Precision Air Entrapment through Applied Digital and Kiln Technologies: A New Technique in Glass Art

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PRECISION AIR ENTRAPMENT THROUGH APPLIED DIGITAL AND KILN TECHNOLOGIES: A NEW TECHNIQUE IN GLASS ART

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A thesis submitted in partial fulfilment of the
requirements of the University of Sunderland
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Abstract

The motivation for the research was to expand on the creative possibilities of air bubbles in glass, through the application of digital and kiln technologies to formulate and control complex air entrapment, for new configurations in glass art. In comparison to glassblowing, air entrapment in kiln forming glass practice is under-developed and undocumented. This investigation has devised new, replicable techniques to position and manipulate air in kiln-formed glass, termed collectively as *Kiln-controlled Precision Air Entrapment*. As a result of the inquiry, complex assemblages of text and figurative imagery have been produced that allow the articulation of expressive ideas using air voids, which were not previously possible. The research establishes several new innovations for air entrapment in glass, as well as forming a technical hypotheses and a practice-based methodology.

The research focuses primarily on float glass and the application of CNC abrasive waterjet cutting technology; incorporating computer aided design and fabrication alongside more conventional glass-forming methods. The 3-axis CNC abrasive waterjet cutting process offers accuracy of cut and complexity of form and scale, across a flat plane of sheet glass. The new method of cleanly fusing layered, waterjet-cut float glass permits the fabrication of artwork containing air entrapment as multi-layered, intricate groupings and composite three-dimensional void forms.

Kiln-controlled air entrapment presents a number of significant advantages over conventional glassblowing techniques of air entrapment which are based around the decorative vessel or solid spheroid shaped on the blowing iron. The integration of digital and traditional technologies and the resulting technical glassmaking discoveries in this research advance potential new contexts for air entrapment, in sculptural and architectural glass applications. Contexts include solid sculptures which explore the internal space of glass, to flat-plane panels and hot glass roll-up processes which take air entrapment beyond the limitations of its previous incarnations.

The creative potential of Kiln-controlled Precision Air Entrapment for glass art is demonstrated through the development of a body of artworks and their dissemination in the field of practice. Documentation of the findings in the thesis has resulted in a

significant body of knowledge which opens up new avenues of understanding for academics, creative practitioners and professionals working with glass.

Contents

i. List of artworks submitted in partial fulfillment of the requirements of the University of Sunderland for the degree of Doctor of Philosophy.

- Corpus
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- Host II
- I.D.
- Legion
- Legion Series
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- Secret Diary

ii. Acknowledgements

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Finally to my daughter, Martha, who waited to make her entrance into the world that I could complete this PhD.

iii. Author Declaration

According to the regulations, I declare that during my registration I was not registered for any other degree. Material for this thesis has not been used by me for another academic award.

1. Aims and Objectives

The aim of the inquiry was to develop a new air entrapment process, through applied digital and kiln-forming techniques, to advance glass practice and create replicable methodologies for future studio application.

1.1 Research Aims

- To research and evaluate methods of producing and controlling air voids within glass and develop a replicable precision air entrapment process to create recognisable imagery and lettering in the kiln.

- To investigate the creative possibilities of air entrapment in float glass for kiln-formed glass applications and produce a body of work based on and informed by this research.

1.2 Objectives

- Investigate how '*Ariel'* air entrapment can be developed using the kiln, as a means of expanding the technique for the purpose of creating artworks that move beyond the blown vessel or spheroid form.
- Develop new combinations of digital processes, glass technology and kiln-forming techniques to control air entrapment in glass in the kiln.
- Create new configurations of air entrapment by investigating increased depth and quantity of layers, scale and contour complexity.
- Record and disseminate replicable methods of practice which add to the creative vocabulary of the artist working with glass.
- Produce a body of work in order to articulate, demonstrate and express the extension of air entrapment in new directions within sculptural and architectural glass.

1.3 Statement of Research Questions

- How can entrapped air be controlled using the *kiln* to create recognisable lettering and imagery?

- What are the creative possibilities of air entrapment through combinations of digital artwork, waterjet cutting, multiple-layered fusing, float glass and kiln forming processes?

- What are the possibilities for air entrapment artworks to be developed into new configurations of solid block and flat-plane forms for application in sculptural, decorative and architectural contexts?

2. Background to the research

This chapter explains the researcher's background in the field of glass practice and the creative and technical exploration and tacit knowledge which set the precedent for this investigation. This personal practice-based exploratory work instigated a set of questions which formed the basis for the PhD proposal.

The idea for the PhD investigation was initiated within the researcher's glassmaking practice. Preceding the research, the investigator's personal studio practice often explored untried glass working methods, to discover the material's inherent properties and push the boundaries of individual knowledge. An interest in diamond wheel cutting and cold working glass, as a means of developing form and creating surface texture was cultivated during a master's degree Scholarship to the crystal glass factory Edinburgh Crystal, in 2001. The scholarship was a training in product design for the glass industry and pushed the boundaries of the technique and processes used in crystal glass production, in order to develop new, more contemporary, design-conscious products for the brand.

Figure 1: Production prototypes (freeblown/ wheel cut/ injection pressed) developed during the researcher's MA Scholarship to Edinburgh Crystal Glass Company 2000-2002

Figure 2: Production prototypes (side-lever pressed) developed during the researcher's MA Scholarship to Edinburgh Crystal Glass Company 2000-2002

An understanding of the industrial and digital technology used in glass manufacture was developed during the scholarship. Knowledge gained included computer aided design (AutoCAD), automated machine cutting, and mechanical glass forming methods such as injection and side-lever pressing. An appreciation of the high level of skill and dexterity required to work glass proficiently was gained by working with master craftsmen in glassblowing and diamond wheel cutting to design and realise production prototypes.

As a result, an interest in experimentation with technology and the co-existence of the cultures of automated and hand-crafted production was carried through into personal practice, after setting up a studio in 2003 at the National Glass Centre, Sunderland.The researcher's studio practice ranged from blown, cut and coldworked vessels to kiln cast and fused artworks.

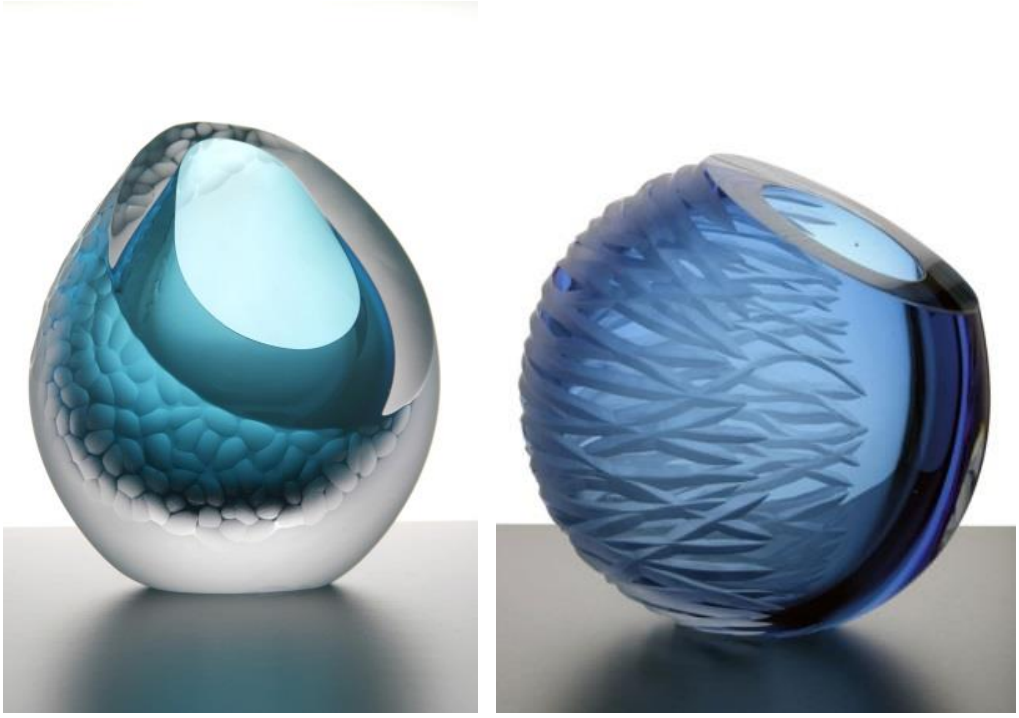

Figure 3: Diamond wheel cut vessels from the researcher's early practice, Joanne Mitchell Glass Design, circa 2003.

Whilst exploring ideas for integrating wheel cutting skills into kiln-formed work using sheet glass, the discovery was made that a wheel cut design carved into 4mm float glass and fused to another float glass sheet at around 800 degrees centigrade, retained its shape and trapped air in the cut voids, creating an interesting pattern of glossy bubbles as the glass softened and fused.

Figure 4: Pre-research wheel cut design carved into 4mm float glass and fused to trap air (circa 2005).

The latent possibilities of developing the idea of air entrapment in kiln forming by integrating existing knowledge and untested techniques (such as combinations of wheel cut, waterjet and kiln fused glass) held potential for interesting new directions. The effect of furnace glass and the cut design was tested using a hot-cast billet, halved and ground flat, fusing the glass in a plaster mould which supported the sides. The technique yielded good results, the cut patterns creating cleanly-formed, reflective bubbles within the body of the glass.

Figure 5: Kiln formed furnace glass experiment with diamond-wheel cut air entrapment, circa 2005.

Figure 6: Kiln-cast work, researcher's early studio practice, lead crystal, c. 2006

Further experiments using float glass sheets developed the idea into slumped float glass bowl forms with the wheel cut air entrapment pattern. The design was deemed semi-successful by the researcher, as the majority of the bubbles were cleanly formed, but the accuracy of air trap was considered not of sufficient quality to present as gallery work. Sections of the air entrapment had settled in the gaps in between the intended pattern. Development of the technique was suspended temporarily pending further experimentation.

Figure 7: Kiln-formed float glass by Joanne Mitchell for Juo Ltd. (circa 2007)

Whilst exploring design ideas for the researcher's fused glass business Juo Ltd, using mark-making onto float glass with a diamond cutting wheel, an effect appeared that showed potential. When coloured float-compatible 'enamel flashed' glass was fused onto the wheel-cut sheet, the resulting air bubbles were trapped and highlighted in ways that the researcher had not seen previously, in historical or contemporary glass practice. The colour was drawn in around the bubbles, leaving a clear 'shadow' where the cuts in the sheet were originally made. The idea was developed into Juo Ltd's panel designs 'Chino' and 'Leaf'.

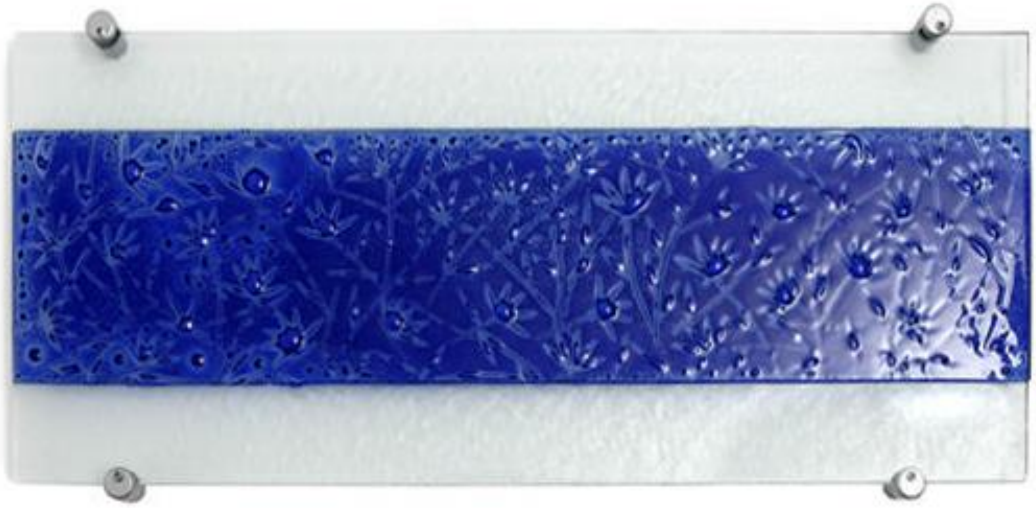

Figure 8: 'Chino' wheel cut and 'enamel flashed' fused air entrapment panel, Joanne Mitchell for

Juo Limited (2007)

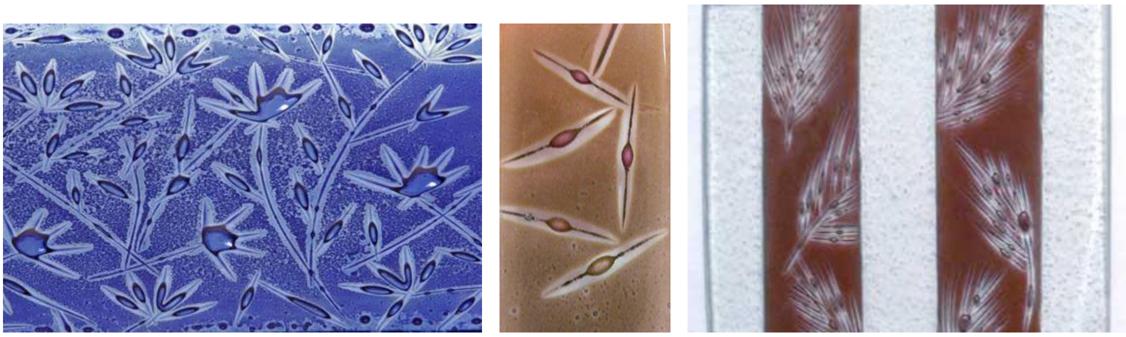

Figure 9: Left: Detail of ‘Chino’ design; centre: wheel cut and fused ‘enamel flashed’ glass test sample; and right: Leaf design, for Juo Ltd (2007)

More intricate exploratory air bubble tests were made using sandblast resists. By deeply sandblasting into a sheet of float glass to 1-2mm depth and fusing a ‘flashed’ float-compatible sheet on top to around 770C, bubbles could be trapped in the channels of the imagery. Digital imagery and logo stencils left from previous commissions were used for the sandblast resists in the tests. The resulting bubbles retained the clarity of the text and were highlighted with deep colour from the enamel flash, concentrated around the edges of the bubbles.

The bubble’s accuracy and subsequent clarity of the text could be adjusted by changing the fusing temperature. As the temperature was increased and the glass viscosity reduced, the bubble inflated and its interior surface smoothed, becoming more spherical: the higher the temperature, the rounder the bubble. An additional variable affecting the result was the length of time the heat was applied to the glass (or ‘soaked’) at a particular temperature, relative to the softening of the bubble; so a longer soak at a lower temperature might have a similar effect to a higher temperature with a short soak time.

Figure 10: Detail of sandblast air entrapment exploratory work, bubble text formed using sandblast resists.

This personal practice-based exploratory investigation instigated a set of research questions and formed the basis for the PhD proposal. The reason for doing the experimental work as PhD research rather than via personal practice was twofold. Firstly, to devote structured time to specifically investigating the enquiry as an academic pursuit in order to push the boundaries of the possibilities of what could be made free from the commercial constraints of a studio practice; and secondly, to embrace the expertise, peer support and facilities of the University environment.

The numerous possibilities that float glass offered for artworks; in terms of its high level of clarity, potential scale due to architectural sheet size, and individual sheet thickness (up to 24mm), as well as cost; presented an opportunity to exploit these qualities for new form configurations in fused glass art. In addition, a documented investigation into firing layered float glass sheets in the kiln and the resulting outcomes would fill a gap in information accessible to the glass artist, providing a resource of technical knowledge for practitioners working with float.

Personal studio explorations, in conjunction with a survey of the contemporary field formed the initial underpinning for the investigation. A literature review sourced available documentation on the research subject.

3. Contextual Review

A contextual review of the research field was undertaken in order to define the sector, discover precedents for air entrapment in glass and position the research topic within an historical, contemporary and technical context. A review of data and literature in the field of practice was carried out through online database searches including Ethos at the British Library, the Corning Museum of Glass Rakow Research Library Online Archives, University of Sunderland Library, major glass exhibition catalogues and glass journals: New Glass Review, Glass Quarterly, Neues Glas, the British Glass Biennale Catalogues 2004 - 2015, Contemporary Glass Society Glass Network Magazine, The Glass Art Society Journal and the Society of Glass Technology and The European Society of Glass Journals, as well as web-based searches via search engines Google and Bing.

Symposia, conferences exhibitions and networking events arranged by member organisations and associations such as the Contemporary Glass Society, the Scottish Glass Society, Society of Glass Technology, the International Festival of Glass and CCGEN (formerly Cohesion Glass Network), were attended through the course of the research (and are listed in the Appendix). Institutions dedicated to promoting glass and applied art such as the National Glass Centre (now the National Glass Centre at the University of Sunderland), the Glass Hub, Broadfield House Museum of Glass and the Crafts Council were visited.

Practical and verbal knowledge transfer in contemporary glass often happens between skilled practitioners and students via conferences, masterclasses, lectures and workshops at artists' own studios, or at educational institutions and independent organisations, and increasingly, via online videos and forums. Examples in Europe include Northlands Creative Glass, Lybster, Scotland and Bild-Werk-Frauenau, Germany; in the USA the Glass Art Society (GAS) and, Pilchuck Glass School and Chiluly Garden & Glass in Washington State; Haystack Mountain School of Crafts, Deer Isle, Maine; Penland School Crafts, North Carolina, and Urban Glass & Brooklyn Glass, Brooklyn, New York, in the USA. These organisations were accessed either in person, or online. Specific *conferences and institutions visited in person are listed in the appendix.*

The review documents and analyses the historical precedents to kiln-controlled precision air entrapment in glass in a chronological order. It also compiles and presents a review of the application of air entrapment in hot glass and kiln-formed glass and details artists and researchers working in the field. The section 3.2.2 describes the Scandinavian 'Ariel' air entrapment technique in detail and the reasons it is considered the most important air entrapment technique in relation to this research. Examples of key works and designers are included to discern the level of sophistication in the air entrapment imagery and place it in context. Analysis of innovation in the technical processes is discussed.

Also discussed in is the emergence of digital technology in the advancement of creative practice and research alongside the integration of the industrial, digital and handmade, with particular reference to glass art and those artists and designers pioneering its development. The process of waterjet cutting and use of float glass are reviewed, with examples of their use for creative expression in the context of contemporary glass practice.

3.1 Timeline of Technical Innovations in Glass Pertinent to this Investigation

Early 16th C. Venice: *Crystallo* invented.

Venetian glass making moves to island of Murano. Creativity and innovation becomes world renowned and unparalleled for centuries. Glassblowing virtuosity leads to Air-Entrapment Techniques such as *Reticello*

↓

1684: *English Lead Crystal* patented by George Ravenscroft.

The softer, more refractive glass led to stemware with solid, knopped 'baluster' stems and teardrop-shaped bubbles as stem decoration. Multiple 'teardrops' turned into twisted air lines in spiral patterns knwon as *'air-twists'* from 1730s onwards. English lead crystal becomes a world leader.

↓

Late 19th C. French *Art Nouveau* pioneers revolutionize the glass Industry.

Galle's Experimental approaches incorporate deep carving and cameo forms. Daum develop the *Pate de Verre* kiln-forming technique. Lalique adapts the *'Cire Perdue' (lost wax)* kiln-forming technique from jewellery making. Art Nouveau elevates the status of glass to 'Art'.

↓

Early 20th C. France: Artist Maurice Marinot

works directly with glass for personal creative expression. He creates his experimental glass forms, developing techniques using acid to deeply etch forms and oxides to create colour in his own art works in glass, which he considered as sculpture.

↓

Early 20th C. Sweden, Collaboration of Artists and Industry.

Inspired by Art Nouveau ideology, artists designing in industry work with deep carving and glass etching techniques to develop the technical innovations of the *Graal* technique and the related *Ariel* air-entrapment technique in the 1930s. Limited edition 'Art Glass' ranges are made by Orrefors glassworks alongside functional production glassware

↓

1952 U.K: The Float Glass Process is invented by Alistair Pilkington.

The revolutionary industrial production process for manufacturing sheet glass is invented. A ribbon of hot glass is floated on a bath of molten tin, allowing for uniform thickness, large scale sheets and smooth surfaces. New architectural applications for glass are made posiible.

↓

1960s America. The Studio Glass Movement.

A group of American artists revolutionise access to hot glass, developing small furnace technology. Glassblowing in artists studios and art colleges becomes possible. Self-taught artists work directly within the material vocabulary of glass as a conduit for individual expression.

The emergence of the Artist/ Maker.

Figure 11: Timeline of innovations in glass which have particular relevance to this inquiry

3.2 Air Entrapment Precedents

Technological advancements and material knowledge paired with skill and creativity have generated fertile periods of innovation in glass through the centuries. Discussed here are several pioneering air entrapment and related processes. Often the techniques have endured and continue to be practiced in contemporary glassmaking.

These examples focus predominantly on hot glass. The reason for this is twofold: hot glass represents the highest level of precision, refinement and complexity in air entrapment techniques preceding this research, therefore this was taken as the benchmark from which this research was undertaken. In addition, air entrapment in kiln forming is relatively unexplored, so there was little literature to draw on, with only unresolved or rudimentary air entrapment formations in evidence to date.

3.2.1 **Historical Precedents**

The Reticello technique emerged in16th Century Venice after the development of Cristallo glass. It is a skilful and technically demanding glassblowing process in which a net of tiny bubbles is formed within an intricate cane lattice design. At the centre of each intersection of cane where the air has become trapped, a bubble is formed.

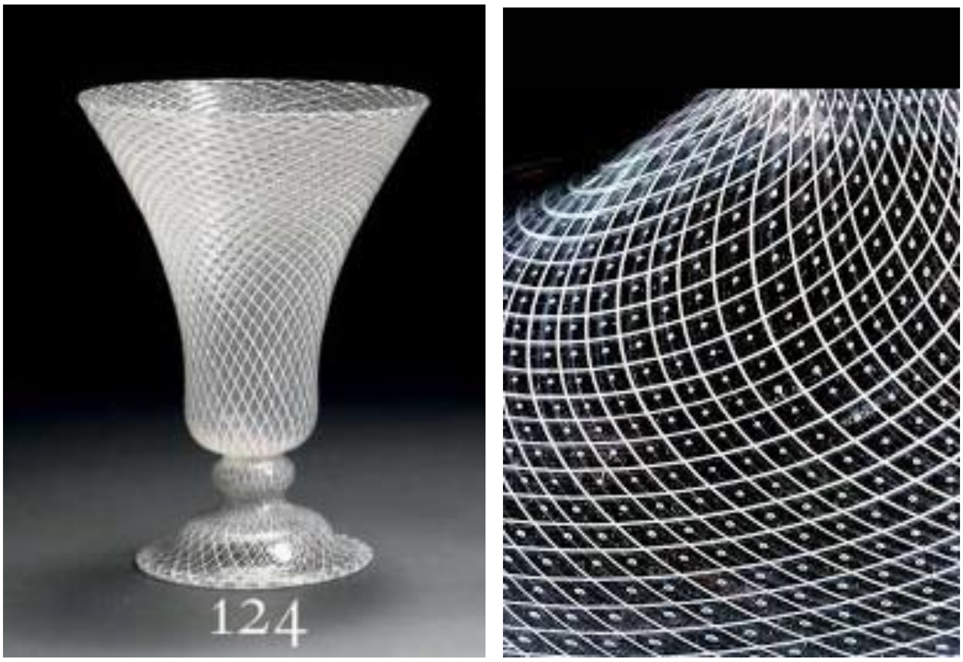

Figure 12: Vetro A Reticello Vase, Venetian, 16th Century (left) and Reticello bubble detail (right).

English lead glass or ‘lead crystal’ was a technical advancement made following the introduction of lead oxide into the glass recipe in the late 17th Century (Cummings, 2002). The result was a successful recipe for clear, highly refractive glass which did not degrade. Lead crystal lent itself to designs which emphasised the new clarity and transparency of the heavy, refractive, colourless glass and goblets with ‘Teardrop’ and ‘Air twist’ patterns of reflective, internal air trap stem decoration emerged. Air twists were made by trapping a ring of bubbles in the molten stem which were then pulled and rotated to form intricate spirals.

Figure 13: ‘Air Twist’ and ‘Mercury Twist’-stemmed Lead Crystal Goblets 16th Century British, Broadfield House Glass Museum.

At the end of the 19th Century in the U.K., production glassware with internal ‘quilted satin air-trap’ decoration was being produced by several factories in the Stourbridge region.

 

Figure 14: Thomas Webb & Sons of Stourbridge, quilted satin air-trap and cameo glass vase, c.1885-90 (left); Bohemian air trap glassware by Loetz c.1888 (right).

The ‘air-lock’ or ‘air-trap’ technique, used in coloured glassware, was patented in 1857 by the the W.H., B. & J. Richardson Glass Company. (www.theantiquetrade.co.uk [Accessed 1/10/14]). In Bohemia in the same period, glass factory Loetz was producing its own air-trap designs.

3.2.2 ‘Ariel’ Innovation and its Legacy: A Point of Departure

The literature review ascertained that the most advanced existing method of air entrapment documented in glassmaking was Orrefors Glassworks’ hot glass *Ariel* technique. Ariel was a revolutionary hot glass air entrapment technique pioneered in Sweden in the late 1930s. Ariel’s ground-breaking designs helped to bring Swedish applied art to global acclaim, and original works are now highly collectable.

With an accomplished intricacy of imagery not previously seen, the level of control and detail achieved in the air entrapment made Ariel ground-breaking. Whilst bubbles have been used decoratively since glassmaking began, ‘Ariel … made it possible to control the shape of the trapped air as well as placing it in a decorative composition.’ (Victor, O., accessed [2011]).

Figure 15: Orrefors Glassworks ‘Ariel’ Vessels, Edvin Ohrstrom, Sweden, 1930s.

Ariel designs are described as ‘air bubbles embedded in glass and arranged in various patterns, either as an actual or abstract representation of an object or figure’ (Shotwell, 2002, p.19). In this research, the definition of Ariel as an air entrapment composition representing an object or figure was used as a point of departure by which to investigate and compare air entrapment for kiln forming.

Scandinavian design successfully integrated traditional craft skills and an affinity with nature into the industrialisation process (Dawson, 2000, p.12) and became renowned for technical and artistic origination in the early decades of the 20th Century. Sweden’s integration of industry and craft was a key factor in the creative success of its glass. In *The Brilliance of Swedish Glass* (1996), Ostergard & Stritzler-Levine explain how factories embraced technology and experimentation, producing limited edition and one-off ‘Art Glass’ pieces alongside serial production, employing trained artists to work with master glassblowers in the development of new designs. The industry ‘continued to extol the individual craftsman … artists were nurtured and respected in a collaborative environment.’ (Ostergard & Stritzler-Levine, 1996, p.13).

By the middle of the century, Sweden’s glass factories had helped develop a world-leading presence and new international identity for Swedish applied arts. In particular, the highly original glass developed at the factory *Orrefors Glassworks*, of which two of the most prominent and influential techniques were *Ariel* and its precursor *Graal*. Named after the god of wind in Shakespeare’s ‘The Tempest’, the Ariel technique furthered the factory’s reputation for technical innovation and aesthetic excellence (Ostergard &Stritzler-Levine, 1996, p. 273). *Ariel* was invented by artists Edvin Ohrstrom and Viktor (Vicke) Linstrand, with master glassblower Knut Bergqvist (Dawson, 2000, p.231).

Figure 16: Fish Graal vessels, Edvard Hald for Orrefors, 1937 (left), 1939 (middle).

Figure 17: Ariel Vessels by Vicke Lindstrand and Edvin Ohrstrom, Orrefors, Sweden, 1930s

The Ariel designs used minimal forms and expressive, often abstract or humorous motifs, featuring human and animal subjects. The air bubbles gave glistening, mercury-like appearance to the imagery encased within the thick vessel wall. Öhrström's background as a sculptor perhaps influenced the artistic style: the three-dimensional air-forms created by heavy sandblasting are suggestive of a quality more linked to stone carving than the softer, more painterly quality of its precursor, Graal.

Figure 18: Edvin Öhrstom Ariel Glass Vase for Orrefors, circa 1965; cased glass with trapped air decoration, 17cm high (Christies Sale 5374, Lot 406). [http://www.christies.com; accessed 28/7/15]

The technical challenges of the *Ariel* vessels' production and the 'high failure rate frequently encountered … meant that few pieces were ever made.' (Ostergard, D./ Stritzler-Levine, N. 1996, p153). Expensive and time-consuming to reproduce, Ariel vessels remained limited edition, 'high end' items for Orrefors. In effect, their innovation elevated the status of glass from functional item to art object, contributing to an appreciation of glass as sculptural medium. The Mykene technique, another innovative offshoot of the Graal process, was developed in 1936 and used patterns of tiny bubbles as decorative motifs.

Figure 19: Mykene vessel, Vicke Lindstrand, Orrefors 1936

In parallel with developments in Sweden in the early 20th Century, Finnish, designer Gunnel Nyman (1909 – 1948) was creating 'art glass' designs which became iconic successes for the Riihimaki (and later Nuutajarvi) glassworks in the 1930s and 40s (Opie, J. 2009, p.40). In the early 1930s Nyman was exploring the sculptural qualities of the thick, transparent glass and the interior form of the material. She explored the delicate use of simple bubble detailing in the design Helminauha *(String of Pearls),* 1948.

