking oven with stillage for glass***

Thermal toughening of glass takes place at around 620ºC, which is necessarily above the softening temperature of soda lime silicate glass. However, it only needs the glass to be re-heated to 320ºC or more for the toughening pre-stress to begin to reduce. The heat-soaking temperature does however need to be close to this to minimise the time required for conversion of the nickel sulfide to take place. The most practicable temperature is 290ºC plus a certain tolerance.

Heat-soaking is currently usually carried out in accordance with the requirements of the German Standard for spandrel panel glass, DIN 18516; pt4. However, this standard only requires the glass to be conditioned in an oven at a temperature of 290 ±10ºC for a period of 8 hours. Of equal importance is the distribution of temperature within the glass while it is in the heat-soaking oven.

There have been many studies into the best combination of time and temperature to be used for heat-soaking. The exact chemical composition of the nickel sulfide crystal will affect the rate at which conversion occurs. Moreover the rate of heating is also significant, as discussed by Kasper (1999), and theoretically the breakages should all occur before a holding temperature is reached. Experience shows that about one-third of the breakages are claimed to occur during the holding phase of the heat-soak process, and that the holding phase may vary from one to eight hours.

It is very difficult therefore, given the wide variability of current heat-soaking ovens, to state just how effective current heat-soaking practice is. Moreover, some of the failures in a typical oven are due to other factors such as too rapid heating or cooling (this generates excessive thermal stresses) or poor edge working (this weakens the edge so that otherwise acceptable levels of thermal stress causes failure).

Another issue with heat-soaking is how the glass is stacked in the oven. For reasons of economy the heat-soaker would like to put as much glass as possible into the oven. However, if the glass is too closely packed then whilst the air in the oven may reach the holding temperature quite quickly there can be a lag of more than an hour before any part of the glass reaches the same temperature. A further delay of several hours may occur before the last part of any pane reaches that temperature. It is clearly important that the glass temperature is monitored as well as the oven air temperature, and it is equally important that enough temperatures are measured to be confident that all of the glass has reached the desired temperature for a long enough period before the cooling cycle commences.

4.3 The European Standard

The intention of the European product standard is to remove the effect of variations between practice in different plants. The current draft of the European product standard makes the following definitions:

- Heat-soaked thermally toughened soda lime silicate safety glass: Glass within which a permanent surface compressive stress has been induced by a controlled heating and cooling process in order to give it greatly increased resistance to mechanical and thermal stress and prescribed fragmentation characteristics. Also it has a known level of residual risk of spontaneous breakage due to the presence of critical nickel sulfide (NiS) inclusions;

- Level of residual risk: The risk of spontaneous breakage of heat-soaked thermally toughened soda lime silicate safety glass, on a statistical basis due to the presence of critical nickel sulfide inclusions, shall not be more than one breakage per 400 tonnes of heat-soaked thermally toughened soda lime silicate safety glass.

The significance of the 'one critical inclusion per 400 tonnes' statement is easy to see; this equates to one critical inclusion per 26,500 m^2 of 6 mm thick heat-soaked toughened glass. Note that even at these low rates of failure it is possible to use a single pane of glass and discover that it contains a critical nickel sulfide crystal. The failure rate in ordinary toughened glass is reckoned to be about 100 times greater. Based on one critical inclusion per 4 tonnes, this is equivalent to 265 m^2 of 6 mm glass.

The heat-soak process defined in prEN 14179 comprises a heating phase, a holding phase and a cooling phase.

The heating phase starts at ambient temperature and employs a rate of heating that is controlled to minimise breakage due to thermal stress. The heating phase is complete when the surface temperature of every pane of glass has reached 280ºC. During this phase the air temperature in the oven is allowed to exceed 320ºC but no glass surface temperature must reach this level. The time that any glass pane spends above 300ºC is to be minimised, as this will avoid problems of de-toughening the glass.

The holding phase commences when the surface temperature of every pane of glass has reached 280ºC. The glass surface temperatures should be held at 290 ±10ºC for a period of two hours.

The cooling phase commences after the two hour holding period and ends when the oven air temperature reaches 70ºC. The rate of cooling needs to be controlled to reduce the risk of breakage due to thermal stress.

Glass can be placed in the oven (which must be heated by convection - i.e. blowing hot air into the oven) either horizontally or vertically. The recommended spacing of glass is 20 mm. The panes must be free to expand and contract, and the panes must have adequate separation to permit free circulation of air. Furthermore, fragments of broken glass must not block ventilation openings around the glass. Separators between panes should not hinder airflow around the glass, and a typical spacer would be no greater than 40 mm wide or high. The spacing of panes may need to be greater if the glass has holes, notches or cutouts.

Calibration of the heat-soaking oven is a key part of the product standard. Calibration needs to be carried out for 100% and 10% load, where full (100%) load is based on 6 or 8 mm glass thickness. The calibration procedure is defined for 1, 2, 6, 8 or 9 stillages used in an oven, and identifies the location of the stillages and the positioning of temperature measurement thermocouples on the glass. Critically no part of any glass should exceed 300ºC or fall below 280ºC once the coolest glass has reached 280ºC.

The purpose of the calibration is to generate a record that proves that the oven is capable of following the time-temperature relationship defined for the heat-soak process. This may require the oven operator to adjust the spacing of glass on the stillages.

The remainder of the product standard concerns itself with the breakage characteristics of the finished product, and with the positioning of holes, notches and cutouts to avoid problems with stress concentrations, which are the same as for ordinary toughened glass.

