Chapter 1

Introduction

This chapter introduces the field of study and describes the background that led to this research. 'Low emissivity' glass has remained a functional architectural product despite the wide use of other types of float glass as an artistic medium. The accidental discovery of its ability to gain strong iridescent colouration when heated, led to the initiation of the project. The approach as a studio artist is outlined with the methods used to provide a basic understanding of the research material.

1.1 Background to the Initiation of the Research

This project is about the creative possibilities of low emissivity glass with the trademark 'K Glass' manufactured by Pilkington United Kingdom Limited, a division of Nippon Sheet Glass Company Limited (NSG) of Japan since 2006. It establishes that this functional coated building product can be manipulated to produce colour and iridescence and offer creative potential for glass artists and designers (*Figures 1.1 and 1.2*).

Figure 1.1 K Glass, pre-fired.

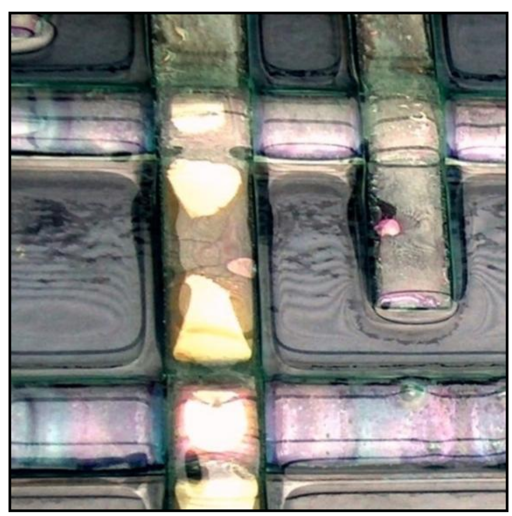


Figure 1.2 K Glass, manipulated and post-fired.

During routine kiln testing by the author for undergraduate artwork, the accidental firing of a piece of K Glass in a batch of float glass off cuts produced an unexpected and unusual reaction. The surface offered significant iridescence with strong pink/purple 'mother of pearl' colouration as shown in Figure 1.3 and which seemed to disappear and reappear with the movement of the glass.

Figure 1.3 4mm K Glass, post-fired showing iridescent colouration to the surface.

Inspection of further fired samples of K Glass confirmed this effect to be on the surface of the glass implying that it was related to a change in the coating after heating. These unusual features suggested potential for a new type of decoration. If subsequent artwork could be made, it would confirm that functional coated glass could be an innovative, inexpensive and exciting medium in the field of creative glass.

1.2 Outline of the Research Field

Low emissivity is one of an increasing number of functional surface coatings on glass with universal applications made for a wide range of industries from everyday household mirrors and light bulbs to 'high-tech' jet fighter cockpit windscreens and photovoltaic cells. Introduced by

Pilkington in the early 1990's, K Glass is one of a range of coated float glass which provides architects with a wide choice for windows or façades. It is described today within the building trade as the 'UK's best-selling and most recognised low emissivity glass' at a cost and availability, comparable to regular float glass (Pilkington, 2011a).

Glass is no longer simply a material which will transmit light. New requirements for buildings (Communities and Local Government, 2010), the increasing demands by occupants for thermal comfort and technological advancements of production mean that window glass is capable of performing many functions additional to its 'fundamental day lighting role' (Button & Pye, 1993, p.vii). This is achieved through the use of coatings that comply with modern architectural and environmental issues. Their growth has 'transformed the performance of glazing' (Wigginton, 1996) by the control of transmission of heat and the management of internal temperature. The coatings with this specific function are known as low emissivity.

The research field of coated glass is examined in Chapter 2 and includes float glass as a creative medium. Reliability, variety of thickness and large sheet size, as well as low cost in comparison to that of traditional coloured architectural glass, have made float glass a premier choice by artists and designers in architectural and interior design today. For example, the large scale work 'Look-out' by Cate Watkinson and sited at the Metro Centre, Gateshead stands at seven metres in height *(Figure 1.4).*

Figure 1.4 'Look-out', Cate Watkinson, Gateshead, UK, 2004, Height 7m.

1.3 Rationale for the Research and Research Questions

To date, although research has been carried out with regard to the functional applications of low emissivity glass, no previous documentation has been identified where K Glass has been used in any creative situation. Searches using the Index to Theses, Journals of the Society of Glass Technology and creative publications Neues Glas, Glass and Glass Art, revealed no publication of K Glass within a creative context.

In addition, no information was available from Pilkington regarding the composition of the K coating. Therefore, in order to gain a better understanding of the behaviour of K Glass when subjected to high temperatures, practical testing was necessary. The reasons for the colouration and iridescence needed to be identified and understood so that creative methods could be developed. These factors would be explored through the initial question:

- What are the practical issues which effect the changes to the surface coating of low emissivity glass when fired in certain conditions?

With this knowledge gained and the subsequent ability to manipulate the coating through experimentally found methods, creative techniques could be developed through artwork and demonstrate a new range of aesthetic possibilities in the field of creative glass. This rationale generated the further question and ultimate purpose of the research:

- What creative possibilities can be derived from manipulated K Glass for the artist or designer?

1.4 Aims and Objectives of the Research

With practical issues identified, methods and techniques could be developed to test the creative potential through artwork. Hence, the aims of the research were:

- To develop new methods of creating artistic effects by exploiting aesthetic qualities derived from low emissivity K Glass in certain conditions.
- To produce a body of artwork developing the creative potential of the techniques.

Within the practical testing stage, the objectives to develop the material through manipulation of the surface coating were undertaken in the first three objectives below. The fourth and fifth objectives used the information gained to develop the techniques through artwork and demonstrated the creative potential.

Objective 1 - To identify the visual changes to the K Glass surface coating when subjected to high temperatures.

Objective 2 - To understand the changes to the surface coating and the factors responsible for the visual effects.

Objective 3 -To control the visual effects through manipulation of the factors.

Objective 4 -To apply the information to the application of new techniques and methods of working for the artist in the field of creative glass.

Objective 5 -To utilise the techniques in a body of artwork that develops and demonstrates the artistic potential of K Glass within the field of creative glass.

1.5 Methodology and Methods Used

A practice and experiment based methodology influenced by an interdisciplinary approach was undertaken from the perspective of an artist or designer working within the area of creative glass. The methods and creative possibilities were those developed by the author of this study in her home based studio.

At the outset, it was the view of the author that within this art project there needed to be an understanding of the material and the surface changes that occurred during the transitional processes that took it from a functional to a creative medium. Although artwork could be produced without this knowledge, exploration of the material properties would assist the control and manipulation of the changes to the coating. To address Objectives 1, 2 and 3, it was felt that the methodology needed to be of experimentation and reflection but with systematic procedures in a scientific or multi-method approach.

While the creative potential of each effect achieved was assessed, the ability to repeat and extend each process was dependent on experimental data. Consequently, over 350 individual tests, known as ‘standardised tests’, were undertaken using 100mm squares of K Glass to fully explore the basic material and to establish terms of reference for subsequent comparison and evaluation.

Although objective non-emotional assessment of all changes was necessary to understand the coating, each test was visually assessed for empirical and qualitative analysis as well as aesthetically evaluated for their creative possibilities in terms of decorative criteria. This practical programme of testing and results are discussed in Chapter 3.

In order to further categorise the visual changes to the post-fired K Glass, a detailed microstructural characterisation of the surface coating was undertaken using light and scanning electron microscopy as well as energy dispersive x-ray spectroscopy for elemental analysis. These results, in combination with Materials Science consultation which, where necessary, assisted the technical interpretation of the changes to the coating are detailed in Chapter 4.

With this knowledge, as well as information from the standardised testing data, Objective 4 was addressed with a new method of working, namely the ‘Mirror Gap Technique’, a term invented by the author. Although based on existing fusing and surface manipulation principles, this creative procedure described in Chapter 5 is unique in its ability to separate and control several iridescence colours on post-fired K Glass.

Throughout all testing, the creative possibilities of low emissivity K Glass were highlighted with experimental artistic pieces. However, it was the Mirror Gap Technique that specifically addressed Objective 5 and, together with manipulation of the open fired surface, enabled the development of a body of artwork to be successfully produced. Inspiration for the artwork originated from the aesthetic characteristics of the manipulated coating with design taken from the geometric form used throughout the research and from micrographic images of the surface structure of the fired K Glass. The artwork presented in Chapter 6 is the product of collaboration between art and science and clearly demonstrates the artistic potential of K Glass within the field of creative glass.

1.6 Components of Work which Constitute the Research Results

The following components of work will be submitted for examination:

- A written thesis documenting the process of research and work undertaken in the production of artwork.
- A body of artwork demonstrating the developed techniques and potential for the creative use of coated glass.

Chapter 2

Contextual Review

This chapter aims to provide an overview of the areas in which the research is located and begins with the creative field of float glass. The material is examined through the development of K Glass and the issues that necessitated the evolution of low emissivity coatings. The position of coated glass within the international market is described which gives a perspective to the scale of its availability. The question of interference is discussed with the response by makers to overcome this visual effect on the surface of the glass. In order to also locate the research within the artistic field of activity other applications which can be considered as creative coatings are outlined. The contextual review concludes with the location of the project within the area of interdisciplinary research.

2.1 Pilkington, Inventors of Float Glass

The name Pilkington has been associated with British glass since the foundation of the St. Helens Crown Glass Company in 1826. The privately owned company became public in 1949 manufacturing flat glass including safety, optic and automotive materials worldwide. All flat glass production of the parent company NSG now trades under the Pilkington name (Pilkington, 2009a). In 1952, Alastair Pilkington invented a process which streamlined the manufacturing of flat glass. By floating a controlled quantity of the melted glass components on to a bed of molten tin at high temperature, a smooth, flat and polished glass was produced. Known as 'float glass' this provided 'the almost perfect production system' and the foundation for the flat glass industry of today (Wigginton, 1996, p.64). A more detailed description of the float glass process can be found in Appendix A, p.248.

2.2 Creative Use of Float Glass

Float glass in the twenty-first century has far outreached its original glazing purpose. It now features in many aspects of a building such as stairs, bridges or balustrades and doors or windows where it can be a canvas for creative imagery such as in the engraved work of John Hutton (*Figure 2.1 and 2.2).*

Figure 2.1 Float glass bridge and balustrade, Co. Durham, UK, 2007.

Figure 2.2 John Hutton, Civic Centre, Newcastle upon Tyne, UK, 1958, 9' x 13'.

The versatility of float glass has enabled development by artists who take the flat glass form and, through kiln firing, re-shape the glass to create two and three dimensional artwork such as that of John Gilbert Luebtow as seen in Figure 2.3. A float glass product called 'Kilolux,' which was originally developed as a functional but decorative material for the Wales Millennium Centre in Cardiff, South Wales, was awarded the runner-up for the prestigious Bombay Sapphire Designer Glass prize in 2003 (BDI, 2006).

Figure 2.3 'Linear Fountain', John Gilbert Luebtow, San Francisco, USA. 2.1m x 1.5m and 3.6m x 3.6m.

Float glass is also used extensively in gallery exhibits. Work such as that by Dutch artist, Jan Hein van Stiphout, reflects the wide range of applications as can be seen in his wall piece in Figure 2.4 and installation from a master class in 2007 at Falmouth University (*Figure 2.5*). Float glass was central to the PhD project by Vanessa Cutler whose investigation into the creative use of abrasive water jet cutting made particular reference to architectural float (Petrie, 2005) as shown in the detail of 'Spinal Wave' (*Figure 2.6*). Artists, such as Gavin Marshall, produce many float glass pieces both functional and decorative offering individual designer work at a cost much lower than that of high quality glass (*Figure 2.7*). This current interest in float glass is reflected in mass produced products, for example, tableware or inexpensive trophies such as those in Figures 2.8 and *2.9*. Much of this is now produced using recycled float glass as a contribution to the ecological reuse of waste material.

Figure 2.4 Wall panel,
Jan Hein van Stiphout, 2002,
float glass.

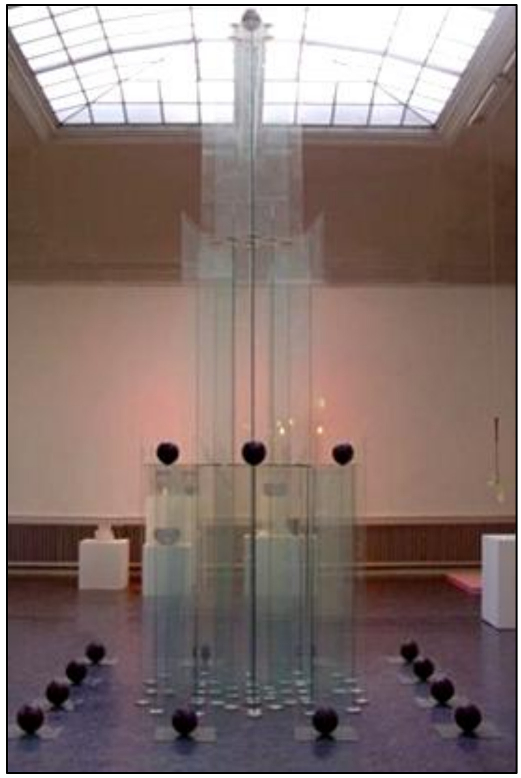


Figure 2.5 'Perpendicular',
Jan Hein van Stiphout, 2007,
float glass installation.

Figure 2.6 'Spinal Wave' (detail),
Vanessa Cutler, 2005,
1180mm x 70mm, float glass.

Figure 2.7 ‘Frozen Form’, Gavin Marshall, 2011, float glass.

Figure 2.8 Recycled float glass tableware.

Figure 2.9 Float glass trophy.

2.3 Development of Coated Flat Glass

Despite the fact that the basic constituents of glass (*See Table A.2, p.247)* have changed little since the early Romans made cast pieces, the demands of glass as a material have increased dramatically. Over the last two hundred years, the application of flat glass in architectural design progressed much faster than the gradual evolution of its industry, significant developments to 1952 being detailed for brevity in Table A.1, p.244.

The early twentieth century saw a new dimension for architects as the ideology of light became paramount to their designs. This challenge was initiated by the radical concept brought to building construction in 1911 by German architect and founder of the Bauhaus[1], Walter Gropius (1883-1969) and his practice partner Adolf Meyer (1866-1950). Their use of glass and steel for load bearing walls in the Fagus Factory, Alfeld, Germany shown in Figure 2.10, began a 'modern ideal designers had strived for - the integration of the outside with the inside by means of a transparent building skin' (Button and Pye, 1993, p.4).

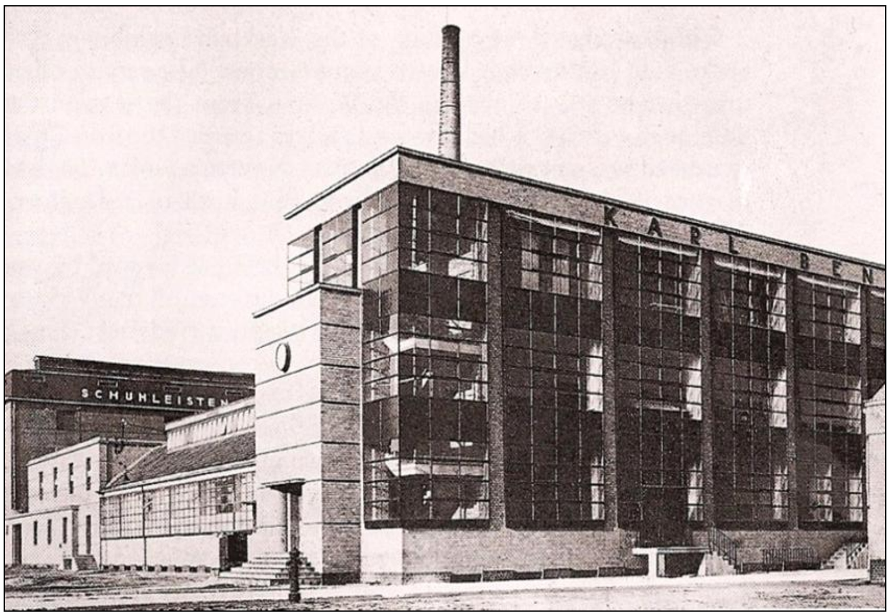


Figure 2.10 Fagus Factory, Alfeld, Germany, 1911.

At the same time, 1914, Scheerbart[2] foresaw a world filled with architecture of which the major material was glass. The concept of the building 'which lets in the light …not merely through a few windows, but through every possible wall, which will be made entirely of glass' (Scheerbart, 1914, p.41) was his dream to generate a 'new culture' of quality and comfort. This desire for light brought with it susceptibility to

[1] Bauhaus. School of architecture and applied arts founded in 1919, became the centre of modern design in Germany. It was closed down by the Nazis in 1933 (Chilvers, Osborne and Farr, 1988, p.43).

[2] Paul Scheerbart, (1863-1915) Berlin Bohemian prophetic poet, novelist and visionary architect (Sharp, 1972, p.8).

widely fluctuating seasonal temperatures, heat loss in winter and too much light and overheating in summer. Scheerbart's glass skin buildings presented the problem of internal air quality and the costs involved for regulating heating or air conditioning.

The early part of the twentieth century saw concepts designed to address the environmental control but the notion of the glass itself protecting the buildings from solar glare was not introduced until the 1950's. Initially green tinted glass used in the United States automotive industry was fitted to large commercial buildings such as the Lever House building[3] (1951-2) on Park Avenue, New York (*Figure 2.11).* Mies van der Rohe[4] subsequently used bronze tinted glass for his New York Seagram Building (1954-8) (*Figure* 2.12).

Figure 2.11 Lever House, New York, USA, 1951-2.

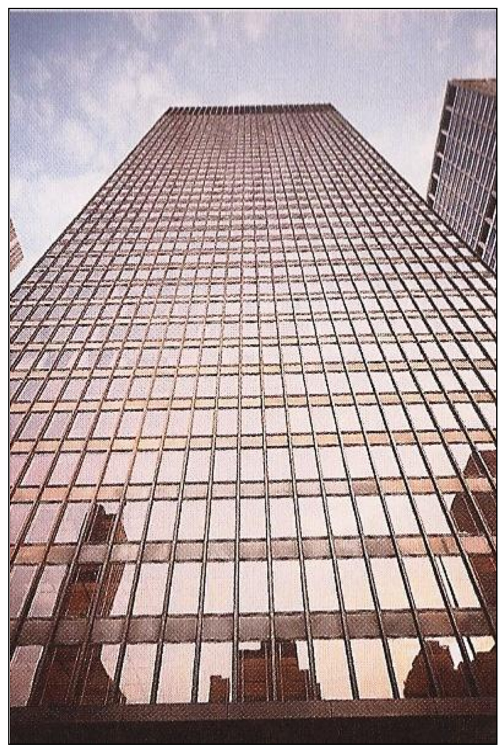


Figure 2.12 Seagram Building, New York, USA, 1954-8.

[3] Designed by Gordon Bunshaft Architect and chief designer of Skidmore, Owings & Merrill LLP, New York (New York Architecture, 2010).

[4] Ludwig Mies van der Rohe, (1886-1969). German born architect and designer. Director of the Bauhaus 1930-1933. Emigrated to the USA in 1938 and became an American citizen in 1944 (Chilvers, Osborne and Farr, 1988, p.331).

This tinted ‘glamour-wrap’ (Wigginton, 1996, p.73) not only reduced the heat but also the light. Its use was curtailed by the introduction of float process technology which coloured the glass at its molten stage. However, when necessary on-line tint changes created a costly interruption to the flow of production, the addition of a compatible coloured layer on top of the float glass substrate was found to be easier than changing the production process. This surface layer became thinner and evolved to a coating which could be modified to suit the performance requirements of its application (Jenkins, 1986, p.36). In the mid-1970’s, Pilkington launched a float glass with coating modified for solar control known as ‘Spectrafloat’. This was followed in 1976 by ‘Reflectafloat’ with a reflective silver surface layer deposited through an advance in production technology and began a process which was the inception of today’s coatings (Wigginton, 1996, p.73).

2.4 Worldwide Energy Issues in Relation to Glass

The question of energy conservation in buildings and architecture has become one of the most important socio-economic factors effecting humans in the present day. Architects are very aware of the delicate balancing act between providing warmth and coolness, light and shade, still and circulating air. ‘Environmental management’ of such operational requirements mean that no matter what the season, ‘power has always had to be consumed for some part of every year, some part of every day’ (Banham, 1969, p.22).

By the turn of the twentieth century the new ‘valuable commodity’ of power was oil due to its versatility for heating and the internal combustion engine. As production costs became less, the ‘efficient use of energy was simply not a concern’ (Union of Concerned Scientists, 2008). Oil production grew unchecked until, in 1973, the members of the Organization of Arab Petroleum Exporting Countries (OAPEC)[5] proclaimed the Arab oil embargo and increased the price fourfold initiating a worldwide power crisis (Ilie, 2006).

It was at this time also that the build up of gases released from centuries of increased energy-driven pollution presented a major factor of issues which became known as the greenhouse effect[6] and global warming[7] (United States Environmental Protection Agency, 2007). Subsequent international reaction has been the subject of much controversy and a major target of policies worldwide. These policies in their turn have dictated the establishment of measures by governments to address the issues, for example, the Intergovernmental Panel on Climate Change in 1988 (IPCC).[8]

The most significant movement towards the international stabilisation of the greenhouse effect was by the United Nations Framework Convention on Climate Change (UNFCCC) in 1994, who set binding targets for the reduction of gas emissions. This was followed by the Kyoto Protocol, negotiated in December 1997 by 160 nations in Kyoto, Japan, to impose a limitation on greenhouse gas emissions and reduce them to the levels of 1990 (UNFCCC, 2004). To address the

---

[5] Arabic Arab organization formed in January 1968 to promote international economic cooperation within the petroleum industry. Member countries include Algeria, Bahrain, Egypt, Iraq, Kuwait, Libya, Qatar, Saudi Arabia, Syria and the United Arab Emirates (Encyclopedia Brittanica.com, 2010).

[6] In 1827, a French scientist named Jean-Baptiste Joseph Fourier had discovered a phenomenon which he called “un effet de verre,” “an effect of glass” where the earth’s atmosphere traps heat to warm the planet. (NOAA/NASA/EPA Climate Change Partnership, no date).

[7] Greenhouse effect increased by release of certain gases into the atmosphere could cause the earth’s average temperatures to rise 2.5˚-10˚F by 2100 (United States Environmental Protection Agency, 2007).

[8] The IPCC is a scientific intergovernmental body set up by the World Meteorological Organization (WMO) and by the United Nations Environment Programme (UNEP) to review all available and ongoing environmental information and provide a framework to support a policy for addressing the worldwide climate change issue (IPPC, 2011).

commitment to meeting these targets, the present European Energy Policy (Commission of the European Communities, 2007) covers a number of legal initiatives which led to standards for energy conservation in western architecture and serves as the benchmark on which the European and UK Building Regulations are set.

Current UK legislation based on the 'Building Act of 1984' includes 'Building Regulations 2000'. Part L of the regulations details the standards to control and conserve energy required by the 'Communities and Local Government' that set local policies. These standards demand the inclusion of new building methods and products in both residential and commercial construction. Two of these, double glazing and surface coated glass are now mandatory for new window applications (Great Britain, HM Government, 2000).

2.5 Double Glazing

As radical new structures made use of its increasing size and strength, glass became the 'fundamental tool in the exploitation of new spatial dynamics' (Davies, 1986, p.53). The application of iron framework and the success of Chances Patent Plate used in the Crystal Palace (*See Table A.1, p.244)* encouraged constructional possibilities in the form of long-span glazed conservatories such as that shown in Figure 2.13 of the Temperate House in the Royal Botanical Gardens, Kew, built in 1860 (Wigginton, 1996, p.38). The quantity of glass that allowed maximum light for these winter gardens[9] gave rise to the need for the regulation of variable external temperatures.

[9] Also known as orangeries, winter gardens were conservatories designed originally to provide a haven for collections of exotic plants. (Wigginton, 1996, p.30).

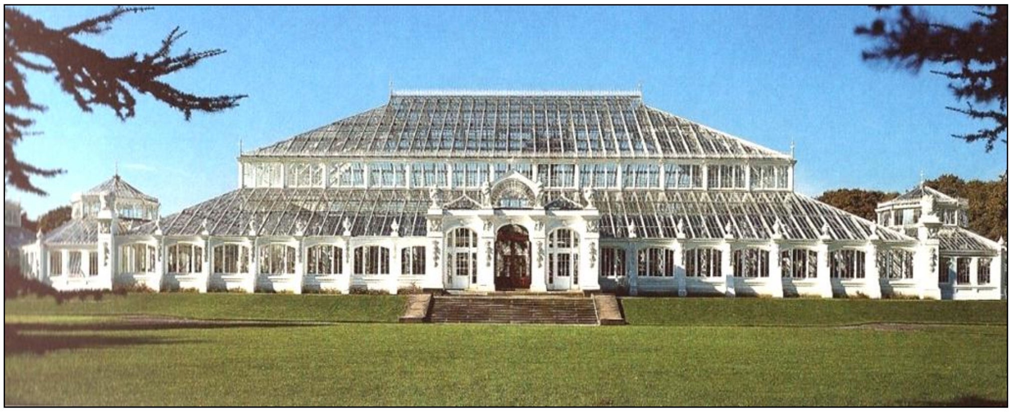


Figure 2.13 Temperate House, Royal Botanical Gardens, Kew, London, UK, 1860.

By the end of the nineteenth century the physical consequences of large glass structures were beginning to be understood. Scheerbart, aware of the problems that his glass architecture would create, suggested a logical solution. 'As air is one of the worst conductors of heat, the double glass wall is an essential condition for all glass architecture' (Sharp, 1972, p.42). In 1930, French architect, Le Corbusier [10] developed his own concept to address this issue for the Cité de Refuge Hostel in Paris (*Figure 2.14).* His design of a multiple glass wall included heating pipes and a method of ventilation he called 'respiration exacte', and a 'mur nutralisant', a double glass wall. This dual system mechanically controlled ventilation with hot or cold air circulating between the skins of the glass wall. However, the project failed due to cutting costs by not fitting an essential inner layer of glass to the 'mur nutralisant' and by fitting opening windows instead of a cooling system. However, in 1831, French glass company Saint-Gobain set up a chamber to test Le Corbusier's theory and concluded that the system would be workable by the inclusion of an additional layer of non-moving air (Banham, 1969, p.156).

[10] Charles-Édouard Jeanneret (1887-1965), Swiss born architect, painter, designer and writer became a French citizen in 1930 (Chilvers, Osborne and Farr, 1988, p.281).

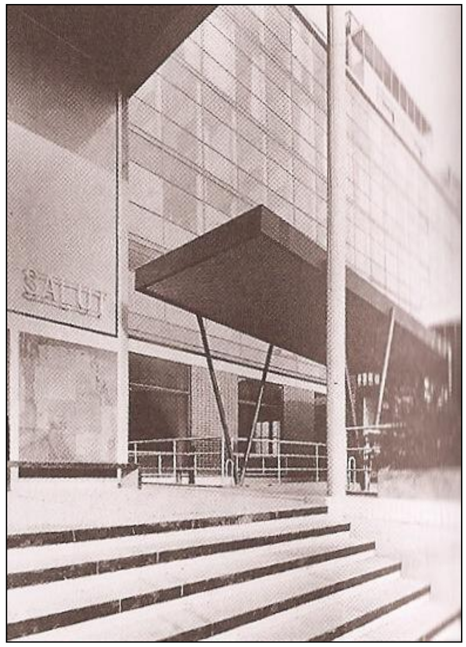


Figure 2.14 Cité de Refuge, Paris, France, 1930-31.

The multiple glass wall idea had been around from the early twentieth century but not universally accepted until the 1960's. In 1961, A. Emslie Morgan, principle assistant to the Borough Architect of Wallasey, Cheshire, designed one of the most important buildings of modern architecture, St. George's School (*Figure 2.15)* and contributed important environmental understanding of the 'total management of heat balance'. The south side of the building consisted of a double 'wall' of glass panels 600mm apart. This wall protected the internal environment by absorbing daylight solar energy and also by preserving heat generated from lighting and the inhabitants themselves (ibid, p.282).

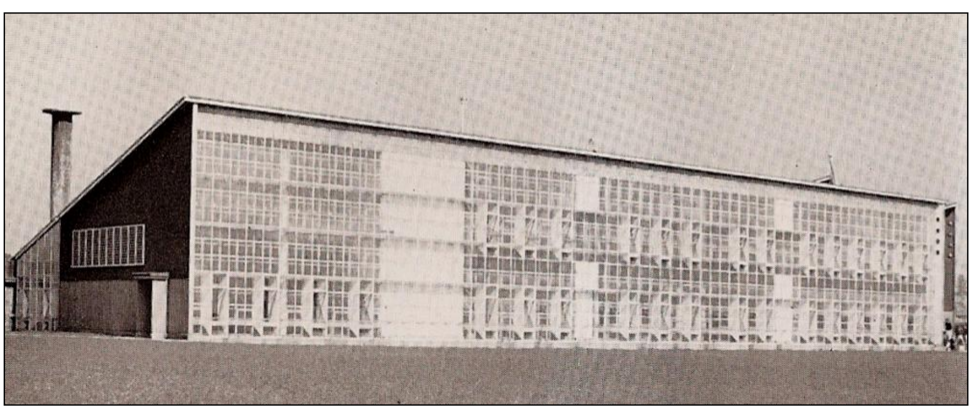


Figure 2.15 St. George's School, Wallasey, Cheshire, UK, 1961.

Float and the subsequent toughening process established glass as a major construction element. The question of environmental control caused by single glazing was answered by the industry to use 'more glass' by 'double glazing' (Davies, 1986, p.53). An early version was Pilkington 'Insulight', composed of two sheets of hermetically sealed glass separated by metal spacers and a cell of dehydrated air (McGrath, 1961, p.180). In practice there were many problems to overcome with these early systems, for example, the build up of condensation or dirt between the panes of glass. With the improvements of a reliable seal, aluminium spacers and a desiccant, the basic format for a stable unit was developed (*Figure 2.16).* The result 'revolutionized glazing' (Wigginton, 1996, p.82).

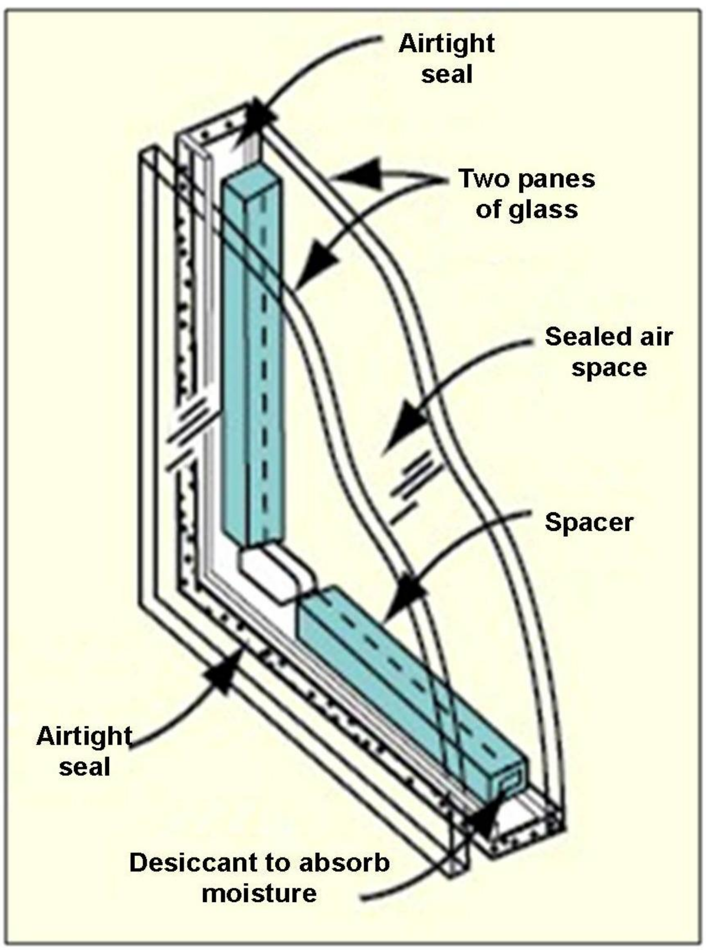


Figure 2.16 Basic Double Glazed Unit.

Since this basic unit was designed many variations have been introduced to improve energy conservation performance, for example, argon gas filled cavities and foam based spacers (Warm Edge Units Ltd., 2011). More recently the term ‘double’ has changed to ‘multiple’ and can incorporate triple panels or inclusions such as fire resistant gels (Wigginton, 1996, p.265). The most significant improvement of recent years is the emergence of coating technology for the management of thermal radiation. Double glazing is now specified by Building Control regulations to include one pane of glass with this coating and is known as an ‘Insulated Glass Unit’ (IGU).

2.6 Low Emissivity Coating: Function and Heat Control

Coatings with the specific function to control of transmission of heat through the glass are known as ‘low emissivity’ or ‘low e’. The word ‘emissivity’ means ‘having the power to radiate light, heat, etc.’ (Oxford English Reference Dictionary, 2002, p.461). Low emissivity, therefore, is a phrase or title of something whose capability in this respect is reduced.

With regular uncoated float glass, heat from the room is absorbed and then radiated out to the colder atmosphere outside. Likewise, solar radiation passing through the window during high temperatures in summer can cause heat discomfort. A low emissivity surface coating on one of the panes used in an IGU, controls this heat transference by reflecting long wave heat energy while transmitting short wave light energy.

In countries such as the UK where it is necessary for heat to be retained within a building, the low emissivity glass is positioned as the internal pane so that heat energy is reflected back into the building reducing the loss, while light energy is able to pass through. The external pane of normal float glass has no coating properties and, therefore, allows light and heat to travel through (*Figure 2.17*). The coating is always placed on the inside of the unit to protect its surface. This is particularly important with soft coatings. Although a low emissivity coating applied to the surface of window glass can assist the transference of heat, to be effective it needs to be part of a multi-glazed unit.

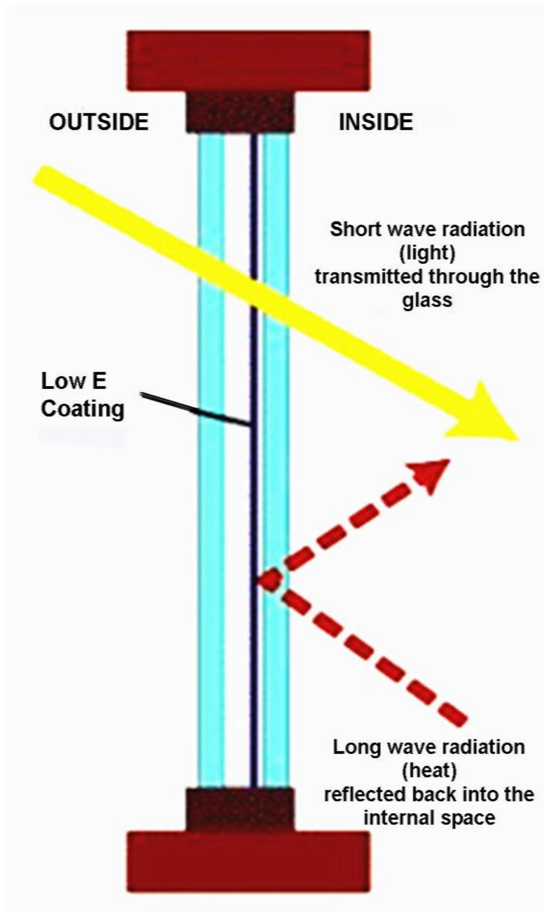


Figure 2.17 Low emissivity heat reflecting coating.

2.7 Coating Processes in Flat Glass Manufacturing

Coating material such as low emissivity is applied to glass using a depositing process which can be ‘off-line’ or ‘on-line’ in nature. Off-line coatings are applied to the pane of glass by a process known as ‘sputtering’, after it has been manufactured and cut to the required size. Although the scientific principle of the method was invented in the mid-1800’s, the process which has been in use since the 1960’s is that of ‘magnetically-enhanced’ or ‘magnetron sputtering’ (Wigginton, 1996, p.281) and combines a non-metallic alloy in a vacuum chamber filled with argon gas (*See Appendix A, p.249*). Coatings, one of which is Pilkington Optitherm, applied in this way are referred to as ‘soft coatings’ and are generally considered to be superior products giving better insulation and optical clarity. They mark easily so require careful handling and storage. They also need to be protected from humidity so must be sealed as a unit at an early stage (Tangram Technology, 2004). Consequently, soft coated glass as a raw material is not readily available for the artist and is considerably more expensive than the hard ‘on- line’ coated glass.

On-line coatings, also known as pyrolitic coatings (*See Appendix A, p.250*), are applied during the manufacturing process between floating the glass on the bed of molten tin and its annealing stage, using a technique called chemical vapour deposition (CVD). The coating is obtained when the chemical vapour which is directed on to the glass reacts with the hot surface (Lo, Hou, Dai, Carson, 2008). This causes the thermal decomposition of the chemicals to form a metal oxide layer with a thickness of less than one micron (one millionth of a metre). In contrast to the off-line coatings these coatings are known as ‘hard coatings’. Although the range is limited in comparison to that of sputter coatings, glass with a hard coating is more durable, can be heat treated and strengthened. Due to the lower cost, easier handling and ability to meet the basic governmental requirements, the hard coated low emissivity Pilkington K Glass has become the best selling product of its type in the UK (Cristal Windows, 2009).

2.8 International Market of Flat Glass

The latest statistical documentation of flat glass production by Pilkington was for the year 2010 when approximately 56 million metric tonnes of flat glass was produced worldwide in a market worth approximately 53 billion Euros and growing at 4-5% per year. Of the total amount, 33 million tonnes was high quality float glass, 20 million tonnes was inferior quality float manufactured in China and the balance was sheet and rolled glass. With 3.7 million tonnes utilised by the automotive industry, the largest sector of 51 million tonnes went to building products. Almost three quarters of that total demand was controlled by China, Europe and North America, the production being dominated by four major companies namely AGC Glass (15%), Saint-Gobain Glass (14%), NSG Group (13%) and Guardian Glass (12%). Much of this is within the market of 'value-added' products for which Europe has the highest demand (NSG Group, 2011).

2.8.1 Value Added Glass

Surface coated glass is one of a number of products referred to as 'value added glass' which is the most rapidly expanding area of the glass industry. Wilberforce (2008, p.39), Financial Director of Pilkington UK Limited, stated that in the context of 'policy and legislative framework on energy efficiency…the coated glass industry is experiencing an unprecedented favourable political environment for the growth of its products'. After the European Green Paper on Energy (Commission of the European Communities, 1995) came into force in 1995, followed by UK Energy Legislation (United Kingdom, Office of Public Sector Information, 2008), the effect was a dramatic increase in functional climate control coatings. For example, in 2005, the coated glass share of the European flat glass market rose from 8% to 25% (*Figure 2.18*). In 2009, Pilkington anticipated that European production of coated and, more specifically, low emissivity glass would be pushed from 60 to 100 million square metres over the following five years (Pilkington, 2009a).

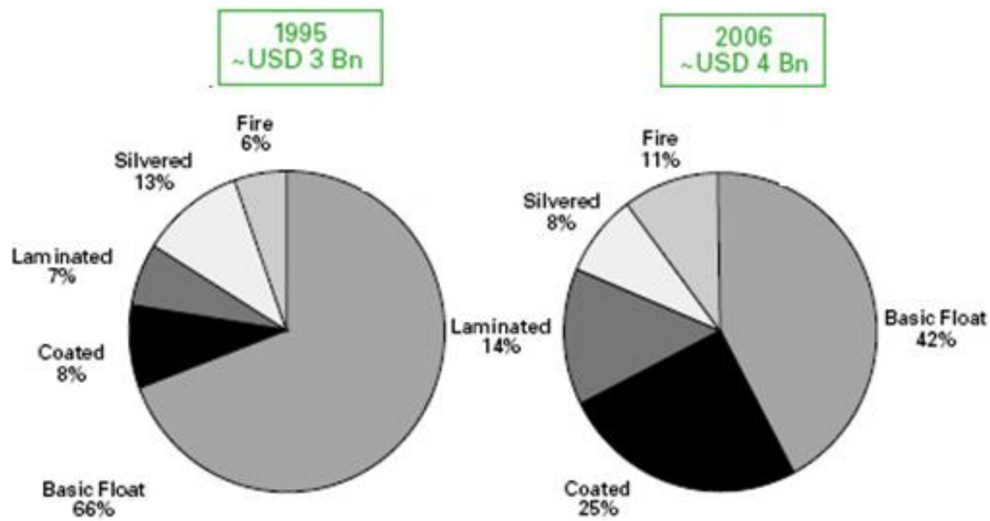


Figure 2.18 European Market Structure Coated Glass Demand by Value, 1995 v 2006 (Pilkington 2009a).

2.8.2 Other Coatings Applied to Flat Glass

Despite the fact that the emphasis of this research is on low emissivity glass, it should be noted that, as shown by the increase in coated products above, there are other coatings being developed that are applied to flat glass. Details of some of these coatings can be found in Appendix A, p.251.

2.9 Interference Issue of Pilkington K Glass and its Resolution

Viewed in isolation, Pilkington K Glass would appear to be no different to any other float glass. However, when in juxtaposition with normal clear float, it shows a slightly brown colouration as can be seen in Figure 2.19. To the artist/designer this disappointing lack of 'vibrancy' of appearance may be a contributing factor for its non-development in creative use.

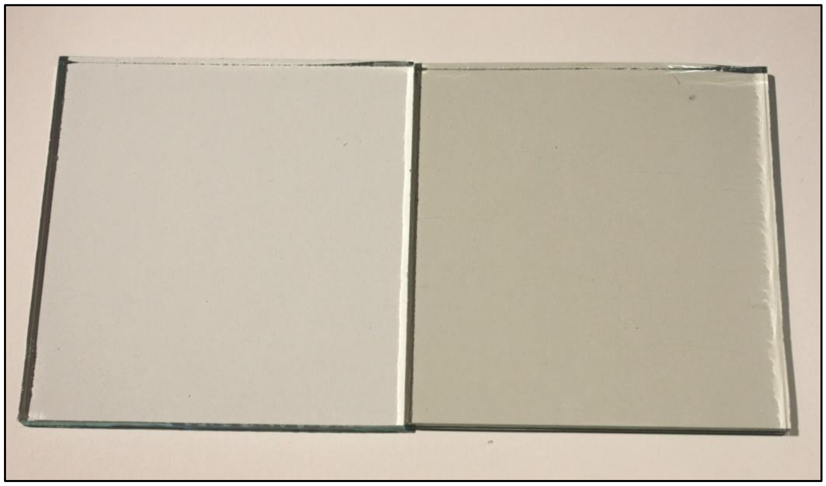


Figure 2.19 Float and K Glass colour comparison.

Pilkington do not ignore this colouration and, in fact, highlight the issue in their K Glass publicity brochure. While claiming it to be 'virtually the same as clear float glass', they also explain that in certain lighting situations a haze may be seen but justify this as evidence of 'the coating's presence'. Pilkington's 1998 patent application GB 2335201A, quoted the 'thicker coatings of transparent metal oxides' required to achieve the desired degree of low emissivity being responsible for the haze 'especially when applied by on-line chemical vapour deposition' (Hurst and Sheel, 1999).

According to Gordon (1980), this problem arises from 'light scattering on surface irregularities'. In the UK patent application GB2031756A, he discussed the other visual problem of low emissivity coating, that of 'interference colours (iridescence)' when viewed in reflected light. This 'objectionable feature' he claimed was 'quite a phenomenon in transparent films' and being 'aesthetically unacceptable' was responsible for the early limited use of coatings on window glass (Gordon, 1980, p.1). Gordon's solution to overcome the problem of iridescence on low emissivity glass was to use a coating consisting of two layers. His patent describes the introduction of an intermediate layer between the low emissivity surface layer and the glass substrate with an intermediate refractive index (Gordon, 1980).

Eight years later, Pilkington's patent GB2199848A described the process developed to enable the commercial operation of the on-line production including the requirements to suppress the reflected colouration. The active over layer of fluorine-doped tin oxide and the 'iridescence reducing under layer' containing silicon and oxygen would both be deposited on the float glass by pyrolitic decomposition on the production line (Jenkins, Simpson and Porter, 1988). Gordon's 'objectionable feature' of iridescence is at the core of this research.

2.9.1 Interference as it Relates to this Research

The word 'iridescence' is from the Latin 'iris' meaning rainbow (Dictionary.com, 2010). The 'complex optical effect' seen in many situations of our daily life like that seen in Figure 2.20 of a film of oil on a puddle of water, is the result of the 'interference of light reflected from the two surfaces of a thin film of material' (Bezúr, 1999). These two surfaces cause the white light from the sun or artificial light to separate into different colours and, when reflected, show an iridescent rainbow or spectrum, the visible effect of interference.

Figure 2.20 Film of oil on a puddle showing iridescence colouration.

Reflection of light and, with it refraction of light, contributes to this optical effect and can be explained simply in the diagram of a glass surface *(Figure 2.21).* A light ray (incident ray) that travels through air meets the surface at point A and is reflected back at the same angle (reflected ray) to the normal N. The light ray will also travel through the surface at point A and into the glass which is a different medium. This change of medium causes the light ray to slow down and, consequently, the angle changes moving towards the normal N'. The refracted ray and how much it moves, depends on the refractive index of each medium. This theory of reflection and refraction is known as Snell's Law[11] and was established in 1621 (Jenkins and White, 1937, p.11).

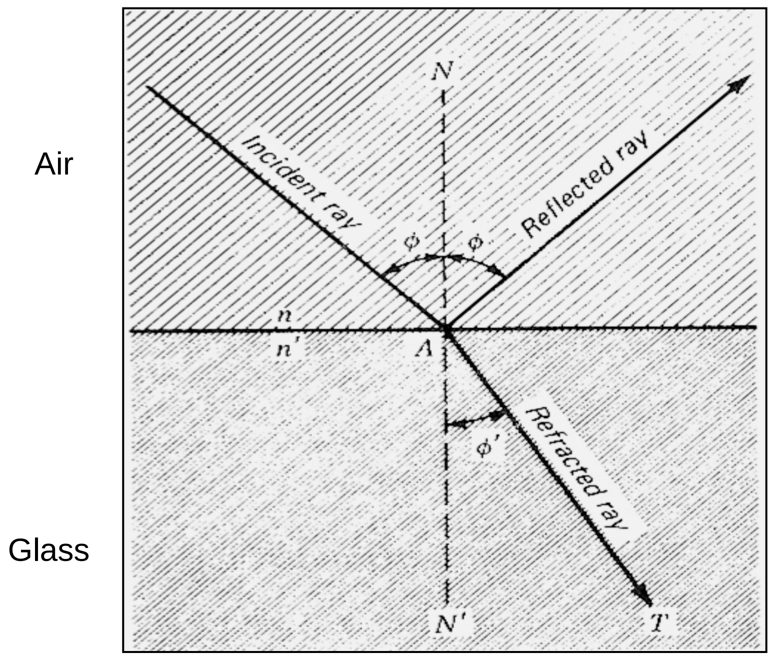


Figure 2.21 Reflection and refraction of light (Jenkins and White, 1937).

With a thin film for example, oil, there are two surfaces and, as such, will have two sets of rays, as shown in the diagram, Figure 2.22. There are those that are reflected from the top surface, A, and those that are reflected from the bottom surface, F. This creates multiple reflections (ibid, p. 289).

[11] Willebrod Snell (1591-1626). Dutch mathematician and astronomer (Oxford English Reference Dictionary, 2002, p.1371).

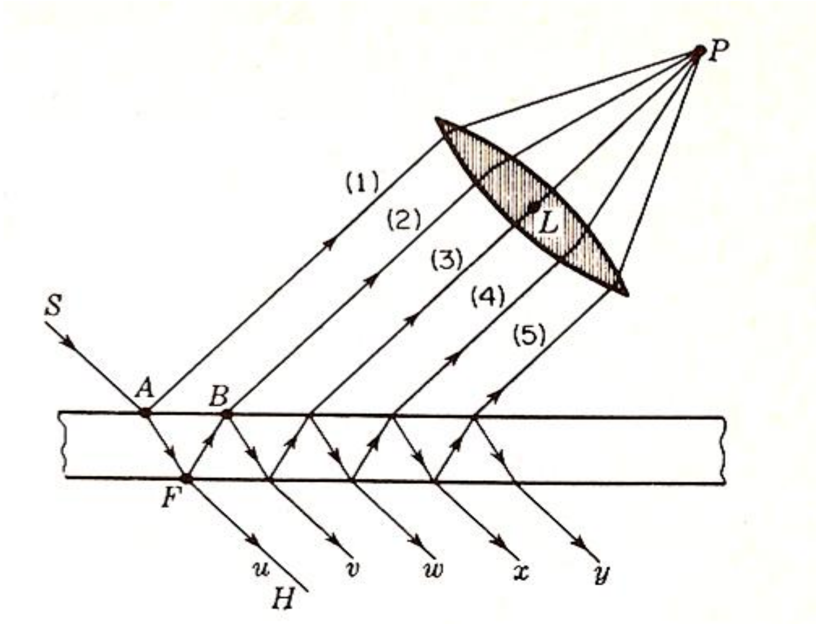


Figure 2.22 Multiple reflections from two surfaces (Jenkins and White, 1937).

Light rays, however, travel as waves and, in following the pattern of reflection and refraction, arrive at the upper surface of the film at B *(Figure 2.23)* and are refracted as they pass through the film to meet the lower surface of the film at C. Some of the light rays are transmitted through this surface (CD) but some are reflected back to the upper surface of the coating where they meet the reflected rays and 'combine' (BE) as 'interference'.

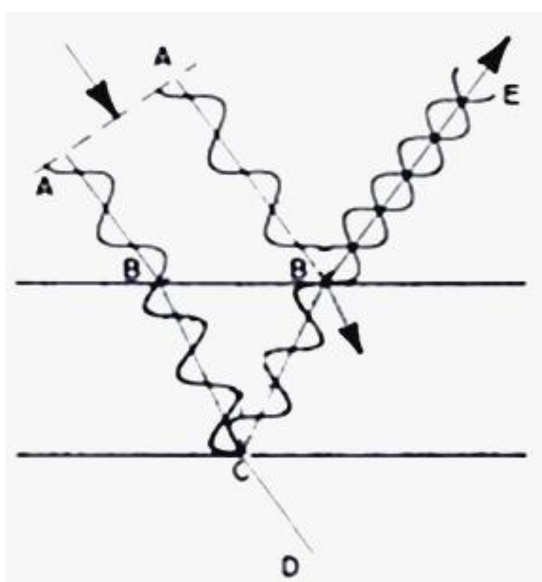


Figure 2.23 Interference.

If the waves of light are of the same wavelength and the crests and troughs align to reinforce each other, they known as being ‘in phase’ and produce ‘constructive interference *(Figure 2.24).* Waves where the crests and troughs do not align are ‘out of phase’ and can cancel out each other, producing ‘destructive interference’ *(Figure 2.25)*. Constructive interference will give a brighter light; destructive interference can result in a total lack of colour (Nikon, 2010). Reflectivity affected in this way is known as ‘interferential’.

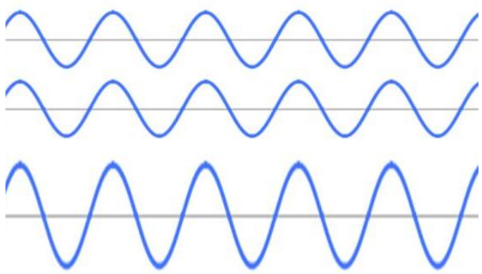


Figure 2.24 Constructive interference.

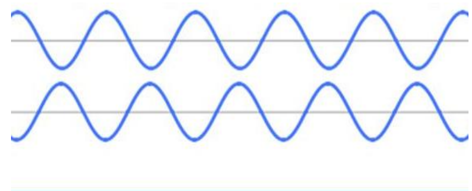


Figure 2.25 Destructive interference.

When two surfaces are involved as in a coating, the light of constructive interference that reaches point C is reflected back to E *(Figure 2.23)* and meets further constructive waves at B which are being reflected from the upper surface. This is increased when the surface itself may not be uniform, as suggested by Gordon regarding the question of haze on low emissivity coating (Gordon, 1980). The combining of these two waves can become out of phase and consequently create destructive interference (Bezúr, 1999).

The reflections of the varying lengths and angles of the paths of light that hit the surface cause both constructive and destructive interference resulting in the spectrum of colours seen in iridescence relevant to the particular wavelengths. This ranges from red being the longest wavelength through orange, yellow, green, blue and indigo to the shortest wavelength, violet (Causes of Color, 2010). Thus iridescence is the visual effect caused by interference.

2.10 Creative Application of Coatings on Glass

Experimentation with materials is a feature of postmodern concepts as artists in the field of creative glass broaden their scope with modification of methods and media. Within large scale presentations, float glass has been the predominant material, however, awareness of the aesthetic values of the surface properties of some recently manufactured functional coated glass is just beginning to emerge. This field of activity would appear to be mostly limited, at present, to installation pieces such as those produced by Marian Karel *(Figure 2.26).* The Czech artist has, for many years, produced large scale geometric forms where the surface is a vehicle for reflections and manipulation of space. Recently, according to Petrova (2008), he gained a greater degree of reflectivity using 8mm Supersilver Stopsol made by AGC Flat Glass (*See Appendix B, p.257*).

Figure 2.26 'Cube', Marian Karel, 1998, glass panels, 3.5m x 2.4m x 1.85m.

While Karel exploited the exceptionally reflective manufactured surface of coated glass, American artist, Larry Bell, explored reflectivity through the structure of a self applied coating. His installations using plate glass began in the 1960's. As thin film technology developed, he experimented with coating surface properties to 'subtly manipulate the level of transparency and opacity' (Guggenheim, 2011). In the mid-1990's, he applied coatings including Inconel[12] and nickel-chrome to increase reflectivity in installations such as that in Figure 2.27 *(*larrybell.com, 2011).

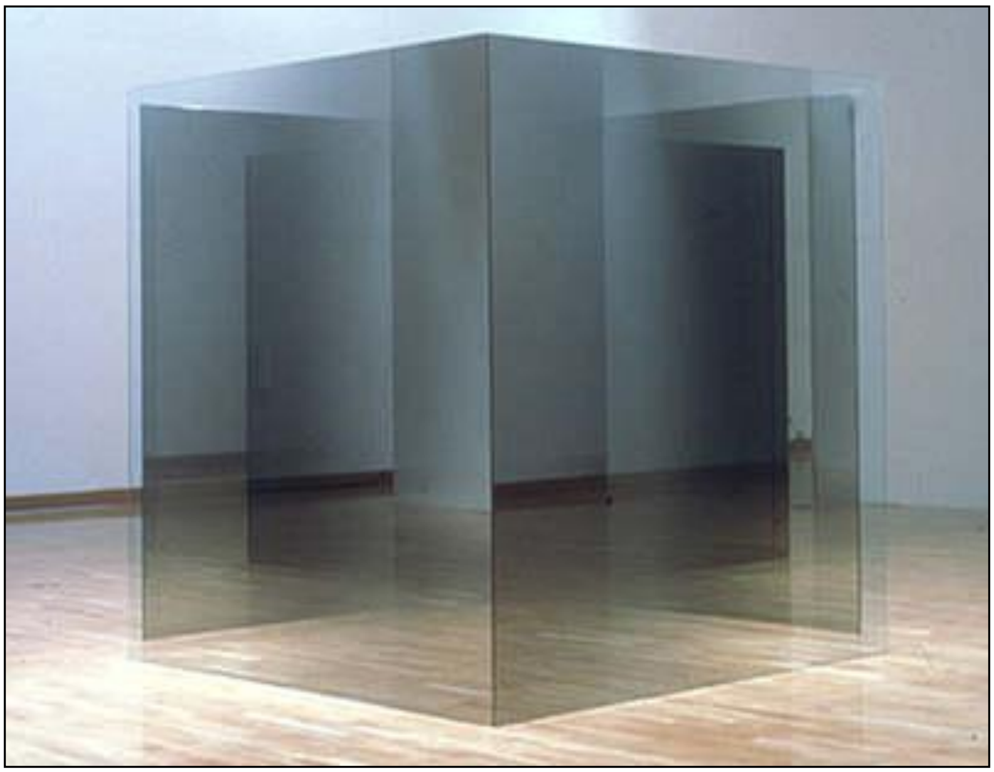


Figure 2.27 '6x6x4-A,B', Larry Bell, 1995,
Four 12mm glass panels coated with nickel-chrome each 6' x 6' x 1/2".

Through his coated surface the elusive reflected image was a visual experience which was created by the position or the movement of the viewer. For artists like Bell, the surface properties of his panels of glass

[12] A high performance alloy used extensively in the field of engineering and anti-corrosion (Special Metals, 2011).

presented a visual and perceptual experience for the observer ‘to interact with the work in the actual space it is presented.’ (Larry Bell Studio, no date).

Anish Kapoor also used the power of the surfaces of his substantial artworks to exercise illusion and the perception of the viewer. While not using reflectivity, it was the angle of viewing that was the factor that created the interaction with his wall piece ‘My Body Your Body’. This was seen as a flat, rectangular, dark blue panel until the viewer moved closer where, from an oblique angle, a deep hole in the centre was observed (*Figure 2.28*).

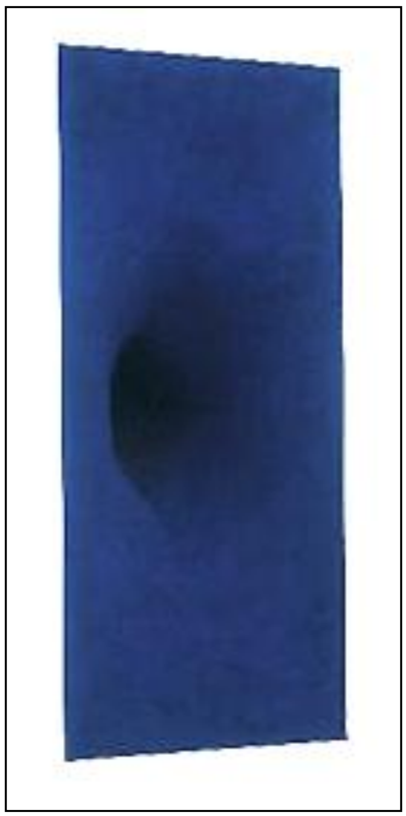


Figure 2.28 ‘My Body Your Body’, Anish Kapoor, 1993.
Fibreglass and pigment, 248cm x103cm x 205cm.

Although Karel and Bell have produced creative work with products destined for the architectural market, no documentation of coated glass being used by studio glass artists has been found. It may be that

Robyn Smith, joint winner of the People's Prize at the British Glass Biennale 2008, used coated glass for her submission. 'Glass curtains', later exhibited at The Biscuit Factory in Newcastle upon Tyne, was described as being made from 're-cycled glass' (*Figure 2.29)*. The surface showed similar colouration characteristics to some of the effects achieved in this research suggesting that the material may have had a surface coating or, alternatively, it may have been the result of prolonged firing. Attempts to contact the artist for comment have proved unsuccessful.

Figure 2.29 'Glass Curtains', Robyn Smith, 2008, recycled glass.

2.10.1 Dichroic Coatings

'Dichrioc' meaning 'showing two colours' (Oxford English Reference Dictionary, 2002, p.395) is a glass specifically designed for decorative application. The coating comprises alternate layers of different chemicals, each with specific properties in relation to light, allowing the transmission or the reflection of certain wavelengths (Bray, 2001, p.101). The colours produced are the 'result of the control of constructive and destructive interference' (Johnston, 1997, p.42) as they alternate between, for example, blue and red or yellow and green depending on the source of light. The value of dichroic glass as a creative medium was established in 1997 by Laura Johnston (*Figure 2.30*) when she was awarded the first UK practice based Doctorate in Architectural Glass.

Figure 2.30 Laura Johnston, ' Prismatics', 2003, dichroic coated glass and stainless steel.

Architectural scale work perhaps shows the alternating colours of dichroic glass to its best advantage as in the sculptural work of several international artists including Ray King, Stephen Knapp and James Carpenter. The movement of the viewer and variable angles of light projecting the colour onto surrounding surfaces can offer a constantly changing aspect to the installation. For the studio artist, the size of sheet and high cost of this specialist glass may influence the design and production of their work. The manufacture of this coating involves the glass being subjected to vacuum evaporation in a frame which according to Johnston (1997, Appendix 2, p.4) limited the size of sheet available for retail, at the time of writing, to 12” x 16”. Today similar sizes are available from companies such as Warm Glass UK who offer dichroic glass which has been ‘coated in circles 48cm in diameter’ as pieces up one quarter circle (Warm Glass UK, 2011). With a 10cm square costing almost £10, designs may need to be composed of small pieces, as shown in the work of Peter Aldridge in Figure 2.31, or in the creation of jewellery. Few manufactures of flat glass offer dichroic glass as part of their range, however in the UK, Schott Glass has recently introduced ‘Narima’ which is coated by a process of dipping (Schott UK, 2011).

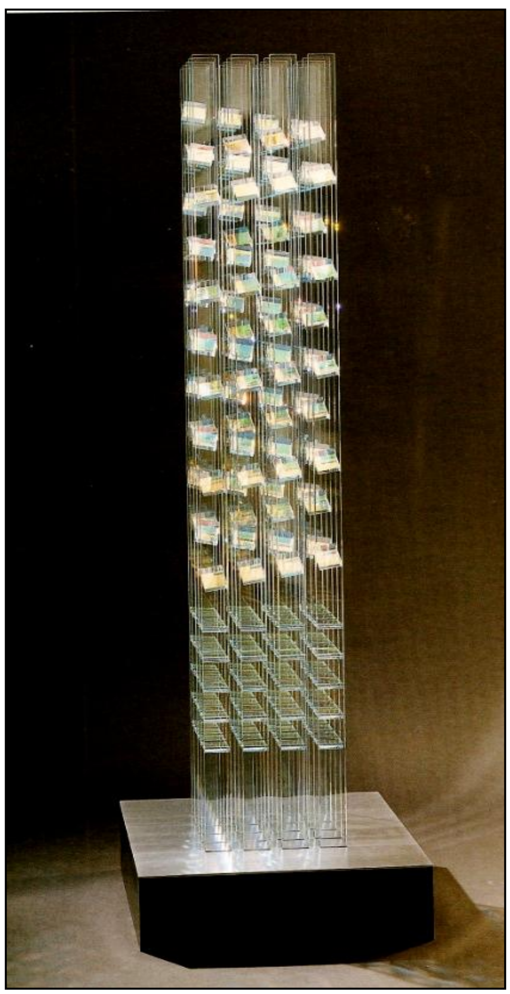


Figure 2.31 ‘A Moment in Time’, Peter Aldridge, 1998, Height 3m. Steuben Starphire lead-free glass and dichroic coated glass.

2.10.2 Colour Surface Applications

For many years artists have added surface decoration to glass with, for example, enamel which, as a colour application, dates back to pre-Christian times. Although still based on glass frit, today's enamels are now of mixed composition, designed to be compatible with the base material and can be applied using traditional methods such as brushing, rolling or spraying (Bray, 2001, p.109). Sophisticated modern equipment including mechanised screen printing, which produces a repeated design by pushing the enamel through a masked screen of silk, metal or synthetic material and economical large kilns, has enabled the production of architectural scale work (Moor, 2006, p.12). Examples of such projects are shown below in Figure 2.32, the Al Faisaliah Centre, Riyadh by Brain Clarke or in Kate Maestri's 100 metre balustrade at the Sage Centre in Gateshead (*Figure 2.33).*

Figure 2.32 Al Faisaliah Centre, Brian Clarke, Riyadh, 1999, 79' x 265', enamel on float glass.

Figure 2.33 The Sage Balustrade, Kate Maestri, Gateshead, 2004, 100m, screen printed enamels on float glass.

Modern coloured glass is normally produced by the addition of metal oxides during the molten state (Bray, 2001, p.79). A method is now available that coats the surface either on flat glass or on a manufactured form such as a container. This process uses particles of material designed to address the specific purpose of the glass and which are deposited on to the surface as a coating (Glasscoat International Limited, 2005). Other systems include a resin coating which can simulate coloured glass at a low comparative cost. Now well established within architecture and interior design, these methods are applied after cutting and processing the glass and can produce both detailed artwork and blanket coverage (Cadram, 2010).

This section would not be complete without a reference to film which falls within the parameters of the coating industry. This is a product which is manufactured independently to the glass and applied at any time, even 'in situ'. The films of today are 'multi-layer assemblies' which can provide similar characteristics to those of energy protecting glazed products but not to the same level of efficiency. They are, however, inexpensive and easy to apply (Elkadi, 2006, p.71).

The relevance of these films in this research is the decorative application and the control of breakage splintering *(See 6.6, p.228)*. Films that have addressed building issues such as safety or privacy for many years are now able to be digitally printed, offering opportunities for creativity and flexibility as well as economy. Several artists have explored this medium such as, German born Michael Bleyenberg. He first worked with scientific teams to understand holographic film and then designed the forms such as in Figure 2.34, to exploit its continually changing images (Moor, 2006, p.182).

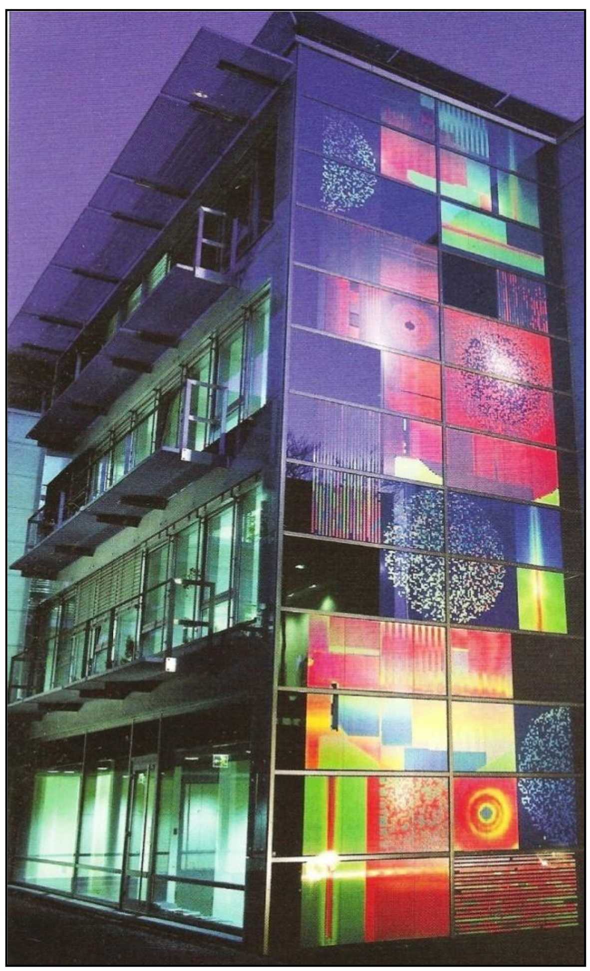


Figure 2.34 'Eyefire', Michael Blayenberg, Bonn, 2000, 5m x 13m, holographic film.

The creativity of the designer and the capabilities of coatings and films are taking the status of glass to a new level of importance in addressing the demands of imaginative energy efficient architecture. In the opinion of British Architect Ian Ritchie,

> 'Glass will become the support medium for holograms, transparent integrated circuits, miniaturized lasers, and biogenetic coatings offering possibilities to improve energy efficiency, create interactive building surfaces for both user and the environment and release new creative energies in the design and visual pleasure of buildings' (Vitkala, 2008, p.114).

2.11 The Iridescent Surface

In 1830, Sir David Brewster[13] wrote about his experiments of obtaining 'brilliant iridescent plates' by 'burning iron wire in chloric gas (Brewster, 1830, p.66). In his documented studies of 1863, he described the 'beautiful iridescent appearance of many ancient glasses' attributing the colouration to 'diffraction effects arising from the thin layers in a weathered crust' (Newton, 1971). Total acceptance of Brewster's weathering theories was challenged by Raman and Rajagopalan (1939). Their investigations to 'clarify the position' of the 'structure and optical characters of iridescent glass' confirmed previous research by Guillot who, in 1934, found that this effect could be induced by soaking alkaline glass for several weeks in a saturated solution of sodium bicarbonate. Detailed examination of surface erosion iridescence includes photographs, one of which is shown in Figure 2.35, of ripple formation from which the light is reflected and responsible for the iridescence (*See 4.7, p.139*).

[13] Scottist physicist (1781-1868). Best known for laws governing polarisation of light (Oxford Reference Dictionary, 2002, p.179).

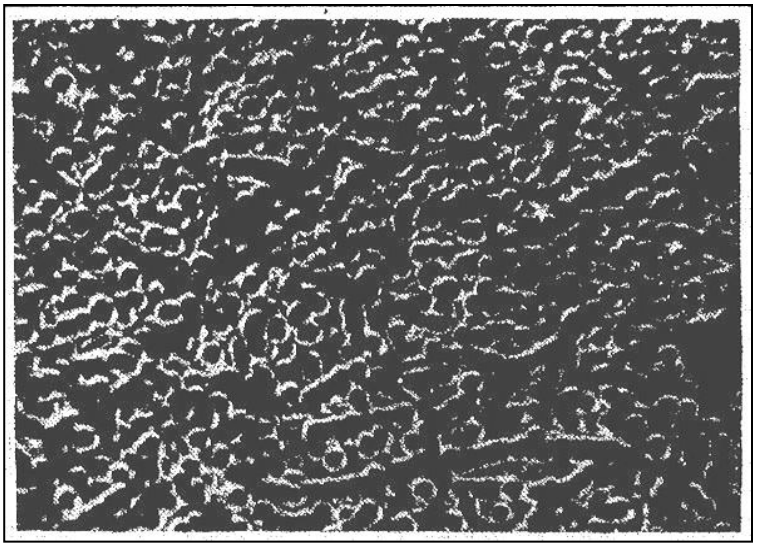


Figure 2.35 Photomicrograph of iridised surface (Raman and Rajagopalan, 1939).

More recent studies using scanning electron microscopy (SEM) confirmed Brewster's early theories of the structure of the iridescent surface. Images, as can be seen in Figures 2.36 and 2.37, of the weathered surface of Iranian glass dating from the third to the sixth century, show the uneven surface and surface laminations that reflect light (Gulmini, Pace, Ivaldi, Ponzi and Mirti, 2009).

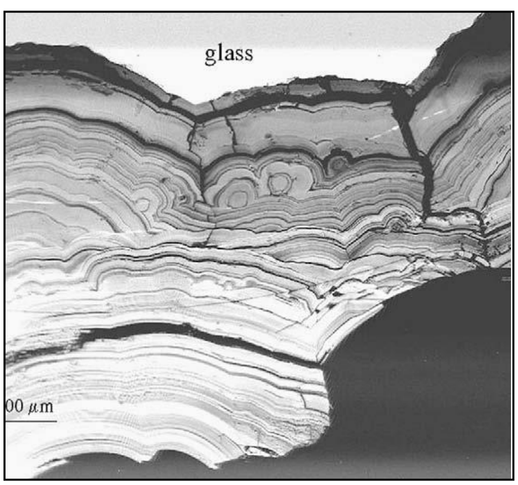


Figure 2.36 SEM image of cross section of iridescent crust.

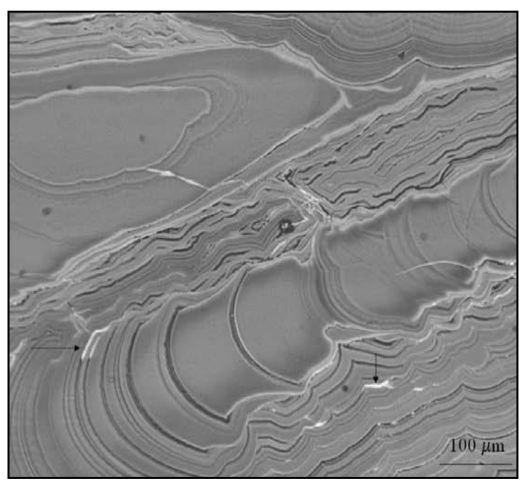


Figure 2.37 SEM image showing surface laminar distribution.

(Gulmini, Pace, Ivaldi, Ponzi and Mirti, 2009).

The surface structure and iridescent effect on ancient artefacts greatly influenced nineteenth century glass workers. Its reproduction was a major characteristic of Art Nouveau glass in Europe and America as makers sought to rebel against the clarity and purity of glass of the Arts and Crafts movement (Potter and Jackson, 1988, p.31). Bray (2001) suggests the first commercial production of iridised glass was by the Austrian Lobmeyr factory about 1863. However, earlier attribution of the development of applied iridescence was in Hungary in 1856 (Corning Museum of Glass, 2011) by Valentin Leó Pantocsek at the Zlatnó glassworks (Pataki, 2007).

The popularity of this iridised effect was confirmed by the number of patents granted in Europe and America. The first recorded was in 1859 to J. J. H. Brianchon of Paris, followed by J. & L. Lobmeyr in 1875. In 1878, both Frederick S. Shirley in America 1878 and Thomas Webb in England were granted patents for their individual versions of Bronze Glass (The Antiquarian, 2008). An example of Webb's iridised work is shown in Figure 2.38.

Figure 2.38 Iridised Bronze Glass vase, Thomas Webb, c.1878.

This fascination with the appearance of ancient buried glass inspired American Louis Comfort Tiffany to experiment to recreate these characteristics from as early as 1872. His patent application for Lustre Ware, as shown in Figure 2.39, describes his method for the production of the effect 'by forming a film of the metal or its oxide, or a compound of a metal on or in the glass either by exposing it to vapours or gases or by direct application' (Tiffany, 1881). His techniques included dissolving metals in the molten glass, then re-heating, followed by spraying the piece with a chloride forming a metallic film (Potter and Jackson, 1988, p.40). He cooled the chemicals at a different rate to the glass causing the film to buckle. This shrivelling of the film created ripples and the light falling on the ripples caused iridescence (Bezúr 1999). The iridescence was created by, what could be described as a 'coating'. This process was later developed by twentieth century flat glass manufacturers as chemical vapour deposition and is explained in Appendix A, p.250.

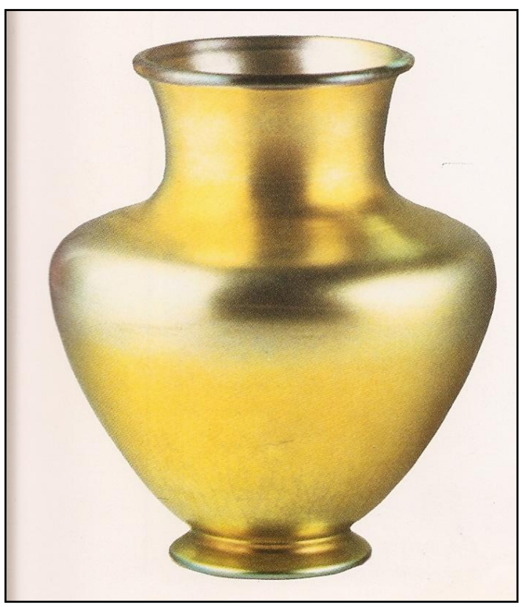


Figure 2.39 Tiffany Lustre Ware Vase, c.1900, Height 10".

The shrivelled iridised coating now described as lustre, when applied to glass 'results from the development of a very thin layer of metal on the surface to give an iridescent effect' (Bray, 2001, p.165). Early lustres were made by a process that included dissolving metal in acid, then simmering the salts in resin before mixing with aromatic oil. Today, lustres are supplied ready for brush application using similar materials to produce a range of post-fired iridised colours (ibid, p.146).

An iridised surface can also be produced on glass by the use of stannous chloride crystals mixed with equal parts of muriatic acid (used to clean brickwork) and diluted to a suitable consistency for spraying. The glass is heated to 815˚C, the kiln is turned off and the glass sprayed, before being reheated and annealed. This is a very hazardous process and should only be undertaken after all safety risks have been addressed (Lundstrom, 1989).

Research regarding iridescence within layers of glass revealed less information. In a recent project, Frances Federer looked at Zwischengoldgläser, the method which laminated gold leaf between two pieces of glass, generally vessels (Encyclopedia Britannica eb.com, 2011). Her blown glass work with gold imagery, as shown below in Figure 2.40, represents her interpretation today of a highly skilled eighteenth century technique (IIRG, 2009).

Figure 2.40 'Test beaker', Frances Federer, 2008, Height 75 cm, blown glass, hot and cold gilded and painted.

2.12 Bubbles

The presence of bubbles in glass can be a measure of imperfection to the artist seeking perfect clarity in artwork. To other artists, bubbles are a source of inspiration and used to produce intricate imagery within the glass itself. Swedish glass company, Orrefors, has ‘sustained commercial and artistic success’ (McConnell, 2006, p.184) with high quality pieces such as that shown in Figure 2.41. Designer, Edvin Öhrström, is attributed with the technique of controlled air bubbles within the glass (Flavell, 2001) on which Orrefors ‘Ariel’ range was based.

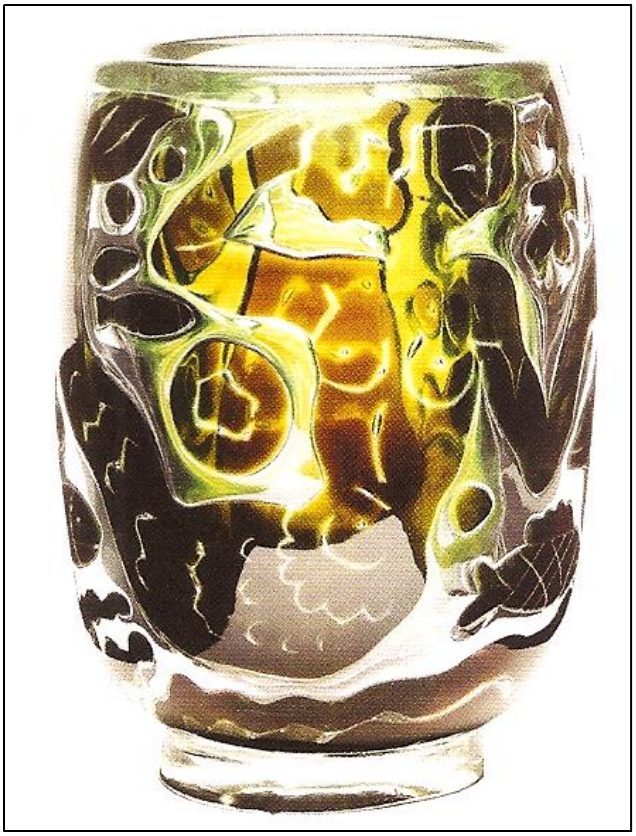


Figure 2.41 Orrefors ‘Ariel’ Vase, Edvin Öhrström, 1937, Height 16.5cm.

Flavell (2001) researched and extended the Swedish sandblasting technique to encase voids creating complex imagery within hot glass blown vessels (*Figure 2.42*). Although, similar methods have been used by the author using float glass, no documentation had been found of encapsulating air within low emissivity glass.

Figure 2.42 'VR Tech', Raymond Flavell, 2001, blown glass vessel with encased voids.

Bubbles are deliberately introduced into commercially manufactured glass used in stained glass windows to reduce the amount of transmitted light into a building. Known as Seedy Glass, illustrated in Figure 2.43, it was originally made by Hartley Wood of Sunderland, but now produced in the USA, by Spectrum Glass (Watkinson, 2011).

Figure 2.43 'Seedy Glass' by Spectrum Glass, USA.

2. 13 The Influence of Science in Art Research

Postmodernism has embraced twenty-first century technology using innovative materials to generate creative opportunities. The disjunction of what was termed an 'art material' or an 'engineering material' is no longer an issue. Instead, as artists challenge tradition, the boundaries of materials are being dissolved. Jones (2005), however, cautious of the danger of loss of identity of art and design disciplines in research warned,

> 'If we do not establish our own pluralistic research-based paradigm for art and design we will not be able to resist the coercion to fit into the research paradigms of other subjects that are currently more explicit' (Jones, 2005, p.33).

Practice-based research by its very nature will encompass methods, processes and approaches as varied as the researchers themselves who have already developed their style within the parameters of their practice. The multi-method or pluralistic approach termed by Gray and Malins (2004, p.121) as 'triangulation', the locating from different positions, could therefore include processes which may be termed scientific. Graham (2010) stated,

> 'Art-practice PhDs involve the making of artwork by the researcher, as a major part of the research process, and may be strongly related to other PhDs involving practice, such as engineering, or experimental science' (Graham, 2010).

While acknowledging the relevance of scientific methods, the protestation that 'our research is not scientific' and the call to 'be brave enough to propose, use and validate our own procedures, or else our research will never be released from the grip of the 'scientific method' (Gray and Pirie, 1995, p.18) may not be entirely relevant within all art research. Allinson (1996, p.10) clearly defined the characteristics of each methodology but emphasised the interaction of several which may be applied within a project. His 1992 Research Index of Art & Design (Gray and Pirie, 1995, p.3) shows experimental methods were used in only 228 out of 2133 art and design based projects. No later figures are available but such approaches are now evident in theses where scientific methods and experimental research were significant contributors within the parameters of art practice based projects.

Johnston's thesis (1997) on the coated glass surface was about the innovative application of decorative glass in architecture. However, her investigation included a brief study of thin film technology and the actual production of the dichroic surface in conjunction with Pilkington. Her pragmatic approach used methods which included material testing and was, at the time quite progressive, in the context of the very traditional area of stained glass.

McCartney (2001) developed a ceramic shell mould of benefit to hot glass artwork which used scientific methodology within an art application. His experimental testing and development of the material and technique was through a 'multi-method approach…involving studies of technical variables' (McCartney, 2001a).

Metcalfe (2007) also employed scientific procedures within the empirical testing necessary for the preparation of new glazes for ceramic application. Knowledge of elemental reactions and the effect of the chemical changes associated with the firing of compounds obtained from natural sources, contributed to her development of the resultant material. She also supported her analysis by energy dispersive x-ray spectroscopy to further understand the composition and properties of the developed ash glaze.

An increasing number of artists are incorporating industrial products within artwork. Bremner (2008) used refractory concrete as the basic material to explore potential aesthetic applications in which 'visual qualities of practice based elements of the research are combined with quantitative research' (Rose, 2010). Of his ethos he says, '…while there is a strong connection between science and art in my research there is also a similar bond between industry and art' (Bremner, 2005).