In the early 1950s, Finnish glass designer Timo Sarpeneva created striking experimental art glass designs at the Iittala factory which incorporated a traditional Venetian method of using a damp wooden stick to produce steam to introduce air bubbles into the clear lead crystal glass. He perfected this process in collaboration with the master-blowers to create innovative art-glass objects.

Figure 20: Helminauha (String of Pearls), 1948, Gunnel Nyman for Nuutajarvi (left) with air bubble decoration; and Orkidea (Orchid) Vases, 1954, Timo Sarpeneva for Iittala: made with the steam stick air bubble technique. Finland.

In Sweden in the late 1940s and 50s, related air entrapment techniques grew out of the *Ariel* experimentation at Orrefors, most notably the Kraka and Ravenna techniques. Another air entrapment technique which evolved from this period was Thalatta. Thalatta shortened the air entrapment process by creating the indentation using tools pressed into the glass whilst hot, before the overlay was applied.


Figure 21: left: Sven Palmqvist, 'Kraka' Vase, (c.1959): right: Sven Palmqvist 'Ravenna' Bowl, 1970s

Figure 22: Bengt Edenfalk 'Thalatta' vase (1962)

In the second half of the 20th Century, *Ariel* art glass continued to be produced at Orrefors. Designs such as Ingeborg Lundin's Picasso-esque Ariel Vessel were popular with collectors; and designer Olle Alberius, produced several successful Ariel designs in the 1970s and 80s.

Figure 23: L-R: Ingeborg Lundin Ariel 'Ansikten' (Faces) Vase, 17.5cm, produced from 1970; Olle Alberius Ariel vase, 1988

The appeal of Orrefors' Ariel designs has persisted throughout the 20th Century and into the 21st, and Ariel-influenced designs continue to be made by Orrefors and sister company Kosta Boda. Pieces of *Ariel* glass from the post-war period are highly sought after today (Miller, 2004). Ariel's ongoing popularity can be evidenced by the numerous internet-based auctions and collectors' websites devoted to it. The 'Ariel' glassblowing technique set the standard on which this inquiry was based as the most sophisticated aesthetic for air entrapment in glass to date.

Figure 24: "Vatten Lek" (Water Games) Ariel Vessel, by Edvin Öhrström, (Orrefors) 1955, 21cm x 10cm (1stdibs online luxury marketplace)

Figure 25: Above: "Vatten Lek" (Water Games), Ariel Vessel (detail) by Edvin Öhrström, (Orrefors) 1955, 21cm x 10cm (1stdibs online luxury marketplace)

Swedish glass artist Goran Warff designed for factory Kosta Boda from 1964-74, and headed the glass course at the University of Sunderland (then Sunderland Polytechnic) from 1981-85. Warff's 1996 sculptures 'Spirit in the Glass' are an example of *Ariel*-influenced sculpture in hot glass using the material's clear inner space and air entrapment for artistic expression.

Figure 26: Goran Warff, Spirit in the Glass (1996) Hot formed glass with air entrapment, metal.

Warff's sculptural aesthetic preceded several contemporary makers who use Ariel and related techniques in their practice.

3.2.3 **Air Entrapment in Contemporary Hot Glass: Research and Practice**

In the research field, Dr Ray Flavell's (2001) practice-based investigation into air entrapment and void-creation in hot glass practice is a notable investigation into air entrapment in glass, in which he details the application of the Ariel technique for creative expression within his own glassblowing practice. In his doctoral research, Flavell documented the hot glass process of air entrapment integral to *Ariel*. His investigation, '*The Development and Application of the use of Encased Voids within the Body of Glass Artefacts as a Means of Drawing and Expression'* (2001) involved rigorous analysis of practice to reveal new insights in glassblowing. The thesis was invaluable in gaining an understanding of the process of air entrapment pertaining to hot glass.

An established U.K. glass artist at the time of his research, Flavell's practice-based inquiry into 'air-voids' in hot glass and fused float glass sandblast trials were important precedents to this research. Flavell undertook training at Orrefors Glassworks to gain an understanding of the Swedish Ariel and Graal processes, and his work is some of the most technically accomplished air entrapment in contemporary hot glass. Flavell describes his creative approach to air entrapment thus:

> *The creative impulse is driven by the relationship between idea/source material, and the unique character of encapsulated air-voids - with their silvery mercurial quality. These mercurial images have an illusive presence and this, in conjunction with a solid material which is transparent, provides an extraordinary 'canvas' on which to explore enigmatic themes.*
>
> (Flavell 2001, p48).

Figure 27: Above left to right: Cyberclone (detail) and Interface (2012), Dr. Ray Flavell, blown glass, Ariel technique.

Flavell’s 2001 research into ‘air- voids’ in his blown vessels, in which he built on his previous practice using sandblasted imagery, incorporated sandblasting using the same method as in the Swedish *Ariel* technique, to abrade deep indents into the surface of a blank. To form the image Flavell used masking tape as a resist, marked the blank with the design and areas which would be abraded for the air voids would then be removed using a craft knife.

Figure 28: Ray Flavell (2001) Masking the blank and cutting the sandblast motif for the Ariel process.

Figure 29: A sandblasting cabinet

As a technique which is easily accessible to most studio glass practitioners, and an alternative to waterjet for small scale and delicate air entrapment, sandblasting was considered a significant method of abrasion to investigate in this research for kiln-forming.

The intricacy of Flavell's air entrapment vessels built on the original Swedish Ariel designs of the 1930s.The complexity and precision of the hot glass-encapsulated 'air voids' achieved by Flavell was a benchmark of quality and control for air entrapment in this investigation.

Figure 30: Left: A two layered 'parison' with sandblasted fish motif ready for casing. Right: The finished Ariel artwork 'Shoal (Double Fish)' (2001) Ray Flavell, blown glass, air entrapment.

Flavell's study is directed both to glass practitioners, and to provide a theoretical approach appropriate for the reflective practitioner working in other media by adopting a parallel method of enquiry.' (Flavell, 2001, p.111). His research constituted a significant body of documented knowledge in the area of hot glass air entrapment, with a deconstruction of the Ariel production process.

Access to Flavell's previously tacit understanding of the Ariel glassblowing process – the techniques used in applying layers of glass over a sandblasted blown glass embrio to trap air - through dissemination of technical diagrams in the thesis, gave the opportunity to examine, step-by-step, the process of Ariel air entrapment. This was highly beneficial to this research in investigating the determinants of effective air entrapment, through scrutiny of the behaviour of the molten material in the blowing process illustrated in Flavell's thesis. Analysis of the process facilitated the transfer of technical knowledge from hot glass into kiln forming, in particular in understanding the relative temperature and plasticity of the added layer of glass when applied to the lower layer in the hot glass overlay process.

Flavell's research touched upon air entrapment in kiln-forming to some extent. He experimented with the use of fused float glass to create air entrapment using 'sandblasted abrasions', in his thesis. Flavell tested sandblasted motifs used in his hot glass *Ariel* pieces abraded into each side of the float glass layers and fused to create air entrapment, however the process remained unresolved. Flavell highlighted the potential of ‘air voids in kiln-fused glass’ as a new pathway with many possibilities for the future (Flavell, 2001, p105).

Figure 31: Sandblasted air-void trial (2001), 6mm kiln fused float glass 20 x 6cm Dr. Ray Flavell.

In discussions with the researcher, Flavell noted the visible problem of *air pooling* in his sheet glass fusings that became apparent in this research. Air pooling became the major challenge which had to be overcome in this investigation in order that a clean fuse could be achieved for successful resolution of Kiln-controlled precision air entrapment.

An objective of this research was to investigate the hot glass air entrapment technique *Ariel* and transpose aspects of the process into kiln-forming in conjunction with the exploration of new methods and combinations of techniques such as digital image creation and CAD/CAM processes, in order to further extend the creative scope of air entrapment in glass. This study moves on from Flavell’s 2001 research, using it as a point of departure.

Simon Hopkinson’s 2011 MPhil research explored methods of creating trapped air designs in blown glass objects, based on a deconstruction of the Ariel process and other ‘air trap’ techniques such as Mykene. Investigations included the use of bicarbonate of soda, perforated masks and sandblasting techniques, resulting in novel methods of air decoration with simple bubbles using the ‘gathering over’ technique, to enable cost effective production by a single glass blower to produce artworks.

Figure 32: Simon Hopkinson - results of 2011 MPhil research using bicarbonate of soda and sandblasted decoration to create trapped air designs in blown glass.

The work of the hot glass artists shown here demonstrates how the technical knowledge and artistry of Ariel and its related techniques have been applied by contemporary practitioners for individual personal expression in the discipline of hot glass. The examples show the legacy of Ariel to contemporary glassblowing and validate this investigation into the technical advancement of air entrapment and its relevance to creative practice in glass in general.

UK glass artist Shelley James' work explores illusion and perception, incorporating air into the work. Shelley researched and developed a method of creating matrixes of internal air bubbles in a solid piece, using flat glass 'plates' made on the blowing iron, onto which a grid matrix of deep indents are sandblasted when cooled. Using the technical skills of glassblowers Liam Reeves and James Devereux, the plates are picked up on the iron and wrapped onto the form when hot, rather than cooling, sandblasting and reheating the piece itself as in traditional Ariel. When heated and shaped, the indents create a grid of small bubbles which can be lined up and layered, to build optical effects.

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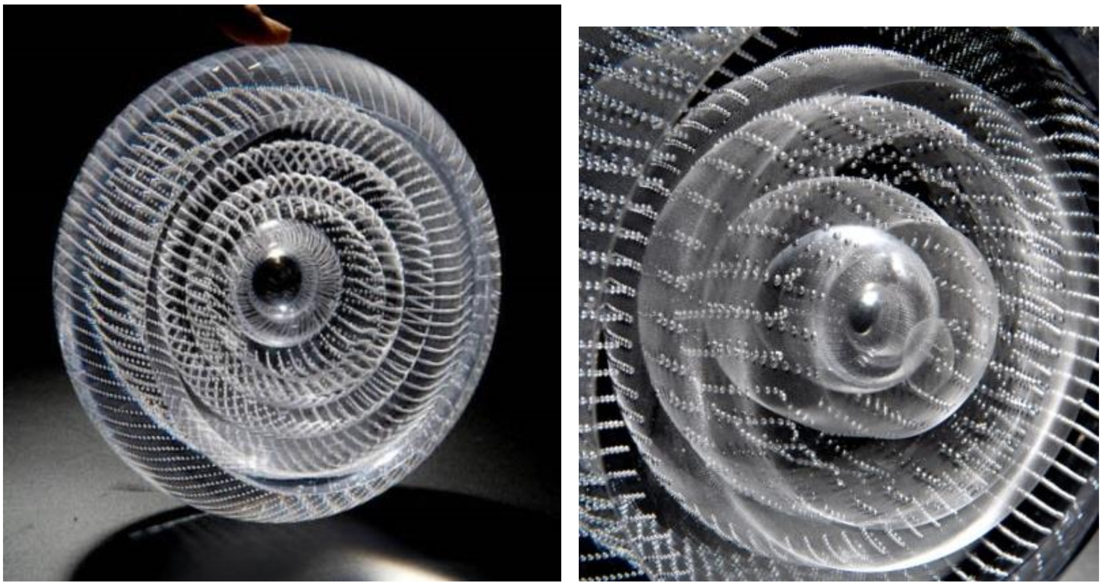


Figure 33: Moiré Matrix 2 and 3 (2012) Shelley James, hot glass air entrapment.

The work of U.S. artist Marc Petrovic in particular has progressed the format of hot glass air entrapment in glass art in recent years. Although the pieces have remained spherical, his work moves air entrapment beyond the vessel wall, into artworks which incorporate air lettering to create concept-led sculptural objects and installations.

Figure 34: 'Find and Seek – Pursuit of Happiness' (2009); 'Hope' (2009); 'Courage' (2014) Marc Petrovic. Hot glass with air entrapment.

Ohio-based glass artist Mark Matthews demonstrated his hot glass air entrapment technique at the 2012 GAS Conference, in Toledo, USA; under the title of 'Precision Air Entrapment: Void as Subject' (Matthews, 2012, p.113). Matthews traps air in hot glass using hand tools or by impressing the glass with a metal tool shaped as the intended void, to create imagery such as masks, rectangles, numbers and letters, within spheres. The use of precision waterjet technology to create metal stamps for use with molten glass to create air entrapment, might be an interesting avenue for the future.

Figure 35: Glass Spheres: Comedy & Tragedy Theater Masks, and Rectangle designs 2-3" diameter, Mark Matthews [accessed 2015] Hot Glass, air entrapment.

Transjö Hytta is a small workshop in southern Sweden, started in 1982 by two Master Glassmakers from the Kosta Boda factory. Skilled glassblowers Jan-Erik Ritzman and Sven-Åke Carlsson Ritzman began working at the Kosta Boda factory in 1957, becoming the Master of the Art Glass team in 1964, producing the designs of the Kosta Boda designers. The studio make their own *Ariel* pieces in the traditional style as well as fabricating work for international artists.

Figure 36: Contemporary Ariel: 'Turbine Vases', 14cm, made by Jan-Erik Ritzman, Transjo Hytta studio Sweden.

Figure 37: Sight Hounds, 13cm, Ariel glass designed by Blum Olsen, USA.

Blum Olsen is a studio based in Minneapolis, USA, which specialises in the production of blown glass inspired by the Scandinavian style. Andrea Blum and Warren Olson design vases in the Swedish techniques of Ariel, Graal and Thalatta, which are blown by Master glassblower Michael Boyd.

Whilst *Ariel's* legacy can be seen in continued use of the technique and its related methods in the work made by contemporary hot glass studio makers, little technical invention has taken the technique forward from its original incarnation. The basic principles of the Ariel process remain essentially unchanged since the pioneering period of its inception.

The availability of digital technology has afforded new avenues for extensive expansion of the level of sophistication and complexity achievable for air entrapment compositions, both for sandblasting and waterjet cutting methods, and the configuration of the final artwork itself, as highlighted in this study.

3.2.4 **The Limiting factors of the Hot Glass Ariel Technique**

The hot glass *Ariel* air entrapment method remains highly skilful and labour intensive, and its process and aesthetic is relatively unchanged since its origination in the 1930s. Pieces predominantly take the form of heavy-walled vessels: A considerable limitation of the Ariel technique as an air entrapment process is that it relies heavily on the virtuosity of the glassblower, meaning scale and form is restricted by aptitude, physical strength and the amount of glass that can be manipulated on the blowing iron. The glassblowing process depends primarily on the artisan's dexterity (Duncan, A. 1995, p.218) and thus Ariel has become a specialism of a few highly skilled hot glass artists.

> *Ariel needs a highly qualified master blower to perform several critical moments demanding talent and experience.*
>
> (Victor, O., accessed [2011]).

To successfully produce air entrapment with the quality of *Ariel* artworks, competency in the difficult 'Swedish overlay' casing technique is required to trap the air. Ample practical understanding of the process, developed over years of working with the material, is needed to allow the correct amount of reheating and shaping to retain the positioning of the air bubbles. Excess reheating and inflation can easily cause distortion of the image and loss of definition in the design. As the glass becomes molten, surface tension and low viscosity cause the air bubble contours to become spherical and, at high temperatures, the forces applied to malleable glass can stretch and twist the design.

Due to the layering process required to execute an Ariel design, the walls are necessarily thicker than in other blown glass pieces, consequently the weight of glass necessitates sufficient physical strength and skill from the glassmaker to be able to handle and keep control of the blowing iron. As a result the forms of Ariel works are restricted to relatively small scale, heavy-walled vessels or paperweight-type solid sculptures and are rarely more than 18cm in height.

Another constraint for an artist wishing to create work in the hotshop using the blown *Ariel* process is time and cost. Numerous stages of heating and cooling are required to achieve a final work with layered air entrapment. First the initial 'blank' has to be blown and cooled completely, usually overnight so that the glass is annealed. Once completely cool the process of creating the channels for air entrapment begins. This involves the manual masking of the glass blank, drawing imagery and cutting out the design using a craft knife, then deeply sandblasting channels to create an embryo.

The embryo is then reheated slowly in a kiln to avoid thermal shock (see Glossary) usually overnight, to around 550 degrees Celsius, so that it can be picked up on the blowing iron, an overlay casing of glass applied, and the vessel inflated and shaped, then placed back in the lehr to cool slowly. Thick glass requires a relatively long annealing cycle so *Ariel* pieces require two or more days to cool. For each additional air entrapment layer, the process is repeated and annealing times proportionally extended. To an artist hiring studio facilities or a glassblower's skills the financial implications and time required can be prohibitive.

Established techniques used in kiln-forming for trapping air include bubble frits (seen below, in the work of glass artist Ruth Lyne), using sections of glass to leave gaps, or using ribbed glass or stringers (fine cane) overlaid to create grids of bubbles.

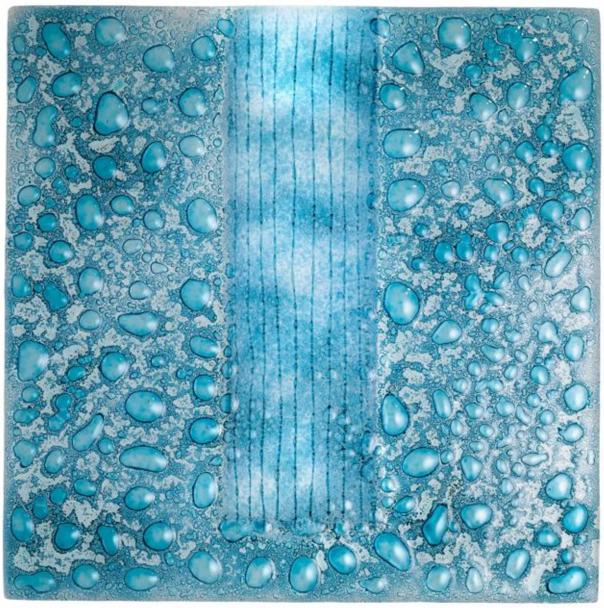


Figure 38: Turquoise jewel. 2008, Ruth Lyne, 45cmx 45cm Fused glass with bubble detail.

The existing methods lack the complexity of imagery and precision sought in this air entrapment study. However there are some high quality examples of artworks by individual kiln formers in which controlled bubbles are an important feature of the work which warrant mentioning in this context. Also included are pieces which are interesting progressions in air entrapment, but in which the technique is yet unresolved.

3.2.5 **Air Entrapment in Contemporary Kiln-Formed Glass**

Kiln forming is any method of shaping glass with heat using a kiln. In studio glassmaking, kiln forming emerged as a method for artistic expression in glass, alongside glassblowing, as the Studio Glass Movement gained momentum. Techniques have progressed though individual creative and technical exploration and the discipline is now subdivided into specialist areas.

Kiln-forming is a very accessible method of glassmaking for the lone studio artist because of the relatively low startup cost of purchasing a kiln, in comparison to the equipment necessary to furnish a hot glass studio. Kiln forming is generally divided into the disciplines of *Casting*, *Fusing*, *Slumping* and *Pate de Verre*. Kiln-formed artworks have steadily shifted in form, from decorative domestic item to standalone sculpture (Cummings, 2009, p57). The Glossary gives details of the most common kiln-forming techniques in glass artists' practice.

Figure 39: Flatbed fusing kiln (left) and casting kilns (centre &right) used in the research, at the Glass & Ceramics Dept. University of Sunderland.

This research incorporates and adapts the kiln-forming techniques of fusing, slumping and casting for the purposes of investigating and controlling air entrapment in glass. The investigation realised new methods to create and control air entrapment in float glass, and a series of procedures for kiln forming which sit between the conventional definitions of fusing and casting.

Air entrapment in kiln forming is relatively un-exploited as a creative technique in comparison to the advancements made in glassblowing. In kiln forming, bubbles are generally avoided as an undesirable side effect of the fusing process. When reviewing literature on air control in kiln formed glass, the information predominantly focuses on the avoidance of bubbles.

> *Some people like air bubbles in their finished glass pieces. They claim that they give the work character and are even attractive in their own right. It's even possible to work with bubbles by manipulating them between layers of glass. But most people think of bubbles as a nuisance. They'd like their finished pieces to be bubble-free and as smooth and untroubled as a piece of plastic. This isn't always possible, but there are some techniques that will help minimize bubbles in the glasswork.*
>
> (Technical advice from Warm Glass, available at: http://www.warmglass.com/Bubbles.htm [accessed 2010]

When researching bubbles in glass in the kiln, numerous methods are suggested as to reduce or eliminate trapping of air between the layers of glass. This has been useful to the research in terms of deducing opposing hypotheses from which to investigate how to control the amount of air that is intentionally trapped between the glass layers. This research investigation developed a new method through which to compose and control air entrapment imagery within sheet glass, to focus the air into specific areas, and eliminate excess air from the areas around it, making possible the specific removal, application and control of air within an art work made in the kiln

.

The following case studies look at artists working in kiln-formed glass who have developed a level of control of the bubble for creative expression in their artwork. Design studio Padlab and glass artist Ray Flavell have taken the kiln-formed bubble beyond the sphere using sandblasting techniques. The problem of *air pooling* (see Glossary), however, is an apparent issue that this investigation resolved and which became part of the contribution to knowledge in the research.

Tom Patti, an US artist who has been working with glass since the 1960s, creates small cubes made of 'plate' glass which focus on the interior architecture of the piece and uses the clarity of industrial sheet glass for this purpose. In Patti's method, the glass is stacked and heated in the kiln up to a molten state, and then an air bubble is introduced into the glass via a blow pipe, which expands downwards through the fused layers. Although Patti was working during the period of the Studio Glass Movement, his work stands quite separate from what was happening in its original direction, in particular through his embracing of industrial glass and the integration of the aesthetic and the technical. (www.cmog.org, [accessed 10/10/11])

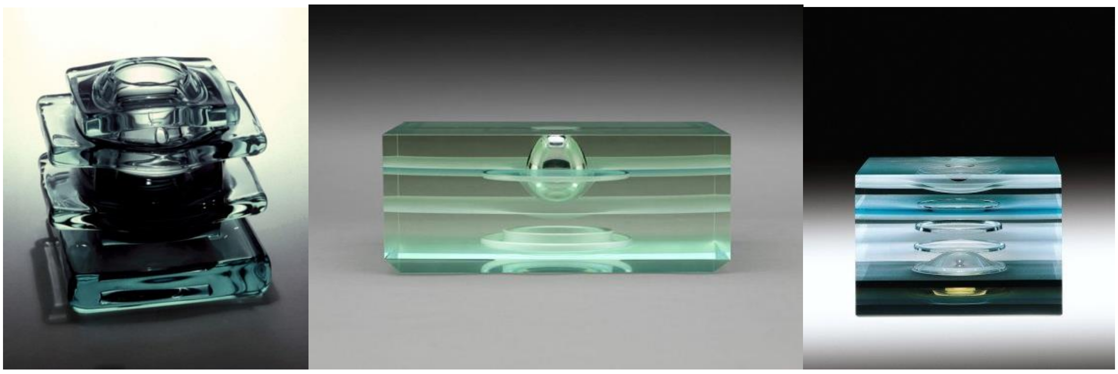


Figure 40: Modulated Blue with Green,1970s (left); Expanded Echo with Line 1989 (centre); Clear Lumina with Azurlite 1992 (right)10.3 x 15.5 x 11.3cm, Tom Patti, kiln-formed (fused) and hot formed (centre and right pieces are ground and polished).

PadLab is an architectural design and lighting studio run by designers Penny Herscovitch and Dan Gottlieb, based in California. 'Bubble glass' comprises flat fused panels and slumped vessel forms, incorporating grids of bubbles and some sandblasted bubble text (probably Bullseye or Spectrum fusing glass). *Air pooling* is visible in the bubble text image (below) which suggests that this issue was the same as that experienced by the researcher, and in Flavell's experiments (see Chapter 3). No further evidence could be found of development of the process since 2009.

Figure 41: PadLab ‘Bubble Glass’ (2004) kiln-formed air entrapment bubbles in fused glass.

Glass and fibre artist Ruth Gowell combines ‘fibre art’ and kiln formed glass in her practice. Her works explore the optical effects of capturing bubbles between layers of glass using a grid of glass stringers (fine canes); a kiln technique that produces texture in the glass in which bubbles are trapped, to distort the underlying pattern.

Figure 42: Optical Vase (2008) Ruth Gowell, 9.5” x 11.5” x 3.25”; and glass from ‘Optical Studies’ exhibition, 2013. 5”x9”x3” fused glass with bubble air entrapment, Ruth Gowell (centre and right).

In kiln casting, Steven Weinberg, one of the second generation of studio glass artists, stands out as one of few kiln casters using the air bubble for creative expression in his artworks. He began kiln forming glass in the late 1970s when casting was a relatively uncommon technique in studio glassmaking. Before casting, fine holes are drilled into the bottom of a block of optical glass. The air in the drilled holes forms bubbles when the glass becomes molten. The air bubbles rise up through the molten glass, pulling a fine trail of coloured glass up into the clear optical glass.

Figure 43: Sydney's Boat (2000) Steven Weinberg, kiln cast glass and air entrapment.

Weinberg's control of the bubble by heating and cooling the kiln to influence its behaviour in the glass is an example of the innovation of individual makers advancing glass art through personal practice-based experimentation and tacit knowledge of the material.

3.3 Glass Practice and Digital Technologies

Advancing technology has quickly brought artists an unprecedented level of access to digital tools which until recently were limited to industrial applications. As digital technologies become part of everyday society, so artists and makers are incorporating them into their creative toolkit and adapting them to the needs of their practices. The computer has grown into a powerful medium in disentangling creative practice from the limitations imposed by traditional methods of making (Shillito, 2013, p.22).

Digital technology has redrawn some of the boundaries of applied art and prompted makers to question and analyse the nature of ‘practice’ which traverses the virtual and the physical. Openshaw (2015) coined the term ‘postdigital artisans’ to describe the innovative artist/maker who has embraced the digital in their craftsmanship. He suggests that, with the millennial generation never having known a world without computers, the distinction between the virtual and ‘real’ is perhaps no longer of interest (Openshaw, 2015, p.5).

Digital and industrial technologies are integrated into creative practice in immeasurable ways: both within the process of imagining, designing and manufacturing an object, and as the art medium itself, opening up new possibilities for innovation. Many artists consider digital tools as simply an extension to the hand: an efficient means of realising pre-conceived ideas. For sculptor Wim Delvoye (as quoted in Johnston, 2015, p.56), the idea comes first, and then the necessary tool is designated. In this way, he considers there to be ‘no difference between artisanal tools and digital ones.’ Others see the digital as transforming their output with results that were previously unimaginable.

In the academic environment students and researchers across creative disciplines can now access software and machinery to design, model, prototype and fabricate. Computer Aided Design software such as AutoCAD is commonly used to create 2D scaled technical drawings for product design, and similarly Adobe Illustrator in graphic design and print. Using such software, images are created as vector graphics, meaning the use of mathematical paths to represent images. Computer Aided Manufacturing (CAM) programmes, such as IGEMS for waterjet, convert the vector paths into CNC machining code known as G-code which controls the waterjet, CNC mill or laser cutter.

Rhinoceros software is used to create 3D CAD models and renderings and can be exported for use in 3D printing (rapid prototyping) to produce physical prototypes. Rhinoceros can also be used to create 2D vector graphics for conversion into CNC files via CAM software. 3D scanners scan real-world objects to create digital models. Portable scanning technology was only recently made available commercially, and can now be bought at a price accessible to the individual artist.

An exciting extension of this investigation occurred through a chance meeting with artist Joseph Hillier who was visiting the University of Sunderland. Utilising Hillier's hand-held 3D scanner gave an opportunity to capture from life a 3D self-portrait scan, to realise an idea that had been proving difficult to accomplish with the available equipment at the University. The scan was imported as a digital model in Rhinoceros, which could then be adapted into contoured layers, turned into closed paths and translated into CNC G-code. The contoured layers for a self-portrait air-void could then be cut from glass on the waterjet cutter via additional CAM software and reconstituted for kiln firing (see Chapter 7.5).

This knowledge transfer and subsequent progression of the idea for a self-portrait air entrapment artwork spurred on the advancement of this research, propelling the possibilities for complex air entrapment further forward than originally envisaged, enabling intricately contoured 3D air entrapment forms. Such access to new technology and knowledge opens avenues for individual expression and experimentation, and, subsequently, progressive and original work.

Gaining knowledge by adapting technologies for practice-based glass research develops individual practice and the glass sector as a whole. Glass artist researchers are often quick to respond to the creative possibilities of advancing technology. Laura Johnston, architectural glass artist and pioneer of practice-based PhDs in glass at the University of Sunderland, stated in 1997 that maintaining awareness of change and emerging technologies in architectural glass practice is 'vital for artists wishing to be engaged in the design of glass for contemporary buildings' (Johnston, 1997, p.79).

Increasingly, researchers are incorporating computer-aided design and manufacture, rapid prototyping and digital rendering software such as AutoCAD and Rhinoceros software into their creative practices. Indeed, since the initiation of this research project, technologies are becoming accessible to artists that only a few years ago were prohibitive because of their newness and cost. Since Hillier's visit, the University of Sunderland has purchased its own portable 3D scanner for use in the Glass & Ceramics Department alongside a Makerbot 3D Printer which is currently being used in glass research.

Often, the reasons for embracing new technologies are to achieve a form or aesthetic that would otherwise be impossible to create using existing techniques. In 2011, at the 41st annual GAS (Glass Art Society) Conference in Seattle, Dr. Vanessa Cutler, whose 2006 thesis was the first to investigate waterjet cutting as a tool for the glass artist, described how options are opened up when glass processes are combined with technology, allowing 'manipulation of something that would have been unobtainable' (Cutler, 2011, p.57).