4.4 Best current practice and quality assurance

Until the final European product standard is produced there are several steps that can be taken to ensure an acceptable standard of heat-soaking:

i A reputable heat-soaker should already be aware of the recommendations of the draft European product standard, and could be required to work to that draft standard:

ii A reputable processor should be aware of the time and temperature regime required to achieve a given reduction in the rate of failure if the process is applied to a large volume of glass. By specifying a requirement for failure rates for the process for large volumes of heat-soaked toughened glass, an onus is put on the heat-soaker to know the performance of the oven and to have the equipment duly calibrated. Thus a specifier may indicate a requirement for the heat-soaking regime to be designed with an objective of achieving a residual risk of 1 failure per 100 tonnes or 400 tonnes of glass as a statistical average over large volumes of heat-soaking. However, higher or lower rates of failure may still occur on smaller batches associated with individual projects. Appendix B illustrates the potential significance of specifying heat-soaking processes with different attendant statistical risks.

iii A simple statement relating to the number of panes that have failed in the heat-soaking oven has negligible significance as a means of checking the efficiency of the heat-soaking process. This data can tell the manufacturer how many panes have broken but the reason for breakage, e.g. thermal stress, edgework quality, nickel sulfide inclusion, etc, generally cannot be determined. However, this is the only source of data available to a manufacturer and he may use it as the basis for deciding the level of nickel sulfide in the glass by the simple expedient of assuming all breakages are due to nickel sulfide inclusions.

iv Notwithstanding the above, be aware that statistics relating to nickel sulfide failure relate to very large volumes of glass production. Thus, even in well-controlled plants, somewhat higher and lower rates will occur on relatively small batches compared to the average residual rates commonly cited. Thus, building owners should be warned at the glass selection stage that:

- Residual risks are indicative only;
- If toughened glass is used, nickel sulfide induced failures may occur in the life of the building, despite heat-soaking;
- The statistical residual failure associated with heat-soaking regimes (e.g. to the DIN or draft European Standard) is for large volumes of production. Higher or lower rates may occur for the glass volumes associated with individual projects as the residual rates are merely statistical and nickel sulfide inclusions tend to occur in batches;
- If there is a requirement to avoid nickel sulfide induced failures, then toughened glass should be avoided. However, other types of glass have different properties and different attendant risks.

v When procuring heat-soaked toughened glass, obtain details of the heat-soaking regime proposed, including accuracy of temperature control of the glass and proposals for glass stacking in the heat-soaking oven. Also require QA documentation to be provided for the heat-soaking of the batches of glass supplied for your project.

vi Even though prEN 14179 is not available as a published standard the Part 2 - Evaluation of conformity may be referred to. This part details the requirements for the evaluation of conformity of the product and includes:

- Initial type testing of the product
- Factory production control
- The heat-soaking process; that must be undertaken using a calibrated oven. The conditions must be the same as during calibration ad the process parameters, e.g. times, temperatures, etc, must be recorded.
- Final product control

Any manufacturer using the principles of prEN 14179 should be able to confirm that its heat-soaking oven has been calibrated and show that they are operating to the conditions determined during calibration.

4.5 Inclusions remaining after heat-soaking

The European Standard has been developed with the intention of achieving a level of less than one critical nickel sulfide inclusion remaining in 400 tonnes of heat-soaked thermally toughened glass. However, until such time as large glass volumes have been made to the Standard, and used, reliance should not be placed on the accuracy of the indicated statistic of 1 in 400 tonnes; it should be deemed as being indicative only and subject to variation.

It is impossible to guarantee the removal of all critical nickel sulfide inclusions by heat-soaking. Moreover in the period that the glass is held at the holding temperature a particular inclusion may not convert fully - conversion at room temperature after heat-soaking may then lead to failure, but earlier rather than later.

It is not possible to inspect or test toughened glass to ascertain whether it has been heat-soaked because none of the physical or chemical attributes of the glass itself are altered significantly by the process. Therefore, quality assurance depends on process control, documentation and permanent marking of the glass.

5 SELECTING TOUGHENED GLASS

5.1 Introduction

Nickel sulfide inclusions cause failures in toughened glass and heat-strengthened glass. One approach is to not use toughened or heat-strengthened glass. However, toughened glass offers advantages of strength and is a safety glass. These properties cannot always be obtained from other materials.

This Chapter discusses the use of toughened glass and illustrates why it has to be used in some situations.

5.2 Strength

The table below gives an idea of the relative thickness of different glass types required for equivalent strength under windload. This table uses the information in BS 6262 for glass selection, based on a square pane, mounted in a vertical plane, of area 1.8 m^2 under 1500, 2000 and 2500 Pa windload:

Windload	Toughened	Annealed	Wired
1500 Pa	4 mm	4 mm	-
2000 Pa	4 mm	5 mm	7 mm cast
2500 Pa	5 mm	6 mm	-

The variation in glass thickness does not seem much, but an increase of 1 mm in a 4 mm thick pane means 25% greater glass weight, greater transport costs and consequent increases in costs associated with storage and handling. Site safety needs to be considered, and heavier glass requires stronger framing systems. When all of these factors are taken into account toughened glass may be more economical even allowing for the cost of heat-soaking.

One of the most important points about strength is the effect of stress concentrations and relatively poor edge quality of holes and notches. To produce a usable pane with these will almost certainly require the use of strengthened glass if the glass is intended to resist applied loads.

Toughened or heat strengthened glass may also be required to resist excess thermal stresses (Appendix A.6).