Antonio (2009) took a more qualitative approach as she examined creative potential through the development of artwork. Using a basic industrial material, she collaborated with a materials scientist who assisted with the explanation of imagery achieved from the tin residue on float glass. Of her research she has described the 'language of mutual understanding' that developed as both artist and scientist worked together in unfamiliar disciplines (Petrie, 2005).

Petrie (1999) tackled issues arising from solvent-based printing inks for ceramic transfer printing. His approach was taken from the perspective of an artist from Art, Media and Design but working in collaboration as an 'inter-faculty project' with another research student, Alison Logan, from the field of Applied Science. The collaboration of practical testing and artwork had a reciprocal influence in the understanding of each individual discipline. Using both scientific procedures and artwork application, they extended their research with the close association of industry where the transfer printing process was particularly relevant.

The dialogue of understanding between artist and scientist has grown through similar projects over the past twenty years such as that of Colin Rennie whose float glass sculpture in Figure 2.44 was inspired by the molecular architecture of an enzyme called ATP synthase (Newitz, 2011). With imagery created in float glass by water jet technology, Rennie enquired within the world of material science for an understanding which informed and inspired creativity.

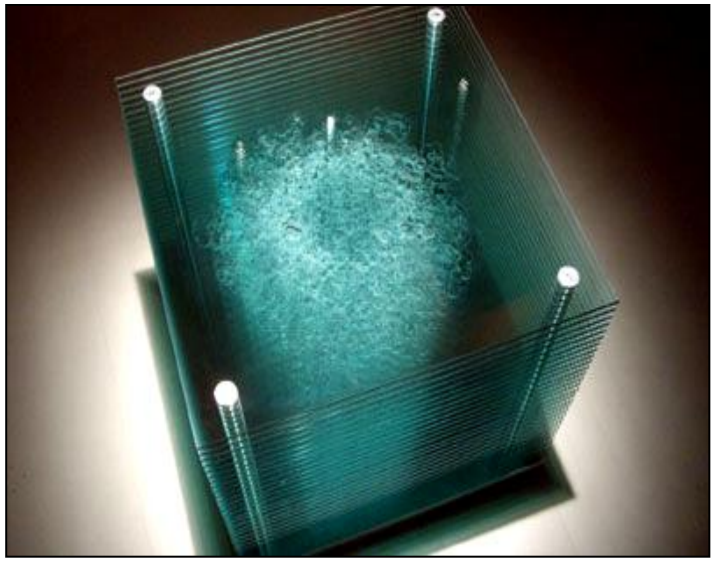


Figure 2.44 'ATP synthase', Colin Rennie, 2007, float glass, 1m x 1m x 1m.

'Experiments', exhibited at the GV Gallery in London in 2010, showed the work of five artists working in different media with a number of scientists. One piece shown in Figure 2.45, by glass artist, Katharine Dowson and psychophysicist, Dr. Gabriele Jordan, was the result of not just collaboration but also the relationship that developed as each worked within the arena of the other, learning processes and concepts that had previously not been within their own sphere of knowledge.

Their original artwork, according to curator Wallace (2010), served to reinforce the benefit to humanity of the understanding of the 'two cultures' a phrase introduced by scientist and novelist C.P. Snow[14] in his Rede Lecture at Cambridge University in 1959 (Wallace, 2010). C.P. Snow's discourse regarding the breakdown of communication within society due to the separation of the arts and the sciences, initiated a debate that not only became a piece of social history but also influenced the new movement towards collaboration between art, science and technology (Sakane, 2003). Forty years on, in answering the issues that were provoked by Experiments, Wallace asked,

[14] Sir Charles Percy Snow (1905-1980) 1st Baron Snow of Leicester (Oxford English Reference Dictionary, 2002, p.1372). Known throughout the world by his initials, 'C.P' (Collini, 1998, p.vii).

‘How on earth, in fact, did we develop the sense that art and science are such separate disciplines that there should be different courses, different universities, different professional outlets, and completely separate training grounds for the two different cultures?’ (Wallace, 2010).

Figure 2.45 ‘Micro Macro 4’, Collaboration Katharine Dowson with Dr. Gabriele Jordan, 2010, acrylic, light reacting glass lenses, 23cm cubed.

2.14 Summary

This chapter has demonstrated the extensive potential for the creative use of glass in which colour and iridescence are important effects. The review of the flat glass market indicates the relevance of coatings and the extent of their increasing availability. Float glass as a medium for glass artists is well established but to explore the creative possibilities of colour and iridescence produced by post-fired low emissivity coated glass, a technical understanding of its capabilities is important. Hence, a programme of practical testing is necessary to develop that knowledge and is detailed in the following chapter.

Chapter 3

Practical Programme of Testing

This chapter gives a detailed description of the programme of practical testing to address Objective 1 'To identify the changes to the K Glass surface coating when subjected to high temperatures', Objective 2 'To understand the changes to the surface coating and the factors responsible for the visual effects' and Objective 3 'To control the visual effects through manipulation of the factors'. In order to compare and evaluate effects, a series of tests was undertaken. Characterisation of the effects is used to analyse both open fired and fused samples through surface, colour, iridescence and bubbles with microscopic examination supported by photographic evidence.

3.1 Practical Programme of Testing

To address the first objective, '*To identify the changes to the K Glass surface coating when subjected to high temperatures'* a testing plan was prepared using knowledge of the material's behaviour gained from previous undergraduate work. All K Glass has to be fired for the effect to the surface to be seen. Groups of standardised tests were devised, therefore, to investigate the effect of heat on the surface coating of the basic K Glass and to explore how the K coating reacted when combined with float glass in a fused format. Each test was reviewed, analysed and evaluated with follow up tests and subsequent variations undertaken as necessary to provide continual assessment of results and review cycles.

The second objective, *'To understand the changes to the surface coating and the factors responsible for the visual effects'* was advanced through modification of both material, namely glass and environmental variables, temperature and air. This was to compare and evaluate the effect of change of criteria. The material variable investigation was focused on the K coating surface and its pre-fired modification; the fused combination with float glass options of thickness, type and colour.

By applying the information gained in the standardised tests, methods were developed which addressed the third objective *'To control the visual effects through manipulation of the factors'* as part of the experimental process.

Throughout the initial standardisation process it was decided to use 100mm x 100mm pieces of both K Glass and float glass. As K Glass is available only in two thicknesses, 4mm and 6mm, the float glass used was mainly 4mm and 6mm for consistency and comparative purposes. It should be noted that at this early stage of testing waste glass off cuts were used. 'Wear and tear' damage to the surface may have had a possible influence on the post-fired visual effects (*See 3.4.3, p.80*). In some tests 3mm or 10mm float was used along with other types of glass namely, tin-free, greenhouse and coloured float.

All glass pieces were tested for the tin side or non-tin side. During its molten phase of production, the lower side of all float glass picks up a residue of tin as it travels along the tin bath. In firing techniques it is important that this tin side is known, as the kiln heat may cause this surface of the glass to become hazy. For this reason, it is often advisable to fire the glass with the tin surface next to the floor of the kiln, shelf or mould. The tin side in this research was accurately detected by the use of a battery operated hand-held UV detector. Information regarding this and other materials or equipment used during the standardised tests can be found in Appendix C, p.265 and Appendix D, p.269.

With the exception of a few tests necessary for specific investigation of the contribution of the tin surface to the visual changes, all tests were placed with the tin side down, i.e. facing the kiln floor. Throughout the tests care was taken to ensure the K surface of the glass was identified with a hand-held fuse tester and documented. All glass was cleaned with Bohle cleaner to ensure contaminant and grease free surfaces. The floor of the kiln was covered with 3mm ceramic matting coated with silica hardener and shelf primer. Ceramic matting, in addition to preventing the glass sticking to the floor of the kiln, encourages an even distribution of heat. The hardener reduces the number of airborne particles of ceramic fibre and allows the matting to be used repeatedly but can cause the glass to stick. The shelf primer provides a separator. Other separators, for example, Bullseye Thinfire or Plaster of Paris are used throughout the research to prevent glass sticking to a mould.

The kiln used for the standardised tests was a flat bed model by Kilncare. Its performance was checked prior to testing and at stages during the research to ascertain controller accuracy or variation of temperature (*See Appendix D, p.271*). Any variations had to be considered where the temperature was critical. In addition, a small laboratory kiln with a Eurotherm controller was used for efficient individual firing of small single pieces.

3.1.1 Identification of Visual Changes

Prior to the standardised test programme, a range of optimum firing temperatures needed to be identified. Having already established that high temperatures caused the K surface coating to modify, the first series of tests aimed to determine the exact points of visual change. The starting target temperature was set at 700˚C which was known to be lower than that which had shown any significant change to the surface. These initial tests used samples of the basic 4mm K as a control with 6mm K as a variable to determine any difference in the coating applied to the two thicknesses of glass. For comparison, it was necessary to fire both 4mm and 6mm K pieces under the same conditions. The small laboratory kiln which was more responsive to control was used and fired at full capacity to the starting target of 700ºC. Once the temperature had been reached the kiln door was opened. This allowed the heat to escape thus ‘freezing’ the surface condition of the glass at that point and prevent any further changes to the coating taking place. Temperature was both increased and reduced at 10ºC intervals until no further changes were noted. With the visual effect temperature range established, further tests were conducted to investigate the consequences of changing the material and environmental variables.

3.1.2 Standardised Open Fired Testing

The term ‘open fired’ is used throughout the documentation of this research to describe single pieces of coated K Glass which were fired uncovered inside the kiln. In some details the full trademark name K Glass has been shortened to K (by which it is known in the glass manufacturing trade) for descriptive simplicity.

With the initial identification of the visual changes to the surfaces of both 4mm and 6mm K coating established, tests were fired at 25°C intervals from 700°C to 925°C to check that no further changes took place above 800˚C and to provide a broad knowledge of the changes to both K thicknesses at a wide range of temperatures. The kiln programme was devised to obtain a regular increase in heat of 125˚C per hour to the target temperature with a short hold time of 15 minutes before cooling and annealing.

More detailed investigation of the individual visual characteristics was undertaken through standardised testing. The comparison of the 4mm and 6mm K coatings were examined through the material variable of glass thickness and the environmental variables of heat and air.

The material variables of the K coating were investigated through:

a) Glass thickness - the comparison between 4mm and 6mm K.

b) Manipulation of the K surface coating.

Modification or physical manipulation of the K surface coating, aids the ability to control visual effects. This manipulation was undertaken through the following methods:

1. Scoring with a glass cutting tool.
2. Scratching using coarse grade steel wool.
3. Sandblasting.
4. Engraving.
5. Etching.

The environmental variables were examined through

a) Heat.

b) Air.

Heat was examined through the effect on the K coating of variations such as rate of heating and cooling. This involved change of target temperature (highest point of the firing), kiln schedule and manipulation of heat during firing by additional means such as ceramic fibre paper matting. During the standardised programme firing schedules were kept to a simple format for analysis and repeatability. They were adjusted as necessary to observe the effect of the target temperature and the length of time held at that point and of multiple firings. The stages of all schedules were plotted with the rate of increase in temperature (heating time), length of time the target temperature was maintained (holding time) and annealing method (cooling time) based on the thickness of glass. This method is described in Appendix D, p.275. However, the schedule was simplified in the standardised tests for easier comparison and to shorten the timescale, shown in Table 3.1.

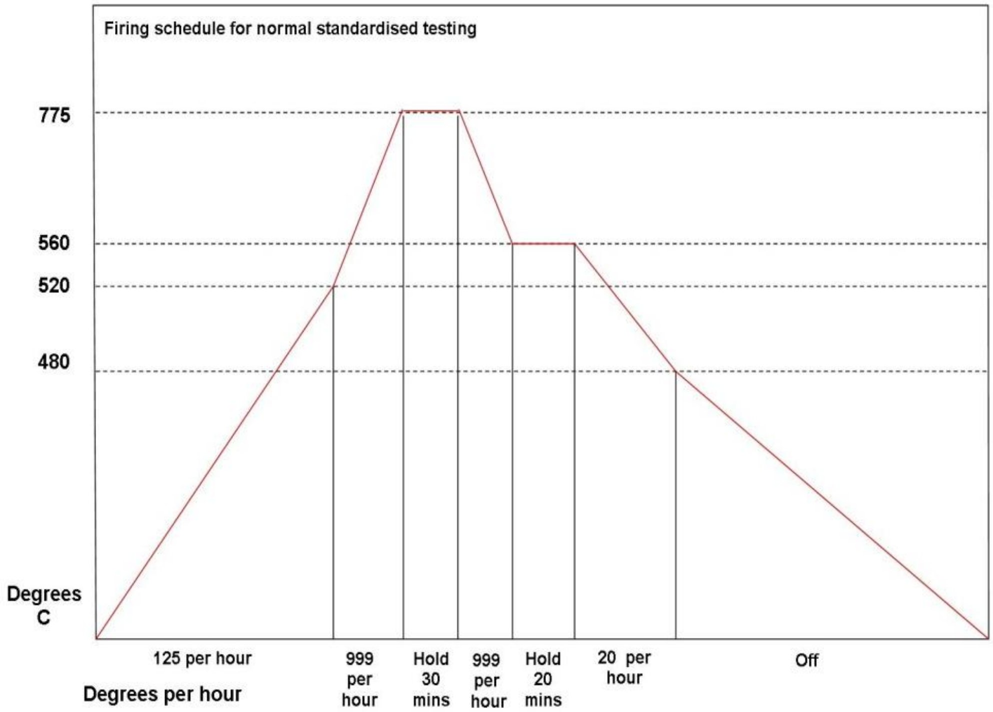


Table 3.1 Firing schedule for normal standardised testing.

To establish the contribution of the second environmental variable, air, to the visual changes, open fired samples were placed on the flat bed of the kiln with the K coating either facing up, i.e. exposed, or down with the coating concealed.

3.1.3 Standardised Fused Testing

The term 'fuse fired' is used to describe pieces of K or float glass fired in the kiln in a double or multiple stacked format to soften and bond as one piece.

With the temperature points at which the open fired K surface visually changed identified, it was then necessary to investigate how K would behave when fused with another glass, for example, float. The fused tests were more difficult to accurately pinpoint the temperature at which the changes took place. To fuse pieces of glass successfully it is necessary to hold the target temperature for a number of minutes (generally from 10 to 30) or to raise the temperature to a point where the hold is not necessary. Either of these two options would present results which could not be compared in precise standards with those of the open fired identification tests where the target temperature was not held.

Three sets of tests were devised in differing formats to investigate reactions to the surface coating when K was fused with float glass. These fused tests were fired over a temperature range between 700°C and 850°C at 10°C intervals. The first format was two sheets of the same thickness, using 4mm K and float glass as a control by which all other combinations could be measured. The square of K with the coating upwards was covered with a piece of float glass of a similar size (*Figure 3.1*). The non-tin surface of the float was uppermost with its tin side being next to the coating of the lower K glass. Unless specified, throughout the standardised testing all float glass is placed in this way, i.e. with tin side down and non-tin side up. For purposes of categorisation this format was named 'Fused Glass'.

Figure 3.1 *Fused Glass format of fusing position of K and float glass.*

The second format, to consider the coating in an enclosed environment was a smaller single piece of 4mm K measuring 80mm square, placed centrally on a 100mm square of 4mm float. This was covered with another 100mm square of 4mm float glass forming a 'sandwich' as shown in Figure 3.2. This format was named 'Enclosed Glass'.

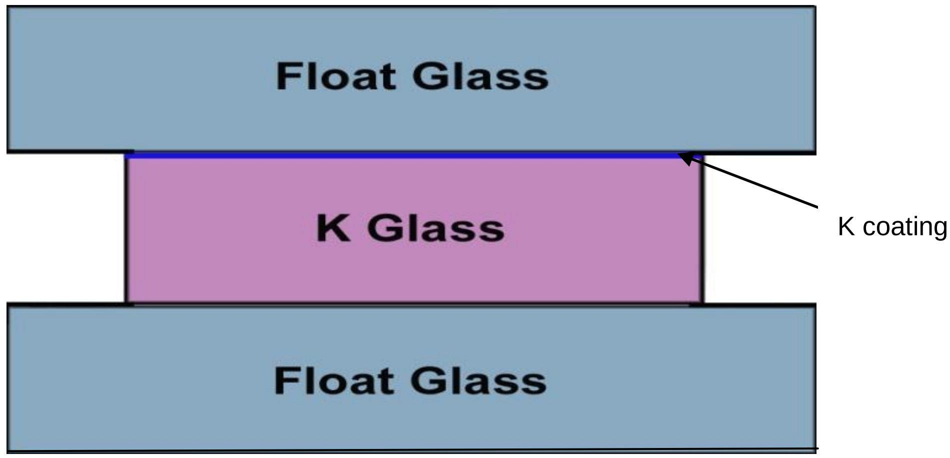


Figure 3.2 Enclosed Glass format of fusing position of K placed between two pieces float glass.

The third format was to examine the reaction of six strips of K sandwiched between two pieces of float glass and how the visual effects differed from those of a single piece of K. Three 10-15mm wide strips of 4mm K, 100mm in length were placed with the K coating upwards at regular intervals on the base square of float glass. A further three strips, again with the K coating up, were placed at right angles on top of the lower strips (*Figure 3.3*). This grid-like structure was then covered with 4mm float glass. This format was named the 'Grid Format'.

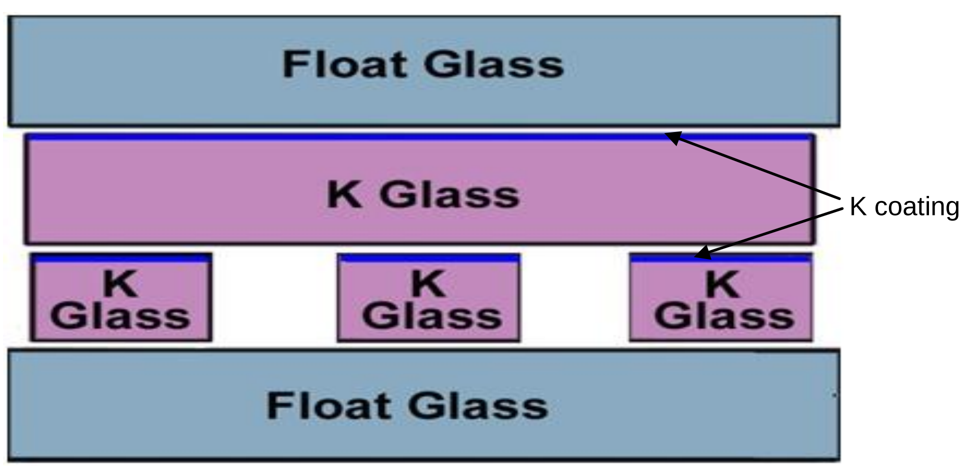


Figure 3.3 Grid Format of fusing position of two sets of three strips of K at right angles to each other between two pieces of float glass.

One important factor in these fused formats was the part that might be played by the tin side of the float glass. Some tests were repeated with the non-tin side of the upper float glass fused next to the K coating. To ensure an environment as free from tin as possible, tin-free glass and greenhouse glass were used. Neither of these is made by the float process, therefore, do not contain any tin residue.

As knowledge of the factors affecting the visual changes developed, a further question was whether the effects of colour, iridescence or the presence of bubbles could be changed through the localised control of the amount of heat to the surface. The temperature was reduced by placing pieces of 3mm ceramic matting and heat screening material, e.g. whiting[15] on the top piece of the float. In additional fused tests, sandblasted channels were created on the K coated surfaces and on the underside of the float glass to try to control the position of bubbles.

To establish the part played by air during the fusing process, a few of the fused format tests were repeated to try to remove the air between the surfaces of the K and float glass prior to firing. This was done by the addition of fusers glue or water, also by placing the two pieces of glass together under water. In the studio situation it was not possible to remove the air from the kiln by any vacuum method. Conversely, to investigate the role of extra air during the fusing process, strips of float glass 6mm x 10mm were positioned between the layers, at the edge of the squares and initially supported the upper layer. This kept the glass separate longer as it softened to touch the lower K layer and, therefore, provided access to a greater period of available air before fusing.

[15] Calcium Carbonate mixed with water to paint like consistency.

3.1.4 Change of Form Testing

For many float glass artists changing the form of glass through heat is an integral part of their work as they transform flat glass to a creative shape. A series of tests were designed to investigate the behaviour of the overall K Glass compared with that of float glass during change of shape or form. Sagging, bending, moulding, suspension and stretching were applied and their effects on the K coating were evaluated after firing. An additional test examined whether the coating was able to 'slide' on the glass substrate during firing. This part of the research was in preparation for the development of sculptural artwork.

For these forming tests two pieces each of 4mm and 6mm K were used so that, for each thickness, the coating could be placed up and down. Identically sized 4mm and 6mm float glass pieces were placed alongside on the forming moulds for comparison. The glass sample size was not restricted to 100mm x 100mm as in the standardised programme but for comparison purposes each test used the same size and the formers had the same profile. As the bending process was simple the firing schedule was that used for the standardised tests shown in Table 3.1, p.58. Although a lower target temperature, for example 730°C, could have been used to change the form of the glass, the heat needed to be high enough for colour development. Thus the kiln was fired to 775°C and held for 30 minutes.

3.1.4.1 Sagging

K and float glass strips measuring 150mm x 50mm were placed, as described above, in a line on a section of corrugated iron so the glass would sag into the curves (*Figure 3.4)*. Bullseye Thinfire was used under the glass as a separator.

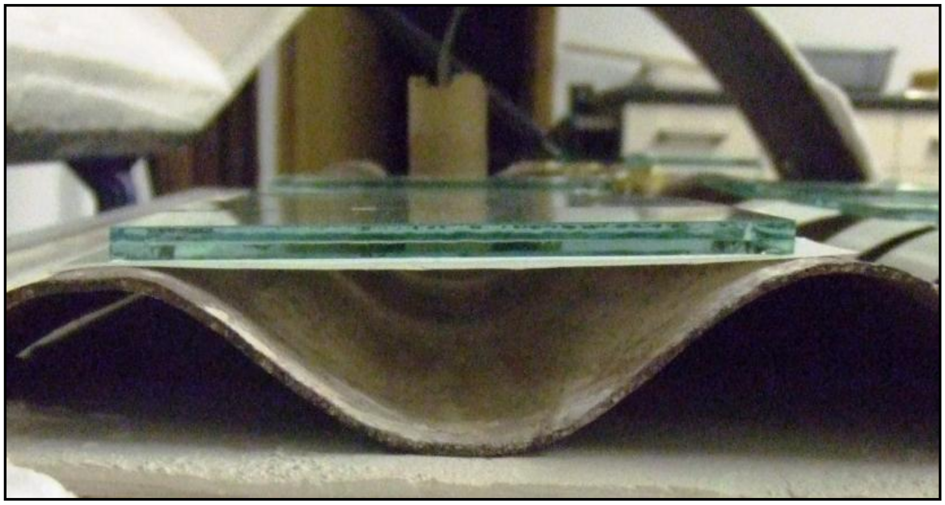


Figure 3.4 *Sagging,*
K and float glass pieces placed on metal form.

3.1.4.2 Bending

The pieces of glass were balanced on the top of the curve (*Figure 3.5*). A further test examined 4mm and 6mm K only with more severe bending over a 40mm steel tube (*Figure 3.6*).

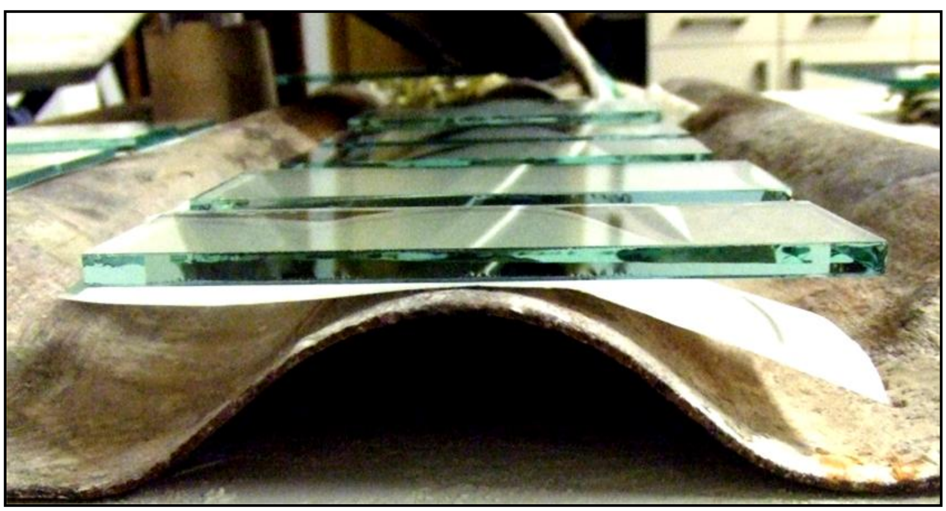


Figure 3.5 *Bending,*
K and float glass pieces placed on metal form.

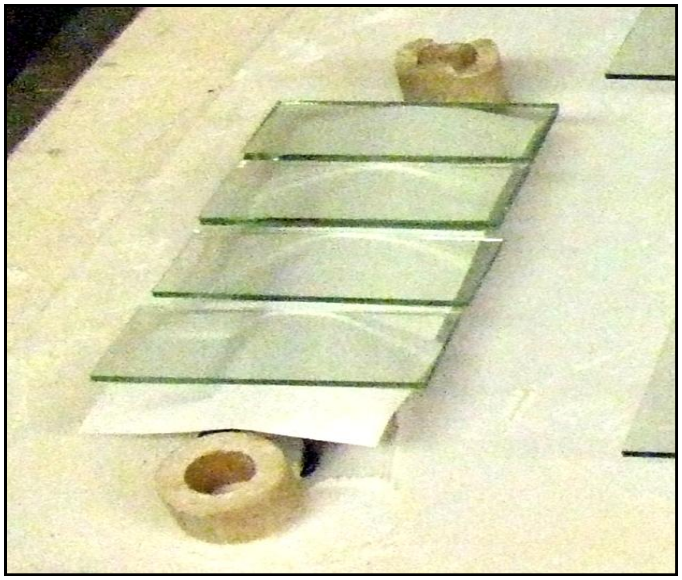


Figure 3.6 *More severe bending, K Glass over steel tube.*

3.1.4.3 Moulding

Larger pieces of 4mm and 6mm K and float glass were used, i.e. 250mm x 125mm, with the coatings of K again placed up and down. These were balanced on brass waste which had been crumpled to form a mound; sieved Plaster of Paris was used as a separator (*Figure 3.7*).

Figure 3.7 *Moulding, K Glass placed over brass waste.*

3.1.4.4 Suspension

Four pieces of 4mm and 6mm K each measuring 300mm x 50mm were placed across ceramic kiln bricks, alternating their surfaces as in sagging and bending tests, along with one piece each of 4mm and 6mm float (*Figure 3.8*).

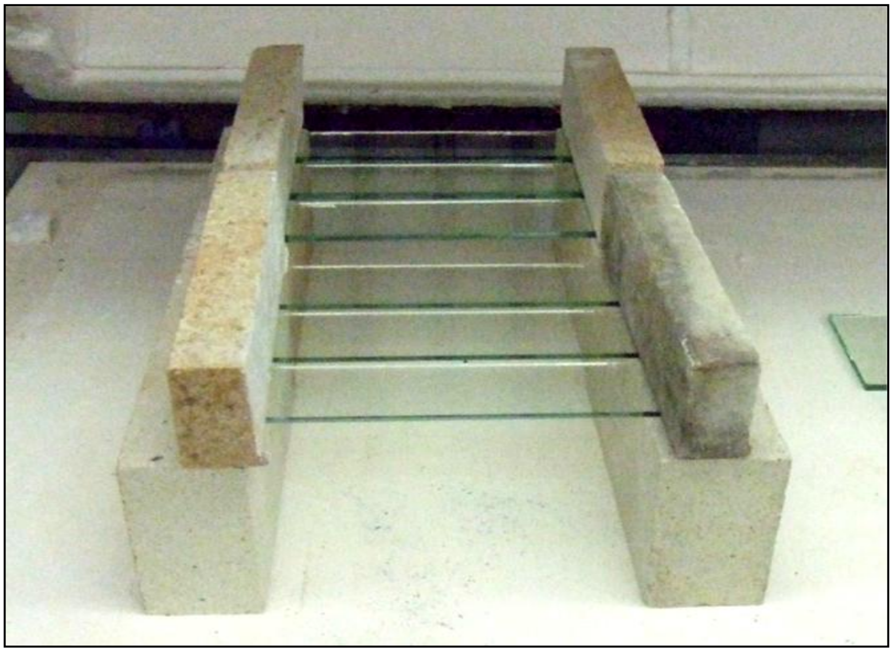


Figure 3.8 Suspension,
K and float glass pieces held in suspension.

3.1.4.5 Stretching

Pieces of 4mm and 6mm K and float glass measuring 180mm x 150mm were drilled with holes and hung from a metal rack using tiny strips of ceramic paper as separators (*Figure 3.9*). The kiln was programmed with the target of 775˚C but as this temperature was approaching the lid was opened enough to check the progress of the stretch. When this was considered to be at a sufficient level the lid was opened further to 'freeze' the form before proceeding through the annealing phase.

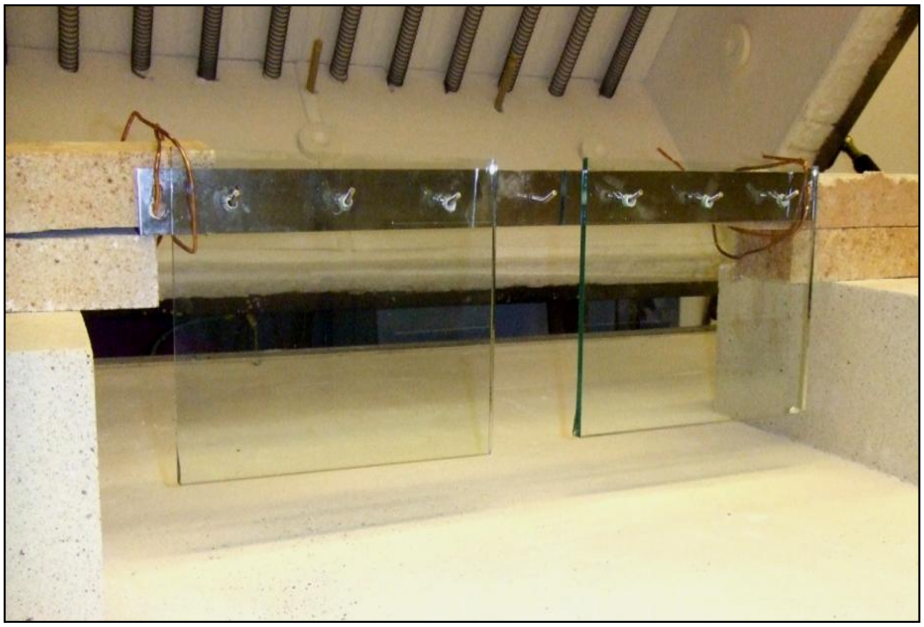


Figure 3.9 *Stretching,*
K and float glass pieces hung in suspension.

3.1.4.6 Sliding

One piece each of 4mm and 6mm K measuring 220mm x 60mm of were fired in an acutely angled position, resting against a metal slope covered with 3mm ceramic matting as shown in Figure 3.10. In this test the coating was fired up only, to allow movement.

Figure 3.10 *Sliding,*
K pieces against metal form.

3.2 Evaluation of Results

Throughout the practical programme of testing all methods, results and outcomes were recorded in a Workshop Notebook with individual information on test sheets. Photographic recording of all pre-fired tests was included to clarify the assembly of the sample with its position within the kiln. Post-fired photographs were included to support the written analysis and characterisation of the visual changes to the K Glass. A summary of each series of tests was prepared to implement a continuous assessment of results and progressive review cycle of issues for further investigation.

3.2.1 Categorisation of Visual Changes to Post- fired K Glass

The surfaces of the open test samples were visually examined after firing to make an initial characterisation of the changes to the K coating. This qualitative evaluation indicated that certain post-fired characteristics were of common occurrence. These changes were categorised under the following headings surface, colour, iridescence and bubbles although not all categories were relevant to every test. The surface of the fused samples could not be fully assessed in this way as the characteristics of the coating were covered by the top sheet of glass. Where necessary the fused sample was cut through to remove the upper glass revealing the fired coating.

3.2.1.1 Colour

The most obvious change to the surface coating was the colour. This assessment was defined in terms of shade and depth as seen by the author. Additional detail was described through intensity, quantity, variation of tone and position on the surface of the sample.

3.2.1.2 Iridescence

Iridescence was seen in both the open and the fused series and recorded in relation to presence, position, area covered, intensity and quality of reflectivity. In the case of the open samples, the iridescence was described in terms of its variable surface appearance.

3.2.1.3 Bubbles

Bubbles were a feature of the fired K coating in both open and fused test results. These were characterised by size, shape, quantity and position relative to the sample.

3.2.2 Microscopic Examination

A more detailed examination of the fired K coating surface was undertaken by means of both light and scanning microscopy. For most of the investigations, a Vickers Instruments small light microscope with lenses giving magnifications of 3, 10 and 30 was used. More detailed images were later achieved using a more powerful light microscope with magnifications of 4, 40 and 100 within the Department of Bioscience at the University of Sunderland. Micrographs were obtained using an HP 812 Digital Camera with retractable Pentax Zoom lens. The aperture of the lens was placed in line with one eyepiece of the microscope as shown in Figure 3.11. The image could then be checked on the digital screen of the camera and the photograph taken.

On most captions the scale has not been included; the size of the image has been presented for the qualitative analysis and illustrative purposes only. Where particular feature of size are needed, e.g. bubbles, they have been described or annotated as necessary.

Figure 3.11   Studio microscope photography.

A significantly higher magnification of the surface of samples of the fired coating was later carried out using a scanning electron microscope which could provide images up to 10,000 times. Analysis of the elements contained in these samples was obtained by Energy Dispersive X-ray Spectroscopy (EDS or EDX). These examinations were undertaken by the Department of Physics at Durham University. An outline of these processes and images of their results can be found in Appendix E, p.280.

3.3 Identification of Visual Changes Results

Changes to the K coating (or the K Glass) from its original 'as received' condition, as previously shown in Figure 1.1, were easily seen with the naked eye on the surface of the open fired samples. These changes began at 690°C as minute ripples on a very tiny area down one edge of the glass. With each 10°C increase in temperature, the area of affected coating also increased. At 720°C the increase took the modified surface area to about 75% and by 780°C the entire surface showed the change. Between 800°C and 850°C no further significant change to the coating was evident.

The following charts plot the identified surface changes which are then explained in more detail through standardised tests in sections 3.4.1 to 3.4.3. The first two charts shown in Figures 3.13 and 3.14 show the amount of visual change to the surface of 4mm and 6mm K Glass at temperatures between 680°C to 820°C. The further six charts mark the amount of visual change in terms of colour, iridescence and bubble formation (*Figures 3.16-17, 3.19-20 and 3.22-23*).

The first assessment was in general terms of the amount of visual surface change and to what extent this was consistent over the whole sample. This was expressed as a percentage of the sample surface area, 100% represents total surface change to sample whereas 0% represents no change. Figure 3.12 shows the area of the affected surface of the 6mm sample at 740˚C, quantified as a percentage, i.e. 60% of the whole sample.

Figure 3.12 6mm K, post- fired at 740˚C, 60% overall change to the surface.

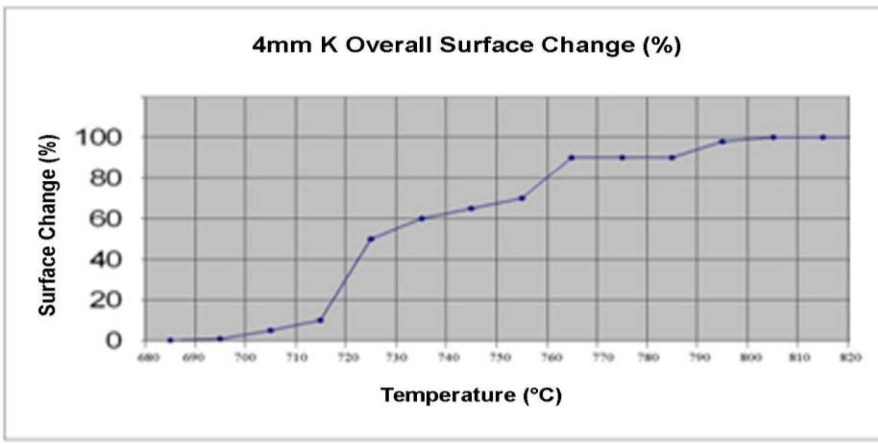


Figure 3.13 4mm K, overall surface change from 680˚C–820˚C.

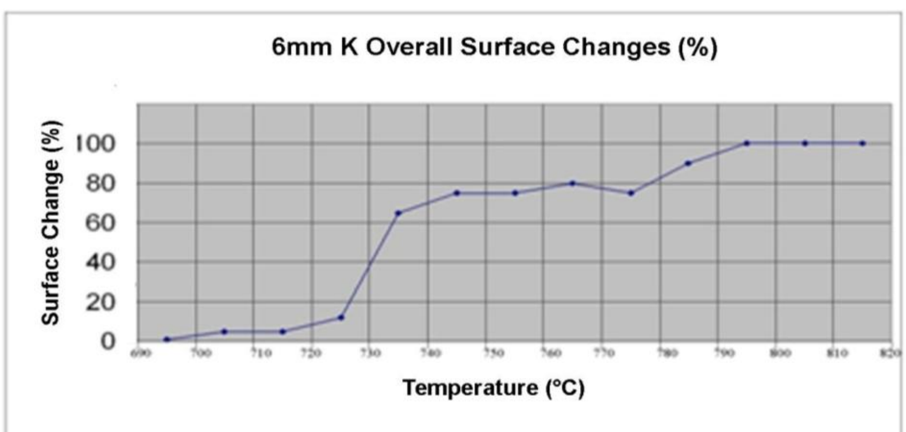


Figure 3.14 6mm K, overall surface change from 680˚C–820˚C.

3.3.1 Colour

Colour change was estimated as a percentage comparison of the maximum shade and depth achieved which was defined as 100% (whereas a pale shade would be classified as 10%). The sample in Figure 3.15 which was fired at 800˚C shows full colour strength.

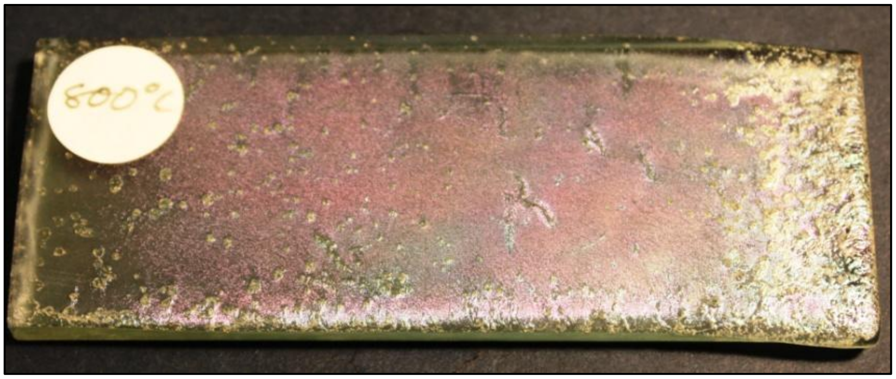


Figure 3.15 6mm K, post-fired at 800˚C, 100% colour change.

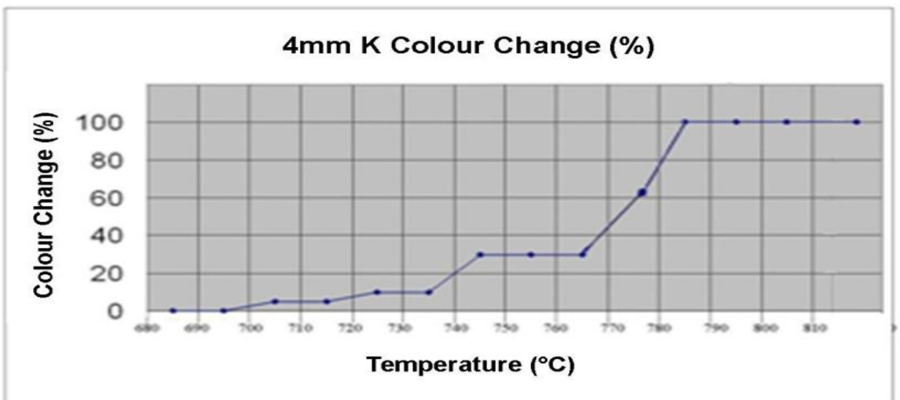


Figure 3.16 4mm K, colour change from 680˚C–820˚C.

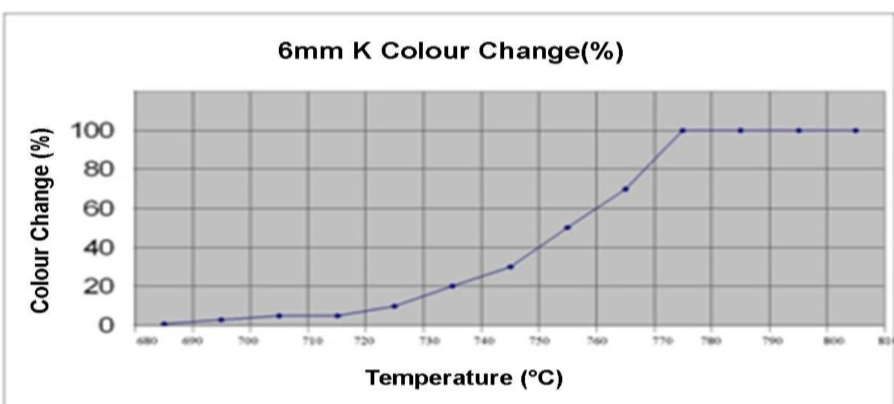


Figure 3.17 6mm K, colour change from 680˚C–820˚C.

3.3.2 Iridescence

Iridescence was evaluated in terms of presence, intensity and quality of reflectivity and quantified as a proportion of the maximum effect. Full iridescence intensity and reflectivity was classified as 100%, a hint of a pearlised effect as 10%. Although the maximum intensity had been obtained in the sample shown in Figure 3.18 part of the surface had not changed. This was therefore estimated at just over 90%.

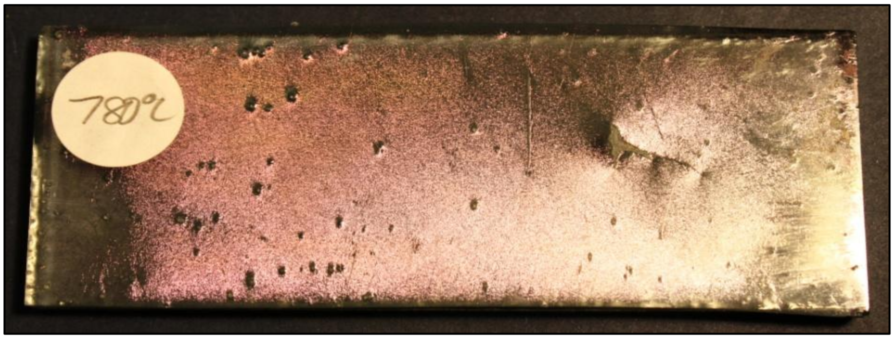


Figure 3.18 6mm K, post-fire at 780˚C, 90% Iridescence change.

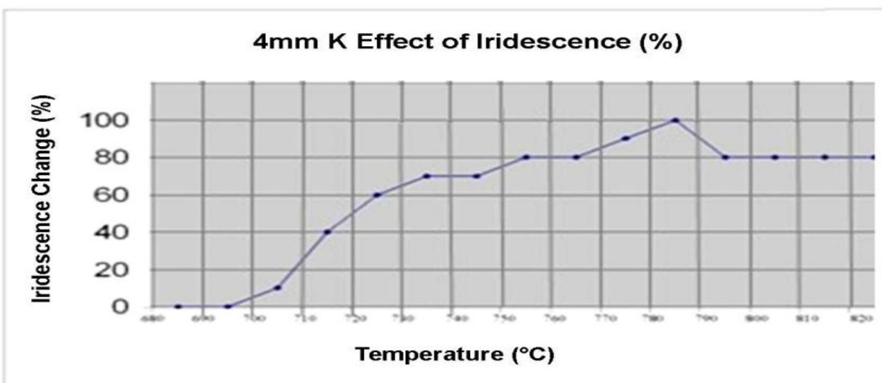


Figure 3.19 4mm K, Effect of iridescence from 680˚C–820˚C.

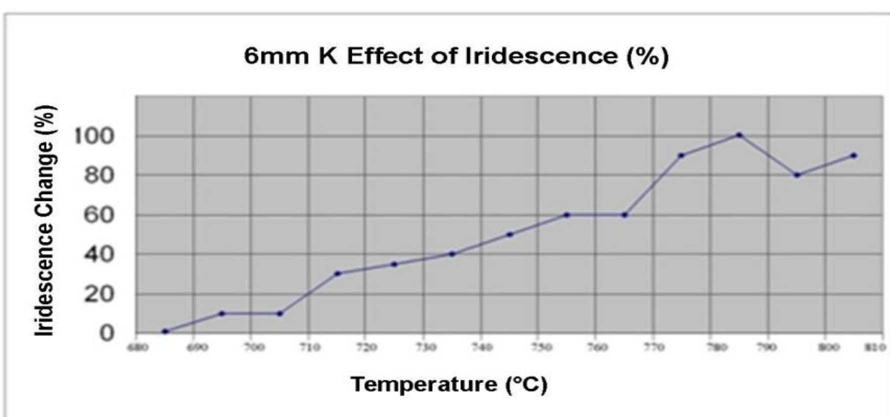


Figure 3.20 6mm K, Effect of iridescence from 680˚C–820˚C.

3.3.3 Bubbles

Presence of bubbles was an indication of the percentage of the total surface area affected by bubbles. This was more difficult to quantify but Figure 3.21 shows an estimate of approximately 25%.

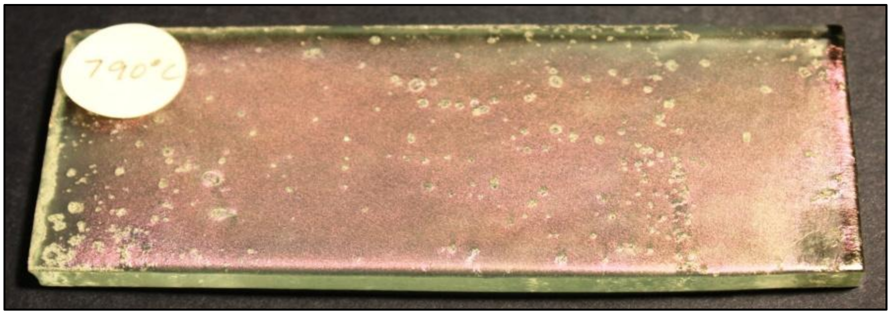


Figure 3.21 6mm K, post-fired at 790˚C, presence of bubbles.

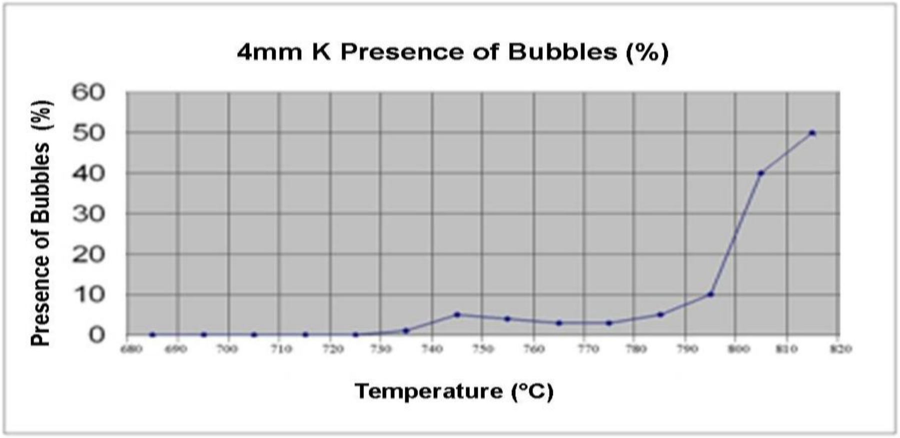


Figure. 3.22 4mm K, presence of bubbles from 680˚C–820˚C.

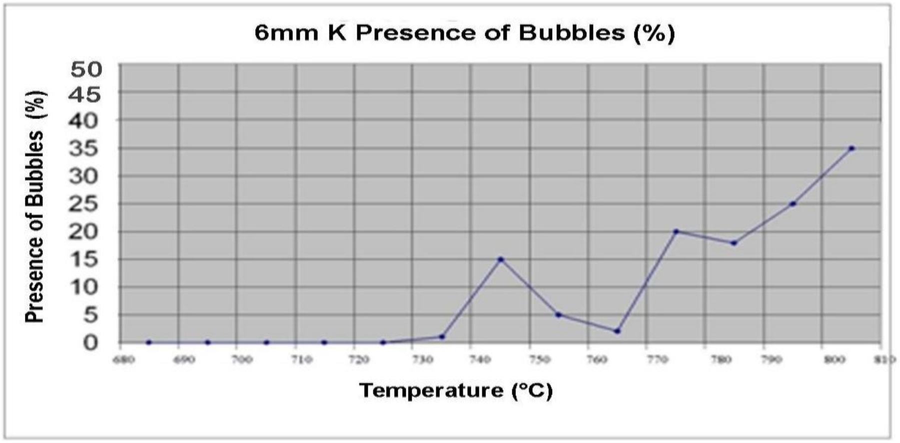


Figure. 3.23 6mm K, presence of bubbles from 680˚C–820˚C.

As it can be seen from all eight charts, with the exception of the two referring to bubbles, the 4mm and 6mm K coatings behaved in a similar manner. The overall changes showed a corresponding pattern which was confirmed by the individual characteristics of colour and iridescence. Although the bubble charts appear to be slightly erratic, the presence was shown to increase with higher temperatures.

3.4 Standardised Open Tests Results

With the initial identification of the visual changes to the surfaces of both 4mm and 6mm K coating established, more detailed investigation of the individual visual characteristics was undertaken through standardised tests.

3.4.1 Colour Changes

Colour changes to both the 4mm and 6mm K Glass which began at 690-700°C were hardly discernable, appearing on an edge of each with very pale greyish tones. With both thicknesses from about 720°C, the K coating took on a pearlised appearance with slight suggestions of pink, blue and gold, which fluctuated with movement. These developed to predominately pink/purple tones at 740°C and peaked, in depth, between 750°C and 800°C. Tones of green, blue and gold were also seen in small quantities on some samples fired above 750°C. These colours were sometimes seen as muted bands (*See 5.4.3, p.165*) and often more noticeable when the samples were examined from the reverse. The strongest colour was seen between 770°C and 800°C.

The photographs and their relative micrographs in Figures 3.24 to 3.29 show the progressive change to the 4mm K coating as the colour intensified. At 780°C, the colour was strong and vibrant; the ripples were tiny 'wrinkles' in an almost linear formation with a few smoother or less wrinkled areas between. At 790°C, the wrinkles became more definite ripples with a chaotic pattern (*Figure 3.27*). At 800°C, the colour had not changed but the surface dullness had increased in intensity; the rippled surface formed 'folds' as the coating buckled at the elevated temperature (*Figure 3.28*). At temperatures above 800˚C when fired with standardised testing schedule, no further colour change was observed. Photographs and micrographs of K coating fired at temperatures above 850˚C can be found in Appendix F, p. 285.

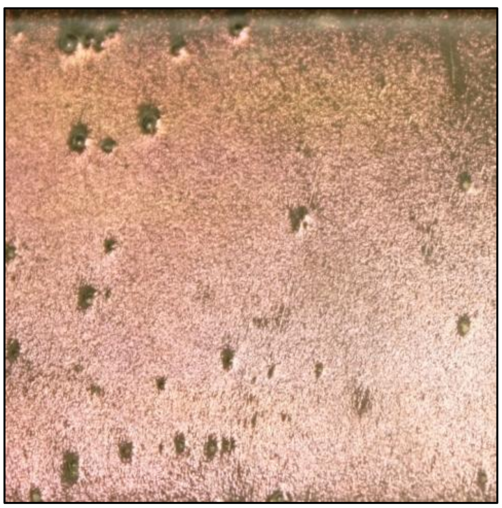


Figure 3.24 4mm K, post-fired at 780° C.

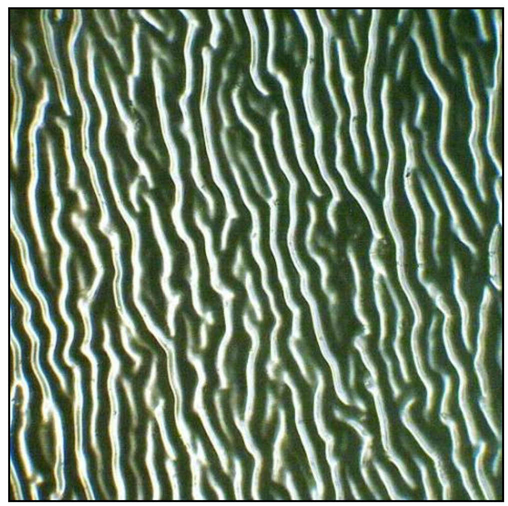


Figure 3.25 4mm K, post-fired at 780°C, showing ripple linear formation.

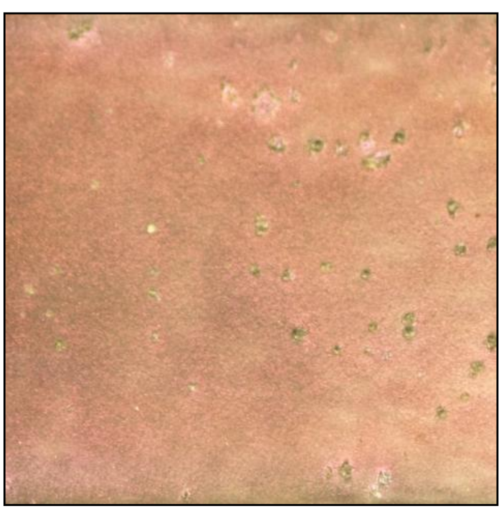


Figure 3.26 4mm K, post-fired at 790°C.

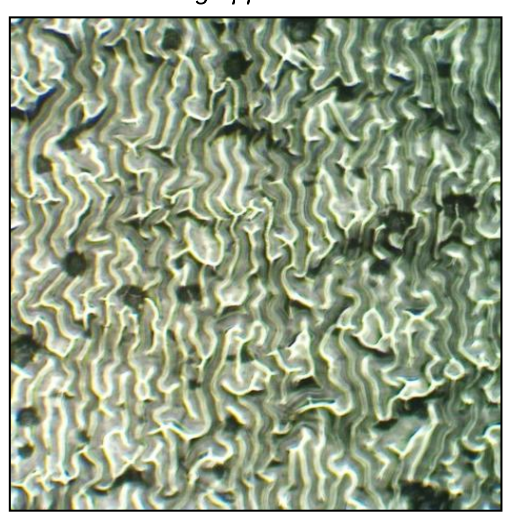


Figure 3.27 4mm K, post-fired at 790°C, showing chaotic ripple formation.

Figure 3.28 4mm K, post-fired at 800°C

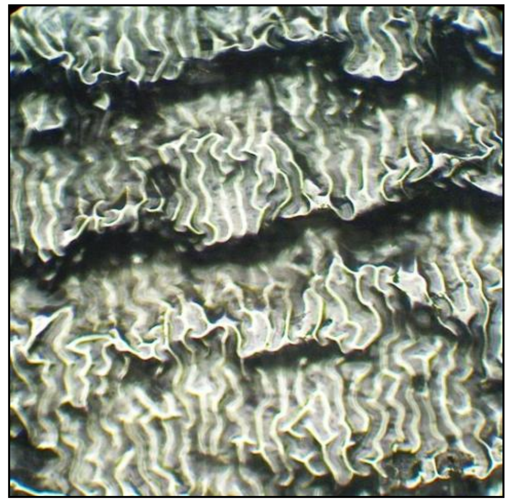


Figure 3.29 4mm K, post-fired at 800°C, showing ripple and fold formation.

Placing the glass with the K coating face down on the kiln floor did not seem to affect the extent to which the surface changed. However this position seemed to encourage a greater depth of colour with the occasional tones of green and blue more evident (*Figure 3.30*). The coating structure was angular, almost geometric in structure with a slightly 'flattened' appearance as shown in Figure 3.31.

Figure 3.30 6mm K, post-fired at 775°C, coating fired down.

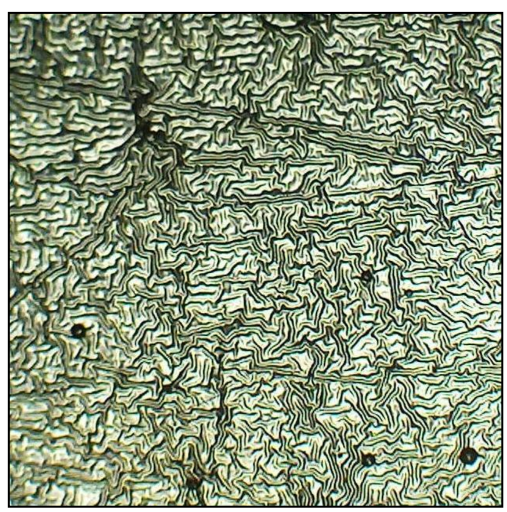


Figure 3.31 6mm K, post-fired at 775°C, coating fired down, micrograph.

It is important to note that the colour, at all stages of development, can only be seen when the light is directional from the front. With backlighting or a light toned background, the colouration of the coating disappears suggesting that this is not a colour within the body of the glass but one that is in reflection.

The first step to control the colour in open firing was to remove the K coating by sandblasting the surface where colouration was not wanted. To ensure that all the unwanted area was clear of coating, the sandblasted glass was inspected obliquely when any remaining surface could be clearly seen. Alternatively, the surface could be checked for the presence of any remaining coating with the use of the fuse tester. This basic process provided a foundation for simple open fired artwork.

3.4.2 Iridescence

The development followed the same pattern as that of colour, its strongest intensity being between 770°C and 780°C. Above that temperature, dullness appeared on the surface marring the luminosity of the iridescence. From the reverse of the fired samples some of the iridescence was visually lost. As with the colour, seeing the iridescence is light dependant, the intensity and presence being variable with the angle of viewing. The visual effect is, therefore, inferential.

Microscopic examination of the fired surface at different temperatures showed a relationship between the intensity of iridescence and the formation of the ripples shown in Figures 3.32 to 3.37. The ripple structure at 750˚C was slightly less linear than that of 770˚C. The strongest iridescence was seen at 770˚C. At 790˚C, the ripples showed a chaotic format; here the iridescence became slightly dull. At 800˚C, the iridescence was duller still. Above 800˚C, iridescence could be seen on the surface of the fired K coating throughout the full range of temperatures to 950˚C. The iridescence varied in quality with patches of dullness.

Figure 3.32 6mm K, post-fired at 750°C.

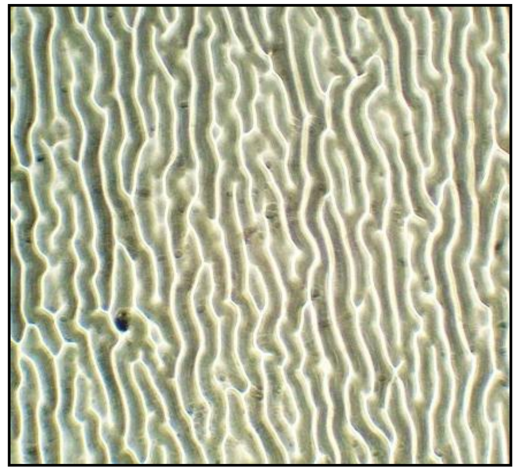


Figure 3.33 750°C iridescence ripples.

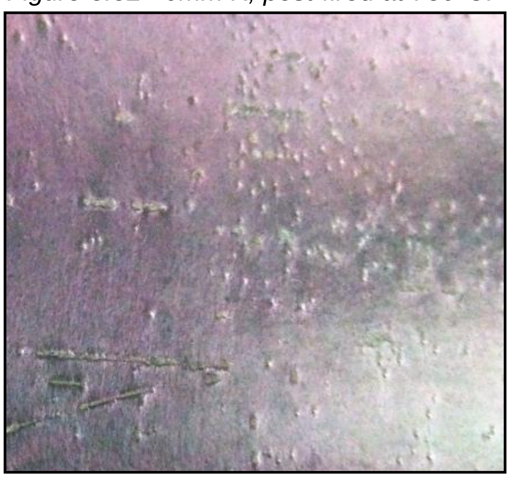


Figure 3.34 6mm K, post-fired at 770°C.

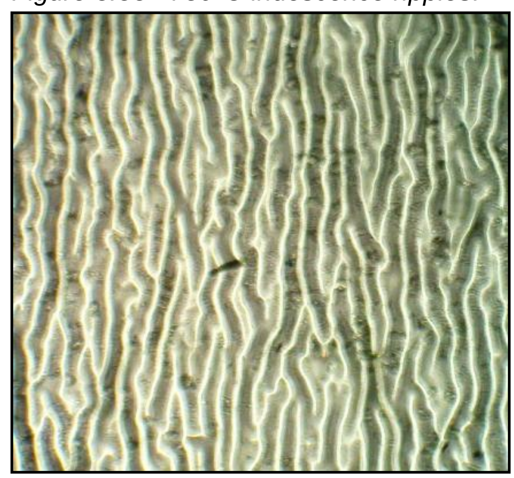


Figure 3.35 770°C iridescence ripples.

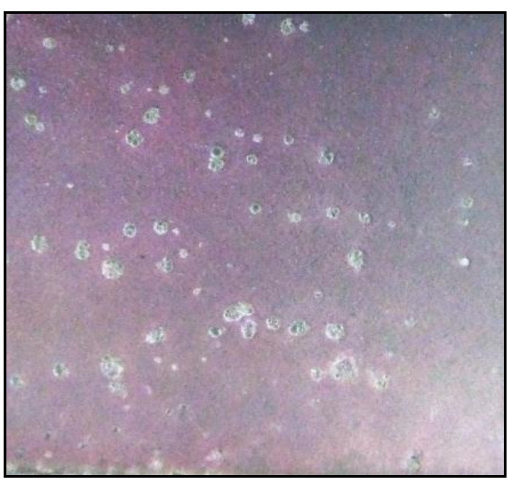


Figure 3.36 6mm K, post-fired at 790°C.

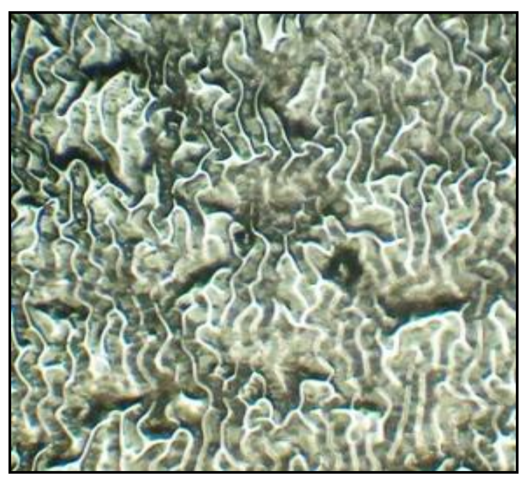


Figure 3.37 790°C iridescence ripples.

3.4.3 Bubbles

Bubbles appeared on the surface of both the 4mm and 6mm K coating at a slightly later stage in the change to that of colour and iridescence. Above 730°C they were seen on every test but in no clearly defined formation. Their position was random and sizes varied from pinpoint to 1.0mm in diameter as shown in Figure 3.38. The area covered was difficult to quantify but Figures 3.22 and 3.33 show a slight increase with temperature. When higher temperatures, for example, 800˚C were held there was an increase in the number of surface bubbles.

Figure 3.38 4mm K, post-fired at 800°C, showing bubble formation.

Although each test varied, in general, a similar number of bubbles and the same random order were seen at a particular temperature, regardless of the facing of the K coating during firing. The random nature of the bubbles may be explained as those which form at nucleation sites, such as scratch marks or impurities on the surface (Princeton University, 2000), some of which on the pre-fired glass, may not be readily visible to the naked eye. During the making of later artwork the post-firing presence of bubbles on new glass that had been protected was seen to be considerably less.

3.4.4 Material Variable: Surface Coating Manipulation by Abrasion

There was a noticeable difference to the fired K coating when subjected to manipulation by abrasion.

3.4.4.1 Scoring

In addition to the randomly positioned and sized bubbles present over the entire 100mm square surfaces, tiny bubbles collected along score lines or scratches. These were larger in the tests where the coating was fired upwards as shown in the comparative micrographs in Figures 3.39 and 3.40. Scoring also caused the K coating to present a much greater reflectivity to the iridescence as in Figure 3.41 with linear ripples visible to the naked eye (*Figure 3.42*).

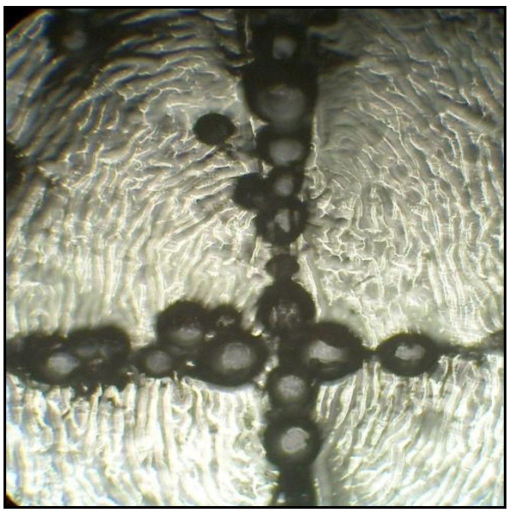


Figure 3.39 4mm K, scored surface, coating fired up showing bubbles along score lines.

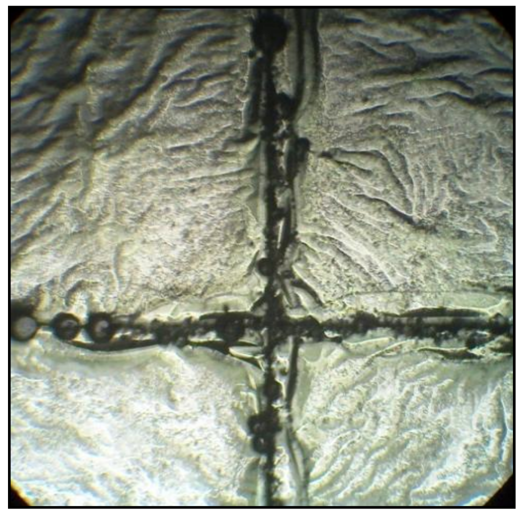


Figure 3.40 4mm K, scored surface, coating fired down showing smaller bubbles along score lines.

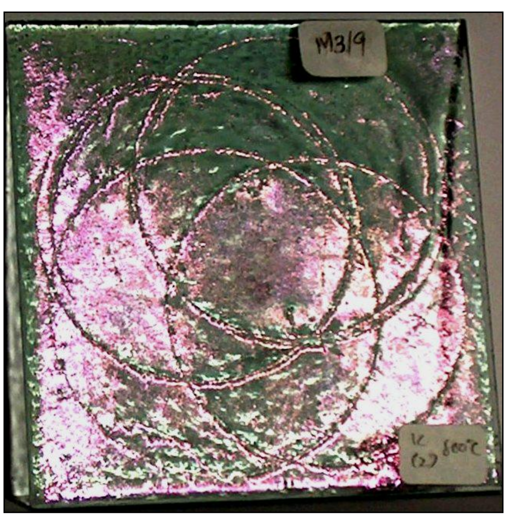


Figure 3.41 4mm K, post-fired at 800°C, with scored surface.

Figure 3.42 4mm K, post-fired at 800°C, photograph of scored surface ripples.

3.4.4.2 Scratching

Scratching the K coating with abrasive products such as wire wool created a variety of effects (*Figure 3.43*). Micrographs of the post-fired surface in Figures 3.44 to 3.47 show how the degree of abrasion caused a variable presentation of bubbles and different visual effects.

1. P100 wet and dry
2. Coarse wire wool
3. Coarse sanding belt
4. Diamond pad

Figure 3.43 6mm K, post fired at 775°C, showing variation of scratching.

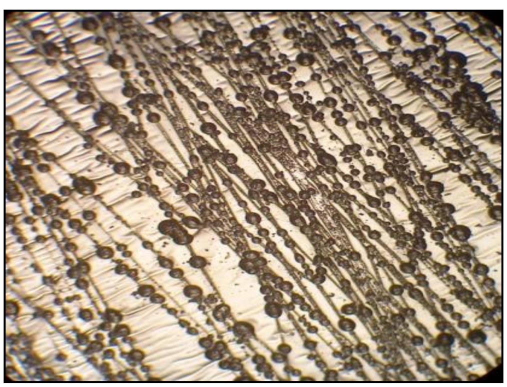


Figure 3.44 P100 wet and dry.

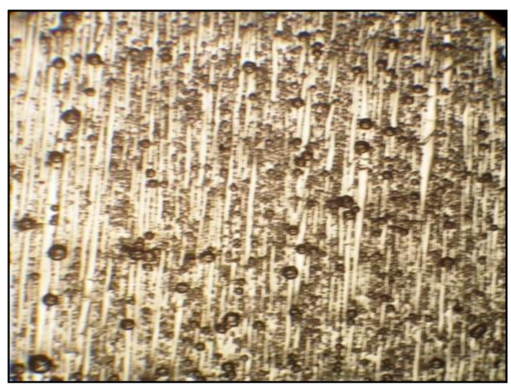


Figure 3.45 Coarse wire wool.

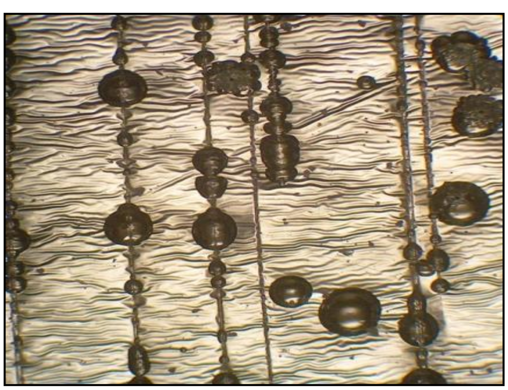


Figure 3.46 Coarse sanding belt.

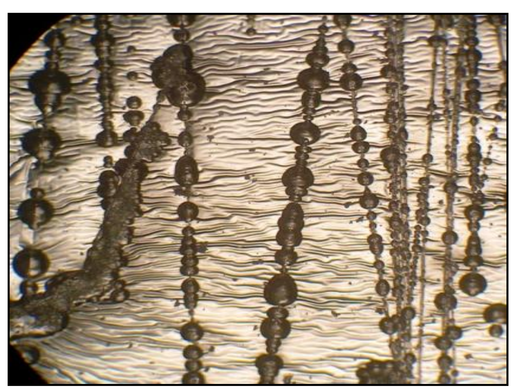


Figure 3.47 Diamond pad.

3.4.4.3 Sandblasting

Removal of the K coating by sandblasting caused the post-fired surface surrounding the cleared areas to show a higher degree of iridescence than that of the area away from the edges (*Figure 3.48*). Microscopic examination showed these edge areas with linear ripples (*Figure 3.49).*

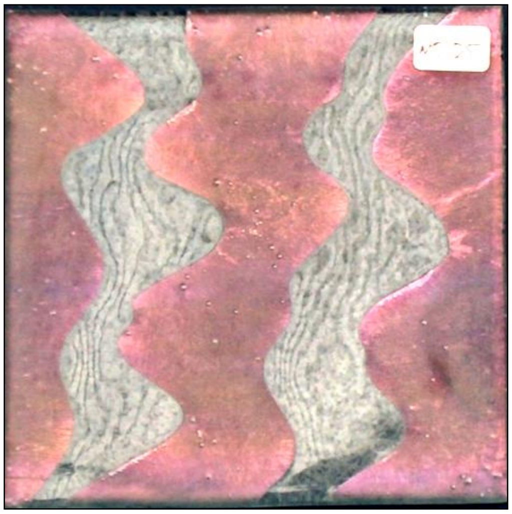


Figure 3.48 4mm K, post fired at 800°C, sandblasted, showing iridescence differences.

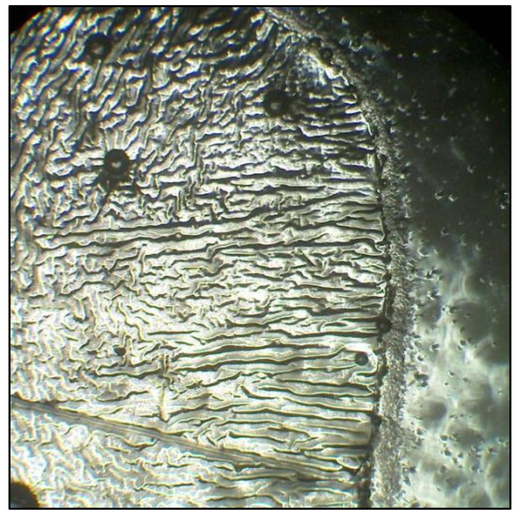


Figure 3.49 Micrograph showing edge of sandblasted area with linear ripple formation.

Partial sandblasting of 4mm K coating in bands of increasing intensity shown in Figure 3.50 gave delineation but a lack of iridescence after firing at 775 °C. Microscopic study of this sample showed no evidence of ripples (*Figure 3.51).*

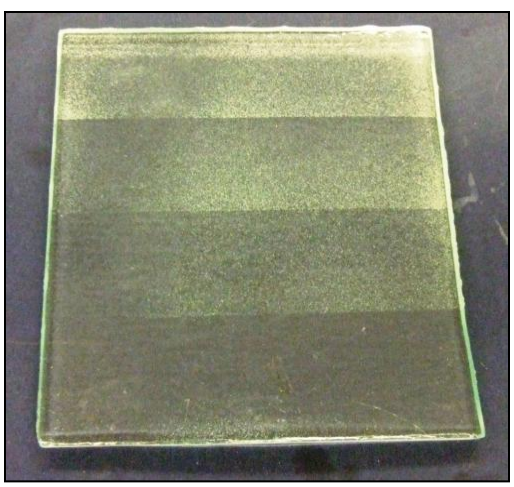


Figure 3.50 4mm K, post-fired at 775°C, showing sandblasting delineation.

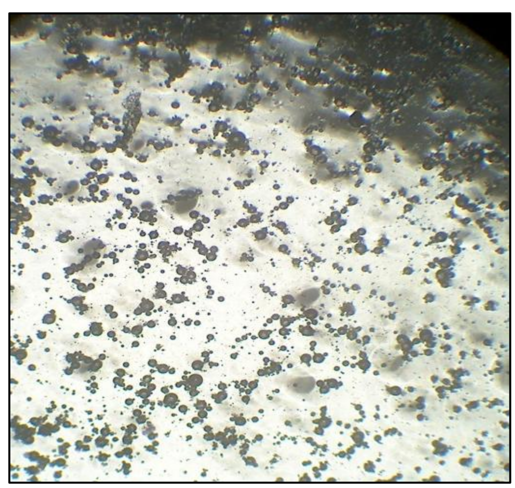


Figure 3.51 Micrograph of top sandblasted area.

3.4.4.4 Engraving and Etching

The manipulation surface treatments of engraving and etching were attempted but not pursued at this standardised testing stage. Although it was later found that engraving would remove the surface coating with similar results to that of sandblasting, it also removed some of the glass substrate. Its application and artwork potential is discussed in Chapter 5. It was also later found that a specific etchant of zinc powder and diluted hydrochloric acid could be used to remove the K coating (*See 4.8.1, p.145*). This was not pursued for artwork due to the difficulty in obtaining the acid. ‘Etchall’, a studio etchant made by B & B Products, Inc., USA, was also tried without success. The etchant, hydrofluoric acid, was not considered to be a suitable method available to the studio artist due to Health and Safety issues.

3.4.5 Environmental Variable: Application of Heat

The rate of firing was proved to be a significant factor in the condition of the post-fired coating. Using the normal standardised testing schedule to 775°C patches, which under the microscope were seen as very tiny bubbles, formed on the coating (*Figures 3.52 and 3.53*). Although the quantity was variable, in general, more were seen on the 4mm K coating. When a slower rate of firing, i.e. 80°C to the target temperature of 775°C was used, very few were seen (*Figures 3.54 and 3.55*). They were also less frequent when this test was repeated with the coating fired down next to the kiln floor. In terms of colour, iridescence and bubbles faster firing did not appear to produce any different reaction.

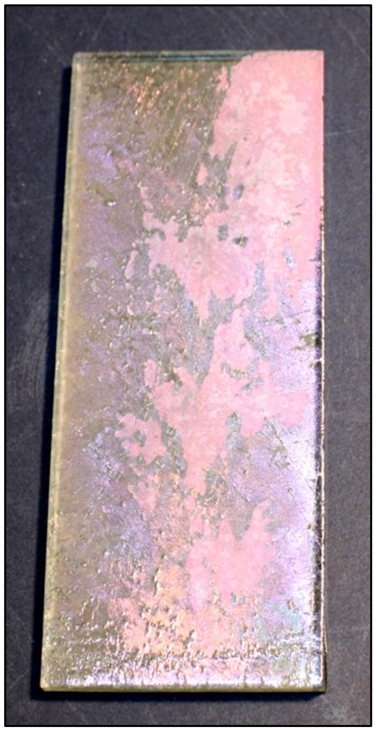


Figure 3.52 4mm K, post-fired at 775˚C, using standardised test schedule showing 'patches' on surface.

Figure 3.53 6mm K, post-fired at 775˚C, using standardised test schedule showing 'patches' on surface.

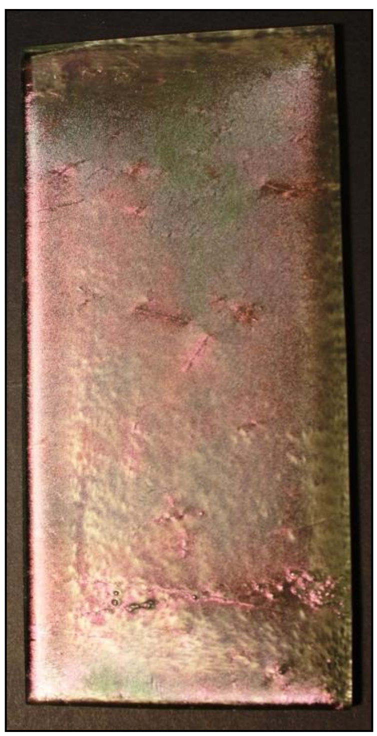


Figure 3.54 4mm K, post-fired at 775°C with slow schedule 2, showing no patches.

Figure 3.55 6mm K, post-fired at 775°C with slow schedule 2, showing no patches.

For the second investigation with regard to the holding time, the K coating was exposed to the optimum temperature of 775˚C for the increasing duration of 10 minutes. The coating had undergone the visual change when the target temperature was reached. The colour was intensified when the temperature was held for 10min. Further increments of 10 minutes at that temperature showed little change, however, at 40 minutes more blue tones were seen. For firing economy the 50 minutes hold was omitted; 60 minutes showed similarity to 40 minutes. This pattern was seen in both 4mm and 6mm K coated glass (*Figure 3.56 and 3.57).*

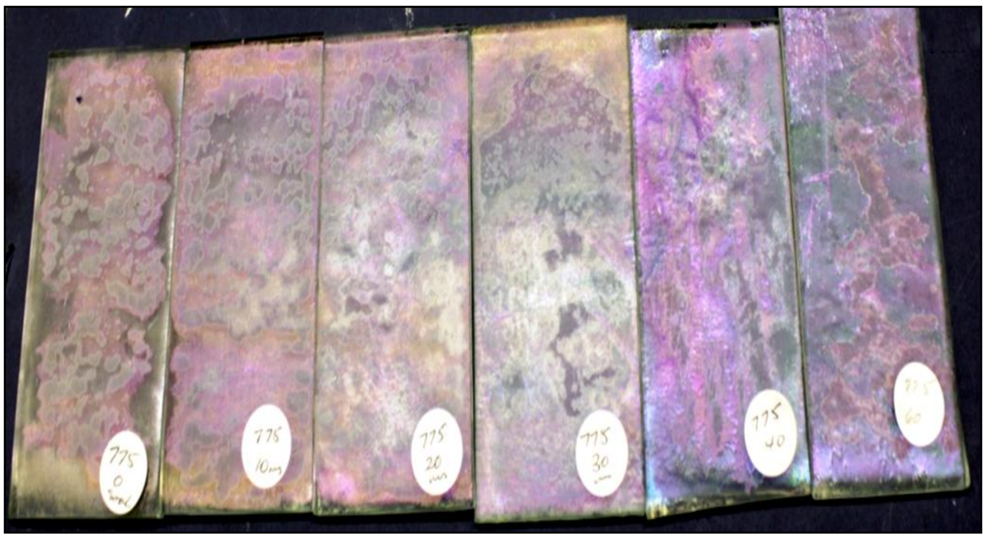


Figure 3.56 *4mm K, post-fired at 775*˚C, *hold time test, fired from 10min to 60min showing change with length of hold.*

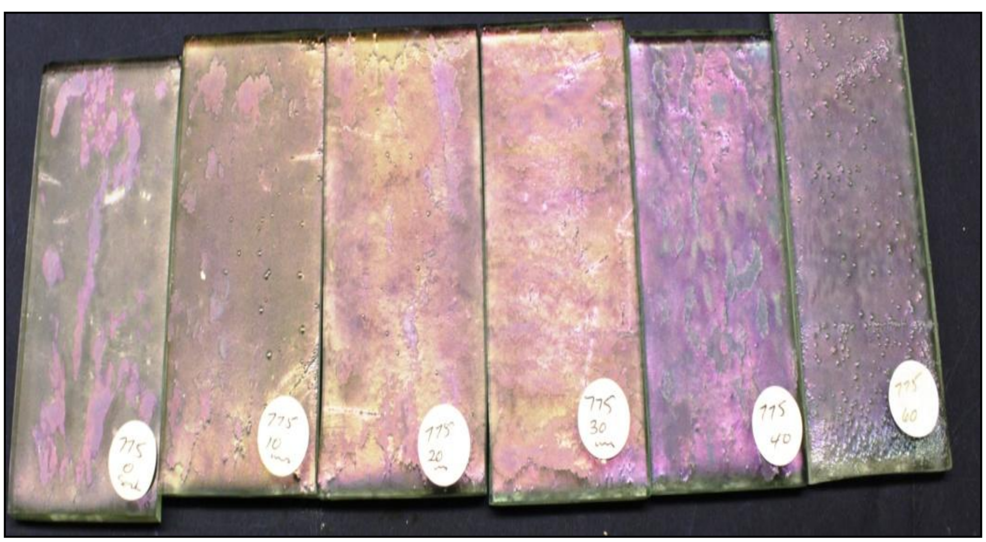


Figure 3.57 *6mm K, post-fired at 775*˚C, *hold time test, fired from 10min to 60min showing change with length of hold.*

When the hold time was increased to 2 hours, the surface presented a greenish colouration, as can be seen in Figures 3.58 and 3.59, which is of a similar nature to the patches seen in previous tests.