In his doctoral thesis, Dr. Anthony Pollock (2013) advocated the growing prevalence of glass practice-based researchers making connections with processes and technologies from outside of the sector in order to enhance creative possibilities and progress the field:

> *Those research projects that have linked non traditional technologies to glass production are important indicators of a general trend of reasoning – that many of the methods to extend form (in non glass materials) are already well advanced in industrial applications, and can bring the opportunity of new forms to artistic glassmaking. Other researchers have placed more emphasis on setting their own practice in context. For sure, this diversity of approaches can only serve to enrich the overall subject area of research into art glass.* (Pollock, 2013, p78)

Collaboration to encourage the sharing of knowledge between disciplines is creating new contexts in which glass artists can innovate. New York State College of Ceramics at Alfred University, one of America's leading art and design institutions, recently developed a new combined course called "Glassart-engine", bringing together engineering students and glass art students, taught by faculty members across both areas and integrating technologies and philosophies. The program aims to foster collaborations and create an opportunity for knowledge transfer across both the creative and scientific disciplines (Powers, 2015, p71).

Ease of access to technology is allowing more independent artists and makers to incorporate digital and industrial processes into their practice. Producers of CAD software are developing affordable or free versions and cloud-based services which are more comprehensible to the novice, such as Google SketchUp and Autodesk's AutoCAD Student. Fablab, a global network of digital fabrication facilities, provides services for students, individuals and businesses to encourage innovation. The workshops offer access to technology such as rapid prototyping, laser cutting, vinyl cutting and CNC milling.

Access to different 2D to 3D subtractive (laser/waterjet cutting, routing, milling) and additive technologies (3D printing) is becoming more straightforward as competing service providers adopt a more user-friendly approach to attract customers, in turn, reducing the costs of manufacture (Shillito, 2013, p.18).

The digital age has given rise to a new aesthetic and new creative possibilities; however there is cognisance amongst 'postdigital artisans' (Openshaw, 2015) of the transience of the 'new' and a desire to think critically, beyond using digital technology as an end in itself. Technologies that now appear cutting-edge will soon become homogenous (Openshaw, 2015, p.9). It is important to consider their relevance, purpose and meaning within creative practice.

Indeed, waterjet cutting is no longer a 'new' technology. Since Cutler's formative 2006 research, the waterjet has emerged from its industrial background to become a recognised piece of equipment in the glass art repertoire. In the UK, cutting services are currently broadly available to creatives commercially and via facilities at academic institutions.

A desktop version of the industrial abrasive CNC waterjet cutter, crowdfunded via the website ‘Kickstarter,’ aimed at ‘individual makers and small businesses,’ is currently in development and soon to be commercially available in the USA and Canada (https://www.kickstarter.com/projects/1294137530/the-first-desktop-waterjet-cutter [Accessed 15/6/16]). This development will bring waterjet technology to many individual creative practitioners, offering new modes of practice to artists within their own studios. Whilst there are differences in the hands-off nature of the process, this democratisation of industrial technology for creative exploration has echoes of the Studio Glass Movement’s modification of the factory glass furnace for individual artists.

The Northlands 20 Glass Conference, 2016, captioned: ‘A Luddite Convention: Making, Technology and Nature’, featured several speakers whose work is heavily integrated with digital technology. What was notable about all of these creatives’ work was their shared view of digital technology as another tool in the artist’s resource, a democratic means of knowledge transfer; and their deep interest in, and affinity for, materials.

Artist Geoffrey Mann’s practice operates at the interface of the handcrafted and the digital. Integrating CAD modelling and 3D printing with conventional ‘craft’ materials such as glass, metal and ceramic, his work pushes the boundaries of process. Speaking at the Northlands 20 Conference, Mann (2016) asserted that the application of digital technology ‘allows craft to become a democratic experience’. The intervention of digital technology in his practice permits the generation of forms which otherwise would remain unseen. As Programme Director of Glass at Edinburgh College of Art, his teaching philosophy ‘examines the space between disciplines and seeks [the] redefinition of such boundaries through thematic cross-disciplinary exploration.’ (http://www.eca.ed.ac.uk/school-of-design/geoff-mann [Accessed 6/11/16])

Figure 44: Flight Take Off, Long Exposure series (2008) Geoffrey Mann, H 35 x W 40 x L 65 cm Cast Clear Glass

Antwerp-based design company Unfold, integrate 3D printed ceramic with glassblowing and other materials, encompassing both the digital and the hand-made in their exploration of process. They advocate a digital open source philosophy, creating online networks for collaboration and knowledge exchange with a nod to the guilds and societies of the Arts and Crafts Movement. Their work, they say, investigates ‘the intersection between craft, industry, and digital making,’ questioning the role of the designer in an increasingly digitized context (http://unfold.be/pages/l-artisan-electronique [Accessed 2/11/16]).

Figure 45: The Transaction Project (2014) Unfold. Steel blue glass in iron oxide clay. Blown glass in printed ceramics.

In this research, craft and industry converge to give form to an idea that was envisaged but previously unachievable with conventional tools. Waterjet, as a CAM process, is combined with several hands-on glassmaking traditions: wheel cutting, grinding and polishing, Similarly, CAD and Photoshop techniques are accompanied by sketching by hand in the design process. To embrace the virtual is certainly not to discount the physical. As designer Bram Geenen suggests, ‘When technology and craftsmanship work in parallel, both applied for their intrinsic strengths, then something special can be achieved.’ (Geenen, quoted in Johnston, 2015, p.81).

At the San Jose glass conference in 2015, the Glass Art Society (GAS) celebrated the new Technology Advancing Glass (TAG) grant, awarded to artists who are using technology to improve and change the way that they, and ultimately the wider glass community, may work with glass. Glass artist and academic David Schnuckel, in his recent essay in the GAS Journal, called for a focus on the significance of critical thinking and its potential to influence the direction the glass art field, highlighting the importance of both technological advancement and critical writing by glass practitioners:

> *The 2015 GAS conference theme, Interface: Glass, Art, and Technology is one that beckons our community to seriously consider what role innovation will play in the future development of our field….The prestige of the Strattman Lecture, which was established in 2004, resides in the presentations designed to shed perspective upon the current condition of the contemporary field of glass and to inspire new direction within its continued development.*
>
> David Schnuckel (GAS News Summer 2015, Vol 26, Issue 2, p.11)

In his 2009 book, Contemporary Kiln-Formed Glass, respected glass artist and academic Professor Keith Cummings warns of the pitfalls of glass's segregation from wider contexts. Emphasising the historical significance of the cross-fertilisation of glass with technology and other media, he highlights how glass thrives in 'vibrant, mixed economies where its constant interaction with other materials, technologies and attitudes is mutually beneficial;' and how conversely, 'it dwindles in isolation.' (Cummings, K. 2009, p.14).

So, it appears technologies are advancing at an increasing rate and, as they become available to artists and institutions, innovative and exciting ways to extend processes and develop new techniques in glass become possible. Digital technology holds exciting potential when knowledge allows artists to think beyond its conventions and limitations.

The experience of the material and object on a tangible level and the emotional response to it still holds relevance for both the maker and audience: whilst the digital offers numerous new ways for artists to express their creativity, the sensory appeal of an original object endures. The 'digital native' generation maintains a hunger for 'analogue experiences … although they demand open access to culture, they also want to touch and be touched by it.' (Openshaw, 2015, p.9).

This integration of the digital, industrial and the traditional leads to fertile ground for inspiration: in the hands of the progressive artist, the spheres of handcrafted and high-tech can co-exist and intertwine with harmonious results. As Shillito (2013) suggests, creative practitioners 'have the resources to combine them so that the results can be far, far greater than the sum of the parts' (Shillito, 2013, p.10). The virtual is not inexorably destined to replace the 'real'. Where new and conventional techniques are combined with experimentation, imagination and tacit knowledge of a material, exciting new directions ensue.

3.3.1 **Abrasive Waterjet Cutting in Glass Research and Practice**

The application of digital technology is particularly exciting for air entrapment because it allows detailed and numerous forms to be drawn to scale in CAD software which can be waterjet cut as voids. Internal shapes can be cut from glass sheet quickly, accurately and efficiently, and at varying scales from 2mm to 30mm thickness. Cutting across a flat plane means that sheets of cut glass can be stacked for firing multi-layered volume compositions, or layered minimally to create flat-plane work.

Waterjet cutting is now one of the fastest growing precision profile production methods in the country (http://www.waterjetsweden.co.uk/ [Accessed 26/2/15]) and was identified as the most appropriate technology to investigate the research question. The research used a Waterjet Sweden abrasive CNC waterjet cutting machine situated within the University of Sunderland Glass and Ceramics Department. It is a 3-axis machine with a single z-unit cutting head, capable of 2D cutting at low and high pressure with water and a garnet abrasive.

The size of the waterjet bed permits cutting at a scale far beyond what is possible by conventional methods of abrading or cutting glass, and the complexity of design and accuracy achievable has opened up new imagery options for the creative practitioner. Digital technology is allowing for a new precision in glass fabrication via computer-aided design programmes. The waterjet machine enables digital imagery to be cut from sheets of glass using CAD/CAM software such as AutoCAD, Rhinoceros, and Illustrator which are transferred directly to the cutting head via programming in IGEMS waterjet software.

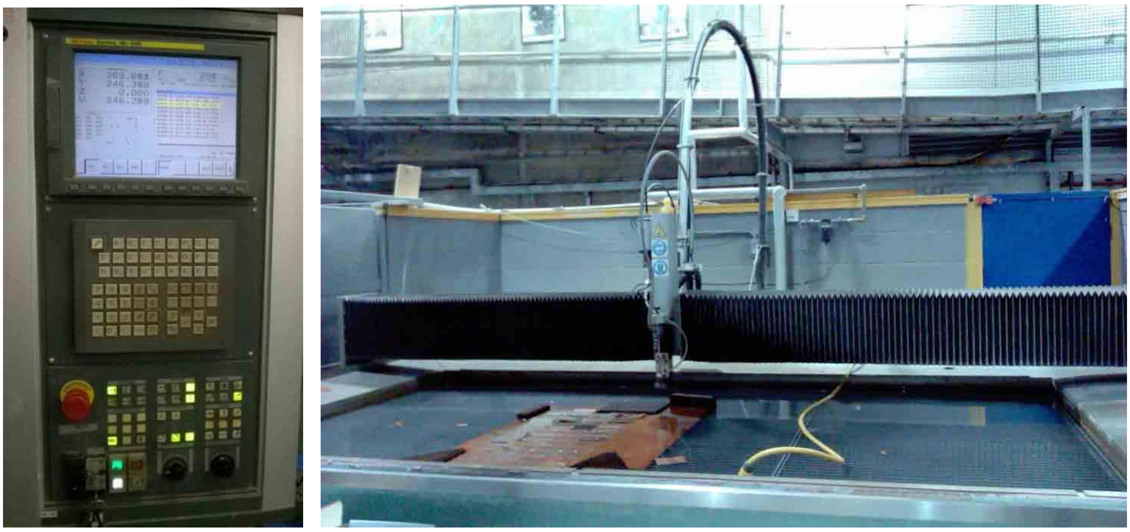


Figure 46: The waterjet machine at the University of Sunderland (right); the console (left).

Utilising the waterjet as a scaled-up replacement for the sandblaster, offered the possibility to create the voids of the ‘abraded’ layer, analogous to the sandblasted channels of *Ariel*, by using three sheets of layered glass. A design is programmed and cut into the first sheet, which is layered it onto a plain base sheet, thus creating the channels required for the air entrapment. A further sheet of glass is then placed on top to fuse and trap the air into the waterjet cut contours, comparable to the ‘overlay’ layer in the *Ariel* process.

Figure 47: Layering float glass for air entrapment: base layer, waterjet cut layer, upper layer.

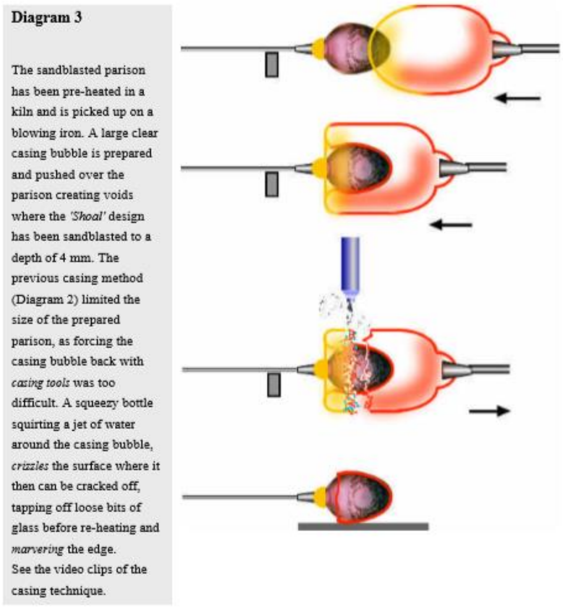


Figure 48: Flavell, 2001, p.29 Diagram of casing technique for hot glass air entrapment developed by Dr. Ray Flavell in his research, based on Ariel Overlay Casing

Before waterjet technology was made accessible to the glass artist, manual sandblasting, wheel cutting or engraving by hand, and drilling, were the main methods of cutting deep voids in sheet glass: approaches which are problematic because of the risk of breakage, or are physically laborious. The low and high pressure options of the waterjet mean that it can be used to cut voids as complex and intricate as lace patterns, hand-written text, or multiples of perfectly replicated figures, over large sheets of glass, to a precise tolerance; shortening a laborious manual task to an accurate process, with rapid results.

Figure 49: Vanessa Cutler, P2 (2006) Partial waterjet pierced (low pressure cut) glass held in metal frame. Size: 600mmx600mm.

By undertaking training in waterjet cutting, the necessary technical expertise was acquired by the researcher to fabricate complex cut-outs from sheet glasses. Whilst the last 40 years has seen extensive research in waterjet cutting for the machine tool industry, such research in the arts-practice-based sector is a recent development. Cutler (2006) initiated research into the creative uses of abrasive waterjet cutting technologies from the perspective of a glass artist. Cutler's doctoral research and subsequent Research Council UK Academic Fellowship led to the acquisition of the 3-axis waterjet machine for creative cutting by the University of Sunderland in 2004 (funded by EU and regional development agency funding).

Cutler entitled her methodology as 'informed play'. She described this as developing an "intimacy" with the waterjet cutting process, documented through personal work and by facilitating the work of other artists through case studies. Her research investigated how integrating the industrial/digital technology of waterjet into the artist's process could extend the boundaries of practice in a creative context. Knowledge was gained in the application of digital technology to engender new modes of practice in glass.

Figure 50: Spinal Wave (2006) Vanessa Cutler, Waterjet cut and kiln-formed (slumped) float glass. Size: 1180mm x 700mm.

Since Dr. Cutler's research, PhD's investigating waterjet's use within glass practice have been undertaken by Troli (2011), Sarmiento (2011) and Doolan (2014). Cutler, Troli, Sarmiento and Doolan each demonstrated new models of practice whereby precision digital technologies and processes from industrial manufacture are integrated into their particular nuanced areas of glass practice in order to extend creative possibilities.

Figure 51: Margareth Troli: Prohibited Articles (2008), waterjet cut glass installation (left). Bar Rockcoco Lamp (2010); float glass; waterjet cut, constructed interlocking form, attached beading (right). (Photo Credits S. Bruntnell).

Troli built on Cutler's research by extending the knowledge into the field of 'digital craft', exploring marquetry, fusing, construction and design in both float and Bullseye glass. Sarmiento framed and recorded the creative and technical processes behind a body of glass artworks, focussing on the graphic image using predominantly kiln-formed Bullseye glass to express aspects of ethnicity.

Figure 52: Comb, (2010) Jeffrey Sarmiento, Bullseye glass; screenprinted, kiln formed, waterjet cut, coldworked.

Figure 53: Propagate, Shelley Doolan, 2012. Lost was kiln cast glass (image Simon Bruntnell)

Doolan works with kiln casting. Her research ‘proposes a model of practice for the use of CAM processes … with specific reference to waterjet technology … within the context of a glass-making practice’, outlining the development of a working method ‘through a process of creative experimental investigation … supported and informed by technical testing’ (Doolan, 2014, Abstract).

Since Cutler’s inaugural research, digital technologies continue to be an area of interest to researchers within the glass and ceramics department at the University of Sunderland, with several further PhDs in progress at the time of writing, such as those focussing on waterjet applications by glass artists Erin Dickson and Mark Hursty.

Figure 54: Emotional Leak (2011) Jeffrey Sarmiento/ Erin Dickson, waterjet cut and assembled float glass sculpture (left); Behind the Clouds (2015), Erin Dickson, waterjet cut and kiln formed Bullseye glass (right).

The industrial and digital technology of abrasive CNC waterjet cutting has been embraced by glass artists and designers in the last decade enjoying the radical changes in glass shaping that access to this cutting technology brought about. The abundant possibilities for cut-out forms, through to abrading, cutting and piercing glass, that the waterjet machine offers, has brought a new creative method and visual aesthetic to studio glassmaking.

Complex forms that were once impossible to create through drilling or cutting glass, now are created on the waterjet with speed and precision. As a result, numerous glass artists have chosen to incorporate the technique into their practice. Artworks from large-scale installation pieces and architectural glass art, through to commercial serial production and jewellery, made using the process, have extended the boundaries of creative practice in glass art.

Figure 55: Fingers platter (2006) Vanessa Cutler. waterjet cut blown glass (blown by James Maskrey),

Vanessa Cutler's 2012 book, *'New Technologies in Glass,'* highlighted how the waterjet enabled the process of cutting glass to be fast, economical and opened possibilities for complex forms. Shapes within shapes were made easy to cut, as opposed to the difficult and time consuming method of manual cutting by scoring with a hand tool and breaking (Cutler, 2012, p.26).

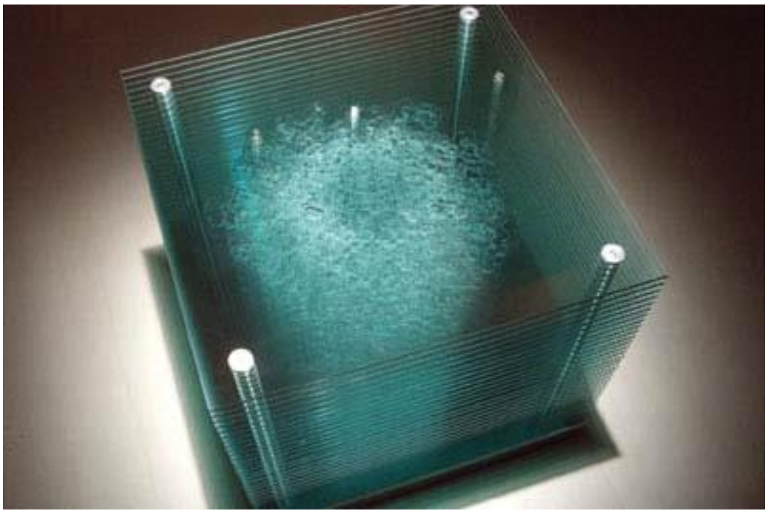


Figure 56: ATP Synthase (2007) Colin Rennie, 100cm square. Float glass, waterjet cut, assembled. Metal supports (right).

Figure 57: Unknown (2010-2013) Alison Kinnaird, Water-jet cut, sandblasted, wheel-engraved, illuminated with LED lighting. Entire installation approx. 190cm x 190cm (left)

Figure 58: Lace (2008) Joanna Manousis, kiln-formed (fused) glass murrini and waterjet cut glass 48 x 3/4 x 16 inches (right).

In May 2014 the U.K. Contemporary Glass Society held a selected online exhibition showing the work of 20 UK and International artists whose work incorporates waterjet. The following artworks used a variety of glass types commonly used in studio practice. Shown here are examples of artworks demonstrating waterjet's various applications. The majority of artists mentioned here outsource the waterjet fabrication of their work.

Figure 59: micro macro (2010) Inge Paneels, (28cm diameter) waterjet cut and kiln-formed (fused) glass.

Figure 60: Fox in a Henhouse (2012) Rachel Elliott, (10x 7 x 1 cm), water-jet cut glass with hand-printed kiln-fired enamels. Empire Necklace (2012) Blanche Tilden, Waterjet cut, flameworked and coldworked borosilicate glass, silver

In this inquiry, the waterjet machine is applied as principally an up-scale sandblaster to cut voids from the glass. Instead of abrading an indent or channel into the glass surface with sand, the waterjet pierces *through* the glass sheet, which is placed on a base sheet. Further layers are added on top, which are then fused together in the kiln, sandwiching the cut contour to form air entrapment when the heated glass softens and bonds.

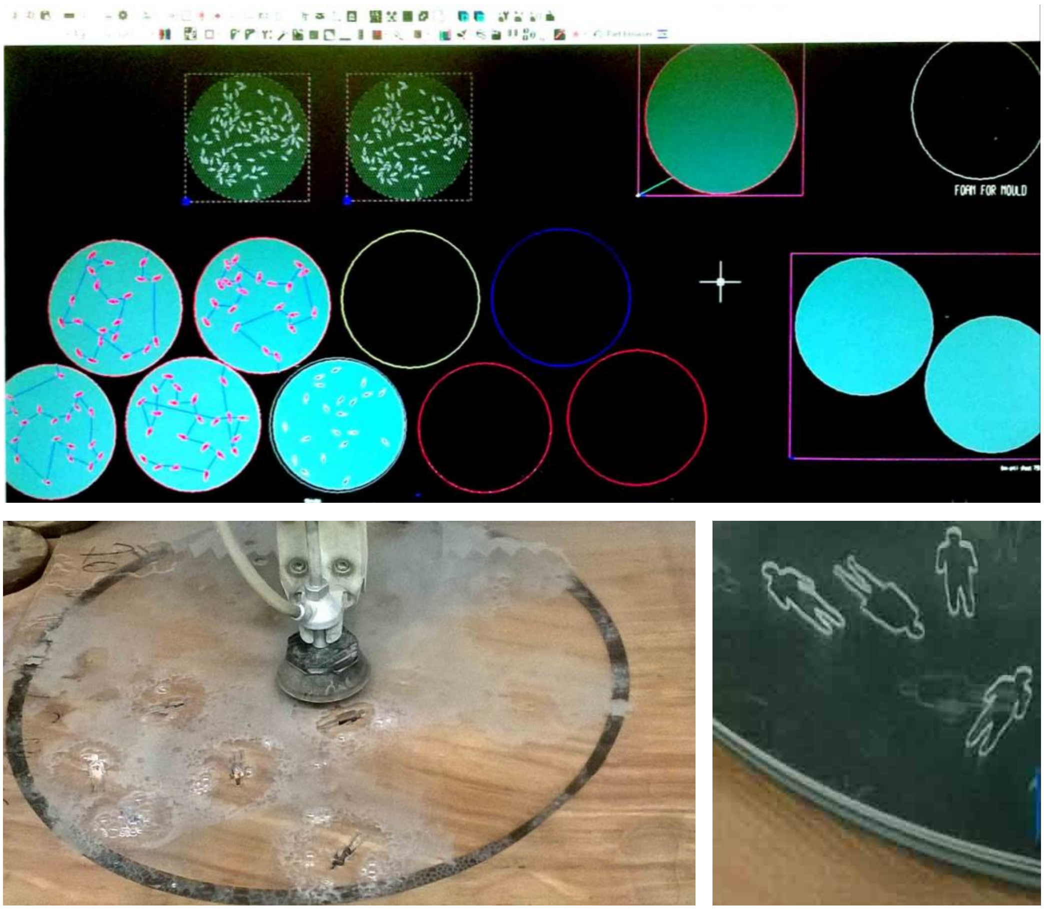


Figure 61: Above clockwise from top: screenshot of IGEMs software with the layers for ‘Host’ artwork programmed for cutting; cutting in progress; detail of cutout figures.

Building on existing waterjet research and practice, this research investigates the waterjet cutter as a tool for subtractive void-contour cutting, and applies CADCAM technology as a tool to develop intricate and multidimensional air bubbles. Waterjet technology is used as one of a series of processes in order to achieve the successful outcome of kiln-controlled air entrapment.

3.4 Sheet Glass: Float Glass & Fusible Glass

In studio glass practice, sheet glasses are predominantly used in applications such as architectural stained glass, as well as studio fusing and slumping to make thin or flat items such as panels, bowls, and jewellery. Sheet glass includes *float glass* and fusible ‘art glasses’. It can be stacked and fused, or laminated (glue bonded) to make thicker work. Part of the investigation was to evaluate which glasses were most appropriate for the research. This research uses Pilkington’s float glass as a key component for the development of *Kiln-Controlled Precision Air Entrapment*. Other glasses were investigated and evaluated to make comparisons in the technical inquiry.

Float Glass is a soda-lime glass which is clear and flat with a uniform thickness. The invention of the float process in 1952 by Sir Alistair Pilkington revolutionised the way sheet glass was manufactured. The capability to produce consistently flat, optically clear sheets at a large scale was a major advancement in glass technology (Bray, 1995, p.110). Pilkington’s innovative technique is described thus on the company’s website:

> *Molten glass, at approximately 1000ºC, is poured continuously from a furnace onto a shallow bath of molten tin. It floats on the tin, spreads out and forms a level surface. Thickness is controlled by the speed at which solidifying glass ribbon is drawn off from the bath. After annealing (controlled cooling) the glass emerges as a 'fire' polished product with virtually parallel surfaces.*
>
> (http://www.pilkington.com/pilkington-information/about+pilkington/education/float+process/default.htm [Accessed 25/02/15])

The float glass process was licenced globally by Pilkington and has become the standard production process by commercial manufacturers of glass for the industry around the world. It is now produced cheaply and on an industrial scale for architectural window and glazing purposes and the automotive industry with clear, tinted and coated glasses manufactured from 0.4mm to 25mm thickness.

Pilkington Float Glass was selected for the research due to its particular material qualities and its ubiquitous availability through various suppliers in the UK and globally. The flawless transparency of the glass was essential for the internal optical clarity intended in the air entrapment artworks. With the ‘float’ method of manufacture, visual distortion when looking through the glass is almost completely removed (hence it becoming standard for windows and doors). For architectural glassmakers, the availability of vast sheet sizes in float glass makes it appropriate for large scale work. The smooth surface of float glass and its accuracy and consistency of thickness also makes it advantageous for cutting, shaping and sandblasting.

In fusing, float is often used as a beginners glass, as it can be bought cheaply and in quantity as an inexpensive learning material to practice with before moving on to the more expensive ‘art glasses’, which are more suited to kiln processing. Float glass does have a predisposition towards unattractive surface effects such as tin bloom and devitrification when fired (see Glossary for terms), has limited colour ranges and can have compatibility issues which can be off-putting for the glass artist.

Following the initiation of the studio glass movement and growth of kiln glass, small businesses emerged specialising in the production of fusible glass for the kiln. The companies were often established by glass artists themselves in order to provide superior alternatives to float or furnace glasses for kiln-forming. ‘Fusible glass’, also called ‘Fusing Glass’ and ‘Art Glass’, are sheet glasses developed specifically for use in the kiln and tested rigorously for this purpose. They are popular alternatives to float glass with many advantages for fusing, and are usually a more favourable choice for the kiln-former than float glass.

The fusible art glass product ranges are designed to provide extensive colour choices which combine well without compatibility issues. They are available for various kiln-forming purposes as sheets, frits (crushed glass) as well as casting billets. Different types of fusible sheet glass commonly used by kiln-formers (and architectural glass artists) in the studio glass sector include Bullseye

Glass, Spectrum and Uroboros glasses.

Cross-over sheet glasses include Artista® made by German multinational Schott AG: an optically clear low-iron sheet glass aimed towards both architectural & fusing applications, produced using the Fourcault Process; Spanish company Vidriarte produces its own coloured float glass range ‘Flosing Glass’, compatible frits and flashed glasses which were relatively recently developed for glass artists to use with standard float glass.

Different types of glass have different coefficients of thermal expansion (COE) which means that they expand and contract at different rates at a specific temperature range. Glasses made for compatibility have similar COEs as they are less likely to form internal stresses and crack during the firing process, although this is not the only indicator of compatibility and glasses with the same COE can still have compatibility issues (further information on these glasses and processes can be found in the Glossary).

Whilst float glasses from different manufacturers tend to have a similar COE*,* for artistic users intending to fuse, it best to consistently use a single brand of float glass, as differences, of no concern in commercial use, can be problematic for fusers – different brands of float glass can be incompatible when fired. Using glass cut down from a single architectural ‘stock sheet’ further reduces potential compatibility issues between batches.

Fusing glasses are formulated for compatibility and to have high resistance to devitrification and numerous colour variations. However, as fusible art glasses are rolled or ‘drawn’, they acquire variations in thickness and a fine, undulating surface texture in the manufacturing process. When several layers are fused, air is often trapped between the undulations in the adjoining surfaces, forming tiny bubbles or ‘seeds’ which inhibit the clarity of the final piece, especially in works with numerous layers. Additional disadvantages of fusible art glass for this particular research included the colour density, beneficial for its vibrancy in thinly fused work, but which in multiple layers hindered light transmission and clarity; as well as the small available sheet size and high relative cost when compared to float glass.