5.3 Safety

Part N of the Building Regulations (England and Wales) identifies critical areas where safety glass must be used. These areas include low-level glazing, and glazing in and around doors, where accidental impact is more likely.

BS 952 Part 1 defines safety glass as:

“Glass which when tested in accordance with BS 6206 either does not break, or breaks safely, and affords protection from cutting and piercing injuries in the event of accidental human impact”

Part N of the Building Regulations requires glass in critical areas to meet Classes B or C of BS 6206. Glass correctly thermally toughened to BS 6206 always achieves the highest class, Class A, because it breaks safely. Laminated annealed glasses can also be safety glasses but not all of them achieve Class A of BS 6206. Laminated annealed glass is limited by its weakness under long term loads - whilst the layers of glass achieve a considerable degree of composite action under short term (wind) loads, the same is not true under long term loads (snow or self-weight on slope glazing) and larger deflections may occur. Laminated glass is a good security glazing but it can also impede access or egress in emergency situations.

Part N of the Building Regulations also permits the use of thick monolithic annealed glass that resists impact rather than breaking safely in the event of impact. There are however implications for the design of framing systems.

Plastic glazing, such as polycarbonate materials, may be used. Plastic materials are less durable than glass, and may easily become scratched and damaged. They also cannot be used as part of sealed multiple glazing units, because they permit moisture migration through the plastic.

If wired glass is used (not all wired glass is safety glass, it depends upon the wire) it must be remembered that wired glass is weaker than the same thickness of annealed glass. The use of wired glass is also limited by the reduced availability in terms of thickness.

5.3.1 Overhead glazing

It is preferable that no glass can fall from a broken pane overhead. It is considered that the use of toughened glass overhead is only permissible provided that a risk assessment shows the consequences of failure to be acceptable, see Chapter 6. The consequences of alarm, disruption and loss of confidence have also to be evaluated by the building owner.

The CWCT *Standard and Guide to Good Practice for Slope Glazing Systems, 1999, (Clause 2.4.2 and Clause 2.4.3),* makes the following recommendations for overhead glazing in buildings accessible to the general public:

For areas of glazing up to 5 m above lowest floor level:
a) laminated glass,
or b) heat-soaked toughened glass,
or c) wired glass,
or d) plastics glazing material.

These glazings offer the least risk to passers-by should breakage occur. Note that in this zone there may be additional requirements for impact resistance, and the glazing shall also be selected in accordance with Approved Document N of the Building Regulations.

CWCT Technical update 4 adds; Glazing at this height is frequently of thinner and smaller panes (Conservatories and walkways). Where thicker or larger panes are used serious consideration should be given to the use of alternatives to toughened glass, such as laminated glass.

For areas of glazing over 5 m and up to 13 m above lowest floor level:
a) laminated glass,
or b) heat-soaked toughened glass, of not more than 6 mm thickness and with a maximum pane size of 3 m^2,
or c) wired glass,
or d) plastics glazing material.

Toughened glass breaks into fragments when it fails, whether due to nickel sulfide inclusion, accidental impact or vandalism. When toughened glass breaks it has no load bearing capacity for self-weight or live loads; in a sloped orientation the glass will fall from its framework. Toughened glass of more than 6 mm thickness breaks into unacceptably large fragments (the largest dimension is at least the thickness of the glass). Note that a 3 m^2 area of 6 mm thick glass weighs 45 kg - this represents a significant weight of falling glass fragments.

If heat-soaked toughened glass is used then consideration should be given to positioning a wire mesh below the glazing, such that falling clumps of broken glass are broken into clusters each no larger than a 25mm square.

CWCT Technical Update 4 adds; A wire mesh should be provided unless the risk assessment shows that it is not necessary.

For areas of glazing over 13 m above lowest floor level:
a) laminated glass,
or b) wired glass,
or c) plastics glazing material.

Fragments of toughened glass will reach significant velocities when falling from greater than 13 m, and so toughened glass shall not be used - the preference is for glazing which will always remain in place until repairs can be effected.

Where multiple glazings are used the lower pane shall be either
a) laminated glass,
or b) heat-soaked toughened glass, of not more than 6 mm thickness, with a maximum pane size of 3 m^2 and no more than 13m above lowest floor level,
or c) wired glass.

The use of multiple glazings suggests a requirement for higher levels of comfort, and thus implies the frequent presence of people beneath the glazing. These types of glazing minimise the risk to passers-by, should the glazing break. Note that plastics glazing materials shall not be used in sealed units, as they are not vapour-tight.

These are minimum requirements for areas accessible to the general public. The actual choice of glass type should always be based on a risk analysis. For example, the *Standard and Guide to Good Practice for Slope Glazing Systems* permits the use of annealed glass overhead in low risk situations, such as horticultural greenhouses not normally accessible to the general public.

The issue of risk assessment is discussed further in Chapter 6.

6 SPECIFICATION

6.1 Introduction

The specifier has a central role to play in ensuring that an appropriate glass is used on a building, although the specifier may seek advice from others. Glass fulfils many functions including appearance, environmental control and integrity. Selection of glass is now one of the more complex aspects of specifying a building.

6.2 Risk assessment

When selecting a glass for use in a glazing screen, as structural glazing or in a roof a risk assessment should be undertaken prior to selection of an appropriate glass. The glass suppliers cannot undertake risk assessments as they will not be fully aware of the circumstances in which the glass is to be used, nor of the clients' broader response to safety issues. The client should commission a risk assessment. This may be undertaken by the design team or a specialist adviser, with the client duly consulted both on the client's requirements and on the risks identified.