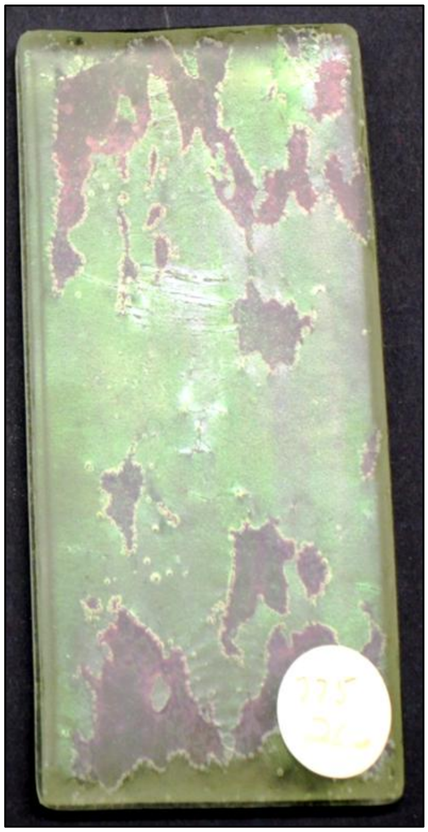


Figure 3.58 4mm K, post-fired, *Figure 3.59 6mm K, post-fired,*
2hr hold tests at 775 °C, *both showing greenish colouration to K coating.*

In terms of repeated firings, samples of 4mm and 6mm K were taken to 775˚C without holding; after each firing, two pieces of each thickness were removed. This was repeated four times. It was found that the visual surface changes of colouration, iridescence and bubbles once established, were not changed in any significant way by additional firings (*Figure 3.60*). However the notable difference was the fewer patches on the 6mm K coating throughout (*Figure 3.61*).

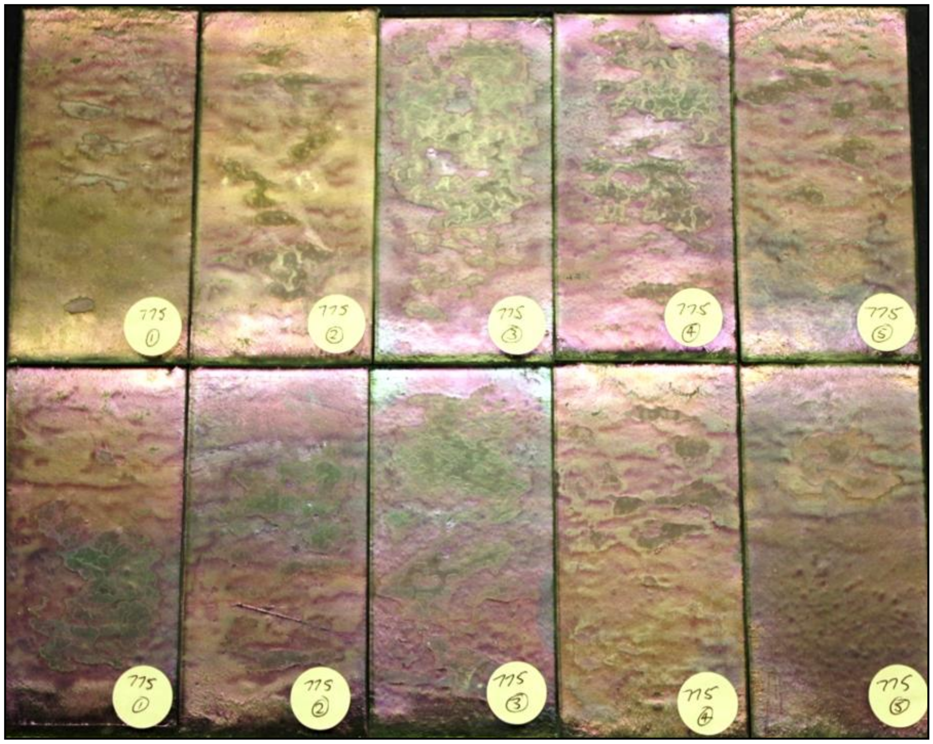


Figure 3.60 4mm K, post-fired at 775°C, test for repeated firings.

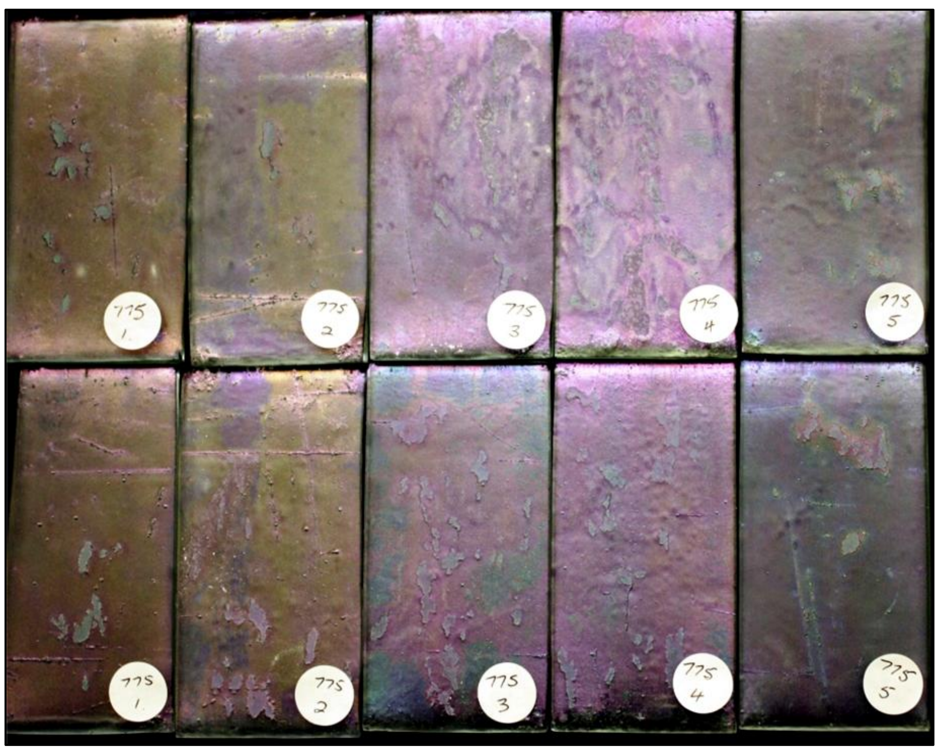


Figure 3.61 6mm K, post-fired at 775°C, test for repeated firings.

Diagrammatical details of firing schedules can be found in Appendix D, p.278.

3.5 Standardised Fused Tests Results

In all fused formats, the K coating was covered by a top layer of float glass. This prevented the direct examination of the fired K coating, consequently, categorisation does not include that of surface. Colour, iridescence and bubbles were relevant features of the fired fused glass and are considered in the following sections with relation to each fused format. Although no two tests gave exactly the same results, group similarities were shown within all testing formats. Additional tests to understand the variables that affected the results and how these may, subsequently, enable the ability to manipulate and control the changes, are also discussed.

3.5.1 Colour

The most visually significant aspect of the changes to the fired 4mm and 6mm K coating in the fused tests was the wider range of colour than in the open tests. In different fused formats, gold, peach, pink and purple were seen in variable amounts with tones of blue and green to a lesser degree. The position, size, shape and tones of the colouration also varied in each test. As with the open fired K coating, the colouration was dependent on reflected light. An attempt was made to create a control test by which others could be compared and measured. As each produced a slightly different visual result this proved to be unsuccessful.

With the visual effects of temperature examined from 700°C through to 850°C, the optimum colouration range was established at 775-800°C. After the identification of temperatures at which visual changes were seen in the fused format samples, three temperatures were selected for further investigation. These were 725°C, which was from the lower end of the range and 775°C or 800°C from the upper end. Holding the target temperature was initially set at 30 minutes although later tests suggested 10 minutes to be sufficient.

Throughout the temperature range a strong and generally circular area of colouration formed within the central area of the standardised samples which at 725°C was pink and gold (*Figure 3.62*). At the higher temperature, the colours were again pink and gold but also purple was seen and, occasionally, blue and green (*Figure 3.63*). The area covered varied from test to test but appeared to be larger and stronger in colour at the higher temperature of 775°C. This also occurred when thicker float glass, e.g. 6mm was placed on top (*Figure 3.64*). In all tests paler tones of pink/purple were evident to the edges of the glass.

Figure 3.62 4mm float over 4mm K, post-fired at 725°C, in Fused Format showing pink/gold colouration.

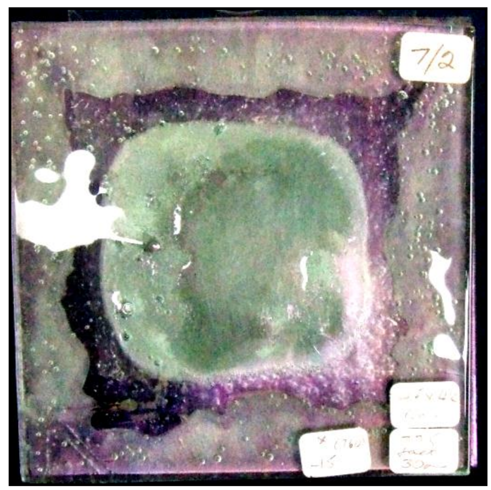


Figure 3.63 4mm float over 4mm K, post-fired at 775°C, in Fused Format showing pink/gold/blue/green colouration.

Figure 3.64 6mm float over 4mm K, post-fired at 775°C in Fused Format showing stronger colouration.

At this stage, it was necessary to investigate factors that may have been responsible for this central area of colour, namely the float glass tin residue, air entrapment during fusing and the thickness of the upper float glass. Several fuse fired tests were repeated at 775 °C, fusing tin free greenhouse glass and also the non-tin side of the float glass next to the K coating. As shown in Figure 3.65 and 3.66 a large strong area of the gold colouration and much bubble development was seen in both tests.

Figure 3.65 3mm greenhouse glass over 4mm K, post-fired at775°C, in Fused Format showing strong gold colouration and bubbles.

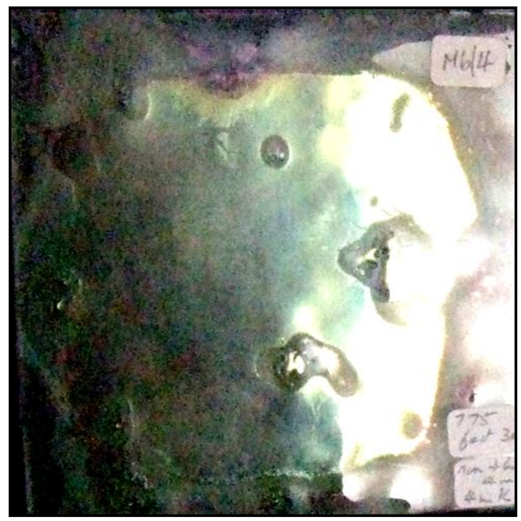


Figure 3.66 4mm float glass with non-tin side over 4mm K, post-fired at 775°C, in Fused Format showing strong gold colouration and bubbles.

The factor of air entrapment during fusing and its effect on colour was investigated repeating a test using fusers glue between the K and float glass to minimise the amount of air prior to firing. In this test at 775°C, a considerable reduction in the central area of strong colouration was observed (*Figure 3.67*). A similar test using water to seal the K and float glass proved inconclusive.

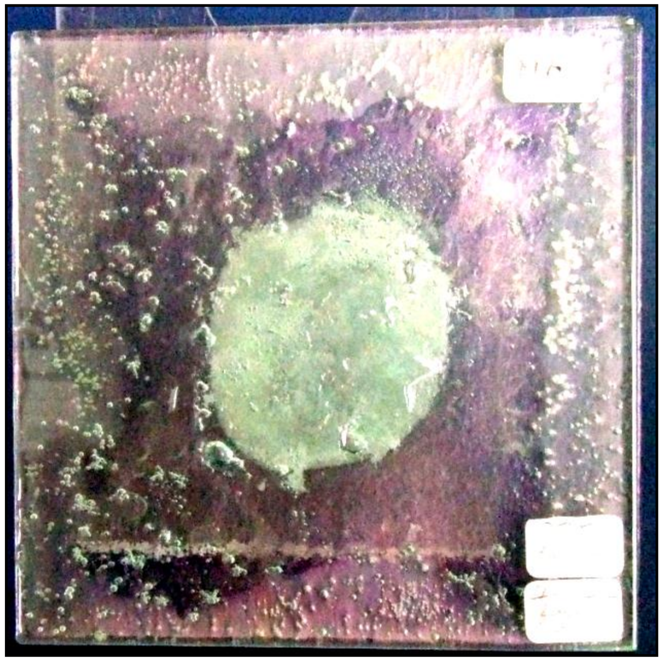


Figure 3.67 4mm float over 4mm K, post-fired at 775°C, with fusers glue showing reduction in colouration.

The factor of upper glass float thickness and its effect on the central area of colour was examined using 3mm, 4mm, 6mm and 10mm float glass fuse fired with 4mm and 6mm K. Throughout the standardised tests, it was noticed that when thicker 6mm float glass was used as the top sheet, a larger area of strong colouration was produced. This was also confirmed when 10mm glass was used. This was tentatively explained by the slower rate of melting of the thicker glass which, therefore, allowed more air to be available between the K and float surfaces before the fusing process was complete.

The enclosed samples were subjected to the same criteria in firings taken at 10°C intervals to 850°C. At 800°C, between 3mm float, the 4mm K produced a large area of gold (*Figure 3.68*). Between 4mm float, 4mm K produced pink/ /blue tones (*Figure 3.69)* and between 6mm float, the 4mm K showed an area of strong gold colouration (*Figure 3.70*).

Figure 3.68 4mm K between 3mm float, post-fired at 800°C, showing gold colouration.

Figure 3.69 4mm K between 4mm float, post-fired at 800°C, showing pink/blue colouration.

Figure 3.70 4mm K between 6mm float, post-fired at 800°C, showing gold colouration.

The areas seen in the centre of the pink/blue colouration in Figure 3.68 and the broken gold colouration in Figure 3.69 were found to have been each caused by the upper float glass having sagged onto the surface of the K coating during firing. This and the air pocket that was found surrounding the enclosed K, suggested that the amount of air present between the surfaces during fusing may have contributed to the strong visual effects.

From these factors it was clear that not one factor alone was responsible for the colouration of the post-fired K coating and that further analysis was required to understand the factors responsible for the changes and address Objective 2.

In the case of the Grid format tests, the post-fired colouration between 770°C and 800°C included both gold and pink/purple/blue tones but was, notably, seen always on opposing strips. Gold was found in patches on the upper strips; purple tones were a generalised colouration found on the lower strips (*Figure 3.71*).

Figure 3.71   4mm K strips enclosed in 4mm float, post-fired at 800°C, showing gold and pink/purple/blue colouration.

Again, this result seemed to suggest the presence, or lack of air, had some influence in the development of the colour in specific positions. To check this finding, a sample was cut using a diamond saw to provide a cross section through the post-fired grid. On closer inspection of the upper strips where strong pink had formed, a very tiny sealed gap was found. Similarly with the lower strips of K, the more regular and strong purple colouration was found to be where there were air pockets formed from the crossing points of the grid. With the heat source from above these lower strips would be fused after the upper strips and, consequently, have more air available during the changing phase.

The amount of air available at the surface of the K coating during firing and its contribution of air to colour development was next explored. In one test strips of 4mm K were placed between two 100mm x 100mm pieces of 4mm float glass so that the ends were not enclosed. Post-fired examination of the ends revealed that tiny gaps had formed above the K strips during fusing (*Figure 3.72*). The two outer strips developed a peach colouration whereas the centre strip was pink (*Figure 3.73)*.

Figure 3.72 4mm K strips enclosed in 4mm float glass (end view), post-fired at 775°C, showing tiny gaps above.

Figure 3.73 4mm K strips enclosed in 4mm float glass (plan view), post-fired at 775 °C, showing pink and gold separate colouration.

3.5.2 Iridescence

The iridescence discussed in the standardised open test results was easily assessed by both the naked eye and microscopy. However, due to the additional layer of float glass on top of the K in the fused tests, visual characterisation was more challenging to define. The glassy planes of the float with two surfaces, created a visual shiny quality to the iridescence, an effect not seen in the open tests. When the fired samples were cut open, the iridescence was examined more closely (*Figures 3.74 and 3.75)*.

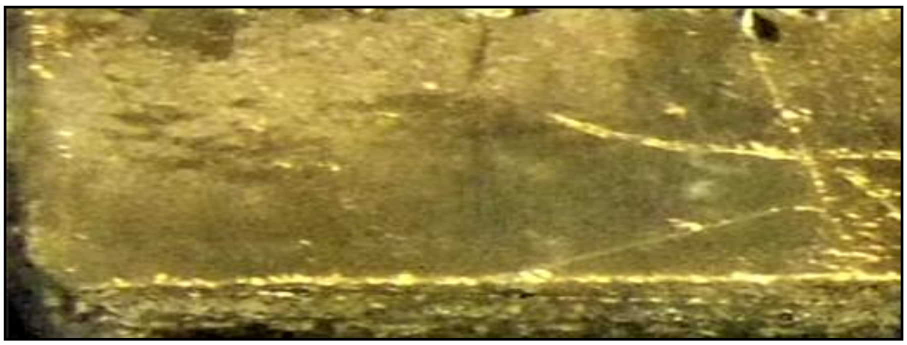


Figure 3.74 4mm K, post-fired at 775°C, fused cut open sample showing gold iridescence.

Figure 3.75 4mm K, post-fired at 775°C, fused cut open sample showing peach/pink iridescence.

As previously stated, each test was different but, as with the colour, the iridescence showed traits that were common in most tests. From 700°C, the pattern of all fused tests had a central, an intermediate and an edge area (*Figure 3.76*). The central area contained iridescence that was seen as shiny and reflective; in some cases it was one patch in others it was broken up with variable colouration. The intermediate area surrounding the central patch and the edge area were varied but generally of a pink/purple transparent iridescence.

Figure 3.76 3mm float over 4mm K, post-fired at 775°C, in Fused Format showing iridescence pattern.

In the enclosed tests, iridescence took on the same shiny colouration of gold, pink and purple as in the fused tests with the purple clear colouration in the background (*Figure 3.77*). The position and shape of this reflective area was not regular but occupied a large proportion of the K surface. A cross sectional cut through this sample also confirmed the presence of the tiny gap above the reflective patch as in the grid test.

Figure 3.77 6mm K between 4mm float, post-fired at 800°C, in Enclosed Format showing gold and purple colouration.

In the grid format, the effects of shiny gold or pink colouration (*Figure 3.78*) and iridised purple tones were seen in each sample. The upper strips exhibit the colouration with the reflective characteristic seen through the upper layer of float. The lower strips display the colouration as iridescence without the reflectivity. Within the lower temperature range of 725-750°C, the lower strips of K were the only strips to display any significant pink/blue/purple colour. The gold iridescent areas only appeared at the higher temperature range on the upper strips as the air became limited during fusing.

Figure 3.78 4mm K strip between 4mm float (detail), post-fired at 775°C, fused in Grid Format showing pink colouration.

3.5.3 Presence of Bubbles

Although bubbles were evident on the surface of the open standardised tests, in the fused series they were a significant characteristic. In all fused formats, bubbles appeared at the lower end of the testing range from about 720°C (slightly earlier than in the open fired tests) when they were random and variable in size, shape and position. As all of the tests were different, this summary can only be a generalisation of the results. However, with each sample there were three areas of bubble activity, the examples shown being typical of the type. In the central area was often a large irregular presentation of bubbles in combination with colouration. The area around the edges of the sample was iridised on which were patches of bubbles and large air pockets. The intermediate area also showed bubbles which were random in size and position (*Figure 3.79*).

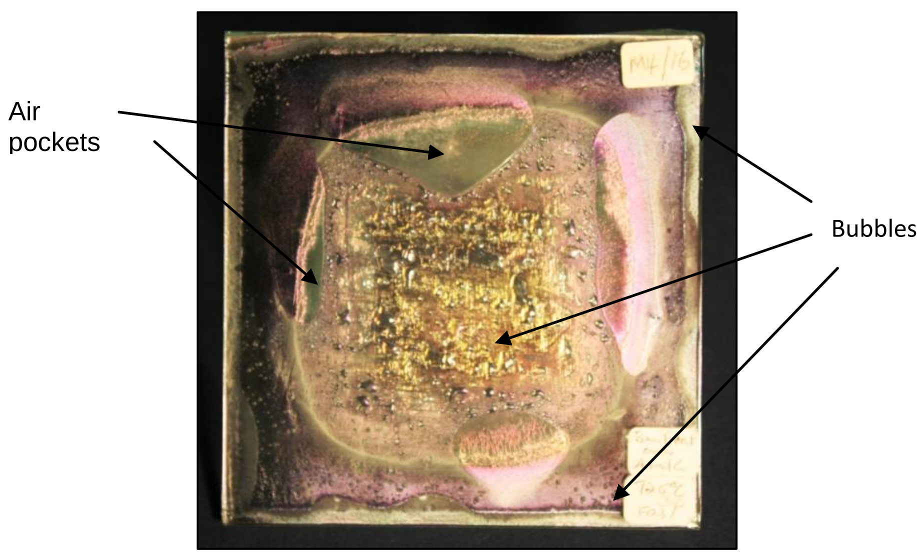


Figure 3.79 4mm K and 4mm float, post-fired at 775°C, in Fused Format showing bubbles.

In the upper temperature range, the bubble formation was profuse and above 825°C restricted the visual effects of colour and iridescence. The example in Figure 3.80 shows the reflective colouration in the central area broken up by massed microscopic bubbles with larger bubbles that appear to be sitting on top of the coating.

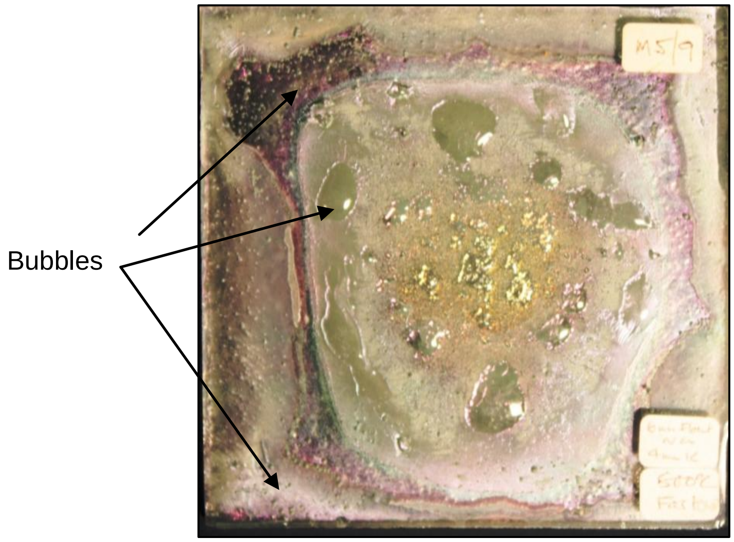


Figure 3.80 4mm K and 4mm float, post-fired at 800°C, in Fused Format showing bubbles.

In the Enclosed Format, the same early progression of random bubbles was seen on the iridised surface from about 720°C. At 800°C, the reflective patches of colour seen previously in Figures 3.67 and 3.68 appeared to be in air pockets, formed under the upper layer of float glass. Microscopic examination of these two areas revealed that in both cases, bubbles were present on the surface. Where the gold colouration was seen, the bubbles were larger and cracks were observed quite clearly (*Figure 3.81)*. In the areas of pink and blue colouration, the bubbles were seen to be 'sitting' on ripples (*Figure 3.82*).

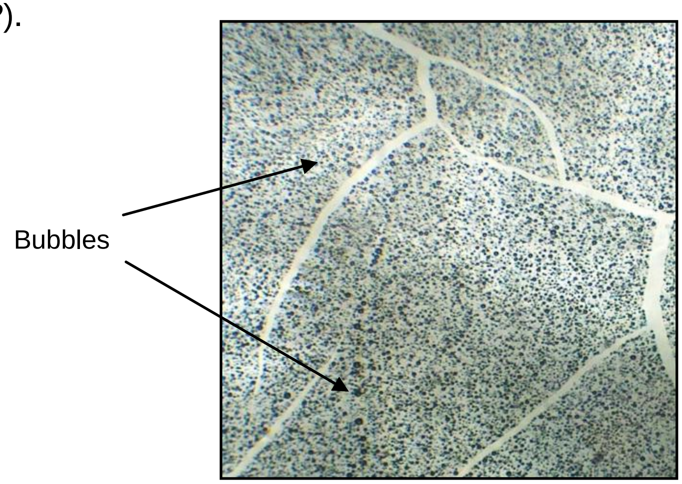


Figure 3.81 4mm K between 4mm float, at 800°C, Enclosed Format gold patch showing bubbles.

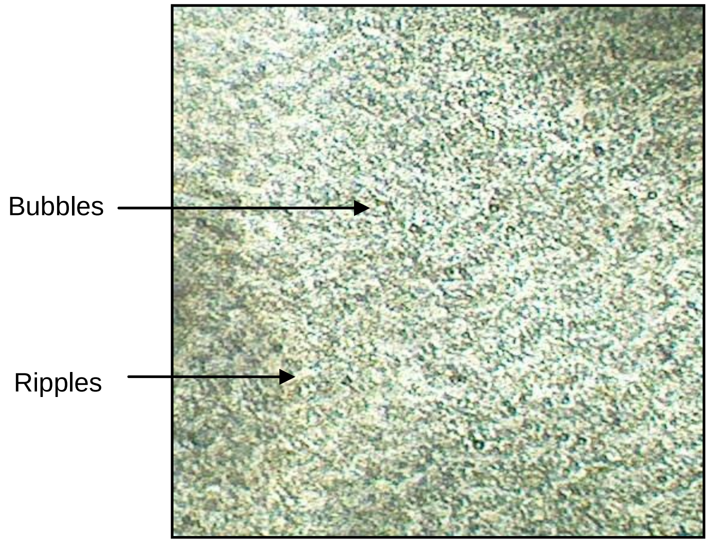


Figure 3.82 4mm K between 4mm float, at 800°C, Enclosed Format pink patch showing bubbles and ripples.

Within the Grid Format, bubbles were formed in a similar way showing on the upper strips only at 720°C; the lower strips developed clear pink iridescent colouration. It was found that at any point throughout the temperature range from 720°C-800°C, the grid showed this same pattern of upper strips bubbles, lower strips iridescence (*Figure 3.83*). Although this could be explained by the source of heat being above the glass in the flat bed kiln, it also suggested greater bubble formation in the limited air situation of the upper fused strips.

Figure 3.83 4mm K strips between 4mm float, post-fired at 800°C, in Grid Format showing bubble formation.

Attempts were made to understand the development and control of the bubbles through two Fused Format tests. In the first, to locally reduce the heat, a strip made up of three thicknesses of 3mm ceramic fibre was placed across the centre of a 4mm K and 4mm float glass sample. Bubbles were seen to be limited to the side edges (*Figure 3.84*). In addition, this also prevented the formation of the characteristic central iridescence.

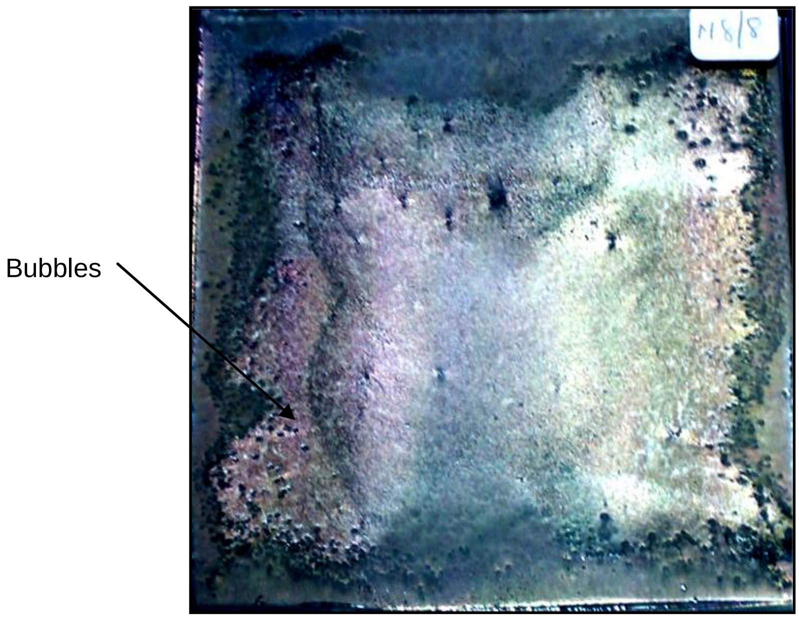


Figure 3.84 4mm float over 4mm K, post-fired at 775°C, in Fused Format with ceramic matting strips placed on top showing limitation of bubbles.

In the second, to try to control and re-direct the position of bubbles, channels were sandblasted in the lower tin side of the float. After firing, there was a clear pattern to the presence of bubbles with fewer within the sandblasted strips. However, another and perhaps more significant outcome of this test was the strong colour development to the coating below the sandblasted strips as can be seen in Figure 3.85. This development was a significant step. The sandblasted channel and the air it had provided indicated a possible route to the control of colouration.

Figure 3.85   4mm float over 4mm K, post-fired at 775°C in Fused Format showing channelling of bubbles.

3.6 Change of Form Testing Results

The results to examine the behaviour of 4mm and 6mm K, including the comparison with similar thickness of float glass, in the change of form tests, are presented in the following sections.

3.6.1 Sagging

In general, it was found that K behaved in a similar way to float glass when subjected to sagging. At 775˚C, all pieces took on a similar semblance of shape with only minor differences due to the surface of the mould. The placement of the surface of the coating up or down appeared to make no significant difference to the results of the sagged shape.

There was a considerable difference, however, in the colour which was particularly strong with the 6mm coating. The samples which were sagged with the coating up showed a strong pink/purple colouration on the coated side with green tones on the underside. Where the samples were sagged with the coating down, the reverse was the case with the colouration on the upper non-coated side seen to be green but on the coated underside it was pink, as shown in Figure 3.86. With the coating upwards, there were shiny stretched areas at the ends and dull buckled areas in the middle. The coating fired down was shiny in appearance with several cracks across the curved area. Microscope examination of both 4mm and 6mm K surfaces was inconclusive, as all samples showed several different areas of post-fired structure.

Coating up

Coating down

Figure 3.86 6mm K, post-fired at 775°C, sagging, showing colour difference.

3.6.2 Bending

The same characteristics of the reversal of colour, although not as strong as in sagging, were seen in the bending tests (*Figure 3.87*). The changes to the coating of both 4mm and 6mm K samples subjected to bending were not consistent across any individual piece. When the coating was fired up it showed cracking, shiny areas, dull patches and variable colouration of pink, gold and blue.

Coating up

Coating down

Figure 3.87 6mm K, post-fired at 775°C, bending, showing colour difference.

More severe bending of both thicknesses of K over a metal pipe produced colouration with varied iridescence but with similarities at corresponding points of the curve, i.e. 1 and 6, 2 and 5, 3 and 4 (*Figure 3.88*). Microscopic examination of sections, shown in Figure 3.89, of the 6mm K fired down, showed a variation in the formation of the ripples (*Figures 3.90 to 3.95*). At this stage, the variation in appearance of the iridised surface could be attributed to the range of ripple formations and the respective variation for their interaction with light found in these bending tests.

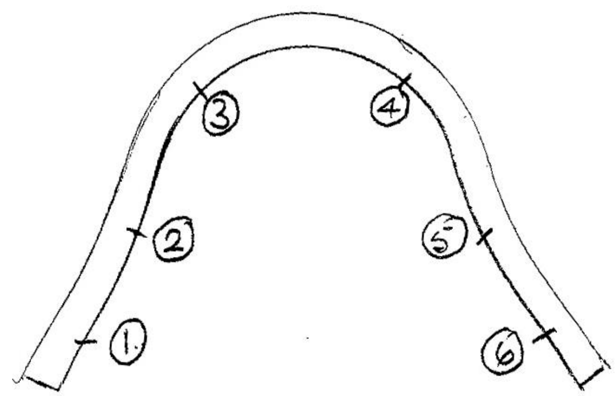


Figure 3.88 Bending curve diagram noting corresponding points of iridescence.

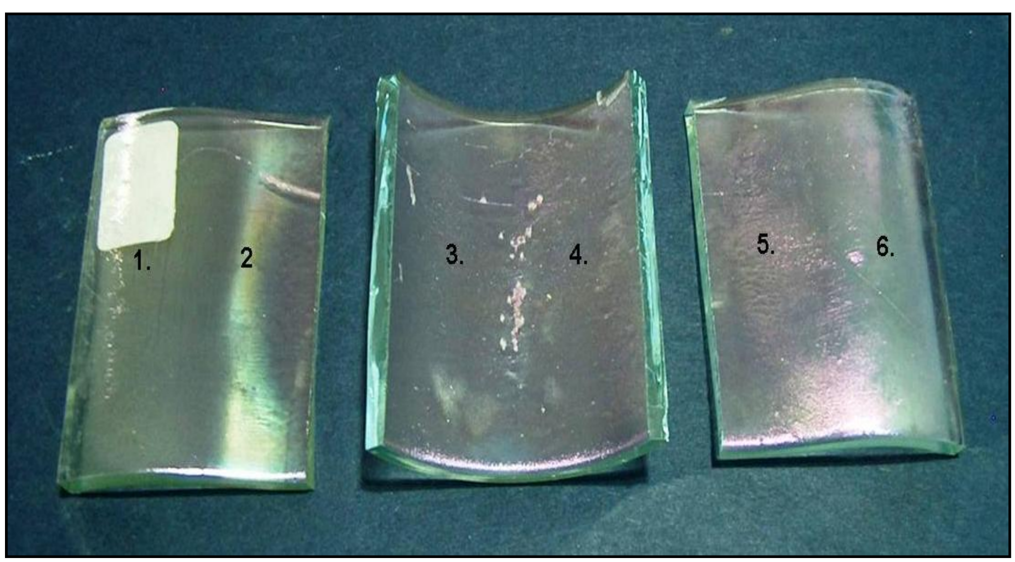


Figure 3.89 6mm K, post-fired at 775°C, bending curve, sections cut for microscopic examination.

Figure 3.90 Bending curve point 1.

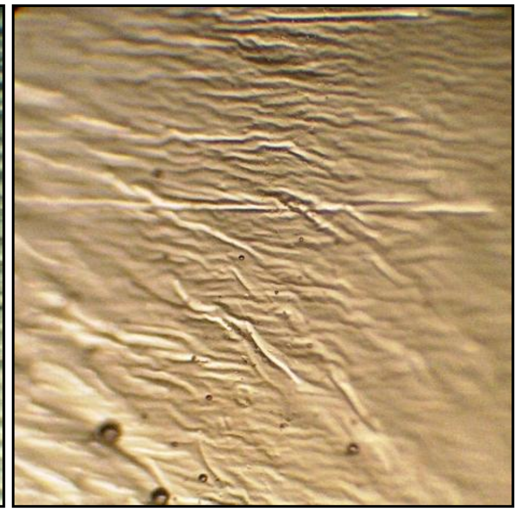


Figure 3.91 Bending curve point 6.

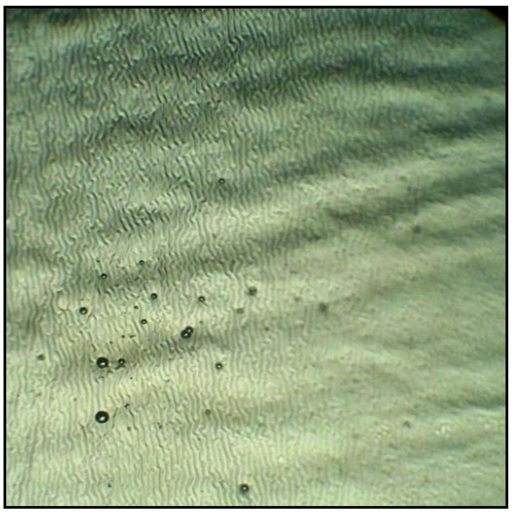


Figure 3.92 Bending curve point 2.

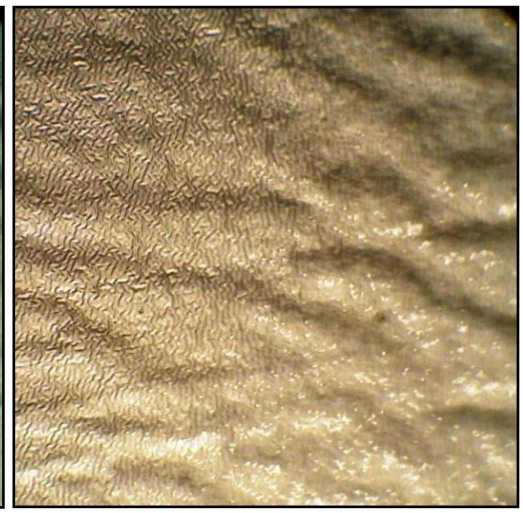


Figure 3.93 Bending curve point 5.

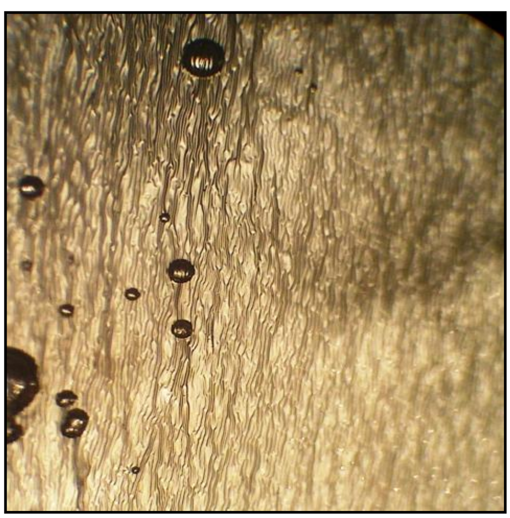


Figure 3.94 Bending curve point 3.

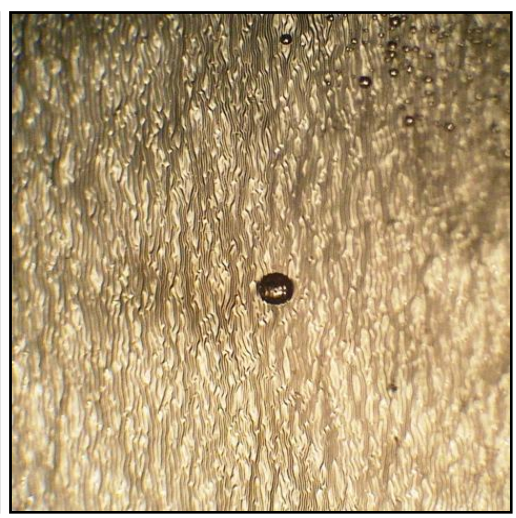


Figure 3.95 Bending curve point 4.

Figures 3.90 – 3.95 showing variation in ripple formation across curve.

3.6.3 Moulding

Colouration of the coating was strongest when the coating was fired down with the 6mm K producing pink/purple and green/gold tones seen in Figure 3.96. When the coating was fired up, the colouration was mainly pink/purple with the 6mm K also exhibiting some dull gold hues. Both coatings showed a variety of iridescent effects with patches as previously described on the 4mm surface.

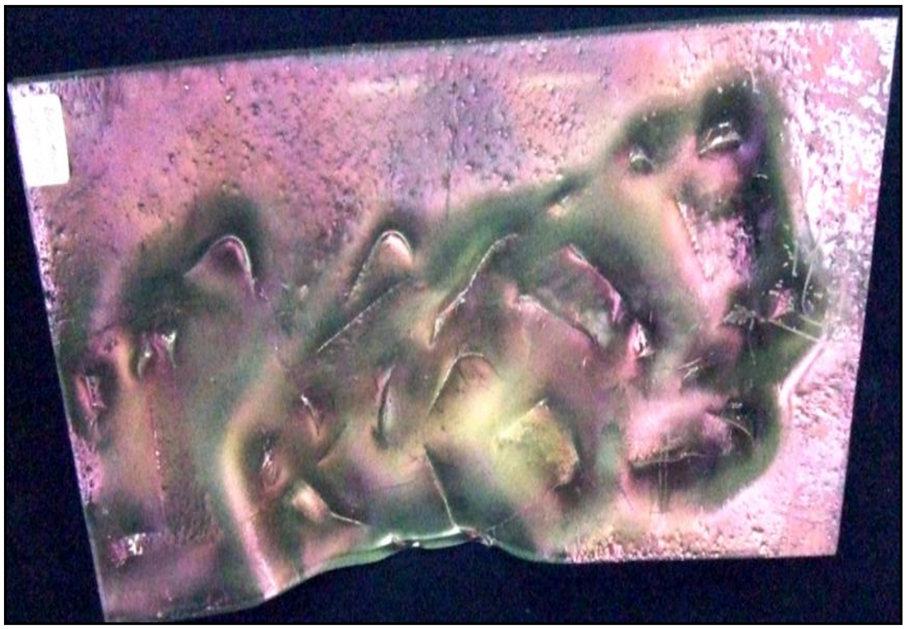


Figure 3.96 6mm K, post-fired at 775°C, coating fired down, after moulding showing strong pink/purple colouration.

The creative potential of K Glass was also seen in a further moulding test shown in Figure 3.97. The 6mm K coating was fired up but appears to have split during firing with lines of bubbles and clear areas where the contours were most pronounced, resulting in an interesting artistic effect. Some of these lines were an iridescent pink which, under microscopic examination, were seen to be bubbles sitting on a strip of fine ripples (*Figures 3.98 and 3.99*).

Figure 3.97 6mm K, post-fired at 775°C, coating fired up, after moulding showing split coating and multiple lines of bubbles.

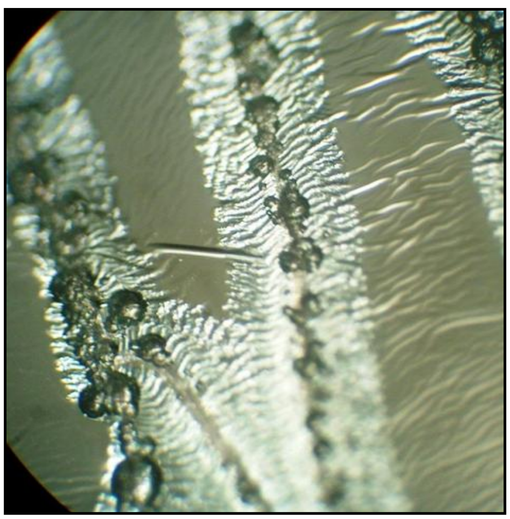


Figure 3.98 6mm K, moulded, showing split coating and line of bubbles.

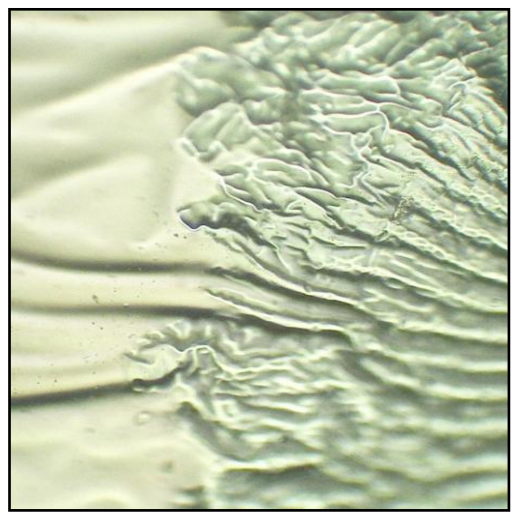


Figure 3.99 6mm K (higher magnification), moulded, showing edge of ripples.

3.6.4 Suspension

Results of the sagging and bending tests suggested that the behaviour of the K coated glass was similar to that of uncoated float glass. In those tests, the K coating appeared to make no difference to the fired form of the glass when subjected to the restrictions of a mould. When the glass was suspended and allowed to fall freely it behaved in a different way. Cracking was more defined in both the 4mm and 6mm coatings, especially when it was in expansion on the lower side of the test piece (*Figure 3.100*). Although some cracking occurred when the coating was in compression on the upper side of the test piece, gaps were only in evidence at the ends where stretching had occurred (*Figure 3.101*). The float glass tests displayed similar stretching characteristics of the tin residue as found by Antonio (2009).

Figure 3.100 4mm K, post-fired at 775°C, suspended, coating on under side showing cracks to coating.

Figure 3.101 4mm K, post-fired at 775°C, suspended, coating on upper side showing less defined cracks.

The shape of the post-fired suspension samples was also determined by the coated side of the glass which caused either a convex or concave profile to the related side. On the 4mm tests, this profile was found to be slightly more accentuated, i.e. 4mm at centre when the coating was on the upper side compared with 2mm when the coating was on the underside (*Figures 3.102 and 3.103*). The 6mm K showed similar profiles with similar measurements. In contrast the float was flat after suspension (*Figure 3.104*).

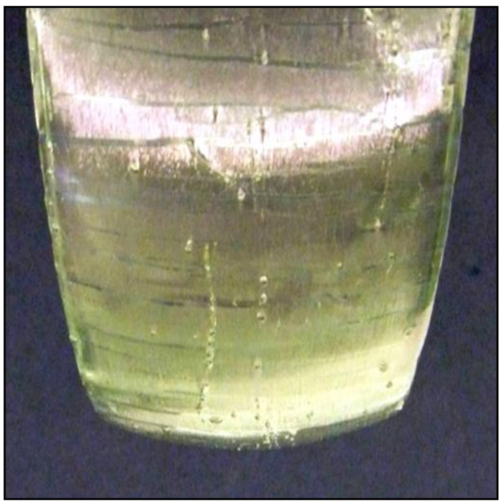


Figure 3.102 4mm K, post-fired at 775°C, suspended, coating under side – convex.

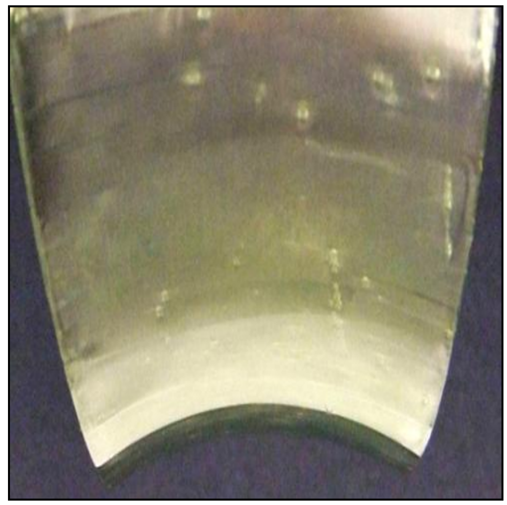


Figure 3.103 4mm K, post-fired at 775°C, suspended, coating upper side – concave.

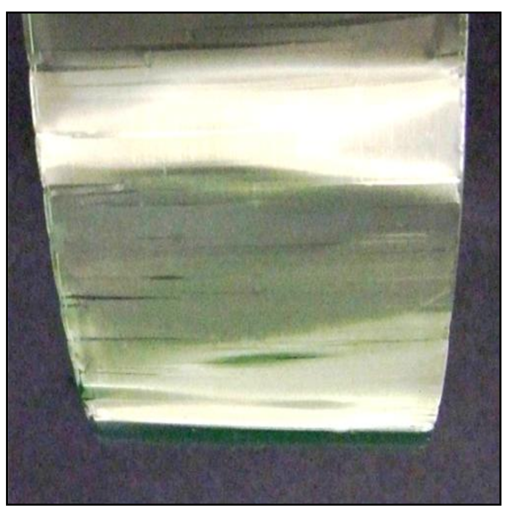


Figure 3.104 4mm float, post-fired at 775°C, suspended - flat.

The individual thicknesses of the K coatings are not documented in any of the manufacturing specifications or patents. However, results of tests which explored the rate of heat applied, suggested that the 6mm coating may be of a more robust nature. This is supported by the evidence of the patches of microscopic bubbles which formed mainly on the 4mm K caused by break up of the coating when fast fired. Micrographs in Figures 3.105 and 3.106 show the post-fired 6mm coating to have a more compact ripple formation which may also suggest a greater stability.

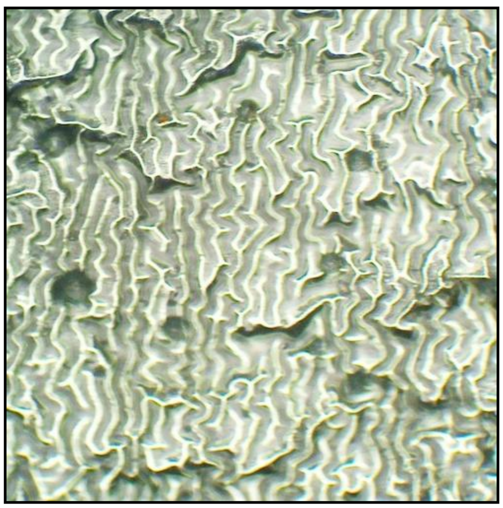


Figure 3.105 4mm K, post-fired at 775˚C, showing ripple formation.

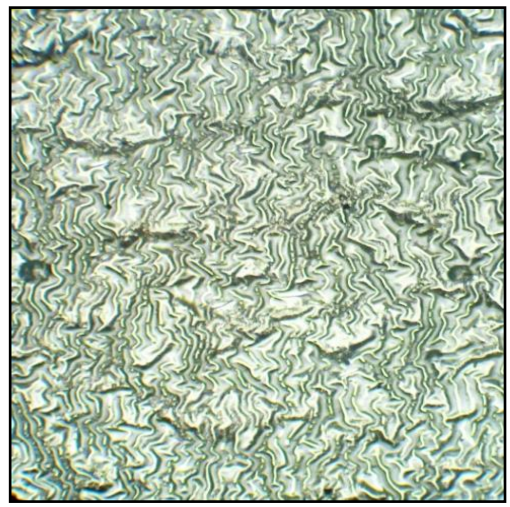


Figure 3.106 6mm K, post-fired at 775˚C, showing compact ripple formation.

In early tests the K coating was found to be of a different stability by the bending of the glass during firing. Narrow strips of 6mm K placed on their edges between two squares of 6mm float glass, were found to be curved after firing, the K coating being on the outside of the curve (*Figure 3.107*). It was surmised that this was caused by the difference in the coefficient of thermal expansion between the coating and the substrate. In soda lime glass this is 8.3 (Pilkington, 2009b) and in tin oxide it is 4 (Batzill and Diebold 2001). The speculation was therefore that the uncontrolled expansion at these different rates produced a curve on cooling.

Figure 3.107 6mm K and 6mm float, coating stability test, showing curve of glass supports.

3.6.5 Stretching

The 4mm K coating stretched in a very similar way to the 6mm K coating. By opening the kiln during the melting phase as it was approaching 775˚C, the two thicknesses of glass were seen to drop at a similar rate. Both coatings cracked and spread as the glass stretched and although there was minimal difference overall, both samples exhibited potentially creative effects (*Figures 3.108 and 3.109*).

Figure 3.108 4mm K, post-fired at c.775˚C, stretching, showing cracking and spread coating.

Figure 3.109 6mm K, post-fired at c.775˚C, stretching, showing cracking and spread coating.

When the test was repeated using 6mm K and 6mm float glass, the K coating was seen to slow down the rate of stretch (*Figure 3.110*). The stretching of the coating prior to cracking caused the ripples to elongate and consequently presented a strong iridescence (*Figure 3.111*).

Figure 3.110 6mm K (left) and 6mm float (right), post-fired at c.775˚C, showing comparative stretching.

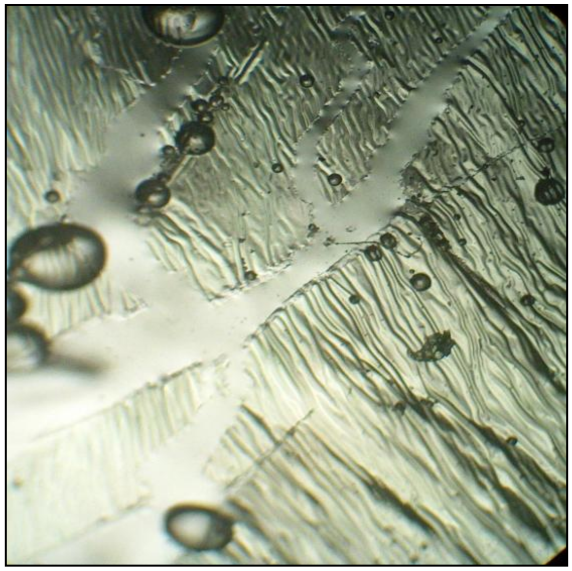


Figure 3.111 6mm K, at c.775˚C, stretching, showing linear ripples and split coating.

3.6.6 Sliding

Tests to ascertain whether the coating actually slid on the surface of the K Glass revealed a double formation to the ripples. In both 4mm and 6mm K at the lower end of each sample, small ripples were seen to run horizontally across the glass in addition to larger ripples running vertically, as can be seen in Figures 3.112 and 3.113 indicating two directions of possible movement at those points.

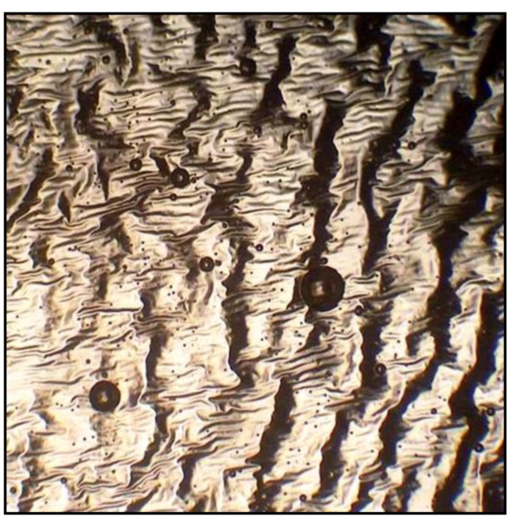


Figure 3.112 4mm K post-fired, showing possible sliding of coating.

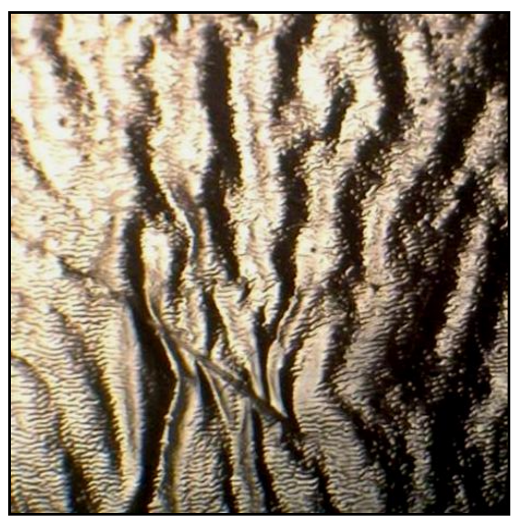


Figure 3.113 6mm K post-fired, showing possible sliding of coating.

3.7 Summary of Practical Programme of Testing

The standardised tests have provided information on which creative artwork can be based. This falls into two categories namely that which will be open fired and that which will be fuse fired. Although very slight changes to the K surface were detected at 690˚C, when open fired at temperatures above 720˚C, a visual effect made up of colouration and iridescence was observed with bubble formation beginning at 730˚C. In addition, the unusual interferential appearance and disappearance of these characteristics created an original effect of which no documentation has been found. Some modification of the surface through abrading has shown that this technique may produce further creative effects. Artwork using a combination of treatments will develop this potential.

The range of colour that developed was considerably increased when K was combined in a fused situation with float glass. In addition to the pink/purple tones of the open tests, reflective areas of gold, peach, pink and blue were developed with temperatures above 720°C and maximising between 770°C and 800°C. The three classes of fusing combinations, Fused, Enclosed and Grid Formats, showed similar properties, not only within their individual arrangement of pieces of glass but also across the groups. Although the characterisation was by surface, colour, iridescence and bubbles; two of these, colour and iridescence, are interrelated and, like that seen in open fired tests, are interferential.

Fuse firing of K Glass has further revealed the possibility of a wider range of interferential colouration as a result of the small gap that is present above the K coating. Samples made during the testing process have shown that it is possible to control colouration and create an original and innovative effect.

Through experimentation and expansion of the variables an initial understanding of the visible changes to the surface of the K coating was attained. However, it was deemed prudent, at this stage, to explore the surface of the fired glass at a closer level with more detailed microstructural characterisation to more fully assess the changes to the coating that were not visible to the naked eye. An evaluation of the physical factors of the changes is described in Chapter 4.

Chapter 4

Evaluation of Post-fired K Glass Visual Effects

This chapter relates to the second objective 'To understand the changes to the surface coating and the factors responsible for the visual effects'. As this understanding was necessary for the ongoing progression of the research, within this chapter is an attempt to explain the complex material changes in a simple scientific interpretation.

4.1 Pre-fired Structure of K Glass Low Emissivity Coating

Although the layers that comprise low emissivity coatings are well documented in patents filed by Pilkington and other glass manufacturers, no specific reference to K Glass with its composition of the two layers was found in those searches. The understandable unwillingness of Pilkington to offer any commercially sensitive information as well as the lack of documentation meant that in order to interpret the visual changes on the K Glass coating, several assumptions had to be made. The information on which these assumptions were based was gleaned from patents and visual examination of the changes to the fired surface.

The K coating was applied to a substrate of float glass, both of which are clear and transparent. The coating is of a different composition to the substrate and consists of two layers, the upper being of fluorine-doped tin oxide, SnO_2:F (Hurst and Sheel, 1999). The under layer, the purpose of which was described in Section 2.7 'is silicon oxynitride' (Gordon, 1980), or contains 'silicon and oxygen' (Jenkins, Simpson and Porter, 1988).

Initial examination of the pre-fired glass using a light microscope was able to detect the coating which appeared to show two layers on top of the darker substrate (*Figure 4.1*). The combined coating is the upper dark line; the palest layer below the dark line is, in fact, a ‘shadow’ caused by the microscope light. It was impossible, however, to visually differentiate between the two coating layers due to both being very thin. The SnO_2 layer is 200-500nm[16] and the under layer is 60-80nm, on top of either a 4mm or 6mm glass substrate (Jenkins, Simpson and Porter, 1988). An approximation of the total thickness of the coating would be 500nm which is 0.5 of a micron or 0.0005mm.

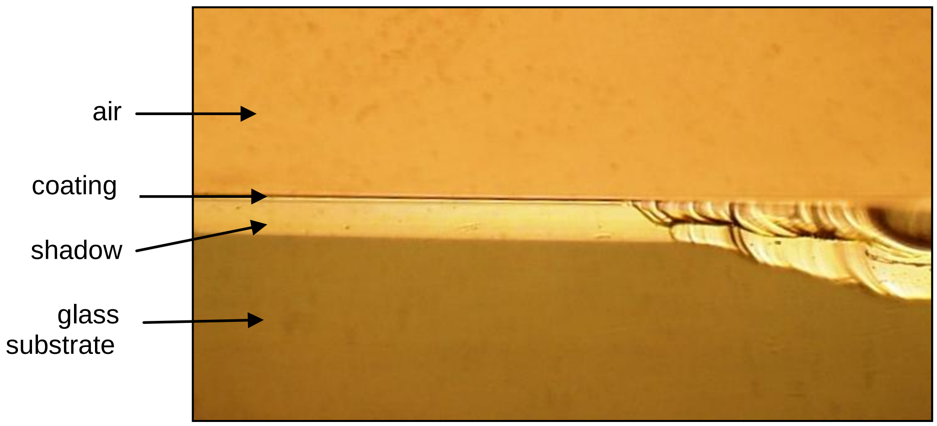


Figure 4.1 Pre-fired 6mm K, edge view showing coating.

4.2 Changes to Post-fired K Coating

For the purposes of this research the K coating has been structurally treated as one layer. The colouration effect was found to be caused by the changes within this coated layer and primarily due to the structure of the material’s fundamental changes during firing. The colour is a reflective interference effect due to the physical structure of the post-fired coating influenced by its optical properties. Although there were fundamental structural changes in the top layer of material which were common to both, for the simplicity of explanation, the open fired and the fused situations have been considered separately.

[16] 1 nm = 0.001 micron, 1 micron = 0.001mm (1000 microns = 1mm)
1nm = 0.000001mm, i.e. 1millionth

4.2.1 Optical Microscope Examination of Open Fired K Coating

The open fired tests were fired on the floor of the kiln with no air restrictions and, as such, were considered an oxidation[17] firing. The post-fired surface as shown in Figure 4.2 had colouration of mainly pink to purple with, occasionally, some tones of gold, green and blue (*See 3.4.1, p.75)* and was of an iridescent nature ranging from dull to shiny (See *3.4.2, p.78*). Examination of this surface with the naked eye and microscope revealed ripples, in variable formation, present on all the open fired coated surfaces (*Figure 4.3*).

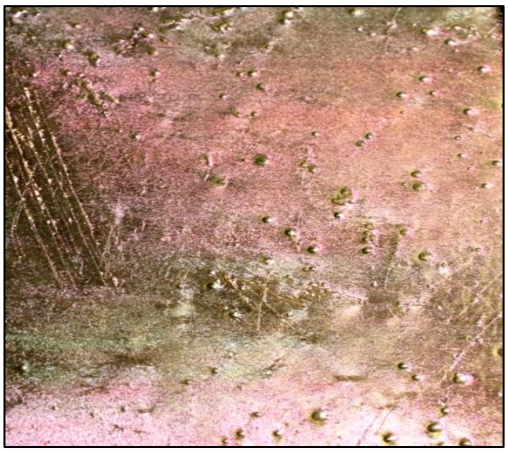


Figure 4.2 6mm K, post-fired surface.

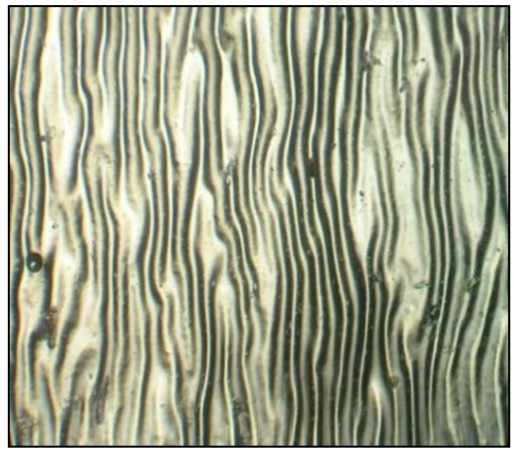


Figure 4.3 6mm K, post-fired surface, plan view showing ripples.

The edge view of the fired 6mm K shows the ripples on the surface in Figure 4.4 and in greater detail when magnified higher (*Figure 4.5*).

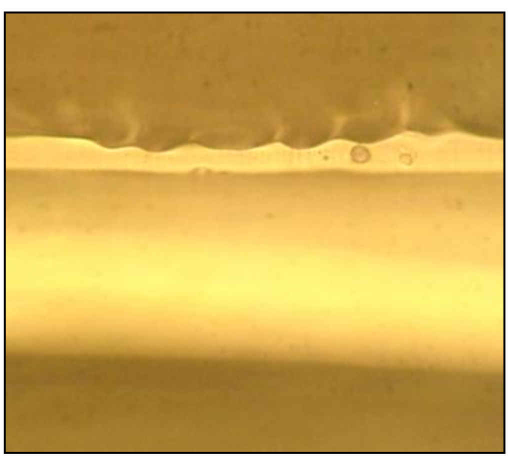


Figure 4.4 6mm K, post-fired, edge view 1 showing surface ripples.

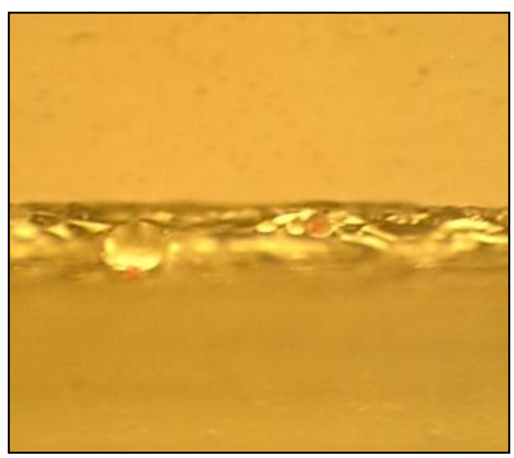


Figure 4.5 6mm K, post-fired, edge view 2 showing surface ripples.

[17] With reference to this research 'oxidation' means the presence of sufficient oxygen to effect the changes to the surface coating.

The ripples in Figure 4.6, in this instance, appear to have caused an overhang seen in Figure 4.7 which may be the coating. The ‘bubbles’ seen in paler area are in glass substrate and not thought, at this stage, to be related to coating.

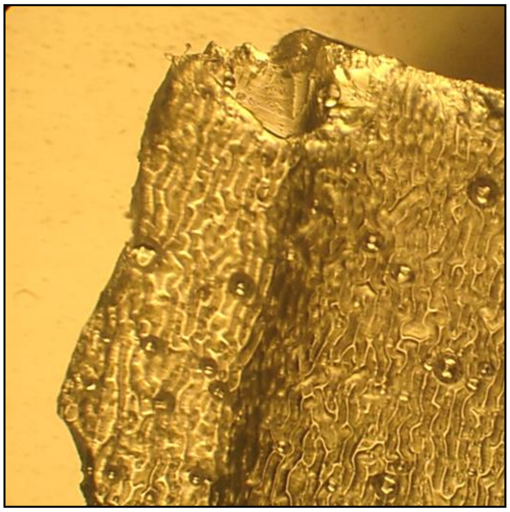


Figure 4.6 6mm K, post-fired, overhang, plan view showing surface ripples.

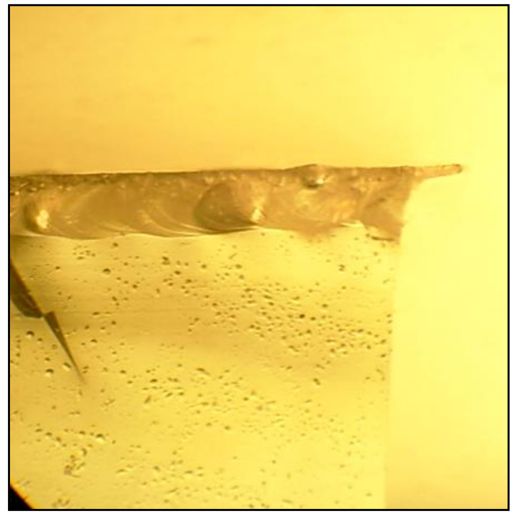


Figure 4.7 6mm K, post-fired, edge view showing overhang.

4.2.2 Optical Microscope Examination of Fuse Fired K Coating

The fuse fired samples gained a feature which provided a further dimension in terms of colouration. During the Fused Glass and Enclosed Glass formats (*See 3.1.3 p.58*) tiny gaps were formed as the upper glass softened (*Figures 4.8 to 4.11*). These gaps above the coating formed an air pocket restricting the amount of air, thus causing a form of reduction[18] firing (in contrast to the form of oxidation firing as seen with the open fired tests). The coating below these gaps took on more intense colouration which included gold, pink, blue and purple. When the gap was artificially recreated by sandblasting, those colours were able to be repeated (*See 5.2.2, p.152*). This colouration was developed after the surfaces of the glass had fused, i.e. above 650˚C

[18] With reference to this research ‘reduction’ means not sufficient oxygen to effect the complete changes to the surface coating

and were therefore contained in an enclosed atmosphere which would dictate the colouration.

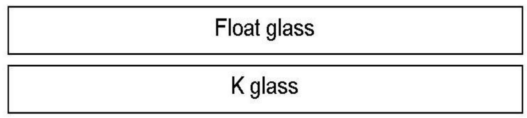


Figure 4.8   Gap formation fused format – pre-firing diagram.

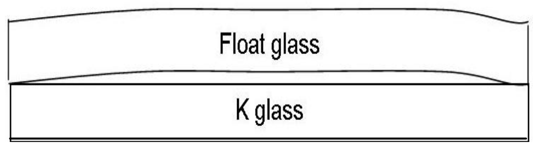


Figure 4.9   Gap formation fused format – post-firing diagram.

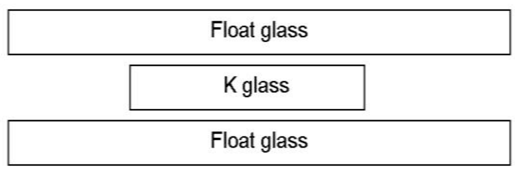


Figure 4.10   Gap formation enclosed format – pre-firing diagram.

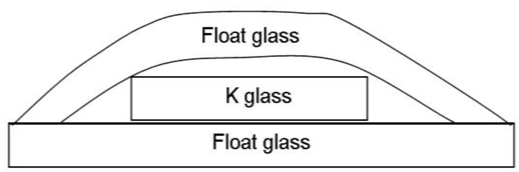


Figure 4.11   Gap formation enclosed format – post-firing diagram.

4.3 Relationship of Bubbles and Ripples to Colouration

For a closer visual inspection of the Fused Format samples, the upper layer of float glass was cut open and removed to expose the coloured K surfaces (*Figure 4.12*). Under microscopic examination the colours exhibited features which, although at first appeared to be individual to that colour, on further evaluation were, in fact, related. The gold colouration which had been achieved by fusing at 775°C, showed a surface of dense bubbles (*Figures 4.13 and 4.14*). Previous identification studies had shown ripples appearing on open fired samples at 720°C so it was logical that ripples could be present. By using a lighting technique of positioning a hand-held light source at an oblique angle to the glass being examined under the microscope lens, it was possible to detect their presence (*Figure 4.15*). Without this artificial and induced lighting the bubbles dominate and completely mask the ripples.

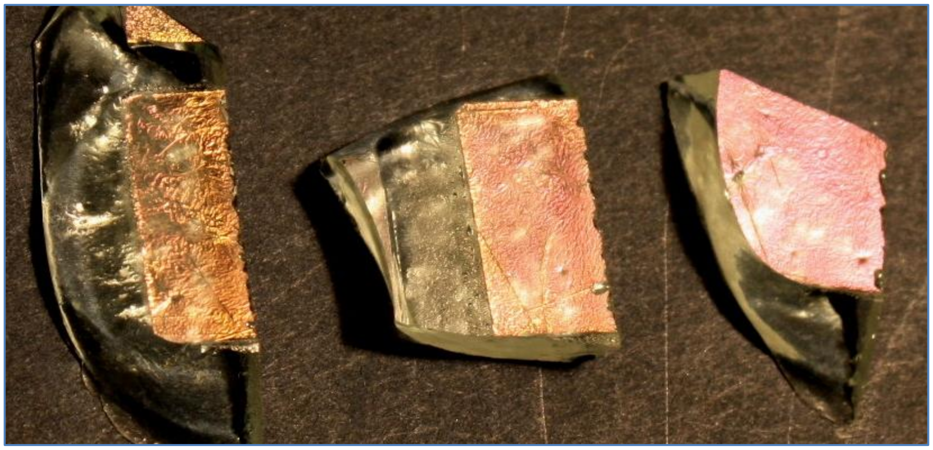


Figure 4.12 Opened fused gold, pink and purple samples.

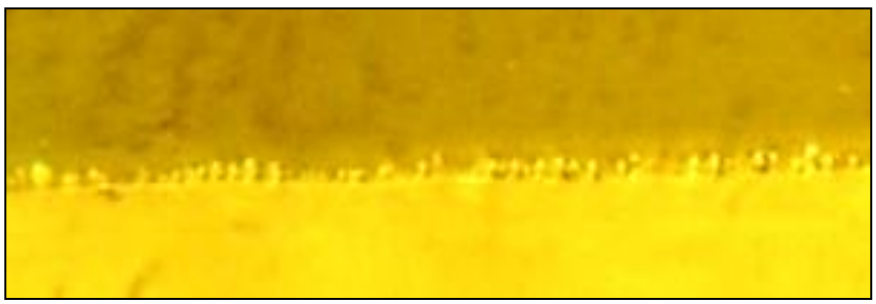


Figure 4.13 Gold fused edge view showing dense bubbles.

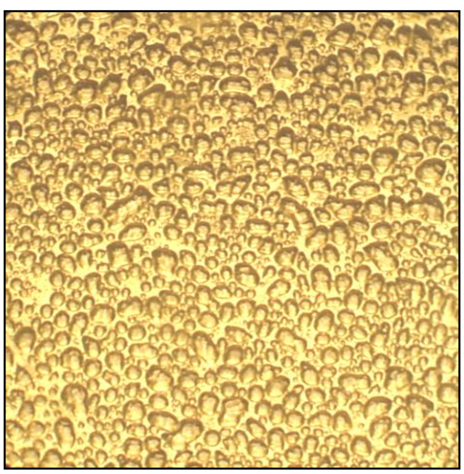


Figure 4.14 Gold fused, plan view showing dense bubbles.

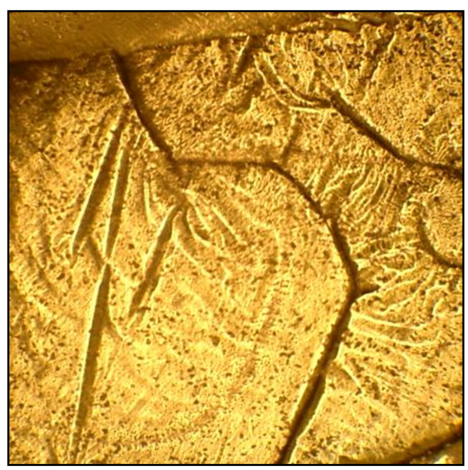


Figure 4.15 Gold fused, plan view, examined under angled light, showing bubbles and presence of ripples.

The Adobe Photoshop generated image below shows the bubbles on top of the ripples (*Figure 4.16*).

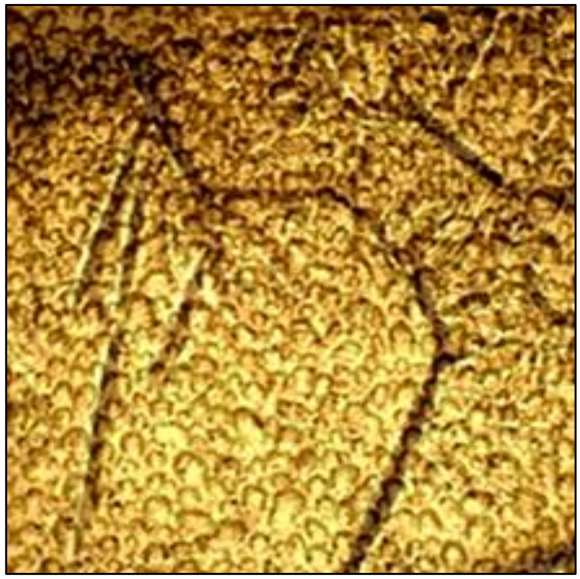


Figure 4.16 'Photoshop' generated image from Figures 4.14 and 4.15 of bubbles on top of ripples.

The pink colouration occurred where the post-fired gap above the K coating was found to be slightly greater than that observed with the gold coloured samples. With more air than in the gold samples but limited by the amount allowed by the gap, a partial reduction firing was created, i.e. not fully oxidative and not fully reductive. Partial reduction resulted in a combination of bubbles and ripples, however, the bubbles were found to be smaller and more sparsely distributed (*Figures 4.17 and 4.18*).

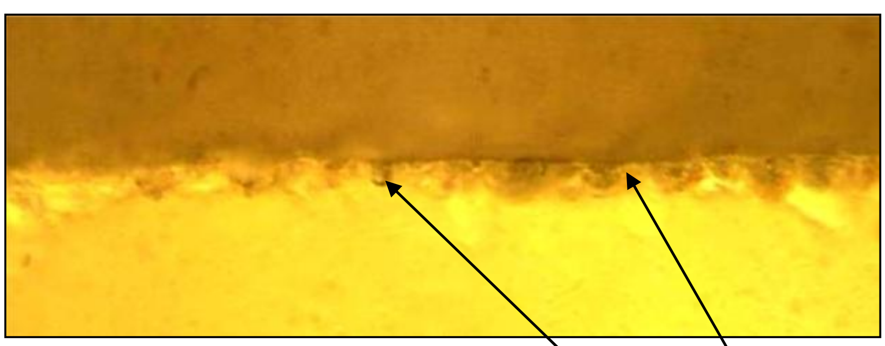


Figure 4.17 Pink fused, edge view showing bubbles and ripples.

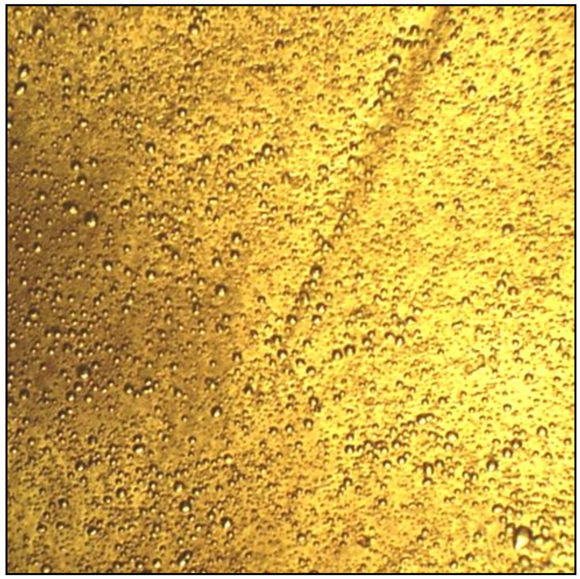


Figure 4.18 *Pink fused, plan view showing less dense bubbles and ripples.*

It was observed that a partial reduction became a full oxidation situation in the fused sample when the gap increased. With an increase in gap depth, the reductive environment effectively changed to, or was equivalent to an oxidation one as seen with the open fired samples, despite still being in a closed or restricted air situation. This is borne out in tests with a graduated gap showing no difference in colour across the depths. Under microscopic examination, deep gap samples revealed ripples and only a very occasional bubble (*Figures 4.19 and 4.20*).

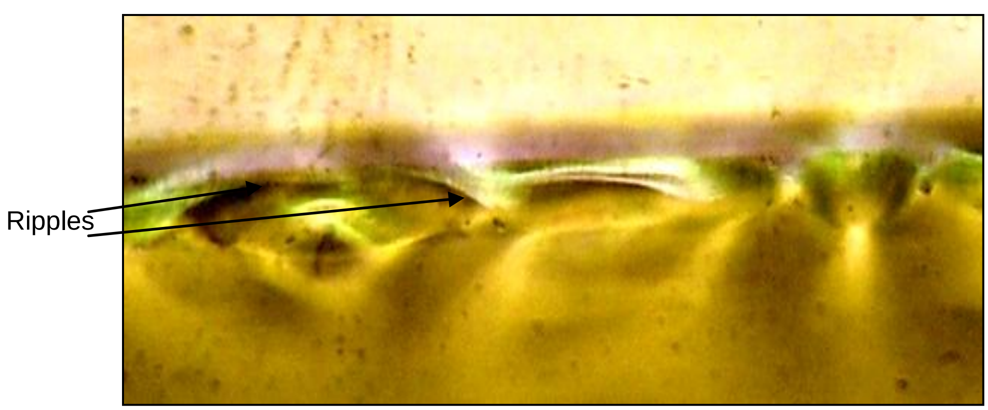


Figure 4.19 *Purple fused, edge view showing ripples only.*

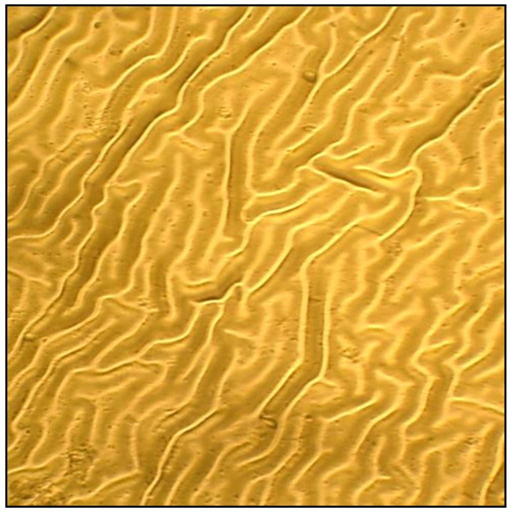


Figure 4.20   Purple fused, plan view showing ripples only.

At this stage, it was concluded that no matter what firing, i.e. oxidative or reductive, ripples were always found to be present but their direct effect on colour was only apparent in partial reduction or oxidative environments where the density of the bubbles was less (*Figure 4.21*).

Gold	**Pink**	**Purple**
Due to bubbles but with underlying ripples	Due to bubbles and ripples	Due to ripples

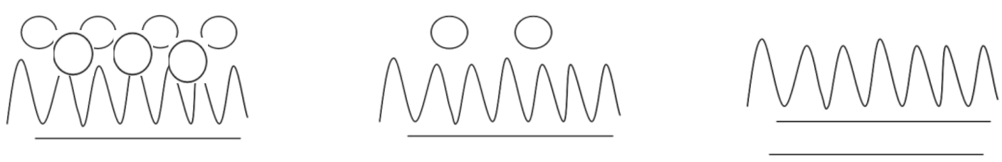


Figure 4.21   *Fired surface structures diagram.*

Visual examination of the fired K Glass tests revealed the presence of bubbles to a lesser or greater degree in all samples whether open or fused. Size, distribution and position varied from test to test but methods developed throughout the programme enabled their control. Throughout the microscopic examination, the gold colouration was only seen when massed bubbles (virtually total coverage) are present on the

surface. Therefore the colour could be described as a 100% optical effect of light that is reflected back from the post-fired coating and is dependent on the profile of the surface. Light shone on bubbles reflected gold whereas light shone on bubbles and ripples, reflected pink. Light + bubbles = gold. Light + bubbles and ripples = pink.
Light + ripples = purple.