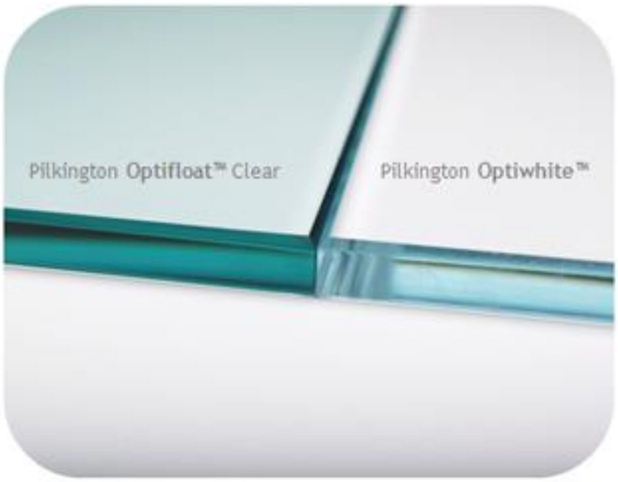


Figure 62: Above: Pilkington's Float Glass and Optiwhite Low Iron Float Glass (www.pilkington.com)

Despite the challenges of float glass as a kiln forming material, when handled with an understanding of its properties, its potential benefits for air entrapment without impairment of the clarity of the glass for its interior space, scale and depth for this research were great. Manufactured to a wide range of thicknesses its sheet area (several metres) and smoothness made it preferable to currently available fusible art glasses.

It was anticipated that for this investigation, float glass layers could be made to fuse cleanly and with little interference to the air entrapment, with the air trapped in the intended channels and likely to remain confined within the borders of the design. The smooth surface and lack of texture of the float glass sheets was expected to leave little space for bubbles to become trapped in surface undulations. In addition, the possibility of producing air entrapment artworks economically and at a greater scale (in terms of both area and depth of thickness) were further incentives. Fusible sheet glasses, such as those described above, were included for comparison.

Many unforeseen technical issues in the kiln-forming process which arose during the investigation had to be understood and overcome in order to develop an air entrapment method which generated replicable results using float glass. Float glass lends itself well to waterjet cutting as a smooth, flat material. The air entrapment artworks in this research comprise assembled waterjet cut layers with uncut layers which are fully fused in the kiln to create glass blocks containing air entrapment within the internal space of the glass object. Despite the numerous challenges, the advantages for optical clarity outweighed the negatives when re-evaluating the choice of glass during this investigation. Ultimately, technical resolution to these challenges was achieved with very successful results. The outcomes of the investigation have created new avenues for creative expression using float glass and offer many possibilities for the future. The following section gives examples of artists who have applied and adapted the intrinsic technical and material qualities of float glass to their advantage.

3.4.1 **Float Glass in Glass Research and Practice**

Several practice-based research projects on float glass and the investigation of its material properties for creative practice have been undertaken in recent years, which have also set precedents in glass art research. Johnston (1997) Antonio (2009), and Leatherland's (2010) doctoral research explored the material and its technical aspects, for artistic and creative purposes. Johnston investigated dichroic coatings on float glass, and their application in new configurations in the context of her glass practice in site-specific architectural installations. Developed for the Aerospace industry, dichroic glass is an example of another technology that has crossed into the creative sector to become used widely in glass practice.

Figure 63: Glass Installation (2006) Laura Johnston. Suspended dichroic float glass and steel.

Antonio (2009) and Leatherland (2010) investigated the artistic application of the material properties of float glass coatings via kiln forming. Antonio’s technical inquiry explored the creative use of the residual tin layer, controlling tin bloom for decorative effect. Leatherland developed new creative uses for Pilkington’s K-glass by investigating the possible iridescent colour effects of manipulating low-emissivity coatings through kiln forming techniques. Both demonstrated the artistic potential of her technical discoveries in their body of artworks. Their research used systematic material testing and analysis to generate technical data, which could be applied alongside tacit knowledge in their own creative practice and for use by glass practitioners and other researchers to extend the field. Their methodologies have been useful as comparative approaches in the structuring of this thesis.

Figure 64: ‘Dhow’ (2007) Eileen Leatherland, ‘Mirror Gap Technique’: Pilkingtons 4mm ‘K’ glass and float glass (height 90cm)

In contemporary glass practice, float glass is used in numerous ways. In the contextual review, a number of artists whose work applies the optical clarity of float glass to expressive effect were found. However, with the exception of Tom Patti’s small sculptural objects, no examples of solid glass pieces made from multiple fused float glass layers could be found as precedents to this research. All evidence of artworks incorporating multiple layers of float glass with the depth and clarity intended were fabricated using glue-bonding methods (sometimes termed ‘laminating’). In this technique, optically clear curable adhesive is used to bond numerous sheets of float glass to create larger works with internal space.

Modern glues such as HXTAL give a very strong bond and work effectively with float glass because of its smooth surfaces, leaving a clean finish with very little interference between layers. This gives the impression of a solid mass, similar to kiln-cast glass, which can be cold-worked and polished. Because the glue-bonding process is a cold process, i.e. the glass does not become molten; it is unsuitable for the air entrapment technique. To demonstrate the creative potential of the internal optical space of float glass, examples are given of artists' work which uses the glue-bonded laminating method to dynamic effect.

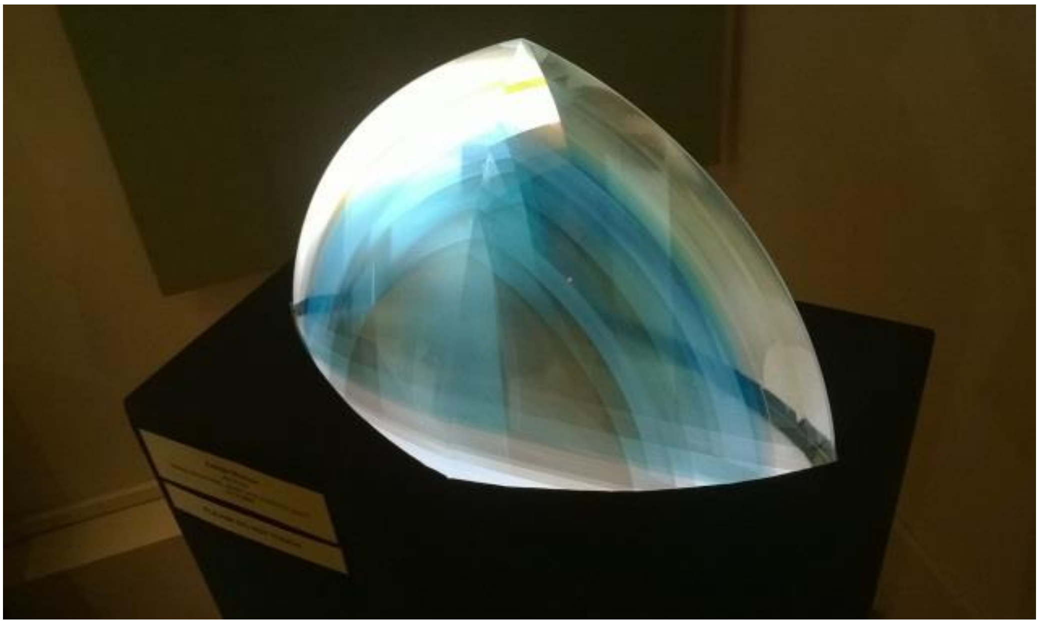


Figure 65: Arches (2014), Zoltan Bohus, metal deposited [dichroic], glued and polished glass

Figure 66: Jewel (2012) Lukácsi László, 'laminated' and cold-worked dichroic-coated float glass

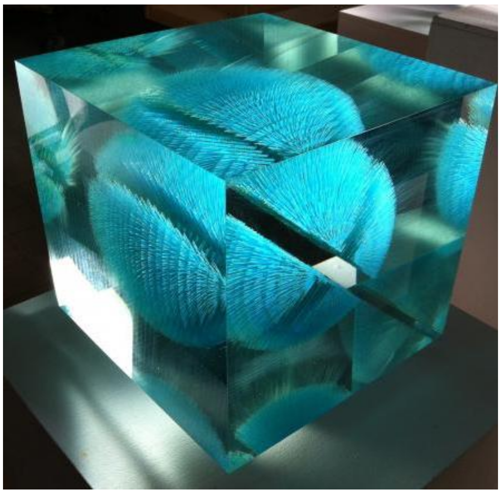



Figure 67: Left: Where The Shark Bubbles Blow Series (2011) Wilfried Grootens. Painted, laminated and polished float glass 23x23x23cm; Right: Reservoir (2011) Stephen Adams. Concrete, laminated, polished float glass, baltic birch plywood. 26 1/2"x13"x7".

These contemporary artworks incorporate the glue-bonding process to reveal the internal clarity of the glass in a similar way to the kiln-formed artwork in this research. Where imagery is used in the body of the glass artwork it has been created by engraving, collage or painting.


Figure 68: Right: Lord Vishnu (2013) Dustin Yellin, laminated glass, ground and polished collage, acrylic paint 72x27x15", psychogeographies series; Right: Folded Voyage (2015) Ben Young, laminated float glass, cast concrete and cast bronze, 35 x 23 x 12cm

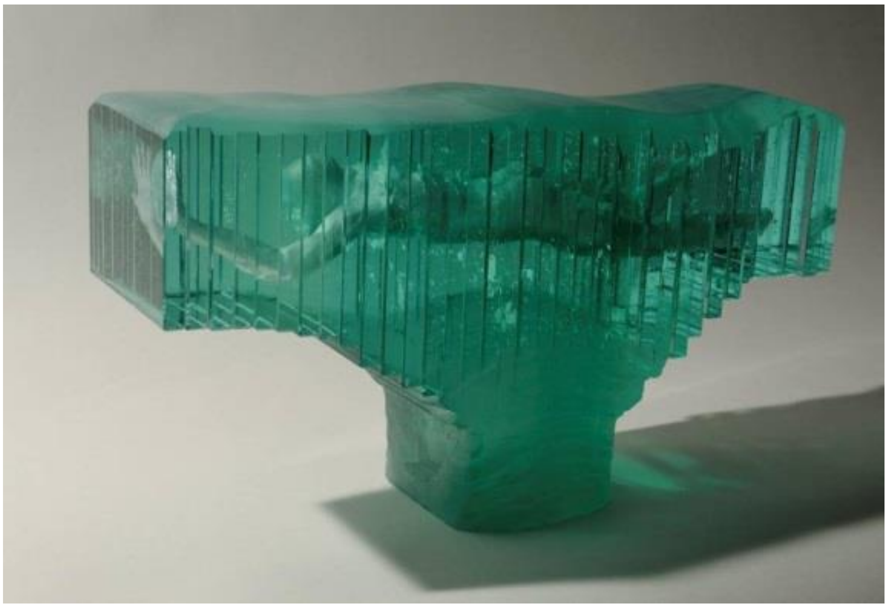


Figure 69: Tunnel (2015) Peter Nilsson, carved, laminated float glass, 30x43x16cm

The ability to utilise the internal space and clarity of float glass with a sculptural approach, incorporating air entrapment, for creative expression, was very important to the development of the body of artworks in this research. The methodology for achieving optically clear kiln-formed float glass layers with minimal interference and controlled air entrapment, and the new knowledge gained in the investigative process, is elucidated in the following chapters.

4. Introduction to the Investigation

This chapter introduces the investigation and summarises the research. It locates the research within the context of contemporary creative practice in glass. The potential for the outcomes of the research is examined and the audience for the body of artwork Is discussed.

The creative potential of developing a technique to make and control air entrapment forms and imagery in kiln-formed glass was the motivation for the proposed research. At the time of researching, no academic texts or literature on the subject of air entrapment and kiln forming in glass practice, and very little documented investigation into the controlled manipulation of air entrapment in kiln-formed glass, could be found to exist.

A contextual review determined hot glass techniques of air entrapment to be considerably further advanced than those used in kiln-formed glass. Air has been used decoratively in glassblowing for hundreds of years, reaching a high level of detail in the control of bubbles, such as in the Venetian *Reticello* goblets of the 1700s and the air-twist stems of 18th Century English drinking glasses. In the 20th Century, the Swedish innovation of the '*Ariel'* glassblowing technique in the 1930s took air entrapment in glass to an unparalleled level of bubble control. Ariel was identified as the apex of air entrapment with its sophisticated designs and complex imagery. Remaining popular in contemporary practice, its method and aesthetic has remained unchanged since its inception.

This research explores digital fabrication technologies integrated with conventional techniques to develop precision in air entrapment in the kiln. The result is a new process for producing highly complex air entrapment in glass. The kiln-forming method of fusing sheet glass allows the creation of sophisticated air entrapment with multi-faceted contours and a new level of control, clarity, intricacy and scale which has generated new possibilities for air entrapment beyond the limitations of the Ariel technique.

In The Craftsman, Sennett explores the ‘intuitive leap’, describing how, in the craftsman’s mind, ‘Specific practices prepare the ground on which people might stumble [upon the unexpected]’.

> *Intuition begins with a sense that what isn’t yet could be. How do we sense this? In technical craftsmanship, the sense of possibility is grounded in feeling frustrated by a tool’s limits or provoked by its untested possibilities…The first stage occurs when we break the mold of fit-for purpose. That break occupies a different part of the imaginative realm than retrospection.*
>
> (Sennett, 2008, p209)

This analogy is useful in describing the possibilities envisaged at the outset of the investigation. This research proposed that the application of the principles of the *Ariel* technique, integrated with knowledge of kiln forming, float glass, and the untapped possibilities of digital technology, in particular waterjet cutting, for air entrapment, offered new prospects for glass art. This could widen the scope of possible artworks using air for creative expression, thus contributing a body of new knowledge to the field of glass.

The researcher’s intuition was that through scientific testing and analysis of previous innovation, and by studying and modifying elements of the *Ariel* process for kiln forming, a similar standard of air entrapment could be achievable in the kiln, generating new glassmaking methods. The aim of the inquiry was to develop and document this technical process and demonstrate its creative possibilities through a body of work. To define the new technique, the term *Kiln-Controlled Precision Air Entrapment* was coined.

The research addresses and resolves how the form of the air entrapment can be structured, sealed, controlled and manipulated in the kiln, and any excess air bubbles removed or prevented. It investigates the application of layers of air entrapment imagery within the body of a glass object through fusing multiple waterjet-cut and uncut sheets of glass at various elevations, as well as single layer air entrapment for flat plane architectural glass designs.

The research further investigates reasons for the problem of ‘air pooling’ in kiln-fused float glass layers (flat puddles of air with a silvery appearance which impinge on transparency) in order to develop a replicable fusing technique so that its possibilities in realising an artistic idea can be explored.

The extensive technical investigation into the air entrapment process made up a substantial section of the research period until the technical outcomes could be applied in the creation of artworks. The ongoing creative inquiry emerged through practice-based experimentation, observation and reflection alongside contextual analysis. The technical testing itself often inspired the creative direction, leading to new ideas for content, subject and the creative expression which emerged in the body of artwork.

The application of float glass and waterjet technology, combined with cold working and kiln-forming knowledge and enquiry, takes air entrapment form beyond the extents of its previous incarnations in glassblowing. The inquiry has generated new practice-based methods which free up the expressive possibilities of composition, shape, form and artistic content beyond the conventional vessel, or spheroid, and an advanced level of control, detail, format and scale, opening up the creative possibilities of sculptural and architectural forms in glass.

The research imparts a body of new technical knowledge which advances air entrapment using the kiln and its creative possibilities, contributing to the field of art glass practice through the innovative application of combined glassmaking processes and digital technology; and produces a body of work which evidences the findings of the thesis and applies them in context.

4.1 Positioning the Research

Like many other creative practitioners in 2015, the researcher's own practice is not limited to a narrowly-defined taxonomy with art & design. The sphere of activity of the 'glass artist', as in other creative practices, is rarely simply working in isolation within a specific section of the field. As well as working across processes, makers can take on multiple roles, in teaching, consultancy, projects or research (Shillito, 2013, p20). Conventional classifications are increasingly difficult to apply to the modes of practice of artists working in glass in the early 21st Century.

Creative practice in contemporary glass is increasingly cross-cultural and collaborative. Diversity, flexibility and collaboration with other specialisms have become key to continuing a viable studio practice, in the experience of the researcher's own practice and observation of peers. Artists who make glass often dislike defining themselves singly in a specific category at the exclusion of others, and many regularly work within different contexts with various methods. However a common link is the notion of independent 'studio practice' which emerged out of the Studio Glass Movement.

Whilst many who work predominantly in the medium define themselves specifically as a *glass artist or glassmaker,* others simply use the title 'artist'. As a result of direct access to glass facilities made feasible by the Studio Glass Movement, an artist can spend years developing a specialism in their chosen medium, and with it, the tacit knowledge and technical skill of the accomplished glassmaker, along with the artistic concerns of the studio artist. Respected American glass artist Mark Petrovic is one such practitioner:

> *I strive to be an artist first and a hot glass sculptor second. Although I primarily work with glass, a material most commonly viewed as a craft material, I strive to make content driven work that stresses the idea at its core rather than the seductive material it is made from.*
>
> (Marc Petrovic, 2014 [Accessed 1/12/14])

Due to the high level of physical competence often required to manipulate glass into an intended form, established glass artists tend to have refined their practice to a level of specialism and technical proficiency equal to, or beyond that of, the traditional craftsman working in industry. As well as being established artists in their own right, these skilled artist/makers often now play the role of artisan or technician to fabricate the artworks of other artists who wish to work with glass, but do not have the necessary technical capability to control the material.

Glass is now a material for artists and designers who work across a spectrum of the arts, and creative practice in glass often straddles previously separate disciplines. For the purposes of this thesis the term '*artist'* is used to describe those working in any or several of the afore-mentioned categories of glass art.

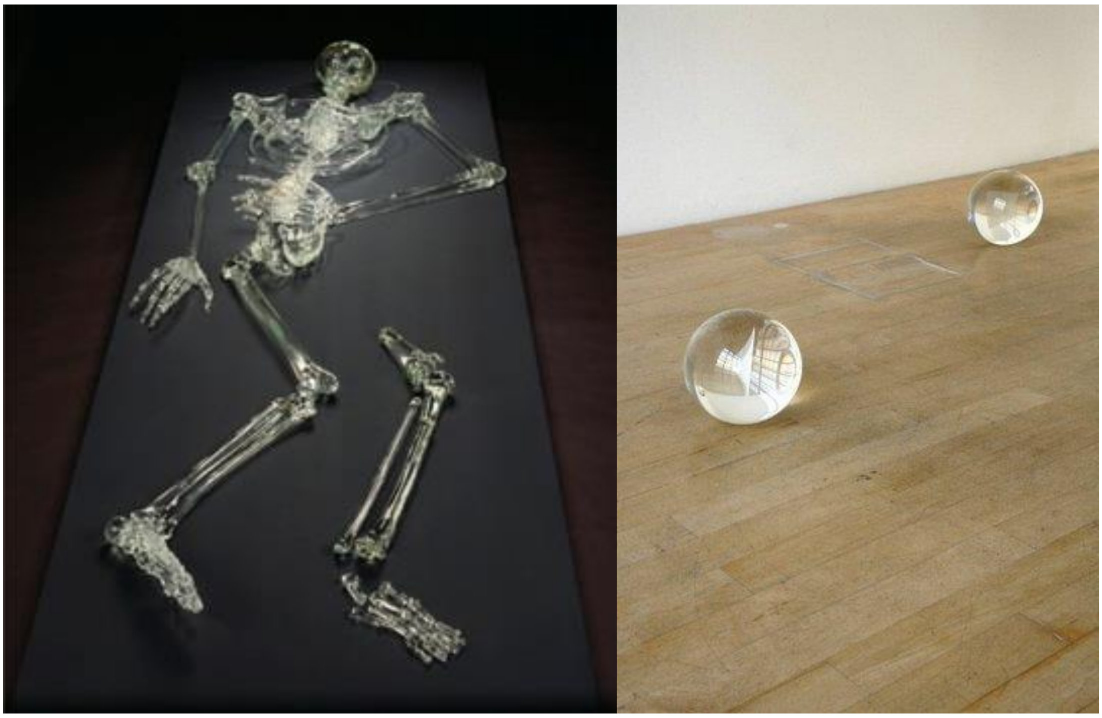


Figure 70 Left: Hunter (1988) William Morris, hot-formed glass, made by the artist. Right: 'A sheet of paper on which I was about to draw as it slipped from my table and fell to the floor' (2008), laser etched glass, Ryan Gander, fabricator unspecified.

In a recent text, Professor Kathryn Best (editorial foreword, Collins, 2010) stated that 'in the creative industries, no one discipline operates in isolation.' It is true that crossovers between traditionally aligned disciplines such as ceramics and glass have long existed in the academic environment and postgraduates working in the creative industries have often extended these connections through collaboration and shared studio spaces with artists and designers in other disciplines. Further, in this era of digital communication, access to online networking and information sharing; on platforms such as Twitter, Pinterest, You Tube and Periscope, as well as the global reach of exhibitions, conferences and juried competitions via the internet; has led a fast-paced exchange of ideas and philosophies across disciplines and cultures. Creatives can connect easily on an international level, leading to new influences and cross-pollination.

Increasingly, glass is being used as a fine art material by artists from outside of the glass world, and those who work primarily with glass are crossing into design and contemporary art (Oldknow, 2008, p.20). In disciplines as diverse as new media, sculpture, performance, site-specific installation, architecture, product design, contemporary craft and science, creative people are forging links and generating new discourse with the material, traversing traditionally defined sectors.

> *Although the international studio glass community has always been, and remains, strong and cohesive, glass has become a material available to all. It has become inclusive rather than exclusive. The methods of working it, and how it may be accessed, have become truly open and transparent.*
> (Oldknow, T. 2008, p20)

As paradigms of professional creative practice have become more fluid, traditional boundaries within formerly distinct creative fields have blurred. As a result, different practice-based methodologies are emerging in the search for knowledge, which reflect the changes in method that creative practitioners use within their own multi-disciplinary practices. Increasingly, this is including digital technologies in all areas of creative practice research.

Digital processes are being combined with more conventional making skills to open new research avenues. A variety of possible approaches to research are emerging in the field that is concerned with, and initiated in, creative practice. Gray & Malins (1993 & 2004) called on art practice-based researchers to make clear their processes, 'to make tacit knowledge explicit' in order to set exemplars for methodological paradigms and standards within the field (Gray & Malins, 2004, p32).

In order to reflect on and evaluate their own methodologies, art-practice based researchers are encouraged to look at ways in which knowledge-building in creative practice relates to other, more established, academic research fields. Newbury (writing in Biggs & Karllson, 2010) called for art-practice researchers to step back from their investigative practices and draw comparisons to practices of research within other disciplines, with the purpose of initiating 'a language with which to speak about research' (Newbury, in Biggs & Karllson, 2010 p. 639).

The nature of this research necessitated an approach to the investigation using experiential knowledge of the material in studio practice as a frame of reference. Undertaken as individual creative inquiry, the research aimed to formulate new knowledge within the field of glass art through technical experimentation, analysis and contextual investigation; and to elucidate and disseminate tacit understandings through reflective inquiry. The outcomes of this research have numerous applications for the creative industries, however the investigation does not sit in the research framework of creative inquiry for the 'applied context' of pre-defined purposes, such as that of a client (Collins, 2010, p45).

The multi-method approach combines experimentation and problem solving on both a technical and artistic level, incorporating both rational and intuitive responses. With the union of digital/ industrial technology with conventional glassmaking skills, the glass artist-researcher's role 'becomes one of combining the arts and engineering' with progress made via 'tactile experience and a tacit knowledge of the materials' (Cutler, 2011, p57).

In this regard, the artistic ideas and technical evidence are brought together in order to apply the outcomes of the research into glass art practice. Either element without the other would not serve to answer the research question in the context that it asked: that of developing meaningful artworks in glass. The investigation developed theories for precision air entrapment as a series of new techniques, and in terms of their creative possibilities, as:

- A technique or 'system of processes' by which to generate, and evaluate, a set of particular aesthetic values in glass, which could be developed to create new modes of practice for producing artworks, and expand the scope of air entrapment in glass;
- A means of exploring concepts arising from the creative exploration of air and glass to create artworks.

In recent years, precedents to this study which incorporate glass, digital and kiln technology have been set in practice-based research. At the time of writing there are no previously published theses on the subject of precision air entrapment through applied digital technology and/or kiln technologies. There are, however, examples of research into air entrapment in blown glass, as well as recent PhD studies investigating creative glass practice and technology, which were relevant to this enquiry and are discussed in the Contextual Review.

4.2 Potential for Air Entrapment Artworks using Applied Digital and Kiln Technology and Integrated Processes

This research takes the possibilities for air entrapment artworks beyond the confines of the hot glass studio. The inquiry integrates knowledge learned from the deconstruction of the hot glass *Ariel* process and the principles of kiln-forming gained through personal practice. It combines contemporary technology with the investigation of new techniques. This applied knowledge advances air entrapment in glass into new forms and imagery that have the opportunity to exploit the expressive, monumental, sculptural and architectural possibilities of kiln-formed glass art. Float glass sheets replace the initial blown and cooled blank; digital design, programming and waterjet cutting replace manual marking/ engraving and masking/ sandblasting. The kiln replaces the hot glass studio.

The image that can be drawn digitally can be cut using the waterjet. The abrasive CNC waterjet cutting machine at the University of Sunderland offered the new prospect of making artworks incorporating air entrapment from digital technology. The application of the digital image via Illustrator and AutoCAD software takes the potential form of air entrapment and artworks themselves beyond the relatively rudimentary imagery of previous air entrapment. Waterjet cutting increases the speed and precision of the abrasive process allowing for more intricate and complex air entrapment designs. Use of the waterjet gave the opportunity to create artworks in new configurations using sophisticated imagery at a much greater scale, complexity and accuracy than works made through manual wheel cutting and sandblasting.

The processes of waterjet cutting and kiln forming release some of the restrictions of form, scale and tacit glassblowing knowledge inherent in the hot-glass *Ariel* process. Use of float sheet glass allows flat planes to be layered, giving the potential of multiple air entrapment layers fired simultaneously, for sculptural kiln-formed artworks and flat, architectural glass panels.

Whilst the hot glass Ariel technique requires a costly infrastructure to execute: glassblower, furnaces, annealing kilns, sandblasting facilities, plus a considerable investment in processing time; kiln-forming air entrapment has several efficiency benefits. The need for reheating is removed, as all layers are fired together in a stack. Air entrapment bubbles become formed during the process of a single kiln firing and multiple layers are fired simultaneously. Although the length of a firing can be several days, depending on the volume of glass, the process happens within the kiln whilst the artist can be working on other projects. This makes the process accessible to a single studio artist to articulate ideas, and to be able to experiment un-aided, reducing the cost of developing new work.

The main potential problem of the investigation was that a replicable process for air entrapment in the kiln could be elusive, however the evidence suggested that if a means of controlling sophisticated air entrapment using glassblowing techniques existed (in which glass temperature and distortion are more difficult to control), then the combination of kiln forming, with advanced digitised temperature control, the precision of float glass manufacture, and the accuracy of the waterjet cut, would be a better prospect for controlling air entrapment in a replicable way. In theory, if the variables could be minimized and controlled as precisely as possible, and the behaviour of the air within the glass when heated understood, through systematic testing and adequate access to kilns; then a method for controlled, intricate, repeatable and transferable air entrapment in kiln-forming would be discovered.

The outcomes of the investigation allowed the creation of original air entrapment artworks of a significantly different scope and format than the *Ariel* designs of the 20th Century and all air entrapment work produced since then.

4.3 Why It Is Important That The Research is Addressed

Advancement in knowledge in the applied arts is often via gradual improvements in personal technique and artistry. This develops through habitual and original methods, becoming *tacit* knowledge: ‘a thousand little everyday moves that add up in sum to a practice’ (Sennet, 2008, p.77); expertise is therefore personal and implicit. In contemporary glass in the UK today, whilst some established studios employ assistants or apprentices, glassmakers are usually self-employed, like the large majority of practitioners within the applied art/ craft sector (Yair, 2012, p.2).

It is important that new techniques and procedures in glass, developed by individual exponents, are documented and disseminated in order to continue the advancement of the discipline. Innovation in contemporary glass tends to be individual, artist-led, undertaken by makers within their own practice. In academia however, an increasing number of individual makers are engaging in practice-based research, leading to technical and critical developments in glass art being more regularly documented in theses. Access to practice-based theses is opening up previously unstated knowledge, for further innovation to build on.

Cummings (2009) describes how complex kiln-forming procedures and technical expertise had led to iconic works being developed in the19th Century by artists such as Decorchement, Argy-Rousseau and Walter. They served as testament to what could be achieved in glass, but knowledge of their specialist processes had died out by the 1950s. However, their glass inspired a new generation of glass artists and the pate-de-verre methods used in the works were ‘painstakingly rediscovered…and continue to inspire and inform contemporary practice’ (Cummings, 2009, p.15).

This research identifies the Swedish factory glassblowing technique *Ariel* as one of the hitherto most innovative, technologically advanced, and imitated, methods of air entrapment. Due to its international commercial success and transformative influence on the applied arts sector worldwide, its history and aesthetics have been well documented via literature. (The impact of Ariel and Swedish Glass is discussed in the Contextual Review.) However, if not for the deconstruction and dissemination of the Ariel *method* transcribed in the research of Flavell (2001) it would have been difficult to source any written knowledge of the technical process itself. Academic research and documentation in the practice-based creative fields allows practical, verbal and tacit knowledge to be documented and disseminated.

The application of existing documented knowledge (Ariel literature and Flavell's research), and practice-based tacit knowledge (the researcher's prior kiln-forming, cold working, hot glass and CAD experience), plus new exploration and learning (waterjet cutting and programming) in a research environment in which technical experimentation and progression could be made, created the opportunity for innovation in this research. Advancements in technical know-how, when combined with artistic intent, extend processes, which can allow the physical parameters of an object to make a significant shift.