Risk assessments should consider:

- Area and weight of glass to be used;
- Location of glazed area;
- The use of alternative types of glass;
- Workmanship and quality;
- Support and framing systems;
- Whether or not to heat-soak;
- Results of any tests to investigate post-failure behaviour.

The risk assessment should take into account factors such as:

- Safety
    - Will the glass break?
    - Will broken glass fall?
    - What weight of glass will fall?
    - Will it fall *en masse*, as a clump of fragments, or as separated fragments?
    - How far will it fall?
    - Where will it land?
    - How many people might be present when the glass breaks?
    - Will alternative glass types provide a safer or less safe solution?

- Repair
- How easily can the glass or glazing unit be replaced?
- Will there be other damage?
- Will there be disproportionate damage?
- What are the potential commercial implications of post-construction glass breakages?

It is unlikely that glass used in domestic glazing will be of sufficient size or weight to present a risk that requires heat-soaking of glass (however, suppliers in this market should consider the safety implications when using large panes of non heat-soaked toughened glass). On the other hand toughened glass should be heat-soaked if it is to be used in:

- Balustrades,
- Overhead slope glazing,
- Spandrels,
- Structural glazing,
- Any other location where there is a need identified to limit, insofar as is reasonably practicable, the frequency of nickel sulfide induced failures in toughened glass.

Vertical toughened glass in a frame, or surrounded by silicone sealant, will often remain in place after fracture but any monolithic toughened glass in slope glazing or structural glazing will normally fall immediately from its frame on fracture. In overhead multiple glazing, unless the broken glass will be retained on a lower pane of glass then it must be heat-soaked. Regardless of whether it is heat-soaked or not, if the lower pane of glass will not break, or fall, safely then it should be laminated glass with at least one pane not of toughened glass, or an underslung mesh should be provide (in overhead double-glazing the preferred combination is toughened glass over laminated).

Spandrel panels and tinted glasses get very much hotter than the plain glass in the vision areas of a building. This harsher thermal regime will generate higher thermal stresses and may also accelerate the conversion of nickel sulfide inclusions. A decision on whether to heat-soak toughened glass will, in part depend on whether the area beneath the wall is trafficked or not, and on balancing the commercial considerations of economy in construction versus subsequent replacement costs.

Disproportionate damage may occur where the activity in the building is affected by breakage of a window. For instance, if glass fragments fall into a swimming pool the pool must be emptied to rid it of glass fragments and damage might then occur to pumps. The nuisance value of nickel sulfide failure is clearly much greater in this situation. Economic losses due to the closure of a building may also become disproportionate to the initial savings achieved when procuring the glazing.

Disproportionate collapse can occur when glass is used as part of a structural glass assembly. Particular consideration should be given to redundancy of such structures and the provision of alternative load paths.

Finally the specifier not only has a duty of care when specifying glass but also has responsibilities under the Construction Design and Management (CDM) regulations in the UK. The CDM Regulations introduced in 1994 and enforced by the Health and Safety Executive (HSE) place duties upon clients, clients' agents, designers and contractors. They are required to consider health and safety at all stages of construction from conception through to construction and use, including repair and maintenance (further guidance on the CDM regulations is published by the HSE). A proper risk assessment and evaluation of the consequences of failure are central requirements of CDM.

6.3 Specifying heat-soaking

6.3.1 Future specification

When the European product standard is issued it will only be necessary to specify heat-soaked thermally toughened glass to that standard to define a requirement for glass with less than a 1 in 400 tonne occurrence rate of critical inclusions. However, until large volumes of glass have been produced to the new standard and used for some years, reliance should not be placed on the residual risk remaining below 1 in 400 tonnes for relatively small batches of glass associated with individual projects.

6.3.2 Earlier specification practice

Previously heat-soaking was specified in several ways:

- A heat-soaking regime should be used in which for large volumes of production the average statistical rate at which the number of critical nickel sulfide inclusions are converted is a percentage of the total, for instance 90 per cent or 99 per cent conversion;

- A heat-soaking regime should be used in which for large volumes of production the average statistical rate at which the number of remaining critical inclusions occurs is specified, for instance 1 in 400 tonnes of processed glass;

- The temperature and time regime is specified, indicating also the need for accurate temperature measurement and calibration, and the permitted variation in measured temperatures.

Some specifiers had been in the habit of requiring that no glass broke during heat-soaking. It may not be possible to achieve this (thermal fractures may occur for other reasons) and in any case the specifier was placing a condition on the manufacturing process, not on the performance of the finished product. The number of breakages during heat-soaking is only an issue for the producer who incurs greater costs.

Conversion rates were based on studies of the rate of transformation of nickel sulfide under laboratory conditions. Specifying the conversion rate (e.g. 90%) did not give an absolute performance for the glass as the number of inclusions remaining depends on the original number of inclusions which will vary from manufacturer to manufacturer and from time to time. Using this method of specification did not allow the specifier or client to carry out a risk analysis.

Specifying the temperature and time regime gives no absolute performance for the reason given above and again does not facilitate a risk analysis. It is also open to abuse by the glass processor unless the heating and cooling cycles are defined. The method and location of temperature measurement in the oven also has to be agreed.

Specifying the number of critical inclusions in the heat-soaked glass is more precise and independent of the number of inclusions present in the basic glass. Common specifications were:

- One critical inclusion in 130 tonnes
- One critical inclusion in 400 tonnes

One UK processor advised that it normally responded to a call for one inclusion in 130 tonnes by heat-soaking for two hours at 290ºC. To achieve one inclusion in 400 tonnes glass is normally heat-soaked for eight hours at 290ºC. Note that these times are different from those required in the European product standard because the product standard defines a method of calibration and is therefore considered more reliable. However, there is no test or measurement that can prove the number of inclusions remaining.