4.4 Energy Dispersive X-ray Spectroscopy

The results from the EDS analysis are presented below and are discussed in terms of the content of gold, pink and purple post-fired K coatings. SEM micrographs are also included for structural and topographical analysis of ripple formation.

4.4.1 EDS Sample: Gold Coloured Coating

The gold sample which had been taken from a section of fused K and float glass was examined to establish the elemental content of the bubbles seen on the surface (*Figure 4.22*). Up to this point, the word 'bubbles' was used as their exact conformation had not been determined by light microscopy.

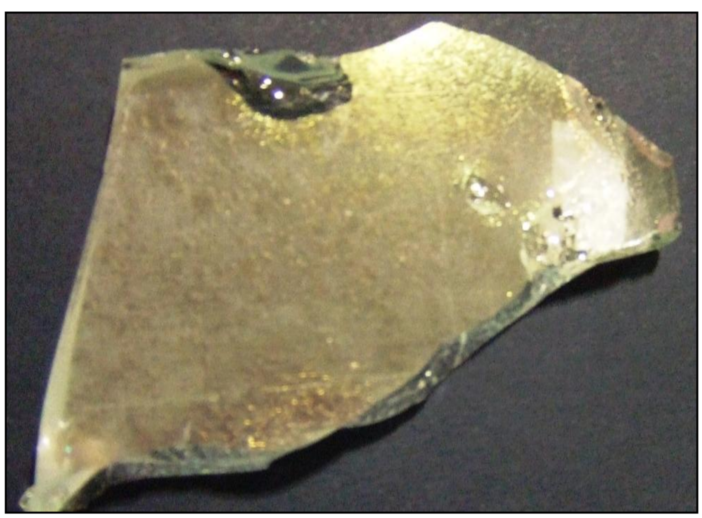


Figure 4.22 SEM gold sample, small piece of fuse fired K (opened) showing coating with gold colouration.

Figure 4.23 shows the surface at 300 times magnification with a mass of 'holes' which were not able to be identified (Monkman, 2010). The analysis, however, was able to identify the 'bright' areas on this micrograph as the element of tin in a 'bead-like' formation – the brighter the pixel the stronger the element (*Figure 4.24*).

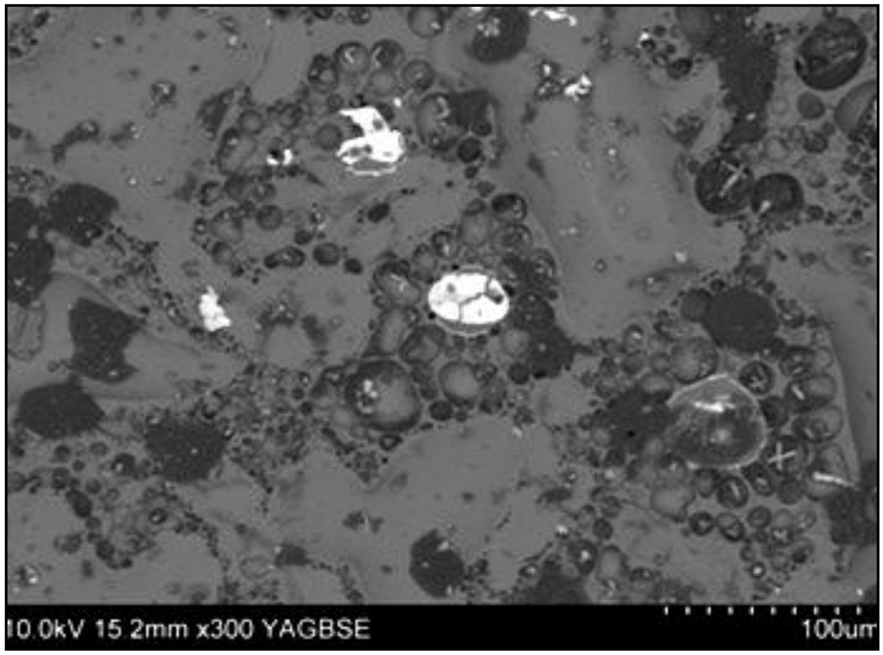


Figure 4.23 EDS gold sample x 300, showing general image of the surface with unidentified holes.

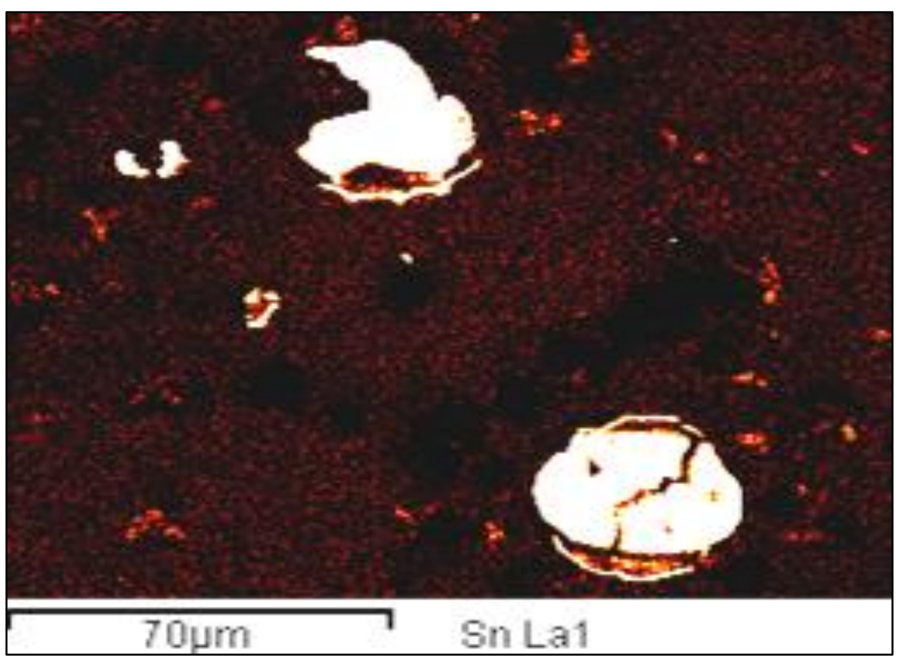


Figure 4.24 EDS gold sample x 2000, showing presence of tin element as white beads.

Further images of the gold sample were produced showing the presence of oxygen, sodium, magnesium, aluminium, silicon, chlorine, potassium, calcium and sulphur (*See Appendix E, pp.282-284*). Most of the elements found on the K surface were attributed to the composition of float glass, as confirmed by research conducted into the 'Surface Analysis of Stressed and Control tin Oxide Thin Films on Soda Lime Glass' (Pankow, 2003). The exception was chlorine which, in the form of stannic chloride, is a constituent of the chemicals used in the CVD process to produce the low emissivity layer (Hurst and Sheel, 1999). The chlorine could have been a residue from this or from the washing process during manufacture (Monkman, 2010). As previously stated, the composition of the upper layer of the K coating was known to be fluorine-doped[19] tin oxide however no fluorine was detected in any of the images. Through Materials Science consultation, it was deemed possible that the doped fluorine could have migrated into the glass during fusing as it is a small ion[20] therefore mobile. This would explain why there was no evidence of it on the K surface (Crozier, 2011).

4.4.2 EDS Sample: Pink Coloured Coating

The sample exhibiting pink coating (*Figure 4.25*) was included for EDS analysis to examine the transitional colouration between gold and purple. The obvious difference between the surface images is the lack of bead-like formations seen in the gold sample but the presence of ripples in this pink sample as can be seen in Figure 4.26. When elementally analysed, the surface showed the overall presence of tin, identified with yellow/white grainy colouration, as a continuous layer (*Figure 4.27*). The other elements found in the pink sample were similar

[19] Here 'doped' is referring to addition of 'impurities' to increase the properties of the conductivity surface of the tin oxide.
[20] An ion is an atom, or a group of atoms, which has either a positive charge due to losing one or more electron or a negative charge due to gaining one or more electrons (Duncan, 1995, p.209).

to those in the gold sample and are shown in the SEM photographs in Appendix E.

Figure 4.25 SEM pink sample, small piece of fuse fired K (opened) showing coating with pink colouration.

.

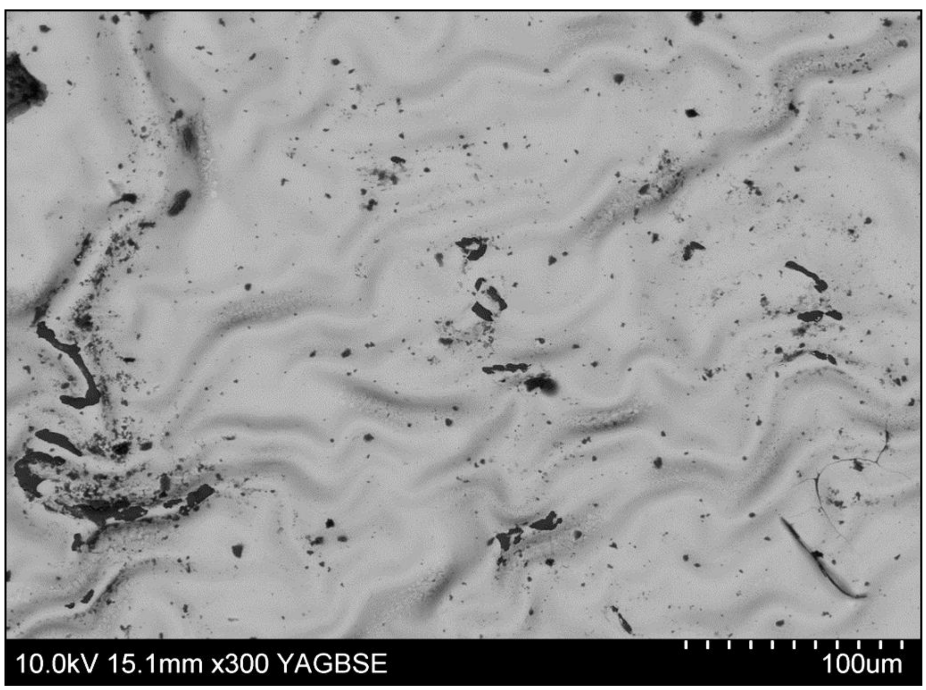


Figure 4.26 SEM pink sample x 300, showing presence of ripples.

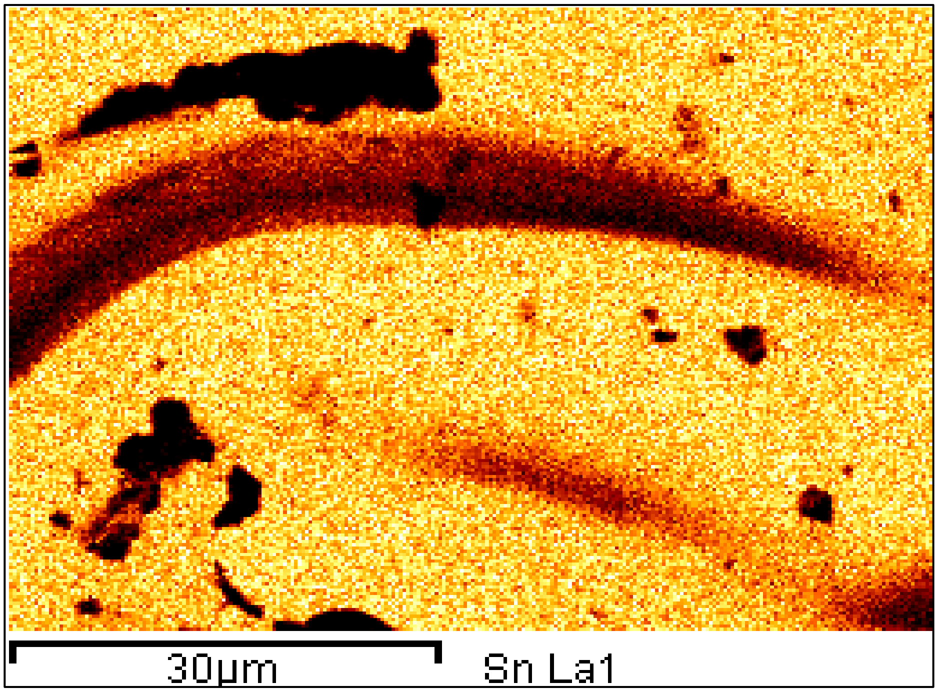


Figure 4.27 EDS pink sample x 2000,
yellow/white grainy colouration representing tin element showing continuous layer.

4.4.3 EDS Sample: Purple Coloured Coating

The sample for analysis of the purple colouration was taken from a piece of open fired 4mm K (*Figure 4.28)*.

Figure 4.28 SEM purple sample showing coating with purple colouration.

The SEM micrograph of this sample in Figure 4.29 shows the surface ripples of the purple colouration to be overall more linear, compact and more defined than those seen on the pink sample above.

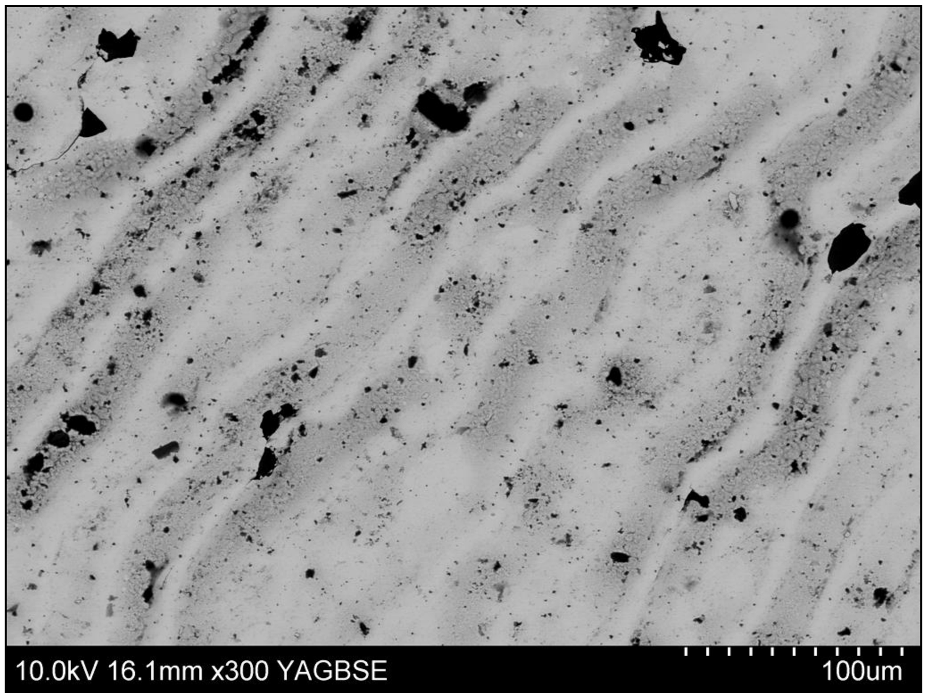


Figure 4.29 SEM purple sample x 300, showing ripples being more defined than those in pink sample.

When analysed using EDS, a similar result to the pink sample was observed. The majority of the surface was found to be tin, as shown by the grainy yellow/white colour in Figure 4.30. The large dark patch on the surface was found to be region rich in chlorine. As in the case of the gold and pink samples, the other elements were found to be comparable (*See Appendix E, pp.282-284).*

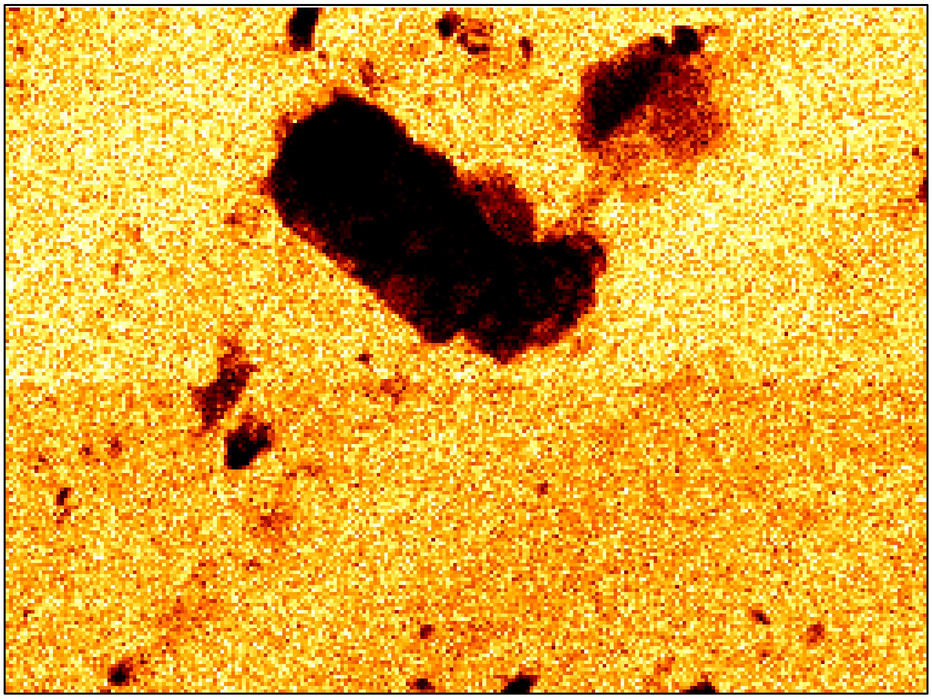


Figure 4.30 EDS purple sample x 2000, yellow/white grainy colouration representing tin element showing continuous layer.

4.5 Contribution of Tin to the Colouration of the Fired Coating

Treating the coating as a whole, i.e. not separate layers, on an elemental level the colour was likely to be due to the presence of, primarily, tin. Tin is chemically known to produce an iridescent lustre in glazes (Bray, 2001, p.165) and is responsible for a pink glaze when combined with chromium oxide (Hamer, 1986, p.57). It is an element which is obtained from cassiterite, a natural ore of tin oxide, the colour of which ranges from yellow to black (Alden, 2009).

It may be that if it is deemed that tin is responsible for the colouration, then it would suggest that it is the structure of the fired coating that is responsible for the production of the range of colours. The evidence at this stage is supported by Algerian solar cell research using high temperature annealing (720-900˚C) of sprayed fluorine-doped tin oxide (SnO_2:F) layers on a silicon wafer (Tala-Ighil et al, 2005). A similarity can be seen between the structure of the SnO_2:F fired surface (*Figures 4.31 and 4.32*) and that seen in SEM micrographs of the purple sample and of the open fired K coating, previously shown in Figure 3.27. This similarity in surface profile would suggest that their results may also be applicable to fluorine-doped tin oxide K Glass. Their evidence of 'the reduction of SnO_2 to metallic Sn' confirmed that elemental tin can be removed from the tin oxide in similar experimental conditions. Hence, if comparable chemical reactions have taken place within K Glass at elevated temperatures, it supports the theory that tin is responsible for the colouration.

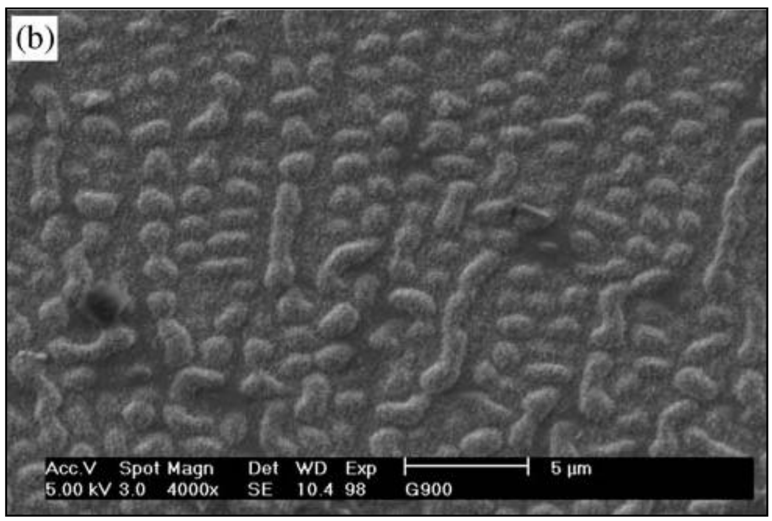


Figure 4.31 Air annealing sprayed fluorine-doped tin oxide at 720°C. (Tala-Ighil et al, 2005).

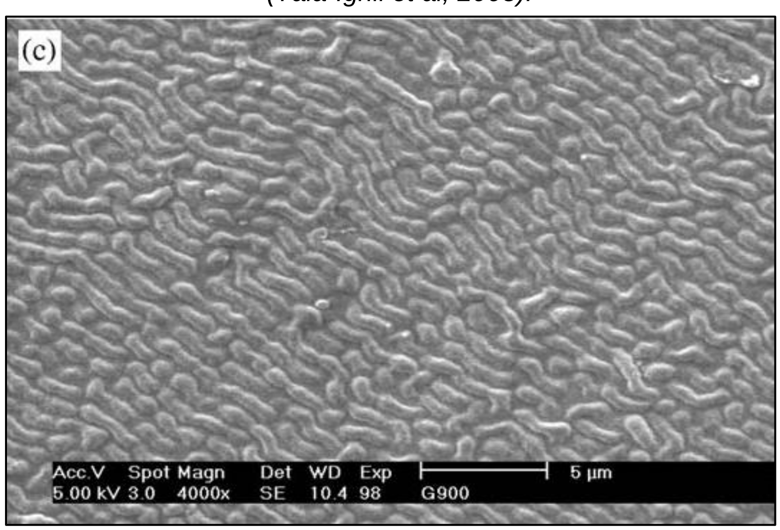


Figure 4.32 Air annealing sprayed fluorine-doped tin oxide at 900°C. (Tala-Ighil et al, 2005).

Further confirmation of the contribution of the tin to the colouration was found in subjecting a 25mm x 15mm sample of indium tin oxide to open firing at 775°C. The sample obtained from Durham University contained no fluorine, did not have an under layer and was fused onto a 0.07mm glass substrate. The delicate nature of the sample made it necessary to place it on a 55mm x 45mm base of 4mm thick float glass for ease of handling. After firing at 775°C, the colouration was a strong iridescent pink (*Figure 4.33*) with the physical structure on the surface of very tiny bubbles and ripples similar to the K samples (*Figure 4.34*).

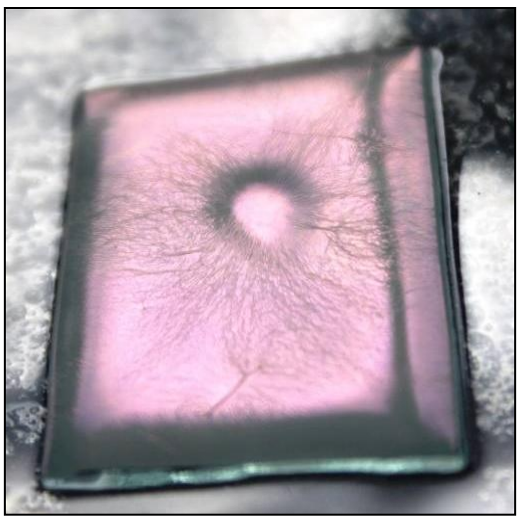


Figure 4.33 Post-fired ITO showing iridescent pink surface.

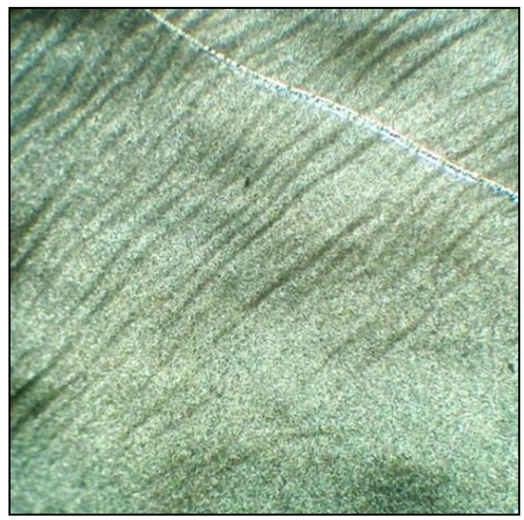


Figure 4.34 ITO fired coating showing ripples on surface.

The common element in both coatings was tin. It can, therefore, be deduced that tin was responsible for the colouration that has been obtained. Similarly, from these results it can also be confirmed that the ripples are responsible for the effect of iridescence on the post-fired K coating. It was found from the bend test results that the K coating is stiffer than the float glass substrate. This means that the coating stays more rigid during firing but the glass, having a higher expansion coefficient, contracts more on cooling (*See 3.6.4, p.112*). This variation in thermal expansion between the K coating and the float glass caused differential expansion and contraction at the interface during fusion and resulted in the formation of a rippled surface once cooled.

4.6 Structure of the Fired Coating: Colouration and Iridescence

The elemental content and the physical surface structure of the purple coating were found to be very similar in both open and fused firings as shown through the EDS examination (*See Appendix E, pp.282-284*). The elemental content of the pink and purple coating showed the overriding and evenly distributed presence of the element tin in a continuous form, whereas with the gold coating, the tin was found to be in bead-like formations. Tin is known to form globules on melting and appear with a shiny white colouration once cooled. Under reducing conditions tin oxide exhibits a brownish tone. Although it has been difficult to prove the exact technical reason for the gold colouration, a tentative explanation may be due to the fact that during the firing, the coating undergoes severe modification in chemical composition and forms a complex compound containing mainly reduced tin in a thin brown opaque layer (Crozier, 2011). According to Keeling and Walker (2002) the melting point of tin oxide in air is about 1630°C and the melting point of tin is 232°C. In a reduction atmosphere where there is a lack of oxygen the tin oxide will form metallic tin on the surface (Tala-Ighil et al, 2005).

The importance of the amount of air, (which due to the process of oxidation we can surmise is oxygen) that is present during fusing has already been discussed. It has been seen how a small increase in the gap depth causes the ‘pure gold’ colouration to become iridescent. This was a very sensitive measurement which did not take much in terms of reduction firing to partial reduction firing, to cause the move from a flat gold, i.e. with lustre but without iridescence, to an iridescent gold when colours, predominately pinks and purples were seen within the gold.

These changes in colouration were seen to the naked eye and their structures were supported by light microscope images such as those in Figures 4.35 and 4.36.

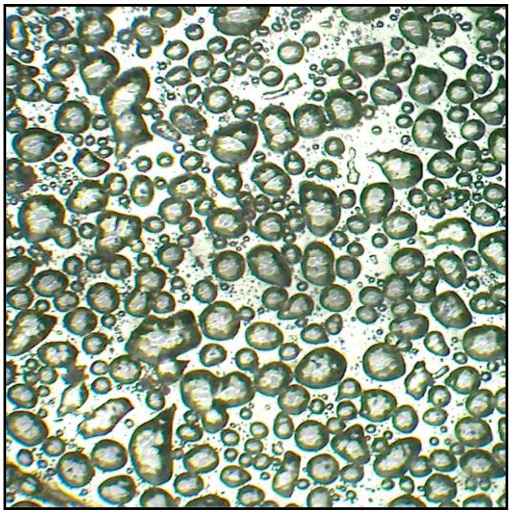


Figure 4.35 Flat gold colouration showing bubbles.

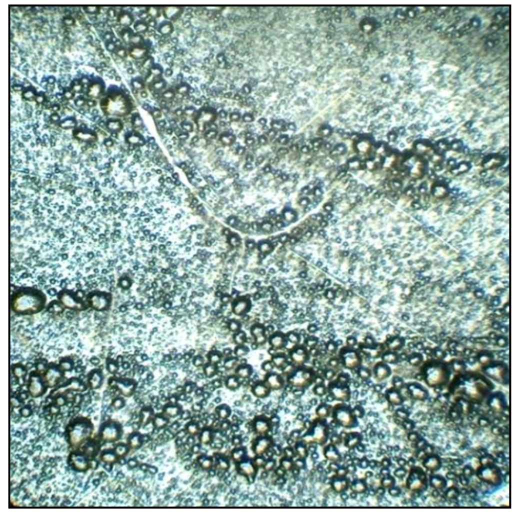


Figure 4.36 Flat gold to iridescent gold colouration showing fewer bubbles.

This transition from flat gold to iridescent gold is very sensitive due to bubble formation. Its control is determined by the firing environment, i.e. as more oxygen is introduced by means of air, the reduction atmosphere is gradually lost and the density of bubbles decreases. As it then becomes an oxidising atmosphere again, the transition to pink and to purple is seen as the fewer bubbles present expose the ripples underneath. However if, as deduced in Section 4.5, the element tin in its overall state was responsible for the colouration, the additional factor of iridescence that was a common characteristic must be considered.

Iridescence seen at this stage is caused by the light falling on the ripples as they gradually become more dominant while the bubbles recede in quantity and size. Primarily in the pink and purple ranges, as seen in the examples in Figures 4.37 and 4.38 respectively, this iridescence now stays throughout the transition to pure purple as the coating is modified.

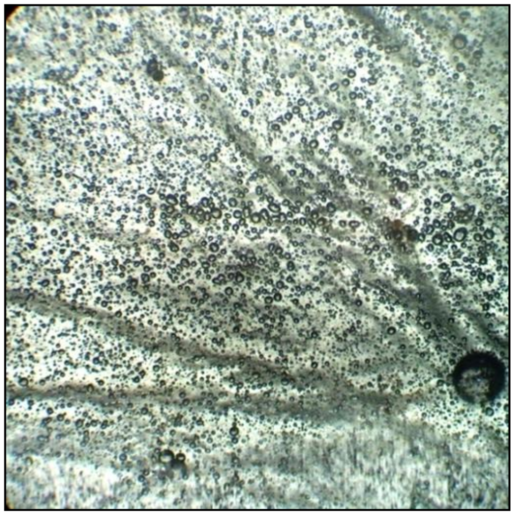


Figure 4.37 Pink colouration showing fewer bubbles and underlying ripples.

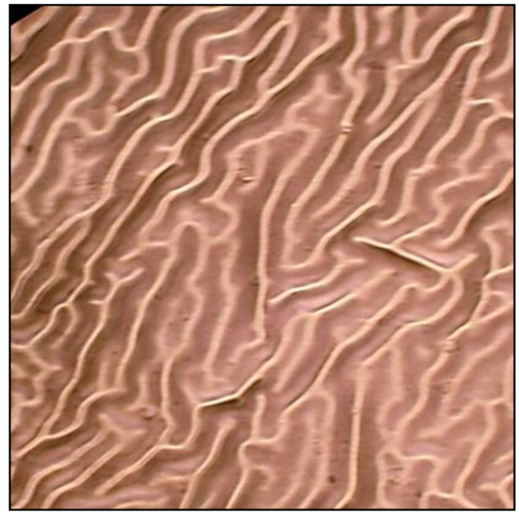


Figure 4.38 Purple colouration showing ripples and no bubbles.

The SEM purple coloured coating image (*Figure 4.29*) shows that the measurement between the centres of the tops of adjacent ripples averages 30 microns. If the ripples act as a diffraction grating[21] effect which splits and diffracts the light, the equation, $d \sin \theta = m \lambda$, can be used to determine the wavelength (symbol λ, lambda) and, therefore, the visible reflected colour range (Resnick and Halliday, 1960, p.1129) .

Calculation: If, d = distance between top of ripples, i.e. peak-to-peak, measuring 30 µm (microns). The mathematical definition of a micron is 10^{-6},

Therefore, $d = 30 \times 10^{-6}$

θ = angle of viewing, taken for this example as 30˚. This is a number which calculates easily.

$\sin\theta$ will therefore = sin30 which is 0.5

[21] 'Diffraction grating is a piece of glass, plastic or metal with a large number of parallel lines marked on it which scatter light and in effect are opaque. The thin clear strips between the lines transmit light and act as slits' (Duncan, 1987, p.45)

m = order number[22] . As we want to know the measurement of 1 wavelength, m = 1

Substitute: d sinθ = m λ will, therefore, read:

$30 \times 10^{-6} \times 0.5 = 1 \times \lambda$

$\lambda = 15 \times 10^{-6}$ m (microns)

The measurement of the wavelength needs to be in nanometres, therefore,

$\lambda = 15 \times 10^{-9}$ m (nanometres)

= 15000nm

Note: 1 micron or micrometre (symbol µ) equals 1000 nanometres (*See footnote p.119*)

The standard human eye is sensitive to wavelengths between 400nm and 700nm with the centre of vision at 555nm (Resnick and Halliday, 1960, p.994). This calculation shows that, as the ripples at 15000nm are much larger and outside the wavelength of light, they are beyond the limits of the eye in detecting colour. It can, therefore, be concluded that the ripples themselves cannot be responsible for the visible colour but will affect the reflectivity and iridescence of the layer.

4.7 Contribution of Ripples to Iridescence and Reflectivity

Microscopic examination of the open fired sample in Figure 4.39 showed areas of different intensities of iridescence with totally different ripple formations. Within areas which appear dull, the pattern of ripples is chaotic or 'maze' like, as in Figure 4.40, causing the light to be reflected unevenly off the irregular peaks and troughs (*Figure* 4.41). This is known as 'scattering'. The shiny areas have a more linear formation as seen in Figure 4.42 whereby the light is reflected evenly (*Figure 4.43*).

[22] Order number – when light is seen through a grating a number of spectra are seen which are said to be of various orders. The number of orders is dependant on the width of the grating.

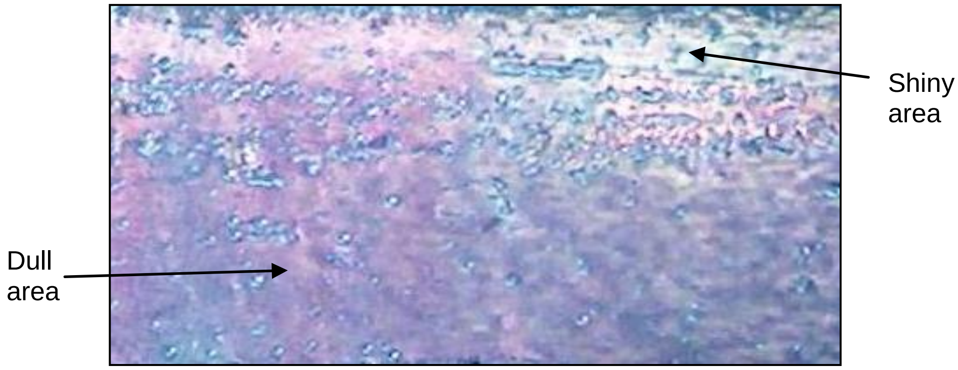


Figure 4.39   Post-fired 6mm K showing dull and shiny areas.

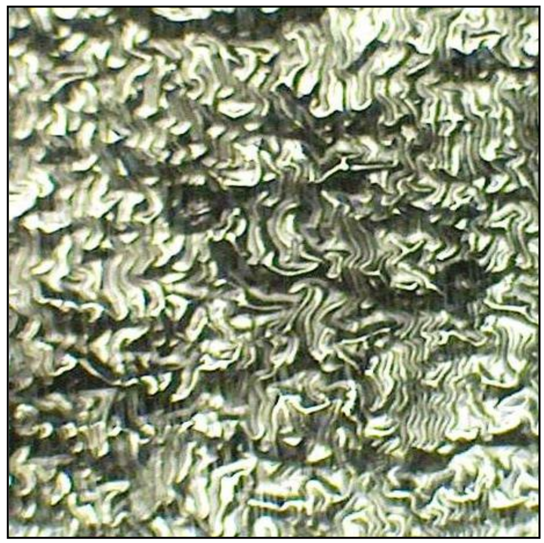


Figure 4.40   Dull area with maze like ripples.

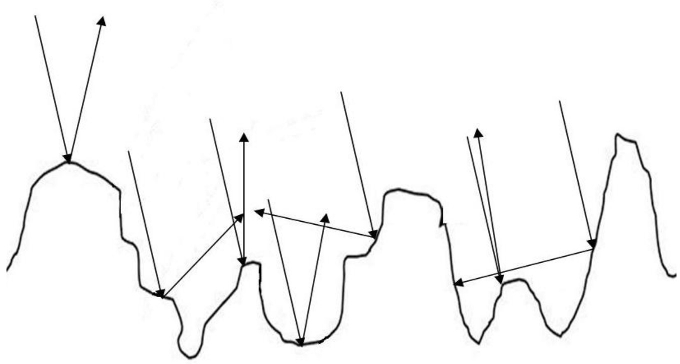


Figure 4.41   Diagram of scattered light resulting in dull areas.

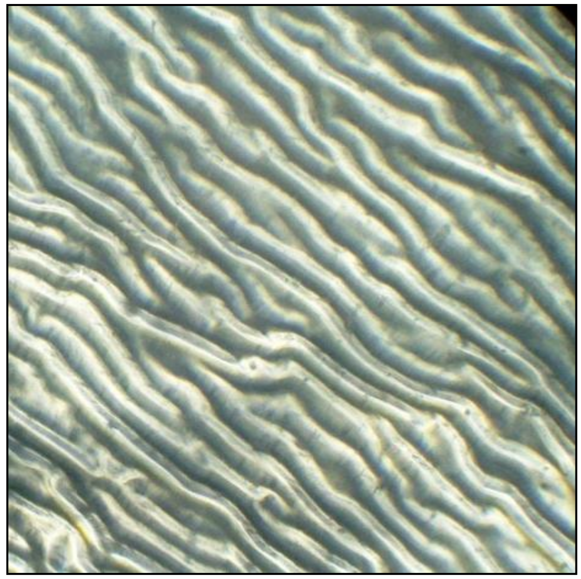


Figure 4.42 Shiny area with elongated ripples.

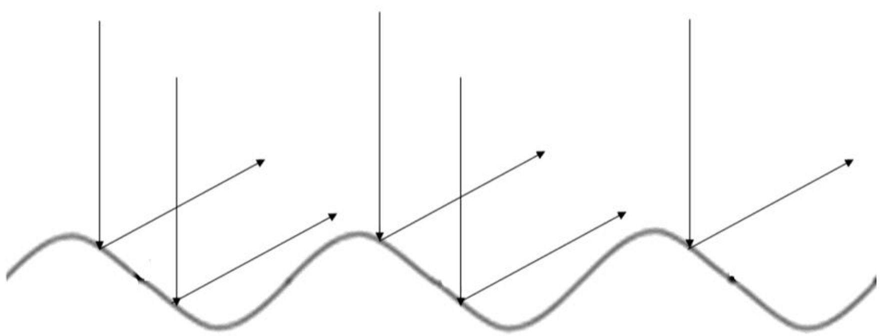


Figure 4.43 Diagram of evenly reflected light resulting in shiny areas.

However, as has been discussed, the coating is a film and as such has two surfaces. The light therefore, will be reflected off two surfaces causing the interference effect of iridescence as described in Chapter 2. The open fired sample in Figure 4.44 shows the upper and lower surfaces of the coating which will reflect the light as diagrammatically illustrated in Figure 4.45.

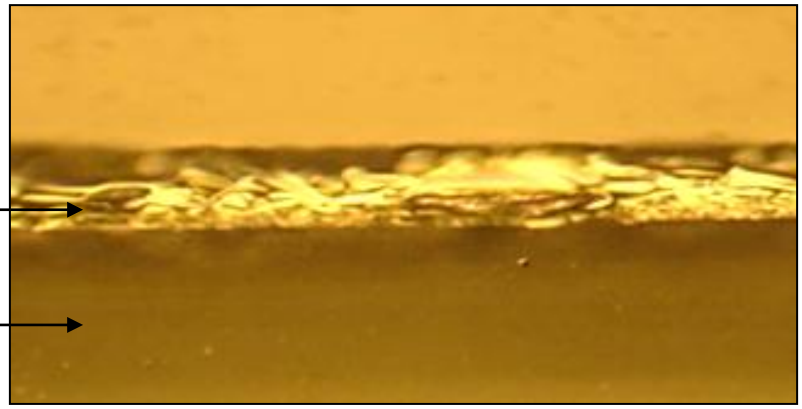


Figure 4.44 *6mm K open fired, edge view showing ripples which will reflect light.*

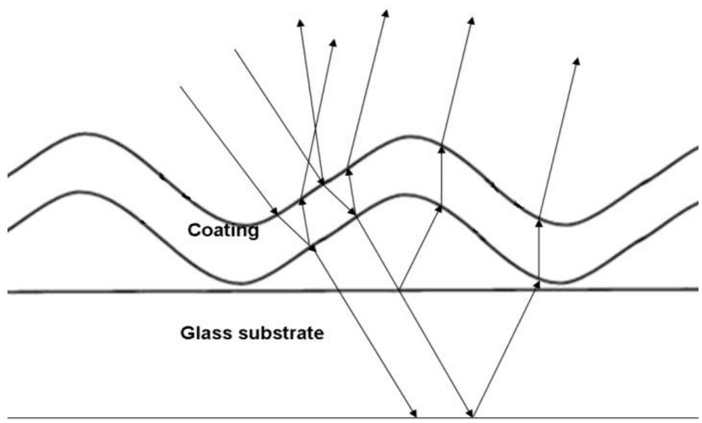


Figure 4.45 *Diagram of light reflected of two surfaces.*

In the fused situation, additional reflectivity is obtained by the light being also reflected from the lower surface of the upper piece of float glass which was the upper surface of the gap (*Figure* 4.46).

Figure 4.46 *6mm K and 6mm float showing fuse fired gap.*

4.8 Pilkington K Glass Coating: the Under Layer

If the tin originating from the upper low emissivity layer of fluorine-doped tin oxide is deemed to be responsible for the overall colouration, the part played by the under layer must also be considered. Up to this point it has not been possible to confirm the exact composition of the under layer but information in patents quote ‘silicon oxynitride’ and ‘silicon and oxygen’ (*See 4.1, p.118*). From a personal ICCG7 conference contact, silicon oxycarbide was also claimed to be the under-layer.

Research published by Brigham Young University, Utah provides a calculator that ‘displays the colour generated by thin films of silicon nitride or silicon dioxide on a silicon substrate’ (Brigham Young University, 2009). Figures 4.47 and 4.48 show the range of colours for which the films of silicon dioxide and silicon nitride are responsible at thicknesses between 1 and 1000 nanometres. As the composition of the under layer has not yet been definitively ascertained, both were included for calculation. The thickness of the under layer is 60-80nm which shows very dark blue for silicon dioxide and blue for silicon nitride. The combined layer thickness is about 500nm which showed a region of the pink/indigo spectrum for both silicon dioxide and silicon nitride and the colouration of the fired coating.

In addition, the calculator was used to define the colours in the range of the thickness of the under layer as defined in the patents (*Figures 4.49 and 4.50*). From the range of gold, pink and purple colours calculated in Figure 4.50, it would suggest that if the under layer contributes to the colour, silicon nitride is a stronger possibility but this cannot be confirmed on this evidence alone. In these examples the angle of viewing, theta, has been taken as 45°. The effects of different viewing angles are discussed further in Chapter 6.

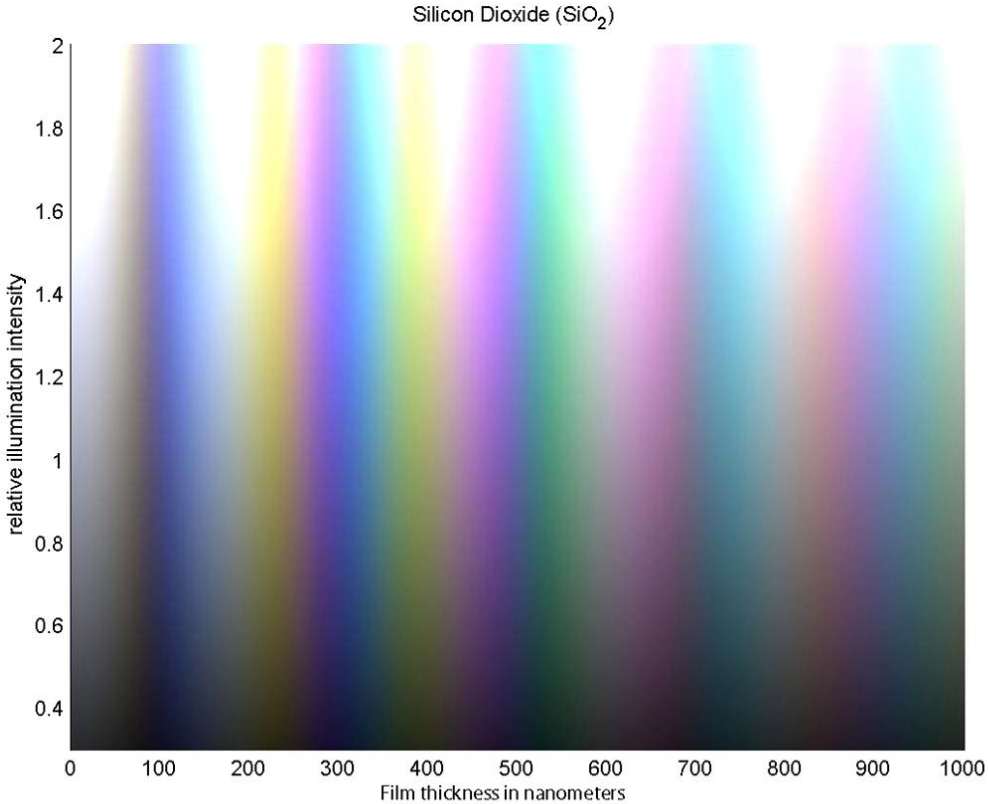


Figure 4.47 *Spectrum of silicon dioxide ($Si0_2$) at thicknesses from 1 to 1000nm.*

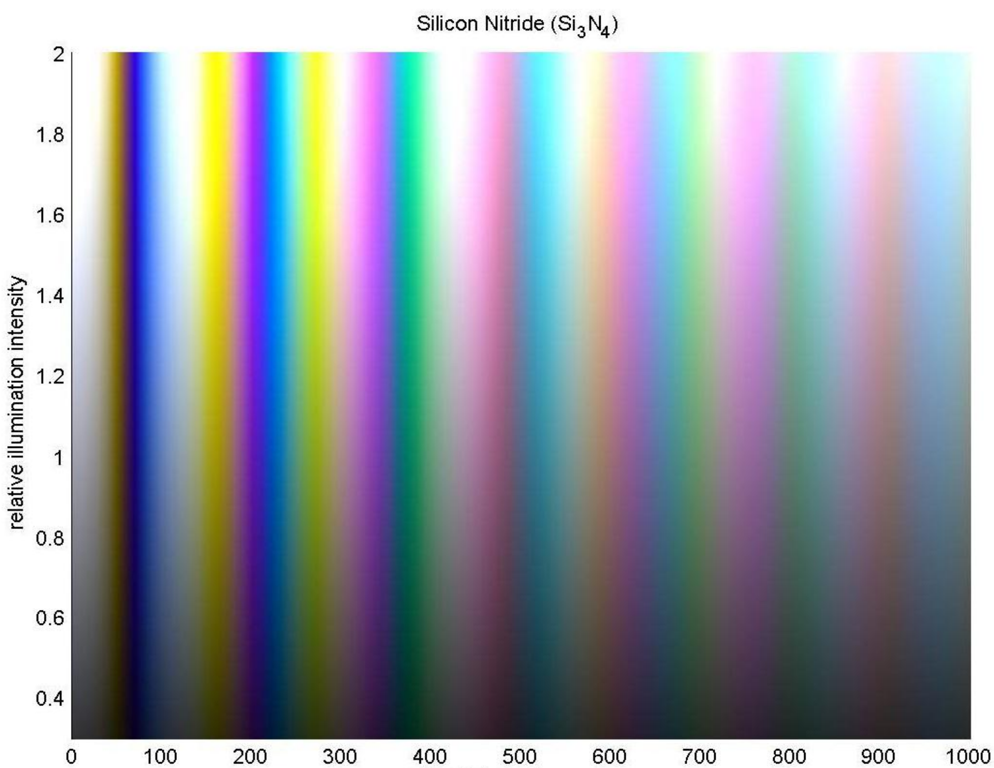


Figure 4.48 *Spectrum of silicon nitride (Si_3N_4) at thicknesses from 1 to 1000nm*

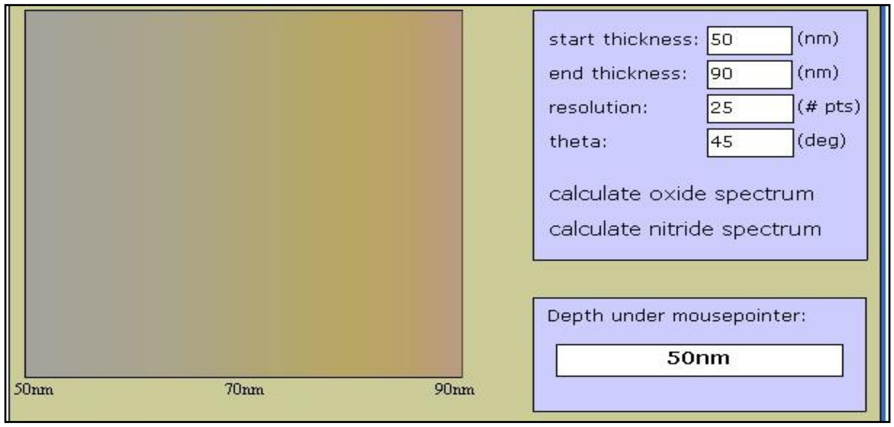


Figure 4.49 Silicon dioxide ($Si0_2$) calculator.

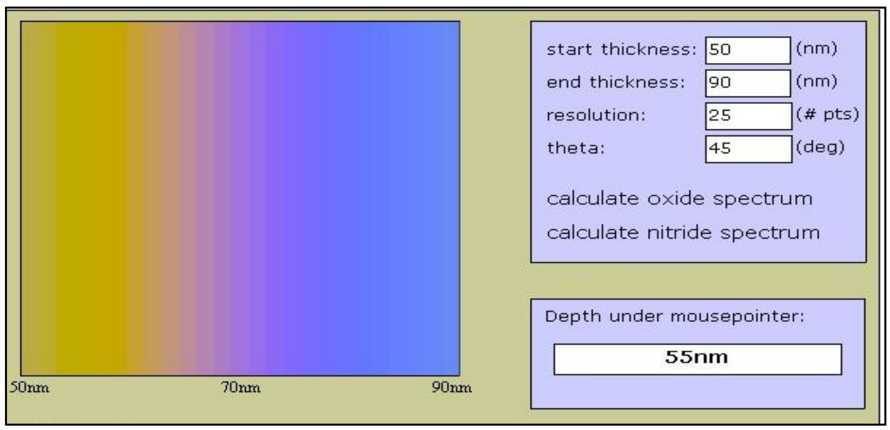


Figure 4.50 Silicon nitride (Si_3N_4) calculator.

4.8.1 Chemical Separation of K Coating Layers

As previously stated, the K coating was treated as one composite layer for the purpose of the creative effects that were able to be achieved. To try to explain more fully the part each of the two layers played in these effects, attempts were made to chemically separate the layers by removal of the upper tin oxide layer. Two patents 'Photoetching of Metal–Oxide Layers', (Bullinger, 1971) and 'Non-iridescent glass structures and processes for their production' (Gordon, 1980), describe the same process for the removal of the tin oxide from a glass substrate using zinc powder and diluted hydrochloric acid.

Following the method, the reaction was immediate and the coating which became liquid and brownish in colour was able to be removed by water and wiping with a paper cloth. The result of the reaction was clearly seen with the disappearance of the darker K surface and the appearance of the underlying clear float glass. Furthermore, the treated surface reacted negative with the fuse tester which implied that the tin oxide coating was no longer present. Gordon (1980) stated that 'this etchant does not affect the silicon nitride under layer'. Keeling and Walker (2010), manufacturers of tin oxide, also confirmed that this process would not affect the silicon dioxide layer. Several pieces of K were treated this way with a variety of quantities and strengths of both zinc powder and hydrochloric acid and were then fired to the target temperature of 775°C (*Figure* 4.51).

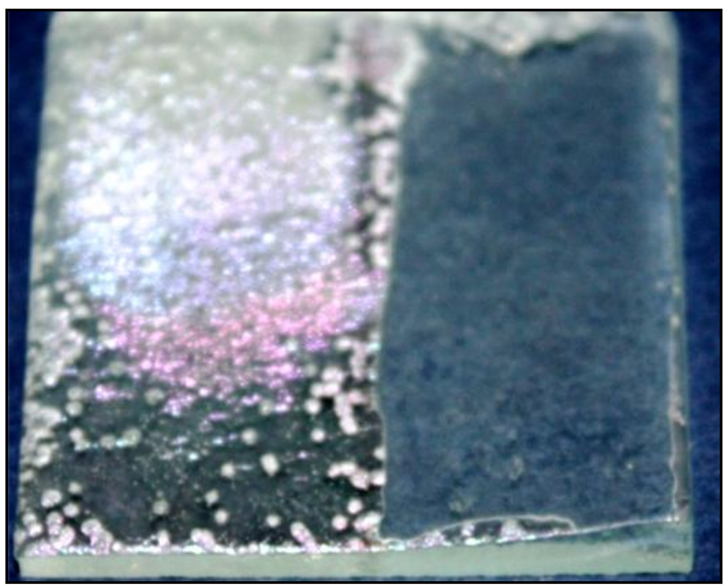


Figure 4.51 6mm K, post-fired at 775 °C, with half of coating removed.

Microscopic examination of the untreated and treated surfaces showed that the ripples had been removed in the tin removal process (*Figures 4.52 to 4.54)*.

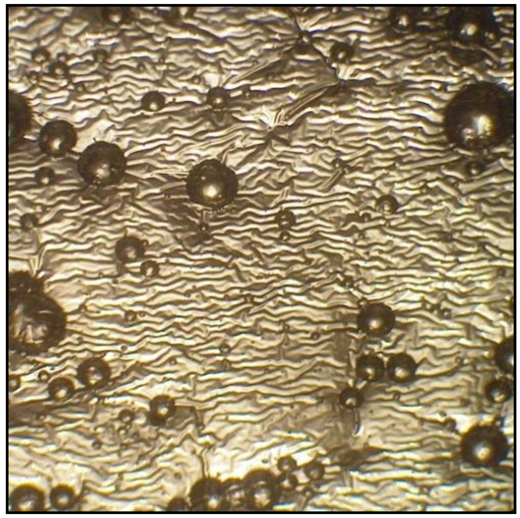


Figure 4.52 6mm K untreated surface showing ripple and bubble structure.

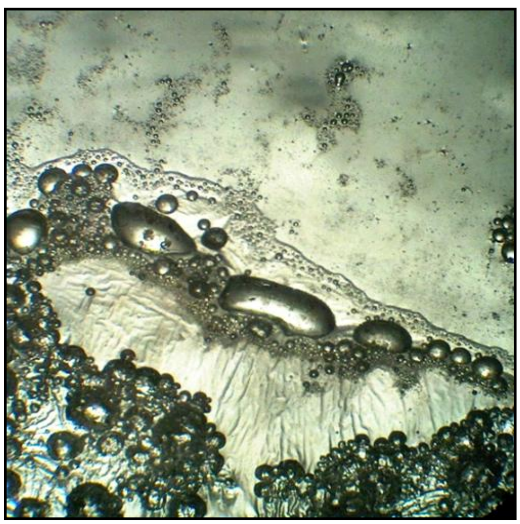


Figure 4.53 6mm K, post-fired, treated/untreated interface, showing removal of coating on treated surface.

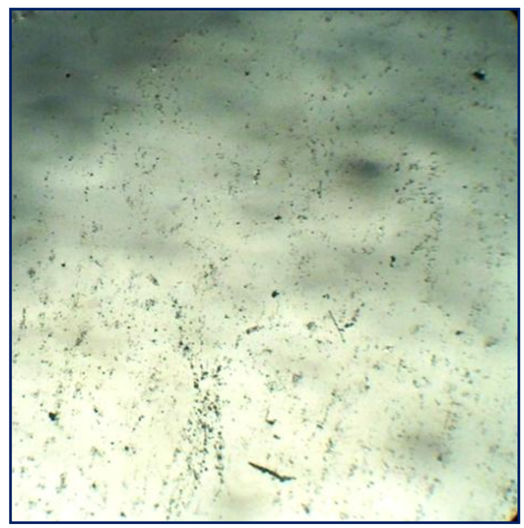


Figure 4.54 6mm K, post-fired, treated surface, showing complete removal of coating.

Based on this evidence in this chapter it may, therefore, be concluded that it is extremely likely that the tin oxide layer is responsible for the ripples and, therefore, the iridescence as well as the colour.

Chapter 5

The Mirror Gap Technique

This chapter addresses Objective 4 'To apply the information to the application of new techniques and methods of working for the artist in the field of creative glass' and describes the development of the Mirror Gap Technique that is one of the main outcomes of this research. The parameters for repeatability for the artist in a studio environment are discussed including the suitability of the method for a multi-production situation. The chapter concludes with the application of the developed methods to other low emissivity coated glass.

5.1 Exploratory Fusing Tests

Chapter 3 described the standardised programme of testing and the effects that were achieved when K Glass was heated to temperatures above 700°C. Synthesis of the knowledge gained, extended the fusing tests to explore the management of the factors responsible for the changes to the coating. The results and their evaluation described in Chapters 3 and 4 respectively, established the relevance of the tiny gap in the development of the colouration. This was confirmed by tests that involved sandblasting channels on the under side of the float glass and which offered an early indication that a separation of colours could be possible. Using that information as a starting point, a range of tests was undertaken to explore the creative possibilities through the manipulation of the K coating by sandblasting and by artificially creating a gap between the surfaces of the K and the float glass. Imagery used for the tests was varied but, for comparative purposes, was proportionate to and based on the 100mm squares used in the standardised testing programme. Having identified the optimum temperature for colour development, the fusing was carried out at 775°C. These tests laid the foundation for the creation and development of the Mirror Gap Technique and addressed Objective 4, *'To apply the information to the* *application of new techniques and methods of working for the artist in the field of creative glass'.*

5.2 Mirror Gap Technique

Figure 5.1 shows the pre-fired arrangement of a K and a float glass square prepared for the Mirror Gap Technique. The coating of the lower K was removed by masking the entire surface and cutting away the unwanted part of the design. The unmasked area was then sandblasted to remove the coating. The lower side of the float glass was masked and a mirror image of the coating that remained on the K surface was cut out. This area was then sandblasted deep enough to create an area of low relief. The two pieces were then placed together as shown.

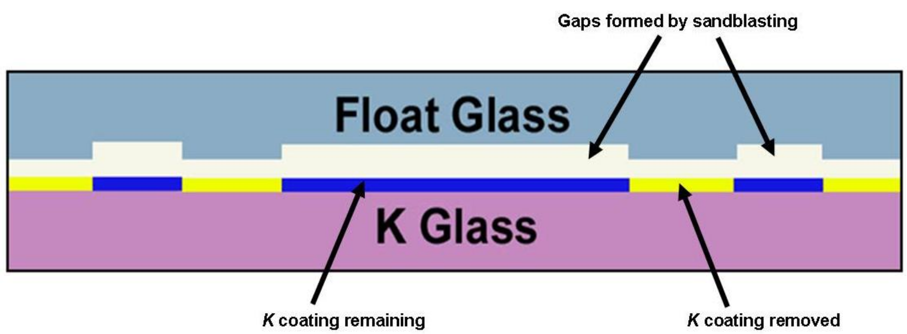


Figure 5.1 Mirror Gap Technique pre-fired positions.

Once fired, the layers fused together but tiny gaps remained above the coating. Iridescent colouration was seen to be formed on the areas of remaining coating under the gap (*Figure 5.2*). The method developed to produce the coloration from the coating of K Glass was named the Mirror Gap Technique for clarity.

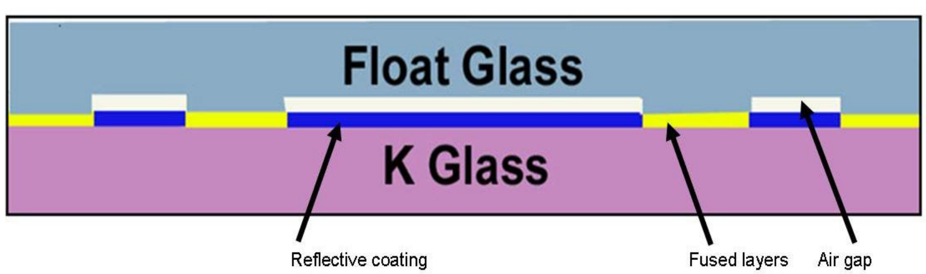


Figure 5.2 Mirror Gap Technique post-fired position.

5.2.1 Colour Variations

During the standardised fused tests, a variation of colours had been seen within the gold/pink/purple range. With the Mirror Gap Technique defined, the contribution of the gap with relation to colouration was examined. Tests which used either 4mm or 6mm K in the format shown above, produced strong colouration, for example, gold as in Figure 5.3, in the designated and manipulated areas within the fused glass. This characteristic was common in all of this series of tests and confirmed the general repeatability of colour development. Using 4mm and 6mm K Glass and float glass with thicknesses from 3-10mm, a range of tests produced results which indicated the possible separation of colours within this fused presentation.

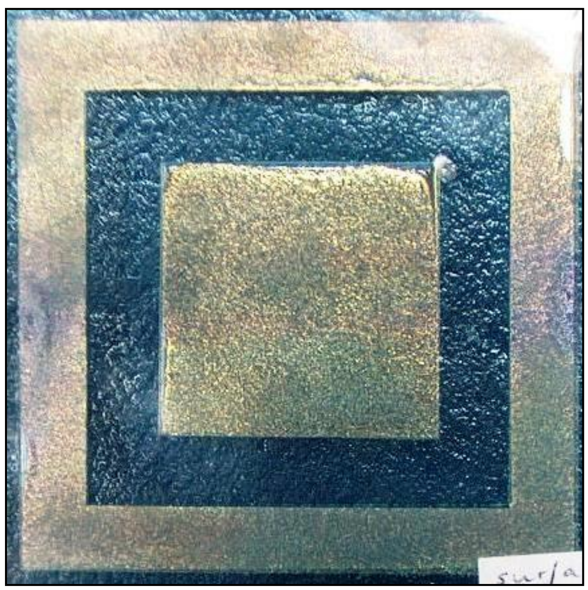


Figure 5.3 4mm K and 4mm float, post-fired at 775˚C, in Mirror Gap Technique format.

A variation in intensity of the gold was seen in some of the tests, for example, the double square in Figure 5.4, created by using two layers of K under the float glass. The inner square showed a ‘mottled’ effect over the gold with opaque areas of massed microscopic bubbles which showed no uniformity of position, size or shape and did not contribute to the gold colouration.

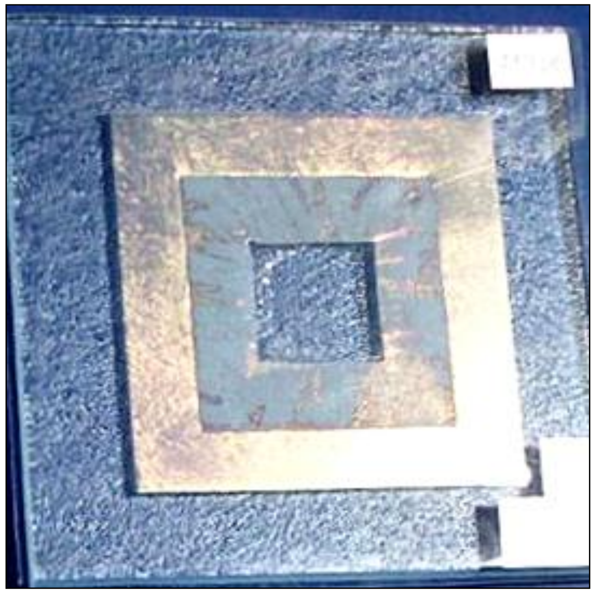


Figure 5.4 Fused format showing variable effects of gold colouration.

Analysis of these differences between the two squares revealed less sandblasting over the inner square. The control of the gold colouration and its variable effect within the fused layers was, therefore, deemed to be governed by the amount of sandblasting applied to the underside of the upper float glass. When the test was repeated and more sandblasting applied to the underside of the upper float to increase the depth of the gap, the colouration in the comparable square became pink (*Figure 5.5*).

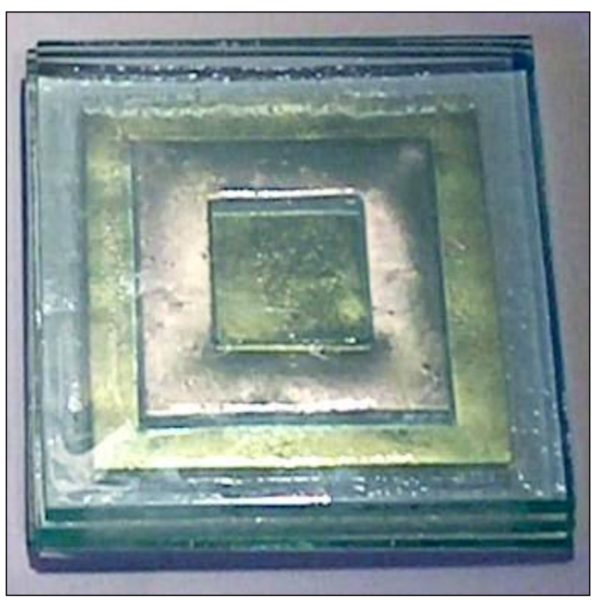


Figure 5.5 Separation of colours in fused double layer test.

5.2.2 Determination of Range of Colour

As the relationship of depth of gap to colour became apparent, comparison tests were carried out where gaps of different depths of surface sandblasting were created. It was not possible with the equipment available in studio conditions to accurately measure these gaps, however, measurements were taken with a Vernier scale. The following approximate depth of gaps appeared to be responsible for the specific tones seen on the post-fired coating:

- Shallow gap - 0.25mm - gold
- Medium gap - 0.50mm - pink
- Deep gap - 0.75mm - purple

Figures 5.6 to 5.8 show the clear separation of colour that was able to be obtained using these gaps.

Figure 5.6. Gold colouration - 0.25mm.

Figure 5.7 Pink colouration -.0.50mm.

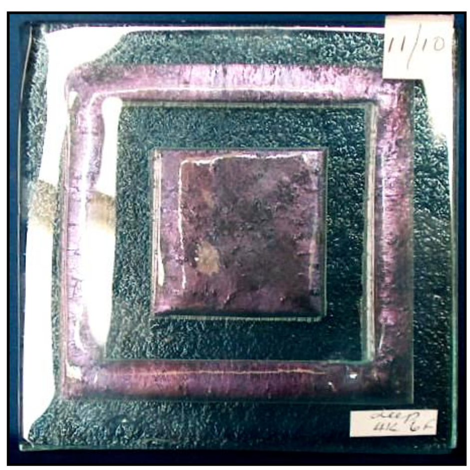


Figure 5.8 Purple colouration - 0.75mm.

5.3 Depth of Gap Study

The ability to isolate colours was a breakthrough and initiated a new level of investigation into the range that might be obtained. The range of colour possibilities was explored using a commercial sandblaster with computerised controls to produce an accurate and uniform depth of gap. This was undertaken at Creative Glass of Stockton on Tees, using their 'Alfema' machine set at speed 20 with a pressure of 100psi (or 7 bar). The grit used was Brown Fused Alumina, Grade 120.

Four float glass panels each measuring 290mm x 210mm were prepared to produce a large range of different gaps that were accurate and uniform in nature. Three were to explore possible differences between 4mm and 6mm K coating and at firing temperatures of 775°C and 825°C. The fourth was to measure each gap that had been produced. The float glass panels were masked with 0.8mm Venture Tape clear resist with 35 squares of 24mm, arranged in 5 rows of 7, cut but not removed. The masked glass panels with the covered squares were taped to a large board and passed through the sandblaster.

The test panels were placed well within the extremities of the gun range to ensure even blasting to each square. The first square of masking was removed and the sandblaster allowed one pass and return. With each pass and return, a further square was removed until all squares had been treated. This procedure created 35 gaps graduating from 1 to 35 passes/returns (*Figure 5.9*). Following the pre-firing assemblies of the Mirror Gap Technique, the K panels were correspondingly masked and the unwanted coating sandblasted away, leaving 35 squares of K coating. One each of the 4mm and 6mm K assembled sets were fired with the standard firing schedule to 775°C; the second 4mm set was fired to 825°C.

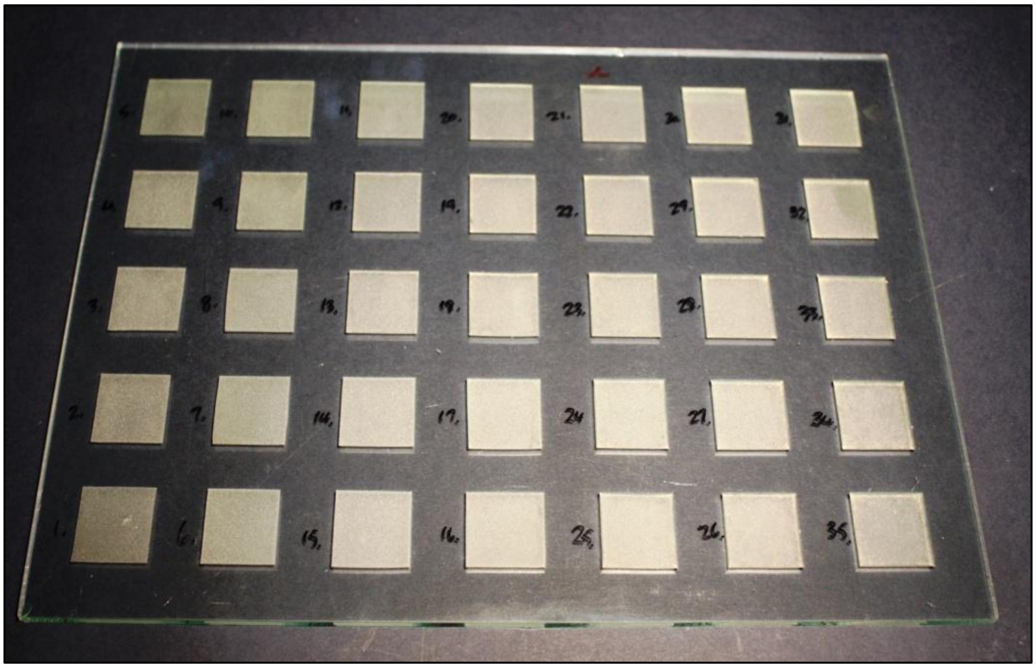


Figure 5.9 *Gap depth study, panel of sandblasted squares.*

All three tests showed a similarity of results with a graded colouration from square 1 to square 35. Square 1, which had received one full pass and return of the sandblaster, showed gold colouration with a textured surface caused by the sandblasted under surface of the float. The gold colour was dominant but with some interferential pink tones until square 15. From squares 16 to 25, the pink tones strengthened through shades of peach to a definitive pink. From squares 26 to 35, blue tones influenced the pink to show mauve and finally, purple hues.

Figure 5.10 overleaf shows the post-fired 4mm K panel fired at 825°C with graded colouration from gold to purple. The clouded patch in the gold squares area (bottom right) is an area of microscopic bubbles which formed between the panels. The very occasional occurrence of this feature may be the result of incomplete removal of the K coating or it may possibly be an impurity in the coating which has caused a physical or chemical reaction at high temperatures (*See 7.3.4, p.242*). Figure 5.11 shows detail of 6mm K panel fired at 775°C.

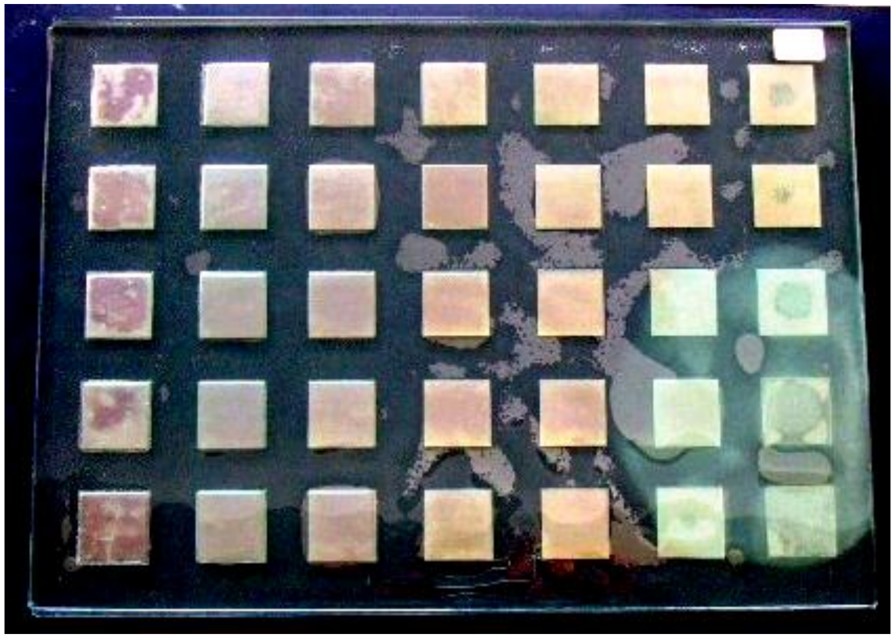


Figure 5.10 4mm K and 4mm float, post-fired at 825°C, gap depth study panel.

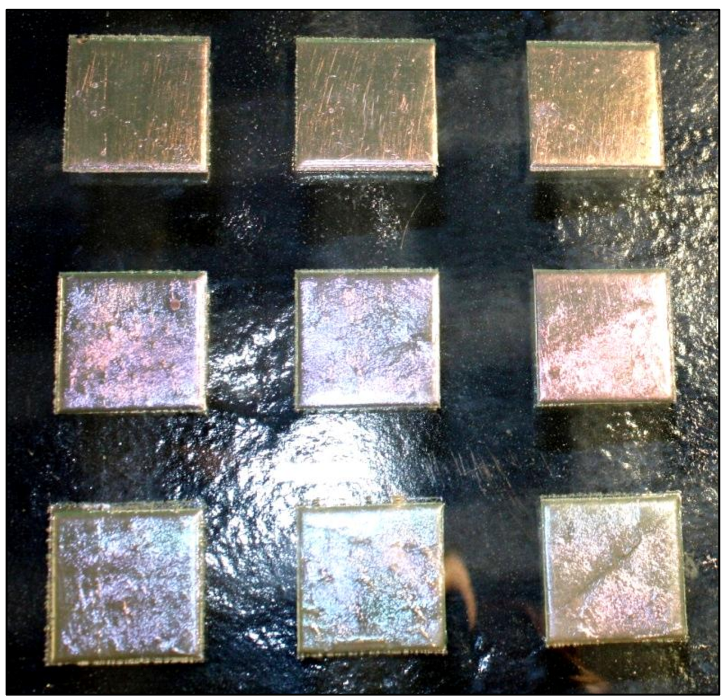


Figure 5.11 6mm K and 4mm float, post-fired at 775°C, gap depth study panel (detail).

Examination of the surface of each square using the small laboratory microscope showed the changes in colouration and provided an early indication of the physical factors of the visual changes to the surface coating. Photographs of four of the squares and their respective micrographs show the resultant colours and changed surface structure of the K coating (*Figure 5.12*). The full range of photographs and micrographs of the 4mm K panel, post-fired at 825°C can be found in Appendix F, p.291.

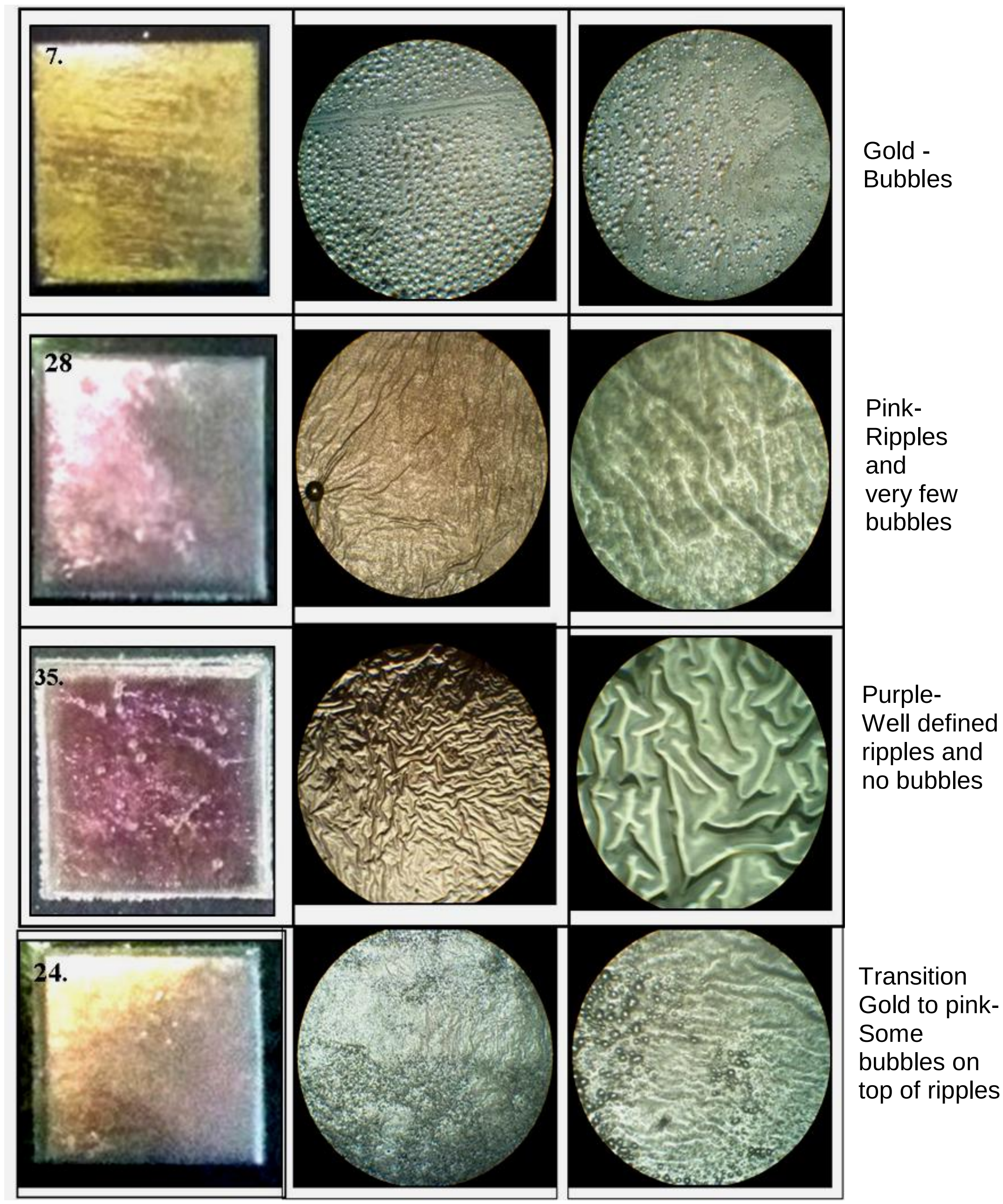


Figure 5.12 Gap depth study selected photographs and micrographs.

The fourth float glass panel with identically formed squares was not fired. The depth of each individual square was measured using a Mercer dial gauge, Type 183 (*Figure 5.13*). Readings were taken from each corner and the centre of the gap. These measurements can only be an approximation due to the nature of the equipment for the following reasons. Readings were only accurate on the calibration lines of 0.00025” and, within that, had to be estimated by eye. The dial gauge was susceptible to movement during use. The post holding the gauge needed to be at an accurate 90˚ but easily moved with the drag on the sandblasted surface. To compensate for possible variations and the uneven sandblasted surface three readings of each square were taken and an average calculated. A table and graph were compiled showing the detailed increase in gap from squares 1 to 35 (*See Appendix F, pp.289-290*).

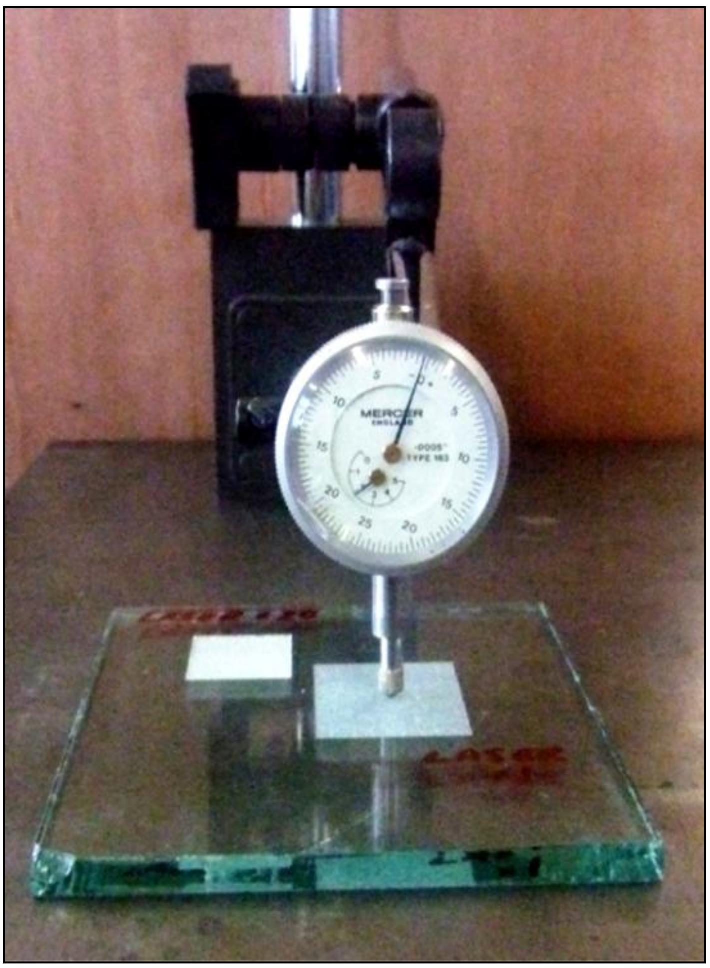


Figure 5.13 *Mercer dial gauge.*

5.4 Repeatability for Artwork

The potential to create artwork necessitates the ability to repeat the processes within the artist's studio. Tests for the Mirror Gap Technique identified areas where variables both direct and indirect may have an impact on results. The following sections will consider areas where the effects of these variables have been quantified.

5.4.1 Dimensional Limitations

During the Mirror Gap Technique fusing tests, the upper float glass presented inconsistent results when the geometry of the internal image was varied. Some tests produced a fired coating which had a visually smooth surface (*Figure 5.14*). In others, the upper float had sagged in the centre causing the under surface of the float to touch the coating and disfigured the otherwise smooth surface (*Figure 5.15*). This also had the effect of reducing the depth of gap. With the problem being common to both 4mm and 6mm K, there were three factors that were deemed to be possibly responsible, namely, the size of image, depth of gap and thickness of the upper float glass.