Undertaking this research in the university environment opened up access to digital technology, particularly the waterjet, for intense experimentation at a level that has been unattainable to the individual glassmaker accessing waterjet technology commercially. New and emerging ways for individuals to access digital technologies are beginning to engender change in creative practice. The discoveries made in this research have founded new methods of practice for air entrapment in glass, which are applied to artworks and evaluated and documented in this thesis for dissemination in the sector, creating further opportunities for individuals to innovate.

The research and body of artwork adds to the archive of technical knowledge and creative development in kiln formed glass, extending the possibilities for glass art practice.

4.4 Audience

The PhD research has multiple audiences. The technical research is pertinent to those in the field of glassmaking: designers, historians, artists and practitioners interested in new glass processes. The new artworks introduced through the findings of this thesis will be of interest to galleries and collectors.

Sector interest in the subject of air entrapment in the fields of glassmaking, applied art history and glass collecting is evidenced through the information collated in the Contextual Review. This includes the commercial success and critical acclaim of previous innovations in air entrapment, such as Orrefors' *Ariel* technique. The numerous contemporary artists who currently use air entrapment techniques in their work are testament to its appeal as a technique.

The peer interest in the technical development through the course of the research process and positive response to the artworks through exhibition demonstrated that the research had an audience that included practitioners, galleries, collectors and the general public. This thesis is a resource for academics and doctoral researchers as the only contextual review of the field which draws together current and new knowledge on air entrapment in glass. It adds to precedents for research into practice-based methodologies in glass; and expands on research in contemporary fused glass. In particular, it adds significantly to literature on kiln forming layered float glass.

In addition, those within the fields of glass, craft, applied art and sculpture, galleries and retailers, periodicals and journals, enthusiasts, collectors and curators are important audiences for the body of artwork resulting from the inquiry. In the final year of this research, images of artworks from the final body of work were selected for the Corning Museum of Glass Publication New Glass Review, a juried worldwide review of contemporary glass from which 100 important works in glass are chosen. All images submitted to the review are retained in the museum's Rakow Research Library.

This is an excerpt from Juror Angus Powers' 2015 Jury Statement explaining the reasons for his choices.

> *For me, scale, simplicity, and technology (both in making and in content) are intriguing ideas that I respond to over and over. I selected Joanne Mitchell's* Figures within Space *because of its playful and haunting look at our relationship with architecture.*
>
> (Powers, 2015, p71)

Pieces from the body of artwork were acquired for museum collections: *Legion* (2015) by the Shanghai Museum of Glass for its Art Collection, and *Memory Echo* (2014) by the Alexander Tutsek-Stiftung Foundation, a German organisation founded to promote art and science.

5. The Methodology

This chapter defines the modes of inquiry used to conduct the research and explains the rationale behind the research methodology. In order for the research to contribute to knowledge and understanding within the practice-based research field the processes, insights and practices are explored, analysed, critiqued and documented. The approach to the technical inquiry is described and the context and parameters of the exploration set. The investigation is situated in relation to wider precedents in research in the arts, and discussed with reference to emergent frameworks within creative practice-based research. Technical terms are defined in the Glossary, Appendix1.II

The bounds of the research were of the experimental approach of a practitioner conducting material enquiry driven by artistic concerns. The investigation used a multi-method approach, which evolved symbiotically through the process of inquiry, drawing on scientific methods of systematic testing and rational analysis; and artistic practices of observation, reflection and intuitive response where appropriate. As Newbury asserted of creative research, such a method is 'not to suggest a linear relationship between ideas and evidence. It is, rather, dialogical.' (Newbury, in Biggs & Karllson, 2010, p.639). The ongoing transaction of technical and creative outcomes, evaluation and propositions formulated a working methodology through which the aims and objectives of the research could be fulfilled.

The technical inquiry began with a 'quasi-experimental' structure (Pollock, 2013), based on speculative testing, trial and error, using initial premises drawn from tacit knowledge of practice-based glassmaking to create kiln-formed air entrapment. The criteria for measuring successful control of air voids, including integrity of imagery and lettering was determined. The aim was to explore various methods to create and control air bubble-entrapment in the kiln.

The transfer of theoretical and practical principles from the Ariel glassblowing technique to kiln forming left numerous unresolved problems and variables to overcome in the application of the research objectives. The inductive investigation began based on the theory of ‘establishing adjacency’; thinking about what two different domains or technologies might share (Sennett, 2008). A ‘scatter-gun’ approach was initially taken in order to explore many variables in a short space of time. Wide ranging exploratory tests became narrowed and more focused as observations could be drawn from the results.

Sennett states that this type of cumulative process is a form of reasoning - not a deductive sort, but an imaginative leap constituting a ‘special form of induction’ (Sennett, 2008, p213). After ‘reformatting’, Sennett describes the process as bringing tacit knowledge into consciousness to make comparison, followed by recognition that unresolved problems *remain* unresolved in the transfer of skills and practices (Sennett, 2008, p211). This might, in a computing context, be called a 'neural network' approach, as opposed to an ordered deductive study (Gelder, 2015).

Tacit knowledge from previous practice in both areas was applied, and used abductive reasoning to take forward the most likely hypothesis as a starting point, based on experience, observation, and educated guesswork. Whilst imprecise, the technique provided new insights, in order to generate the basis for an introductory hypothesis for creative air entrapment in the kiln. The research methodology draws parallels with Newbury’s description of research as ‘the work of assembling ideas and evidence and bringing them into a productive relationship.’ As Newbury states (in Biggs & Karllson, 2010), the hypotheses and outcomes are formed via the intertwining of technical knowledge and creative learning.

The practice of sketching, modelling, making and reflecting upon the three-dimensional object informed the emergent content underpinning the artworks during the period of extensive technical inquiry. Development of an idea was followed by evaluation and critical reflection. Written and photographic documentation of the making and testing process, as well as a visual diary and ongoing note-taking, concept mapping and discussion were part of the process of reflective critical thinking through practice.

The outcomes of the initial tests were evaluated against a predetermined definition of ‘successful’ air entrapment to generate information on which to base a more structured technical investigation. Akin to this research structure, Pollock (2013) developed a new technique for kiln forming for application in creative practice (in his case casting thin-shell and higher-aspect ratio glass vessels.) Industrial processes were also modified or ‘blended’ with more traditional glassmaking methods, in order to create new techniques and reach possible extensions to artistic forms in glass (Pollock, 2013, p.70).

Pollock described his practical studio experimentation as employing both ‘quasi-experimental’ and ‘true experimental’ methods (Pollock, 2013, p27) defining *quasi-experimental* as when not all variables in an experiment have been (or could be) controlled. *True experimental* is characterised as when all known variables have been reasonably controlled, except the one under investigation.

A similar quasi-experimental approach was undertaken in the initial testing phase of this research, at a time when not all of the potential variables were either known, or their impact on the air entrapment understood. Experiments were employed in order to generate data for observation and reflection, so that relationships between variables could be established and theories formed (Collins, 2010 p.42-3).

The preliminary experiments brought forward new testing propositions, and the testing conditions and variables could then be narrowed sufficiently to begin a more refined, systematic enquiry. Once the testing field was narrowed down, a more scientific, ‘true experimental’ procedure was followed, in order to present or disprove emerging theories. The inquiry became gradually more hypothetic-deductive in structure in a step-by step approach, as more became known about which variables impacted on the test outcomes.

An empirical system consisting of evidence-based testing and analysis, interpretation of data, refinement of the experiment and re-testing, was then applied, using a quantitative methodology. Collation of data in the form of photographs and technical test logs and analysis was used (disseminated in The Technical Inquiry, Chapter 6).

In addition, technical data from glass manufacturers and technologists

(Pilkington, Pearsons, Bullseye, System 96, Kiln Care) was gathered and reviewed to inform the investigation. Material science engineer Eric Mitchell and former Pilkington mathematician David Gelder were consulted on aspects of the technical investigation to aid evaluation and analysis of the research data and testing outcomes.

In this research, the application of the research outcomes from the technical inquiry to artistic practice were essential to answer the second and third research questions, and to position the research in the field it initiated, that of Glass Art. This transformation is deconstructed and evaluated and the creative development of the final body of artworks documented in Chapter 8, *Creative Possibilities.*

The body of artwork demonstrates the successful application of a new technical process, and represents the integration of that process into a mode of practice, instigated and developed for the purpose of creating new forms of glass artwork (in order to answer research objectives 1 and 4).

5.1 Structuring the Inquiry

The inquiry was structured according to the requirements of the research aims, and methods chosen according to their relevance to the specific avenue of investigation. The research was necessarily creative practice-based and the study practice-led, and therefore set within the context of the glass studio environment.

The investigations were undertaken with the aim of providing data to make generalisations to bring about an answer to technical ends, specified in advance: How trapped air can be formed and controlled using the kiln to create recognisable lettering and imagery? The limitations of the research period and the university studio environment meant that it was unfeasible to test for all possible scenarios and allow every variable to be precisely controlled and measured, however testing routes were designed in order to generate the most informative outcomes within the available facilities and timescale.

The research structure predominantly appropriated the scientific method of inductive reasoning; using experimentation designed to make connections and induce propositions or probable outcomes based on qualitative observation. Once a testing route generated sufficient data, from which propositions could be drawn, a deductive approach for testing particular variables was applied in order to test hypotheses and disprove assumptions.

The technical inquiry was based on eliminating variables, subjecting a group of hypotheses to a test. However, where an experiment does not follow a prediction, what is learned, as Duhem (1906) asserts, is that: ‘at least one of the hypotheses constituting this group is unacceptable and ought to be modified; but the experiment does not designate which one should be changed’ *(*Duhem, 1906, p.187).

The methodologies for answering the research question ultimately depended on how to best address the goals set by the question:

- *How can trapped air voids be controlled using the kiln to create recognisable lettering and imagery?*

The deductive approach begins with creating a testing structure by defining the parameters of a hypothesis and limiting potential variables. The deductive approach used, as described by Collins (2010) involved:

- Identifying a testable proposition, which details the relationship between two concepts or variables, *(for example: 'the tin coating on float glass is the cause of the air pooling problem').*

- Indicating how the concepts or variables can be measured (*for example: by testing similar samples in float glass (tin-coating) and Spectrum glass (no-tin)*

- Testing this proposition *(for example: to ascertain whether the air pooling problem also occurs in the Spectrum samples.)*

- Studying the outcome of the research, which will confirm the theory or establish how the proposition needs to be modified (*for example: air pooling occurred in both the tin and non-tin samples, disproving that the tin coating is the cause of air pooling. Test an alternative variable.)*

- If necessary, modifying the proposition and then repeating the process

- Generalisation

To begin to answer the research question, the limitations and definitions within the question had to be addressed: What are the expectations of the terms 'recognisable lettering and imagery'? What potential methods of trapping and controlling air voids could be tested? What type of glass and what type of kiln would be best used? These questions are addressed in section 5.2, The Parameters of the Technical Investigation.

An empirical framework for the technical investigation into *control* of air in glass was thus employed, with a strategy based on experimental investigation, inductive reasoning and evidence-based data analysis. This experimental method was used to explore the various potential hypotheses for the success and failure of air entrapment in the kiln, working in a structured step-by-step manner to generate data and eliminate variables. This formalised structure was the means by which a process for kiln-controlled air entrapment was achieved. Following this, a generalised theory was formed for a series of methods of air entrapment with repeatable results, and subsequently a rationale for transferring the procedure between various kilns was developed.

Diversifying the scale and form of the air entrapment and the glass forms themselves required new hypotheses and further systematic testing to account for the new changes in variables, using the process of testing and analysis as described in the diagram below. The generation of a series of techniques and a method of practice that could be adapted for various studio situations was then developed using this approach, resulting in the series of techniques collectively titled *Kiln-Controlled Precision Air Entrapment*.

Literature on arts and design research has been influential in understanding the context of the contribution to knowledge within the creative research field, such as Morwenna Griffiths discussion on ‘Research and The Self’ (Biggs & Karllson, 2010 p.169), which outlines of the stages of the ‘arts-based, practice-based’ research process.

Grounded in practice-based arts research *and* technical enquiry, parallels in the overall methodology used in this research project can be drawn between both qualitative, practice-based research structures in teaching, social work and psychology, and those of quantitative, evidence-based research methods used in engineering and science. Indeed many of the components of the structures described by Newby and Griffiths can be applied to the methodology within this research. The differences are not necessarily in the basic *structure or logic* of investigation, but rather in the expectations and context of the enquiry and the methods of *evaluating* the ‘data’ in order to document the development of knowledge and understanding.

***Arts Practice-Based Structure* - Griffiths (Biggs & Karllson 2010):**	**Common Methods:**	***The Deductive approach* - Collins (2010):**
1. Focus; *2. Rationale;* *3. Method or intervention; (including artistic processes or productions* *4. Data collection or collation;* *5. Analysis, Theorizing and argument;* *6. Outcomes** **'these may be in the form of conclusions and/or insights and/or questions.'* *7. Presentation and dissemination*** ***'the form of presentation and dissemination varies with the purpose of the research and with the intended audience. For instance it may be published, presented, performed or exhibited.'*	1. Focus/ question, 2. Rationale/ hypothesis, 3. Intervention/ testing, 4. Observation/ data collection, 5. Analysis/ theorising, 6. Result/ outcomes, 7. Articulation/ dissemination.	*1. Writing a testable proposition, which details the relationship between two concepts or variables;* *2. Indicating how the concepts or variables can be measured;* *3. Testing this proposition;* *4. Studying the outcome of the research, which will confirm the theory or establish how the proposition needs to be modified;* *5. If necessary, modifying the proposition and then repeating the process;* *6. Generalisation*

Above: *Table showing common methods (middle box) used in both qualitative, practice-based structures (left) and a quantitative, evidence-based methodology (right).*

So, how to critically analyse the investigation? One view is that hypothesis-testing experiment is only one of *several kinds* of experiment, each with its own logic and criteria of success and failure (Schön, 1983). Schön conceives additional types of experiment: *exploratory experiment:* action which is undertaken only to see what follows, without accompanying predictions or expectations, which succeeds when it leads to the discovery of something; and *move-testing experiment:* in which action is taken in order to produce an intended change, however an outcome may be intended or not, resulting in affirmation or negation of the move. *Hypothesis testing* is described as succeeding when it effects a predicted consequence: confirming the hypothesis and disconfirming conflicting hypotheses (Schön, 1983, p145).

The technical approach is also cyclical and based on experimentation as a means to an ends. This included *move-testing experiment* initially (induction), followed by *hypothesis testing* as the variables were narrowed (deduction) and predictions formed and tested (observation) to form generalisations to then re-test (hypothesis). Schön's acknowledgement of different paradigms of testing and evaluation for different types of enquiry are particularly relevant to this practice-based study in glass, and Schön's interpretations of exploratory and move-testing experimentation were used in both the inductive technical tests and the artistic development, alongside hypothesis testing in the technical inquiry.

Pollock (2013) used the empirical determination process of 'cause and effect', carried out by the sequential approach of hypothesis, experiment and observation/evaluation (Pollock, 2013, p24). The structure of his thesis was particularly influential in considering effective ways to present a scientific and practice-based methodology with technical findings, with the development of artworks as part of the research. Employing both an experimental and 'quasi-experimental' approach, Pollock described this as 'predominantly carried out by practical studio experimentation – using both qualitative evaluation and quantitative deduction… centred on creative practice rather than science' (Pollock, 2013, p.24). Similarly, in this research scientific approaches were used where necessary to structure the investigation.

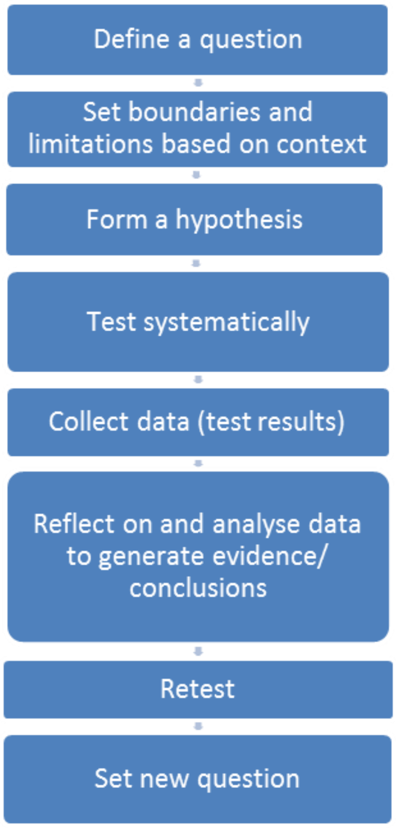


Figure 71: Methodology structure used in technical investigation

5.2 The Parameters of the Technical Investigation

A review and evaluation of existing methods of creating air entrapment and controlling bubbles in glass was undertaken to define expectations of quality for 'recognisable lettering and imagery'. The benchmark for air entrapment in the kiln was to achieve a level of sophistication and control comparable to the *Ariel* technique in its air-entrapped form and imagery (see Contextual Review).

In order to apply air entrapment to glass in the kiln, the research introduced several new elements to the principles behind *Ariel.* These elements were: the material float glass sheet in place of furnace glass; the electric kiln and controller as the heating equipment, in place of the glory hole (see Glossary1.II); CAD/CAM technology in place of hand drawing and the waterjet cutter as the abrasive tool as in place of/ as well as the sandblaster or cutting wheel.

'Successful' air entrapment was defined as the trapped air filling the intended design within the distinct boundaries of the cut-out, channel or pocket, with no air escape or unintended 'air pooling' (see Glossary) between the layers of glass and the cut contour. Initial images and lettering were based on speculative creative ideas.

<u>Benchmark for successful testing:</u>

- Intended imagery and text recognisable and well defined.
- Minimal 'interference' or air escape/pooling in design.

<u>When test is deemed unsuccessful:</u>

- Design compromised by air escaping and pooling outside of the design boundaries
- Design compromised by interference to the glass clarity (e.g.by excess air, debris, numerous bubbles).

Figure 72: Successful air entrapment (left), unsuccessful air entrapment with escaped 'air pooling' (right). Waterjet cut text.

'Softening' of the form would be acceptable to the extent that the intended form was easily recognisable with no concession to the integrity of the design or interference to the clarity of the glass surrounding the boundaries of the cut-out design. Negligible distortion in the sense of a natural 'rounding off' for forms was acceptable.

Three different methods of abrading and cutting the glass were identified by the researcher as appropriate to carve deep air channels into float glass sheet: waterjet machine cutting as a new method, diamond wheel hand-cutting (previously used in the pre-research furnace glass and float glass air entrapment tests) and deep sandblasting (the method used in *Ariel*).

The waterjet machine was chosen for the investigation because it made repeated and multiple cut-out contours more viable in terms of the time, accuracy and physical exertion needed to execute a design, when compared to sandblasting. Outer contours could also be cut on the waterjet which were impossible to cut by hand: a design that would take hours to sandblast could be produced in minutes, and repeated in multiples, once programmed into the waterjet console. This expanded the possibilities for the form of the artworks.

Figure 73: Waterjet and sandblasted exploratory work using text (left); repeated waterjet cut-out fused figure tests (right).

The method for trapping and controlling air voids was identified as the process of layering or ‘sandwiching’ abraded or cut-out sheets of glass between uncut layers, and heating them in a kiln until they fuse together. The air becomes trapped, and sealed in the internal cut-out shapes, forming an air entrapment, or bubble, in the void space. The resulting form of the air entrapment could be controlled and varied by the amount of heat applied to the glass in the kiln via the firing programme.

Float glass was identified as the preferred choice of sheet glass for the investigation; however other glasses were also included to draw comparisons (the choice of glass is discussed fully in Chapter 3.4) It was also intended that subtle colour would be used in the artworks, leading to further questioning: Could combinations of blue, bronze and grey tinted, low iron Optiwhite and standard Pilkington float glasses be used together within an artwork? Would compatibility change, how would scaling up affect the outcomes? To test this compatibility tests were undertaken by experimenting with firings of the various glasses. Firings of ‘fusible glasses’ such as Bullseye and System 96 were also undertaken to draw visual comparisons, the results are discussed in Chapter 6.

Initially the choice of kiln was dictated by the available access to glass kilns in the Glass & Ceramics department. As the investigation developed and the analysis required more structured testing routes, a particular kiln, K19: a 3-phase Kilncare 9KW toploader with FK4 thermocouple and IPCO 3300 controller was identified as the research fusing kiln.

Once the investigation reached the stage at which methods could be transferred between kilns, various Kilncare casting kilns were used. These are identified according to specific tests in the Technical Inquiry.

Figure 74: Left: Toploader Kilncare Kiln (K19) identified for tests controlling variables; Right: Kilncare casting kiln used for transfer of the technique to alternative kilns for new artworks.

This thesis does not attempt to find a scientific formula for all shapes and volumes of air entrapment for any conceivable artwork. The variables within those parameters are too great and are beyond the scope of this enquiry. The investigation is undertaken within the bounds of the facilities, access to equipment and time limitations available to the researcher in a University Glass and Ceramics environment, and technical interpretation with help from material scientists. It documents outcomes which have been found to be repeatable and thus generalizable within the testing framework of a small number of regularly used kilns which are comparable to those often used by glass artists in a practice-based studio context, thus offering a transferable methodology and adaptable series of new techniques and data for others working in glass.

6. The Technical Inquiry

This chapter relates to the objectives:

- *Investigate how 'Ariel' can be developed using the kiln, as a means of expanding the technique for the purpose of creating artworks beyond the blown vessel or spheroid form.*
- *Develop new combinations of digital processes, glass techniques and kiln-forming technology to extend methods of controlling air in glass in the kiln.*
- *Create new configurations of air entrapment by investigating float glass, increased depth and quantity of layers, scale, contour complexity, and three-dimensionally contoured air entrapments.*
- *Record and disseminate replicable methods of practice which add to the creative vocabulary of the artist working with glass.*

The Technical Inquiry is explained in a predominantly chronological order where possible to explain the pattern of thinking generated by step-by step testing and analysis of various routes of action. The hypotheses, testing procedures and outcomes are discussed and evaluated. Tests were often undertaken in parallel, leading to divergent avenues, and thus the documented order of the testing routes is not always linear. Conclusions were drawn once a series of tests were completed and evaluated.

6.1 Stage 1: Exploratory Pilot Tests

Pilot tests investigated and evaluated methods of mark making to surface abrade the glass to create voids for the pockets of air to form. Various methods were used; such as sandblasting using plotted vinyl and UV exposed resists, waterjet cutting, freehand diamond wheel cutting and combinations of these methods; with various thicknesses of float glass, and other glasses available to hand.

Figure 75: Inductive testing: Initial comparative pilot tests in (left) wheel-cut clear Spectrum S96, creating a triple dot effect; and (right and far right) sandblasted and wheel-cut tests in enamel-flashed float glass and Pilkington float.

Figure 76: Inductive air entrapment exploration combining sandblasted, enamel-flashed and waterjet cut channels in a single piece to compare results.

The diamond-wheel cutting technique of mark-making was tested, a method of abrasion that the researcher had acquired a certain level of familiarity and skill with through previous practice. Whilst the abrasions were successful in trapping air in the exploratory firings, the diamond wheels allowed only limited motifs which had a fairly crude appearance when compared to the accuracy of waterjet-cut contours or sandblasted imagery, and the size of sheet glass that could be physically held up to the cutting wheel safely for the time needed to create adequate channel depths was constrained to small sheets.

Figure 77: Diamond wheel-cut 'wings' air entrapment, wheel cut by hand onto standard 10mm float glass, topped with 10mm float glass and fused. Some air pooling is visible in the top left corner.

Sandblasting offered a route to relatively more sophisticated air channels. In conventional sandblasting for *Ariel*, a resist such as masking tape or vinyl is used, with the design drawn onto the surface and cut through by hand with a scalpel before sandblasting. This research expands on the techniques used by Flavell (2001) in the use of digitally generated sandblasting masks. Imagery was digitally scanned and designs were developed in Adobe Photoshop which combined computer font text and scanned handwriting.

A process similar to screen printing was used to create sandblast resists, whereby high quality UV-sensitive self-adhesive film was exposed under the printed image in a UV light exposure unit. APM Plus Photoresist film, a sandblasting film which has strong blast resistance, for deep abrasion, was used. The resist film was then washed out with water to reveal the image, dried, applied to the glass and sandblasted. This digital technique allowed for more intricate detail in the design as well as the application of imagery direct from a digital scan, or jpeg image.

Figure 78: Initial air entrapment exploratory artwork with sandblasted text (taken from scanned handwriting) using UV-exposed photosensitive resists.

Text was used as a measurable motif to ascertain the success of the air entrapment through its legibility. Exploratory samples were produced, using available float glass sheet and some coloured enamel flashed float glass, with satisfactory initial results showing good air entrapment bubble formation.

Sandblasted text was used as a comparative process to waterjet in the initial technical testing in order to compare and analyse variables. In later pieces where thinly layered glass and fine detail is important in the artwork, sandblasting was used for its specific properties (as in the postcard piece *Memory Echo),* as only two sheets of glass were required to sandwich the sandblasted air channel, as opposed to three needed when using waterjet cut-outs*.* Text and imagery in the final artworks *Memory Echo* and *Secret Diary* employ the sandblasting technique (see Chapter 8.1).

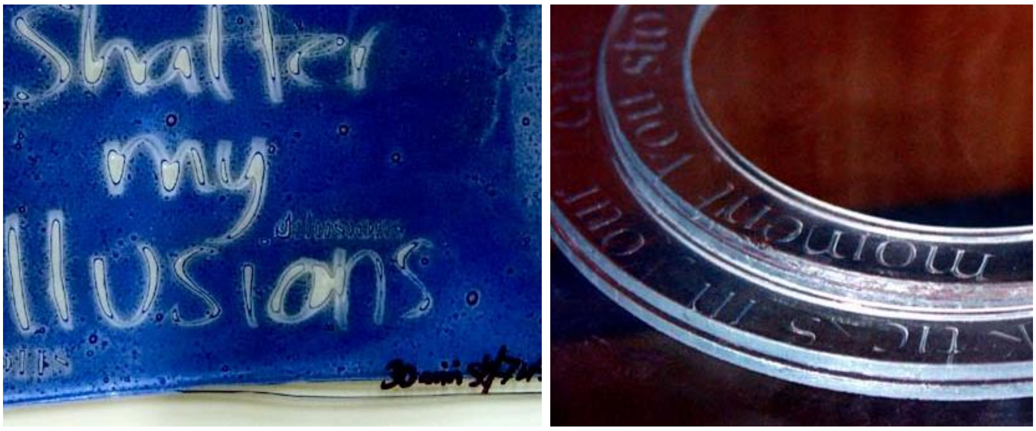


Figure 79: Exploratory samples with sandblasted text using UV-exposed photosensitive resists. Left: Fused enamel ‘flashed’ float glass topped with float glass; right: float glass layers.

Waterjet cutting was selected as the principal method of creating the air entrapment designs due to the accuracy, possible design complexity and scale potential of the cut-out channels. Training on the waterjet machine and the programming software LANTEK (and later the upgraded version, IGEMS), was undertaken, so that waterjet-cut air entrapment channels could be investigated.

The researcher’s previous knowledge of AutoCAD design software (learnt during the Edinburgh Crystal Scholarship), meant that shapes could be drawn quickly in AutoCAD and converted into the waterjet’s LANTEK software, which encoded them into a CNC cutting file. Programmes saved as .dwg and .dxf files are importable into the waterjet software. Adobe Illustrator was also learnt as a method of transferring text from a .dxf file into the waterjet software.

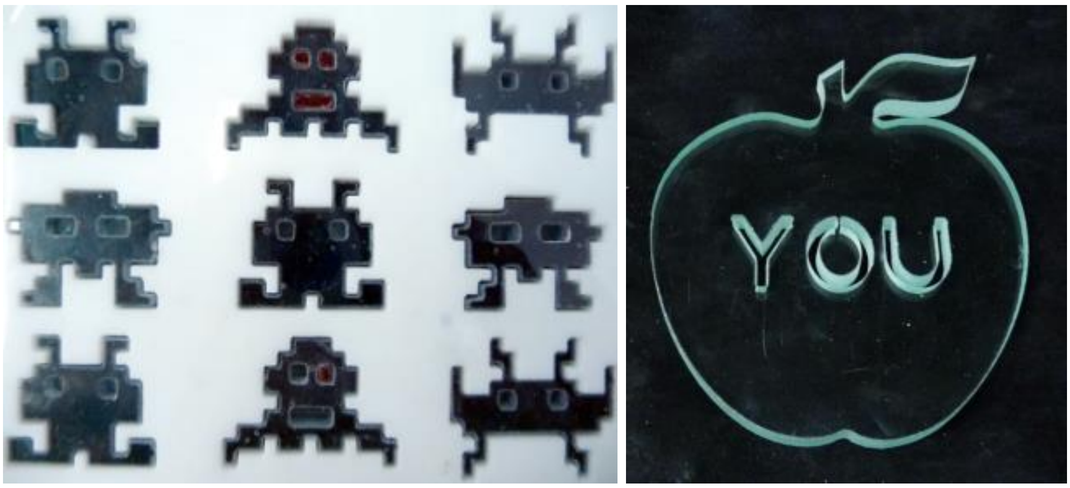


Figure 80: Exploratory work for waterjet cut inner and outer forms and different glasses: Bullseye and 10mm float glass

Figure 81: Forms and text designed on AutoCAD and Adobe Illustrator software and cut following training on the waterjet. Left to right: 10mm safety glass and standard 10mm float

Various design ideas for the air entrapment cut-outs were waterjet cut from sheets of float glass and fusible glasses of various thicknesses. To form the air entrapment bubble, the cut-out sheet was sandwiched between blank sheets of the same type of glass, placed in a kiln and heated to fuse the layers, with the intention of trapping air in the cut-out channels, to form controlled bubbles.