The following table indicates the theoretical number of panes containing critical nickel sulfide inclusions for different degrees of heat-soaking:

	Number of panes[1] per critical nickel sulfide inclusion		
Thickness	Not heat-soaked[2]	One critical inclusion in 100 tonnes	One critical inclusion in 400 tonnes
4 mm	220-720	5,500	22,000
6 mm	150-480	3,700	14,800
8 mm	110-360	2,750	11,000
10 mm	90-290	2,200	8,800
12 mm	75-240	1,850	7,400
15 mm	60-190	1,450	5,800
19 mm	45-150	1,150	4,600

[1] Based on a pane size of 1.8 m^2
[2] Assuming one inclusion per 4 -12 tonnes of glass

As a rule of thumb, glass can be taken to weigh 2.5kg/square metre/mm of thickness. This can be used to calculate the weight of toughened glass proposed on a project and from that, the predicted residual risk of nickel sulfide induced failures can be calculated, assuming that higher or lower rates do not occur in practice.

Example

If 10000 m^2 of 10 mm toughened glass is required for a project, then the total weight is,

Weight = 10000 x 10 x 2.5 = 250000 kg

= 250 tonnes

If an average statistical rate is specified of 1 in 130 tonnes, then on average, two nickel sulfide induced failures may be expected after heat-soaking the 250 tonnes of glass. However, due to the tendency for nickel sulfide inclusions to occur in batches, higher or lower rates may occur in practice.

Notwithstanding the above, it should be noted that numerous buildings predicted to incur one or two such failures have none at all whereas in a few cases, half a dozen failures have occurred as opposed to the one or two predicted. In very rare cases, more than fifty nickel sulfide induced failures have been reported but these have occurred on buildings where toughened glass had not been heat-soaked.

6.4 Other requirements

When specifying glass the specifier should also take into account the requirements of:

- Part N of the Building Regulations;
- BS 5516 - Code of practice for design and installation of sloping and vertical patent glazing;
- BS 6206 - *Specification for impact performance requirements for flat safety glass and safety plastics for use in buildings;*
- BS 6262 - Code of practice for glazing for buildings;
- CWCT - *Standard and guide to good practice for slope glazing systems;*
- CWCT Technical Update 4 - *Use of glass overhead.*

7 DIAGNOSIS AND REMEDIAL ACTION

7.1 Diagnosing toughened glass failures

Nickel sulfide breakage of glass exhibits a characteristic fracture pattern. However, toughened glass may fall from its frame or fixings when broken, thereby preventing examination of the fracture pattern and origin.

Assuming that the fractured pane remains in place, at the origin or epicentre of the fracture there may be located two fragments which are larger than the rest and which form a ‘figure of 8’ or ‘butterfly’. This fracture pattern indicates the point where the fracture was initiated but is not proof that the failure is due to a nickel sulfide inclusion.

For any cause of fracture of toughened glass, whether from the surface or the body of the glass, the internal stresses are sufficient to propagate any crack that forms. From the fracture origin the crack will propagate 5-6mm in both directions before it bifurcates. All of the following cracks will each propagate for 5-6mm before bifurcating and thus all fragments except the two at the origin have, typically, all facets of 5-6mm and are significantly smaller than the two particles at the point of first fracture.

Causes of fracture which always produce a butterfly are wind, snow, soft body impact, centre punch, any inclusion causing fracture and surface chips.

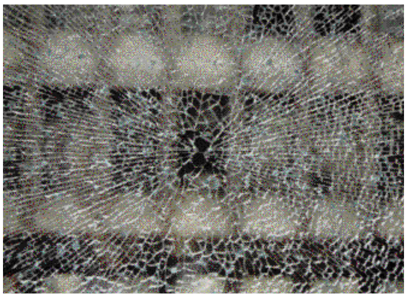

Fig 8 ***‘Butterfly’ shaped failure found with nickel sulfide failure***

7.2 Diagnosing nickel sulfide induced failures

For a nickel sulfide induced failure there will be located at the centre of the butterfly an inclusion, which is often invisible to the naked eye. The inclusion is a small, round, shiny, yellow-black particle which may be as small as 0.05mm in diameter, and as large as 0.2 mm or greater. The cause of failure can be confirmed to be a critical nickel sulfide inclusion by the use of:

- Scanning electron microscope (SEM)
- SEM with energy dispersive spectrometer (EDS)
- SEM with energy dispersive x-ray spectrometer (EDAX)

If a proper diagnosis of the cause of failure is to be achieved it is essential that all of the broken glass fragments from near to the origin are recovered. If this is not possible then all of the glass should be collected. If the glass is still in position in the frame then it should be photographed or the crack pattern should be sketched. Where the fractured glass is retained in the glazing frame it may be possible to secure the glass with a clear adhesive film prior to removal. This will greatly simplify the process of diagnosing the cause of failure.

Too often investigators are presented with a large bin of glass in which to search for a nickel sulfide inclusion, or worse are told that there was an unexplained failure that has been cleared away. Nickel sulfide is potentially costly, and its presence should always be confirmed by examination of the fragmentation pattern and if necessary the use of a scanning electron microscope.

7.3 Action in the event of glass failure

After the initial action to secure the safety of people by cordoning off the area beneath or around any broken glass, the first step should be taken to establish the cause of failure.