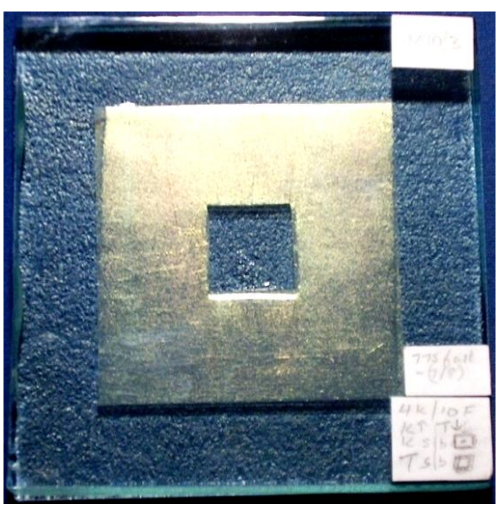


Figure 5.14. Mirror Gap Technique showing smooth coating.

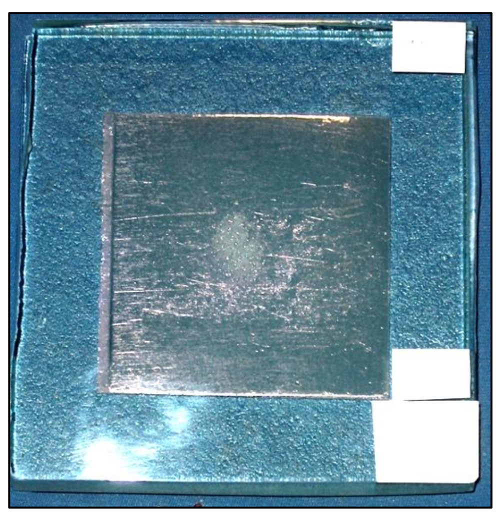


Figure 5.15 Mirror Gap Technique showing sagged centre area.

Firstly, the size of the image to be created was considered. Using the standardised procedure of 100mm squares, the image was limited to dimensions of 80-90mm. Some were a ‘solid’ square with only the outer clear area of fusing to support the gap. Some were a ‘concentric’ format of multiple squares which provided more support to the fused areas within the design.

Secondly, the depth of the mirror gap was varied. By increasing the amount of sandblasting to create a deeper gap the float glass above the gap became thinner and easier to soften. Consequently, the degree of sag was increased during firing and the upper glass could ultimately touch the surface of the coating.

Thirdly, the thickness of the upper float glass was varied. In general, thicker glass takes longer to soften and does not sag to the same degree at a given temperature. This allowed an image of a larger area. The thickness of the glass was also significant in creating the gap. When thicker float is sandblasted there is more remaining glass to support the gap over the coating and, consequently, a larger image can be created.

The results of each component of the dimensional investigation provided information that was interlinked. The size of the potential area of reflective colouration that could be created through the Mirror Gap Technique was found to be relative to the degree of sagging that occurred during the firing process and was a direct consequence of the glass thickness above the image. This factor will, therefore, inform the dimensional proportions and design possibilities of artwork.

5.4.2 Multiple Production Potential

In the previous section, the relationship between the gap depths and the colour created through the method of the Mirror Gap Technique was defined. When the Mirror Gap Technique was applied to multiple production of a piece of artwork, some inconsistent results were obtained.

In April 2008, the author was invited to create 65 speakers gifts and present a paper to support the commission at the International Conference on Coatings on Glass and Plastics 7 (ICCG7) at Eindhoven in the Netherlands. Using the Mirror Gap Technique, combined with an APM Photographic Stencil system, vinyl stencils and screen printed enamel, a multi-layer paperweight was designed *(Figure 5.16).* This enabled the testing of the practical repeatability of the process and its possible commercial suitability.

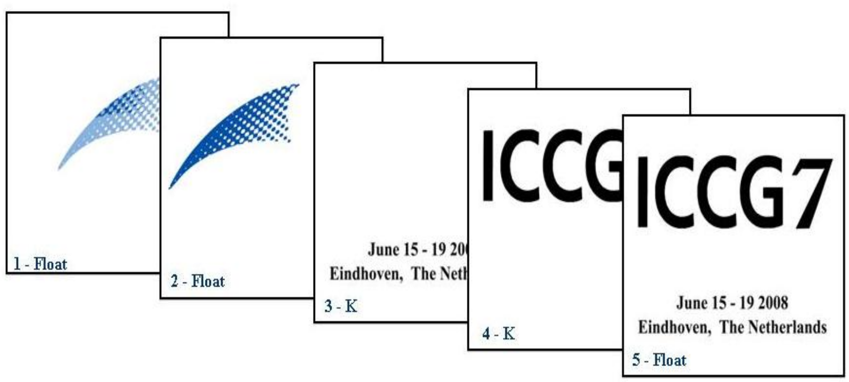


Figure 5.16 Design templates for ICCG7 2008 Conference gift.

The multiple production trial was undertaken at Creative Glass of Stockton on Tees, to test its potential in conjunction with a small glass processing company. Figure 5.17 shows the ICCG7 float glass gap being sandblasted by Creative Glass; other surfaces were sandblasted, by the author in the studio. All layers were then compiled, fired and hand finished (*Figures 5.18 and 5.19*).

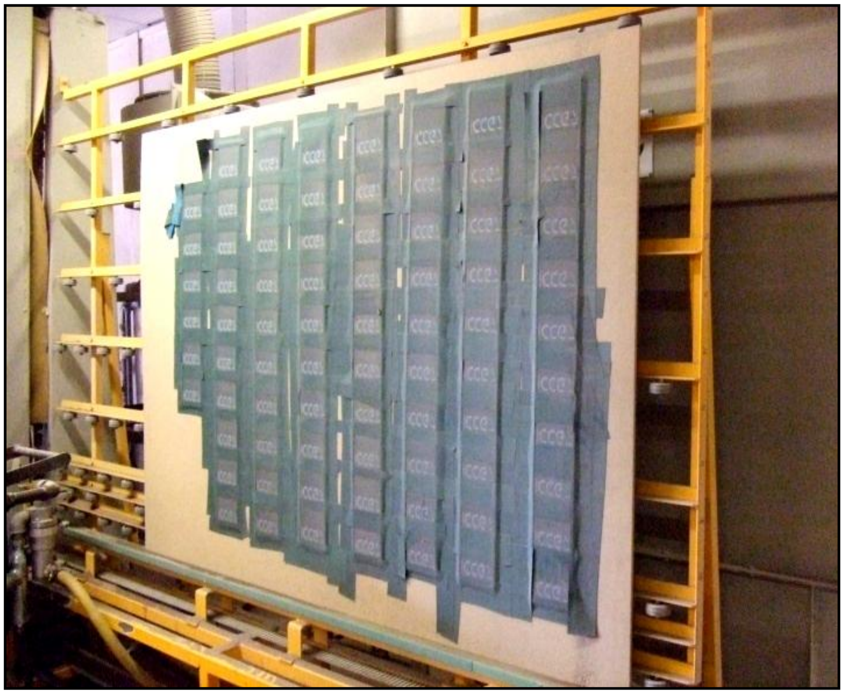


Figure 5.17 Pieces ready to sandblast at Creative Glass.

Figure 5.18 ICCG7 Finished Gift.

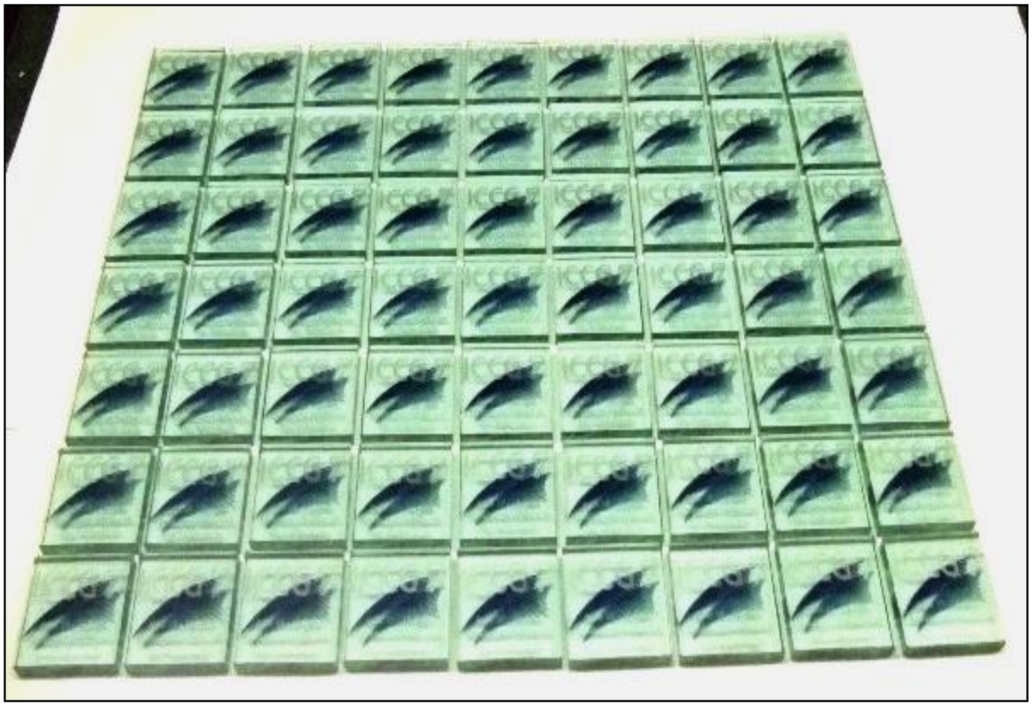


Figure 5.19 *Commission of finished gifts for ICCG7 Conference.*

Settings for the sandblasting equipment had been taken from the gap depth tests to produce gold colouration as in Square 8, at a depth of 0.2mm (*See Appendix F, p.289*). Being electronically controlled, it was expected that there would have been a consistent text colour after the firing, however, this proved not to be the case. Ultimately, approximately 100 pieces were produced during the commission due to small flaws and visible imperfections and across the entire range was a variation of colour showing tones from gold to mauve. Fortunately, this did not detract from the aesthetic presentation and the commission was very well received.

To try to ascertain why the colour had not been uniform, the ICCG7 text on surplus unfired squares was measured to check the depth against those recorded for the dial gauge readings on Table F.1, p.289. The sandblasting machine at Creative Glass had been set for the number of passes that would produce the gold colour achieved for Square 8.

Several readings taken within each letter found a wide range of depths, the average being equivalent of Square 6, gold. The actual colour of the text of the finished pieces ranged from Square 6 gold to Square 30, purple. To understand these anomalies, tests were undertaken to explore the gap in relation to its volume of air and shape of image.

5.4.3 Gap Volume

Using the Mirror Gap Technique, 100mm squares of 4mm and 6mm K and float were prepared for firing using gaps of variable rectangular shape but with the same proportionate volume as shown in the template (*Figure 5.20*). The square measuring 24mm x 24mm was included to check the post-fired colour against the gap study panel results (*See 5.3, p.155*).

Sandblasting was again undertaken by Creative Glass to ensure comparability with the 35 gap panel tests. Across several tests, two different depths of gaps were created with the number of passes defined by the gap study table to produce gold at 10 passes and a strong pink at 25 passes. Some of the results showed the same colour for different shapes which would suggest the relationship of colour to volume of air. All results, however, did not show a consistency of colour within each test. Using 4mm K and 4mm float, although the gaps had been sandblasted to the gold colouration depth of 0.24mm, as in the 24mm square control, other rectangles with less volume showed pink or gold (*Figure 5.21*). Similarly, in the volume test piece with gaps sandblasted to the depth known to produce pink colouration, i.e. 0.52mm a variety of colouration was produced after firing as in Figure 5.22.

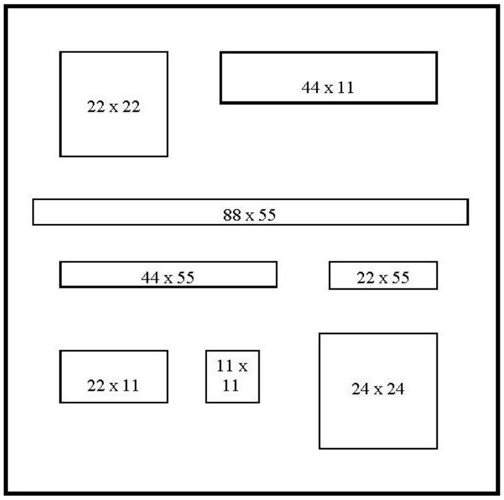


Figure 5.20 Volume test template (mm).

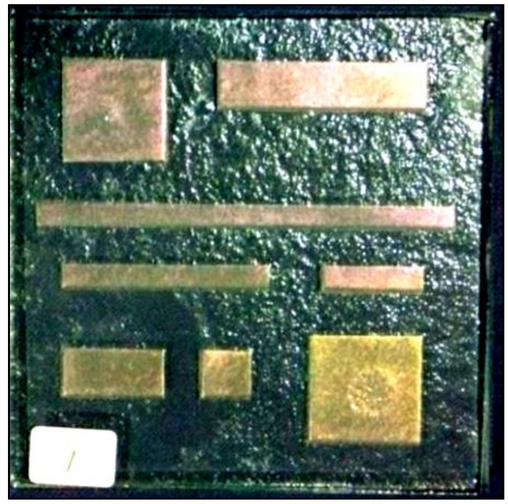


Figure 5.21 4mm K, post-fired at 775˚C, volume test for gold colouration.

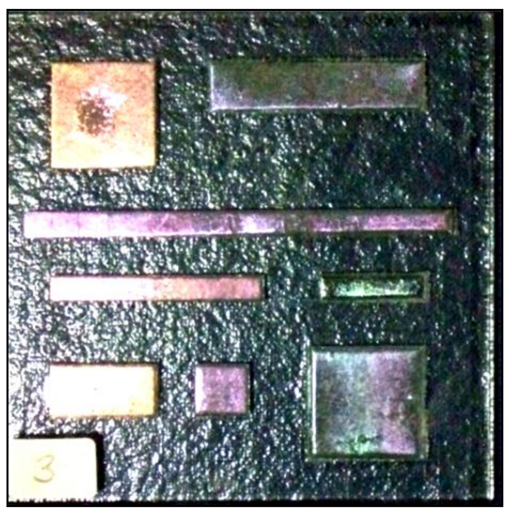


Figure 5.22 4mm K, post-fired at 775˚C, volume test for pink colouration.

Inconsistency seen across this range of tests suggested that other factors may be responsible for the variation in the resultant colouration. One possible explanation could be the chemical vapour deposition process during manufacturing. As the glass travels through the float bath and the vaporised tin oxide is deposited, the forward movement could cause bands of post-fired colouration that has been seen on isolated tests during the research, for example, that shown below in Figure 5.23.

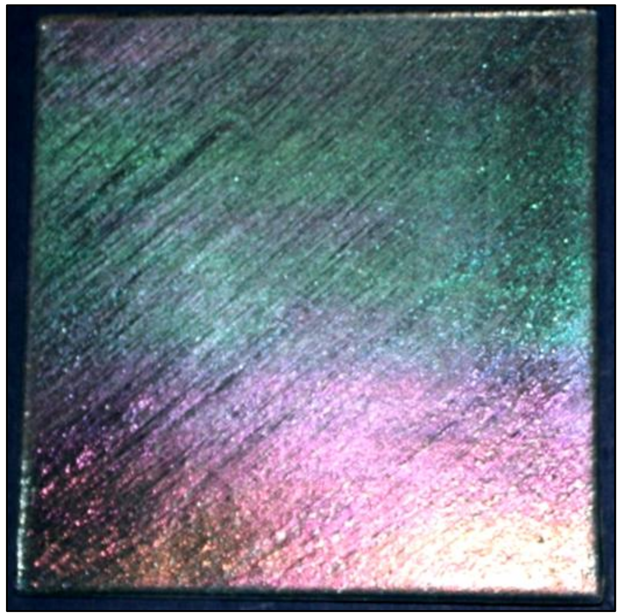


Figure 5.23   4mm K, post-fired at 775˚C, showing bands of colouration.

5.4.4 Reliability of Temperature

Although colour development within the Mirror Gap Technique can be achieved by firing within a range of 750–825°C, the temperature for the optimum effect is about 775°C. The length of time that this temperature was held was not crucial. Colour was found to be established after 10 minutes but a longer hold of 30 minutes created a greater depth of tone. The schedule for normal standardised testing was used for most Mirror Gap Technique work.

To obtain a reliable expression of repeatability, uniformity of temperatures within the kiln needed to be determined. A test was carried out when the kiln was new and repeated during this investigative phase of the research. Variations amounting to 10°C at 700°C (only 0.014%), were identified with a definite hot spot within the central area of the kiln. While temperature variation was found to be important in evaluating results, its consideration for artwork was more relevant for open fired than fused fired. A full description of the methods used to provide a kiln temperature grid showing 30 individual areas has been included in Appendix D.

Towards the end of the period of research, the incidence of patches on the surface of the 6mm K when fired with the normal standardised test schedule appeared to be more than at the beginning of the research. Although these patches could be avoided by slower firing, as discussed in Section 3.4.5, p.84, this may suggest a modification of the coating specification by the manufacturers, as was seen in Saint-Gobain Coolite (*See 5.5, p.179*). It is, therefore, advisable that before any artwork is fired, a test to check the consistency of the coating is carried out and, if necessary, adjust firing schedules accordingly.

5.4.5 Degradation of Sandblasting Grit

Results from the gap volume tests suggested that the physical sandblasting may have an effect on the repeatability the Mirror Gap Technique. Variables are not simply the machine but also the grit and the difficulty within the control of application. A commercial machine can have an accurately defined pressure, controlled sandblasting distance, flow rates and speed at which it moves across the surface. Unfortunately, this is not always available to the studio artist whose equipment may be very basic and whose regulation of its capability is their own skill. The grit is easier to prescribe being available in several acknowledged grades. However, if the process of sandblasting itself alters the grit then the results of using ‘new’ grit could differ from using ‘old’ grit. Hence, the possibility of grit degradation during sandblasting was examined through the following study.

The aim of the grit study was to measure the degradation and reduction in effectiveness of the grit by creating five Mirror Gap Technique samples using the same grit and standards of blasting. The sandblasting cabinet used was a ‘Guyson’ 400/40 model powered by a ‘Clarke’ Air industrial compressor model SE16C150. The equipment was set up to maintain a consistent application of distance and pressure (*Figure 5.24*). At the beginning of the test, a new ceramic nozzle was inserted to ensure the new condition of all elements. The sandblasting settings were as follows:

- Pressure set at 80psi, working at 50psi during blasting.
- Glass positioned at 200mm from point of nozzle.

Figure 5.24 *Arrangement for sandblasting grit study.*

The grit used was 80 Grade Brown Alumina Saftigrit High Performance Blast media with 6000g in the hopper at the start of the test. The glass used was 6mm K and 6mm float. The float glass was cut to 150mm x 100mm and masked. The additional 100mm x 50mm allowed the piece to be held in the clamp at the measured 200mm distance from the gun but was cut off before firing (*Figure 5.25*). The glass was blasted for 90 seconds before it was removed from the clamp and the gap measured at four corner points using a Vernier Scale (*Figure 5.26*).

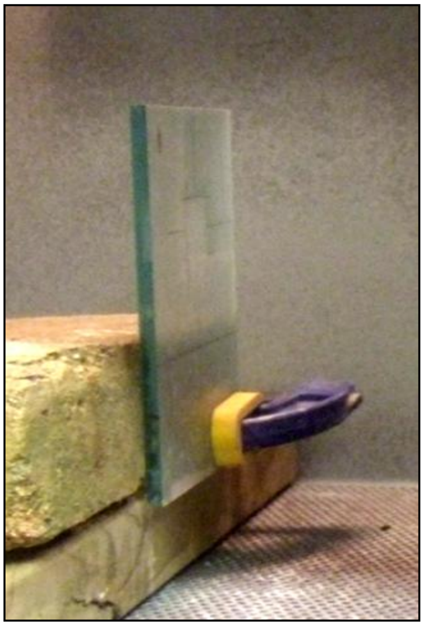


Figure 5.25 Grit study glass.

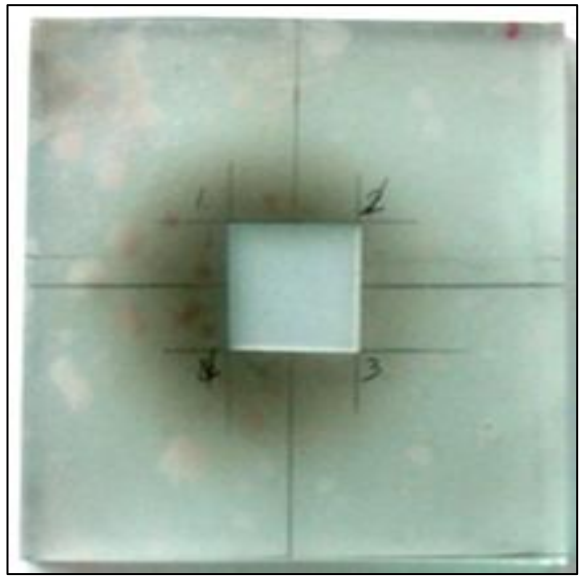


Figure 5.26 Grit study showing blasted gap.

The 100mm square of K was sandblasted leaving a mirrored 24mm square of the K coating in the centre. This was not undertaken at the same time to prevent distortion of the results by using the same grit. The K and float were subsequently fused at 775°C. A sample of the used grit was taken for assessment and microscopic evaluation. The K and the float glass pieces were placed together in Mirror Gap Technique format and fired. This test was repeated four times after which the remaining grit was weighed.

The amount of grit that remained weighed 5515g, a difference of 485g. Some of the loss was due to leakage and some had been drawn into filter bags. This meant that there was a reduction of the amount of grit in the feed hopper at the beginning of each test and, therefore, would be used at an increasing speed and subjected to more deterioration. Samples taken after each test were assessed blindly for feel. Although it was difficult to grade all samples in order, there was a definite difference between the new and the used grit. The used grit had a noticeably smoother feel. Microscopic examination of the grit samples suggested a gradual rounding of the edges of many of the particles (*Figures 5.27 and 5.28*).

Figure 5.27 New grit, showing sharp edges.

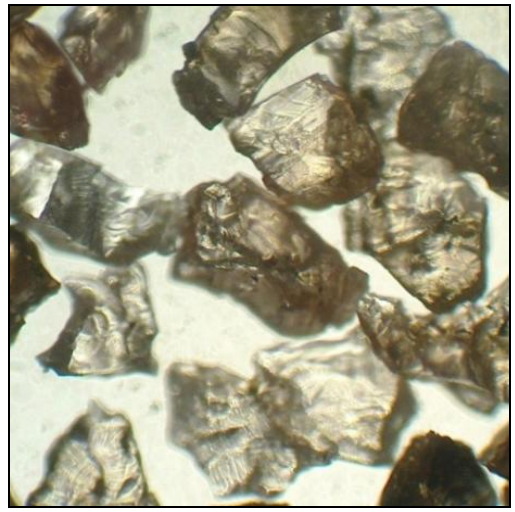


Figure 5.28 Used grit, showing rounded edges.

The measurements of the gap depths saw a decreasing scale from 0.920mm using new grit, to 0.425mm with the used grit *(See Table 5. 1).* This was supported by the colours obtained in the fired Mirror Gap Technique samples. The new grit created a deeper gap with post-fired purple colouration whereas the used grit created a shallower gap with gold colouration (*Figures 5.29 and 5.30)*.

Test order.	Corner 1.	Corner 2.	Corner 3.	Corner 4.	Average
1st.	1.10	0.76	0.8	1.0	0.92
2nd.	0.56	0.98	1.18	0.8	0.88
3rd.	0.54	0.58	0.8	0.56	0.62
4th.	0.4	0.5	0.66	0.5	0.515
5th.	0.36	0.4	0.46	0.48	0.425

Table 5.1 Degradation of grit test – results measured in mm.

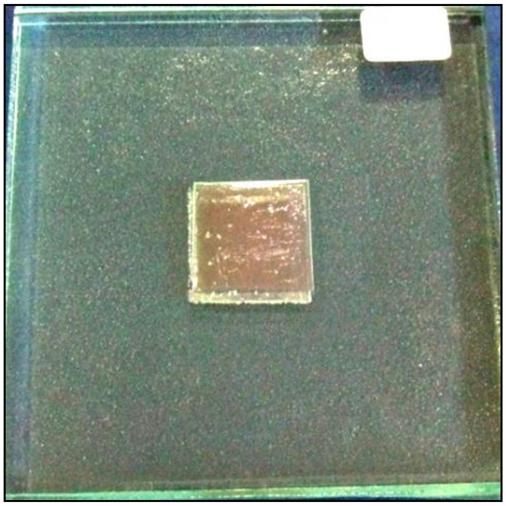


Figure 5.29 First Mirror Gap test with new grit showing purple colouration.

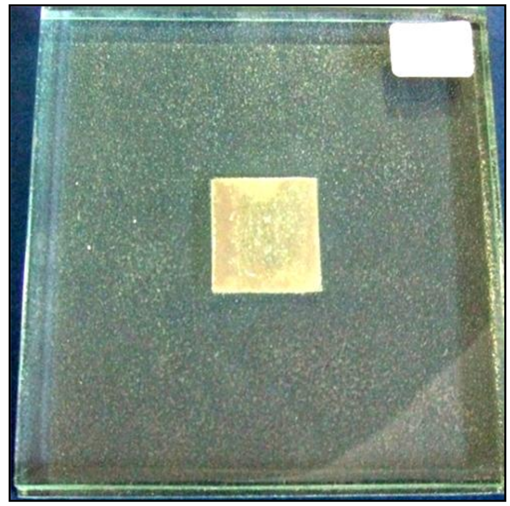


Figure 5.30 Fifth Mirror Gap test with used grit showing gold colouration.

A further test to assess the amount of grit lost in each blasting session confirmed the degradation of abrasive quality of the grit and its subsequent effect on the Mirror Gap Technique. Three off-cuts of 6mm float glass from the previous test were each blasted for one and a half minutes using the same configuration and conditions shown in Figure 5.22. New Saftigrit weighing 2000grams was placed in the empty hopper and weighed again after blasting each piece of glass. The following grit weights recorded were:

- Weight of grit after the first sandblasting: 1870g – used 130g
- Weight of grit after the second sandblasting: 1720g – used 150g
- Weight of grit after the third sandblasting: 1690g – used 130g

The gradual loss of grit with each session meant that more recycling of grit was taking place and therefore more degradation (or rounding) of the edges. The K coating in the gaps developed colouration consistent with the previous test and confirmed that the quality of the grit was responsible for the variation in gap depth and resultant colouration. As shown in Figures 5.31 and 5.32, fresh grit produced a deeper gap and purple colouration whereas recycled grit produced shallower gap and gold colouration.

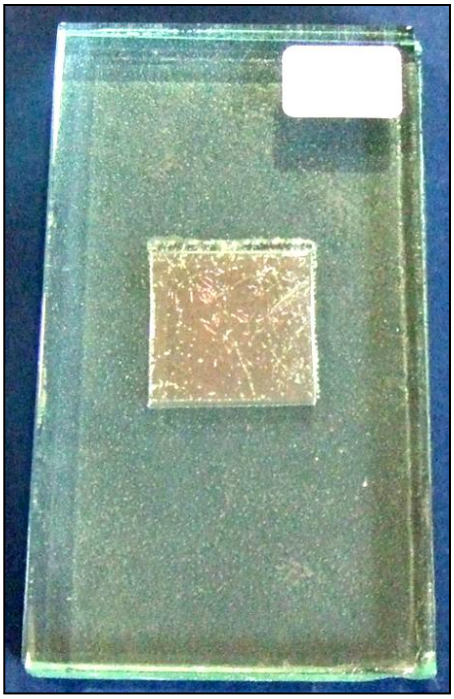


Figure 5.31 First sandblasted gap showing purple colouration.

Figure 5.32 Third sandblasted gap showing gold colouration.

5.4.6 Alternative Methods of Gap Creation

Most artists have the availability of sandblasting equipment, however, this generally will not be electronically controlled to provide an exact gap depth. A possible alternative method of creating the gap was erosion by means of a laser. Using a computerised cutter courtesy of the University of Sunderland, School of Education, a 100mm square of float glass was subjected to one pass of the laser gun which had been programmed to erode a 30mm square on the surface. This created an opaque square but gave no discernable depth to the surface. The intention to create a 30mm square gap with a 0.25mm depth by this method was unviable due to the time taken for one pass. A smaller square of 20mm was programmed with 20 passes of the laser gun.

After cutting, the gap depth was measured at each corner and in the centre using the dial gauge. It had been anticipated that this method would provide a very uniform level, however this was not the case. The gap depth was found to vary between 0.1mm and 0.25mm across the square.

The main disadvantage of this method was the heat generated by the laser within the glass. This necessitated regular stopping after only 2-5 passes to allow the glass to cool. The ability of the laser control programme to cut detailed imagery gaps may have positive application in the creation of artwork. Further investigation of creating the gap by means of a laser could be useful if suitable equipment became available.

Further alternative methods for creating the gap included using cut pieces of 3mm float glass between the lower K and the upper float glass leaving spaces which would form gaps. A piece of scrap water jet cut 4mm float glass with internal spaces, was also used as a middle layer. In both cases, this produced a strong pink colouration (*Figures 5.33 and 5.34*). The gaps made in both these ways were too great in volume to encourage the reductive atmosphere required for gold colouration.

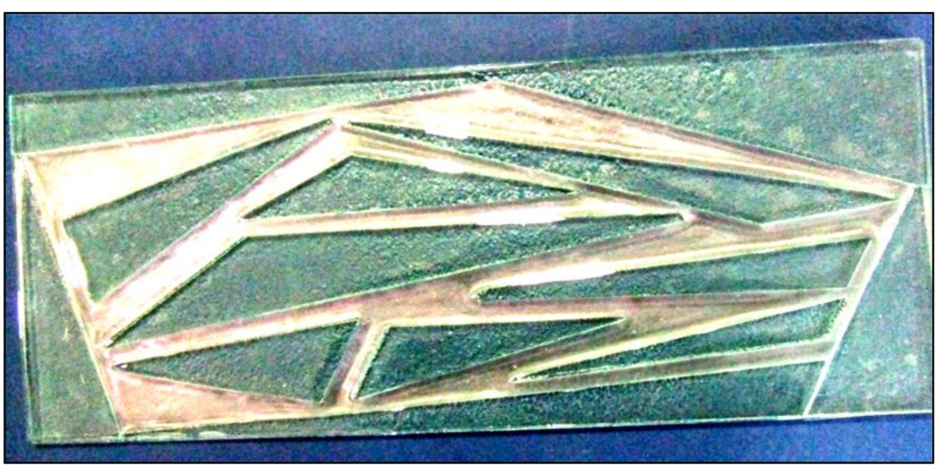


Figure 5.33 4mm K and 4mm float glass, post fired at 775˚C, gaps made with 3mm float glass pieces between.

Figure 5.34 4mm K and 4mm float glass, post fired at 775˚C, gaps made by with water jet cut 4mm float.

Engraving the surface of the K Glass had not been pursued at the standard testing level for open fired pieces (*See 3.4.4.4, p.84*) but was considered as an alternative method for creating a gap. A random design was worked into the tin side of 6mm float glass by glass artist Claudia Phipps who created deep cuts with an engraving wheel. The K coating was removed in a mirror image by sandblasting. Once fired, the result ‘Fireworks’ was an exciting effect of a variable range of colours and shapes obtained through simple engraving (*Figure 5.35*).

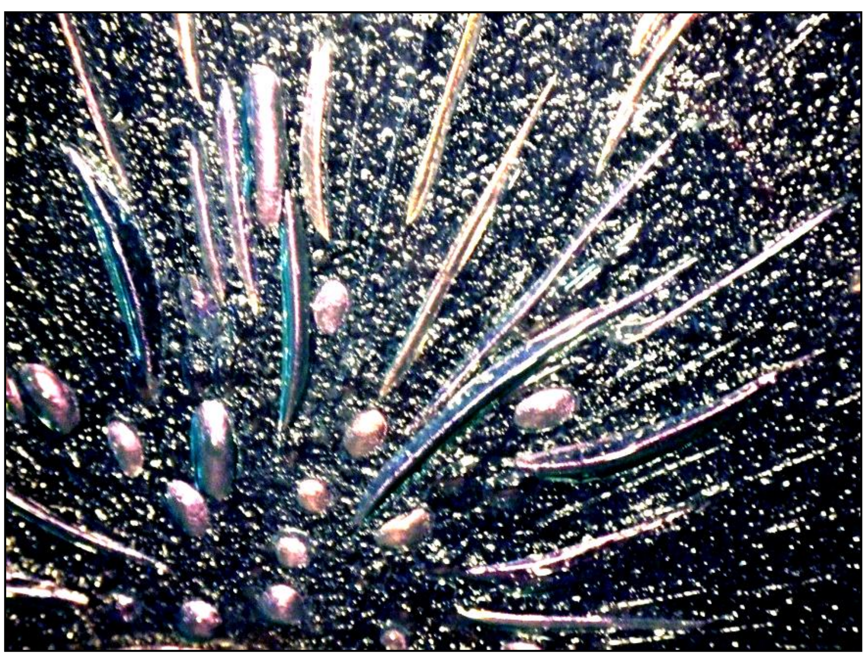


Figure 5.35 ‘Fireworks’, artwork test piece, 2007, 300mm x 250mm, 6mm K and 6mm float, engraved by Claudia Phipps.

The creation of the gap between the K and float glass was also explored through a number of variations using ceramic fibre sheets from 0.7mm Bullseye Thinfire to 3mm matting. The unwanted K coating was removed leaving squares. Corresponding squares were removed from the matting which was then positioned between the K and the upper float glass. In all tests, after firing, the colour obtained exhibited strong consistent iridescence which, using Thinfire was in the blue and purple range. The 3mm matting enabled more air to be available and the K coating produced a deep pink mauve (*Figures 5.36 and 5.37*).

Figure 5.36 4mmK and 4mm float, post-fired at 775˚C, gaps made with 3 thickness of 0.7mm BullseyeThinfire.

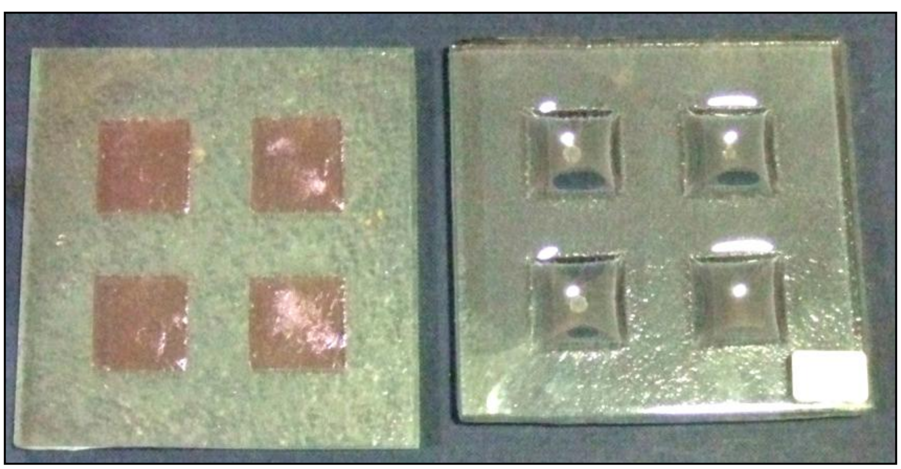


Figure 5.37 4mmK and 4mm float, post-fired at 775˚, gaps made with 1 thickness of 3mm ceramic matting.

This experiment was extended to investigate whether the colouration could be developed using the same method as in the test squares above but without the removal of the K coating. The aim was to create the gap and, simultaneously, protect the K coating, usually removed by sandblasting, from heat exposure through the use of the ceramic matting. A piece of matting was cut with an image, placed on the 4mm K surface and fired without the upper layer of float glass (*Figure 5.38*). However, the ceramic matting did not reduce the temperature on the K surface to a sufficiently low level to totally prevent the changes but did produce an interesting 'embossed' image which could be taken forward to artwork design *(Figure 5.39).*

Figure 5.38 Design cut out of 3mm ceramic matting.

Figure 5.39 4mm K, post-fired image.

An attempt was made to obtain colouration through the Mirror Gap Technique without the upper fused float. A 230mm square of 4mm K was framed by double strips of Thinfire to form a seal as shown in Figure 5.40 and a circular ceramic kiln shelf was placed on top to exclude air (*Figure 5.41)*. The post-fired K coating produced a very pale pink iridescence. The Thinfire had not provided a seal, thus, the amount of air available had caused an oxidative firing with colouration of a lower temperature due to the ceramic shelf, compatible with that seen at approximately 730˚C (*Figure 5.42*).

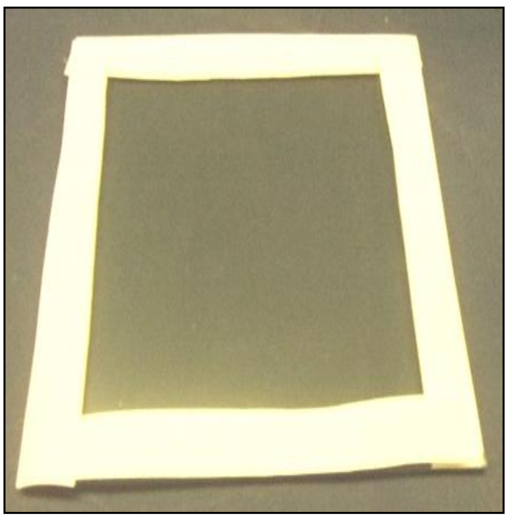


Figure 5.40 4mm K with double 'Thinfire 'frame'.

Figure 5.41 4mm K and Thinfire covered with kiln shelf.

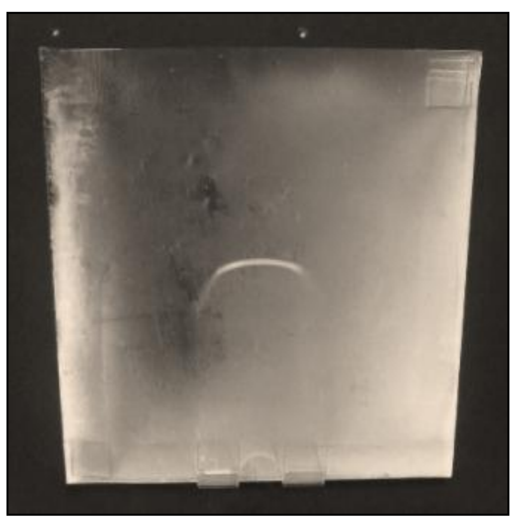


Figure 5.42 4mm K, post-fired at 775˚C, showing a very pale pink iridescence.

5.5 Alternative Low Emissivity Coated Glass

To explore wider creative opportunities for the Mirror Gap Technique, it was necessary to investigate alternative low emissivity coatings. Optitherm, also made by Pilkington, has a soft coating and is only supplied to the general public as an insulated glass unit. Samples were subjected to both open and fused firing. Optitherm produced a pale yellow-gold at 775°C but with a lack of iridescence or reflectivity (*Figures 5.43 and 5.44*). Similarly, the Mirror Gap Technique did not produce the range of colouration or iridescence as seen with the K Glass. Creative possibilities using Optitherm were found to be similar to those of K Glass but with a much more limited yellow colouration.

Figure 5.43 4mm Optitherm, post-fired at 775˚C.

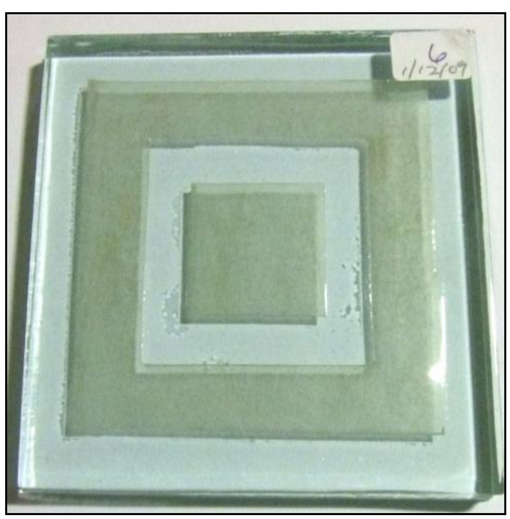


Figure 5.44 4mm Optitherm and 4mm float, post-fired at 775˚C, Mirror Gap Technique.

Low emissivity glass from manufacturers other than Pilkington was not so easily accessible. Saint-Gobain produced Planitherm which had not been obtainable at the time of study from the author's supplier. However, Bioclean 'Cool-Lite' also by Saint Gobain, known in the trade and referred to in this research for simplicity as ST150, was available. This was is a highly reflective glass with hard coating to both sides of the glass one of which was low emissivity (Saint-Gobain Glass, 2011) and offered the opportunity to explore additional coatings. The solar coating has bronze tones and the low emissivity coating has a silver grey hue. Firing in both open and fused situations suggested that although giving completely different effects to those of K Glass, this coating had creative potential and was used for the commission for Clayton Glass monthly awards (*Figure 5.45*). Detailed images in Figures 5.46 and 5.47 show the different tones of the fired surface coatings.

Figure 5.45 4mm ST150, post-fired at 775˚C.

Figure 5.46 ST150 solar coated side, post-fired at 775˚C.

Figure 5.47 ST150 low e coated side, post-fired at 775˚C.

During the time of working with ST150, the coating changed its response to firing, producing a dull brownish appearance and distorted shape. Further trials and enquiries with the supplier confirmed that the specification had been altered. When the target temperature was lowered from 775°C to 750°C and the hold reduced to 10 minutes, satisfactory results were achieved. However, the gold effect produced by the solar coating was replaced by a stainless steel appearance which, when viewed form the reverse, showed as a blue grey. Open firing and acute bending gave interest to this surface with marking and cracking to the coating *(Figure 5.48).* Artwork created using the Mirror Gap Technique produced strong reflective 'metallic' imagery but without the interferential colouration as seen in K Glass panel made for a commission application (*Figure 5.47*).

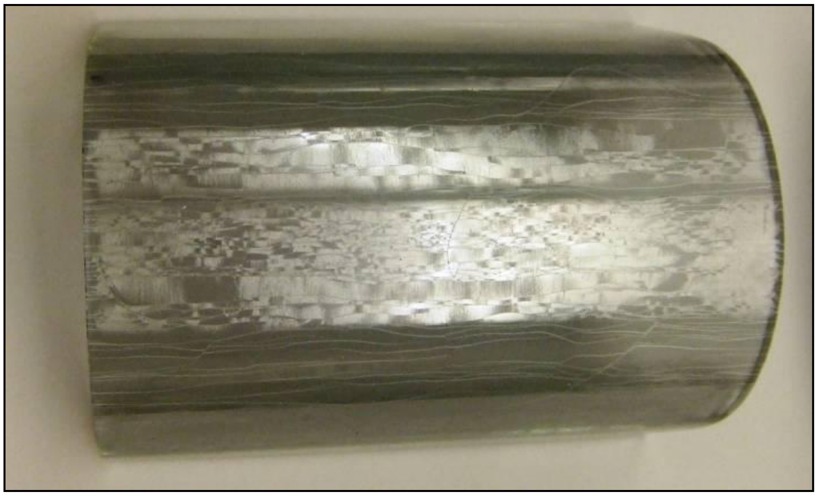
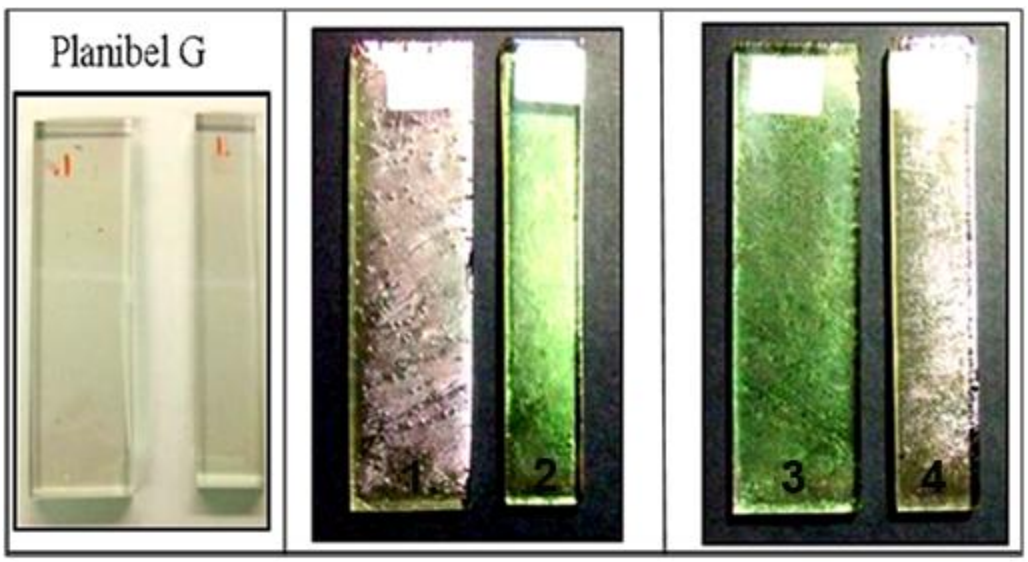


Figure 5.48 4mm ST150, post-fired at 775˚C, bending test.

Figure 5.49 ST150, Mirror Gap Technique commission application panel.

Obtaining other low emissivity coated glass was not easy. Sample size pieces only were supplied by two manufactures, AGC Flat Glass Europe (AGC) and Guardian Industries UK Limited (Guardian). AGC supplied clear and coloured hard coat samples from their Planibel, Sunergy, Stopsol and Stopray ranges. Guardian provided soft coat samples from the ClimaGuard and Sunguard Solar ranges including clear, tinted and some reflective coatings. Details of the test results for AGC Glass and Guardian Glass can be found in Appendix B.

Open firing clear glass samples from the Planibel and Sunergy range produced similar visual effects as those seen on K. Coloured glass samples showed the appearance of stronger colour and greater intensity of iridescence due to what was in effect a dark background (*See 6.5.2, p.223*). The colours seen on the reverse were in contrast to those seen on the upper surface (*Figures 5.50 and 5.51)*. This was similar to the colouration found on the upper and reverse sides of the K samples in the sagging and bending tests described in Chapter 3. Most of the Stopsol samples displayed a metallic sheen similar to that on ST150.

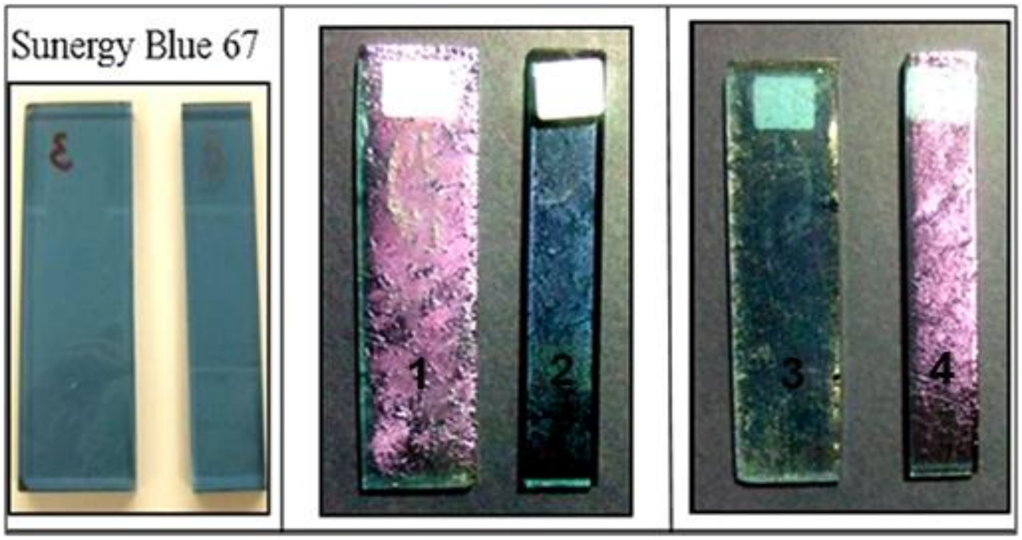


Pre-fired

Post-fired from front
1. Fired coating up
2. Fired coating down

Post-fired from reverse
3. Fired coating up
4. Fired coating down

Figure 5.50 *AGC Planibel G, pre-fired and post-fired at 775˚C.*



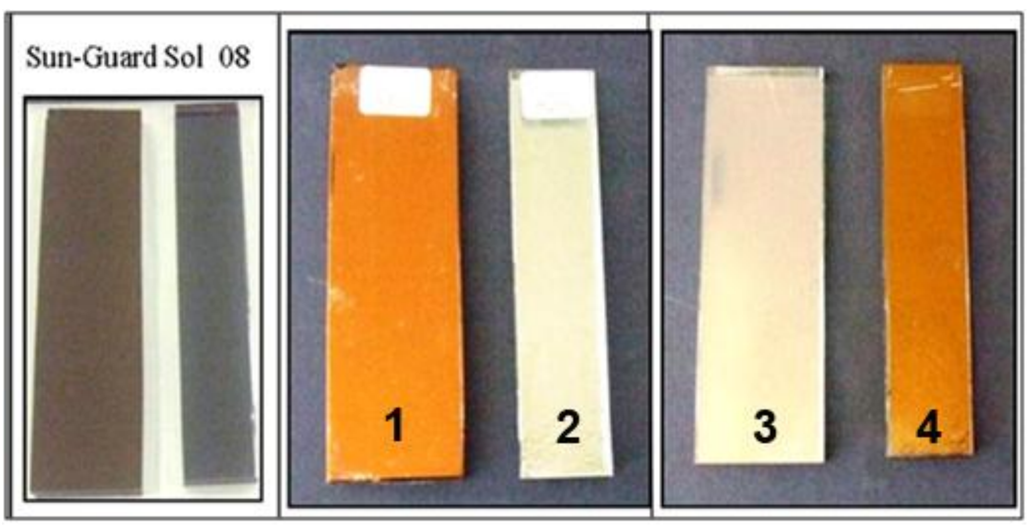
Pre-fired

Post-fired from front
1. Fired coating up
2. Fired coating down

Post-fired from reverse
3. Fired coating up
4. Fired coating down

Figure 5.51 AGC Sunergy Blue, pre-fired and post-fired at 775˚C.

The Guardian glass which was supplied in insulated glass units was open fired alongside the AGC samples. The clear and neutral options of Climaguard N produced only a grey dullness. The remaining group including SunGuard Solar Silver produced strong colouration as in Figure 5.52 but with a surface that was easily marked may not, therefore, be appropriate for artwork.



Pre-fired

Post-fired from front
1. Fired coating up
2. Fired coating down

Post-fired from reverse
3. Fired coating up
4. Fired coating down

Figure 5.52 Guardian SunGuard Solar Silver 08, pre-fired and post-fired at 775˚C.

Due to the fact that the AGC low emissivity glass had exhibited similar visual changes to that of open fired K, small samples were also tested using the Mirror Gap Technique. When the substrate glass on which the coating was applied was coloured, the post-fired visual effects were particularly striking. The tinted substrate influenced the pinks and purples of the fired coating and gave an additional dimension to the effects (*Figure 5.53*). Although the Stopray Vision sample did not produce variable colouration, the intensity of its gold effect increased with the depth of gap (*Figure 5.54*). Full results of the AGC Mirror Gap Technique tests can be found in Appendix B, p.26. Insufficient reaction to open firing of the Guardian glass suggested that it would not be suitable for the Mirror Gap Technique.

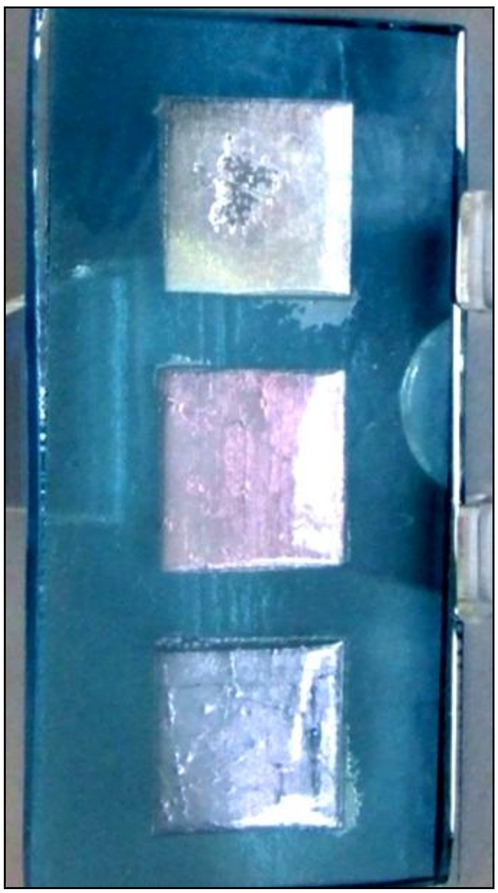


Figure 5.53 Sunergy Dark Blue, Mirror Gap Technique test.

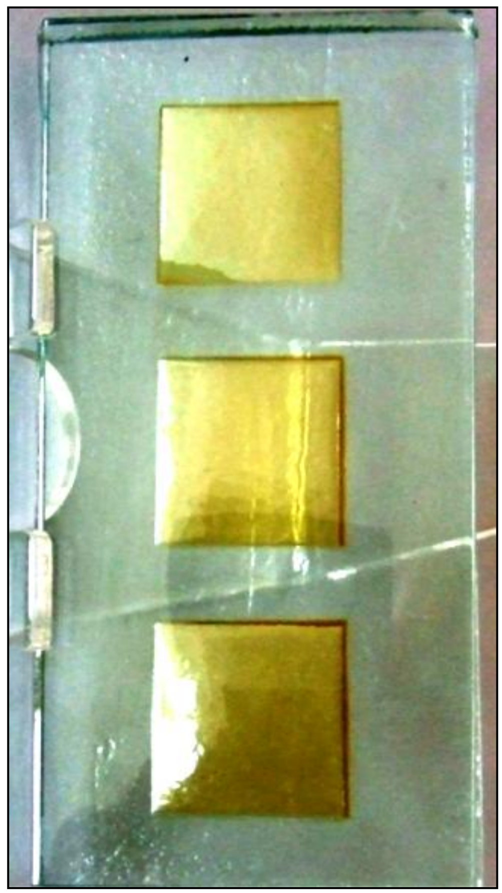


Figure 5.54 Stopray Vision, Mirror Gap Technique test.

5.6 Summary

Experimental fusing tests revealed a tiny gap under the upper layer of float glass and above areas of colouration. To recreate this situation the K Glass was manipulated by sandblasting to leave an area of coating on the surface. A gap, which was a mirror image of the remaining coating, was made by sandblasting on the underside of the upper layer of float glass. This combined process was called the Mirror Gap Technique.

By varying the depth of the gap it was possible to separate the colouration. The range of colouration was explored through the gap depth study and carried out under controlled conditions. This produced a graded range of colour with gaps from 0.01mm to 1.17mm. Within this range the optimum gap depths of 0.25mm produced a gold colour, 0.5mm produced pink and 0.85 produced purple.

The Mirror Gap Technique was tested through artwork produced for commissions and its multiple production potential with the use of commercial equipment. Repeatability factors were examined through dimensional limitation, kiln temperature, volume of air and the sandblasting grit condition. The possibilities for the extension of the Mirror Gap Technique and the application of the findings of the research to other emissivity coated glass were also explored.

Chapter 6

Creation of Artwork with Low Emissivity K Glass

This chapter discusses the production of artwork related to the fifth objective, 'To utilise the techniques in a body of artwork that develops and demonstrates the artistic potential of K Glass within the field of creative glass'. The methods that evolved during the practical programme of testing and specifically, the Mirror Gap Technique, have been developed through artwork to demonstrate the visual characteristics of colour, iridescence and bubbles achieved on the surface of K Glass and the potential of the creative possibilities found in this research. The interferential nature of the characteristics is discussed in relation to the location of the artwork.

6.1 Rationale for the Development of Artwork

Low emissivity glass is a functional architectural product but it was realised at an early stage of the research that the developed material and methods had potential within several areas of creative glass. Ideas which were not confined to one specific area were generated using the methods devised and described in Chapters 3 and 5 to show the creative possibilities of the manipulated surface coating of K Glass. Through artwork the unique artistic characteristics of reflective colouration and iridescence of the manipulated coating were developed. The innovative visual effects of the fired surface and their relationship with light were the main inspiration for form. Two of the main considerations of design, therefore, were the pre-fired surface treatment and the profile with relation to the angle of viewing (*See 6.51, p.221*).

Some of the pieces of artwork were based on the geometric theme used throughout the standardisation programme. More detailed imagery was suggested from the microscope photographs of the variable ripple and bubble formation of the changed surface coating. Further artwork was developed through the application of the methods to the presentation of text. During experimental testing artwork was produced, some of which has been included to show the diversity of techniques. Pieces were also produced for exhibition and commission purposes during the research (*See Appendix G, p.296)*. The sale of three of these pieces in the United States of America reinforced the creative potential of manipulated low emissivity K Glass alongside other types of glass, for example, float.

6.2 Creative Characteristics of Manipulated K Glass

Karel and Bell (*See 2.10, p.32*) explored the characteristic of reflectivity through the surface of coated architectural glass. This research has identified characteristics of reflectivity, created through the manipulated and post-fired surface of coated architectural K Glass. Visual effects of colouration ranging from gold to purple, variation of iridescence and bubble formation have been achieved which, when developed through artwork, are original, innovative and cannot be produced by using regular float glass.

6.2.1 The Nature and Interrelationship of Surface Characteristics

Although the overall post-fired visual effect on the surface of K Glass is due to the interrelationship of colouration and iridescence, the evaluation of each has been considered separately. The range of colouration achieved within this research falls into two categories. Firstly, the predominantly pink/purple open fired spectrum (*See 3.4.1, p.75)* of which the strength and hue can be controlled through abrasive treatment of the pre-fired K coating and the adjustment of the firing schedule. Secondly, gold and pink to purple in the Mirror Gap Technique which can be controlled through depth of gap (*See 5.3, p.153*).

Iridescence is interrelated with colour through the structure of the post-fired coating and evident on all surfaces open or fused fired. With variations that ranged from very shiny to very dull, the iridescence effects were also managed by surface abrasion and through the firing schedule.

An intrinsic feature of iridescence is its interferential nature as described in Chapter 2. This is seen in all pieces as the visual effect appears and disappears with the movement of the viewer and provides the feature of elusiveness which adds to the originality of the results of this research. Consequently, the position of artwork is of extreme importance and, therefore, each piece must be designed with respect to location, background and lighting. The interferential properties of iridescence and how they relate to artwork are discussed in Section 6.5, p.221.

6.3 Creative Possibilities of Open Fired K Glass

The surface qualities identified during the experimental phase of the research were developed and utilised through a series of plates. The key identifying characteristic was the variation of surface effect including colour and iridescence. The square form, which was the blue print for the standardised tests, generated the ideas for pieces to recognise and reflect the innovative interferential effects of this research.

Manipulation of the K surface coating prior to firing was used to encourage a range of visual effects. Scoring, with a variety of grades of diamond pad and/or sanding material as well as the additional partial removal of areas of K coating through sandblasting, were used in combination with firing schedules, to manage reflectivity and strength of colour. Unless specified, artwork was produced in the studio kiln at 775˚C with a 30 minute holding time, as had been used for most of the standardised tests. The rate of firing and the holding time were varied to obtain better results, particularly in terms of more reflective iridescence. Individual details regarding the preparation of the following plates and their respective firing schedules can be found in Appendix B, p.253.

The simplicity of the geometric design of Plate 1 is an example of the potential of firing the glass with no further manipulation other than removal of the unwanted coating. The colouration and iridescence, which were controlled by the width of the squares, produced both pink tones with duller iridescence and blue tones with reflective or shiny iridescence (*Figure 6.1*). This visual effect shows a similarity to the iridised purple surface developed by Webb (*See 2.11, p.43*).

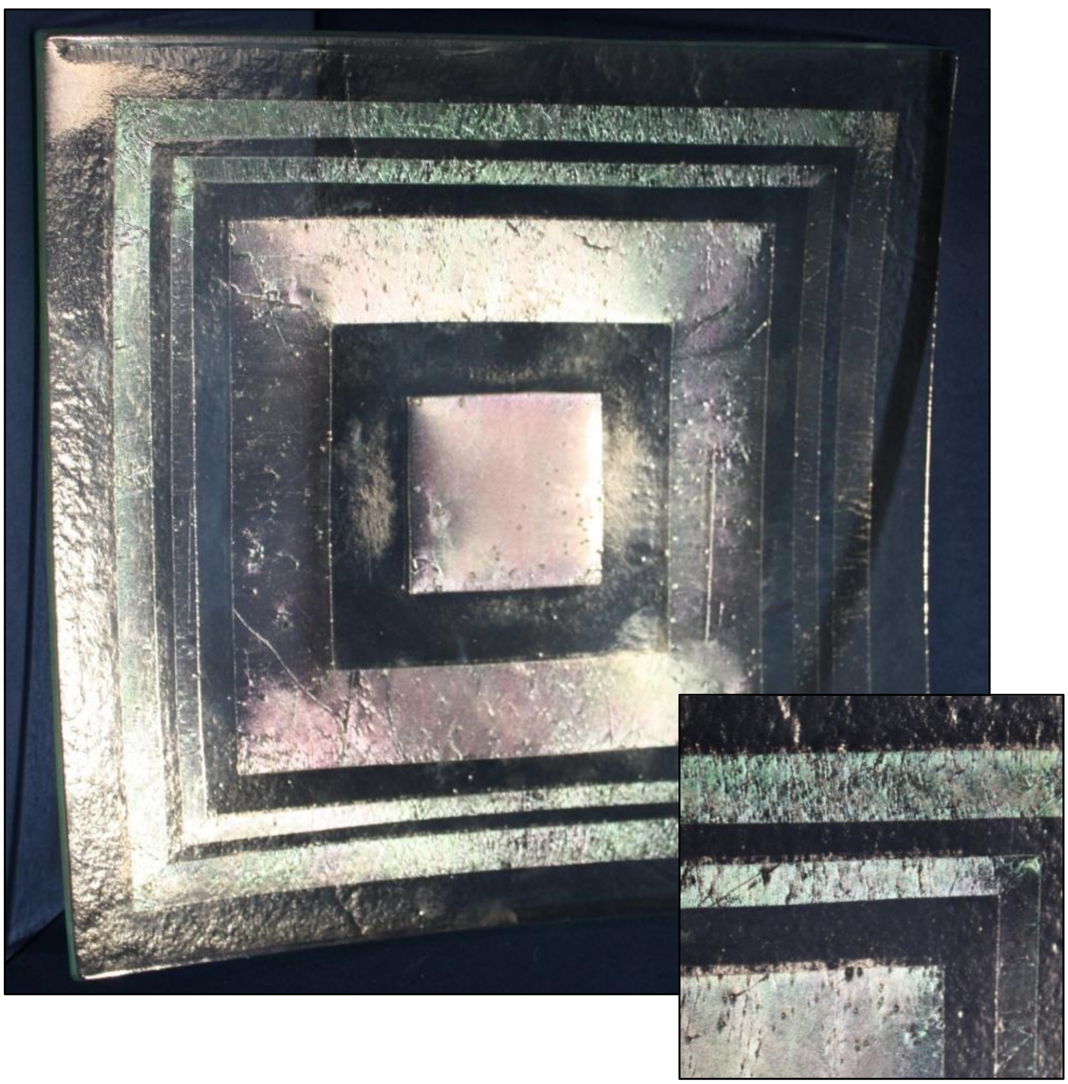


Figure 6.1 'Plate 1', Eileen Leatherland, 2011, 230mm x 230mm, 6mm K, detail showing blue border colouration.

This effect was extended to Plate 2 using a geometric design generated from ideas from the testing programme and developed through screen printing. Figure 6.*2* shows how 6mm K was selectively scored using a rough diamond pad prior to the sandblasted removal of small squares. Several identical pieces were tested, varying the scoring strengths and firing schedules, to obtain the most pleasing effect based on the strength of colouration and intensity of iridescence, given balance by clear squares. The deep score lines and their accumulated bubbles, had enabled the coating to be mainly reflective with small slightly dull areas where no scoring had taken place.

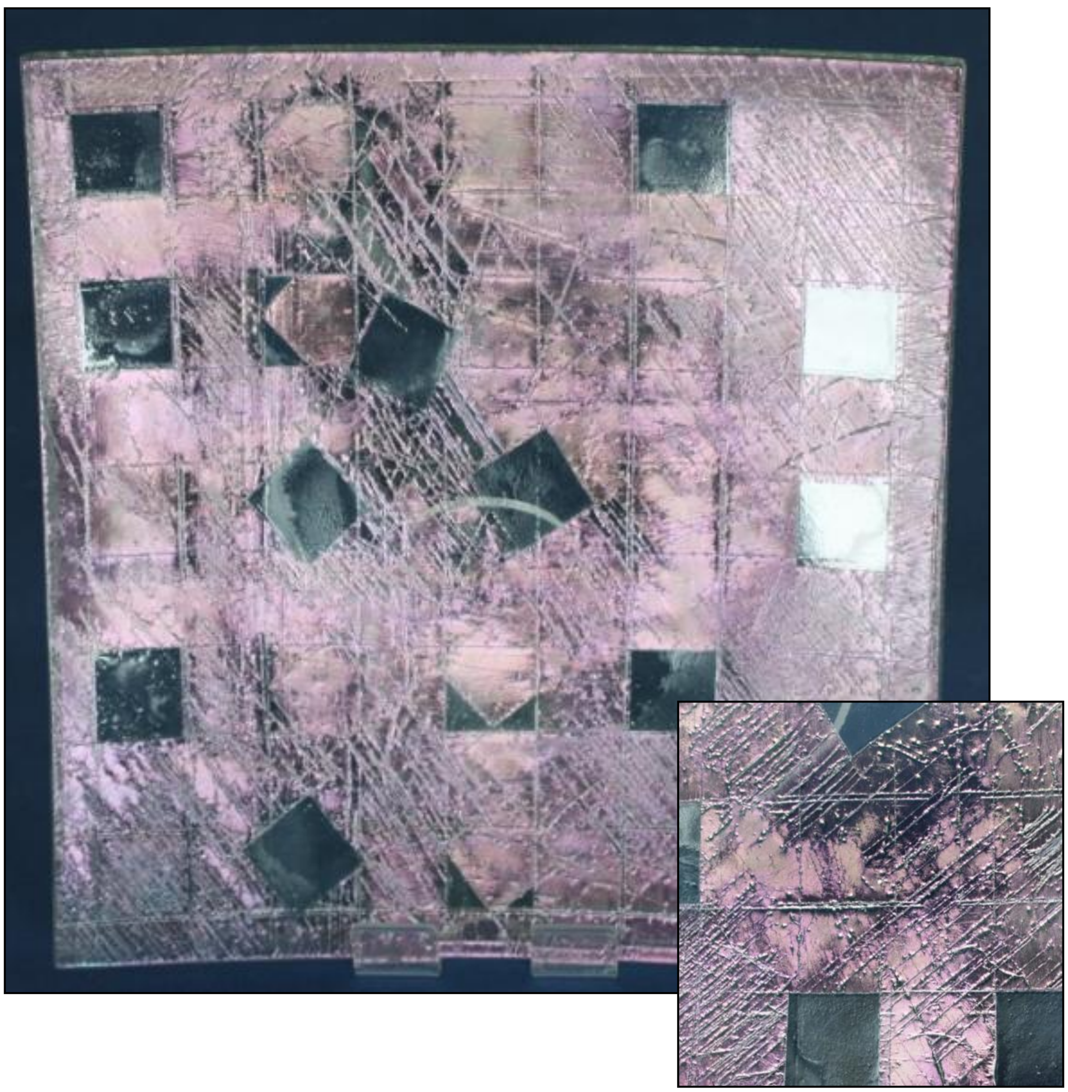


Figure 6.2 *'Plate 2', Eileen Leatherland, 2011, 250mm x 250mm, 6mm K, detail showing scoring and sandblasting design.*

The design of Plate 3 was taken from a modified microscope image of fired coating ripples and developed from the surface features of Plate 2. The entire surface of the 6mm K was scored with a fine diamond pad prior to the design being sandblasted to encourage detail through microscopic bubble formation on the remaining coating. Several tests were undertaken before the preferred grade of scoring and colouration was achieved. Slower firing of 150˚C per hour above 520˚C encouraged some blue tones within a very strong pink colouration and iridescence; the clear sandblasted areas prevented the effect from being too overpowering. Figure 6.3 shows how the interferential response to light creates differing visual effects when photographed from different angles.

Figure 6.3 'Plate 3' and detail, Eileen Leatherland, 2011, 250mm x 250mm, 6mm K, showing interferential colouration and iridescence.

The microscopy theme was continued in the design of Plate 4 which was inspired by one of the many images of bubbles (*Figure 6.4*). The aim was to produce a plate where the design would echo the relief through a three-dimensional surface. To achieve this, metal ball bearings were pushed into 3mm ceramic matting, lining a ceramic mould. The first firing of the scored 4mm K gave a poor degree of 'roundedness' and inadequate colouration (*Figure 6.5).*

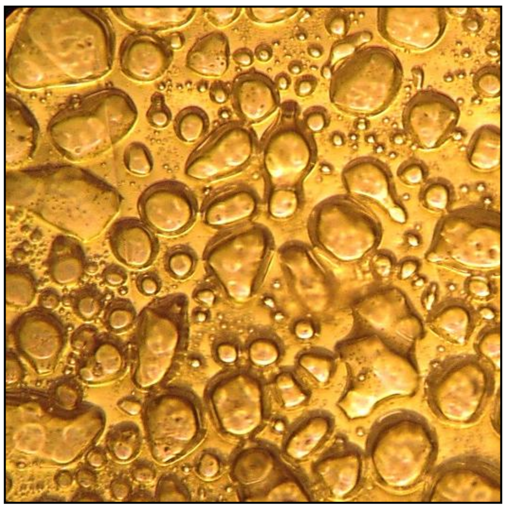


Figure 6.4 Microscope image of bubbles.

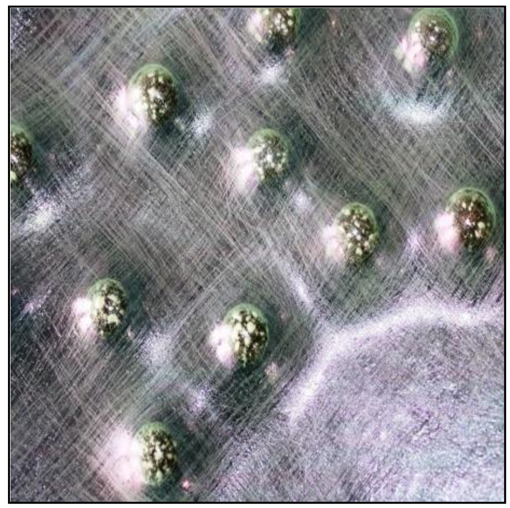


Figure 6.5 'Plate 4', (detail) after first firing showing 'bubble' relief.

A higher temperature of 800˚C was used to encourage greater bubble formation along the score lines. Pushing the ball bearing further into the matting achieved better relief definition but there were still two unsatisfactory features. Inside each 'mound' an amount of metal debris had remained and the colouration of the surface, although an interesting green/blue with mauve iridescence, was of a shallow nature (*Figure 6.6).* Both these issues were addressed by sandblasting the reverse of the plate and resulted in an additional dimension to the colouration palette, namely a 'softening' of the colour to give a pastel tone (*Figure 6.7).*

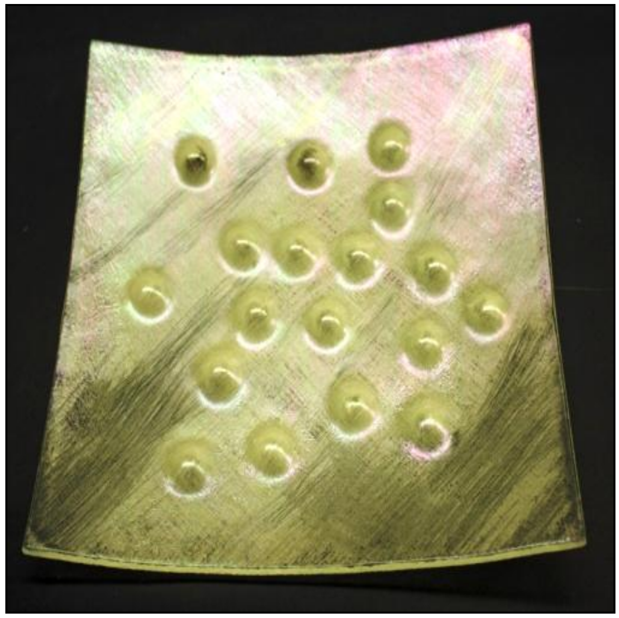


Figure 6.6 ‘Plate 4’ after second firing showing debris in mounds and poor surface marking.

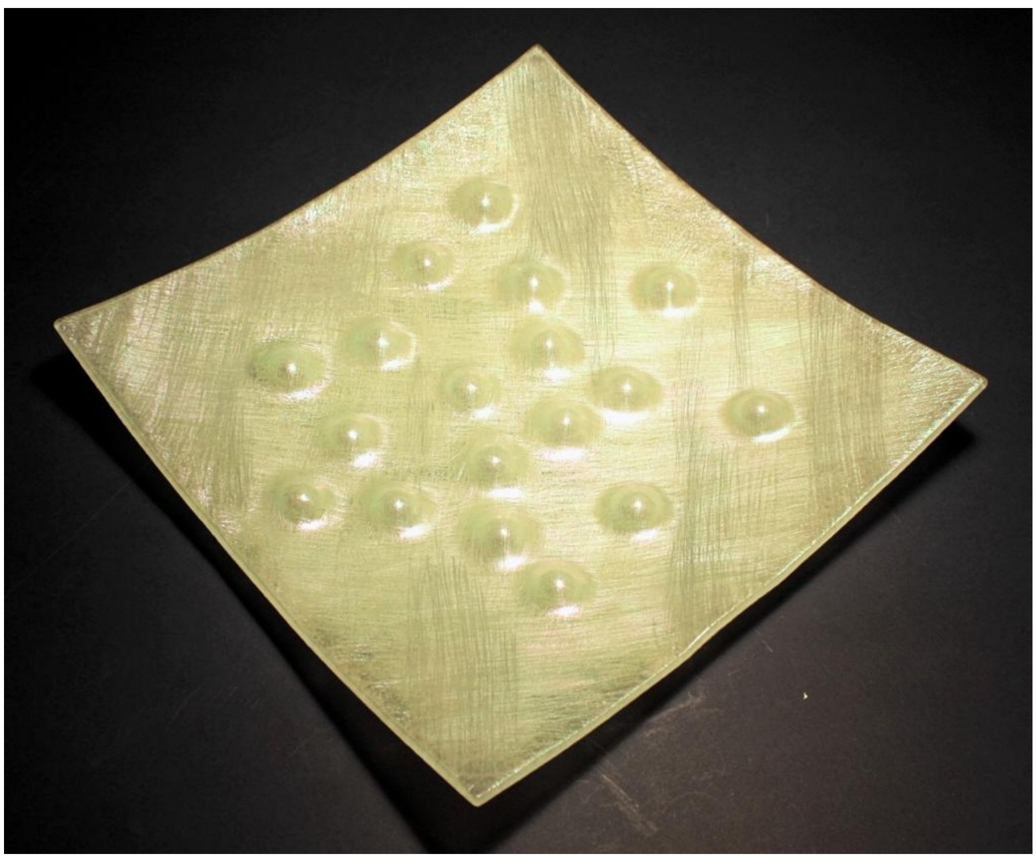


Figure 6.7 ‘Plate 4’, Eileen Leatherland, 2011, 250mm x 250mm, 6mm K, showing improved relief ‘bubble’ design.

The potential of the variable colouration that appears on small individual pieces of the fired glass inspired the design of geometric repetition for Plate 5. Rectangles measuring 50mm x 15mm of 4mm K were placed in tile formation on a square of 4mm float glass and fired with a slower rate of firing to 800˚C (*See Schedule Slow 3, Appendix D, p.279*). The glass was initially fired flat to prevent any movement of the tiles before being returned to the kiln to be sagged in the mould. Although the second firing caused a very slight reduction in the intensity of iridescence, the colouration seen in each small piece when placed together offered an interesting wide spectrum of glistening tones (*Figure 6.8).* This concept suggested opportunities for interior design applications, for example, wall tiles, cladding and decorative panels among the possibilities.

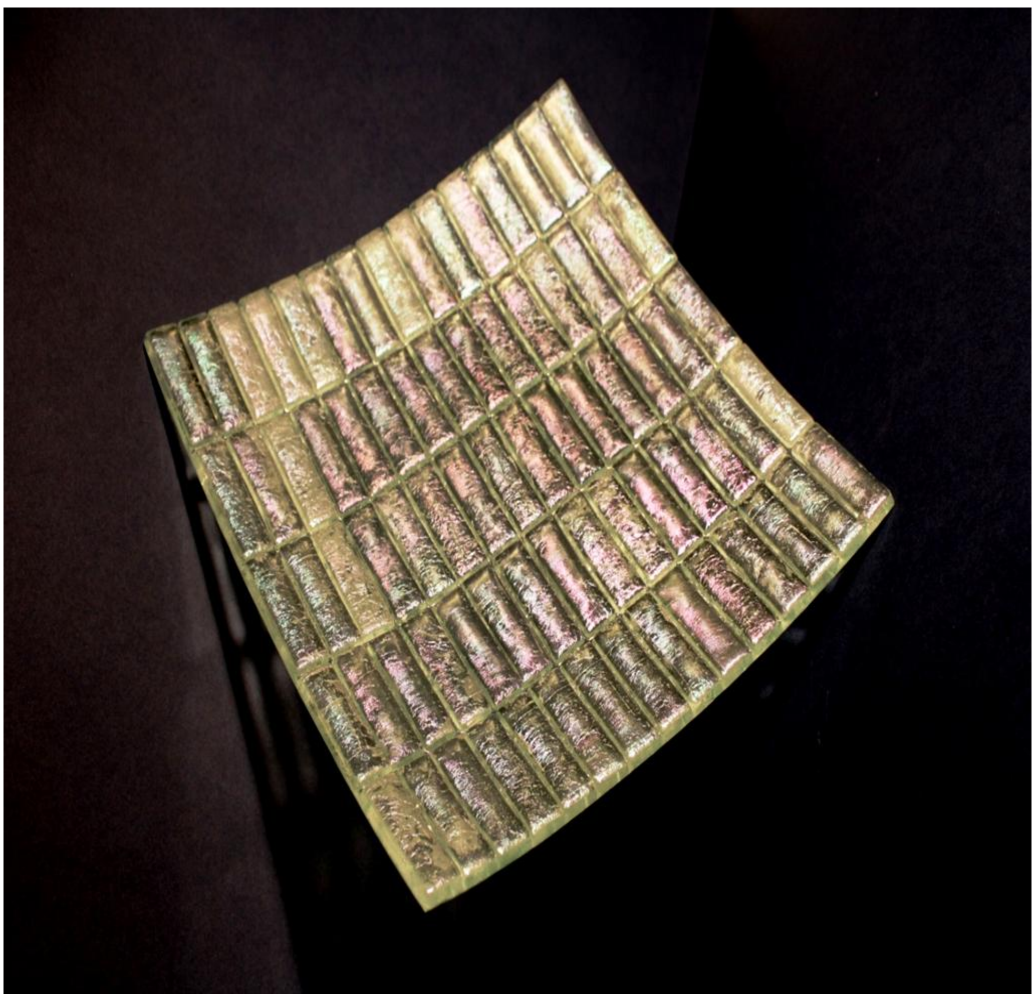


Figure 6.8 'Plate 5', Eileen Leatherland, 2011, 250mm x 250mm, 6mm K, pieces in tile formation.

Plate 6 demonstrated the development of the research through its application to other commercially available coatings. Experimental testing of ST150 glass provided criteria for firing and coating manipulation possibilities. The coating on each side of the glass suggested a simple double sided design of geometric images which would interact as one. Slightly different shades of metallic grey were produced with ‘crack-like’ markings visible on parts of the solar coating but which did not mar the reflective effect. Due to the lower firing temperature of 750˚C (*See 5.5, p.179*), the sandblasting did not become fire polished[23] but remained as a finely textured surface giving contrast and balance to the design (*Figure 6.9).*

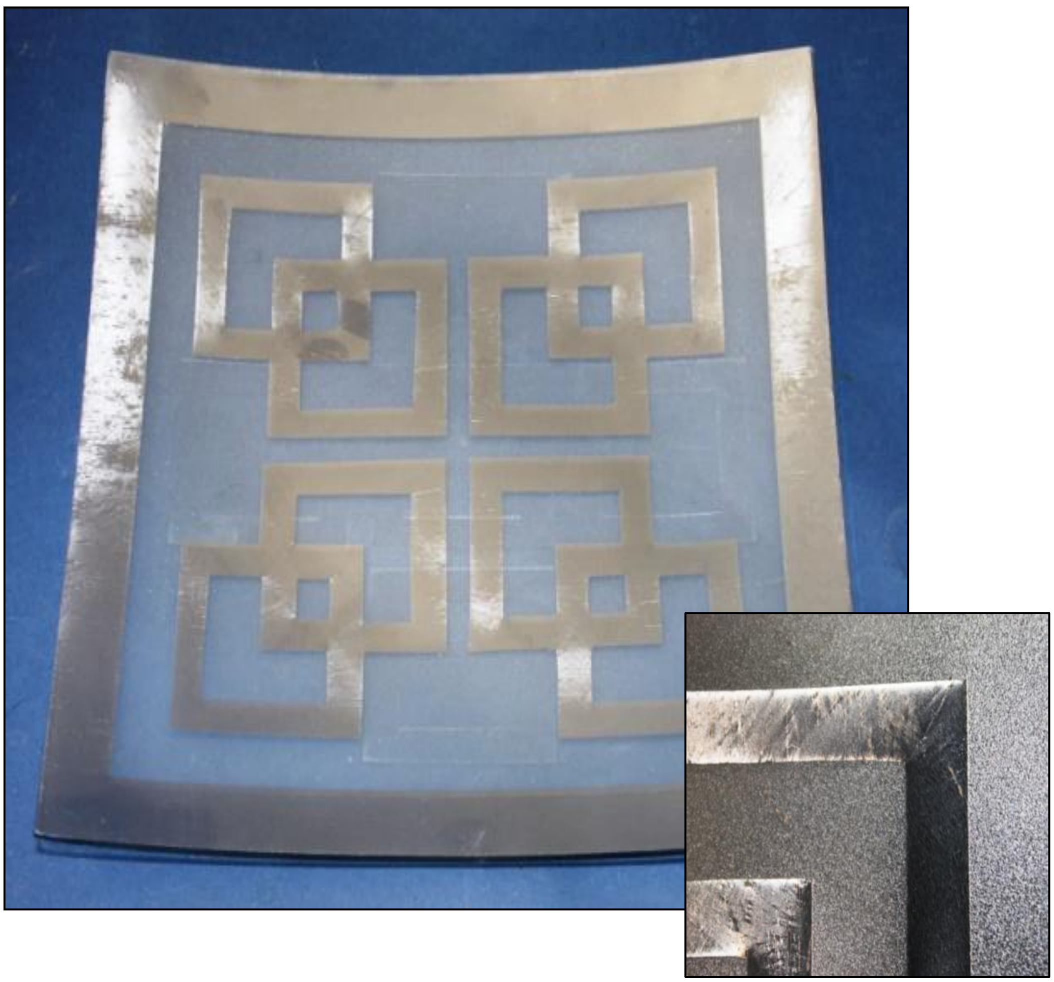


Figure 6.9 *‘Plate 6’, Eileen Leatherland, 2011, 250mm x 250mm, ST150, showing double sided design. Detail showing ‘unpolished’ sandblasted surface.*

[23] Fire polished – the introduction of glass to a source of sufficient heat to fuse the surface to a bright polished finish (Bray, 2001, p.116).