A particular benefit of using the waterjet machine for the cut-out channels was that it allowed for a high level of consistency for testing, in terms of depth of cut. When sandblasting or wheel-cutting by hand, the depth of abrasion is a variable that is difficult to keep constant. Float glass sheet, cut on the waterjet, gave control of the depth of the carved abrasions by cutting voids *out*, rather than carving them *into* the glass surface.

Whilst the waterjet can also be used to pierce and abrade glass, cutting *through* the sheet ensured that the depth of the channel always remained equal to the glass thickness. So for example, cutting through a 4mm float glass sheet would give a cut-out channel of a consistent depth of 4mm, with the cut width accurate to a tolerance of 0.35mm.

A waterjet-cut test tile could be re-produced repeatedly and relatively quickly so that test firings could be compared with a degree of accuracy and repetition not possible in conventional sandblasted *Ariel* air entrapment. This method also had the benefit of potential for air entrapment of a much larger scale, only limited in glass sheet size by the available kilns and the area of the waterjet bed, at 175cm x 315cm.

Creating air channels in this way on the waterjet made the channels much deeper than in the other methods: 4mm cut-outs in standard float sheet as opposed to an approximate 1mm depth of cut for abraded sandblasted and wheel cut air channels. This meant that a greater volume of air had to be controlled, and initial tests had limited success in comparison to the sandblasted and wheel cut samples, signifying that air volume/ channel depth was a significant variable in the testing.

Figure 82: Unsuccessful waterjet cut fused tests. Left: stacked10mm float glass layers with ‘air pooling’ in all layers, no bubble formation; Right: no bubble formation, distortion of text and ‘air pooling’.

It was reasoned that the schedule previously used in the researcher’s practice to fuse float glass layers of the same type and similar thickness, and in a similar kiln (Kilncare toploader kiln) that would be used for the research, would be a rational starting point, as diamond wheel-cut air entrapment had been successfully created in the *Chino* designs (see Chapter 2). Pilkington float glass was the preferred choice for both its clarity and economical cost, and previous experience with the material.

The firing schedule used the annealing temperature of 548C, based on Pilkington’s published technical data for standard float glass. Compatibility tests for Pilkington tinted float glass, as a more transparent alternative to flashed float glass, to add colour and tone into the designs, were undertaken.

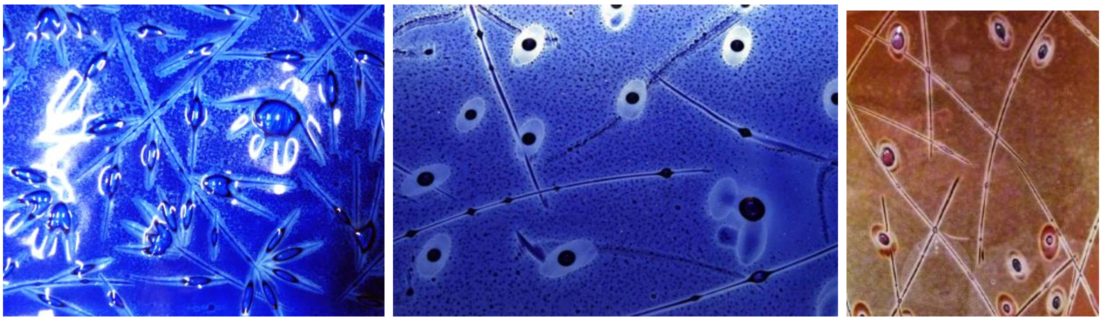


Figure 83: Detail of the researcher’s previous kiln-formed wall panel work. Incised wheel-cut pockets in 4mm float glass, fused with 2mm coloured enamel flashed float glass in cobalt blue and red/brown showing bubble formation.

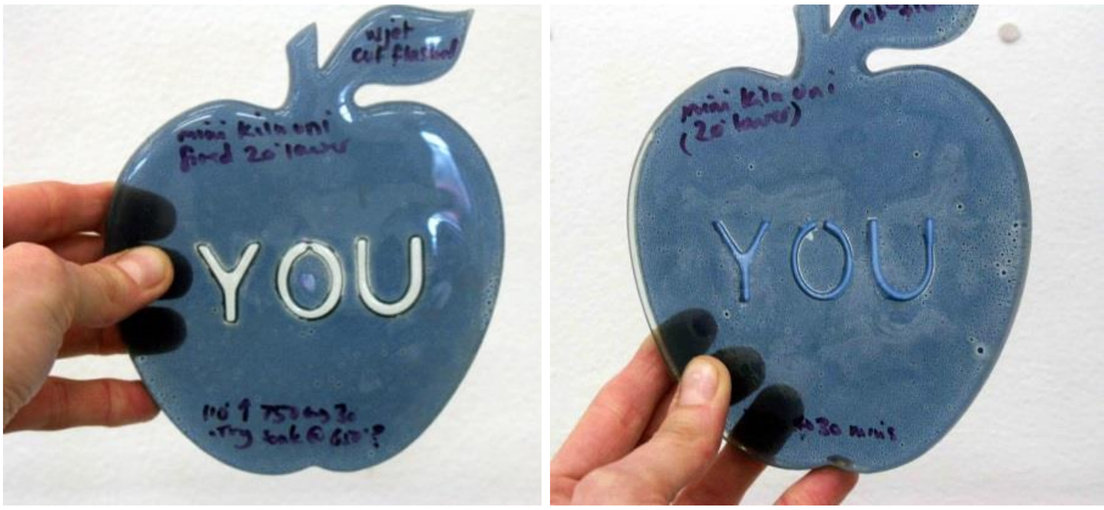


Figure 84: Exploratory testing investigating the effect of waterjet cut-outs with enamel-flashed glass. Left: channels are cut through the enamel-flashed glass; Right: channels cut through float glass, with enamel flashed glass beneath.

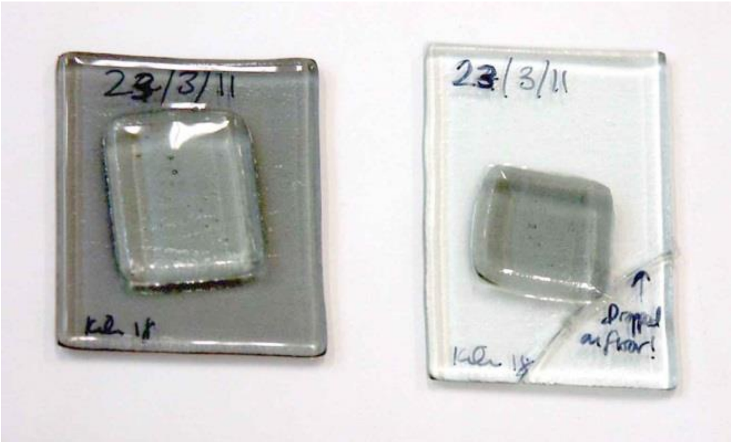


Figure 85: Compatibility chip tests using Pilkingtons grey tinted and standard float glass (4mm).

Alternative methods of generating air bubbles were also investigated to prompt any potential new data. The effect of trapped silicon carbide grit on bubble generation was tested, based on *Ariel’s* related technique, *Mykene* (see Contextual Review for images of Mykene vessels). Interestingly, the carborundum created a reaction with the enamel-flashed float glass, causing random formations of air bubbles which did not occur in the plain float.

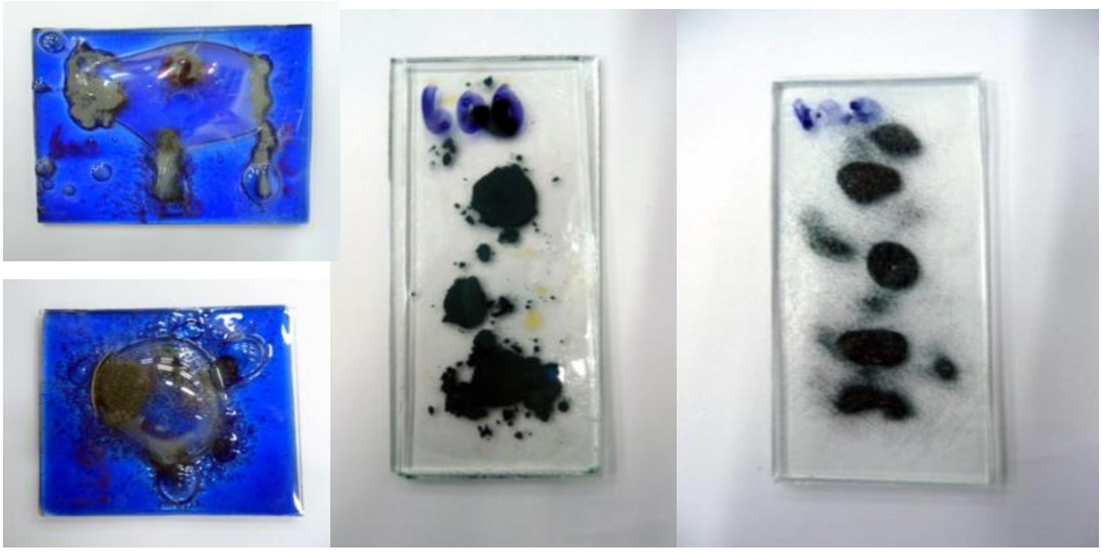


Figure 86: Exploratory approaches: inductive testing based on the principle of the Ariel–related 'Mykene' process: various grades of silicon carbide fused between glass layers to produce trapped gas bubbles.

Samples were fired in mixed groups at various temperatures to determine whether a specific sample emerged with successful air entrapment. Some air entrapment tests fired more successfully than others. It was apparent that the schedule for 4 and 6mm layers was not successful in 10mm layers. The 10mm cut-outs were all unsuccessful; it was proposed that the volume of air this depth of cut-out was adversely affecting the fuse, so 10mm layers were abandoned in favour of shallower cut-outs of 2mm, 4mm and 6mm layers.

Figure 87: Sandblasted and silicon carbide tests, plain float and 'flashed' float show successful air entrapment in finely sandblasted text channels

After firing, some designs showed an unwanted effect described in this research as *'air pooling'* (see Glossary).

Figure 88: 4mm tinted grey float – successful sandblasted air- entrapment text (left and middle); right: larger scale unsuccessful air entrapment with extensive ‘air pooling’ and lack of bubble formation, fired to same schedule.

Increasing the scale of the design seemed to adversely affect the success of air entrapment (see above). Multiple layers and glass thicknesses were tested using the sandblasting method with differing effects. The sample below showed air pooling in the central layers but successful air entrapment in surface layers. This suggested that layer quantity and potentially heat penetration was a variable which affected the success of the air entrapment and was a factor in the ‘air pooling’ issue.

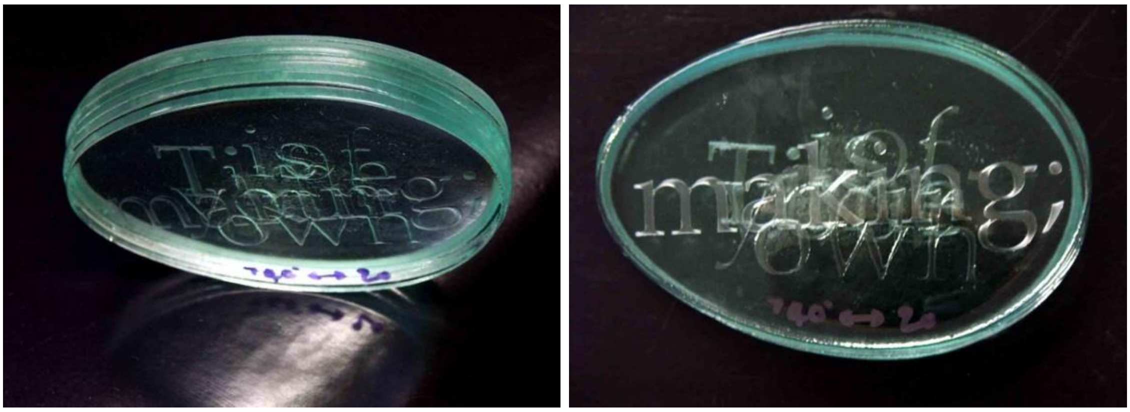


Figure 89: Test sample using sandblasting and multiple layers of 4mm float glass, fired to a low fuse temperature to retain shape (740C).

The properties of float glass generated another set of challenges to the investigation. As it is manufactured for the glazing industry, not specifically for re-melting, in comparison to ‘fusible’ glasses little published data or advice was available to the researcher to access on best practice with float glass in kiln forming. Possible stress and compatibility issues due to air being introduced into the glass were an additional factor to be considered. As such, an area it was deemed this research should address, in order to expand available information for future kiln-forming float glass use.

Firing float glass can cause the surface effect *tin bloom* (an unattractive residue on the glass surface caused by tiny particles on the surface) and the potential effect of this on the tests was unknown. Float glass is also prone to the surface 'fogging' effect of devitrification (see Glossary), when fired. Anecdotal advice and previous experience of fusing with float glass were used for the avoidance of surface devitrification and tin-bloom in general fusing, but it was unknown how this might affect the adhesion of the layers when air channels were introduced.

To minimise tin bloom in decorative fusing, accepted wisdom is for the 'tin' side of the glass to be placed down, a procedure followed by the researcher in previous practice. This was continued in the testing, and for multiple layers, all surfaces were initially fired tin side down. The tin side was tested using a UV tin tester for glass. Additionally a rapid period known as a crash cool (fast as possible temperature drop) from the top fuse temperature to just above the annealing temperature was incorporated into the firing schedule as an aid to minimize devitrification. These additional variables had to be taken into consideration in the testing, however finding out *which* variable was affecting the air entrapment meant that many individual testing routes had to be taken.

The technical challenges that the numerous variables brought into the research formed a substantial and intensive proportion of testing and investigation in the research period; alongside which, the artistic exploration took place. The pilot tests gave a broad range of inductive data from which an indication of significant variables could be drawn as routes for further testing and actions to be taken in order to narrow the testing field.

6.1.1 **Evaluation of Pilot Tests and Determining Testing Structure**

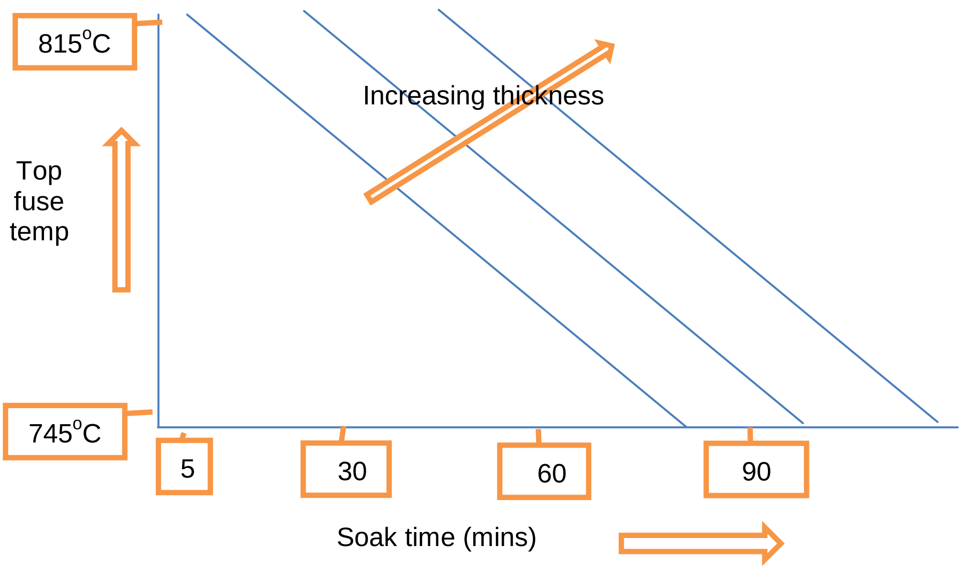
The initial findings brought a range of routes for experimentation and also revealed the need for refining of testing methods. It was clear from the pilot tests that several methods of cut and abrasion were suitable for making channels and voids in float glass for producing air entrapment in the kiln. In order to understand the technicalities and *control* the air to generate a replicable technique, it was evident that further testing with reduced variables was required, to determine which variables directly affected the success of the air entrapment, and which did not.

Figure 90: Sandblasted air entrapment test pieces, digital text, made using UV-exposed film resist method.

The pilot tests indicated that in the test samples of 2-5 layers of 4 and 6mm standard float glass, bubble formation could be achieved over a range of ‘top fuse’ temperatures between 740^{o}c and 815^{o}c, at which range the glass could be sufficiently molten for the bubble to form. Taking the temperature beyond this range or soaking for too long at the lower end of the range resulted in the bubble contours drawing in and eventually becoming spherical.

Figure 91: Bubble formation at various with top fuse temperature/soak times: Left: 780c fuse temp/ 80min soak shows bubble contours drawing in becoming spherical; Right: 745c fuse temp and 20 min soak shows successful air entrapment and retained within the design contours.

Control of bubble formation over top fuse temperature range



Graph shows relationship between top fuse temperature proportional to soak time with increasing glass thickness for modification of bubble characteristics

The top fuse temperature was variable in inverse relation to the ‘soak’ period, i.e. the length of time the kiln temperature was held. A top fuse temperature toward the lower end of the range with a longer soak, and a higher temperature with a shorter soak had a similar effect on the viscosity of glass and thus the bubble formation. Results suggested that increased layer quantities and using thicker glass affected the necessary top fuse temperatures and longer soak times for the bubble formation, however this was not a controlling factor in whether or not *air pooling* occurred.

Figure 92: Tests exploring the behaviour of air entrapment at the extreme end of the top fuse temperature range (843C, soaked for 2hrs), before firing.

Figure 93: Tests from Figure 92 after firing. The lines and figures have distorted to form spherical bubbles.

Whilst successful air entrapment had occurred in numerous designs, no clear trend was visible which might give clues to the success of certain designs, and failure of others. However the pilot tests showed that the predominant factor in identified ‘failure’ of air entrapment in the 4mm and 6mm tests was not that air was not being trapped between the glass layers, but rather that ‘air pooling’ occurred, distorting the design and impaired clarity between the layers.

Example pilot test firing schedule:

Ramp ^{o}C/ hr	*Temp ^{o}C*	*Soak (mins)*
75	*600*	*0*
100	*745*	*35*
full	*590*	*0*
50	*548*	*20*
75	*150*	*end*

Steps were taken to formalise the testing structure. Methods of cutting were separated into replicable testing routes. Tests were undertaken repeating the same void creation method under different firing temperatures. They were also repeated with the same cut-out design using different glass types. Preliminary tests showed that the successful bubble creation and containment of the air entrapment within the design varied between similar samples.

Figure 94: Waterjet-cut test showing 'air pooling' around the cut-out.

Figure 95: Test with air entrapment contained within the cut-out using same kiln firing as Fig 79. Variable changes: tin side of cut layer placed down & layer quantity increased by 1 x 4mm layer.

Interestingly, whilst a trend toward successful air entrapment in the sandblasted samples suggested that lower air volume was a factor in successful designs, with *air pooling* occurring more in the waterjet-cut samples, anomalies meant that no definitive conclusions could be made. For example, in a retest under the same firing conditions, results would be different; a sandblasted sample would show air pooling in the same firing and same layer quantity that a waterjet-cut air entrapment was successful, despite the fact that the volume of air was much greater in the waterjet cut channels, and so on. This revealed that many more variables were at play than simply the volume of air in the cut channel.

The shape of the sample, quantity of layers, glass tint, size of sample, and proximity of cut-out design to edge, placement inside the kiln and design of cut-out were all variables which had an unknown effect on the potential air pooling. The inductive testing method brought up an assortment of variables on which further tests could be based, which could then be narrowed down. The pilot tests had established that no single variable, but *various* and *multiple* contributing factors, were affecting the success of test tiles.

To find a successful route for a repeatable method of air entrapment it was concluded that the causes of the *air pooling* must be understood in order to eliminate it. The next stage was to isolate and test the most likely variables.

Variables identified for testing air pooling:

- Consistency of kiln choice
- Thickness of glass sheet
- Depth/volume of air channel
- Cut-out design, size, scale
- Layer quantity above the air channel
- Programme heating (ramp) speed
- Temperature used to tack fuse (at which layers bond)
- Tack fuse soak (hold) time
- Heat transfer through piece in relation to thickness of glass (thermal conductivity)
- Effect of tin residue

6.2 Stage 2: Refining Testing Routes

The investigation was focussed on specific testing routes in order to eliminate certain variables and the outcomes analysed, to explore potential causes of air pooling. A formalised testing structure was created to test the effects of:

- Ramp speed (rate at which glass is heated)
- Tack fuse (bonding) temperature
- Length of soak at the tack fuse temp
- Weight of glass (by increasing layer quantity) on top of cut-out in relation to air volume/pressure

Tests were undertaken with the intention of investigating the occurrences of air pooling, based on discovering the point at which the glass layers bond at the interface of the cut-out channels , and controlling the ‘tack fuse’. The hypothesis was that if adjoining layers could be successfully fused before the formation of the air bubble, the air pooling problem might be resolved. Two routes were identified: varying the rate at which the glass was heated (ramp speed) and adjusting the soak temperature to discover at which point adjoining layers might start to bond (the tack fuse).

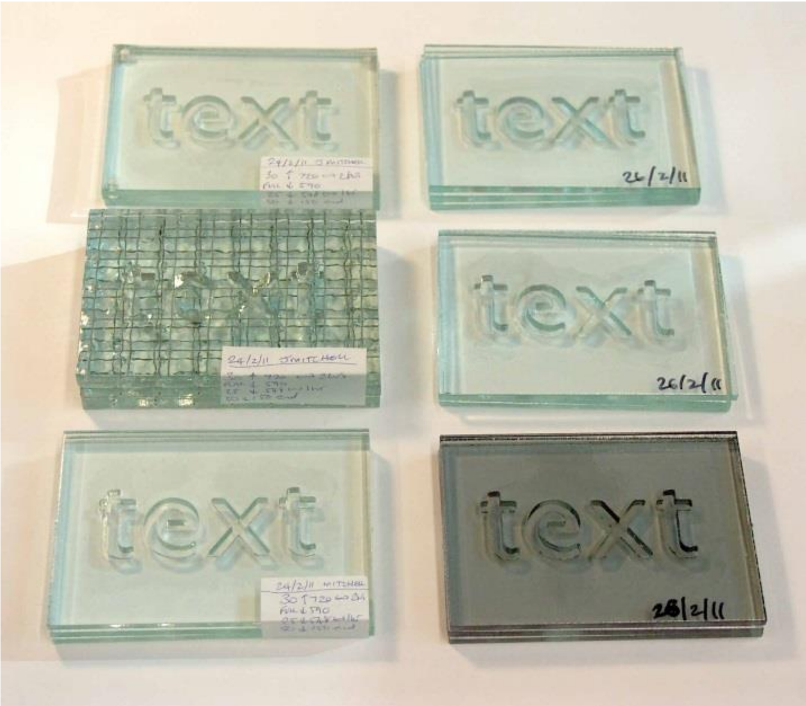


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Figure 96: Examples of selected ramp speed tests: 30c/hr to 720C, 120 minute soak: (left hand column, top-bottom); and 110c/hr to 745C, 30 minute soak (right hand column).

Figure 97: Example of testing tack fuse temperature: 650 degrees, 3hr soak: Air escape visible in waterjet cut samples alongside successful sandblast sample on right.

A review of material science research into the properties of glass when heated found that the molecular structure of glass changes continuously with temperature, rather than passing through a sudden phase transition (Cooke & Howells, 1998, p.21 [accessed 26/6/14]). This suggested that whilst analysis of temperatures was useful in determining beneficial heat ramp speeds and soak temperature ranges, there was no one *definitive* 'tack fuse' temperature which could be applied for sealing the adjoining surfaces of float glass as a general rule.

A reasonable assumption would be that a slower ramp speed would mean that the glass would heat gradually and evenly through the piece and therefore the layers would fuse fully. However inconsistent results in the pilot tests and a further review of technical data suggested that heating slowly through this range increased the risk of tin bloom, and its effect on the air channels on the adjoining surfaces was unknown (see Glossary for terms).

Successful sandblast samples fired in the same ramp test firing as unsuccessful waterjet samples indicated that finer cutouts had a wider tolerance for variations in soak temperature. It was decided that waterjet cutouts (which had a larger air volume and more accurate depth) would be more informative in ascertaining a tack fuse temperature analysis. The quantity of glass layers above the cut-out was varied from 1 to 3 and other known variables were controlled.

Figure 98: Formalised tests investigating incremental rises in 'tack fuse' soak temperature. Tests at 600C, 620C and 640C, for 76 minutes (Kiln 17) with single, double and triple 4mm layers above cut-out layer. (Top fuse 745C, 35min soak.)

Figure 99: Successful waterjet-cut test at 620 degrees tack fuse with 2hr soak, plus 3 x 4mm layers above the cut-out layer. (Top fuse 745C, 35min soak.)

Inductive testing routes were undertaken in order to explore beneficial firing schedules, using graduated temperature tests. The temperatures were chosen based on reviews of documented *bend*, *bubble-squeeze* and *tack fuse* points in glass, soak times were varied.

Variations to the firing schedule were explored as follows:

- Slow ramp speed (30c/hr)
- Fast ramp speed (without risking thermal shock to glass) (110c/hr)
- Soaking at temperatures through the viscoelastic phase and '*bending* point' of float glass (580-650c)
- Soak at documented *fusible* glass softening point (671c)
- Graduated ramp and soak tests through the *softening* point of float glass (715 Celsius)
- Soak at a temperature of 650C (*'the point glass begins to slump'* (Lundstrom B, 1983) & Pilkingtons documented 'bend point').

Tests were also undertaken to explore the effect of increasing layer quantity between 1-4 layers above the cut-out:

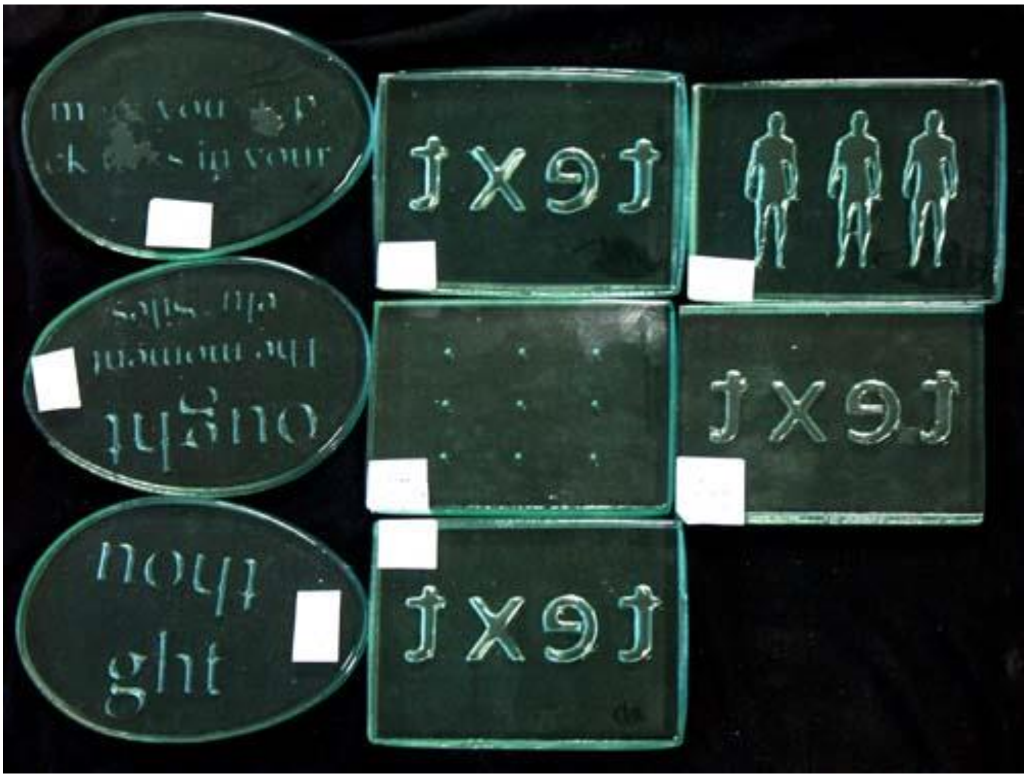


Figure 100: Test 19/4/11, tack fuse temperature and soak, K17.

The above example shows a successful firing using 4mm layers with a minimum of 2 and 3 added layers, various designs; soak at 620C for 120mins (with top fuse of 745C for 35mins). All air entrapment is successful except the top left sandblasted sample of two 6mm layers.

Figure 101: Tests 23/6/11 and 1/7/11, Kiln 17: testing tack fuse temp/soak period.

The further examples above show tests for the tack fuse temperature and soak period. In the left samples the firing was soaked at 630C for 2h32mins, with variations of 1-3 additional layers (shown top-bottom). All samples showed air pooling, with some reduction with +3 layers. The right image shows the results of the tack fuse temperature at 620C with 2hr32min soak with 1-4 additional layers. The most success occurred in the samples with +3, +4 and +1 layer (all samples were fired to top fuse temperature of 745C with a 35 minute soak).

6.2.1 **Evaluation of Stage 2, Technical Issues and Problems Arising**

Following extensive testing of repeated firing schedules, and analysis of the testing in various kilns, results based on ‘tack fuse’ hypotheses suggested that a soak around the ‘bend point’ of the glass (approximately 620C) was beneficial, as results showed a tendency towards the success of the air entrapment when a 3hour soak between 610C and 630C was included in the firing cycle. This did not *guarantee* successful air entrapment however, meaning that other factors were influencing the outcome. Variations in the temperature could potentially be accounted for by slight differences in kiln thermocouple readings in various kilns caused by the height of the thermocouple in the kiln in relation to the glass.