If possible, photographic evidence should be gathered along with sketches of failure patterns and the environmental conditions (wind, temperature, time of day). This information will be required not only to diagnose the immediate problem but also to establish a pattern of behaviour if several panes of glass fail. All too often the first and second failures are replaced without full investigation. Only when a third pane fails are questions asked about the sequence of failures. **All failures should be investigated by suitably experienced persons.**

The glass supplier/producer or the specialist contractor may want the failed glass to ascertain the reason for failure. However the client/owner should determine if an independent consultant should be brought in, in which case the particles of glass should be passed to them for independent analysis.

Should laboratory examination of broken glass confirm the presence of a critical nickel sulfide inclusion, the following reasons for the presence of the inclusion should be considered:

- The heat-soaking process may not have been undertaken to the standard required. Review of the quality assurance documentation for the heat-soaking batches concerned will be required to ascertain this. Such a review will be easier to undertake if a requirement for the requisite record keeping is specified at the outset.

- The heat-soaking process may have been successful in eliminating the intended percentage of critical inclusions but the batch of float glass may have had an above average number of nickel sulfide inclusions prior to heat-soaking

7.4 Remedial work

Before any remedial work is undertaken the cause of failure should be established. Remedial work should be appropriate to the failure mechanism and the threat presented

If the glass failure has been caused by vandalism then the appropriate action may not be connected with the glass performance. It may for instance be more appropriate to restrict access, provide better surveillance or other security measures.

If failure occurs with a random distribution during wind loading then the cause may lie with the glass. Should a regular geometrical pattern of failed glazing occur the cause may be lack of tolerance between the frame and glass or incorrect positioning of setting blocks. This should be regarded as a design or construction problem, not a glass problem, and investigated appropriately. In each case the fracture pattern may give tell-tale indications of the cause of failure.

The risk associated with glass failures can be mitigated by:

- Re-glazing;
- Applying a film to the glass;
- Catching the falling glass on netting or on staging;
- Causing the glass to fall more safely.

Re-glazing is expensive and may not be necessary. Single panes could be removed and heat-soaked to find any further critical nickel sulfide inclusions. However this is not possible for glass that has been laminated or assembled into sealed glazing units. Also it means that the glass is removed from the building for a period of time. Re-glazing should use appropriate materials, identified by a full risk analysis. Where deemed necessary, heat-soaked toughened glass or laminated glass should be used as would be the case for a new building.

Films are applied to the glass in an attempt to hold any breaking glass together in a similar manner to laminated glass. There are many different films available, some are intended only to modify the light transmission properties of the glass. Films must be selected to have the correct strength. If wrongly applied films can simply hold the glass together so that it creates a greater hazard by falling as a blanket. Any safety film should be retained in the glazing rebate to prevent falling of the glass. This is often difficult and may not be possible. Films also modify the light and heat transmission of the glass. The use of inappropriate films can increase the heat absorption of the glass causing it to get hotter and increasing the risk of thermal fracture. This should not be a problem for toughened glass that is filmed but it may accelerate the occurrence of nickel sulfide induced failures.

Falling glass may be caught by the use of netting slung below the glass or staging above the floor. This can be unsightly and unnecessary if alternative solutions are possible.

It may be acceptable to ensure that toughened glass breaks into small fragments as it falls from the frame. This can be achieved by fixing bars or wires beneath the glass so that it must break to pass them. In the USA the use of toughened glass overhead is often only permitted if a wire mesh is positioned immediately beneath the glass.

For vertical glazing the weight of glass does not cause it to fall freely from the frame and it may be acceptable to simply adopt a strategy of cordoning off the area beneath the glass until it can be removed safely. The glass should normally be removed within 24 hours as it may be disturbed by temperature changes, wind loading and so on.

7.5 Risk assessment

If the cause of failure is shown to be due to a nickel sulfide inclusion it should be remembered that even heat-soaking of toughened glass does not remove all critical nickel sulfide inclusions.

If possible the provenance of the glass should be checked to ascertain whether or not it has been heat-soaked and to what temperature and time regime. However, it is impossible to predict or eliminate the possibility of further failure.

Any decisions about remedial action should only be taken following a full risk assessment taking into account both short-term and long-term risk.

The long-term implications of remedial action can be assessed by following the guidance given on Specification in Chapter 6.

A CAUSES OF GLASS FAILURE

A.1 Introduction

The potential causes of breakage of annealed glass include:

- Uniform load;
- Impact;
- Edge damage;
- Poor glazing;
- Site damage;
- Thermal stress.

The same causes apply to toughened and heat-strengthened glass although they will fail at a higher stress, and in the case of toughened or heat-strengthened glass there may be stresses due to a nickel sulfide inclusion.

A.2 Uniform load

The most significant form of uniform loading on glass is normally wind load although other loads such as snow may occur in some situations. The safe load on a pane of glass is related to the size of the pane and glass thickness. BS 6262 gives guidance on the selection of glass thickness.

If the glass has been incorrectly selected (i.e. it is not thick enough) or if the peak wind load has been incorrectly assessed, then the glass may not have adequate bending resistance and will ultimately break.

A.3 Impact

Glass may break as a result of impact. The impact may be accidental, (e.g. from human collision), or deliberate, (e.g. through vandalism). Breakage may also be caused by thrown or wind borne projectiles (e.g. gravel or flashings blown from roofs).

Part N of the Building Regulations (England and Wales) places requirements on the use of glass in locations vulnerable to human impact and BS 6262: Part 4 gives recommendations for the use of glass in areas liable to human impact.