During testing it was found that by placing two identically sized pieces of K Glass together with their coatings ‘face to face’, not only did they not fuse but they also produced mirror image patches of strong iridescent colouration as shown in Figure 6.10, similar in intensity to that seen on surfaces of Tiffany vases (*See 2.11, p.44*). Using single open fired pieces of K Glass, the colouration achieved had been mainly pink/purple. With this technique it appeared that a gold surface was possible which opened up a whole new range of creative possibilities. To explore this potential, the surfaces of two identically sized pieces (220mm x 110mm) of 4mm K were sandblasted leaving mirror images of a simple shape on each. After the two pieces had been fired face-to-face at 775˚C for 20 minutes with Bullseye Thinfire between the non-coated area, they were separated and then re-fired individually over a tube mould to form the free standing pieces shown in Figure 6.11.

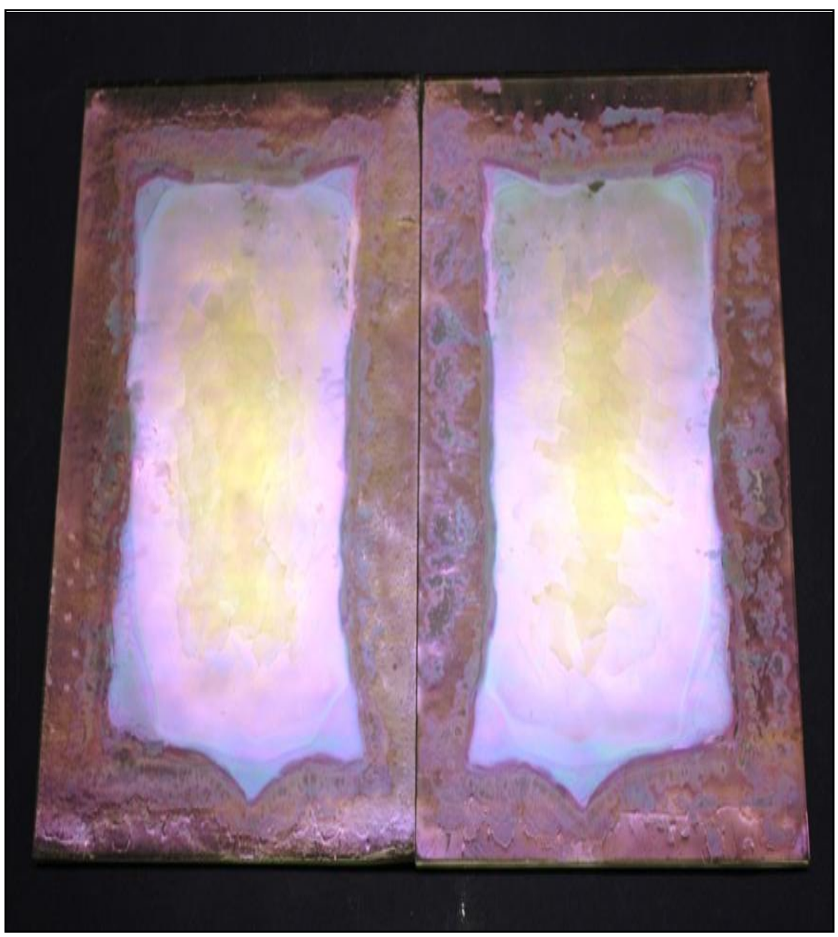


Figure 6.10 4mm K fired ‘face to face’ at 775˚C.

Figure 6.11 *4mm K, post-fired face to face test piece, after sandblasting and bending.*

Selective cutting of face to face fired K suggested several possibilities. Using only the gold area, a 'jig-saw' design could be produced and on the outer area the markings on the mosaic pieces were very similar to those seen in marble. Consequently, a design was tested by fusing small pieces onto a rectangle of float glass which had been painted and pre-fired with ceramic enamel to provide a dark blue background (*Figure 6.12*). Firing to 750˚C for 10 minutes ensured a fuse but no change to the K coating. The pieces kept their colour but the blue base caused the gold colouration to appear dull and needed stronger direct light to restore the iridescence.

Figure 6.12 *4mm K, post-fired face to face, test piece showing cut and fused to blue painted float.*

To try to regain the iridescent vibrancy through reflectivity, mosaic pieces were fired with a sheet of 3mm float glass on top in a piece called ‘Chequer Board’ as shown in Figure 6.13. The result was not as expected. Some of the iridescence of the colouration was lost despite having gained the reflectivity of the glass surface. It still provided, however, an interesting and unusual effect which could be extended for interior design applications such as wall tiles or table tops. A second attempt to try to regain the characteristic of the original post-fired colouration used blue glass as a base. Although this added blue tones to the purple translucent areas, in doing so, it diminished the strength of the gold colouration (*Figure 6.14*).

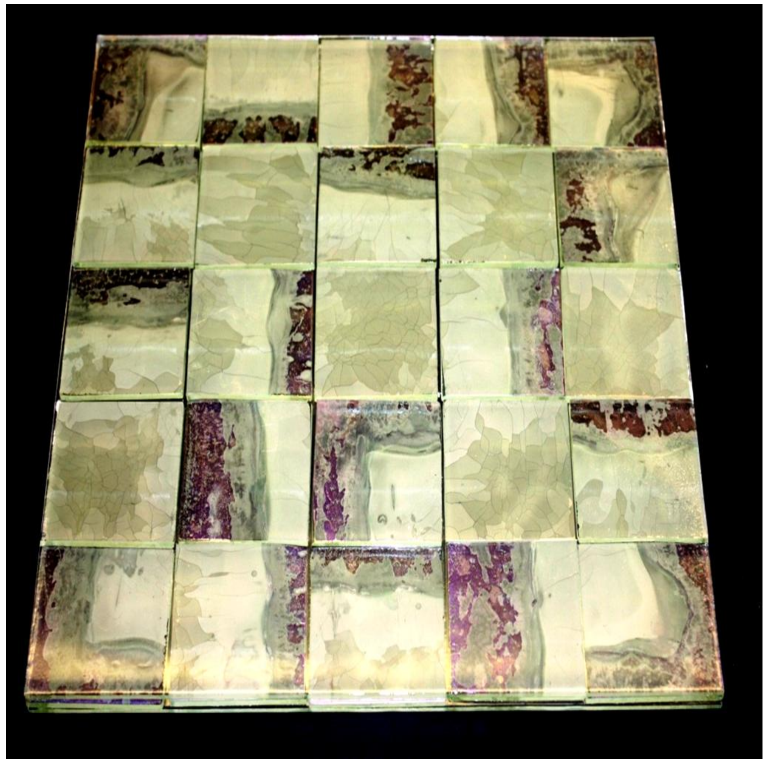


Figure 6.13 Test for 'Chequer Board', Eileen Leatherland, 2011, 4mm K fired 'face to face' cut and fused between float.

Figure 6.14 Test 2 for 'Chequer Board' , Eileen Leatherland, 2011, 4mm K fired 'face to face', on blue enamelled float glass.

Potential for the application of fired K Glass without any pre-fired treatment is quite extensive. As previously stated, it can be used as the glass artist would use regular float glass but with a different visual effect. Small pieces laminated as, for example, in a small decorative wall panel as shown in Figure 6.15, could be enlarged to create a room divider. Pieces of fired K Glass could also form part of a traditional stained glass window. It would have to be remembered that transmitted light would not contain colour as seen through stained glass, nor would colour be seen indoors with natural light from outside (*See 6.5.3, p.224*). However, its colour and iridescence could be seen in reflection from the sun or would befit an internal window with artificial front lighting in, for example, a restaurant or nightclub. At night, with external darkness the internal surface of the window may become a dynamic focus as the artificial glow reflects iridescence and colour. It also should be noted that the firing process damages any low emissivity properties but these could be reinstated with additional panels through lamination.

Figure 6.15 Laminated wall panel, Eileen Leatherland, 2011, 4mm K between 4mm float glass.

The surface of K coating, manipulated by abrasion, formed the basis of several designs. To have comparative information of the variable effects that could be achieved for artwork design, a standardised study of various abrasive forms and strengths was undertaken, firstly, in flat firing (*Figure 6.16*) and, secondly, in the curved form (*Figure 6.17)*.

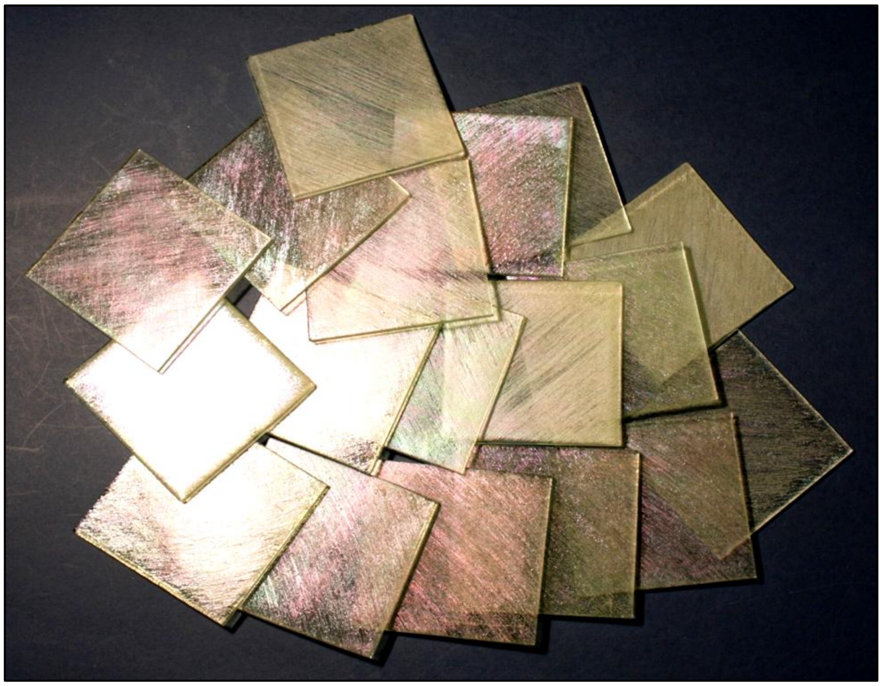


Figure 6.16 4mm K and 6mm K, flat abrasion test squares.

Figure 6.17 4mm K and 6mm K, curved abrasion test pieces.

The unique interferential characteristic developed during this research, like the experience created by Bell, involved the participation of the movement of the viewer. Although in evidence on a two-dimensional piece, as the viewer moves his head, this feature is particularly obvious on the curved or bent surface. The curved surface which presents variable colouration can form the basis of many exciting design concepts, two or three-dimensional. Curves can be vertical, horizontal or diagonal as in Figures 6.18 and 6.19 or in combination with added surface design for example in Figure 6.20, each showing its individual characteristic of colour or iridescence in response to the angles of viewing and source of light. Potential application is wide throughout the field of creative glass but particularly appropriate for interior design, where hanging features, wall panels, bowls or free standing sculptures would exhibit the response of the interferential colouration to artificial light.

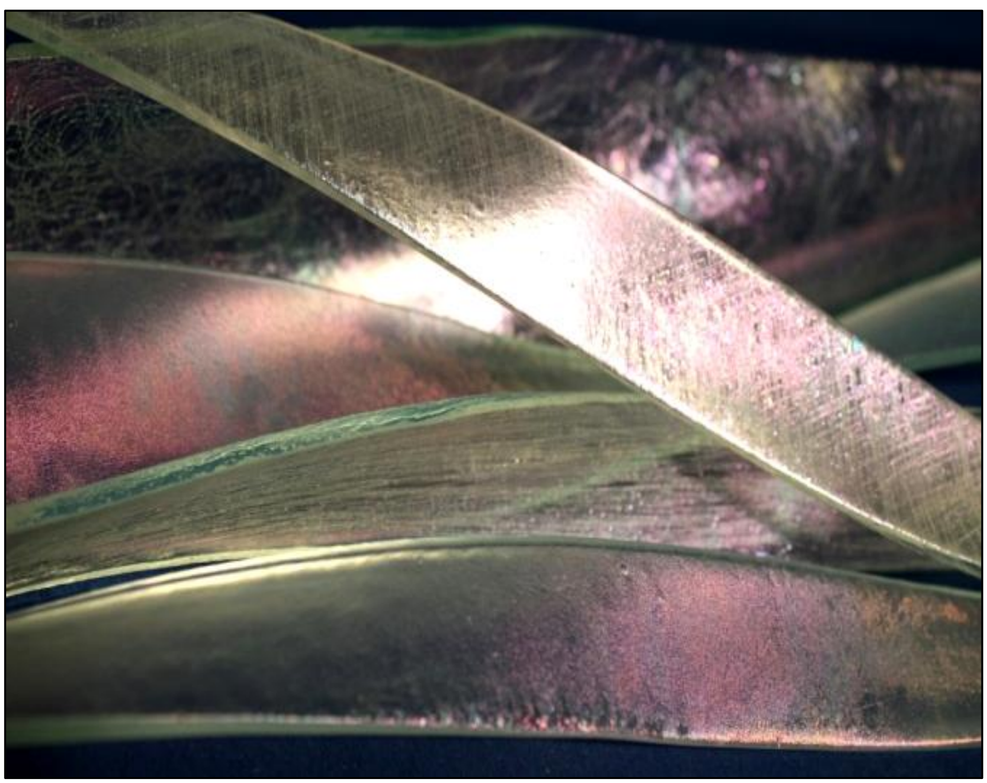


Figure 6.18 *4mm K, curved diagonal strips showing interferential response to light source.*

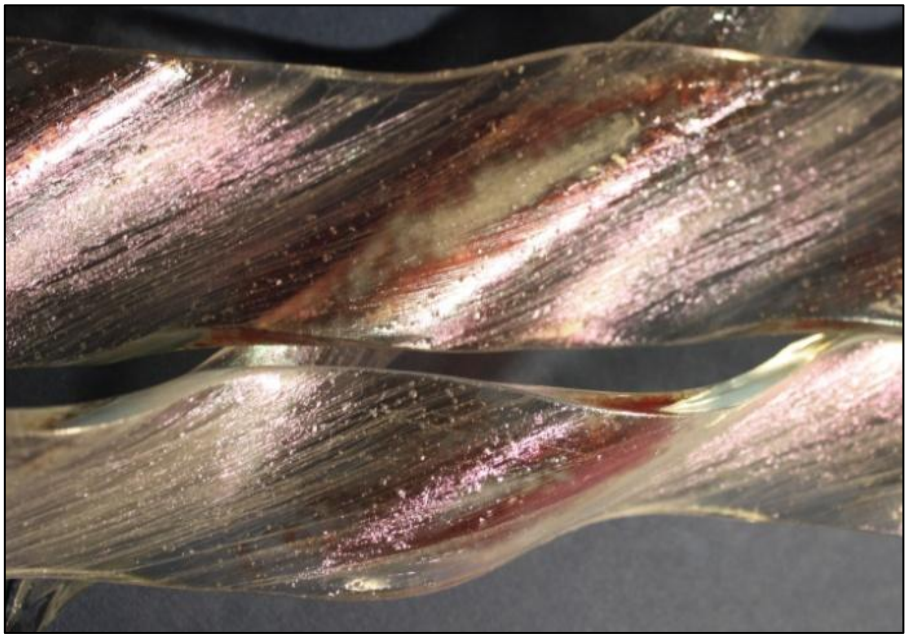


Figure 6.19 4mm K, curved diagonal bent over copper pipe.

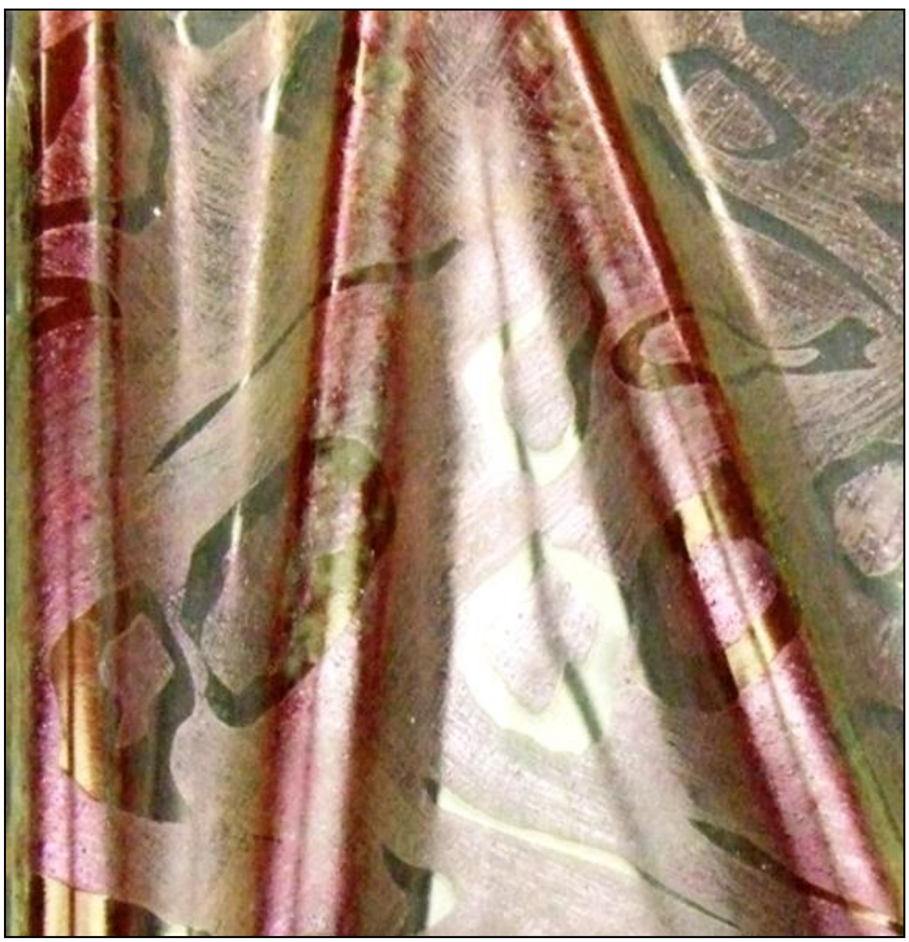


Figure 6.20 4mm K, sandblasted bubble and ripple test design bent over copper pipe.

Leading the eye of the viewer around the artwork to appreciate the interferential nature of the effect was the aim in the test piece shown in Figure 6.21, by using text on a curved form. This was a more formal design approach but one which was very much suited to the coated surface. To achieve the contrast of text on float glass, treatments such as engraving or sandblasting have to be applied. Letter artist, Peter Furlonger, uses both these in his beautiful calligraphic work on glass. Text produced using K Glass has the added effects of unique colouration, iridescence and interferential elusiveness of the K coating image.

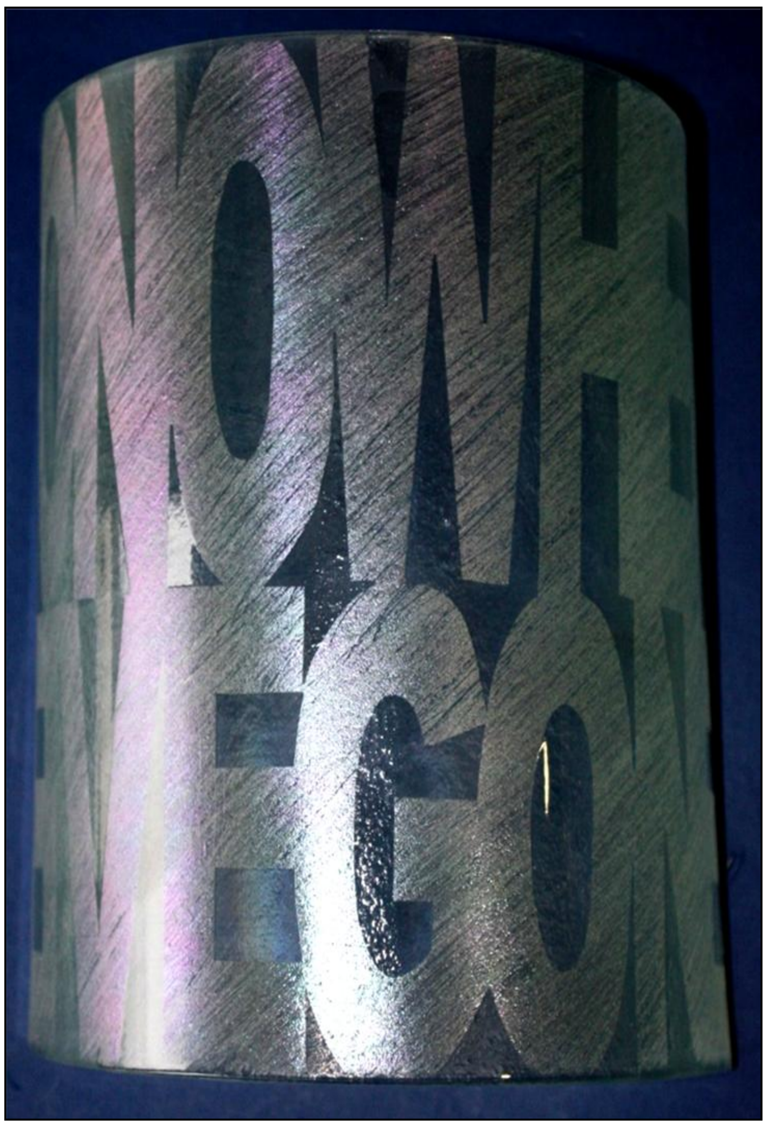


Figure 6.21 'To Nowhere', Eileen Leatherland, 2011, 6mm K, scored text design.

The versatility of manipulated open fired K Glass takes its application from large scale architectural features, through interior design to gallery presentations including very small items such as jewellery (*Figure 6.22*).

Figure 6.22 *'Necklace', Eileen Leatherland, 2011, 4mm K.*

A small experimental three-dimensional sculpture created late in the research programme underlined this versatility. A pyramid with a base measurement of 100mm square was built upwards with decreasing sized squares of 6mm K glass. This stacking structure, used in the work of several artists, for example, Danny Lane, is not new. What is unique is the post-fired effect that was created. Throughout this research the loss of colour due to the positioning of the flat surface in front of a light source has been relevant. This piece shows in Figure 6.23, the possibilities of transmitted light reflecting the interferential colours off the internal coated surfaces through the exposed edges of the glass and opens up a whole new area of application. This effect has great potential in the area of, again, interior design, for wall or ceiling features.

Figure 6.23 *Small pyramid, 100mm x 100mm x 60mm, 6mm K.*

6.4 Creative Possibilities of Fired Low Emissivity K Glass using the Mirror Gap Technique

The format used for the Grid tests produced such unusual colouration that it was the inspiration for larger square pieces including several plates, two of which were similar to those in Figure 6.24 and sold at the 'Glass 3' exhibition in Washington DC in 2008.

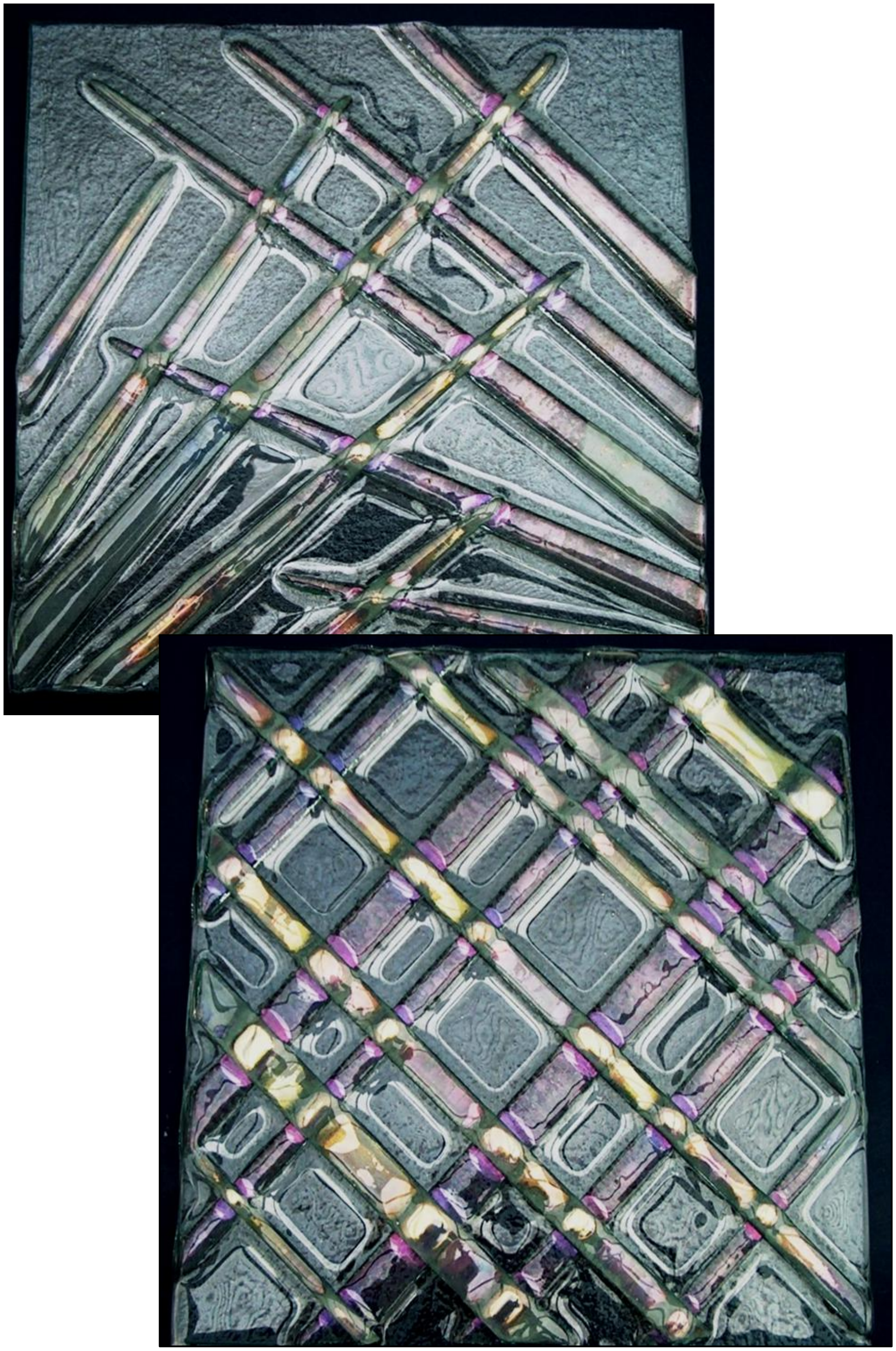


Figure 6.24 'Washington Bowls', Eileen Leatherland, 2008, 300mm x 300mm. 4mm K and 4mm float glass.

This fused artwork was the precursor to that which has been developed using the Mirror Gap Technique. This innovative effect has been a main feature of the research and the creative development through artwork exhibits its unique characteristics. Each design was developed to exploit the possible range of colouration and iridescence as well as the overall interferential effect, as seen in the fused glass combination. The ability to produce gold colouration within the glass directed the inspiration for artwork imagery in the same way as the interferential aspect influenced the form.

Plate 7, in Figure 6.25, was designed using the Mirror Gap Technique for exhibition in Dubai and was influenced by the geometric style and gold colouration found in Middle Eastern Art. The reaction from members of the Association of Professional Interior Designers (APID) and, in particular, Leo William Biles and Leslie Jones of John R Harris and Partners, suggested this method was relevant to their customers requirements and might have a positive application within the area of interior design. Their use of gold leaf was expensive and was a material which degraded losing its appearance over time. The developed gold effect of K Glass was inexpensive and the colouration within the fused glass layers cannot be abraded or affected by the external environment.

During the trials for these plates the possibility of providing a dark background for the imagery was considered. Coloured float glass, which, according to the suppliers Pearsons of Liverpool, was compatible with regular float glass, was used as an additional base layer for Plate 8. The strength of the blue background enhanced the gold colouration obtained by the Mirror Gap Technique but, during fusing, large bubbles formed between the blue base and the intermediate layer (*Figure 6.26*). This problem was addressed in later work by using the coloured float in small sections. Tests using glass and ceramic enamels proved successful in providing additional colour as a design feature.

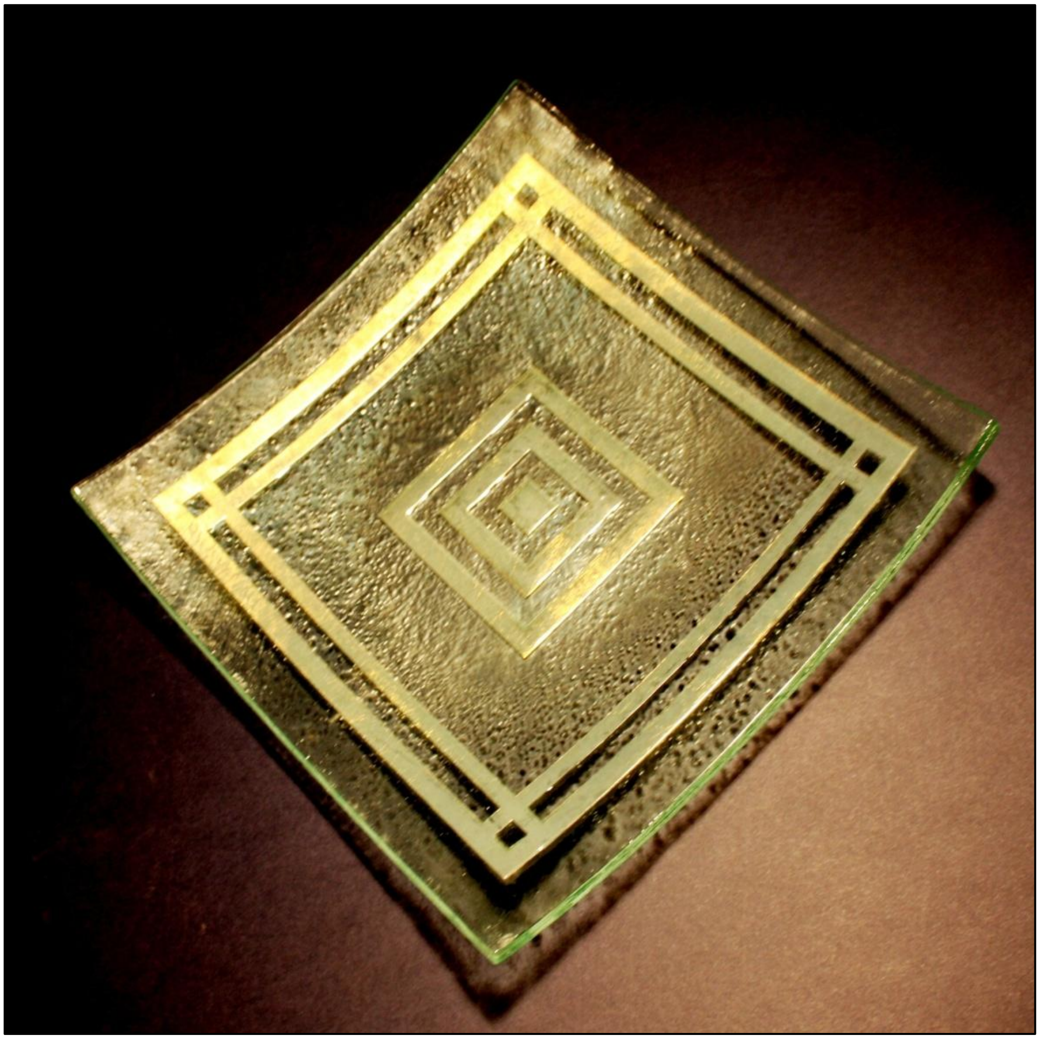


Figure 6.25 'Plate 7', Mirror Gap Technique. Eileen Leatherland, 2007, 300mm x 300mm, 4mm K and 4mm float glass.

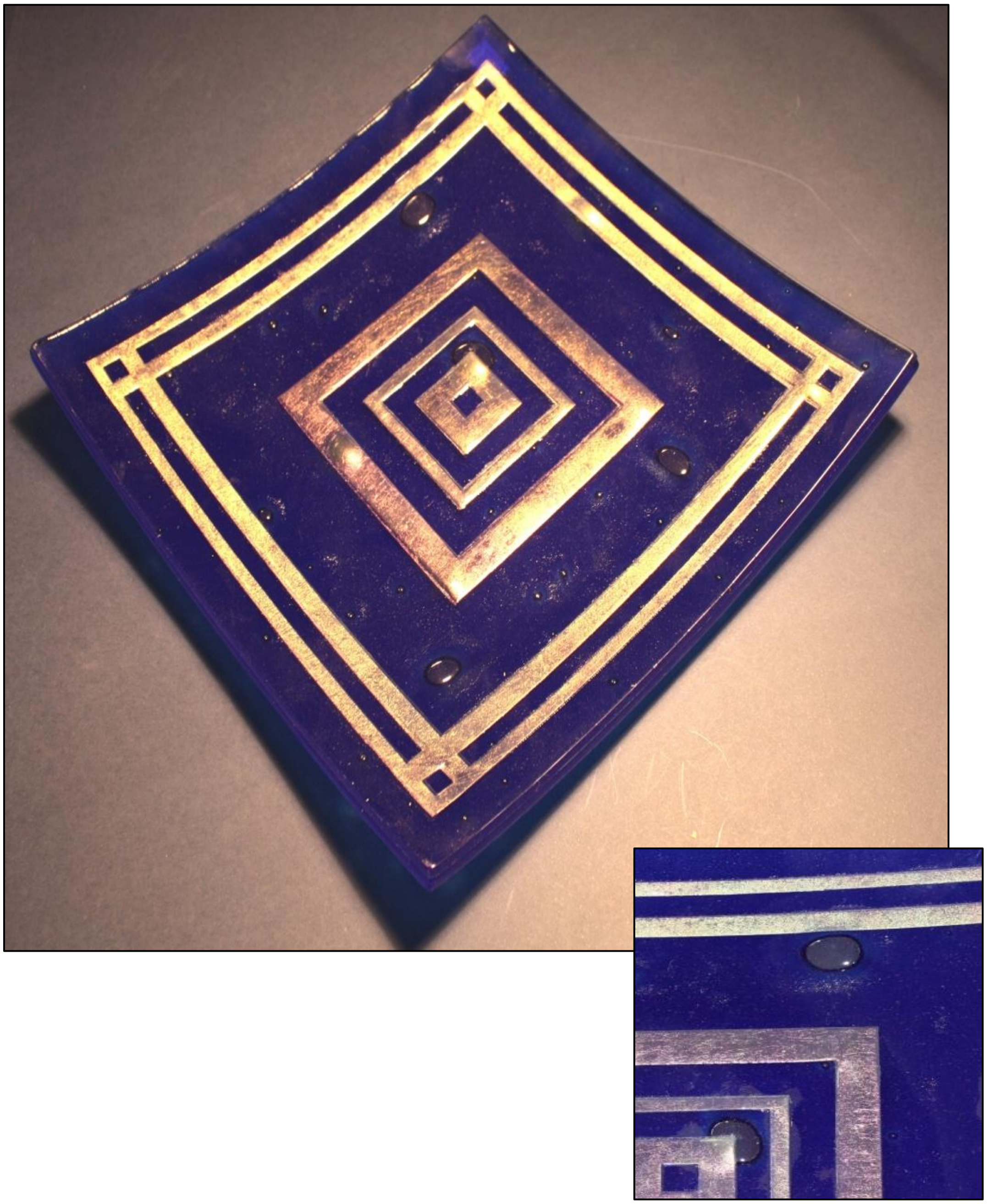


Figure 6.26 'Plate 8', Mirror Gap Technique, Eileen Leatherland, 2007, 250mm x 250mm, 4mm K, 4mm float and blue float. Detail showing bubbles formed between fused layers.

Plate 9 continued the geometric theme and aimed to combine the gold from the Mirror Gap Technique with the surface erosion effects used for Plates 2 to 4, using K for the top layer as well as for the base. As with the open fired plates, the curved form encouraged the maximisation of the interferential characteristics of the post-fired K coating and could be used to great effect for items such as table ware.

Although, as stated previously with regard to the firing of the open fired artwork, most of the Mirror Gap Technique procedures used the normal standardised testing schedule. However, two different programmes were tried with two separate plates. The first plate revealed air patches between the layers and the strong pink colouration was incongruous with the gold within the small squares (*Figure 6.27).* The second plate, using the slower programme to 800˚C and held for 40 minutes, produced a more subtle and compatible colouration and fewer patches (*Figure 6.28).* The problem of trapped air between layers of glass is one which is well known to glass artists working in the area of fusing. At present, Joanne Mitchell, from the University of Sunderland, is currently working on a solution for her PhD dissertation.

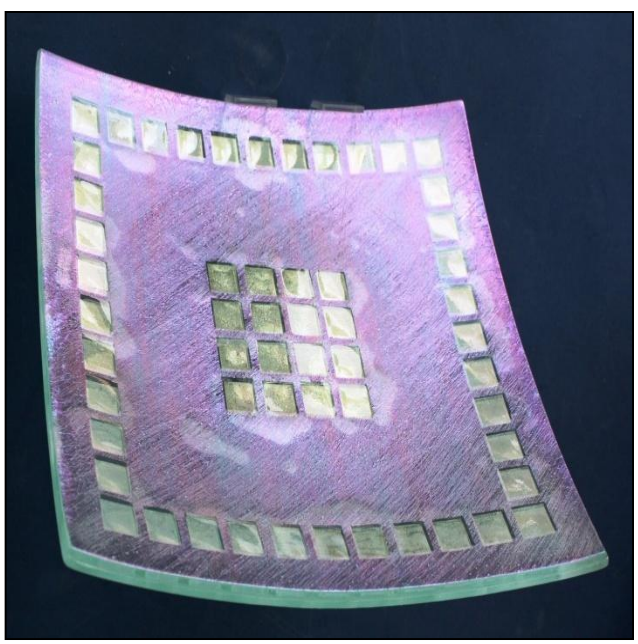


Figure 6.27 ‘Plate 9’, Test plate,
4mm K and 4mm float, Mirror Gap Technique with scored upper layer.

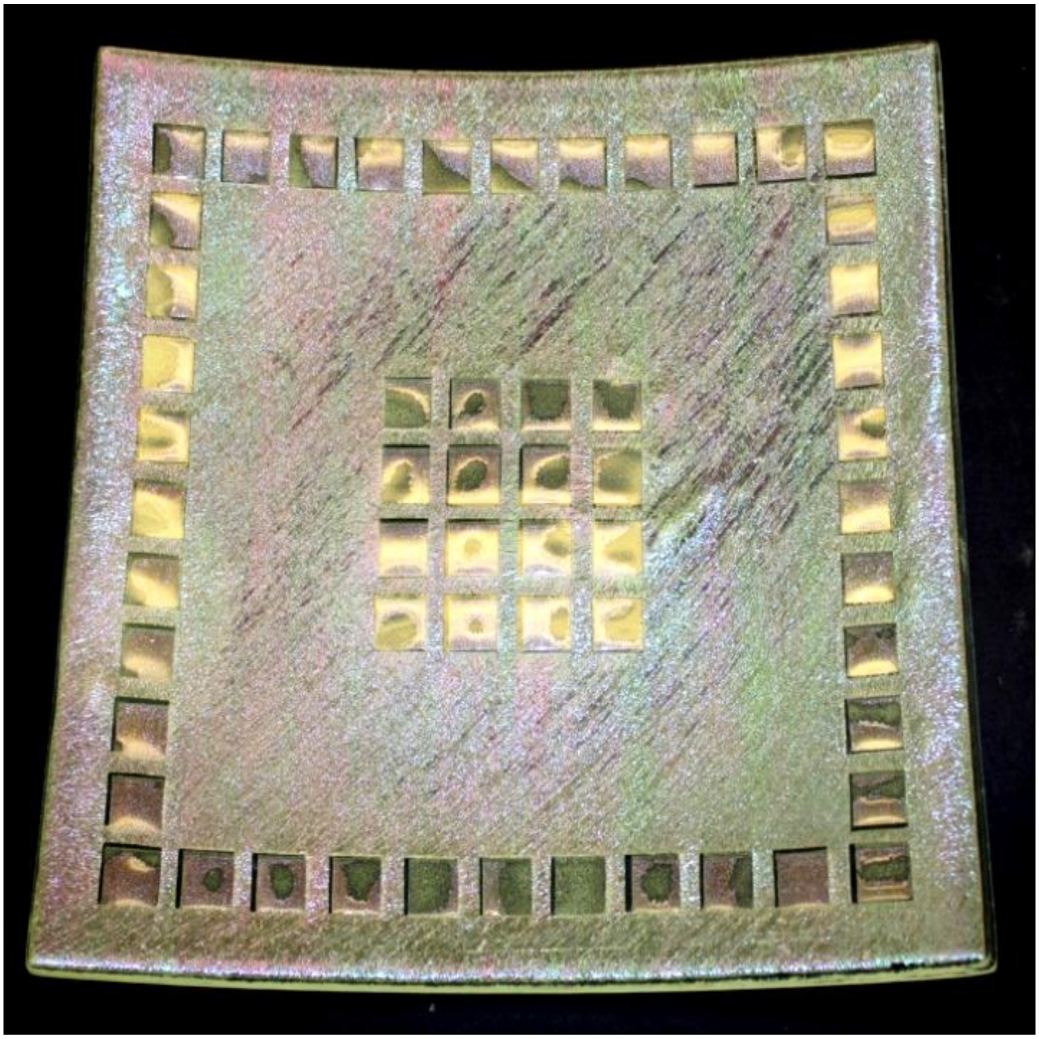


Figure 6.28 *'Plate 9', Eileen Leatherland, 2011, 250mm x 250mm.*
4mm K and 4mm float glass, Mirror Gap Technique.

As part of the Clayton Glass award scheme, Plate 10 was designed and prepared using ST150 (*Figure 6.29).* The process was identical to that used for K Glass but used the lower temperature, necessary to protect the coating from heat damage. The result was without the interferential effect of the colouration but its metallic appearance was entirely suitable for the purpose.

Figure 6.29 *'Plate 10', Eileen Leatherland, 2009, 280mm x 280mm.*
4mm ST150 and 4mm float glass, Mirror Gap Technique.

The preparation of the glass used for the Mirror Gap Technique required positive and reverse images to be masked, cut and sandblasted (*See 5.2, p.149*). Using the APM photographic stencil method much more accurate and finer detail, such as in the Dubai stencil in Figure 6.30, was achieved than that using masking film and a craft knife. This method can be adapted, with preliminary preparation in Adobe Photoshop, to convert a photograph to a format suitable for stencil making. Although the resultant image of the falcon in Figure 6.31 was not a perfect representation, the method is one which has potential using the Mirror Gap Technique.

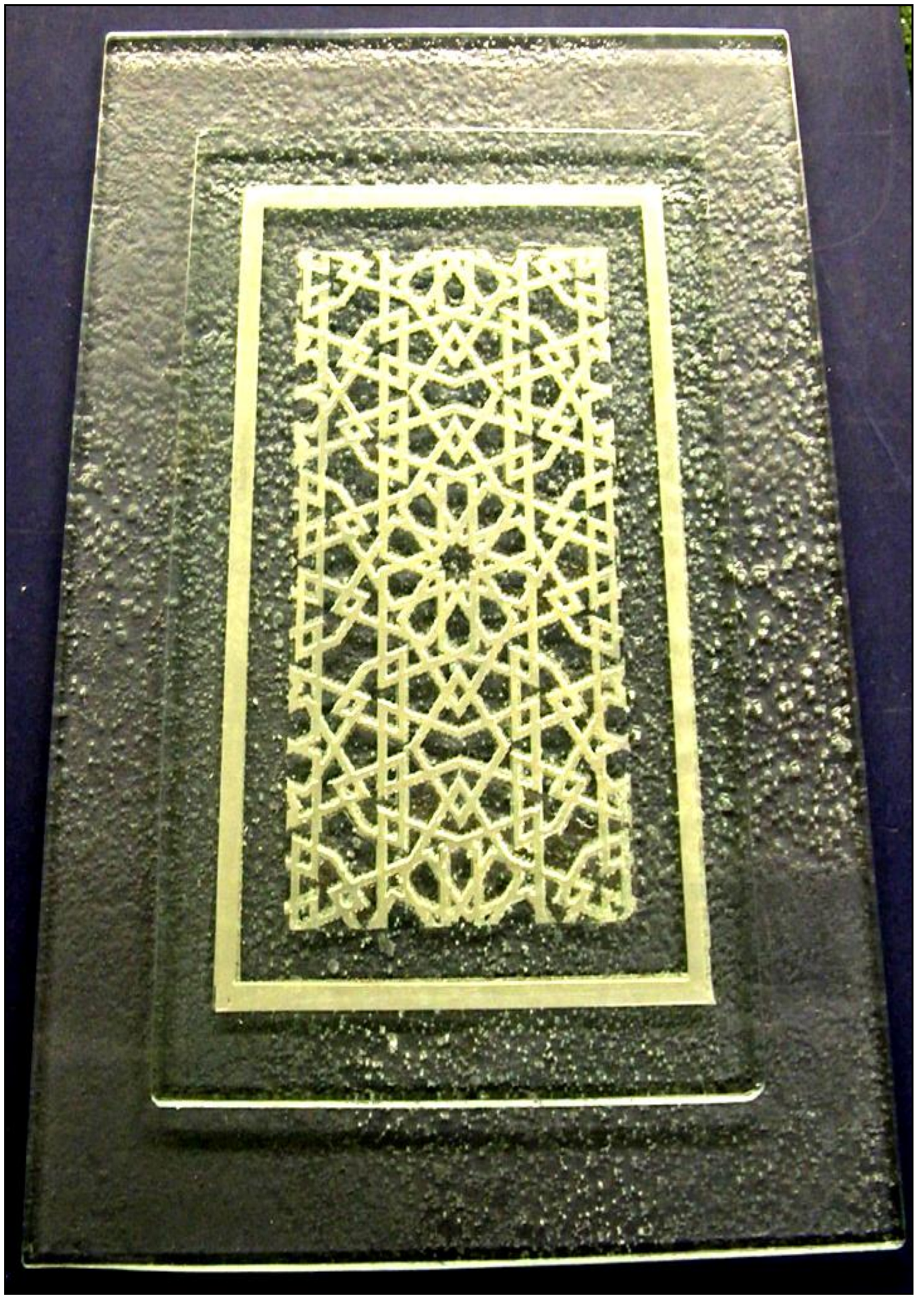


Figure 6.30 Dubai stencil, 270mm x 200mm, 4mm K and 4mm float, Mirror Gap Technique.

Figure 6.31 *'Falcon', 330mm x 270mm, 4mm K and 4mm float, Mirror Gap Technique.*

Unlike artwork using the open surface of K, the Mirror Gap Technique necessitates a much more controlled design. The limitation of size of the colouration (*See 5.4.1, p.158*) may mean that a design could be made up of small areas or converted to one of more suitable proportions. To test this through artwork, two images of a face, one positive and one negative were made from a photograph. These were then translated through the Mirror Gap Technique to a line image and a smaller block image (*Figure 6.32*).

Figure 6.32 'Faces 1 and 2', 300mm x 210mm and 220mm x 160mm, 4mm K and 4mm float, Mirror Gap Technique. Positive and negative versions of photographic image.

The controlled design and gold colouration indicated the technique was particularly suitable for text applications, for example, the ICCG7 Conference gift in Section *5.4.2, p.160*, or 'Morning Sunlight' in Section 6.5.3, p.226, which was inspired and developed using the creative calligraphy of Dr. Manny Ling of the University of Sunderland. 'Triptych', shown in Figure 6.33 is a wall presentation of Old English style text on three curved panels. As with float glass, a three-dimensional work such as 'Triptych' can be constructed using K but, using the Mirror Gap Technique, has the additional innovative effect of coloured and iridescent imagery enclosed within the glass. Once the colouration has been established during the initial firing, it is not affected in the subsequent process of bending. Curved pieces of this nature are suitable for areas where the fascination of the interferential effect could be witnessed by passing viewers, for example, along a walkway. The safety implication in such public situations is discussed in Section 6.6, p.228.

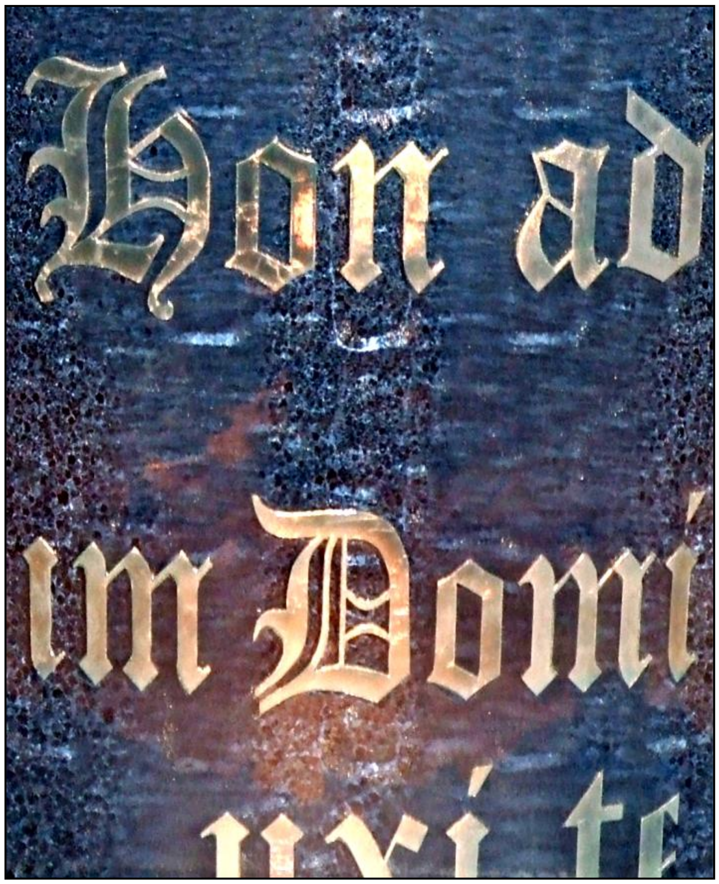


Figure 6.33 'Triptych' (detail), Eileen Leatherland, 2006, One of 3 Panels each 300mm x 250mm, 4mm K and 4mm float, Mirror Gap Technique.

Three-dimensional artwork using two-dimensional flat panels was made in the early stages of this research. The free standing structure 'Pyramid' in Figure 6.34 allowed access to viewer movement so that the internal colouration within each panel could be seen in its interferential form being reflected back up to the eye from the sloping sides. In daylight the effect was less vibrant. With natural light falling on all sides, there was a constant source from the back of each panel and the overall effect was a diminution of colour. However, when artificial light was focused directly on the panels, the success of the piece was evident.

Figure 6.34 'Pyramid', Eileen Leatherland, 2006, Height 950mm, 4mm K and 4mm float, stainless steel base, Mirror Gap Technique.

The use of broken K pieces as a three dimensional casting medium proved to be disappointing with no coating colouration development seen within the reformed kiln cast fired glass. An attempt to use K as a blowing medium was also found to be unsuccessful due to its inability to soften to the required consistency. However, further three-dimensional possibilities were explored using the Mirror Gap Technique within several layers of glass, fused together to form a cube (*Figure 6.35*). This was a piece which suggested significant creative potential, not only as an individual sculptural artwork but also within the area of interior design for inclusion in, for example, small items of furniture.

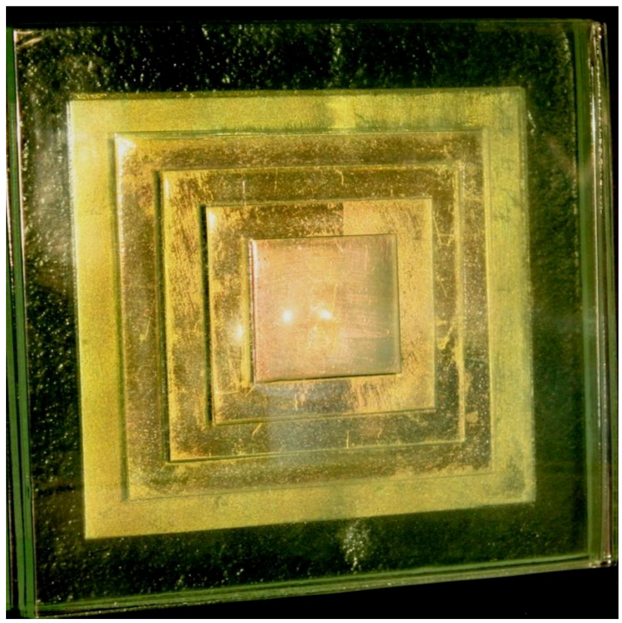


Figure 6.35 'Squares', 165mm x 165mm x 23mm, 6mm K and 6mm float, Mirror Gap Technique.

In the latter stages of this research a new coated glass known as KOW, by Pilkington, has entered the construction market. It has a K low emissivity coating deposited on the low iron glass Optiwhite, which has a far less green appearance than float. After an investigation to confirm that the coating would react in the same way as the original K coating, a small test piece shown in Figure 6.36, was made using KOW and Optiwhite, similar to 'Squares' above. The result has opened a new area of enquiry. Similar to K Glass, KOW glass had a slightly brownish appearance in its as-received condition. However, once the unwanted coating was sandblasted away, the fused sheets were left almost colourless and no longer tainted by the green float. This allowed the warm, rich, iridescent, colouration to radiate through the clear glass. Although KOW and Optiwhite are more expensive than regular Pilkington K, for Mirror Gap Technique artwork, the visible advantage justifies the cost.

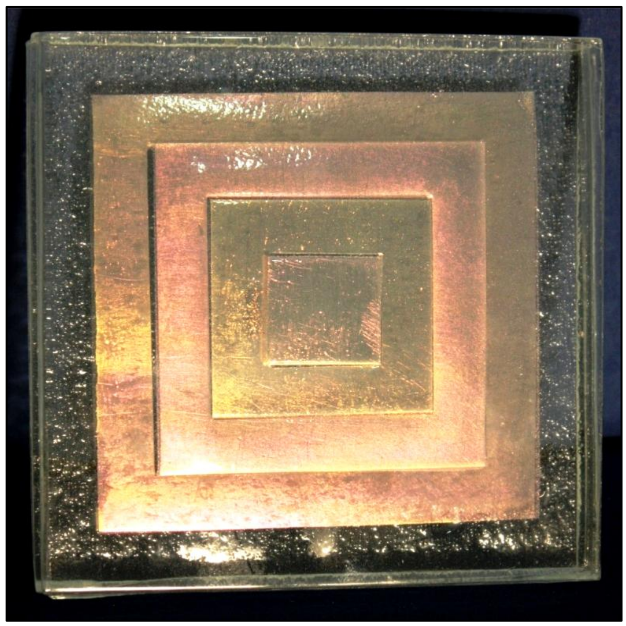


Figure 6.36   KOW fused test piece, 100mm x 100mm x 23mm, 2011, KOW and Optiwhite square, Mirror Gap Technique.

Complex water jet cutting, such as that seen in the work of Vanessa Cutler (*See 2.2, p.12*), was particularly suited to the Mirror Gap Technique. Narrow sections of glass offered the ideal base for the development of colouration and enabled the production of a wall panel which was created for Dubai but sold in Washington DC. The design in three parts was inspired by the traditional boat of Dubai, the Dhow. Each part was cut to allow mirror gaps to be created along 'stripes' where the colouration could be developed. At the time of photography, 'Dhow' was set on a blue background (*Figure 6.37*). When exhibited and sold, it was fixed to a panel of sectioned blue float glass to ensure the permanency of the optimum viewing effect.

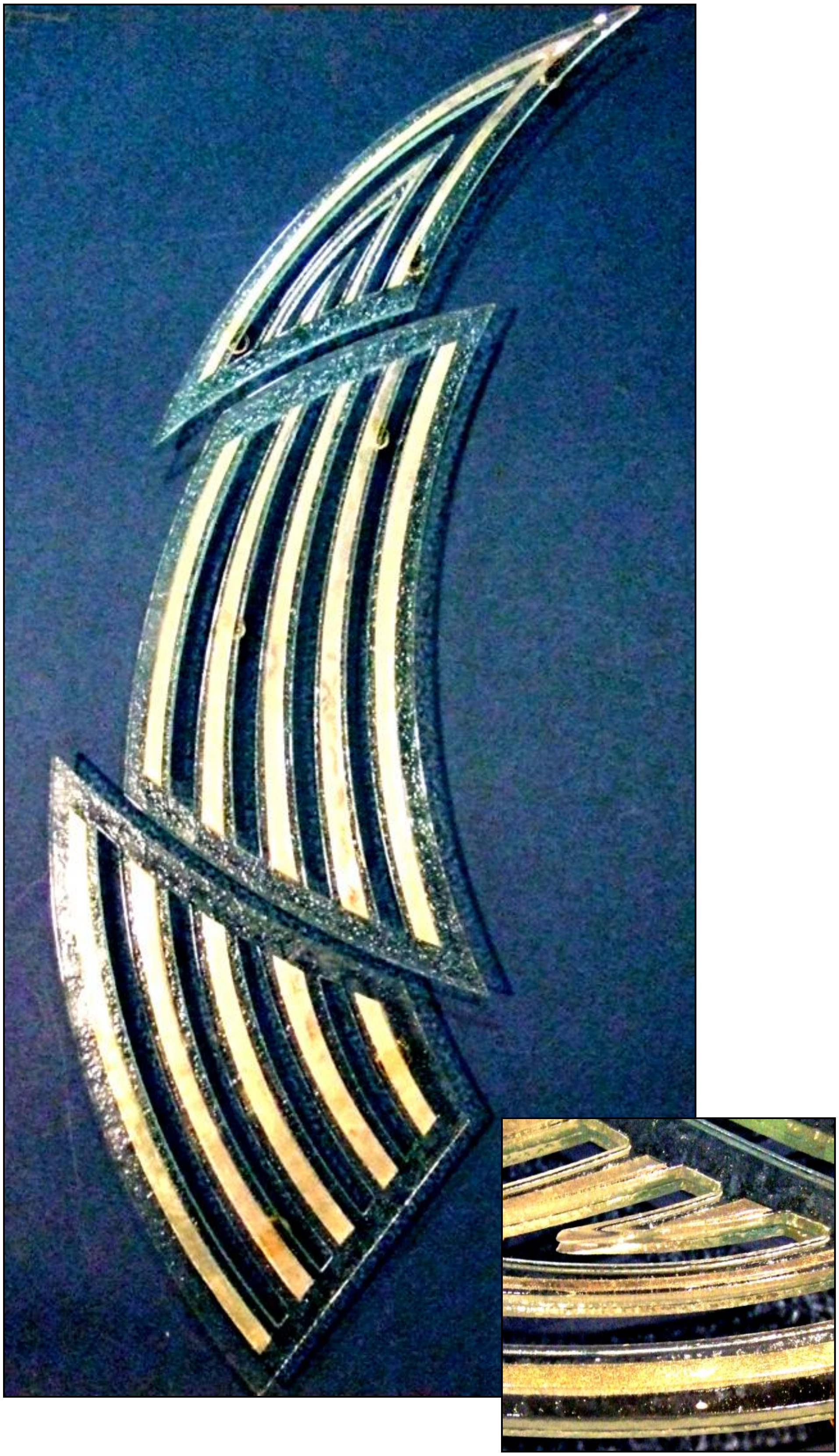


Figure 6.37 'Dhow' and detail, Eileen Leatherland, 2007, Height 900mm, 4mm K and 4mm float glass, Mirror Gap Technique.

6.5 Interferential Properties of the Post-fired K Glass

The interferential properties of the post-fired K Glass were deemed to be responsible for the unusual and elusive colouration and iridescence seen within the artwork. Due to the nature of interference, in order to create and develop artwork, the location or position of each piece as well as the background setting and the source of lighting was extremely important. These have been considered in this section.

6.5.1 Angle of Viewing

The colouration developed in this research and its interferential nature which causes it to appear and disappear with the movement of the viewer, defines the elusive characteristic of the manipulated K coating. As well as being a major factor of consideration in the overall concept of artwork, it has created a benchmark for its location in a position where this characteristic can be exploited such as airport walkways or hotel lobbies.

The study of the surface effects with regard to the angle of viewing could be complex if all options in relation to position, height, or distance were considered. For the purposes of this research, an outline examination only was undertaken to demonstrate the changing appearance of the artwork from a variable viewpoint. Two viewing situations were examined namely, all the angles in front of a piece of flat glass and the similar viewing angles around a piece of curved glass.

With an artificial light source at 90˚ (or normal) to the surface of a flat piece of post-fired K Glass, the colouration can be seen with the eye from almost all angles either side of the normal to the glass surface, i.e. 80˚ to the left of the normal and 80˚ to the right, not completely 180˚ (*Figure 6.38*).

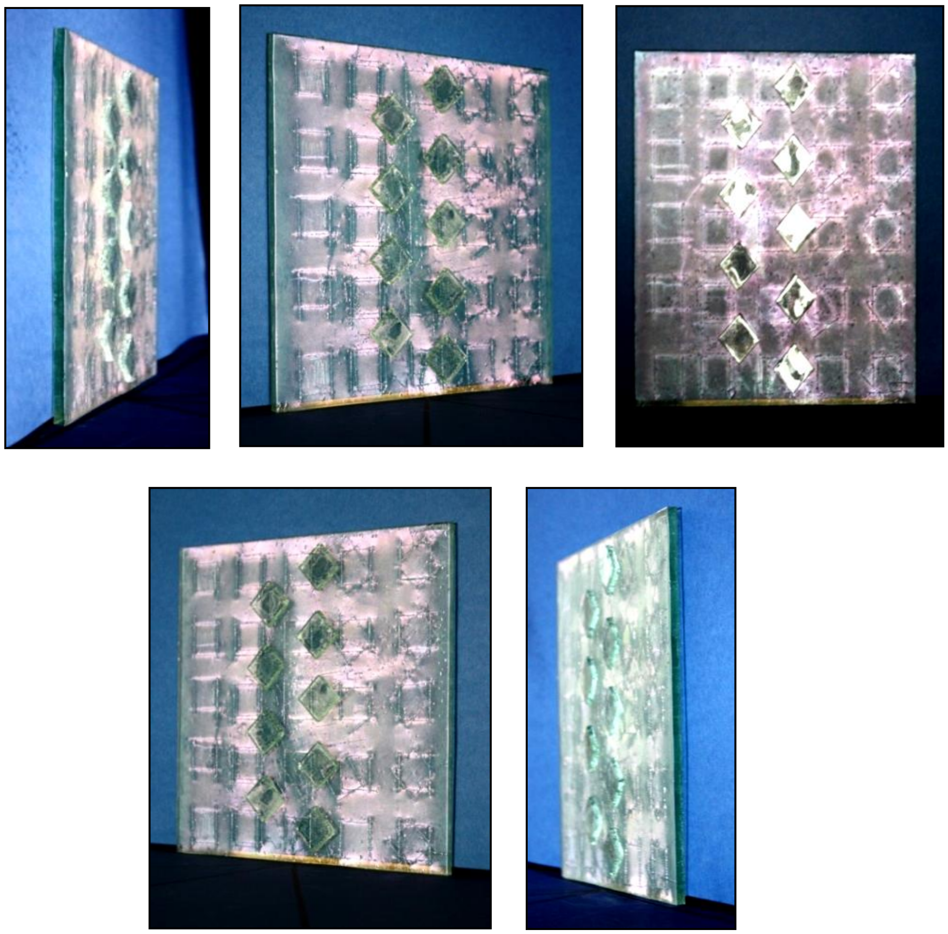


Figure 6.38 Angle of viewing of flat glass showing colour seen at angles through 160˚.

On a curved surface, the colouration can only be seen on the specific area of glass which is reflecting the source of light, as the viewer is always at an approximate normal to the surface if they walk round or past the piece (*Figures 6.39*). As the position of the viewer changes so does the area of colouration. This factor is relevant to all artwork undertaken with this manipulated glass but particularly with regard to free standing pieces.

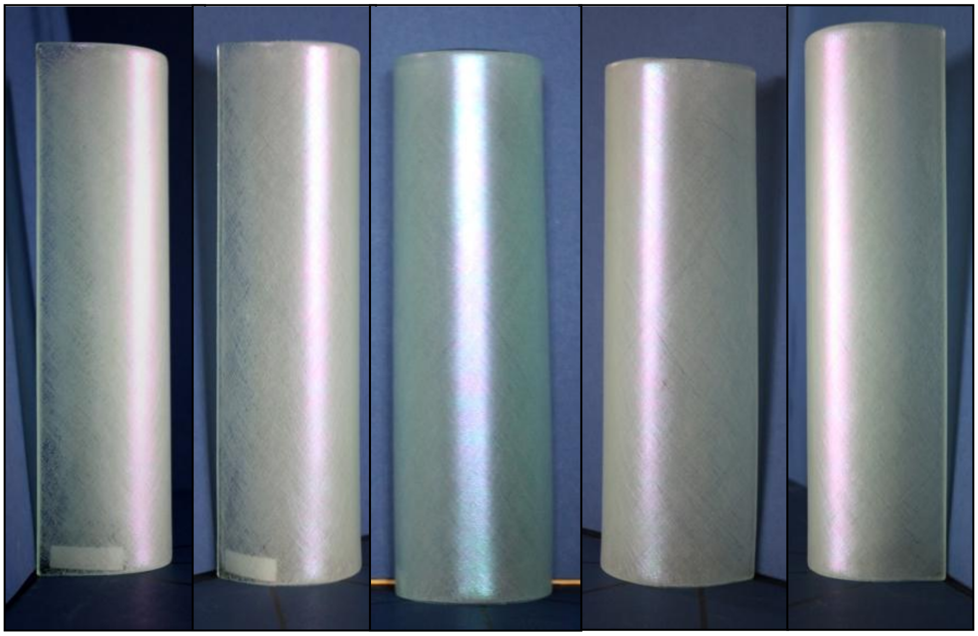


Figure 6.39 *Angle of viewing of curved glass showing colour seen at angles of reflection of light through 160˚.*

6.5.2 Background

The transient property of the achieved colouration is perhaps its most unusual characteristic. This is a reflected colouration and not a pigment within the body of the glass (*See 3.4.1, p.78).* This causes the colouration to mostly disappear when presented on a light coloured background; the lighter the background, the greater the loss of colour (*Figures 6.40 and 6.41*). This is neither total nor permanent, as with movement some colouration will be observed. To try to overcome this situation, some artwork was designed with a base of either blue glass or applied enamel to provide a background colour. After experiments with background of other colours, blue was considered the optimum colour for the appreciation of the colouration and iridescence. Images taken on red and green backgrounds can be found in Appendix B, p.256.

Coloured film was also considered and is discussed in relation to the options to ensure the safety aspect of work (*See 6.6, p.228).*

Figure 6.40 4mm K moulded test on a dark background.

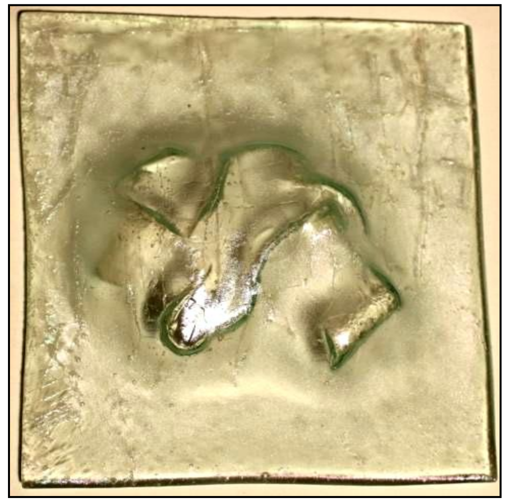


Figure 6.41 4mm K moulded test on a light background.

The loss of colour is not necessarily always a drawback. It may add interest to the work by offering an additional feature of imagery that can be monotone, as in a sandblasted design, but recurring with colour as lighting conditions change. It therefore follows that the specific background colour, as well as the lighting, of each interferential surface of a piece of post-fired K Glass, needs to be considered in the design of artwork.

6.5.3 Light Source

As discussed above, a light background will cause the colouration to be seriously diminished. However, if there is also a strong source of front lighting some of the iridescence and colour may still be seen. Colouration is at its most intense when facing the direct line of rays of strong natural or artificial light. The implications of this must be taken into consideration for all potential applications of this manipulated glass, large or small, home or gallery, interior or exterior setting. Lighting options need to be individually tailored to specific artwork and location but can basically be categorised by lighting from the back and lighting from the front (*Figures 6.42 to 6.45*). Variations within these categories are wide but offer indicators as to some of the requirements for the display of post-fired K Glass.

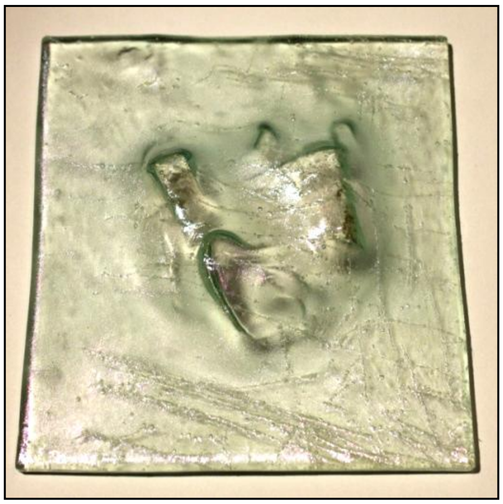


Figure 6.42 Light background. No additional lighting.

Figure 6.43 Light background. Additional front lighting.

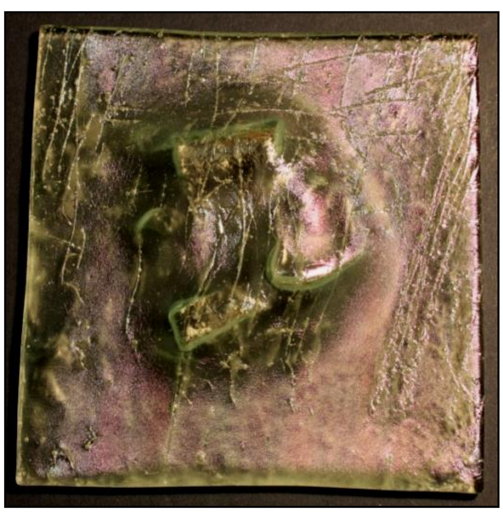


Figure 6.44 Dark background. No additional lighting.

Figure 6.45 Dark background. Additional front lighting.

6.5.3 Photography

The nature of the developed colouration caused it to be exceptionally difficult to interpret through the lens of a camera. Even those with the highest specification may not reproduce the character of the visual effects. The interferential characteristic is not only responsible for the difference in what the naked eye sees but also what the camera lens captures. It was found that a photograph of post-fired K coating needed to be taken at an oblique angle to the glass but the slightest movement of the camera could cause the loss of colour.

In some situations more than one source of light was necessary. Front lighting required to maximise colouration was less of a problem with open fired than with Mirror Gap Technique work. The light that was required to reveal the colour, also reflected off the top surface of the fused float glass and the resultant glare obscured the image. Professional glass photographer, David Williams, resorted to taking two images of the laminated panel 'Morning Sunlight' and uniting them in Adobe Photoshop (*Figure 6.46*). A high resolution distance shot which can be cropped later can help to encompass an overall effect.

The photographed colour is often not true to the work and can differ with natural or artificial light or the setting used on the camera. A dark background absorbs some of the light and allows a more accurate representation of the actual colour seen. For this reason, throughout this thesis photography of the glass has been taken on a dark background. For consistency this has been restricted to blue so that details can be observed and compared clearly.

Figure 6.46 'Morning Sunlight ', Eileen Leatherland, 2009.
Design by Manny Ling, 950mm x 450mm, 4mm K and 4mm float glass.
Laminated with fabric enclosures and Mirror Gap Technique.

6.6 Safety of Presentation

The potential of the creative use of Pilkington K low emissivity glass and the subsequent extending of this application to other coated glass raises an important question regarding the use in public areas and especially in the field of interior and architectural design. K Glass in its manufactured state can be toughened (Pilkington, 2006). However, according to Stephenson (2011), the post-fired K coating would render it unsuitable to undergo the toughening process. In addition, in the case of the Mirror Gap Technique artwork, the air contained within the fused glass layer could explode in the toughening furnace.

When required by Health and Safety regulations alternatives are possible, for example, lamination or the application of safety film to contain splintering in the event of a break. Lamination for large pieces which is offered by processors such as Peterlee Glass Company Limited would involve an additional sheet of float glass with an intermediate layer of resin (PLG Glass, 2006). The resin itself could be coloured or include other materials as in ‘Morning Sunlight’ which presents a further possibility of creative options.

Applied film is an alternative where lamination may not be suitable as in the case of Mirror Gap Technique artwork. This can be specifically for safety but can also be coloured (Abode Window Films, 2011) or printed with a graphic design (*See 2.10.2, p.40*). A further option suitable for artwork of a complex form is a brush applied liquid which dries to form a protective film (Ifoha, 2011). It is worthy of note that none of these methods cause any further change to the surface of the manipulated glass.

6.7 Summary

This chapter has outlined creative possibilities that have been developed through artwork and show three clear lines of potential:

- Manipulation of the surface of Pilkington K low emissivity glass in an open fired situation.
- Through the Mirror Gap Technique.
- Opportunities using other coated low emissivity glass.

The artistic outcomes can be summarised as follows:

- Unusual surface effects can be achieved by heating low emissivity K Glass in an open fired situation. These include pink/purple colouration, iridescence, bubbles and an interferential angle of viewing.
- New concepts in visual effects have been created through the interferential properties of the fired surface coating.
- Site and lighting of artwork need to be considered to obtain optimum effect.
- Unique creation and development of the Mirror Gap Technique.
- Dimensions of imagery in Mirror Gap Technique adjusted to accommodate sagging of upper piece of float glass during firing.
- Repeatability can be affected by variables such as the quality or freshness of sandblasting grit.
- Methods to manipulate and open fire the surface coating of K Glass and fusing techniques including the Mirror Gap Technique can be applied to many areas of creative glass.
- Methods developed to manipulate the surface coating of K Glass can be applied to other coated glasses extending the range of creative possibilities.

Chapter 7

Conclusions and Areas for Further Research

In this chapter, the research outcomes are described in relation to its aims and objectives. Specific reference is made to the originality of these outcomes and the possibilities for the protection of the intellectual property. Areas for further research include the opportunity to expand the techniques through the increasing range of surface coatings and the commercial potential of the developed techniques.

7.1 Outcomes in Relation to the Aims of the Research

The aims of the research were addressed through five objectives (*See 1.4, p.6).*

7.1.1 In Relation to the First Objective:

'To identify the visual changes to the K Glass surface coating when subjected to high temperatures'.

The identification of the visual changes was undertaken through the programme of standardised tests. From these results, it was concluded that:

- Coatings on 4mm and 6mm K Glass produced similar post-fired visual effects in terms of colour, iridescence, and bubbles.
- Visual changes to the open fired K surface were detected at 690˚C with no significant changes taking place above 800˚C.
- Colouration on the open fired K surface began as very pale pink at 720˚C with maximum pink/purple strength seen between 775˚C and 800˚C.
- Iridescence was first seen at 690˚C and increased to maximum intensity at approximately 775˚C.
- Colouration was interferential in nature.

- Bubbles appeared at approximately 730˚C and increased randomly in size and position at 800˚C. Bubble production increased with holding time.
- When fused with float glass, gold, peach, pink and, occasionally, blue colouration developed on the K above 720°C and maximised in depth between 770°C and 800°C.

This identification provided points of reference on which the understanding and subsequent control of the visual changes to the K coating could be based.

7.1.2 In Relation to the Second Objective:

'To understand the changes to the surface coating and the factors responsible for the visual effects'.

In order to fully understand the visual changes to the post-fired K Glass, the material variables of the K Glass and coating as well as the environmental variables of temperature and air were examined. These findings in conjunction with a detailed microstructural characterisation of the surface coating findings enabled the following conclusions to be drawn:

- Variations in the visual changes were related to the temperature, the rate of heat applied and the amount of air available to the K surface during firing.
- The post-fired K coating presented a changed surface structure of tiny ripples with peak-to-peak distance of approximately 30 microns and small bubbles from pin-point to approximately 1mm in diameter.
- The form of the ripples controlled the degree of iridescence.
- Bubbles in the fused situation were responsible for the gold colouration.

- A combination of ripples and bubbles were responsible for the pink colouration.
- Pure ripples were responsible for the purple colouration.
- The interaction of light with the surface structure was responsible for the interferential effect.
- Tin from the coating was found to be responsible for the change in surface structure and hence, the overall colouration within the range of gold, pink and purple. Variations of tone within this range were due to iridescence.

Due to the inherent complexity of the physical and chemical reactions between the K coating and float glass at elevated temperatures, as well as the lack of technical specifications for all of the material variables involved, it was deemed beyond the scope of this research to provide a full scientific explanation of the individual visual changes.

7.1.3 In Relation to the Third Objective:

'To control the visual effects through manipulation of the factors'.

Colouration, iridescence and bubble formation on the open fired K were managed through pre-fired manipulation with abrasive treatments such as sandblasting and scoring. In addition, the quality of the post-fired coating, colour strength and iridescence intensity were controlled by temperature, kiln presentation and firing schedule. The rate of firing was important to the quality of the post-fired coating especially with the 4mm K. For example, a decrease from 125˚C to 80°C per hour encouraged a surface with more uniform visual changes.

In the Fused, Enclosed and Grid formats, control of the visual effects was achieved through the manipulation of both K and float glass variables. The thickness of the upper float glass contributed to the size of the area of the colouration. Furthermore, different thicknesses of glass softened at different rates and provided variable amounts of air during the fusing process. This availability of air was found to be responsible for the colouration control within fused glass. The optimum temperature for colour development in the fused formats was 775˚C, held for 30 minutes. Above 800˚C, bubble formation increased and marred the visual effects of colouration and iridescence.

7.1.4 In Relation to the Fourth Objective:

'To apply the information to the application of new techniques and methods of working for the artist in the field of creative glass'.

A significant new method of working was created called the Mirror Gap Technique. Developed from information gained during standardised tests, the Mirror Gap Technique utilised a sandblasted gap on the underside of the upper layer of float glass before fusing. Although based on existing principles, it was found to be unique in its ability to separate and control several colours with iridescence on post-fired K Glass.

Variation of the gap depth enabled separation of colours within the Fused format. A graduation of colour from gold, peach and pink to purple was produced with 35 gaps from 0.01mm to 1.17mm in depth. Optimum depths for gold, pink and purple were found to be approximately 0.25mm, 0.50mm and 0.85mm respectively.

The repeatability and commercial potential of the Mirror Gap Technique was confirmed through the successful commission of 65 international conference gifts. The optimum firing temperature for the development of colour was 775˚C with a 30 minute hold for depth of colouration. The quality (or freshness) of the sandblasting grit was vital for accurate depth control.

New ways of working with K Glass were established through extensive testing of abrasive surface treatments and heat variation. The research techniques were also confirmed using coated glass from other manufacturers, e.g. AGC and Saint-Gobain. The Mirror Gap Technique was successfully used with Saint-Gobain Coolite ST150 for the commission and production of monthly and annual company awards.

7.1.5 In Relation to the Fifth Objective:

'To utilise the techniques in a body of art work that develops and demonstrates the artistic potential of K Glass within the field of creative glass'.

The techniques and methods were maintained and developed through artwork which demonstrated the potential of K Glass as a creative medium. Outcomes of the research regarding the artistic possibilities were found to be relevant to the method of firing. For open fired artwork it was concluded that:

- Sandblasting created imagery and cleared unwanted areas of coating. 'Plate 1' (*See Figure 6.1, p.188*) confirmed this technique and highlighted how different colouration and iridescence could be obtained in a profiled format.
- Abrasion, such as scoring, encouraged bubbles for surface interest and texture; their presence and form was directly correlated to the quantity and quality of the abrasion prior to firing. Visual effects ranged from a fine textured surface reflecting interferential colouration, to delineation of design by larger bubbles along score lines seen in 'Plate 2' (*See Figure 6.2, p.189*).
- Smaller pieces of post-fired K (150mm x 50mm) appeared to show a greater variety and intensity of colour on each piece than that seen across larger pieces. Hence a combination effect,

utilising several small pieces together as in ‘Plate 5’ (*See Figure 6.8, p.193*) and in jewellery was found to be equally visually effective in comparison to individual piece presentation.

- Bending and forming techniques stretched the K coating and successfully formed the glass into more three-dimensional pieces as in ‘To Nowhere’ (*See Figure 6.21, p.203*) which offered the interferential light reflecting property of the surface its greatest potential.
- Pieces of K fired face-to-face developed iridised surfaces with the additional colouration of gold. Although less reflective than standard open fired K surfaces, the selective use of sectioned pieces produced a gold mosaic. The outer areas, similarly applied, replicated the natural effect of marble as in ‘Chequer Board’ (*See Figure 6.13, p.198)*.