Observation of the results of variations to the firing schedule led to speculation that rising air trapped between the layers had prevented fusing of the contours of the cut-out channels to the upper layer in the centre of the tile, making space for the trapped air to pool outside and above the cut-out boundaries.

The reasoning as to why this might occur more regularly in the new waterjet cut samples, as compared to previous wheel-cut and sandblasted designs, was that the relatively large volume of air present in the waterjet cut-outs exerted a greater pressure on the upper sheets of glass, as compared to the small air channels of the wheel-cut and sandblasted tests which had shown minimal air pooling in comparison to waterjet cut samples.

6.3 Stage 3: Reducing Variables

In order to apply a deductive methodology to the technical enquiry it was necessary to focus the strand of technical investigation by further reducing variables to create a more systematic approach to testing. The two most significant variables which were most easily investigated, with the facilities available, were the accuracy of the kiln temperature reading and the consistency of the test tiles. Investigations into accuracy of the kiln controller reading via comparative tests and development of replicable test tiles, which would allow more accurate data for analysis, were undertaken.

The sample quantity had to be of a sufficient size to ensure that inferences could be made (Collins, 2010 p.42) to formulate generalisations for the next testing stage. Therefore following evaluation of the pilot testing phase it was decided that a selection of specific size tiles would be repeatedly tested with a set glass thickness, layer quantity and design, and a single kiln would be identified to carry out the testing where possible.

The variables would be systematically reduced by alternately testing different variables during separate firings in the same kiln. Due to the time for each firing being a minimum of 24 hours, this process was very time consuming and took up a substantial amount of the research process.

To control variables the following restrictions were applied to the testing after analysis of the pilot tests:

- Use of a single testing kiln
- Focus on 4mm glass layers to give consistent sheet thickness
- Repeated rectangular sample size at 10cm x 7cm
- Consistent depth of air channel, position and motif design
- Consistent top fuse temperature

It was noted that the point at which the air entrapment formed had a range of between 745 Celsius up to 815 Celsius. Above this temperature range float glass softens to the point where the bubble starts to become spherical and lift to the surface. The top fuse temperature level for ideal bubble formation, deemed as an air bubble with softened edges but retained within the shape of the contour design, needed to correspond to a viscosity proportional to the soak time (the length of time the kiln is held at temperature). For example, in a repeated sample, a long soak at 765 Celsius would give a similar effect in terms of air-bubble formation to a short soak at 800 Celsius.

6.3.1 **Developing Consistency of Testing Tiles**

To narrow the testing field and apply a more rigorous testing procedure, a set of replicable waterjet-cut designs were chosen that could be reproduced and used repeatedly, in order to more accurately evaluate results. Using the waterjet ensured maximum consistency of the depth and volume of the cut-out design. Pilkington 4mm float glass was used for the tiles because pilot tests had shown best results in the 4mm cut-out samples. Multiple flatbed fusing kilns had previously been used according to availability. A single testing kiln was identified in which to fire all future tests, so that any variation between kilns was removed.

Three waterjet cut-out designs were chosen:

- The digital lettering ‘text’: to evaluate varying shapes within the same tile, and assess legibility.
- The human figure in triplicate: to evaluate multiple repetition within one tile, and as a form of interest to the artistic enquiry.
- Increasing line with: to assess the effect of increasing air volume/channel width within the same tile.

New sets of test tiles were waterjet cut from large sheets of 4mm Pilkington float glass, each tile cut to the same size (10 x 7cm) with waterjet cut-out designs chosen and repeated on each tile.

Figure 102: Uniform test samples being cut on the waterjet

Figure 103: Test samples designs of text and increasing line width. (Yellow colouring visible on left tests is silver stain residue from the kiln shelf).

The format of the revised testing tiles was used through further testing routes in order to maintain consistency and form a basis for comparable analysis of on-going tests.

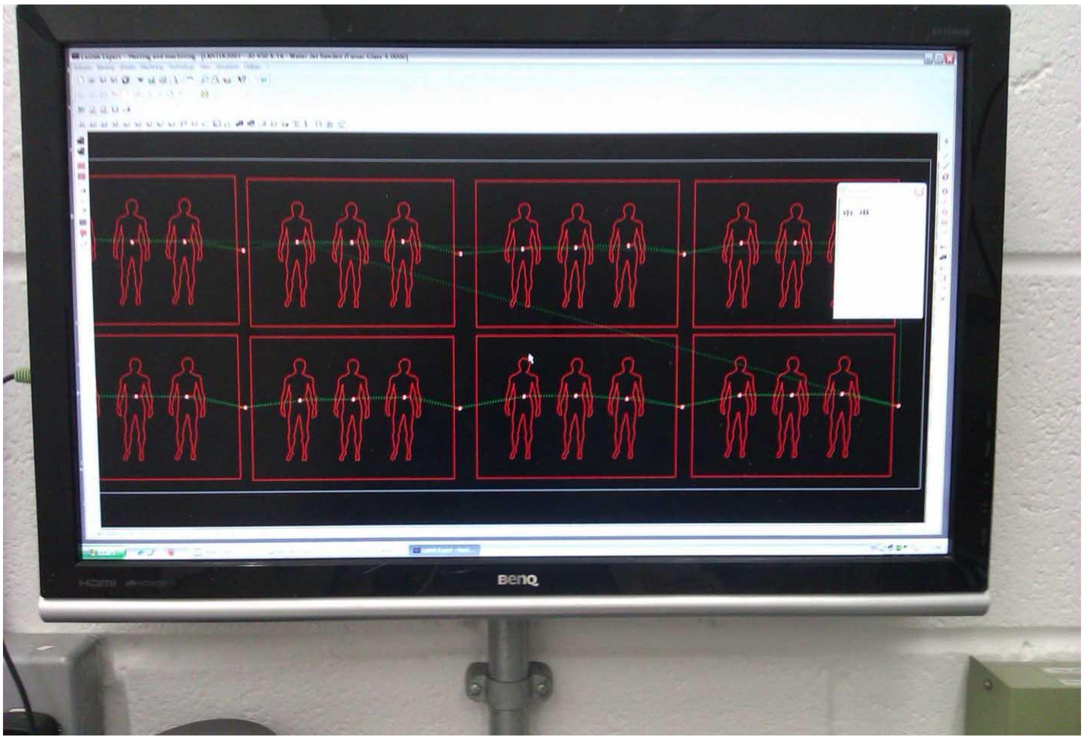


Figure 104: IGEMS program for figure samples - test tiles at 10 x 7cm, 4mm float glass.

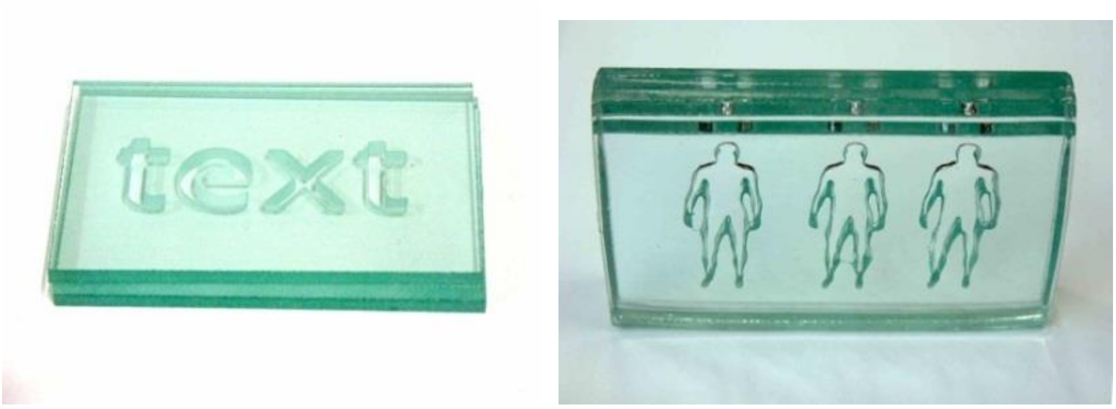


Figure 105: Designs for test tiles. Left: Waterjet-cut ‘text’ test tile (unfired); ‘repeated figure’ test tile after firing with successful air entrapment.

6.3.2 **Testing the Kiln Temperature Accuracy**

A setback in the research occurred when the kiln used for the majority of the inductive testing, K17, came to the end of its viability and was removed from the department. Further tests in the replacement kiln (K19), with similar test samples and an identical firing cycle, yielded unsuccessful results that had previously been successful in the preceding kiln.

Tests were repeated in another kiln (new17) using the same temperature firing schedules as the inductive testing. Results were again inconsistent: replicable test tiles that had fired successfully in the original kiln were now unsuccessful. At this stage in the experimentation it had become apparent that accuracy of the temperature reading was needed for any method of practice to eventually be transferable between kilns in general studio practice. The outcomes of previously successful tests which failed in the replacement kiln suggested that the variable of inaccuracies in the temperature readings between the kilns was affecting the outcomes and needed to be accounted for as much as possible.

It was surmised that the results gained from Kiln K17 would have to be considered invalid as comparative tests to those undertaken in the new kilns, because the temperature readings were potentially incorrect. The reasoning for the change in results to be investigated was that the preceding kiln (17) was firing at a different temperature than the new kiln; perhaps due to its age and the location of the thermocouple in relation to the elements, and possible hot or cold ‘spots’ inside the kiln; which could add to variations in the temperature reading. Unfortunately, disposal of the original kiln meant that comparisons could not be taken between the temperature of the original kiln 17 and the replacement kiln 19, meaning that limited conclusions could be drawn from the previous test samples from the inductive tests.

A means of gaining better accuracy of the temperature reading was deemed necessary to ensure that the controller readings on the new kiln were correct to as accurate an extent as possible in the university/studio environment. The image below shows the kiln (numbered Kiln 19) used for the research, a 2005

Kilncare Glasscare 9KW kiln, serial no. 156905, with a K-type thermocouple FK4, and an IPCO 330 Controller.

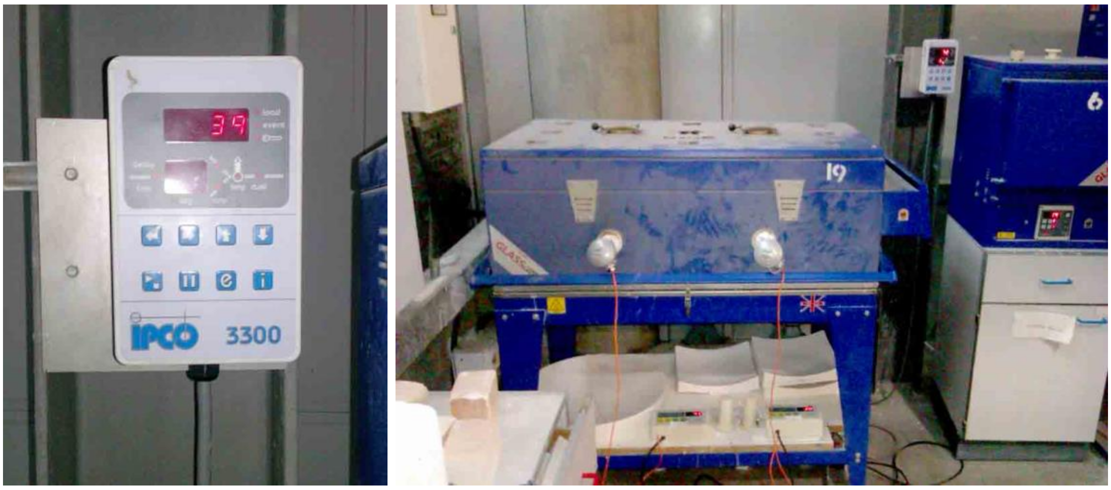


Figure 106: Left: Kiln controller (K19). Right: specified test kiln (with added probes for testing calibration).

After discussions with Senior Glass & Ceramics technician Tim Betterton at the University of Sunderland, it was deemed that various factors could affect the calibration of the controllers and therefore the kiln’s temperature reading: the age of the kiln, disturbance to insulation and corrosion, all being factors.

To control the accuracy of the firings the inquiry was narrowed to a single test kiln which was calibrated to discern an accurate temperature reading. To determine correct the kiln temperature it was necessary to and find out the accuracy of the internal thermocouple which generated the temperature reading on the kiln’s controller. In order to test the accuracy of the thermocouple, it was necessary to add additional thermocouples, and compare readings.

Initially, a portable infrared pyrometer was used to attempt to get a temperature reading from the surface of the glass inside the kiln during the firing cycle; targeting the glass surface through the bung holes of Kiln 19 (testing in a different top-loader kiln was also undertaken as a control). The readings however were wildly inaccurate, due to the laser hitting the reflective surface of the glass. After researching this it was discovered that optical pyrometers and infrared thermometers can only detect radiance of opaque objects (http://www.pyrometer.com/processheating.html [Accessed 19/9/11]).

An alternative method was sought, and a testing method using ceramic probe thermocouples was used. This was in line with the Bullseye Glass Company's documented method of temperature testing using controllers for different kiln zones, and on the advice of Kilncare engineer Brian Sherwin and Senior Glass & Ceramic Technician Tim Betterton. Two ceramic-sheathed probe K-type thermocouples attached to unused calibrated controllers were used. The thermocouples were placed through the kiln's bung holes to investigate the kiln's temperature readings throughout the firing cycle in conjunction with the kiln's own thermocouple and controller (see image below).

The probes were inserted through the left and right bung holes of the kiln, extending into the left and right central zones of the kiln cavity, with the kiln's original thermocouple positioned in the centre back of the kiln's internal cavity.

Figure 107; Testing kiln temperature readings using ceramic probe thermocouples and controllers and comparing readings. Kiln controller shown mounted on the wall to the right.

The images above show the kiln temperature calibration tests using ceramic probe thermocouples. The images show the ceramic probes inserted through the bung holes and protruding into the kiln cavity. The kiln's internal thermocouple can be seen at the rear of the kiln in the centre image.

Data from the three thermocouples was gathered to ascertain the accuracy of the new kiln (K19) temperature reading, and additionally, the consistency of temperature throughout the kiln, by comparison of the three readings.

Figure 108: Additional controllers attached to ceramic thermocouples employed through bung holes to test variation in temperature readings.

If the data corresponded from the three controllers, it would signify that the kiln temperature reading was correct and that the kiln's own thermocouple was correctly calibrated and heat evenly distributed through the kiln cavity. The Type K Thermocouple has a temperature range of -200c – 1250c and standard error limits 2.2c or 0.75% (whichever is greater) Special Error Limits 1.1c or 0.4%.

Firing Schedule for Kiln temperature test:

Temp. Degrees C/hr	Temp degrees C	time
200	630	3 hours
FULL	765	45min
FULL	590	0
50	555	1hr 10mins
20	505	0
75	150	end

The results of the tests can be seen on the table below.

THERMOCOUPLE READINGS TABLE 1- 22/1/13:

Time	Probe 1 (Temp, degrees C)	Probe 2 (Temp, degrees C)	Kiln Thermocouple (Temp, degrees C)	Difference between Probe 1 and Kiln Thermocouple
11:56am	49	20	78	29
12:55pm	249	45	266	17
2:24pm	554	76	566	12
2.30pm	572	78	584	12
2.31pm	575	78	587	12
2.54pm	619	82	630	11
3.27pm	617	87	630	13
NEXT DAY				
10:18am	106	N/A	124	18
NEXT DAY (END)	9	N/A	34	25

THERMOCOUPLE READINGS TABLE 2 – 1/2/13:

Time	**Probe 1 (Temp, degrees C)**	**Probe 2 (Temp, degrees C)**	**Kiln Thermocouple (Temp, degrees C)**	**Difference between Probe 1 and Kiln Thermocouple**
12:32pm	18	24	32	14
1:05pm	130	49	144	14
1:35pm	243	77	250	7
2.11pm	361	103	363	2
2:26pm	438	116	439	1
2:35pm	**442**	118	**442**	**0**
2:36pm	**445**	120	**445**	**0**
2:37pm	**449**	122	**449**	**0**
3:09pm	**556**	144	**558**	**2**
3:10pm	**559**	145	**559**	**0**
3:11pm	**560**	145	**562**	**2**
3:11pm	**561**	145	**563**	**2**
3:11pm	**562**	145	**564**	**2**
3:12pm	**563**	145	**565**	**2**
3:12pm	**564**	145	**566**	**2**
3:53pm	**625**	151	**630**	**5**
3:57pm	**624**	-	**630**	**6**

THERMOCOUPLE READINGS TABLE 3 – 21/3/13:

Time	**Probe 1 (Temp, degrees C)**	**Probe 2 (Temp, degrees C)**	**Kiln Thermocouple (Temp, degrees C)**	**Difference between Probe 1 and Kiln Thermocouple**
6.27pm	377	79	384	9
6:29pm	373	80	380	7
6:30pm	379	80	386	7
6:31pm	382	80	389	7
6:31pm	383	80	390	7
6.32pm	385	80	392	7
6:32pm	386	80	393	9

Probe 2 was discounted due to malfunction. Conclusions drawn from analysis of the above readings from Probe 1 and the Kiln Thermocouple showed that at the tack fuse temperature the difference in readings was in the range of 0-12 degrees Celsius. At the start and end of the firings the difference between temperature readings was higher and when heated to temperature the difference between readings lessened.

The results from the probe thermocouple tests therefore showed that a 12C margin of difference had to be taken into account in the temperature reading, and that the kiln controller reading was reading at the higher end of the margin. A soak temperature of 630C based on adjustments made for the higher reading was included in the firing cycle. Following removal of the variables of test tile consistency and kiln calibration, the effect of further variables could be explored to narrow the testing field.

6.3.3 **Testing the Effect of Tin Residue on the Fuse**

Tests were undertaken to assess the whether the factor of the 'tin' side of float glass was an influencing variable on the success of the air entrapment. Testing was formulated to determine whether the tin side of the float glass (caused by residue from the float manufacturing process) had any adverse or positive effect on the fusing of the two surfaces. Tin residue initially seemed a potential reason for air pooling because exploratory Spectrum S96 glass tests (Spectrum S96 is hand rolled and therefore has no tin side) had fused successfully without any air pooling. Testing was undertaken based on the theory that tin residue could be a factor in preventing the layers around the cut-out channel from fusing fully, thus causing the pooling effect.

The tin side was tested using a UV light tin detector placed against the surface of the glass. The tin side was detected by a visible 'mist' on the tin-side surface. To test whether the tin residue had an effect on the fuse, the tin surface on different samples was placed either face-down, face up, tin to tin, or tin on the lower or upper side of the cut-out; and repeated using the same firing schedule, to assess any difference to the air entrapment. Despite extensive testing, results showed no conclusive difference between the samples.

Figure 109: Testing for the tin surface of float glass

Further tests using fast and slow heating ramps were also compared to test whether tin bloom – a crystallization of the tin layer on the glass surface through gradual heating - might be a factor causing the *air pooling*. This was based on the article *'Float Glass in Bloom and Other Stories. Extract.'* in the European Journal of Glass Science and Technology 49 (4) pp189-194 by Gelder, cited by Jenny Antonio on her thesis investigating creative use of the tin coating on float glass: '*The artist wanting to seal glasses together or bend glass without bloom needs to heat up quickly'.* (Gelder D. cited in Antonio, 2009, p.153)

The ramp tests results were inconclusive, so additional comparative tests with non-tin glasses horticultural window glass and Artista were carried out. The results negated the idea that tin residue was responsible for air pooling, because the pooling had also occurred in the two glasses. A further testing route to investigate fusible art glasses was constructed.

6.3.3.1 Tests with Alternative Glasses

Testing with alternative glasses was undertaken to compare results of air pooling with the float glass. Tests with the fusible sheet glass Spectrum System 96 yielded very successful initial results on a small scale. The 3mm blue Spectrum S96, a relatively smooth surfaced fusible glass, gave an excellent level of clarity in the surrounding glass, similar to successful float glass samples. Further experiments using Spectrum and Bullseye fusible (non-tin) glasses were undertaken to test whether air pooling occurred. The resulting air pooling in the non-tin glass further disproved the proposition that tin side was a contributing factor to air pooling in the float glass.

Figure 110: Spectrum S96 samples: air pooling is visible in the left clear (textured) sample and not in the right samples (smoother surface).

The outcomes showed various levels of air pooling in the Spectrum samples, from which it could be accepted that the tin side of the float glass was not the cause of the air pooling. Bullseye glass tests also demonstrated small amount of air pooling, predominantly the air settling as small bubbles between all layers in the textured surface of the glass The appearance of air pooling after scale was increased in the Spectrum tests brought forward the proposition that the small scale of the original Spectrum tests was a factor in the lack of air pooling in the successful air entrapment.

The relative high viscosity (a fluid's internal resistance to flow) of float glass relative to 'art glass', was an alternative variable that was also thought to be a potential factor in the lack of air pooling in initial Bullseye and Spectrum tests. Whilst air pooling then occurred in the tests (shown above) in Spectrum S96 and Bullseye glass, the air entrapment within the contours of the cut-out fused quite evenly and the pooling was more evenly distributed in many small bubbles. This suggested that the texture of the Bullseye and Spectrum S96 glass might be a factor in assisting in the dispersal of the air pooling into the layers.

Conclusions drawn from the alternative glasses led to the theory that it was not the tin properties of float glass which had a direct effect on the air pooling, but a more general glass/heat/air interaction. Slight differences in the way the bubbles settled in the alternative glasses backed up speculation that the smoothness of the float glass surface caused the visual 'pooling' in the float glass, which was also happening in the fusing glasses but more evenly dispersed throughout the textured surface of the Bullseye and textured Spectrum S96 glasses. Based on this theory, viscosity and tin residue were reasoned to be minimal influencers on the success of the air entrapment.

Figure 111: Bullseye test samples 26/1/13, air entrapment has remained within the contours of the figures but pools in the texture forming numerous bubbles which interfere with the clarity of the design.

Following analysis of samples in fusible glasses, the assumption was made that the indented texture on the fusible glass surface had allowed some air to flow out, with air successfully contained in the design contours. The residual air had remained in the intermediary layers creating tiny bubbles (known as seeds) through surface tension drawing together ring contact points around the textured indents. This outcome was deemed a more aesthetically pleasing effect than the flat pools of air in the float glass samples (the ‘air pooling’). However the seeds impaired the overall clarity of the glass and reduced the integrity of the artwork.

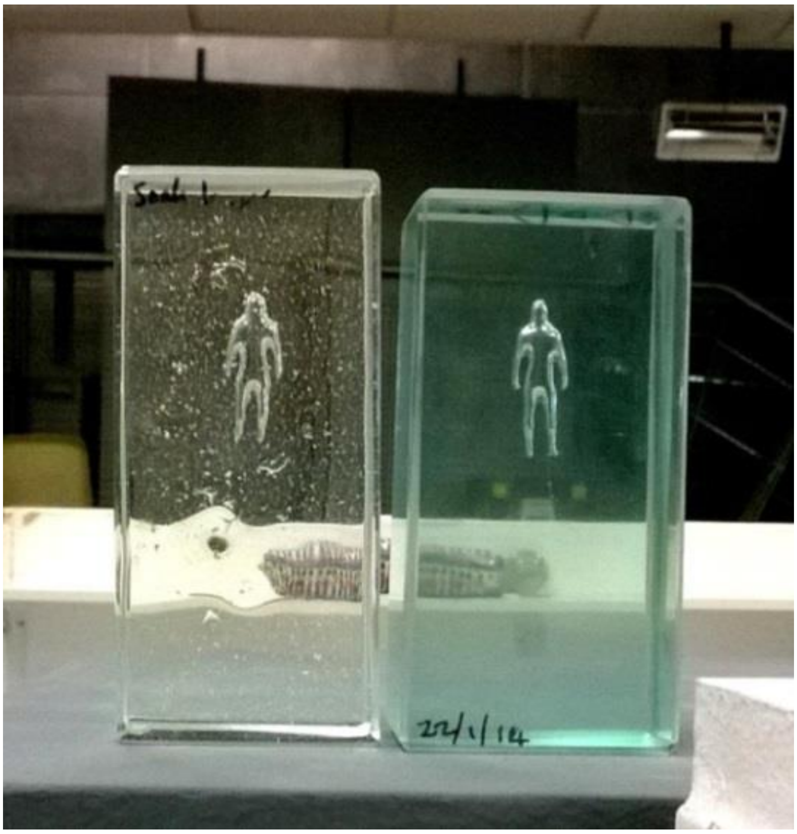


Figure 112: The difference between Bullseye glass (with seeds visible between layers), and a successful float glass sample showing preferred level of clarity (float glass on right).

6.3.4 **Testing the Benefit of Increased Layer Quantity Above Cut-out**

To investigate the variable of increased glass layers above the cut-out, tests were undertaken to explore theory of additional mass assisting the fuse between the cut-out layer and the upper layer. A 10 x 7cm rectangle was placed in the kiln with the waterjet cut-out placed on top, and then one to four 4mm float glass layers added in sequence to increase the mass of glass above the cut layer. The top temperature of 745 Celsius was chosen to fuse the layers whilst retaining the basic shape without distortion by slumping.

This test was based the hypothesis that a double or triple layer of 4mm float added above the (4mm) cut-out aided successful air entrapment and minimized air pooling, based on the results of the inductive tests. Observed trends in the pilot tests suggested that increasing the layer quantity would reduce the occurrence of ‘air pooling’. Evaluating the outcome of the structured tests on increased layers above the cut-out, the results indicated that the application of a minimum of two additional 4mm layers would be beneficial to the success of controlled air entrapment.

Figure 113: Repeated test samples with varying results 4mm float glass (air pooling visible in right-hand example).

Reasons for the air pooling were unclear: in the same test tile, the letter ‘t’ in cut-out word ‘test’ formed as a successful bubble with no air pooling, whilst the other letters in the same word (including another ‘t’) had air pooling above them. This effect seemed to occur in one, but not another, in very similar samples. No reasonable conclusions could be drawn as to why one sample might have emerged as more successful than another in the same glass thickness and design.

Following the calibration of the thermocouple to determine the accuracy of the temperature reading in Kiln 19, tack fuse temperature and soak period test firings were repeated in conjunction with sequentially increasing layer quantities. A trend towards successful air entrapment results in Kiln 19 supported the theory for the additional layer quantity. In the majority of tests, increased layers had a beneficial effect on the success of the air entrapment, however this did not eradicate the air pooling in all cases, therefore the conclusion could be drawn that whilst increasing layers above the cut-out layer was a beneficial factor in assisting the fuse, other factors were also contributing to the air pooling.

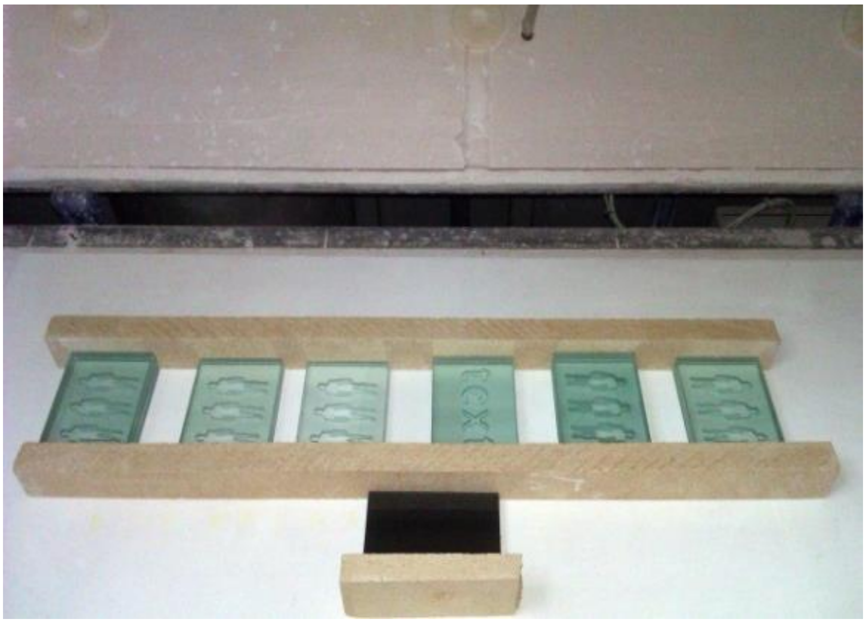


Figure 114: K19 22/10/12 Deductive testing of the increasing layers above the cut-out layer.

Figure 115: K19 1/12/12 Repeated firing to retest the increasing layers above the cut-out layer.

In the tests shown above, 6mm and 4mm cut-out layers with up to four x 4mm additional layers above the cut-out were fired using the firing cycle below. In the left hand firing all samples showed successful air entrapment except the single layer sample. The black sample is comparative testing using enamel as a bonding agent in the intermediary layers between the cut-out and adjoining layers. (Bullseye thinfire paper separator was added before firing as in the right hand test above.) In the right hand firing the conditions were repeated. Some unexplained air pooling occurred in the second firing.

Figure 116: Repeated tests with increasing layer quantities.

Below: Example firing schedule for tests with increasing layer quantities (used in test samples shown above.

Ramp. Degrees C/hr	Temp. Degrees C	Soak Time
200	630	3 hours
FULL	765	45min
FULL	590	0
50	548	1hr 10mins
20	505	0
75	150	End

The outcomes of the tests into kiln temperature accuracy, added layer quantity, tack fuse temperature and soak period were evaluated. The results of the tests suggested that because of the multitude of variables at play, from tack fuse temperature/ soak time differential to the air volume / layer quantity ratio, finding a precise and replicable formula for all possible outcomes was not viable within the constraints of the studio environment. Through the minimizing of variables, however, conclusions for preferable conditions could be drawn from the generated data, which could be applied in practice and for the purposes of this study.