A.4 Edge damage

Edge damage can impair the bending strength of a pane of glass by creating stress concentrations.

Edge damage often occurs as a result of poor handling but can also occur when cutting glass (difficulty increases with thickness) although this is much less likely to lead to breakage than damage due to poor handling. There are no standard acceptance criteria for the edge condition of glass, although glass with edges that are severely feathered or have deep, pointed shells/vents are generally unacceptable, especially in glass types that absorb a high percentage of solar energy.

Toughened glass is edge worked and often arrised to give a good edge. Lack of edge working makes it susceptible to failure from edge damage

A.5 Poor glazing

Insufficient clearance between the glass edge and glazing frame will cause the glass to come into contact with the frame under frame movement, or the thermal expansion of glass, increasing the likelihood of breakage, especially if there is localised contact (e.g. with a fixing screw). Insufficient clearance may result from the incorrect sizing of glass, or excessive deviations of size.

Before glazing, the glass should be checked for size against that of the glazing opening. Glass that is wrongly-sized must not be glazed and nor should its size be reduced by nipping or grinding as this damages the edge of the glass and the hermetic seal of insulating glazing units.

The wrong width of setting block may result in uneven support across the bottom of a glass unit or piece of laminated glass. In general, the width of setting blocks should be equal to the sum of the glass unit thickness and the back face clearance to guarantee full support across the width of the unit. Laminated glass and glazing units usually only have two edges on which the separate panes of glass are aligned.

Glass breakage can also arise from setting blocks being too rigid (e.g. very hard nylon) and damaging the edge; a slightly softer compound would eliminate this risk and may also prevent relative movement between the block and glass unit. Too soft a material may cause the glass to sink into the setting block and cause localised frame contact.

Recommendations on good workmanship in relation to glazing are given in BS 6262 and BS 8000: Part 7.

A.6 Thermal stress

Glass can break as a result of excessive thermal stress. Thermally induced stress within a pane of glass results from a temperature differential between two areas of the pane. For instance in hot weather the centre of the glass warms up faster than the edge, because the edge is within the glazing rebate and shaded from direct solar radiation. Assuming the area of glass within the frame is insignificant compared with that exposed to solar radiation, as the centre of the pane expands due to the increase in temperature, the edge will be forced to expand by a similar amount inducing a tensile stress.

To check for thermal safety project-specific calculations should be undertaken and any glazed areas found to be at risk should be thermally treated by heat-strengthening or toughening (and heat-soaking). The safety check should take account of temporary conditions such as scaffolding and cleaning cradles and future conditions such as trees planted in close proximity to a glazed wall.

A.7 Other causes of failures

There is clear evidence that nickel sulfide induced failures are more likely to occur earlier in roof glazing, coloured glazing and spandrels that are insulated behind the glass where the glass is subjected to high thermal stresses and more rapid conversion of critical nickel sulfide inclusions. In each case the glass will reach higher temperatures than glass in other situations.

Glass in roofing systems may also be installed into a framing system that moves more than a wall. Movement of the frame may close the space between the edge of the glass and the glazing rebate and transfer structural loads to the glass.

All design of buildings attempts to quantify risk and provide a safe and economic environment in and around buildings. However, wind loading, snow loading and the risk of impact are all parameters that vary statistically.

Similarly material strengths vary on a statistical basis. The design charts in BS 6262 ‘Glazing for buildings’ and BS5516 ‘Design and installation of sloping and vertical patent glazing’ imply an assumption that there will be a failure rate of 1 in 10,000 panes during maximum design wind loading. North American practice requires the specifier to decide what failure rate to accept.

B TABLES OF OCCURRENCE OF NICKEL SULFIDE INCLUSIONS

This Appendix provides a ‘ready reckoner’ of the number of panes of glass per critical inclusion on the basis of different statistical residual rates of occurrence for large volumes of heat-soaking. As noted elsewhere in this document, higher or lower residual rates of occurrence may occur on individual projects than for large volumes of production; such variations in frequency are not necessarily indicative of defective heat-soaking.

B.1 Expectation of nickel sulfide for toughened glass that has not been heat-soaked

Based on the European average rate of occurrence of one critical nickel sulfide inclusion in every 4 tonnes there will be one critical inclusion in every 265 m^2 of 6mm glass or one in every 145 panes. Thicker glasses give a greater density of inclusions as follows:

Glass thickness	m^2 per inclusion[1]	Panes per inclusion (1.8m^2 panes)	Panes per inclusion (5.0m^2 panes)
4mm	400	220	80
6mm	265	150	55
8mm	200	110	40
10mm	160	90	32
12mm	135	75	27
15mm	105	60	21
19mm	85	45	17

[1] Assumes 1 inclusion in 4 tonnes of toughened glass

B.2 Expectation of nickel sulfide for one critical inclusion remaining in 400 tonnes of heat-soaked toughened glass (99% conversion)

At a residual occurrence of one critical nickel sulfide inclusion in 400 tonnes of heat-soaked toughened glass there will statistically be one inclusion in every 26,500 m^2 of 6mm toughened glass, or one in every 14,500 panes of 6mm glass. This is the standard that will be achieved by glass specified as being in accordance with the European product standard for heat-soaked thermally toughened soda lime silicate glass. At this level the chance of a failure occurring on a typical building is extremely low. Even for thicker glasses the incidence is still low. Assuming an occurrence of 1 inclusion in every 4 tonnes of toughened glass prior to heat-soaking this table also represents 99% conversion:

Glass thickness	m^2 per inclusion[1]	Panes per inclusion (1.8m^2 panes)	Panes per inclusion (5.0m^2 panes)
4mm	40,000	22,200	8,000
6mm	26,500	14,800	5,300
8mm	20,000	11,000	4,000
10mm	16,000	8,800	3,200
12mm	13,500	7,400	2,700
15mm	10,500	5,900	2,100
19mm	8,500	4,700	1,700

[1] Assumes 1 inclusion in 400 tonnes of heat-soaked glass

B.3 Expectation of nickel sulfide for one critical inclusion remaining in 130 tonnes of heat-soaked toughened glass (96% conversion)

At a residual occurrence of one critical nickel sulfide inclusion in 130 tonnes of heat-soaked toughened glass there will be one inclusion in every 8,700 m^2 of 6mm toughened glass. Assuming an occurrence of 1 inclusion in every 4 tonnes of toughened glass then this table also represents 96% conversion:

Glass thickness	m^2 per inclusion[1]	Panes per inclusion (1.8m^2 panes)	Panes per inclusion (5.0m^2 panes)
4mm	13,000	7,200	2,600
6mm	8,700	4,800	1,730
8mm	6,500	3,600	1,300
10mm	5,200	2,900	1,040
12mm	4,300	2,400	870
15mm	3,500	1,900	690
19mm	2,700	1,500	550

[1] Assumes 1 inclusion in 130 tonnes of heat-soaked glass

B.4 Expectation of nickel sulfide for one critical inclusion remaining in 40 tonnes of heat-soaked toughened glass (90% conversion)

At a residual occurrence of one critical nickel sulfide inclusion in 40 tonnes of heat-soaked toughened glass there will be one inclusion in every 2,650 m^2 of 6mm toughened glass. Assuming an occurrence of 1 inclusion in every 4 tonnes of toughened glass then this table also represents 90% conversion:

Glass thickness	m^2 per inclusion[1]	Panes per inclusion (1.8m^2 panes)	Panes per inclusion (5.0m^2 panes)
4mm	4,000	2,220	800
6mm	2,650	1,480	530
8mm	2,000	1,100	400
10mm	1,600	880	320
12mm	1,350	740	270
15mm	1,050	590	210
19mm	850	470	170

[1] Assumes 1 inclusion in 40 tonnes of heat-soaked glass

C TERMINOLOGY

Annealed glass See basic glass.

Basic glass (Annealed glass) Ordinary glass that can be cut by scoring and snapping. Annealed glass, if broken, produces large fragments with sharp edges.

Critical inclusion A nickel sulfide inclusion that by virtue of its size and position in the glass can cause failure. See critical nickel sulfide inclusion

Critical nickel sulfide inclusion A small impurity in the glass that can cause fracture of toughened glass some time after toughening. Failure is also possible in heat-strengthened glass.

Cullet Broken glass recycled for use in the glass-making process.

Float glass Glass which has been manufactured by floating the molten glass on a bed of molten tin until it sets, producing a product with surfaces which are flat and parallel.

Fully-tempered glass Glass that has been subjected to a thermal treatment characterised by rapid cooling to produce a pre-stressed compression surface layer (US term equivalent to UK's 'thermally toughened'). Sometimes abbreviated to tempered glass.

Glass structural member Glass used in a manner where it transfers loads other than those directly imposed on it. For instance glass mullions and balustrades.

Heat-soaked toughened glass Toughened glass that has been heated for a period of time at moderately high temperatures to reduce the possibility of nickel sulfide induced fractures in service.

Heat-strengthened glass Glass, which has been heated past its softening point and chilled rapidly to increase its strength, but which still breaks like annealed glass (US practice defines heat-strengthened glass by its surface stresses. At the top end of the range the glass breaks like toughened glass; this is not acceptable in Europe).

Inclusion Either a localised impurity in the glass or a visual imperfection in the glass. These two are often confused in specifications.

Laminated glass Product that comprises two or more sheets of glass laminated together with sheets of plastic or resin. Any type of glass may be included in a laminate.

Nickel sulfide inclusion A small impurity in the glass which can cause fracture if it is a critical inclusion. See critical inclusion.

Overhead glazing Sloping horizontal glazing above a trafficable area, usually in roofs.

Pane A piece of glass.

Sloping glazing Glazing which is either horizontal or sloping up to 75º from the horizontal.

Spandrel panel A glass panel, commonly in a curtain wall, which is made of an enamelled glass or an opacified glass in order to hide parts of a building structure, such as the edge of floor slabs.

Spontaneous breakage An alternative term for spontaneous fracture.

Spontaneous fracture Loose terminology referring to an unexplained fracture. All fractures have a cause.

Stone Generic name for an inclusion. Hence, nickel sulfide stone.

Structural glass Glass used in a manner where it may be supporting other building components (e.g. glass mullions) or where it performs a semi-structural role (e.g. free-standing glass protective barriers). The term may also be used for glass fixed using bolted connections (frameless glazing), even if it performs no structural function.

Tempered glass See fully tempered glass.

Thermal stress Stress developed in glass due to differences in temperature across its surface or through its thickness. In buildings, this is commonly related to glass exposed to the sun, where the central part is heated, but the edges, in the frame, remain relatively cool. Too high a temperature difference can result in thermal fracture of the glass.

Toughened glass Glass which has been heated past its softening point and chilled rapidly to build in a surface compressive stress which gives it greatly increased strength and makes it break into small fragments if broken.

Wired glass Generic term which covers polished wired glass and wired patterned glass. Wired glass has a continuously welded wire mesh set into the centre of the glass.

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