Similarly, for fuse fired artwork and in particular, the pieces created using the Mirror Gap Technique, the following conclusions were drawn:

- Iridescent colouration appeared much stronger and more reflective than the open fired surface with the upper layer of float glass adding a quality of sheen and lustre as seen in ‘Washington Bowls’ (*See Figure 6.24, p.206)*.
- Separation and control of colour was attainable with varying form. Gold, pink and purple was produced in separate encapsulated voids and combined to produce multi-colour design as in ‘Squares’ (*See Figure 6.35, p.218)* whereas gold was isolated individually in ‘Plates 7, 8 and 9’ (*See Figures 6.25, p.208, 6.26, p.209 and 6.28, p.211)*.
- Fine precision detail was successfully produced through the use of stencils as shown in the ‘Dubai’ (*See Figure 6.30, p.213)* or ‘Falcon’ (*See Figure 6.31, p.214)* pieces. The strength of the technique was deemed especially appropriate for text and

additionally demonstrated and by the clear cut lines in ‘Plate 10’ (*See Figure 6.29, p.212)*, ‘Faces’ (*See Figure 6.32, p.215)* and ‘Triptych’ (*See Figure 6.33, p.216)*.

- Change of form was achieved without affecting colour as seen in all the plates and the convex curved panels of ‘Triptych’. Once the colouration was established it was not affected by further form firing or bending.
- Design considerations due to the limitation of size of the viewing area of unbroken colouration can be addressed by multi-panel construction as in ‘Pyramid’ (*See Figure 6.34, p.217)* or by creating a ‘jig-saw’ effect with a segmented design. ‘Dhow’ (*See Figure 6.37, p.220)* confirmed that water jet cutting could aid in the precision necessary to produce larger scale ‘composite’ work made up of separate pieces with no diminution to the overall artistic effect.
- Imagery was protected within fused layers of glass and therefore from the surrounding environment. Hence, the technique has potential for exterior application as well as suitability for grime vulnerable areas.

The artistic value of K Glass using the Mirror Gap Technique was further demonstrated with positive appraisal of the pieces ‘Pyramid’, ‘Dhow’, ‘Morning Sunlight’ (*See Figure 6.46, p.227)* and ‘Triptych’ at national and international exhibitions. Furthermore, ‘Dhow’ together with some early technique bowls, found buyers at ‘Glass 3’ in Washington DC. Repeated commissions for Clayton Glass employee awards (*See 5.5, p.178)* as well appreciation for a commission for gifts for an international coatings conference in Amsterdam (*See 5.4.2, p.160)* confirmed the acceptance of the technique in finished artwork.

The combination of the effects of colouration, iridescence and, in the case of open fired K, formation of surface bubbles produced interference that was a major consideration for the development of artwork. In both open and fuse fired K, the interferential response of colouration was accentuated with profile. The concave form of the piece concentrated the intensity of the effects, as can be seen with the range of plate pieces. In comparison, the convex profile encouraged an interactive reaction as the viewer lost and regained visual effects with movement. Vertical difference in angle of viewing created the same elusive response.

Each piece was, therefore, designed in terms of form, lighting and location to maximise the artistic response to its environment. Specifically:

- Angle of viewing - movement of the viewer or piece caused the colouration and iridescence to appear and disappear.
- Lighting - front lighting enabled the reflection of the colouration whereas with back lighting the colouration was lost.
- Background - a light coloured background caused a diminution of colouration.

In summary, it can be concluded that K Glass, whether open or fuse fired as in the Mirror Gap Technique, can be used in the same way as float glass but with visual surface effects. It can be presented on its own or in conjunction with non-glass materials such as stainless steel for larger constructed sculptures and backed with protective film for location in the public domain. Furthermore, this artwork has demonstrated that the creative possibilities of low emissivity K Glass could be limitless to the many kiln glass artists who, at present, work with float glass but could extend their capacity with a new and exciting range of media.

7.2 Originality of the Research and its Contribution to Knowledge

Prior to this research there was no documented evidence of the creative potential of the functional building product, Pilkington K Glass. This research has successfully examined the effect of high temperatures and the manipulation of the surface coating of this low emissivity glass. In addition, it has explored the artistic possibilities and showed the potential of a new palette containing highly reflective and interferential surface effects.

The initial outcome of the research of an unusual pink/purple iridescent to the surface of open fired K Glass was modified and controlled through abrasive techniques and firing management. Creative possibilities were developed through artwork and demonstrated by a range of visual surface effects. The innovative and creative Mirror Gap Technique within fused K Glass enabled and controlled colour separation ranging from gold to purple within the layers of glass. This original technique with its particular relevance to line and text offered a new concept of detailed and reflective imagery within a protected environment.

The visual effects achieved in both open fired and fuse fired K Glass displayed the added characteristic of interference. This created an additional dimension to the colouration and iridescence and a quality which, through the manipulated surface of coated low emissivity glass, had not previously been exploited. Artwork that has subsequently been produced using both open and fused K Glass to indicate the wide area of application for the artist from small items such as jewellery to applications within architectural design.

Following this research, there now exists documentation of methods and techniques that can be used as a reference by artists in several areas of creative glass to explore the expanding range of functional coatings. As artists constantly search for the novel use of available materials, this research has broken new ground with pioneering creative work using functional coated glass. It has provided an opening to the exploration of a new media through the creative possibilities of manipulated surface coatings and introduced an additional vocabulary for artists and designers in the field of creative glass.

This documentation also contributes, in terms of technical data, to the knowledge of the behaviour of this functional material outside of its intended building application and expectation. The author has already presented findings from this research at the International Conference on Coatings on Glass and Plastics (ICCG7) in 2008 in support of the conference gifts (*See 5.4.2, p.160*). In addition, the research has featured within a paper published by Gelder (2008) in Glass Technology: European Journal of Glass Science and Technology. For the interest of the reader, extracts can be found in Appendix H, p.297.

The making of the ICCG7 conference gifts tested the possible commercial application of the Mirror Gap Technique. The outcome tentatively suggested that with more sophisticated equipment, the multiple production of similar items could be possible. In addition, the technique could be adapted to produce signage or imagery within the glass, for example for company logos in interior or exterior architectural features where float glass would be the normally accepted material.

This research may also suggest opportunities for further academic and/or art research. The field of functional coated glass has not previously been involved with the creative possibilities of its manipulated surface but, through collaborations that unite artistic and material investigation, a new area of research could develop.

7.2.1 Patent Possibility

Interest in a patent application for this technique has been shown by the author as well as senior university supervisors and conference delegates throughout this research. The University of Sunderland solicitor was consulted in 2008 for advice regarding the procedure. She explained that the application would be for the Mirror Gap Technique as a new and original method within glass processing. The patent would, primarily, be for consideration in the UK but could be extended internationally on a country by country basis (Cutting, 2008).

The initial step would be to conduct a global patent search prior to appointing a Patent Agent who would prepare and file the application. Patent Office costs, at the time of writing, for filing are £200 and the Agent's fees are approximately £2000, with a further £2000 for the work involved in pursuing the application to the stage of being granted. To extend the patent into Europe, the fees would be approximately £6000 plus £1000 for every individual language involved. If the patent was extended globally, worldwide intellectual property office fees would be £2900 plus search and attorney fees. These are guidelines only as fees vary between countries (Patent My Idea.org, 2010).

It can be seen from these figures that the process can become expensive especially as the product in question has international relevance. When the enquiries were made the author was preparing to visit the United Arab Emirates, the United States and the Netherlands. Consequently, the cost to cover the patent process was anticipated to be approximately £30,000. Although there was the possibility of support from the University of Sunderland this would also involve legal rights. Legal rights regarding the material would also have to be obtained from Pilkington and other manufacturers whose glass was included in the process (Cutting, 2008).

A further issue was that of confidentiality. The Mirror Gap Technique had been trialled at Creative Glass, therefore, a confidentiality agreement would have to be made with that company. However, the most relevant question that might make the application void was one which is essential to research, the dissemination of findings. The author had presented papers at several conferences where the Mirror Gap Technique had been described. As the process had been discussed in open forum, the application could be void (Intellectual Property Office, 2010a, p.3). After careful consideration the author decided not to pursue the patent application.

7.3 Areas for Further Research

The following areas of further research were identified.

7.3.1 Development of Artwork using Optiwhite

The latter stages of research revealed two exciting possibilities for the development of artwork. KOW glass, or K coating on the low iron glass Optiwhite, offered a new visual dimension to the creative potential identified using the original K Glass. In addition, the stacking technique described in Section 6.3, p.205, which presented unique optical effects, could be explored for its use in the area of interior design.

7.3.2 Extension of Developed Methods to Alternative Coatings

Alternative low emissivity coatings produced similar effects to those of K Glass and suggested an exciting opportunity to develop further artwork with coloured substrates (*See 5.5, p.181*). Coated glass from other manufacturers was not easily obtained and hindered the opportunity, within the parameters of this investigation, to examine further creative possibilities that this range of new and inspiring media might offer.

7.3.3 Commercial Feasibility of the Mirror Gap Technique

The ICCG7 conference gifts commission provided the opportunity to trial the Mirror Gap Technique under industrial conditions (*See 5.4.2, p.160*). One of the several procedures, the gap itself, was prepared by the computerised controlled system of the commercial sandblaster; the positioning and registering of the stencils had to be done manually. To assess the commercial feasibility of the Mirror Gap Technique, further trials need to be undertaken. Creative Glass was unable to offer any other process to streamline the production. An alternative glass processing company may be able to incorporate the technique either for the total production or to assist with labour intensive aspects such as polishing.

7.3.4 Investigation of Mirror Gap Technique Fusing Anomaly

The area of cloudiness shown in Figure 5.10 and referred to in Section 5.3, p. 154, was an unpredictable feature occasionally found between the layers of glass that had been fused by means of the Mirror Gap Technique. Such areas were of irregular size, shape and position and composed of massed microscopic bubbles. As this feature has not been found in float glass, the cause was thought to have been the outcome of incomplete removal of the K coating. However, attempts to reproduce these bubbles have not been successful. It may therefore be due to isolated impurities or imperfections in the K Glass coating that has caused an unknown physical or chemical reaction at high temperature. This anomaly could be investigated during further research.

7.3.5 Further Technical Enquiry

This research has been involved with a low emissivity surface coating applied online by the manufacturer. As described in Chapter 4, tin oxide, the main constituent of the upper layer of coating, is responsible for the colouration effects achieved by high temperatures. It is possible to coat glass and create the iridised effect within studio conditions using stannous chloride (Liquida, 2009). This was confirmed by Crozier (2011) who, while warning of the hazards involved, suggested possible further enquiry with scientific collaboration to create original and innovative coatings with a wider range of colour and iridescent effects.

7.3.6 Intellectual Property Protection

The possibility of a patent having been dismissed, the question of the protection of the outcomes of this research still remained. There are several alternatives to safeguard intellectual property among which are trade marks, designs and copyright. With a variety of ways in which a design can be protected, the route to achieve this could be addressed during further research.

7.4 Concluding Remarks: Dissemination of this Research

Through the development of innovative and original effects, this research project has opened the door to a new range of material with an aesthetic potential that may be applied to many areas of creative glass. The documentation offers guidelines that can be applied to the wide and ever increasing range of glass with other surface coatings. It is hoped that this research will inspire artists to explore similar inexpensive functional material and bring a new dimension and vocabulary to the artistic world of float glass.

> 'The new materials, with their potential for ambiguity and change, will present us with a wonderful new palette and great new challenges which many of us cannot wait to explore' (Wigginton, 1997, p.51).

Appendix A

The Industry of Flat Glass Manufacture

Table A.1 Chronological Summary of Significant Developments in Flat Glass Production from the Medieval Period to 1952

Date	Process	References
1226	Broad Sheet Glass industry established in Surrey and Sussex.	McGrath, 1996, p.38. Tangram Technology Ltd, (2010).
1330	Crown Glass industry established in Rouen France.	McGrath, 1996, p.34. Tangram Technology Ltd, (2010).
1615	Royal Proclamation forbidding the use of wood fuel for glassmaking. Industry moved geographically to areas of coal mining.	McGrath, 1996, p.39. Tangram Technology Ltd, (2010).
1620	Blown Plate produced in London by grinding and polishing Broad Sheet. Used for mirrors and coach plates.	London Crown Glass Company, (2011).
1685	First recorded use of the sliding sash window in England.	McGrath, 1996, p107. Wigginton, 1996, p.29.
1687	Bernard Perrot developed a process for casting, and polishing glass.	Wigginton, 1996, p.27.
1688 - 1702	Abraham Thévart developed Perrot's invention in Paris and moved to the Chateau de St Gobain in 1693, casting mirror plates.	Wigginton, 1996, p.27.
1697	Window Tax introduced by William 3rd. Abolished in 1851.	Tangram Technology Ltd. (2010).
1773	British Cast Plate Glass Company formed in Ravenhead, St. Helens.	McGrath, 1996, p.42. Wigginton, 1996, p.30.

1789	Steam engine introduced at St. Helens to grind and polish cast glass.	Tangram Technology Ltd, (2010).
1826	St. Helens Crown Glass Company formed in St. Helens by what is now known as Pilkington UK Limited.	Wigginton , 1996, p.284.
1839	Robert Lucas Chance invented 'patent plate'. An innovative method of grinding and polishing glass sheets which had been made by the blown cylinder process on wet leather.	McGrath, 1996, p.45.
1847	James Hartley of Sunderland invented 'Rolled Plate', a thin cast plate produced by rolling during the casting process. This enabled thinner glass to be produced of larger size sheets.	McGrath, 1996, p.46.
1760 - 1850	Industrial Revolution—advances in industry and transportation especially cast iron technology enabled the construction of glass and steel skeleton buildings.	Button and Pye, 1993, p.2.
1851	Crystal Palace designed by Sir Joseph Paxton using Chance Brothers Patent Plate the 'largest single glazing contract ever attempted'.	Wigginton, 1996, p.51.
1896	The American Window Glass Company introduced a machine blown process invented by John Lubber enabled larger sized sheets. Patented Pilkington 1910.	Wigginton, 1996, p.55.

1903	Laminated glass discovered by Eduoard Benedictus a French Scientist.	Tangram Technology Ltd. (2010).
1904	Fourcault Process patented in Belgium. Flat drawn sheet drawn vertically then flattened and cooled by pulling it through asbestos rollers.	McGrath, 1961, p.49. Tangram Technology Ltd, (2010).
1905	Libbey-Owens in USA—a similar system to the Fourcault process. Later improved by the Pittsburg Plate Glass Company.	McGrath, 1961, p.51.
1918	The Bicheroux Process—glass poured from a pot, passed through rollers to produce a long ribbon of glass which was cut, annealed and polished.	Bray, 2001, p.49.
1923	Ford Motor Company refined Bicheroux process with continuous feed and a mechanised polishing and grinding process.	Wigginton, 1996, p.55.
1928	French company, Renuies des Glaces, developed a method to toughening glass after previous attempts by De la Bastie and Siemens of Dresden from c.1870.	McGrath, 1961, p.65.
1935	Pilkington developed the ‘twin’ machine which ground both side of the glass at the same time.	Pilkington (2011d).
1952	Float Glass process conceived by Sir Alastair Pilkington to form a ribbon of glass floating at high temperature over a bath of molten tin. In production by 1959.	Pilkington (2011d).

Table A.1 Chronological summary of significant developments in flat glass production from the medieval period to 1952.

Constituents of Float Glass

Although the constituents may vary in their fine detail, according to Pilkington (2008) and Bray (2001, p.131) the following is the basic composition of float glass.

Table A.2 Constituents of Float Glass

Constituent	Amount	Purpose
Silica (SiO_2)	72.6%	High quality sand the commonest and most widely used glass former.
Soda ash (NaO_2)	13%	Used a flux for easier melting.
Limestone ($CaCO_3$)	8.4%	For durability and stability.
Dolomite ($CaMg(CO_3)_2$	4%	For working and weathering properties.
Alumina (Al_2O_3)	1%	Used to suppress devitrification and to raise viscosity of the glass.
Others: eg. Iron oxide (Fe_2O_3) or lead oxide (PbO)	1%	For colouring or refractive purposes melting and refining (bubble removal).

Table A.2. Constituents of float glass.

In their report of the Flat Glass Industry 2010, Pilkington state that 15% of the constituents is now recycled broken glass replacing some of the sand in the fabrication of flat glass, with the other constituents adjusted accordingly (Pilkington, 2010, p.56).

The Basic Float Glass Process

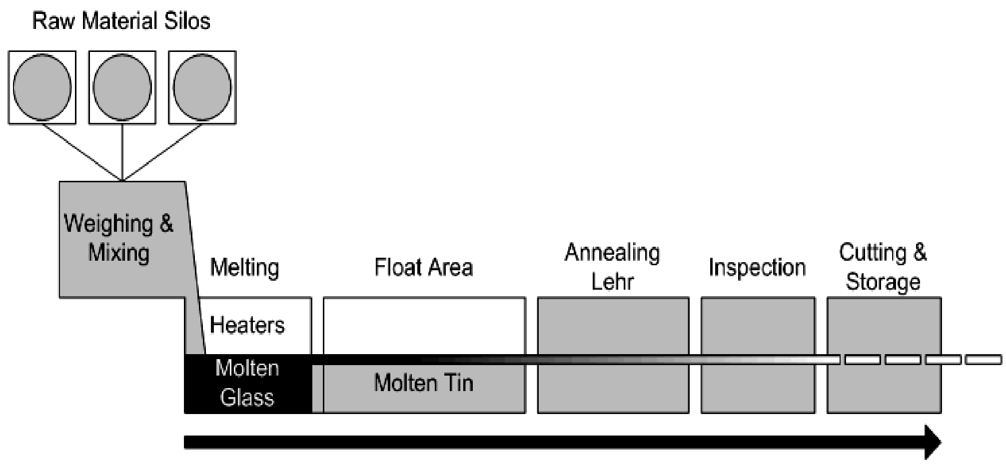


Figure A.1 The basic float glass process.

- Raw materials weighed and mixed and added to melting furnace. Temperature of melting around 1050˚C.
- Mixture flows over a dam onto bath of molten tin. Molten glass spreads with flat top and bottom surfaces. Thickness is controlled as glass cools by stretching effect of conveyors as it is pulled along the surface of the molten tin. If not controlled glass will form at equilibrium thickness[24] of 6-7mm (Gulotta, 1969).
- At 600˚C it is passed to the lehr for annealing.
- Glass inspected and cut **(**Tangram Technology Ltd. 2004).

[24] Glass in its molten state will try to settle at a thickness of 6-7mm.

Off line Coating Process

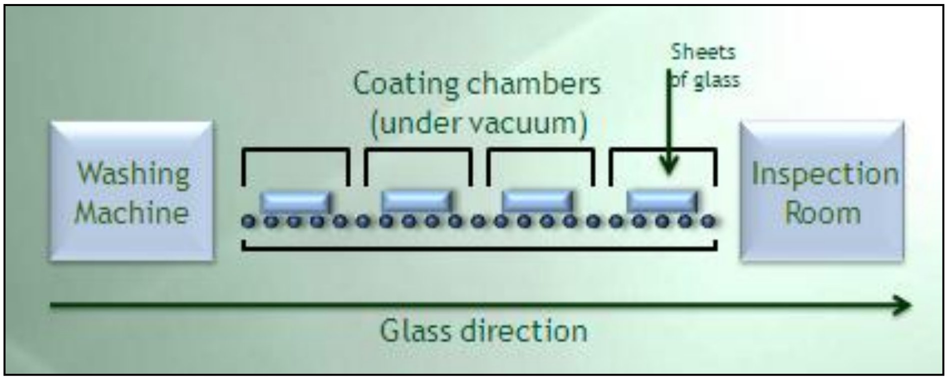


Figure A.2 *Off line coating process.*

Off line coatings are applied after the glass has been manufactured with a process called 'magnetron sputtering'. The cut float glass up to 3000mm x 2000mm, is mechanically polished, washed and dried under pressure before entering a series of coating chambers. The chambers, which are under vacuum, each have three cathode target positions. The cathodes are designed for the specific coating and give the potential for several materials to be applied onto the glass as it moves through the chambers. When the vacuum is filled with the sputter gas, for example, argon and a negative charge applied to the cathode a 'glow discharge' occurs and electrons are removed from the argon. The positive ions that remain bombard the target cathode and eject atoms which condense on to the surface of the glass. This process enables a more complex range of coatings to be produced than online (Pilkington, 2011e, Wigginton, 1996, pp. 279-282).

Online Coating Process

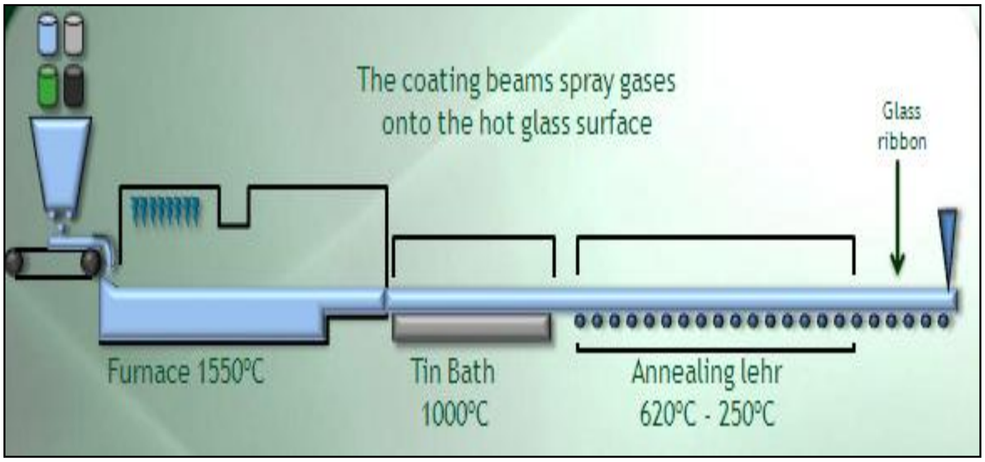


Figure A.3 Online coating process.

The online process is pyrolitic which is chemical decomposition brought about by heat and is consequently known as Chemical Vapour Deposition. It takes place during the float manufacturing process while the glass is still in the molten state in the tin bath, during the annealing stage or between the two. The gases are sprayed on to the hot glass. The chemical reaction that takes place between the vapours condenses to form a thin solid film and becomes part of the glass surface. The thickness of the film is between 20 and 120 nanometres which is thicker than that of the coatings applied off line. The properties of the film are dependent on the constituents of the application (Wigginton, 1996, p.279).

Table A.3 Types of Coatings and their Flat Glass Applications

Although coatings are found in many areas of industry those listed below have flat glass application and are, therefore, located within the field of research.

Coating Type	Application	References
Thermal Insulation	'Low-emission glass (Low-E) is a clear glass; it has a microscopically-thin coating of metal oxide. This allows the sun's heat and light to pass through the glass into the building. At the same time it blocks heat from leaving the room, reducing heat loss considerably'	Glass on Web (2007b).
Solar Control	Solar control glass can be used to minimise solar heat gain, help control glare and to balance solar control with high levels of natural light for any situation where excessive solar heat gain is likely to be an issue, e.g. large façades.	Pilkington (2011g).
Reflective/ metallic	An ordinary float glass with a metallic coating to reduce solar heat. The coating also produces a mirror effect, preventing the viewer from seeing through the glass. Mainly used in façades.	Glass on Web (2007).
Self-cleaning	A 'photo catalytic' coating absorbs the UV light to break down surface deposits. A second 'hydrophilic' coating prevents the rainwater from forming droplets and grime is washed away.	Pilkington (2011b).
Anti-reflective	Anti-reflective glass is float glass with a specially-designed coating which reflects a very low % of light. It offers maximum transparency and optical clarity, allowing optimum viewing through the glass at all times.	Glass On Web (2007a).

Mirror	One of the oldest techniques in the glass industry, mirror coating is now applied by the CVD of silver on high quality glass.	Wigginton, 1996, p.279.
Photovoltaics	One of the methods of production uses thin film technology. Layers of film are laid over each other and protected by a glass layer. Important for power generating systems by converting sunlight to energy.	Wigginton, 1996, p.268.
Photochromic	Coatings which can change shade intensity according to light conditions.	Glass on Web (2009).
Electrochromic	Coatings that can respond to external conditions when the coating on the glass surface is activated by low-voltage electrical charges causing a change in colour from clear to dark.	Glass on Web, (2010).
Thermochromic	Glass which changes not only its solar gain properties but also its colour by reacting to temperature is still in development.	Lynch, 2010.
Dichroic	A multiple coating layer which produces multiple interference layers. Used widely for applications such as light bulbs but also as a flat glass in the field of creative architectural installations.	Wigginton, 1996, p.224.

Table A.3 *Types of coatings and their flat glass applications.*

Appendix B Experimental Issues

Table B.1 Experimental Procedures used for Artwork

Plate	Method	Firing Schedule
1	The surface of a 230mm square of 6mm K was masked with Venture tape, cut and unwanted tape removed. Surface then sandblasted to remove the coating, leaving a concentric square.	125˚C per hour to 520˚C; Full power to 775˚C; Hold 30 min; Fast drop to 560˚C; Hold 20 min; 20˚C per hour to 480˚C; Off.
2	The surface of a 250mm square of 6mm K was selectively scored using a rough diamond pad, then masked and sandblasting to remove a number of small squares. Repeated to explore firing schedules. Preferred schedule – 4	1. As Plate 1 to 775˚C for 20 min. 2. As Plate 1 to 750˚C for 10 min. 3. 125˚C per hour to 520˚C; 150˚C per hour to 800˚C; Hold 40 min; Fast drop to 560˚C; Hold 20 min; 20˚C per hour to 480˚C; Off. 4. As Plate 1 for 30min.
3	The entire surface of a 250mm square of 6mm K was scored with a fine diamond pad prior to the design masked cut and sandblasted. Repeated to explore firing schedules. Preferred schedule – 3	1. As Plate 1 to 775˚C for 15 min. 2. As Plate 1. 3. 125˚C per hour to 520˚C; 150˚C per hour to 800˚C; Hold 40 min; Fast drop to 560˚C; Hold 20 min; 20˚C per hour to 480˚C; Off.

4	The surface of a 250mm square of 4mm K was scored with very fine cross hatching. Metal ball bearings were pushed into 3mm ceramic matting which had been cut to line the mould. After firing the result was a poor degree of ‘roundedness’ and inadequate colouration. New clean ball bearings were pushed deeper into an additional square of 3mm ceramic matting then covered with full size square of Thinfire to try to reduce debris in humps – this made no difference. Firing repeated at slightly higher temperature, schedule 2, to help formation of humps. Reverse of plate sandblasted after second firing.	1. As Plate 1. 2. As Plate 1 to 800˚C for 30 min.
5	75 pieces of 50mm x 15mm 4mm K were placed in ‘tile formation’ on a 250mm square of 4mm float using fusers glue to secure each into position. To prevent the possibility of movement before the tiles had fused into place, the square and tiles were initially fired flat in higher temperature to ‘round’ the edges. Second firing placed on mould with Thinfire separator for 20min at 775˚C.	1. 125˚C per hour to 520˚C; 150˚C per hour to 800˚C; Hold 40 min; Fast drop to 560˚C; Hold 20 min; 20˚C per hour to 480˚C; Off. 2. As Plate 1 to 775 ˚C for 20 min.
6	Using a 250mm square of St. Gobain Bioclean Coolite glass. Masked on both sides and cut with slightly different geometric designs. Sandblasted and fired on schedule suitable for this glass *(See 5.5, p.178).*	As Plate 1 to 750˚C for 10 min.

7	300 mm squares of 4mm K and float were prepared using the Mirror Gap Technique with a shallow gap to create gold colouration. Fired flat then returned to kiln and fired on ceramic mould with Thinfire separator.	1. As Plate 1.
8	250mm squares of 4mm K and 4mm float were prepared using the Mirror Gap Technique with a shallow gap to create gold colouration. 250mm square of blue compatible float placed underneath the lower layer of K. Fired flat then returned to kiln and fired on ceramic mould with Thinfire separator.	1. As Plate 1 to 750˚C for 15 min.
9	250 mm squares of 4mm K and 4mm float were prepared using the Mirror Gap Technique. In addition, the upper surface of the top K layer was scored with a fine diamond pad. Fired flat, then returned to kiln and fired on ceramic mould with Thinfire separator. Repeat using schedule 2 Preferred schedule – 2	1. As Plate 1 to 775˚C for 20mins. 2. 125˚C per hour to 520˚C; 150˚C per hour to 800˚C; Hold 40 min; Fast drop to 560˚C; Hold 20 min; 20˚C per hour to 480˚C; Off.
10	280 mm squares of 4mm St. Gobain Bioclean Coolite and 4mm float were prepared using the Mirror Gap Technique. Fired flat, then re-fired on mould with Thinfire separator.	1. As Plate 1 to 750 ˚C for 10 min. 2. As Plate 1 to 750 ˚C for 10 min.

Table B.1 Experimental procedures used for artwork.

Effect of coloured base on surface changes

6mm K Glass post-fired placed on red, yellow and green backgrounds for comparison with blue background used throughout research.

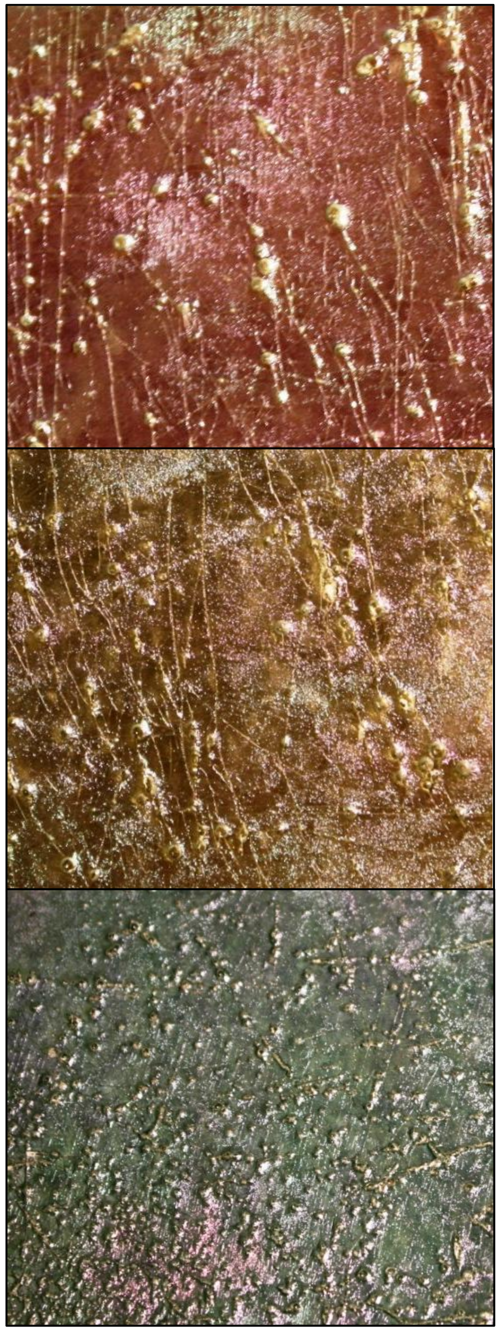


Figure B.1 Effect of coloured base on surface changes.

Testing of Coatings by Other Manufacturers

AGC Flat Glass Europe

As the samples received from AGC Glass were only 100mm x 150mm experimental work was limited. Tests were prepared using both the open fired and Mirror Gap Technique formats for comparison with K Glass firing.

Open fired tests: 100mm x 30mm pieces were fired with the coating up and pieces 100mm x 20mm were tested with the coating down. All were fired to 775°C.

Mirror Gap Technique tests: Glass pieces 100mm x 50mm were cut and unwanted coating removed by sandblasting, leaving 3 squares of 20mm down the centre. Using the corresponding thickness of float glass the gaps were sandblasted so that each sample had one shallow, one medium and one deep gap. It was not possible to use the commercial sandblaster for this test so the gun control had to be regulated as accurately as possible by hand. The shallow gap was given 10 passes of the gun, the medium gap 25 passes and the deep gap 50 passes. The samples were fired to 775°C.

Guardian Industries UK Limited

Samples received were in the form of insulated glass units and therefore had to be opened to obtain the glass. Results of the initial open fired surface testing suggested the coatings were considered not suitable for MGT. Open fired Guardian Glass results only are shown.

AGC Flat Glass Europe – Open Fired

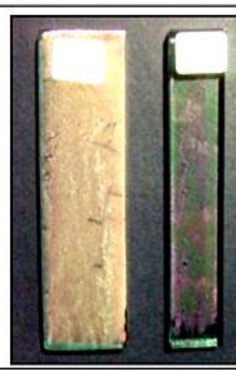
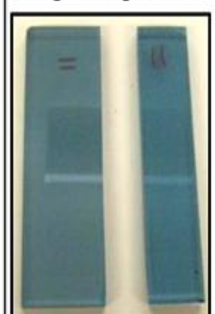
Name of Glass	Exposed surface	Reverse photograph
Planibel G 		
Sunergy Clear 		
Sunergy Blue 67 		
Sunergy Azur 		

Figure B.2 AGC Glass coatings open fired (1).

Name of Glass	Exposed surface	Reverse photograph
Sunergy Green 		
Stopsol Cl.Clear 		
Stopsol Cl.Grn 		
Stopsol Cl.Grey 		

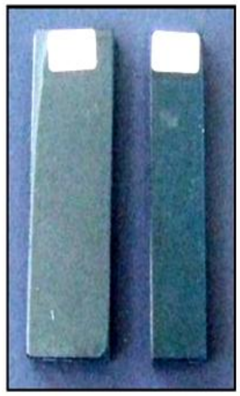
Cl = Classic; Grn = Green

Figure B.3 AGC Glass coatings open fired (2).

Name of Glass	Exposed surface	Reverse photograph
Stopsol Cl.Brnz 		
Stopsol Sprs Clr 		
Stopsol Sprs DB 		
Stopsol Sprs.Gy 		

Cl = Clear; Brnz = Bronze; Sprs = Supersilver; DB = Dark Blue; Gy = Grey

Figure B.4 AGC Glass coatings open fired (3).

Name of Glass	Exposed surface	Reverse photograph
Stopsol Sprs.Gn 		
Stopsol Slvt PB 		
Stopsol Visn 50 		

Slvt PB = Silverlight Privablue; Visn = Vision

Figure B.5 AGC Glass coatings open fired (4).

AGC Coatings - Mirror Gap Technique

1. Planibel G
2. Sunergy Azur
3. Sunergy Clear
4. Sunergy Blue
5. Sunergy Green
6. Stopray Vision

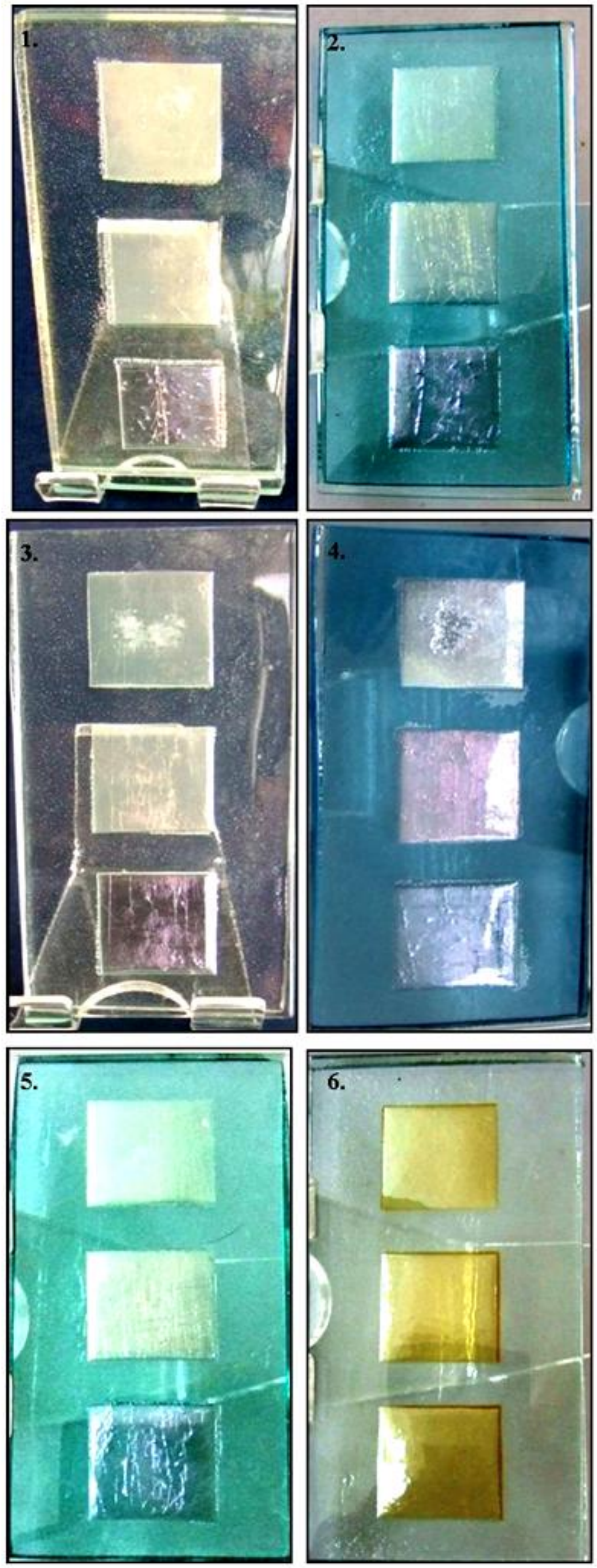
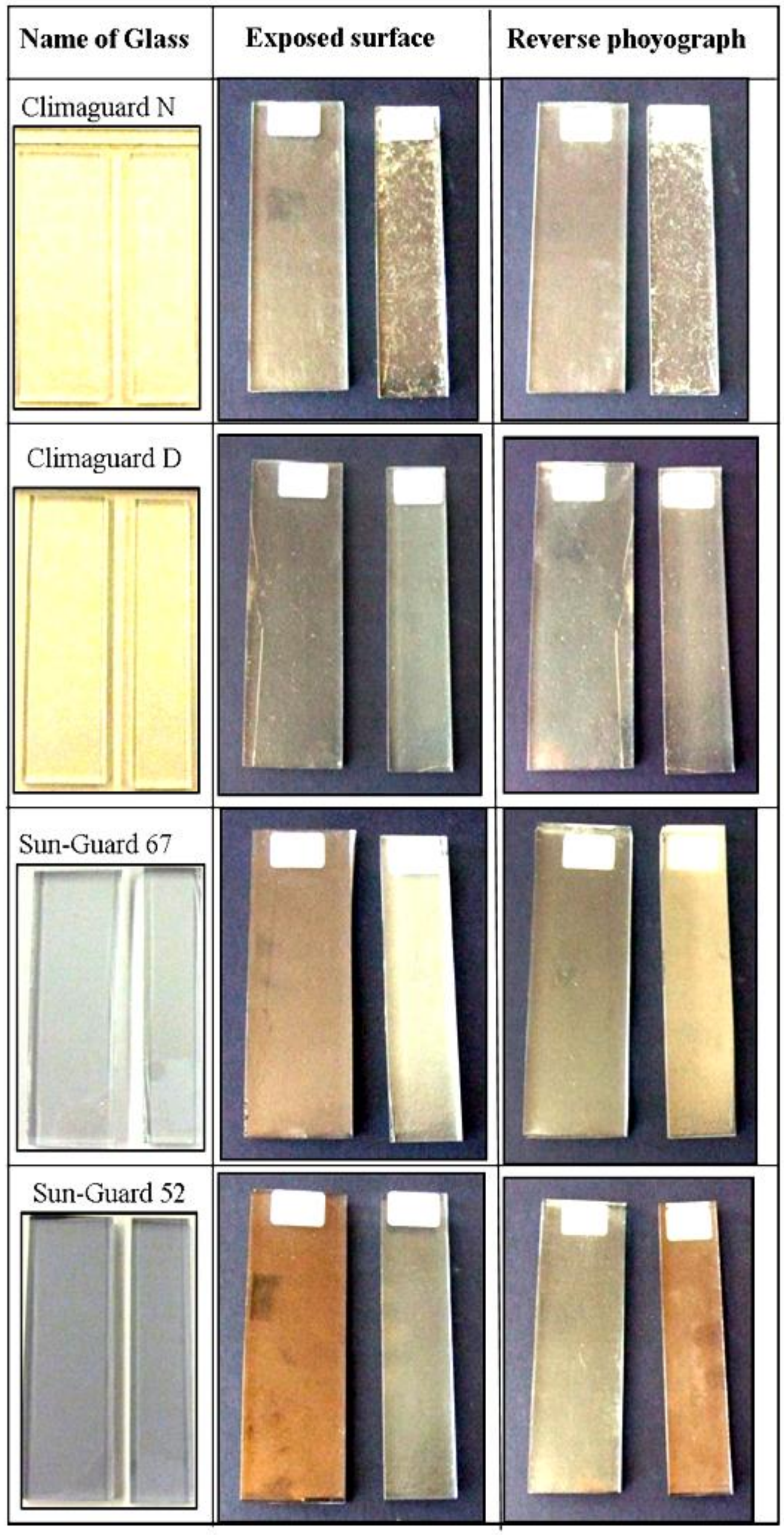


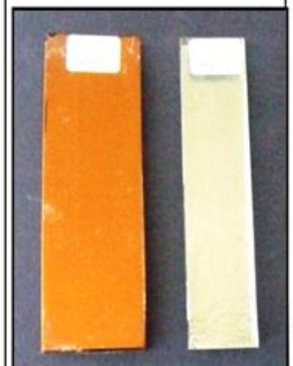
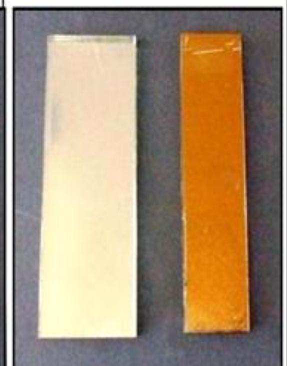
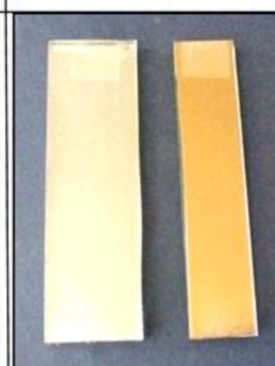
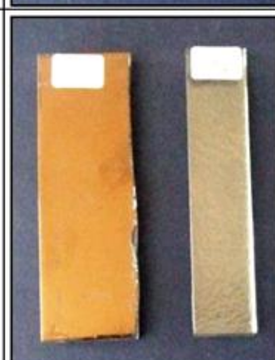
Figure B.6 AGC Glass coatings - Mirror Gap Technique.

Guardian Industries UK Ltd.



Sun-Guard 67 = Neutral; 52 = Light Blue

Figure B.7 Guardian Glass coatings open fired (1).

	Name of Glass	Exposed surface	Reverse photograph
1.	Sun-Guard Sol 20 		
2.	Sun-Guard Sol 08 		
3.	Sun-Guard Sol 20 		
4.	Sun-Guard Sol32 		

1. Sun-Guard Solar 20 = Royal Blue; 2. Sun-Guard Solar 08 = Silver;
3. Sun-Guard Solar 20 = Silver; 4. Sun-Guard Solar 32 = Silver Grey

Figure B.8 Guardian Glass coatings open fired (2).

Appendix C

Equipment/Materials Used During the Practical Research Process

Identification of Coated Side of Low Emissivity Glass

Littlefuse Blade Fuse Tester (*Figure C.1).*
The small green light illuminates on detection when contact made with all three points (Digital Fusion Ltd., 2000).

DIG Low-Emissivity Coatings Detector (*Figure C.2).*
Direct contact with the glass surface and button activation causes a visual (red light) and audible signal for coating identification (RussellFraserSales Pty. Ltd.).

Figure C.1 Littlefuse Blade Fuse Tester.

Figure C.2 DIG Coatings Detector.

NB. In the absence of this tester, the K surface can be deduced by identifying the tin side as the K coating is applied to the upper non-tin surface of the glass. Alternately, by simply attempting to mark with a ‘lead’ pencil, the K surface can be recognised as being the side which will accept the mark. The K coating which has a ‘rougher’ feel can also be distinguished simply by touch.

Detecting the Tin Side of Float Glass

UV Tin Side Detector - Model TS380 (*Figure C.3*)

Figure C.3 Tin side detector.

The Tin Side Detector helps identify the tin side of float glass. When the lamp is viewed through the glass, if touching the tin side, the short wave UV radiation causes the tin residue to glow with a fluorescent (milky white) light (*Figure C.4*). With the lamp on the non-tin side, only the violet UV light will be seen (*Figure C.5*).

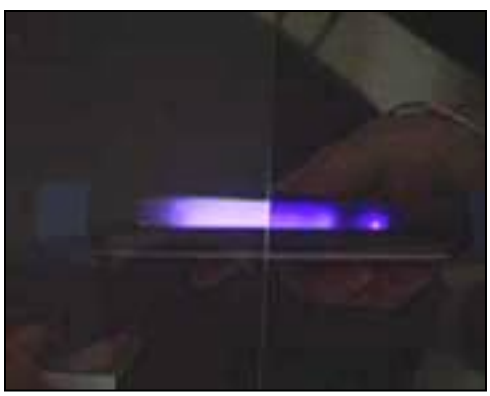


Figure C.4 Detector showing tin side.

Figure C.5 Detector showing non- tin side.

Venture Tape for Sandblast Resist. Venture tape is a strong conformable vinyl graphics masking tape, coated with a specially formulated removable acrylic pressure sensitive adhesive (PSA).

Specifically designed to be blade cut by hand or plotter, Venture Tape 470 applies easily and removes cleanly. Thicknesses: 0.127 mm, 0.235mm. Colours: clear and white (Venture Tape, 2011). It may also be used as a sandblasting mask as in this research.

Hotline Fusers Glue. Hotline Fusers Glue is available in either powder form that needs to be mixed with water or as a liquid for holding pieces of glass in place prior to firing. Slow setting and drying, it claims not to leave a carbon spot residue (Glass Fusing Made Easy, 2007).

Bohle Professional Glass Cleaner. Used to clean all glass prior to firing, it claims to prevent fresh smudging with no streaking. It also claims to be environmentally sound as it is a biologically degradable product. Available as aerosol or spray bottle.

According to the COSHH data information it is a highly flammable alcohol based product which, although it has no known adverse affect on human health, the vapours may cause drowsiness or dizziness and can be irritating to eyes (Longhorn, 2011).

BullseyeThinfire. 'A heat-resistant light weight ceramic impregnated paper, Thinfire shelf paper provides excellent separation between kiln shelf and glass in kiln firing applications up to 1,600˚F. Benefits, when compared to more conventional ceramic fibre materials: glossier finish on the shelf side of the finished project, less binder burnout odour, and lighter weight for easier handling and storage. Compared to kiln washes, Thinfire reduces shelf preparation time and improves surface release qualities' (Alpine Stained Glass, 2009). On firing, Thinfire disintegrates to a ceramic dust which must be removed with great care to prevent its dispersal. A respirator should be worn during disposal.

Ceramic Fibre Paper Matting. Produced from pure ceramic fibres held together with an organic binder which burns off during firing without producing harmful gases, it is available in thicknesses from 0.5mm to

3mm. Matting can be used as a separating agent or shaping element (Bohle, 2004).

Silica Hardener. In liquid form is applied to ceramic matting for durability and to stabilise the particle. Allow to dry, then fire to 700˚C (Bohle, 2004).

Hotline Hi-fire Shelf Prime. A pink powdered shelf primer to be mixed 1 part to 5 parts with water. The colour disappears when fired. The liquid is applied using a soft wide brush onto the shelf, allowed to dry then repeated. The primed material is cured by firing at 260˚C for 10 minutes. In addition to providing a powder-less separator it extends the life of the ceramic matting. In terms of health and safety, the cured matting is less prone to degradation by reducing the airborne fibres. The product needs careful handling in its powder form to prevent inhalation.

APM Plus. APM Plus is one of a range of photographic masking films which can be sandblasted.

1. Self adhesive film is light sensitive - use out of direct sunlight.
2. Lay the slip sheet side (duller appearance) towards the UV light source and place the toner side of the printed design on top of that.
3. The film is UV exposed for approximately 25 seconds on a Pluvex exposure unit or 12 seconds on a Pressure Pad exposure unit, (test first).
4. Remove the slip sheet and wash film in a washout booth with a water pressure of approximately 90psi.
5. The film can either be dried at room temperature or it can be dried in 3-4 minutes in a drying unit.
6. The self adhesive film can then be adhered to a backing sheet for storage or it can be applied to the glass (Glass Engraving Supplies, 2010).

Appendix D

Kiln Specification, Kiln Tests, Firing Schedules

Kiln: Kilncare FK-5 (purchased 2003)

Manufacturer: Kilncare, Stoke on Trent, Staffordshire ST2 7HQ

Figure D.1 Author's Kilncare FK-5 Kiln.

Kiln Specification:

Serial No: 109102

Voltage: 240 415/50 Phase: 1/3 + N

Amps: 42

Maximum Temperature: 1000˚C

Controller: Stafford Instruments ST105

Manufacturer: Stafford Instruments Ltd., Stafford, ST18 0GA

Figure D.2 Controller.
Stafford Instruments ST105.

This is a very 'simple to use' controller which will accommodate temperatures from 0°C to 1310°C. It has a 10 adjustable programme facility with up to 30 segments per programme for heating and cooling, with 1 ramp + dwell (hold) per segment (Stafford Instruments Ltd., 2011).

Kiln Test

The test was carried in May 2005 at the commencement of the research to check the reliability of the kiln. Glass bridges, as described below, were used to gauge variations. After their removal the accuracy of the readings of the controller was checked with a CJ Comp Indicator, by placing the thermocoupling on the floor of the kiln in positions corresponding to those of the glass bridges. After readings from both kiln controller and indicator were taken, the thermocoupling was moved to the next ‘square’. The test was repeated twice to confirm results and averages taken (*Table D.1).*

683	686	690	692	684
689	690	693	693	685
689	691	693	693	689
690	690	692	693	691
683	684	691	691	690

Table D.1 Kiln Test 2005. Temperature (˚C) on indicator when reading 700˚C on controller.

The above readings were taken on the floor of the kiln. The kiln pyrometer probes are positioned near the top of the roof, just under the heating elements. To check the temperature at this level the thermocouple was placed on a metal mould covered with ceramic matting, to be as close to the position of the probes as possible. The temperature was allowed to steady at 700˚C shown on the kiln controller. The reading on the indicator was also 700˚C. It was therefore assumed that the controller was presenting the correct temperature.

A more detailed assessment was carried out in August 2006 to check the ongoing performance of the kiln. This test of twenty five identical arrangements of 6mm float glass was prepared under strict measurement controls. A rectangle, 160mm x 40mm, was placed on top of two towers each made up of 4 pieces of 6mm float which measured 40mm x 20mm, forming a bridge as shown in Figure D.3. The exact measurement at the centre point of the top of the bridge to the floor of the kiln was taken. This distance was 30mm (5 x 6mm thicknesses).

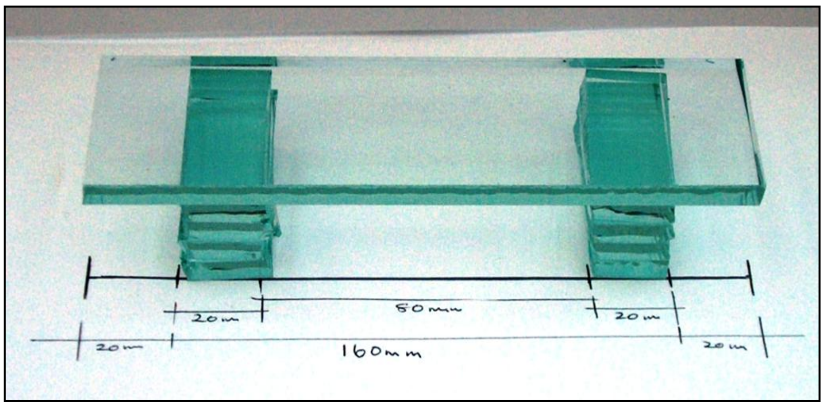


Figure D.3 Kiln test 2006, bridge of 6mm float glass.

The twenty five sets of this arrangement were placed at measured distances on the kiln floor and each checked for consistency of arrangement (*Figure D.4).*

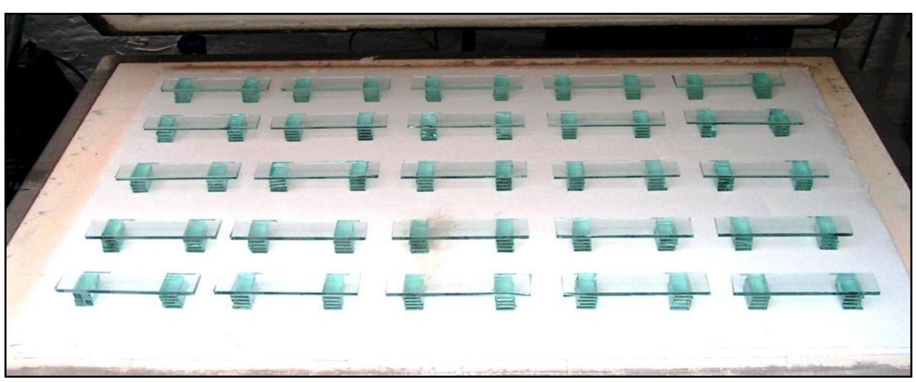


Figure D.4 Kiln test 2006, pre-fired.

The kiln was fired using the following schedule:

125˚ per hour to 520˚C, full to 700˚C, hold for 20 mins.
Full cool to 560˚C, hold for 20mins, 20˚ per hour to 480˚C. Off.
After firing the bridges sagged as can be seen in Figure D.5.

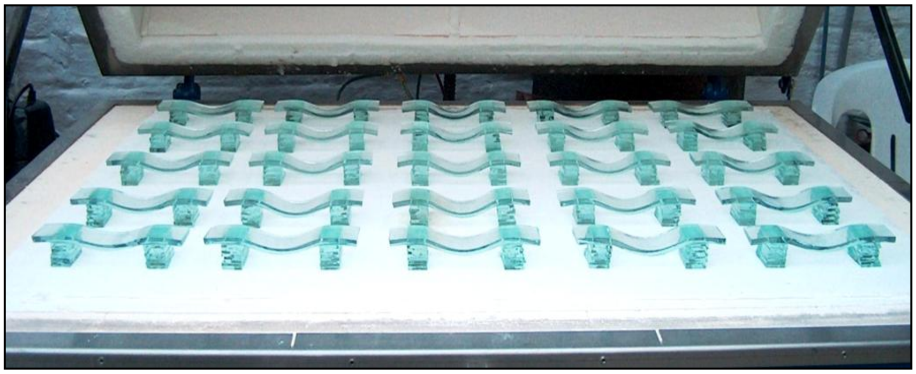


Figure D.5 *Kiln Test 2006, post-fired.*

Each bridge was measured in the same place for the depth of sag using a Vernier Scale shown in *Figure D.6*. Three sets of readings were taken to ensure accuracy and averages calculated (*Table D.2*). The test was repeated and the measurements plotted on a plan to identify the variations in temperature throughout the kiln (*Table 7*).

Figure D.6 *Measurement of sag with Vernier Scale.*

Kiln Test August 2	0								
Test No.	Norm mm	Test A Vernier measurement	Test B Vernier measurement	Vernier Average mm		Test No.	Test A Slump measurement	Test B Slump measurement	Slump average mm
1	36.0	27.2	27.3	27.3		1	8.8	8.7	8.75
2	36.0	25.4	25.2	25.3		2	10.6	10.8	10.70
3	36.0	25.0	23.0	24.0		3	11.0	13.0	12.00
4	36.0	24.2	24.4	24.3		4	11.8	11.6	11.70
5	36.0	27.2	27.3	27.3		5	8.8	8.7	8.75
6	36.0	26.0	27.1	26.6		6	10.0	8.9	9.45
7	36.0	23.8	25.0	24.4		7	12.2	11.0	11.60
8	36.0	23.6	23.0	23.3		8	12.4	13.0	12.70
9	36.0	22.0	24.8	23.4		9	14.0	11.2	12.60
10	36.0	25.2	24.8	25.0		10	10.8	11.2	11.00
11	36.0	26.7	26.5	26.6		11	9.3	9.5	9.40
12	36.0	24.3	24.1	24.2		12	11.7	11.9	11.80
13	36.0	23.6	23.3	23.5		13	12.4	12.7	12.55
14	36.0	23.3	24.0	23.7		14	12.7	12.0	12.35
15	36.0	24.0	25.1	24.6		15	12.0	10.9	11.45
16	36.0	26.0	26.5	26.3		16	10.0	9.5	9.75
17	36.0	24.0	23.8	23.9		17	12.0	12.2	12.10
18	36.0	23.0	23.2	23.1		18	13.0	12.8	12.90
19	36.0	24.9	25.5	25.2		19	11.1	10.5	10.80
20	36.0	25.6	25.8	25.7		20	10.4	10.2	10.30
21	36.0	28.2	28.5	28.4		21	7.8	7.5	7.65
22	36.0	26.0	26.2	26.1		22	10.0	9.8	9.90
23	36.0	25.2	25.5	25.4		23	10.8	10.5	10.65
24	36.0	25.8	24.5	25.2		24	10.2	11.5	10.85
25	36.0	27.8	26.8	27.3		25	8.2	9.2	8.70
	NB. 'Norm' and 'Vernier Measurements' include 6mm glass used as base for readings								

Table D.2 Kiln test August 2006. Vernier scale readings.

1. *27.3*	2. 25.3	3. 24.0	4. 24.3	5. 27.3
6. 26.6	7. 24.4	8. 23.3	9. 23.4	10. 25.0
11. 26.6	12. 24.2	13. 23.5	14. 23.7	15. 24.6
16. 26.3	17. 23.9	18 23.1	19. 25.2	20. 25.7
21. 28.4	22. 26.1	23. 25.4	24. 25.2	25. 27.3

Table D.3. Kiln test 2006. Temperature variations plotted from the sag of glass readings as shown in Table D.2. The lower figures show the greater sag and therefore the hotter zones.

The results of the 2006 kiln test showed similar variations to those found when the kiln was new in 2003. The first 2006 test was fired with the bungs in to ensure a consistency of heat. A second identical test was carried out with the bungs removed. This second test resulted in a marginal overall reduction in the degree of sag suggesting a very slightly lower temperature as a result of ventilation. The knowledge of these variations provided a guide for the positioning of artwork during firing.

Firing Schedules

Throughout this research the firing process was kept to a very simple series of schedules to be able to understand the direct effect of heat on the surface coating of the K Glass. Complicated programmes would not allow the evaluation at specific temperatures to be assessed. All firing was based on a formula that had been provided by glass artist, Jan Hein van Stiphout, at a workshop attended by the author in 2003. This method provided firing and annealing rates which can be applied to the relevant thickness of glass being used.

The principle works on two key numbers. For glass between 1 and 20mm in thickness the key number is 17; for glass between 20 and 100mm the key number is 27. These numbers represent the number of minutes per mm for total thickness of glass.

Example:

2 thickness of 6mm glass = 12mm x 17 (Key number) = 204

204 is the number of minutes required to take the glass to the strain point. The strain point of float glass is 525˚C (Cummings, 1997, p.165). Therefore, the kiln needs 3hours and 24 minutes to heat to strain point which would necessitate a rate of 155 degrees per hour.

Once strain point has been reached, it is advisable to heat as fast as the kiln will allow, i.e. full power to target temperature. This may avoid the forming of devitrification (or crystallisation) which can occur especially during slow firing between 600˚C and 800˚C. When the target temperature has been reached, it is held for example for 30min, to cause the glass to react as required. The temperature is then allowed to drop, as quickly as possible back through the devitrification zone, to just above the annealing point. Although Cummings (1997) states that this is 552˚C for window glass, there can be slight variations between glass from different manufacturers, therefore, a slightly higher temperature is recommended, i.e. 560˚C.

Annealing is necessary to ensure that the glass is allowed to cool back to the strain point evenly and throughout, so that there is no stress remaining within the glass that could cause it to crack, even at a later time. Van Stiphout described it like a playground full of excited children who needed to be formed into orderly lines before they are allowed to return into the school building. To ensure that both annealing and strain points are covered, a range of 80˚C is considered suitable for the annealing section. The key number is again used for this calculation. However, due to the equilibrium thickness of 6-7 mms that the glass wants to achieve, the fused glass as it enters the cooling section will be not be the same thickness as when it was heated. The annealing section, therefore, will be calculated using the estimated new thickness as the key number, as follows.

When the upper annealing point, is reached take 1/3 of the new number and hold that temperature for those minutes. Then take 2/3 of the new number, and drop the temperature by 20˚C during that time. Again, hold that temperature for 1/3 of the new number, then drop to the lower annealing point taking 2/3 new number of minutes.

Example, as shown in Table D.4: If the two thickness of 6mm glass are now expected to be, say, 10mm, the new number will, therefore, be 10 x 17 =170

New number 170. 1/3 = 57, 2/3 = 113

From target temperature, full cool to 560 ˚C.

At 560 ˚C, hold for 57 minutes.

Drop to 540 ˚C taking 113 minutes = 10.6˚C per hour

At 540 ˚C, hold for 57 minutes.

Drop to 480˚C, taking 113 minutes = 31.9˚C per hour

The kiln can then be switched off, if the process has been fusing flat glass. Cast pieces need to be cooled over a longer period of time.
NB. The annealing and strain points above are for float glass only. For any other type of glass the temperatures may be different.

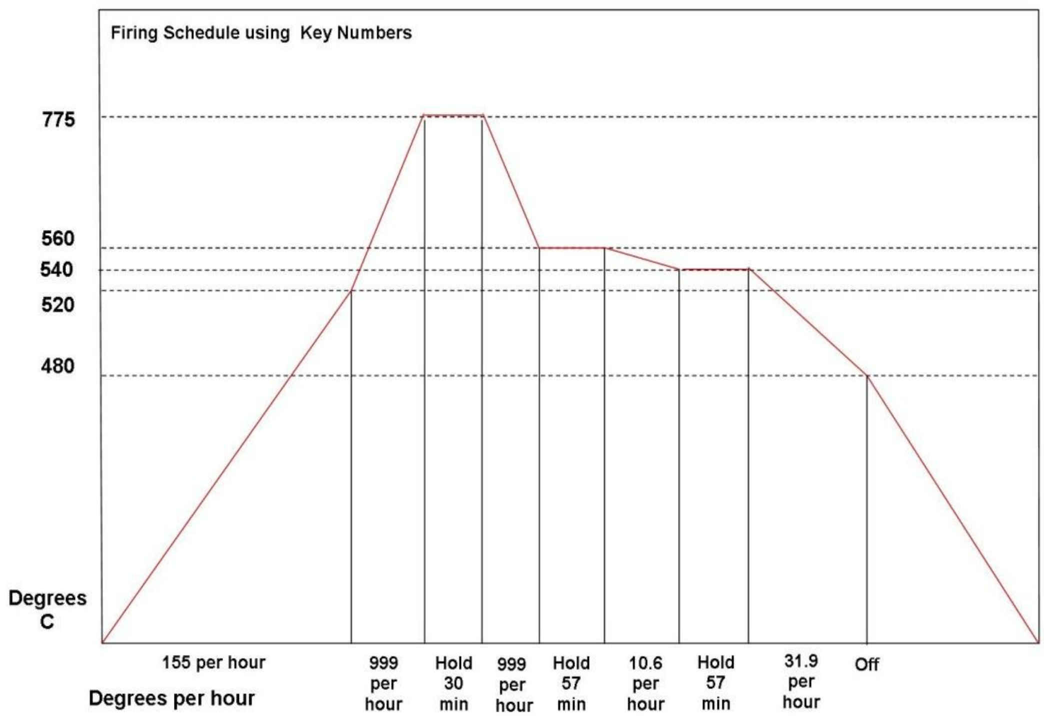


Table D.4 Firing schedule using Key Numbers.

The rate of firing can be reduced, however, for fusing glass which is of the same type. Also for small single pieces of glass this programme is not essential. This method is very reliable and will ensure that annealing has been completed in a safe and satisfactory way.

For most of the standardised tests after the initial identification tests, a simplified version of the annealing programme was substituted. This began at 560˚C with a 20 minute hold; the temperature was then reduced by 20˚C per hour to 480˚C when the kiln was switched off.

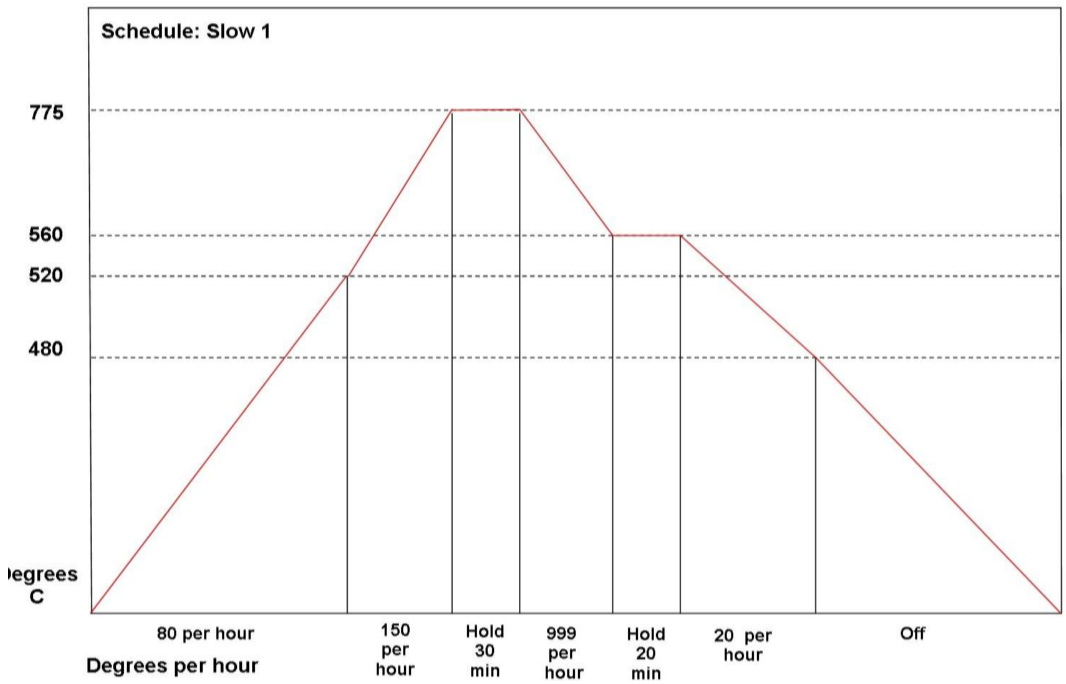


Table D.5 Firing schedule: Slow 1.

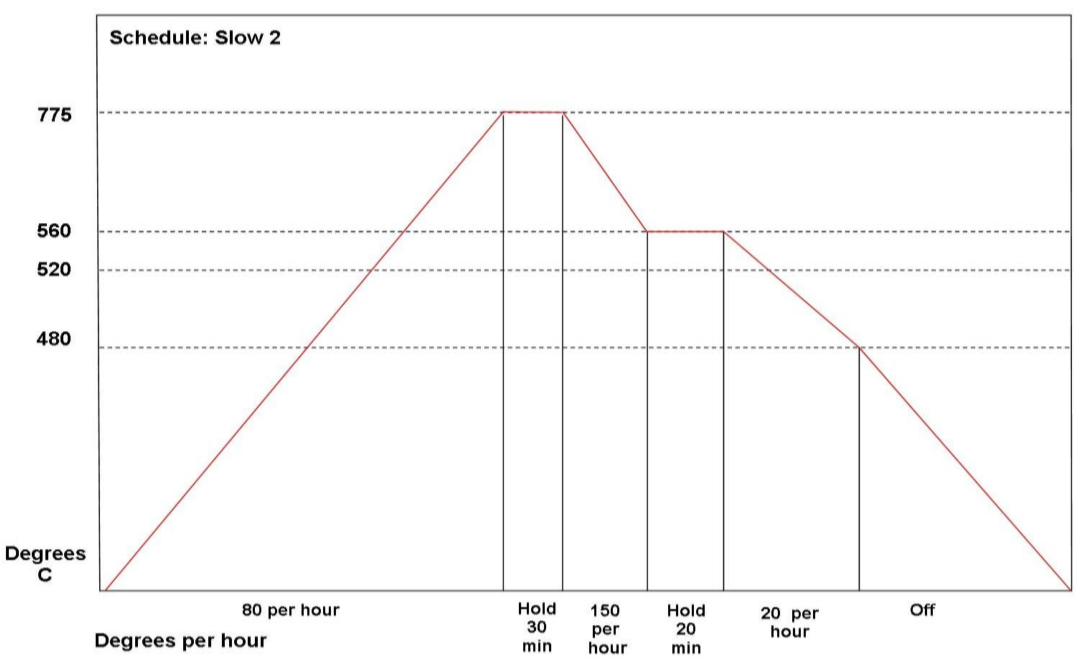


Table D.6 Firing schedule: Slow 2.

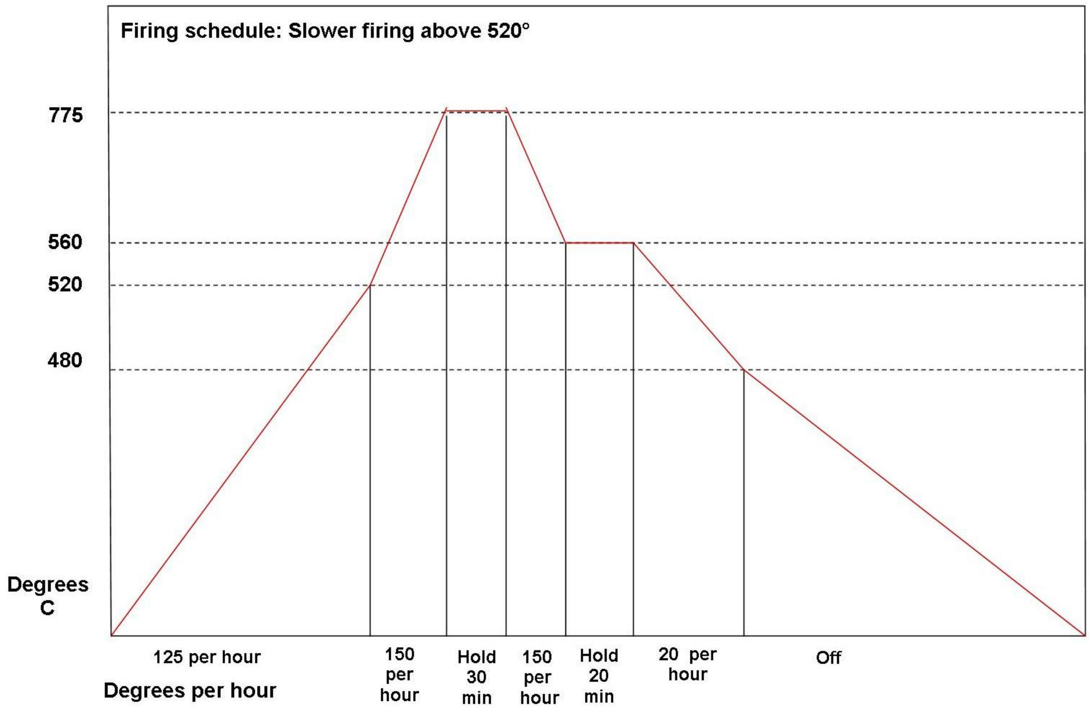


Table D.7 Firing schedule: Slow 3 (Slower firing above 520˚C).

These schedules formed the basis of the simple firings that were undertaken during this research. Variations were made to rate of heat applied, the length of hold and rate of cooling.

Appendix E

SEM/EDS: Scanning Electron Microscopy/ Energy Dispersive X-ray Spectroscopy

Figure E.1 Scanning electron microscope (SEM).

Description provided by the University at Buffalo

‘In scanning electron microscopy, (SEM) an electron beam is scanned across a sample's surface. When the electrons strike the sample, a variety of signals are generated. It is the detection of specific signals which produces an image of a sample's elemental composition. The three signals which provide the greatest amount of information in SEM are the secondary electrons, backscattered electrons and X-rays. Secondary electrons are emitted from the atoms occupying the top surface and produce a readily interpretable image of the surface. The contrast in the image is determined by the sample morphology. A high resolution image can be obtained because of the small diameter of the primary electron beam.

Backscattered electrons are primary beam electrons which are 'reflected' from atoms in the solid. The contrast in the image produced is determined by the atomic number of the elements in the sample. The image will, therefore, show the distribution of different chemical phases in the sample. These electrons are emitted from a depth in the sample, therefore, the image resolution is not as good as for secondary electrons.

Interaction of the primary beam with atoms in the sample causes shell transitions which result in the emission of an X-ray. The emitted X-ray has an energy characteristic of the parent element. Detection and measurement of the energy permits elemental analysis (Energy Dispersive X-ray Spectroscopy or EDS). EDS can provide rapid qualitative, or with adequate standards, quantitative analysis of elemental composition with a sampling depth of 1-2 microns. X-rays may also be used to form maps or line profiles, showing the elemental distribution in a sample surface' (University at Buffalo, no date).

The images on the following pages are those provided by Durham University to determine the elemental content of the fired K samples.

EDS Sample - Gold Colouration

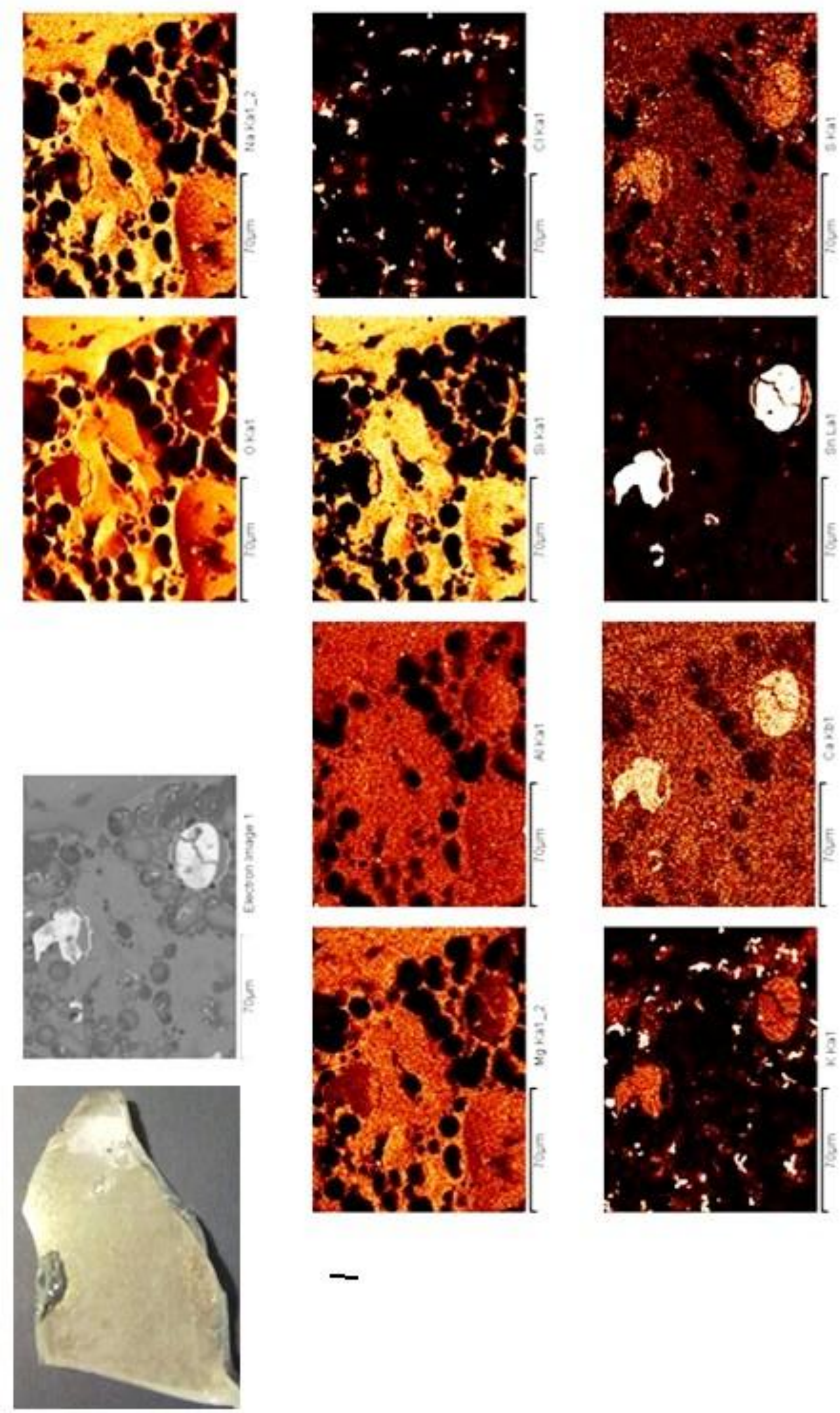


Figure E.2 *SEM images - gold sample.*

EDS Sample - Pink Colouration

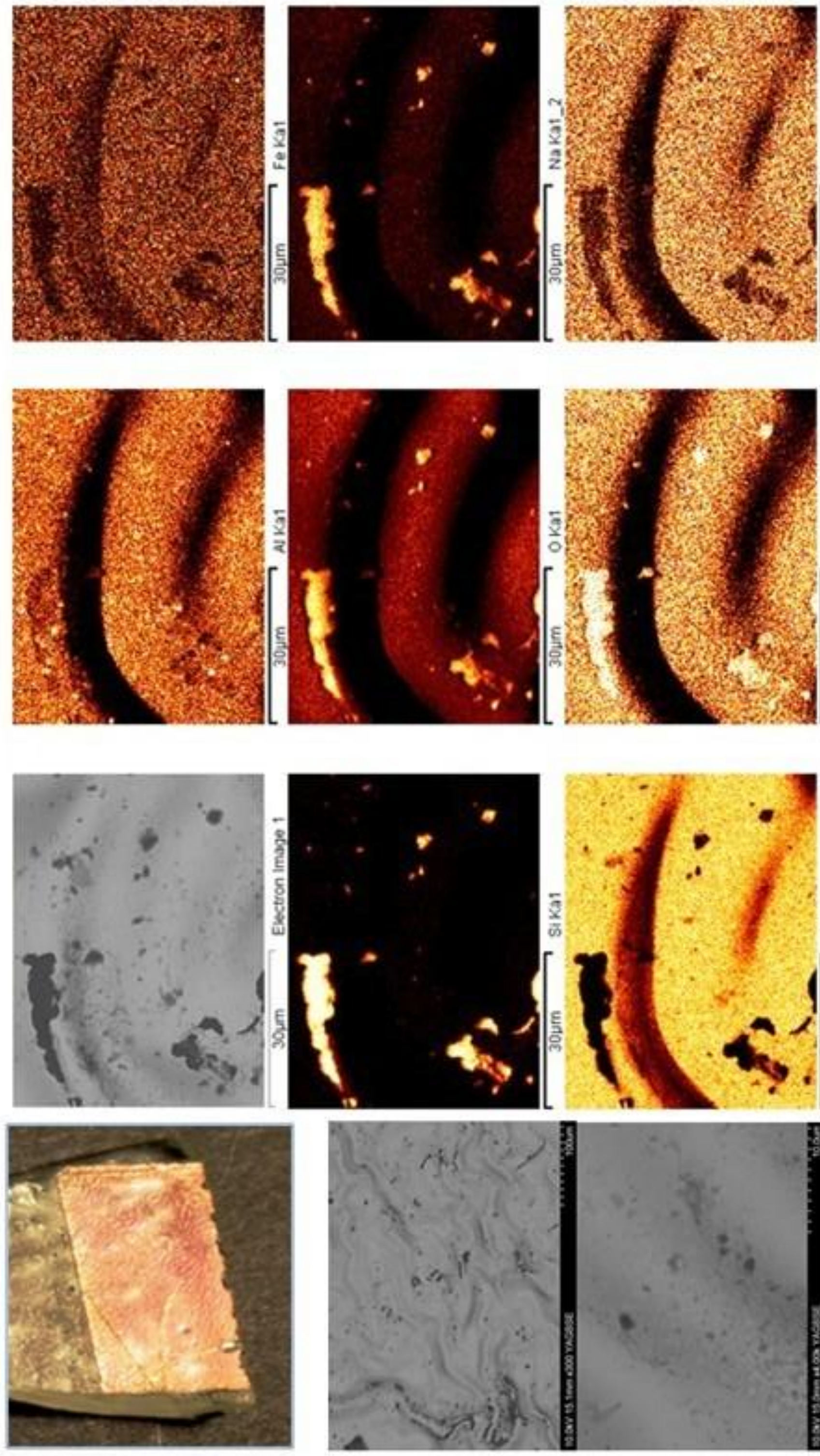


Figure E3 *SEM images - pink sample.*

EDS Sample - Purple Colouration

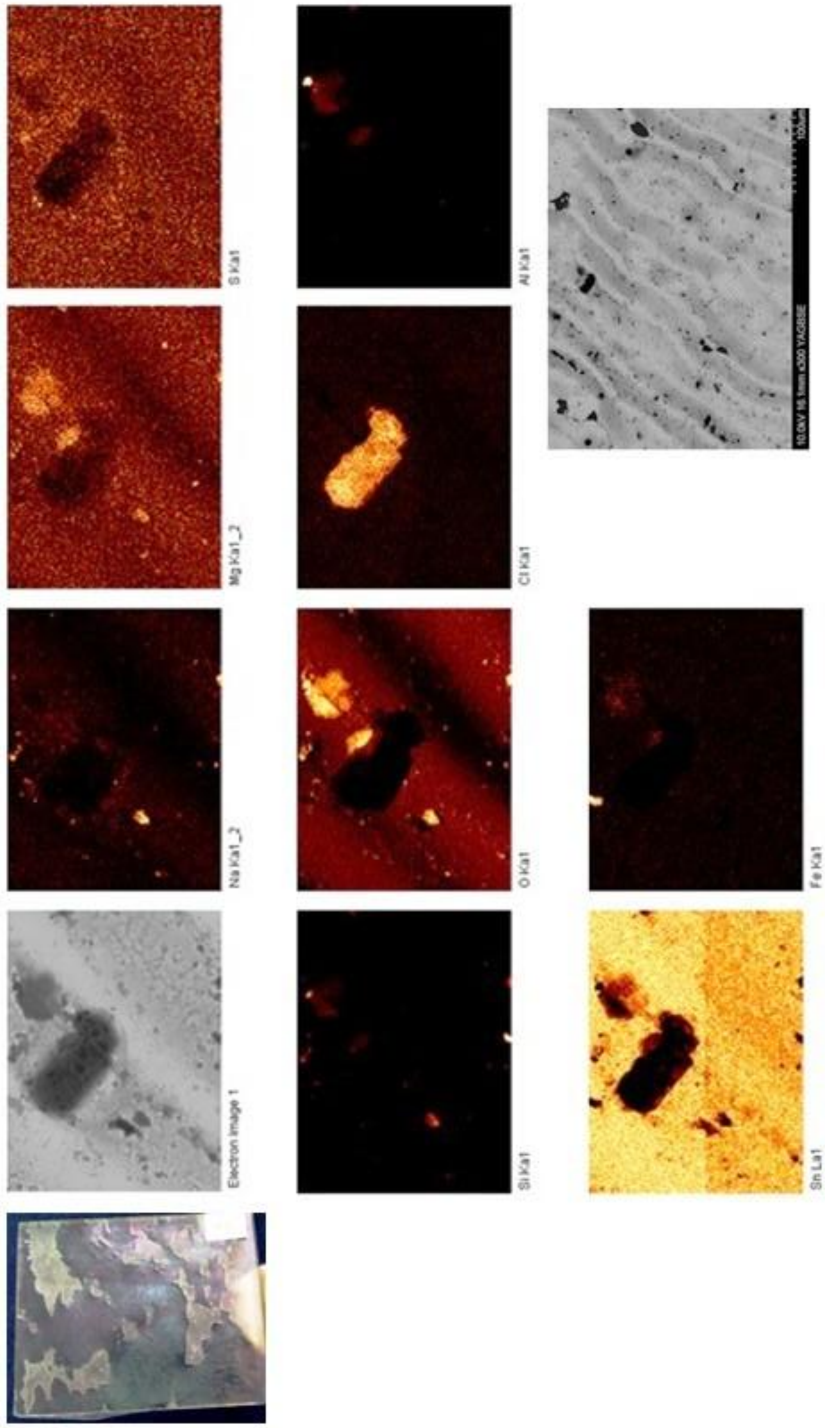


Figure E.4 *SEM images - purple sample.*

Appendix F

Additional Test Results

Effect of Temperatures from 850-950˚C on 4mm and 6mm K Glass

Figures F.1–F.5 show the post-fired surface coating of 4mm K at 25˚C intervals from 850-950˚C, with micrographs that revealed bubbles, in patches, over ripples.

Figures F.6–F.10 show samples of the 6mm K at the same temperatures and may suggest a more stable coating than that of 4mm K at these higher temperatures.

When the 6mm K was held for longer at 925˚C (*Figure F.11*) the coating showed a different structure. Higher temperatures and holding at those temperatures may encourage the dispersal of the bubbles.

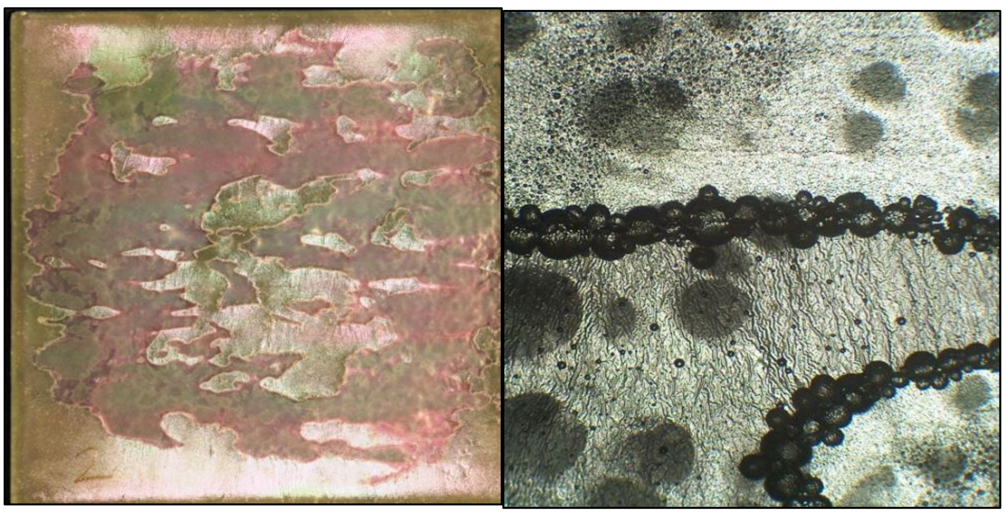


Figure F.1 4mm K at 850˚C for 30min and micrograph.

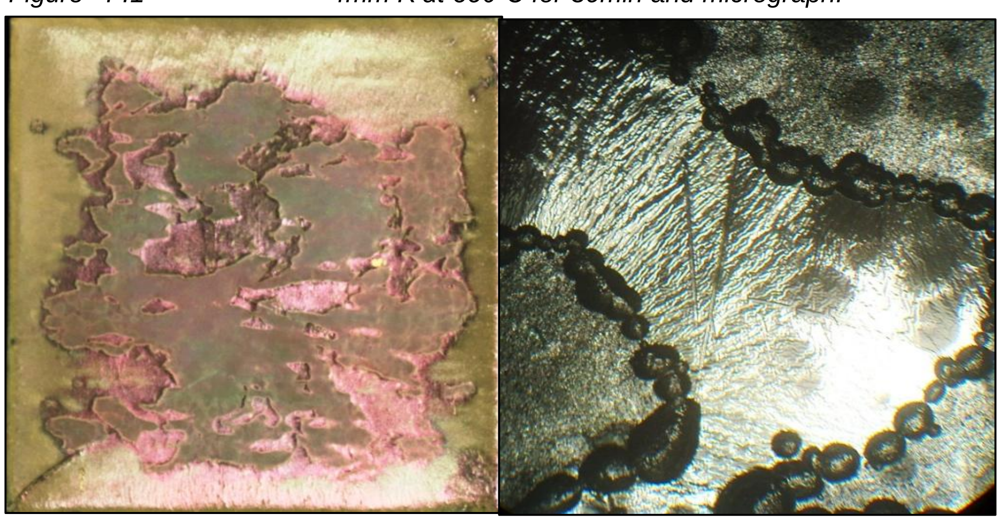


Figure F.2 4mm K at 875˚C for 30min and micrograph.

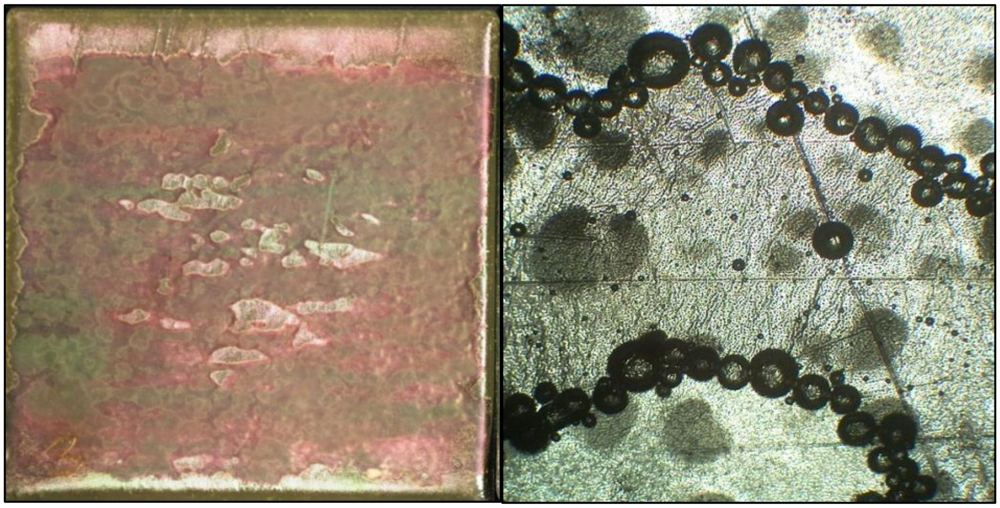


Figure F.3 4mm K at 900˚C for 30min and micrograph.

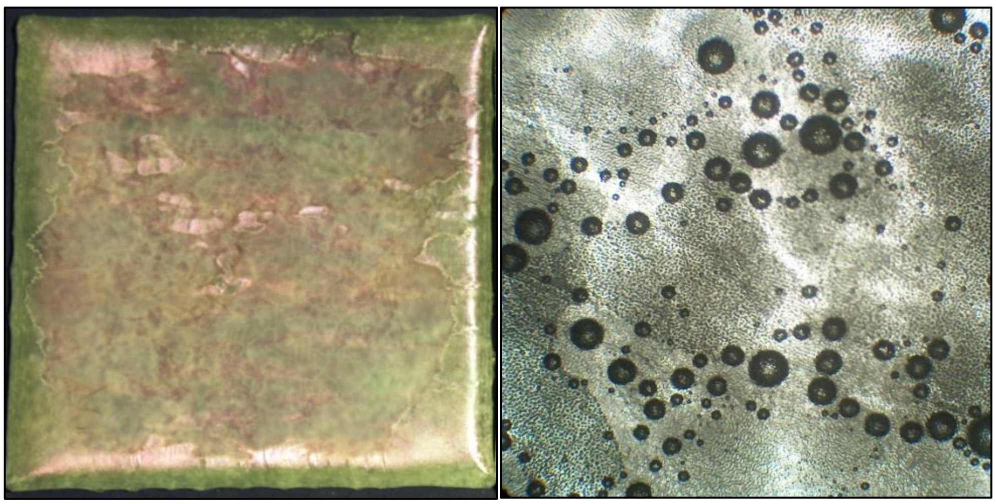


Figure F.4 4mm K at 925˚C for 30 min and micrograph.

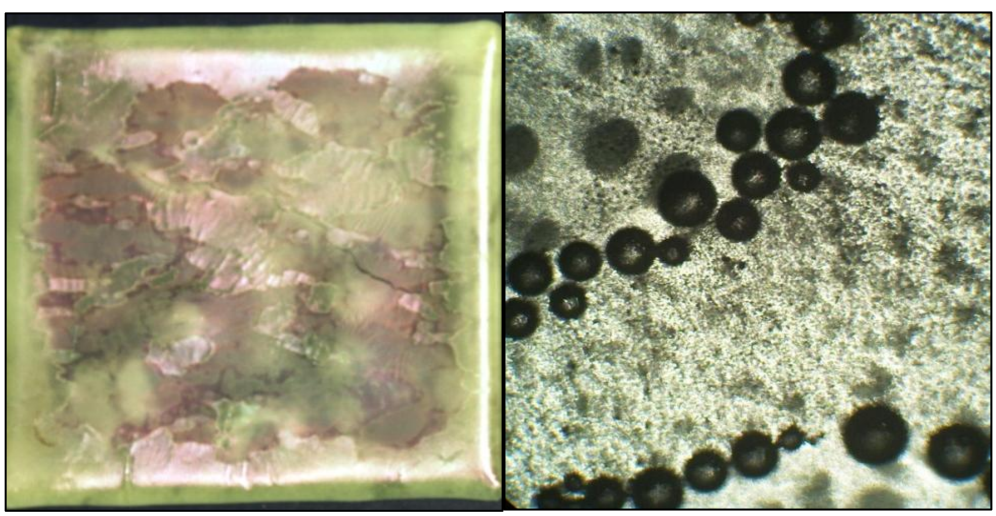


Figure F.5 4mm K at 950˚C for 30min and micrograph.

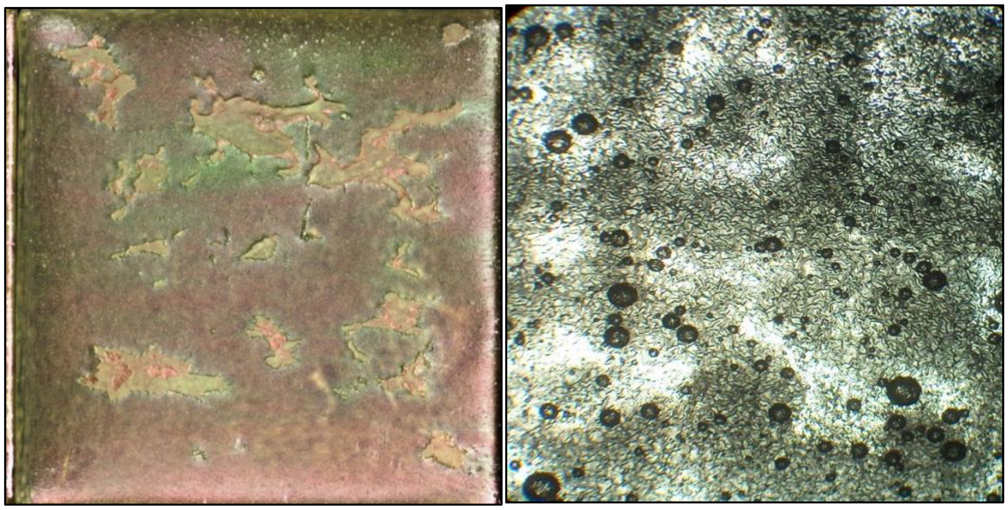


Figure F.6 *6mm K at 850˚C for 30min and micrograph.*

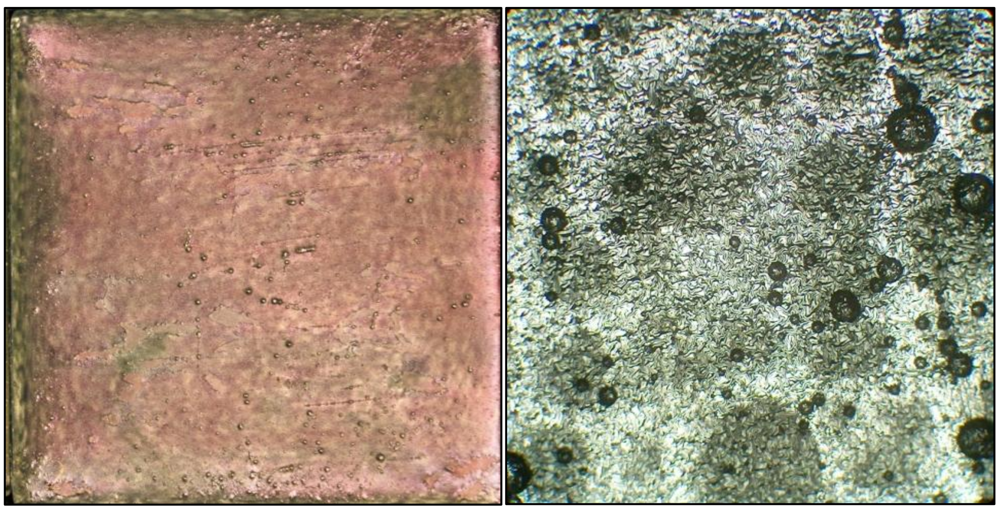


Figure F.7 *6mm K at 875˚C for 30min and micrograph.*

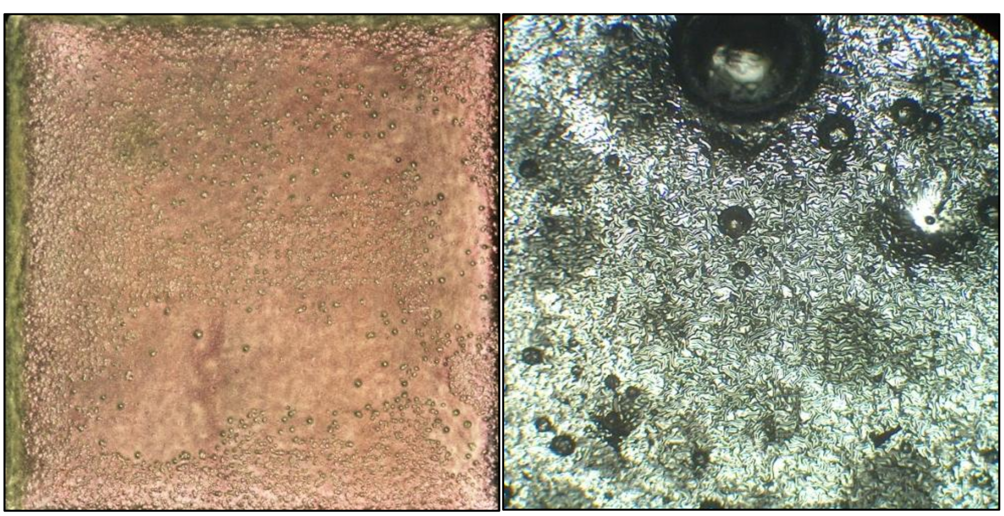


Figure F.8 *6mm K at 900˚C for 30min and micrograph.*

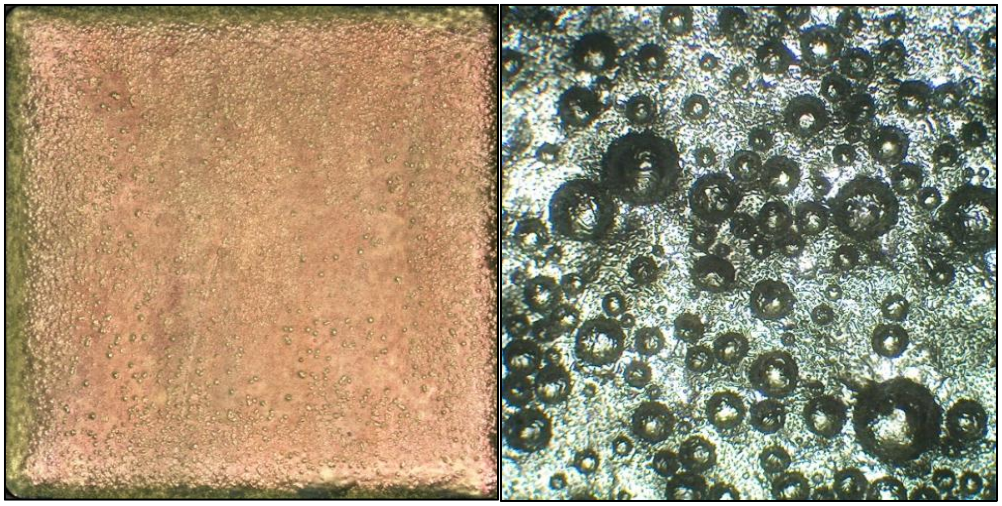


Figure F.9 *6mm K at 925˚C for 30min and micrograph.*

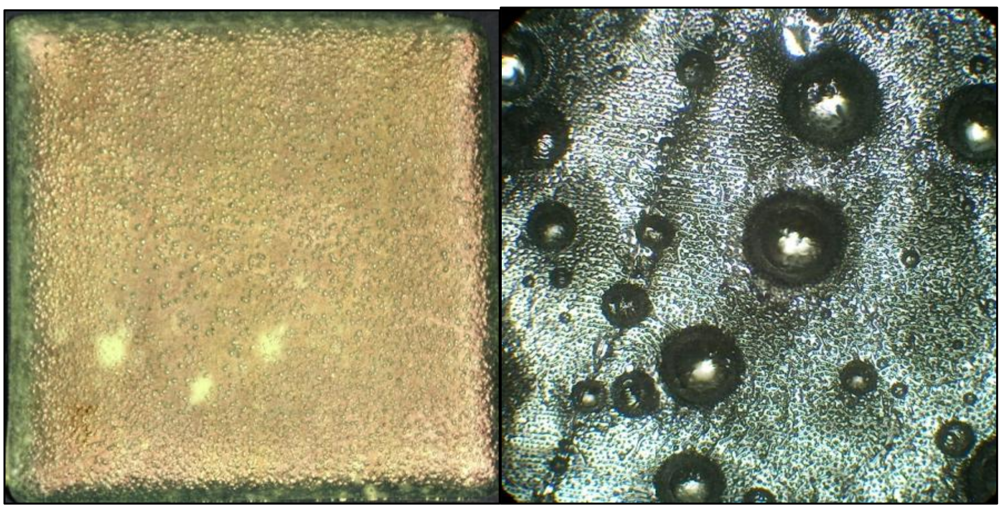


Figure F.10 *6mm K at 950˚C for 30min and micrograph.*

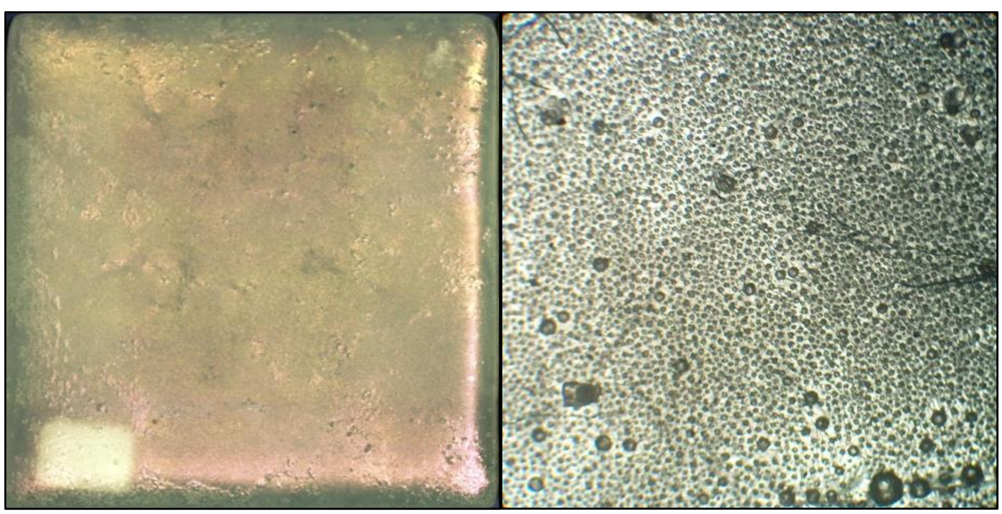


Figure F.11 *6mm K at 925˚C for 1hour and micrograph.*

Dial Guage Readings 3 March 2009										
Cumulative										
	Top Left Corner Reading			Centre Reading			Bottom Right Corner Reading			Average
Square	Calibration			Calibration			Calibration			Reading
No.	Reading	Conversion Readings		Reading	Conversion Readings		Reading	Conversion Readings		mms
	0.0005	To inches	To mms	0.0005	To inches	To mms	0.0005	Inches	To mms	
1	1	0.0005	0.0127	0.8	0.0004	0.0102	0.4	0.0002	0.0051	0.0093
2	3	0.0015	0.0381	3.4	0.0017	0.0432	3	0.0015	0.0381	0.0398
3	5.3	0.0027	0.0673	5.8	0.0029	0.0737	5.7	0.0029	0.0724	0.0711
4	7.5	0.0038	0.0953	8	0.0040	0.1016	8	0.0040	0.1016	0.0995
5	9	0.0045	0.1143	9	0.0045	0.1143	10	0.0050	0.1270	0.1185
6	13	0.0065	0.1651	13	0.0065	0.1651	13	0.0065	0.1651	0.1651
7	15	0.0075	0.1905	15	0.0075	0.1905	14.5	0.0073	0.1842	0.1884
8	16	0.0080	0.2032	16	0.0080	0.2032	16	0.0080	0.2032	0.2032
9	18	0.0090	0.2286	19	0.0095	0.2413	19	0.0095	0.2413	0.2371
10	20	0.0100	0.2540	18.5	0.0093	0.2350	18.3	0.0092	0.2324	0.2405
11	22	0.0110	0.2794	22.5	0.0113	0.2858	23	0.0115	0.2921	0.2858
12	26.3	0.0132	0.3340	26	0.0130	0.3302	26.2	0.0131	0.3327	0.3323
13	27.5	0.0138	0.3493	26.8	0.0134	0.3404	28	0.0140	0.3556	0.3484
14	29.2	0.0146	0.3708	29.3	0.0147	0.3721	30.5	0.0153	0.3874	0.3768
15	29	0.0145	0.3683	29.5	0.0148	0.3747	28.9	0.0145	0.3670	0.3700
16	34.5	0.0173	0.4382	366-	0.0180	0.4572	37	0.0185	0.4699	0.4551
17	38	0.0190	0.4826	36.5	0.0190	0.4826	38	0.0190	0.4826	0.4826
18	40	0.0200	0.5080	41	0.0205	0.5207	42.5	0.0213	0.5398	0.5228
19	46	0.0230	0.5842	45	0.0225	0.5715	46.5	0.0233	0.5905	0.5821
20	47.5	0.0238	0.6033	46	0.0230	0.5842	48	0.0240	0.6096	0.5990
21	52.5	0.0263	0.6668	51.5	0.0258	0.6541	53	0.0265	0.6731	0.6646
22	56	0.0280	0.7112	57	0.0285	0.7239	58	0.0290	0.7366	0.7239
23	58.5	0.0293	0.7430	59.5	0.0298	0.7557	60.5	0.0303	0.7684	0.7557
24	63	0.0315	0.8001	64.7	0.0324	0.8217	64.5	0.0323	0.8192	0.8136
25	67	0.0335	0.8509	68	0.0340	0.8636	69.5	0.0348	0.8827	0.8657
26	74.3	0.0372	0.9436	72.5	0.0363	0.9208	72	0.0360	0.9144	0.9263
27	75	0.0375	0.9525	74	0.0370	0.9398	74	0.0370	0.9398	0.9440
28	76	0.0380	0.9652	75	0.0375	0.9525	76	0.0380	0.9652	0.9610
29	77.5	0.0388	0.9843	78	0.0390	0.9906	79	0.0395	1.0033	0.9927
30	80	0.0400	1.0160	79	0.0395	1.0033	80	0.0400	1.0160	1.0118
31	82	0.0410	1.0414	78	0.0390	0.9906	76	0.0380	0.9652	0.9991
32	84	0.0420	1.0668	81.8	0.0409	1.0389	79	0.0395	1.0033	1.0363
33	85.5	0.0428	1.0859	84	0.0420	1.0668	89.5	0.0448	1.1367	1.0964
34	91	0.0455	1.1557	87.5	0.0438	1.1113	87	0.0435	1.1049	1.1240
35	95	0.0475	1.2065	91	0.0455	1.1557	90.5	0.0453	1.14935	1.1705

Table F.1 *Gap depth study : dial guage readings.*

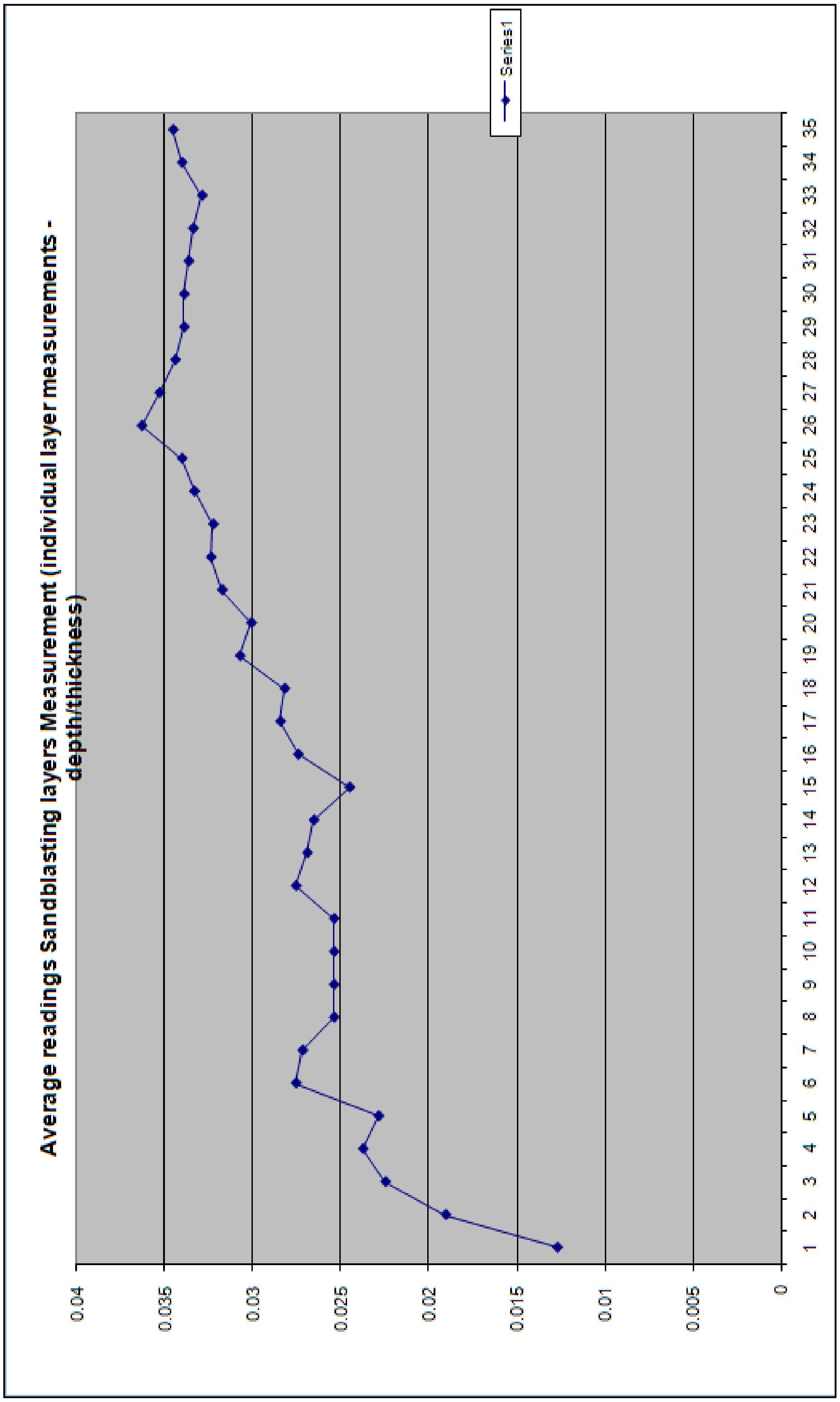


Table F.2 Gap depth study : graph showing increase in depth of gap.

Gap Depth Study Results and Micrographs

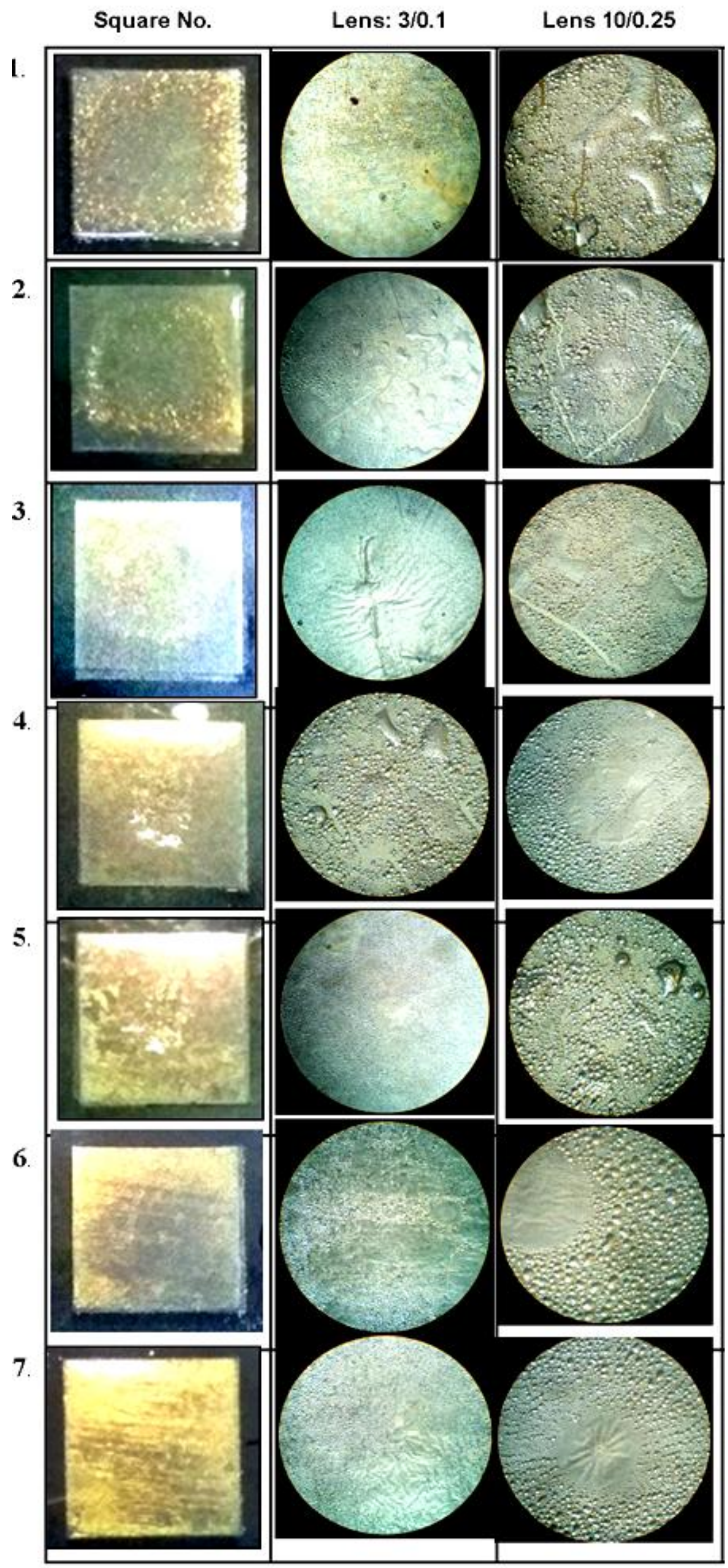


Figure F.12 Sandblasted squares 1-7.

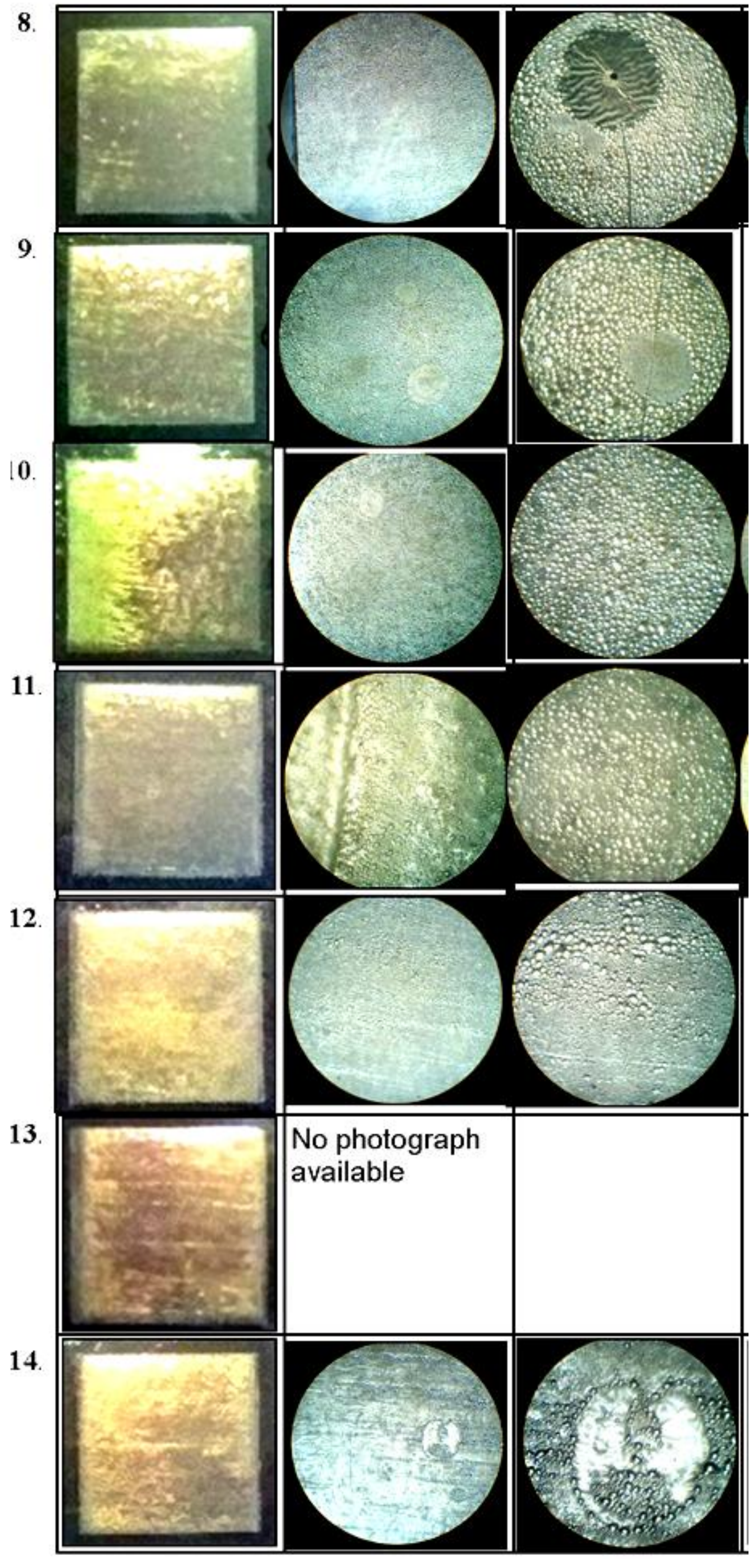


Figure F.13 Sandblasted squares 8-14.

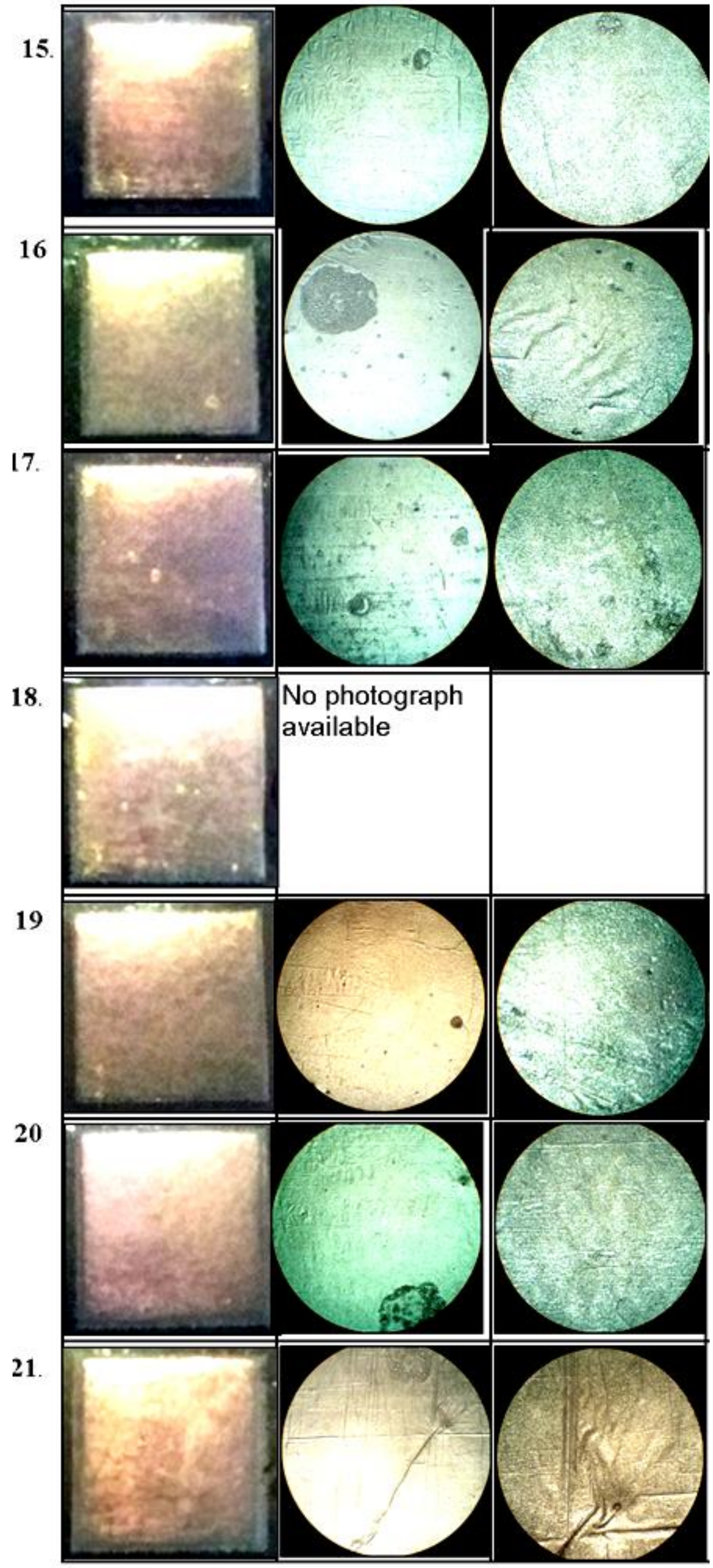


Figure F.14 Sandblasted squares 15-21.

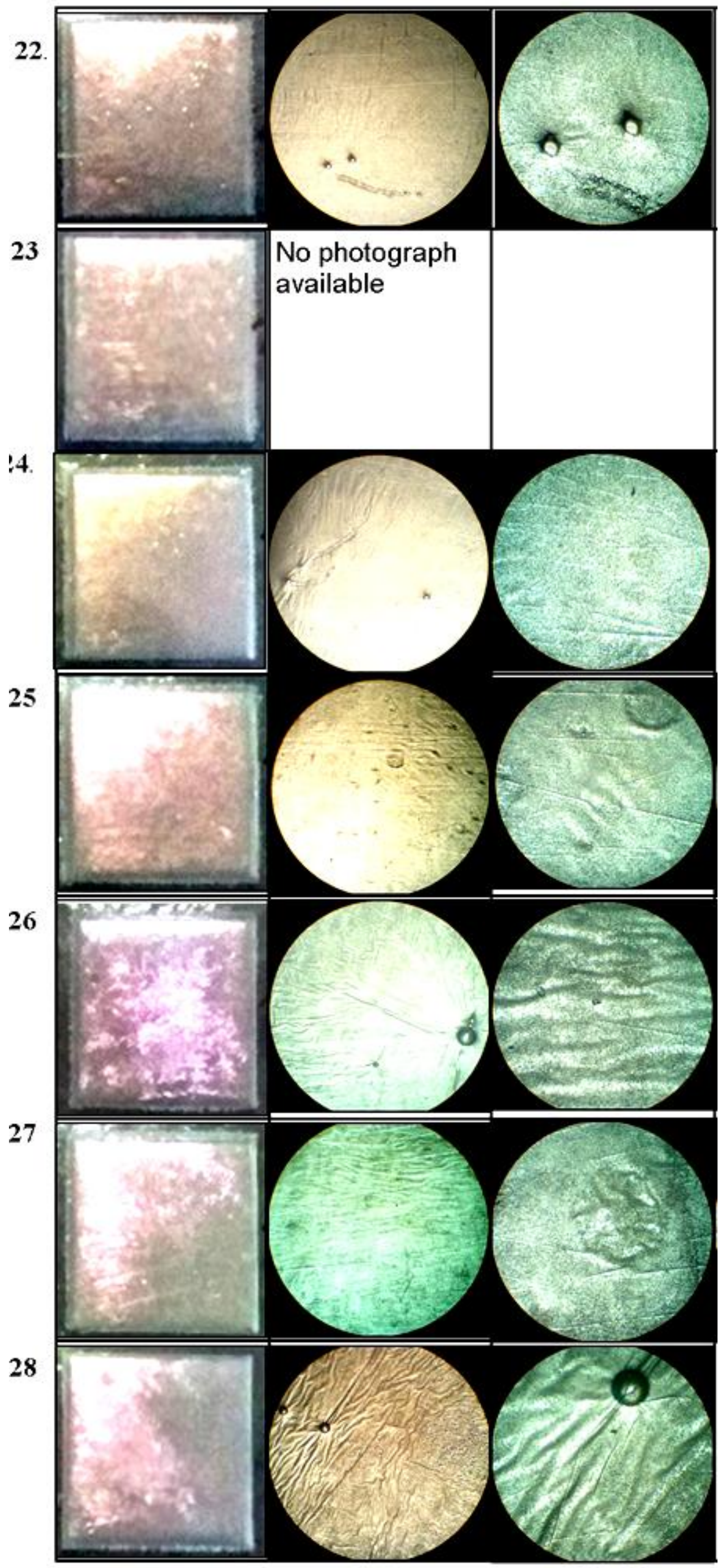


Figure F.15 Sandblasted squares 22-28.

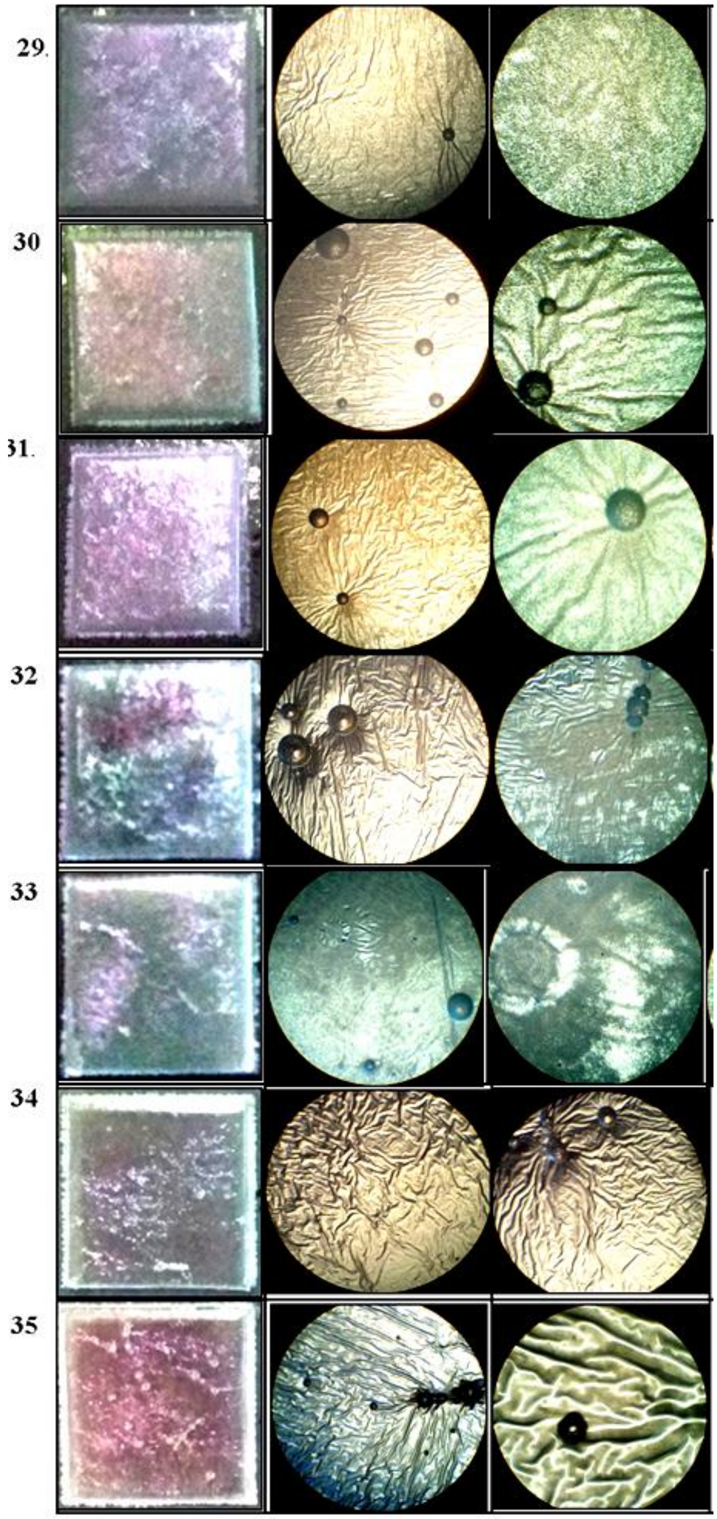


Figure F.16 Sandblasted squares 29-35.

NB. It was not possible to observe squares 13, 18 and 23 through the microscope eyepiece due to the position of the square on the glass grid.

Appendix G

Exhibitions Featuring Artworks Developed During Research

2004 '**Blast!'** Cork Street Gallery, London.

2005 **'NGC Showcase',** National Glass Centre, Sunderland.

2006 **'Weardale Artists Annual Exhibition',** Stanhope, Co. Durham.

2007 **'Cohesion Glass Showcase',** British Embassy, Dubai.

'Cohesion Glass Showcase', Crowne Plaza Hotel, Dubai,

2008 **'Cohesion Selected Artists Exhibition',** Majlis Gallery, Dubai.

'Glass 3, An International Exhibition', Georgetown, Washington DC.

2009, '**Artomatic 2009',** Washington DC.

2010 **'Art in a Small Garden',** Brandon, Durham.

Commissions undertaken during this research

2008 **Clayton Glass**, Employee of the Year Award.

2008 **ICCG7,** Conference Gifts, Amsterdam.

2008-9 **Clayton Glass**, Employee of the Month Awards.

2009 **Clayton Glass**, Employee of the Year Award.

Award received during this research

2010 Collin Gill Award for Technical Excellence

Appendix H

Research Papers Published Relating to this Research

Extracts from paper prepared for publication in
GlassTechnology: European Journal of Glass Science and Technology 49 (4), pp.189-194

Float Glass in Bloom and other stories

David Gelder

ABSTRACT: The interactions between high viscosity surface layers and the bending and stretching of flat glass are sometimes of concern to industrial manufacturers. They are of much more interest to creative workers who may wish to exploit the various effects which the industrialist tries to avoid. This paper explores these interactions from the viewpoint of a 'mathematical modeller' and attempts to interpret them in a way which makes sense to those who are interested in using them.

KEY WORDS: Float Glass Bloom, Stretching Distortions

Introduction

This paper was presented in the context of the 'Art meets Science' sessions of 'Glass: The Art of Science' organised by the Society of Glass Technology in Sunderland in September 2006. It brings together all three themes of this meeting in a case study of 'Mathematical Modelling' applied to glass processing by artists. The artists featured both use commercial flat glass: ordinary Float glass, or Pilkington K glass. Almost by accident, they found that heating these glasses above normal processing temperatures develops surface texture and colour which can express various concepts in the way they can be made to emerge in 'space', or more precisely in an invisible sheet of glass. Art is sometimes thought of as the opposite of science, but many materials used by artists require meticulous care and control to achieve the desired effect, and the renowned centres of glassmaking have emerged out of generations of experience. Scientific knowledge can provide a route to interpreting and exploiting unexpected phenomena in years rather than decades. 'Mathematical Modelling' is concerned with extracting the simplest approximation to complex science – often a range of scientific knowledge from diverse fields of study, enriched by the careful use of the ways in which practitioners interpret what they see – so as to effect knowledge transfer.

Technology Transfer between Art and Science

'Appropriate Technology' and similar phrases play down the transfer value of science developed in large scale enterprises. There is some truth in the concept, but the problem is largely in matching the source to the need in making wider use of such 'Technology Transfer'. The SGT is particularly successful in bringing together almost all parties interested in glass, and in this case study the transfer proves to be very much in both directions. Regarded as covering issues in Material Science, the industry has a considerable body of scientific knowledge. However in working beyond the normal range of applicability of float glass, the artists' interpretation of what they see can provide valuable information and bring together apparently disparate strands of the information needed for the large scale applications of the material. Pending possible future publication, the artistic work by Jennifer Antonio and Eileen Leatherland which forms the basis of this case study is largely covered in the Conference Presentations disc available via the SGT.

Overheated K Glass

The various coatings deposited on glass are often unstable to a greater or lesser extent when heated above the deposition temperature. As with bloom, this is normally taken to be a factor limiting how the glass should be processed and used. Again almost by accident, Eileen Leatherland discovered that overheating Pilkington 'K' glass produces various effects which she could use in her exploitation of glass in ways perhaps most easily contrasted with Jennifer's as being 'sculptural' rather 'artistic.

Unlike bloom, many of the effects she has seen come as a surprise even to those familiar with the commercial use of such coatings. The primary functional purpose of the fluorine doped tin oxide coating on 'K' glass is to provide high infra red reflection in an optically clear coating, permitting a substantial reduction in heat loss through double glazed windows. However in isolation this is a thin coating of high refractive index which produces unacceptably strong colour in reflection. This is suppressed using a reduced silica undercoat – reduced to increase the index towards that of silicon, and optimised to minimise the reflection from the back surface of the tin oxide and suppress the interference colour. On one view Eileen heats the glass to a high enough temperature to change the coating structure, and recovers a controllable range of interference colours. Additionally under suitable conditions the silica may be further reduced so as to become partially reflective – such coatings are used in various commercial products and are sometimes referred to as SiCO coatings as the reduction normally involves the incorporation of some carbon.

While in principle coatings could be prepared specifically to match all that Eileen has used, the production process is time consuming and intrinsically large scale. Her handling of a readily available commercial glass is enabling her to produce a wide range of effects based on the opportunities provided by the material.

List of References

Abode Window films (2011) *Safety and Security Film*. Available at: http://www.abodewindowfilms.co.uk/acatalog/Safety_Window__Film.html (Accessed :24 August 2011).

Academic dictionaries and encyclopedias (no date) *John Claudius Loudon.* Available at: http://en.academic.ru/dic.nsf/enwiki/511486 (Accessed: 29 September 2008).

Alden, A. (2009) *About.com.geology Cassiterite Oxide Minerals.* Available at: http://geology.about.com/od/minerals/ig/oxides/minpiccassiterite.htm (Accessed: 29 December 2010).

Allinson, B. (1996) 'Research Methods' in Allinson, B., O'Sullivan, T., Owen, A., Rice, J., Rothwell, A., Saunders, C. *Research Skills for Students.* London: De Montfort University, pp.1-26.

Alpine Stained Glass (2009) *Fiber Paper Sheet - 1/32" 24" x 24" Sheet.* Available at: http://www.alpineglass.com/shop/detail/1684 (Accessed: 1 February 2011).

Antonio, J. (2009) *'The creative use of the tin-containing layer on float glass'.* PhD thesis. University of Sunderland.

Banham,R. (1969) *The Architecture of the Well-tempered Environment*. London: Architectural Press.

Batzill, M. and Diebold, U. (2005) *The surface and materials science of tin oxide.* Available at: http://shell.cas.usf.edu/~mbatzill/papers/paper%207.pdf (Accessed: 23 August 2011).

BDI (2006) *Design and innovation news.* Available at: http://www.britishdesigninnovation.org/index.php?template=bdi_print&page=newsservice/view&news_id=3781 (Accessed: 22 November 2011)

Behling, S and S. (1998) *Glass, Structure and Technology in Architecture*. Munich: Prestel Verlag.

Bezúr, A., (1999) *Iridescence on Glass.* Available at: www.ic.arizona.edu/ic/mse257/class_notes/iridescence.pdf (Accessed: 26 July 2010).

Bohle (2004) *Glass +Glazier 2004-2005.* Trade catalogue Oldham: Bohle.

Bray, C., (2001) *Dictionary of Glass, Materials and Techniques* (2nd edn.). London: A and C Black.

Bremner, A. (2005) *New Possibilities for Refractory Castable.* Available at: http://www.artdes.mmu.ac.uk/rnsacg/downloads/ab.pdf (Accessed: 5 September 2011).

Bremner, A. (2008) *'An investigation into the potential creative applications of refractory concrete'*. PhD thesis. University of Central Lancashire.

Brewster, D. (1830) *The Edinburgh Encyclopedia Volume 16.* London: Blackwood, Reprinted (1999) London: Routledge. Google Books [Online] Available at: http://books.google.co.uk/books?id=s4RZnW-B0-wC&pg=PA66&lpg=PA66&dq=sir+david+brewster+iridescent+glass&source=bl&ots=n0_wqgyNB5&sig=TYMelmPvc1PAkV9o_dcFFwzHt0Y&hl=en&ei=Gu1rTarXLuSAhAewsqjyDg&sa=X&oi=book_result&ct=result&resnum=3&ved=0CCkQ6AEwAg#v=onepage&q=iridescent&f=false (Accessed 28 February 2011).

Brigham Young University (2009) *Silicon Dioxide/Nitride Color vs. Film Thickness and Viewing Angle Calculator.* Available at: http://www.cleanroom.byu.edu/color_chart.phtml (Accessed: 2 January 2011).

Bullinger, H.B. (1971) *Photoetching of metal-oxide layers*. United States Patents No. 3615465 [Online]. Available at: http://www.freepatentsonline.com/3615465.pdf (Accessed: 9 September 2010).

Button, D. and Pye.B. (eds) (1993) *Glass in Building*. London: Butterworth Architecture.

Cadram (2010) *Imagination to Reality.* Available at: http://www.cadram.com/products_dispsys.html (Accessed 31 August 2011).

Causes of Color (2010). Available at: http://www.webexhibits.org/causesofcolor/15.html (Accessed: 26 July 2010).

Chilvers, I., Osborne, H and Farr. D. (1988) *Oxford Dictionary of Art.* Oxford: Oxford University Press.

Collini,S. (1998) Introduction in Snow, C.P. *The Two Cultures*. Cambridge: University Press.

Commission of the European Communities (2007) *An Energy Policy for the Europe* [Online]. Available at: http://ec.europa.eu/energy/energy_policy/doc/01_energy_policy_for_europe_en.pdf (Accessed: 30 October 2011).

Communities and Local Government (2010) *Planning, building and the environment Building Regulations* . Available at: http://www.communities.gov.uk/planningandbuilding/buildingregulations/ (Accessed: 12 September 2011).

Corning Museum of Glass (2011) *Iridescent Glass.* Available at: http://www.cmog.org/dynamic.aspx?id=1384 (Accessed: 1 October 2011)

Cristal Windows (2009) *Glass & Glazing.* Available at: http://www.cristalwindows.co.uk/Information/GlassGlazing.aspx (Accessed: 12 March 2011).

Crozier, D. (2011) Discussion with Eileen Leatherland, 28 July.

Cummings, K. (1997) *Techniques of Kiln-formed Glass*. London: A and C Black.

Cutting, H. (2008) Meeting with Eileen Leatherland. January 2008.

Davies, M. (1986) 'A Wall for all Seasons: Towards the Design of the Intelligent Environment' in Wigginton, M. (ed) *Glass in the environment conference April 1986.* London: Crafts Council, pp.53-56.

Dictionary.com (2010) *Iridescent.* Available at: http://dictionary.reference.com/browse/iridescent (Accessed: 26 July 2010).

Digital Fusion (2000) *Littlefuse Blade Fuse Extractor/Tester.* Available at: *http://www.auto-connect.co.uk/Autoconnect_Littelfuse_Holders___3370.html* (Accessed: 5 January 2011).

Duncan,T. (1995) *GCSE Physics*, (3rd edition). London: John Murray. Reprint 1996.

Elkadi, H. (2006) *Cultures of Glass Architecture*. Aldershot: Ashgate Publishing Limited.

Encyclopedia Britannica eb.com,2011 *Zwischengoldgläser.* Available at: http://www.britannica.com/EBchecked/topic/658624/Zwischengoldglaser (Accessed: 20 September 2011).

Encyclopedia Brittanica, Inc. (2010) *Organization of Arab Petroleum Exporting Countries (OAPEC).* Available at: http://www.britannica.com/EBchecked/topic/31502/Organization-of-Arab-Petroleum-Exporting-Countries (Accessed: 29 December 2010).

Flavell, M.R. (2001) '*The Development and Application of the use of Encased Voids within the Body of Glass Artefacts as a Means of Drawing and Expression'*. PhD Thesis, Edinburgh College of Art / Heriot-Watt University.

Gelder, D. (2008) "Float glass in bloom and other stories", *Glass Technology: European Journal of Glass Science and Technology* 49 (4), pp.189-194.

Glasscoat International Limited (2005) *Colour Coating Glass Worldwide.* Available at: http://www.glasscoat.co.uk/index_machinery.htm (Accessed: 6 November 2011).

Glass Engraving Supplies (2010) APM Plus Self Adhesive. Available at: http://www.glassengravingsupplies.co.uk/product/product.php?pid=PS24 (Accessed: 20 March 2011).

Glass Fusing Made Easy (2007) *Hotline Fusers Glue.* Available at: http://www.glass-fusing-made-easy.com/hotline-fusers-glue.html (Accessed: 5 January 2011).

Glass Online (2011) *Illustrated Glass Dictionary Low Emissivity Glass.* Available at: http://www.glassonline.com/infoserv/dictionary/584.html (Accessed: 22 August 2011).

Glass On Web (2007) *Basic glass Reflective glass.* Available at: http://www.glassonweb.com/glassmanual/topics/index/reflective.htm (Accessed: 22 August 2011).

Glass On Web (2007a) *Special glass Anti-reflective glass.* Available at: http://www.glassonweb.com/glassmanual/topics/index/antiref.htm (Accessed: 22 August 2011).

Glass On Web (2007b) *Basic glass Low-e glass.* Available at: http://www.glassonweb.com/glassmanual/topics/index/lowe.htm (Accessed: 22 November 2011).

Glass on Web (2009) *Windows of the future*. Available at: *http://www.glassonweb.com/articles/article/520* (Accessed 25 August 2010).

Glass on Web (2010) *Electrochromic glass*. Available at: http://www.glassonweb.com/glassmanual/topics/index/electrochromic.htm (Accessed 25 August 2010).

Gordon, R.G. (1980) *Non-iridescent glass structures and processes for their production.* European Patent Office Patent no. GB 2031756A [Online]. Available at: http://v3.espacenet.com/publicationDetails/biblio?DB=EPODOC&adjacent=true&locale=en_EP&FT=D&date=19800430&CC=GB&NR=2031756A&KC=A (Accessed: 9 December 2008).

Graham, B. (2010) *Art Research Methodologies:Section.* Available at: http://seacoast.sunderland.ac.uk/~as0bgr/asunder/mods/met1.htm#artprac (Accessed: 20 October 2010).

Gray, C. and Malins, J. (2004) *Visualizing Research.* Aldershot: Ashgate Publishing Limited.

Gray, C. and Pirie, I. (1995) *Artistic' Research Procedure: Research at the Edge of Chaos ?* Available at: http://design.osu.edu/carlson/id785/ead.pdf (Accessed: 29 December 2010).

Great Britain. HM Government (2000), *Building Regulations 2000 Conservation of Fuel and Power* [Online]. Available at: http://www.planningportal.gov.uk/uploads/br/BR_PDF_ADL1A_2010.pdf (Accessed: 29 December 2010).

Guggenheim (2011) *Larry Bell.* Available at: http://www.guggenheim.org/new-york/collections/collection-online/show-full/piece/?search=Larry%20Bell&page=1&f=People&cr=1 (Accessed: 24 July 2011).

Gulmini, M., Pace, M., Ivaldi, G., Ponzi, M.N. and Mirti, P. (2009) 'Morphological and chemical characterization of weathering products on buried Sasanian glass from central Iraq'. *Journal of Non-Crystalline Solids,* 355, pp.1613–1621, Elsevier [Online]. Available at: http://www.sciencedirect.com/science?_ob=ArticleListURL&_method=list&_ArticleListID=1507766839&_sort=r&_st=13&view=c&_acct=C000050221&_version=1&_urlVersion=0&_userid=10&md5=1e4d18be888269c1ec7ccc397632b2da&searchtype=a (Accessed: 20 October 2010).

Gulotta,J.A. (1969) *Manufacture Of Float Glass Of A Thickness Greater Than Equilibrium Thickness.* United States Patent no. 3432284 [Online]. Available at: http://www.freepatentsonline.com/3432284.pdf (Accessed: 4 January 2011).

Hamer, F.and J. (1986) *The Potters Dictionary of Materials and Techniques* (2nd edn). London: A and C Black.

Hurst,S.J. and Sheel,D.W. (1999) *Glass coated with two doped oxide layers.* European Patent Office Patent no. GB 2335201A [Online]. Available at: http://v3.espacenet.com/publicationDetails/biblio?DB=EPODOC&adjacent=true&locale=en_EP&FT=D&date=19990915&CC=GB&NR=2335201A&KC=A (Accessed: 12 December 2010).

Ifoha (2011) *Splinter protection paint - the solvent safety film.* Available at: http://ifoha.com/en/security-films/splinter-protection-paint-the-solvent-safety-film.html (Accessed : 24 August 2011).

IIRG, (2009) *Parallels & Connections: A Ceramic and Glass Research Student Conference 2009.* Available at: http://glassresearch.sunderland.ac.uk/images/federer.pdf (Accessed: 20 September 2011).

Ilie, L., (2006) *Economic considerations regarding the first oil shock, 1973 – 1974.* Available at: http://mpra.ub.uni-muenchen.de/6431/1/MPRA_paper_6431.pdf (Accessed: 26 October 2011).

Intellectual Property Office (2010a) *IP Healthcheck Series Non-Disclosure Agreements.* Available at: http://www.ipo.gov.uk/licensingbooklet.pdf (Accessed 1 December 2010).

Intellectual Property Office (2010b). *Trade Marks*. Available at: http://www.ipo.gov.uk/types/tm.htm (Accessed 1 December 2010).

IPCC, (2011) *The Intergovernmental Panel on Climate Change*. Available at: http://www.ipcc.ch/organization/organization_history.shtml (Accessed: 12 September 2008).

Jenkins, F.A. and White, H.H. (1937) Fundamentals of Optics (4th edition). Kogakusha: McGraw-Hill.

Jenkins, M. (1986) ‘Coatings’, *Glass in the environment conference April 1986*. London: Crafts Council, p.36.

Jenkins,M.S., Simpson,A.F. and Porter,D.A. (1988) *Inorganic Coatings on Glass.* European Patent Office, Patent no. EP02756621A, [Online]. Available at: http://v3.espacenet.com/publicationDetails/biblio?DB=EPODOC&adjacent=true&locale=en_EP&FT=D&date=19880720&CC=GB&NR=2199848A&KC=A (Accessed: 9 December 2008).

Johnston, L. (1997) *The Innovative Application of the Coated Glass Surface in Architecture.* PhD thesis. University of Sunderland.

Jones, T.E. (2005) 'A Method of Search for Reality' in *Printed Project.* Dublin: Sculptors Society of Ireland, pp. 20-34.

Keeling and Walker (2002)
Material safety data sheet.Tin oxide (sno$_2$) -all grades. Available at: http://www.armadilloclay.com/images/Tin_Oxide.pdf (Accessed : 26 September 2011).

Keeling and Walker (2010), Telephone conversation with Eileen Leatherland, 2 February 2010.

larrybell.com (2011) *Available Inventory Larry Bell Studio.* Available at: http://www.larrybell.com/available/glass.html (Accessed: 23 August 2011).

Liquida (2009) *Tin Oxide Conductive Glass - Stannous Chloride.* Available at: http://www.liquida.com/video/a7ff007ef/tin-oxide-conductive-glass-stannous-chloride/ (Accessed: 28 December 2010).

Lo, C.Y., Hou, Y.L., Dai, D.J. and Carson, S.W. 'Chemical Vapour Deposition on Float Glass', in Spee, C.I.M.A., de Groot, J.L.B., Meinema, M.A. and Pütz, J., (2008) *7th International Conference on Coatings on Glass and Plastic.* Eindhoven: Organising Committee of the 7th ICCG.

London Crown Glass Company (2011) *London Crown Glass Company History* . Available at: http://www.londoncrownglass.co.uk/London_Crown_Glass/History.html (Accessed: 18 August 2011).

Longhorn (2011) *Bohle Glass Cleaner.* Available at: http://www.longhornonline.co.uk/Products/glass-accessories/1700050026 (Accessed: 5 January 2011).

Lundstrom, B. (1989) *Advanced Fusing Techniques: glass fusing book two.* Colton, Oregon : Vitreous Publication

Lynch,H. (2010) *Heart of Glass.* Available at: http://www.mondoarc.com/comment/Henrietta_Lynch/453970/heart_of_glass.html (Accessed: 14 September 2011).

Macartney, A. (2001) *The Design and Utilisation of the Ceramic Shell Mould Technique in Forming Studio Glass*. PhD thesis. Central Saint Martin's College of Art & Design.

Macartney, A. (2001a) *Index to Theses, The Design and Utilisation of the Ceramic Shell Mould Technique in Forming Studio Glass*. Available at: http://www.theses.com/idx/scripts/it3.asp?xml=Z:\index\idx\docs\all\51\it00318086.htm&subfolder=/search (Accessed: 5 September 2011).

McConnell, A. (2006) *Millers 20th-century Glass.* London: Octopus Publishing Group.

McGrath,R. (1961) *Glass in Architecture and Decoration.* London: Architectural Press.

Metcalfe, C. (2007) 'The development of ash glazes from arable crop waste'. PhD thesis. University of Sunderland.

Monkman,A. (2010) Email to Eileen Leatherland. 26 April 2010.

Moor,A. (2006) *Colours of Architecture.* London: Mitchell Beazley.

Newitz, A, (2011) *An Enzyme That Gives Your Body Energy – Modelled in 900 Kilos of Glass.* Available at: http://io9.com/5154115/an-enzyme-that-gives-your-body-energy-+-modeled-in-900-kilos-of-glass (Accessed 6 November 2011).

Newton, R.G. (1971) 'The enigma of the layered crusts on some weathered glasses, a chronological account of the investigations', *Archaeometry,* 13 (1) pp.1–9, *Wiley Online Library* [Online]. Available at: http://onlinelibrary.wiley.com/doi/10.1111/j.1475-4754.1971.tb00024.x/abstract (Accessed 2 January 2011).

New York Architecture (2005) *Skidmore, Owings, and Merrill LLP.* Available at: http://nyc-architecture.com/UES/UES012.htm (Accessed: 2 September 2011).

Nikon (2011) *Microscopy U Introduction to Light Interference.* Available at: http://www.microscopyu.com/articles/polarized/interferenceintro.html (Accessed: 12 September 2011).

NOAA/NASA/EPA Climate Change Partnership (no date) *Climate Change, The Greenhouse Effect*. Available at: http://www.alachuacounty.us/DEPTS/EPD/DOCUMENTS/Pollution/greenhouseeffect.PDF (Accessed: 31 August 2011).

NSG Group, (2011) *NSG Group and the Flat Glass Industry 2011.* Available at: https://assetmanager.pilkington.com/fileserver.aspx?cmd=get_file&file_id=4386&digest=ZASNX4Dd98XAuuFFFoe/8g==&ct=pdf&file_name=NSGFGI_2011LR.pdf&cd=yes%3E (Accessed 2: November 2011).

Oxford English Reference Dictionary (2002) *(Rev 2nd edn.).* Oxford: Oxford University Press.

Pankow, J.W. (2003) *Surface Analysis of Stressed and Control tin Oxide Thin Films on Soda Lime Glass*. Available at: http://www.nrel.gov/docs/fy03osti/33602.pdf (Accessed: 1 October 2010).

Pataki, J. (2007) 'When Art Nouveau Turned to Glass', *The Hungarian Quarterly,* XLVIII, 185. [Online]. Available at: http://www.hungarianquarterly.com/no185/10.shtml (Accessed: 20 October 2010).

Patent My Idea.org (2010) *'Patent Cost - Guide to patenting costs'.* Available at: http://www.patentmyidea.org/international-patents/cost-of-patenting.php (Accessed: 1 December 2010).

Petrie, K. (1999) *Water-based ceramic transfer printing. The development and creative use of a new on-glaze screenprinting system.* PhD thesis*.* University of the West of England, Bristol.

Petrie, K. (2005) *Art and science in glass and ceramics: Case studies from the post-graduate art and design sector.* Available at: http://www.artdes.mmu.ac.uk/rnsacg/downloads/kp.pdf (Accessed : 23 August 2011).

PLG Glass (2006) *Peterlee Glass Architectural Glass Processors*. Available at: http://www.peterleeglass.com (Accessed: 1 April 2011).

Petrova, S. (2008) Email to Eileen Leatherland. 15 December 2008.

Pilkington (2006) *Pilkington K Glass Glazing and Handling Guidelines for Finished Size.* Available at: http://www.pilkington.com/assetmanager_ws/fileserver.aspx?cmd=get_file&file_id=1100&digest=WIlTc0WzFjkKatnevNCSmg==&ct=pdf (Accessed: 23 August 2011*).*

Pilkington (2008) *This is Pilkington Making glass for the world's buildings and vehicles.* Available at: http://www.pilkington.com/resources/10052_tip_useng_fin.pdf (Accessed: 23 August 2011).

Pilkington (2009a) *Pilkington and the Flat Glass Industry 2009.* Available at: http://s3.amazonaws.com/zanran_storage/www.pilkington.com/ContentPages/49046762.pdf (Accessed 2 November 2011).

Pilkington (2009b) *Technical Information Properties Of Soda-Lime-Silica Float Glass.* Available at: www.pilkington.com/resources/ats129swproperties20090804.doc (Accessed: 23 August 2011).

Pilkington (2010) *Pilkington and the Flat Glass Industry 2010.* Available at: http://www.pilkington.com/resources/pfgi2010.pdf (Accessed: 18 September 2011).

Pilkington (2011a) *Pilkington K Glass.* Available at: http://www.pilkington.com/europe/uk+and+ireland/english/products/bp/bybenefit/thermalinsulation/kglass/ (Accessed: 15 March 2011).

Pilkington (2011c) *Pilkington Activ Self -cleaning Glass.* Available at: http://www.pilkingtonselfcleaningglass.co.uk (Accessed: 23 August 2011).

Pilkington (2011e) *Pilkington Activ Suncool Off-line coating glass* Available at: http://www.pilkington.com/products/bp/bybenefit/selfcleaning/activsuncool/default.htm (Accessed: 23 August 2011).

Pilkington (2011f) *Pilkington Activ Suncool On-line coating glass*. http://www.pilkington.com/products/bp/bybenefit/specialapplications/tecglass/default.htm (Accessed: 23 August 2011).

Pilkington (2011g) *Solar Control*. Available at: http://www.pilkington.com/europe/uk+and+ireland/english/products/bp/bybenefit/solarcontrol/default.htm (Accessed: 23 August 2011).

Pilkington (2011h) *Surface Coatings.* Available at: http://www.pilkington.com/europe/uk+and+ireland/english/building+products/pilkington4architects/reference/energycontrolthermalsolarproperties/coatings.htm (Accessed 23 August 2011).

Pollution Issues (2011) *Industry*. Available at: http://www.pollutionissues.com/Ho-Li/Industry.html (Accessed: 22 August 2011).

Potter, N. and Jackson, D. (1988) *Tiffany,* London: Pyramid.

Princeton University (2000) *Background material: mixtures and solutions.* Available at: http://www.princeton.edu/~pccm/outreach/scsp/mixturesandsolutions/background.htm (Accessed 15 August 2011).

Raman, C.V. and Rajagopalan,V.S. (1939) 'The structure and optical characters of iridescent glass' *Proc. Indian Acad. Sci*. A9 pp.371-381. Available at: http://dspace.rri.res.in/bitstream/2289/1861/1/1939%20Proc%20Indian%20Acad%20Sci%20A%20V9%20p371-381.pdf (Accessed: 20 October 2010).

Resnick, R. and Halliday, D. (1960) *Physics.* New York, John Wiley and Sons, Inc.

Rose, Y. (2010) *University of Central Lancashire, Refractory Concrete.* Available at: http://www.uclan.ac.uk/schools/adp/silicate_research_unit/refractory_concrete.php (Accessed: 5 September 2011).

Russell Fraser Sales Pty. Ltd. (2006) *DIG Low-Emissivity Coatings Detector.* Available at: http://www.rfsales.com.au/others/sub_category/products/index.php?ID=DIG+Low-Emissivity+Coatings+Detector (Accessed: 5 January 2011).

Saint-Gobain Glass (2011) SGG *BIOCLEAN COOL-LITE ST Self-cleaning glass with solar control properties.* Available at: http://uk.saint-gobain-glass.com/b2c/default.asp?nav1=pr&nav2=single pane&id=1899 (Accessed: 14 June 2011).

Sakane,I. (2003) *Toward the Innovative Collaboration Between Art and Science: The Task in the Age of Media Culture through Case Studies in the Contemporary Field of Media Arts.* Available at: http://www.computer.org/portal/web/csdl/doi/10.1109/VR.2003.1191134 (Accessed: 1 November2010).

Scanlon, K J. and Greenberg, C.B. (1983) *Thermochromic vanadium oxide coated glass*. United States Patent Office 4400412 [Online]. Available at: http://www.freepatentsonline.com/4400412.html (Accessed: 8 December 2010).

Scheerbart, P. (1914) 'Environment and its influence on the development of culture', in Sharp, D. (ed.) *Glass Architecture by Paul Scheerbart translated by James Palmes, Alpine Architecture by Bruno Taut translated by Shirley Palmer.* London: November Books, p.41.

Schott UK (2011) *NARIMA™ Color Effects Dichroic Glass.* Available at: http://www.schott.com/architecture/english/products/narima/index.html?so=uk&lang=english (Accessed: 29 July 2011).

Sharp, D. (ed.) (1972) *Glass Architecture by Paul Scheerbart translated by James Palmes, Alpine Architecture by Bruno Taut translated by Shirley Palmer.* London: November Books, p.41.

Snow, C.P. (1959) *The Two Cultures.* Reprint, Cambridge: Cambridge University Press, Canto edition 1993, reprinted 2010.

Special Metals, (2011) *Inconel Alloys.* Available at: http://www.specialmetalswiggin.co.uk/products/by-alloy/inconel (Accessed: 13 September 2011).

Stafford Instruments Ltd. (2011) *ST501A.* Available at: http://www.stafford-inst.co.uk/st501a.html (Accessed: 23 August).

Stephenson, G. (2011) Telephone call to Eileen Leatherland. 6 July 2011.

Tala-Ighil, R. BoumaourM., Belkaïd, M.S., Maallemi, A., Melhani, K. and Iratni, A. (2005) *High temperature annealing of sprayed SnO_2: F layers in a silicon solar cell process with screen-printed contacts.* Available at: http://www.sciencedirect.com/science?_ob=ArticleURL&_udi=B6V51-4J146MD-1&_user=10&_coverDate=07%2F24%2F2006&_rdoc=1&_fmt=high&_orig=search&_origin=search&_sort=d&_docanchor=&view=c&_searchStrId=1594155981&_rerunOrigin=google&_acct=C000050221&_version=1&_urlVersion=0&_userid=10&md5=a0dc6e1f0285f5fb8a2ac523a8fdfea9&searchtype=a (Accessed: 29 December 2010).

Tangram Technology Ltd. (2004) *Float Glass Production.* Available at: http://www.tangram.co.uk/TI-Glazing-Float%20Glass.html (Accessed 8 December 2010).

Tangram Technology Ltd. (2010) *Glass Timeline.* Available at: http://www.tangram.co.uk/TI-Glazing-Glass_Timeline.html (Accessed: 12 September 2011).

The Antiquarian (2008) *History of Mt. Washington Glass Co.* Available at: http://theantiquarian.us/Hist.%20Mt.%20Washington%20Glass%20Co%20.htm (Accessed: 20 October 2010).

Tiffany, L.C. (1881) *Method and apparatus for creating design insulated glass.* United States Patent Office Patent No.237418 [Online]. Available at: http://www.google.ru/patents/about?id=p_8_AAAAEBAJ&vq=237418 (Accessed: 20 October 2010).

UNFCCC (2004), *Essential Background, the Convention and the Protocol.* Available at: http://unfccc.int/essential_background/items/2877.php (Accessed: 9 September 2008).

Union of Concerned Scientists (2008), *Clean Energy*, *A Short History of Energy.* Available at: www.ucsusa.org/clean_energy/clean_energy_101/a-short-history-of-energy.html (Accessed 31August 2008).

United Kingdom Council for Graduate Education (1997) *Practice-based doctorates in the creative and performing arts and design.* Lichfield: UK Council for Graduate Education.

United Kingdom, Office of Public Sector Information (2008), *Home Energy Conservation Act 1995,* London, HMSO [Online]. Available at: http://www.opsi.gov.uk/acts/acts1995/ukpga_19950010_en_1 (Accessed 16 August 2010).

United States Environmental Protection Agency (2010) *Welfare Effects - Greenhouse Effect.* Available at: http://www.epa.gov/apti/course422/ap7b2.html (Accessed: 22 August 2011).

University at Buffalo (no date) SEM/EDS: Scanning Electron Microscopy with X-ray microanalysis. Available at: http://wings.buffalo.edu/faculty/research/scic/sem-eds.html (Accessed: 7 January 2011).

Venture Tape (2011) *470 4 mil Sandblast Resist.* Available at: http://www.venturetape.com/product.php?productid=1000&cat=24&page=1 (Accessed: 5 January 2011).

Vitkala, J. (2008) 'GPD Call includes Special Architects' Forum', Intelligent *Glass Solutions,* (2) 2008, pp.111-4.

Wallace, M. (2010) *Experiments Art and Science.* Exhibition held at GV Art, 49 Chiltern Street, London W1U 12 March – 29 May 2010 [Exhibition catalogue]. Available at*:* http://www.gvart.co.uk/press/Experiments_E-Catalogue.pdf (Accessed: 1 January 2011).

Warm Glass UK (2011) *Dichroic Glass FAQ sheet.* Available at: http://www.warm-glass.co.uk/images/pdfs/products/Dichroic%20Glass%20FAQs.pdf (Accessed: 5 October 2011).

Warm Edge Units Ltd (2011.) *Warm Edge Super Space.* Available at: http://www.warmedgeunits.com/what.html (Accessed: 2 January 2011).

Watkinson,C. (2011), Telephone call to Eileen Leatherland, 22 November 2011.

Whitford, F. (1984) *Bauhaus*. London, Thames and Hudson.

Wigginton, M. (ed.) (1987) *Glass Today, Report on the Proceedings of the Glass in the Environment Conference, London, April, 1986.* London: Crafts Council.

Wigginton,M. (1996) *Glass in Architecture*. Reprint, London: Phaidon Press Limited, 2004.

Wiggington.M. (1997) 'Glass and the Architecture of the Future', in Lochart,A., and Taylor,L. (eds) *Glass, Light and Space*. London: Crafts Council.

Wilberforce,R. (2008) 'Legislation, policies and drivers for energy efficient buildings', *7th International Conference on Coatings on Glass and Plastics* Eindhoven/Veldhoven – The Netherlands, June 15-19 2008. Eindhoven: Organizing Committee of the 7th ICCG, pp. 37-41.