The findings suggested that placing the tin side down on all layers, a minimum of three additional layers for a single cut-out air entrapment, and a soak at 630c for 3hours were conditions conducive to successful air entrapment. These findings were carried through as a basis for further avenues of testing.

6.3.5 **Tests with Frit as an Intermediary Layer**

Tests with frit – fine glass granules – sieved between the adjoining layers as an intermediary layer produced successful results in a number of tests in terms of the air entrapment remaining confined within the cut-out contours. The less successful effect of the frit layer was a significantly reduced transparency in the piece. Whilst the frit gave an effect which inspired creative thinking, it was deemed by the researcher that using this method for the body of artworks compromised the integrity of the artistic enquiry and did not fulfil the aims of the research because of the adverse effect on the overall clarity of the glass.

However the success of the frit as an intermediary layer, whether as a bonding agent, or to assist in dispersal of air, showed some consistency with the successful original enamel-flashed pilot tests with enamel as an intermediary layer. This put forward new hypotheses: either that the frit allowed excess air to disperse before the edges sealed, or that it had an effect on the surfaces that assisted the layer bonding before the air inflation - such as reducing the surface tension, or both.

Figure 117: Sample using frit as an intermediary layer between the cut-out layer and the upper layer: successful air entrapment but reduced glass clarity.

Comparative testing with frit continued and proved successful in terms of eliminating air pooling but with reduced clarity. After repeated tests with frit as an intermediary it could be deduced that its application enabled air entrapment to be successfully contained, however the question remained as to why some samples were also successful without frit in the intermediary layer.

It was decided to continue investigations into avenues for resolving the air pooling using other methods, to retain clarity in the artwork, and attempt to discover reasons for the inconsistency of successful samples which did not contain the frit layer.

6.4 Material Science Consultation

During year four the technical research into float glass had reached the limits of evaluation achievable within the restraints of the glass & ceramics department at the University of Sunderland, and independent specialist mathematical expertise was consulted to assist with analysis of the data generated in the testing routes. Contact was made with former Pilkington mathematician David Gelder, a glass scientist who had worked with Dr. Jenny Antonio on her doctoral research into the tin coating of float glass. Gelder agreed to offer his scientific expertise in the evaluation of the testing samples.

Some conclusions could be drawn from the preliminary fusing tests: A soak at temperatures between 610-640C (in various kilns) had shown some beneficial effects but was inconsistent, with the longer soak seemingly increasing chance of successful air entrapment. Sandblasting, wheel cutting and waterjet cutting had been semi-successful: the imagery and text were visible and clear as air bubbles, and where the air entrapment had not been successful, the results showed that air was visibly ‘pooling’ in areas between the layers, rather than in the cut-out channels where intended.

The tests appeared to show that where pooling had occurred, the air had predominantly pooled *above* the air channels. Also, through testing increased quantity of layers above the cut-out from 1-4, the samples with 3-4 layers showed tendencies towards more successful air entrapment, with reduced occurrences of air pooling.

The question of how to find a repeatable method to successfully fuse the layers of glass around the contours of the cut-out, before the formation of the air bubble, without an intermediary layer that compromised the clarity of the glass, was still to be answered at this stage. Initial firings had focussed on trapping the air between the layers and attempting to fully tack-fuse the adjoining layers to retain the air in the cut-out channels.

Review and evaluation of samples in collaboration with David Gelder, and additional advice from engineer Eric Mitchell, led to consideration of the thermal expansion of air when heated and its effect on the volume of air within the cut-out. This extended knowledge moved the analysis forward from researcher's original assumption that air was *rising* as the glass heated and softened. This input led to new avenues of exploration into the relationship between the increase in *volume* of air and the changing physical properties of glass as it heated, as well as the action of the heat transfer through the glass.

In discussion with the material scientists it was proposed that the air's expansion when heated meant that whilst air was being trapped in the cut-outs, heating the glass meant that the trapped air's volume was also increasing. Its increased volume could not be contained within the cut-out boundaries. This forced the layers apart, resulting in the 'pooling' effect. The air pooling predominantly concentrated in the centre of the test tiles, around the cut-outs, which led to the proposition that the outer edges were sealing before the centre of the test samples.

Based on the assertion that trapped air in the glass expanded during the heating process, a new hypothesis was formulated which premised that the volume of air when heated became too large to stay within the boundaries of the cut-out, and thus the pressure of the *expanded* air could theoretically prevent layers from fusing altogether around the cut-out, regardless of fuse temperature or the weight of increased layers.

This led to a new hypotheses based on finding methods of reducing air volume or evacuating *excess* air by allowing expanded air to *escape* from the design. This could mean that the layers might then fuse properly at the cut-out design/adjoining layer boundary, removing the air pooling effect. The hypothesis could also explain why the intermediary frit layer tests yielded good results as air was able to escape between the grains of the frit. However, some air would need to remain in the cut-out boundaries to form the air entrapment and prevent void collapse on cooling. Theoretically, any air remaining trapped in the cut-out would continue to expand with the continued heating.

A new testing route needed to be explored in order to reduce or evacuate the excess air volume. Further tests were planned that might yield a successful outcome for expelling excess air, based on practical knowledge of glass fusing.

6.4.1 **Additional Tests for Assisting the Fuse and Evacuating Air**

New tests introducing a soak period at a 'bubble squeeze' temperature in the firing cycle were investigated. The bubble squeeze temperature was based on published fusible glass data relating to a soak to reduce bubbles in glass by *removing* air from between the layers. This was based on Warm Glass advice on avoidance of bubbles in the fuse:

> *Fire slowly between 1100 and 1300F (593c-704.4c) this allows the air to escape… you might also consider soaking a few minutes at the point in this range where glass softens (try around 1240F (671C)*
> (www.warmglass.com/bubbles.htm [Accessed 3/5/12])

Whilst this is advice was specific for Bullseye glass, it was considered worth investigating to ascertain whether float glass might behave in a similar way in this temperature range. The proposition that was by allowing pressure to be *evacuated* during the heating up phase, the layers would fuse fully, and any expansion of the remaining air might stay within the cut-out channels and thus retain the shape of the intended air entrapment design.

Further alternative avenues were tested in parallel to explore methods to assist bonding of the glass surfaces. Pre-fusing the top layer and cut-out layer together, and fusing the base layer on a second firing cycle was route tested. This theory was based on discussions with Gelder, and the proposition that microscopic fractures in the waterjet cut-out edges might be affecting the fuse, causing points of nucleation.

These fractures could potentially be sealed by pre-fusing and fire polishing the cut and top layers, and fusing them to the base in a further cycle. This would also give the opportunity to test the actuality of the bond between the two layers at the proposed 'tack fuse' temperature range. The samples were fired at 200c/hr to 635c and soaked for 60 mins (based on beneficial results in tests soaked between 610-640C in various kilns). The tests below show the pre-fused layers. To test the fuse they were filled with water and ink and retained the liquid in the cut-outs; whilst not scientific, this gave a visual indication of the extent to which the layers had fused.

Figure 118: Testing adhesion at 635C fused base and cut-out layers. The fused samples were filled with a water/ink mix to view the level of adhesion between the two layers.

Other speculative ideas were tried. Grinding the adjoining surfaces to a finely abraded finish with 600 grit to 'key' layers together, and the application of fusing glue between layers, showed moderately less air pooling but again no solid conclusions could be drawn. Retrospective reflection upon the ground adjoining layers supported the theory that the granular surface, similarly to with frit as an intermediary layer, assisted in evacuation of the air pressure. Adaptations to the test sample were made to increase the separation of the text letters so that more glass surface area was available for adhesion. The results again generated no generalizable data.

Glass chips were placed in the outer corners of the cut-out layer: the theory being to avoid sealing the outer edges of the glass before the centre fused, to assist the evacuation of excess air as from between the layers. These tests were unsuccessful.

6.5 Evaluation of Stage 3 Tests & Conclusions

The following conclusions were drawn from the stage 3 testing route.

- The tin side as a specific cause of the air pooling was disproved following tests with tin-free horticultural glass, Artista Bullseye and Spectrum S96 which also demonstrated air pooling.
- Increasing layer quantity above the cut-out layer was shown to be beneficial in reducing the likelihood of air pooling.
- Adding frit or enamel as an intermediary layer negated the occurrence of 'air pooling' (but adversely affected clarity)
- Float glass layers without the trapped air appeared tack-fuse bonded at 635C.

These conclusions brought forward the following re-framed questions:

- Did the addition of a frit or enamel layer assist in evacuation of air or surface bonding? Or both? Do other intermediary layers have similar results to frit and what does this tell us?
- What other methods could be used to further test the air evacuation theory?

Following further material science consultation, testing routes were formulated for the reframed questions as follows.

- Investigating the physics of air expansion and contraction: Can rapid cooling potentially aid the layer fuse adjoining the cut-out by *contracting* the expanded air, and with it, the softened glass surrounding it?

- Can the outer edges of the glass be protected from the heat in order to assist in keeping edges cool and fusing the centre, allowing any excess trapped air to be evacuated from the edges before they seal?

These questions formed the basis for the next phase of inquiry.

6.6 Stage 4 Testing Routes

Alternative testing routes to reduce air volume and/or evacuate air were identified. The following methods were introduced to further investigate the outcomes of Stage 3:

Testing routes to prevent the edges fusing before the centre to assist air evacuation:

- A bubble squeeze soak was included in the firing to assist the evacuation of excess air.
- A rapid cool during the initial heating phase of the firing cycle was explored to attempt to *contract* air bubbles and potentially 're-stick' the softened separated layers, based on the premise that cooled air contracts.
- Speculative methods of protecting the edges of glass layers from *direct* heat from the kilns elements were explored, in order to retain cooler edges of the sample, with the intention of allowing excess air to evacuate.

To investigate the theory that the intermediary layer of frit or enamel was assisting layer bonding and/or assisting in the evacuation of the air:

- Testing other surface bonding agents in intermediary layers to identify whether similar results occurred.

6.6.1 **Rapid Cooling and Varying Sample Size**

The theory of reducing air pressure to control the air expansion and contraction was investigated. Tests were undertaken exploring cooling to create shrinkage (see table below). In addition, the dimensions of the cut-outs and area of glass surrounding it were varied. A soak at the Pilkington transitional temperature of 565C was included in order to ensure an even heat in advance of softening, and a cooling period introduced after the tack fuse soak temperature (that had seen most successful outcomes of air entrapment).

During these trials the top fuse temperature was raised to give an aesthetically pleasing softness to the bubble contour. The glass softness at this temperature required side supports to due glass fluidity. Batwashed ceramic kiln-shelf sections were used as supports to retain the outer shape of the glass.

Test firing schedule with cooling phase:

Ramp. Degrees C/hr	Temp. Degrees C	Soak Time
200	565	3hrs
200	635	3hrs
40	605	0
FULL	790	60mins
FULL	590	-
40	548	2hrs
75	150	END

Figure 119: Tests samples varying relative glass scale and cut-out dimensions, two supported edges with walls, before firing.

Figure 120: Fig above after firing: Minor air pooling occurred around head in frit sample (bottom left) and sample with glass props (top right in left-hand image). All other samples with three added layers added above the cut-out layer were successful.

As comparative tests, samples with the frit intermediary layer and also with glass ‘props’ between the cut-out and upper layer were included. Whilst the results were predominantly successful using the rapid cooling method, it was unclear why minor air pooling in the frit sample and sample with glass edge props would occur.

In parallel to the above tests, speculative experiments were carried out using thinfire paper – a ceramic-impregnated paper which acts as a separator between glass and shelf –as an aid to evacuate air from the outer edges of the samples by acting as a barrier to the direct heat from the ceiling elements. Results were inconclusive and this method was deemed insufficient in preventing the edges of the glass from sealing. It was reasoned that thinfire paper did not offer adequate heat protection to ensure that the cooler areas of glass were retained in order to allow the expanded air to evacuate, or reduce the heat conduction sufficiently from the side edges of the test pieces. An alternative method of expelling the expanded air or controlling the heat transfer into the glass needed to be found.

6.6.2 **Testing Intermediary Layers**

Further intermediary frit layers were tested to assess the effect on the air entrapment: if samples showed that air entrapment was retained within the cut-out, as in the majority of glass frit tests, this would suggest that the intermediary layer was assisting in the evacuation of the excess air and/or assisting layer bonding.

Discussions with ceramic technician Robert Winter led to speculative tests incorporating frit fluxes in the intermediary layers. (Ceramic fluxes lower the melting point of the glass formers in glaze, and theoretically would have some compatibility with the glass.) Borax, lead bisilicate, alkaline, calcium borate – all available within the Ceramics Department - were applied as a sieved frit layer in the same way as the glass frit. Three additional layers above the cut-out were added in all samples.

Figure 121: Test samples with fluxes as intermediary layer

<u>Softening points of intermediary frit flux layers:</u>

Lead bisilicate 880-1050c

Calcium borate 1100c

Borax 743c

Alkaline (unknown melting point).

Analysis of the results suggested that because the softening points of the fluxes were towards the top end or above the top fusing temperature range of float glass, they most likely acted as a separator between the adjoining glass layers, preventing the outer edges fusing before the central area, during which the expanded air is able to evacuate. Reflection on the results and outcomes of the tests using textured fusible glass supported the hypothesis of the pressure of the contained air as a cause of the air pooling.

A revised program raising the soak temperature from 635c to 671c was tried in continuing parallel tests as exploring the point at which the adjoining layers fused which were still giving inconsistent outcomes. The rationale for this kiln programme was based on increasing the temperature of the tack fuse to within the *slumping* range of float glass, 650 – 760c (Lundstrom, B. 1983).

6.7 Evaluation of Stage 4 Testing

Tentative hypotheses were drawn from the outcomes of the Stage 4 testing routes. It was proposed that during the process of heating, the glass was fusing from the outer edges inwards. The expansion of the encapsulated air was causing pressure which raised the upper layer, preventing the fusing of the inner adjoining surfaces, leading to the ‘air pooling’ effect.

Material scientists Mitchell and Gelder were in agreement that the poor thermal conductivity of glass, and the fact that air is an even poorer conductor of heat, meant that the glass nearest to the heat source would become visco-elastic first – sealing the outer edges before the glass around the central cut-out void had become semi-fluid or slumped. The trapped excess air would then increase in volume as the temperature increased. The probability was that the amount of stress and hence structural deformation of the glass around the air pocket would be reduced if some of the air was able to evacuate before becoming encapsulated.

6.8 Stage 5 Testing Routes: Air Evacuation

Reflection upon the various testing routes brought forward new thinking based on practical ways of assisting the air evacuation from between the glass layers to reduce contained air pressure. During observation of test samples connections were made with the sag of the molten glass in the kiln to the form of the glass during the documented overlay methods used in *Ariel*. Drawing from experiential knowledge of glass slumping, tests routes encouraging a top layer of glass to *slump* onto the base and cut-out layers were identified. This direction was based on bonding the layers from the centre of the glass outwards, ensuring the centre fused first by increasing the bend in the glass.

6.8.1 **Investigating Slump and Sag Methods of Air Evacuation**

The inspiration for the investigation into slumping and sagging as a method to evacuate air came from analysis of Flavell's (2001) research into the hot glass *Ariel* method of hot glass air entrapment, using the technique of Swedish overlay (see Figure 48, p53.) In his research, Flavell noted that the surfaces of a flattened vessel needed to be slightly convex when being cased/ sealed to allow any surplus air to be expelled. (Flavell, 2001, p.96).
On re-analysis on previously successful samples, it was noted that in some cases the sides had been supported on two edges, with two unsupported, which could have created a venting/slumping effect, releasing expanded air via the two supported sides.

Figure 122: Re-evaluating early tests supported by walls on two sides seemingly backed up the hypothesis for the slump method.

Figure 123: Sample showing visible slump of the layers in a successful early test.

Whilst tests using glass props and corner shards had been ineffective previously, and general results when supporting walls were used inconsistent, it was proposed that the bend in relation to the expanding air had not created an adequate ‘slump’ to allow the centre to fuse before the outer edges sealed.

New test pieces were made to explore this idea, slumping layers *over* a convex mould to avoid trapping unwanted air. This theory presented an alternative to attempting to slumping the top layer *concavely* from the centre outwards using bending points and bubble squeezes added in the firing schedule, or by trying to protect the edges from sealing.

By slumping the glass layers *over* a *convex* mould, it was reasoned that the bottom layer was likely to begin to slump before the top layers fused to it, thus allowing gradual slump from the centre outwards, reducing the quantity of air trapped in the central cut-out, and less likelihood of edge-fusing which resulted in trapping the air before any excess air had been evacuated.

The firing temperatures were revisited and adjusted after further literature research. Pilkington defines the float glass ‘transition point’ of glass as 565°C, the viscoelastic phase 580°C - 640°C, the bend point as 650°C and the softening point as 715°C (Pilkington [Accessed 22/4/13]). Changes were made to the firing programme as follows: a long soak at the pre-transition temperature of 520°C was introduced to ensure an even heat throughout the glass before reaching the ‘bend to slump’ temperature range. The tack fuse soak point was set at 671°C based on documented slump range of float glass of 650°C -760C (Lundstrom, 1983), and analysis of bend test results. The annealing point for standard float was set at 548°C (NSG Group, 2013, p.2. [Accessed 3/7/14]).

Example Firing Schedule (<max 16mm total thickness) Including soaks when glass is still solid (520C) and in the mid slumping range (671C):

Ramp. Degrees C/hr	Temp. Degrees C	Soak Time
80	520	1hr
80	671	2hrs
150	800	1hr
FULL	590	-
40	548	2hrs
75	150	END

Figure 124: Tests investigating convex and concave ‘slump and sag’ methods to avoid excess trapped air.

Observation of the slump test outcomes suggested that, although some excess air remained trapped, it had been pushed away from the central apex of the slump by the convex shape of the mould, and gathered at the outer edges of the fuse.

Figure 125: Slump tests showing air pooling pushed to the outer edges by the slumping action of the glass.

This method was retested using a concave slump, with an elevated upper layer based on the principle of evacuating the air from the centre outwards, and a higher slump. The results of repeated tests using the slump and sag processes appeared to successfully back up the new hypothesis.

6.8.2 **Investigating Vertical Firing**

In parallel to the technical exploration, ideas were developing for artworks based on an eventual successful resolution to the problem of ‘air pooling’. A test piece was produced, to explore the idea for the artwork ‘Legion’, in which with multiple air entrapment figures were incorporated in rows, using several layers of cut-out sheets within the piece, separated by uncut layers of the same thickness.

A speculative experiment, stacking the glass layers on their edge so that the glass fired vertically rather than horizontally, was tested, initially with a single figure, then multiples, with the reasoning that some rising air might evacuate. The layers were stacked in an upright position in the firing with layers standing on their narrow edge, supported and kept together by vermiculite walls, but with supported sides. This was important in discovering whether the cut-out forms would distort when stacked horizontally (as the height of stacked artworks would be restricted in a shallow laser kiln with upper elements).

The vertical sample had been tested in the same firing as the thinfire paper tests, with the exposed upper edges covered with double-layered thinfire paper. The test was influenced by technical notes on float glass bending by Gelder (Antonio 2009) suggesting that bending causes tension in the outer surface. Testing the vertical firing was explored to reduce horizontal surface tension as well as the potential to allow excess air to escape vertically.

The results of the vertical test in the firing were initially unclear. The air had not expanded sufficiently at 765C with 45min soak to ascertain whether pooling had occurred as well as texture from the walls and devitrification (see Glossary) clouding the view through the surface of the glass. The vertical test was re-fired to a higher temperature.

Schedule for vertical firing test 1:

Ramp. Degrees C/hr	**Temp. Degrees C**	**Soak Time**
200	635*	3 hours
FULL	800	45min
FULL	590	0
50	553*	1hr 10mins
20	505	0
75	150	end

**The soak was increased by 5C to account for the difference on the probe/ kiln thermocouples.*

The results of the re-fired test showed that air had expanded and pooled around the upper edge and in the head of the figure, showing that the air had travelled to the top of the piece, but remained sealed in. Testing the vertical firings explored the ability of air to escape vertically, but the effect on the cavity proved of more interest: the increasing pressure in the glass from top to bottom was clearly significant with an intermediate near uniform air pressure through the depth, with the lower part contracting and the top bulging, and both top and bottom rising; instead of the more even distribution of air through the cut-out design retaining the overall shape in the horizontal firings.

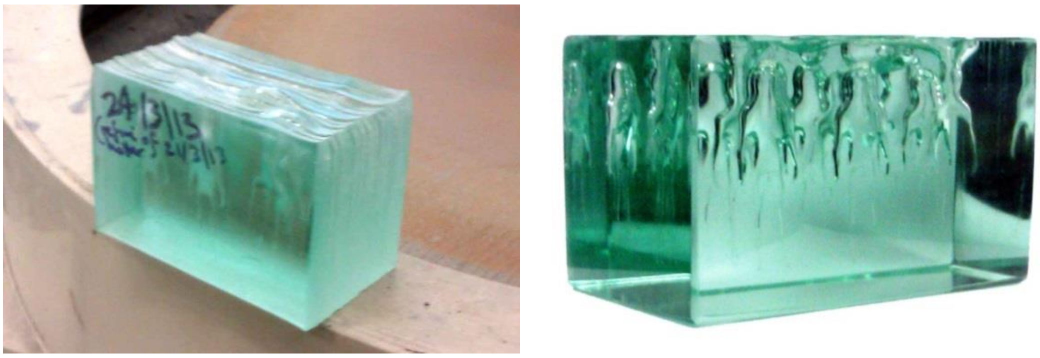


Figure 126: Vertically-fired test showing air pooling visible at the vertical edge seam, and figures' heads expanded. Shown before grinding and polishing (left image), and after (right image).

The tests demonstrated that the edges had sealed along the vertical seams, trapping the air at the top surface. A second vertical test made with multiple figure layers and fired in the subsequent firings, showed a similar result. In the images above, the air pooling can be seen at the top edge of the piece (which was nearest to the heat source –the kiln elements).

The outcome suggested that the air was moving upwards in the glass as it expanded. Some of the air in the cut-out figures had escaped, and the heads had kept their intended shape, whilst it appeared that in others the top edge had sealed, keeping the air in and forcing the heads to expand. This led to increased understanding of the behaviour of the glass and expanded air, generating ideas for hypotheses for evacuating the air pressure in the next stage.

6.9 Evaluation of Stage 5 Testing Routes

The results of the vertical firings showed that the expanded air had moved upwards but was trapped by the sealed edges. The slump and sag methods demonstrated that the convex former created a gradual slump which evacuated excess air to the edges of the design, but again it had been trapped in by the pre-sealed edges.

It was hypothesised that a way of assisting the escape of the excess air in the vertical test could be:

- To insert a small pre-cut ‘vent’ channel from the cut-out channel to the edge, to potentially evacuate the air pressure. Using the poor thermal conductivity of the glass to an advantage, the cut vent would potentially seal from the outer edge inwards, allowing some air to escape but then sealing in remaining air for the design as the glass became more molten, due to the direct heat on the outer surfaces from the elements.

A new supposition proposed to resolve the sag and slump route was:

- To increase the slump height as a means of preventing the edges from meeting until the central area had sealed.

These hypotheses formed the basis for the Stage 6 tests which led to resolution of the air pooling, described in the next chapter.

6.10 Stage 6: Breakthrough Tests: Rationale for 'Air Pooling' and Successfully Controlling Air Entrapment in the Kiln

It was proposed that in order to eliminate the pressure of the expanded air, and thus avoid the 'air pooling' the pressure had to be released via an escape route. As attempts to achieve this through temperature control by rapid cooling and cooler edges was not conclusive in the test firings, two propositions were put forward, as possible solutions:

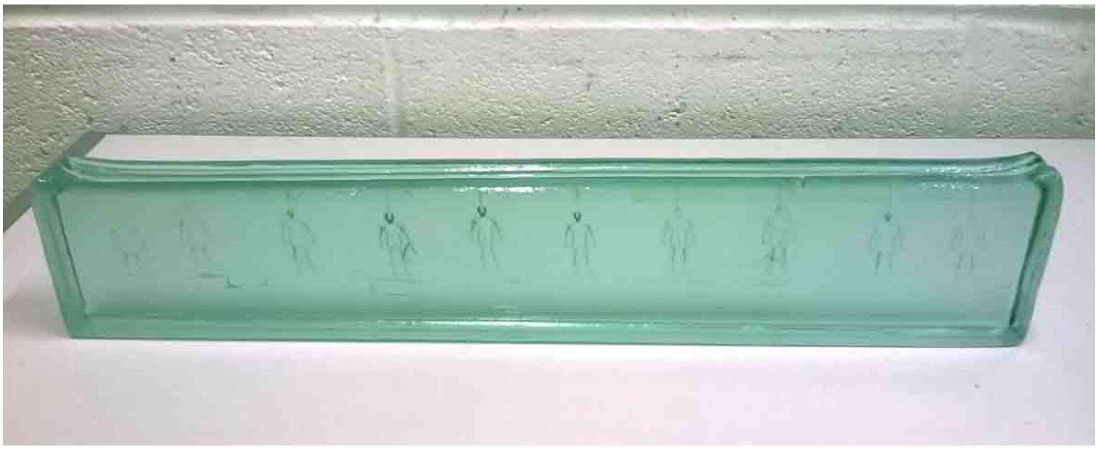
- The High Slump Theory: Introduce a 'high slump' causing the glass to sag and fuse from the centre outwards, thus avoiding edge sealing until reaching top fuse temperature when the full fuse occurs.

- The Cut Vent Theory: Introduce pre-cut fine lines into the design to vent excess expanded air, which re-seal at top (full) fuse temperature, trapping sufficient air for the entrapment.

6.10.1 **Testing the 'Cut Vent Theory'**

A sample was designed to test the proposition that a cut channel could assist air evacuation, and then seal as the glass reached a semi-liquid state at the outside edge. This would theoretically solve the air pooling problem, based on the thermal conductivity of the glass and the observation that the outer edges exposed to the heat source, soften and seal first.

A cut-out layer of identical figures was made with waterjet-cut 'vent' channels leading from the top of the figures' heads, up to the outer edge of the glass. The cut-out layer was sandwiched between plain layers and placed vertically in kiln, supported by ceramic kiln-shelf walls. It was fired using the revised firing cycle used in the slump and sag testing route.



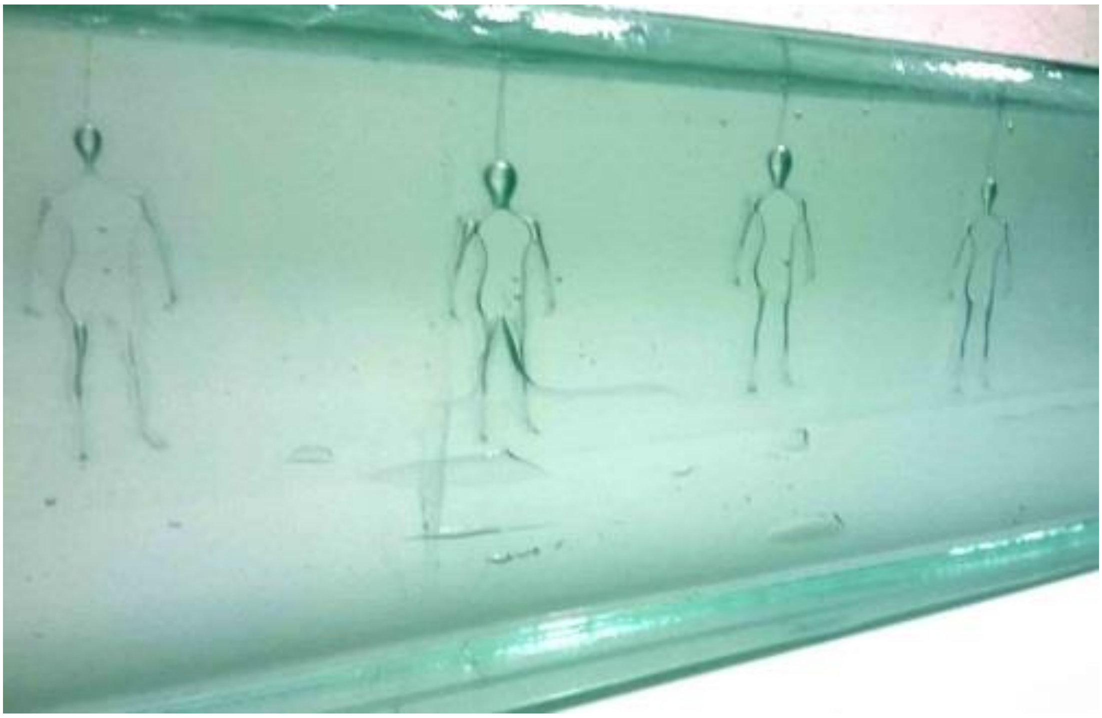


Figure 127: Testing the 'Cut Vent Theory': figure test with waterjet-cut vents fired vertically (test after second firing).

The sample was re-fired as the first test to 790C with 1hr soak had not created satisfactory bubble formation (probably due to the heat protection from the kiln-shelf support walls). The second firing (image above) showed that most of the air had escaped from the cut-out, leaving an outline 'veil' of the figure, and a small air bubble trapped in each of the figures' heads. A fine veil remained in place of the contracted cut-out channel.

Example firing cycle 16/8/13, 'cut vent' theory re-fire:

Ramp. Degrees C/hr	Temp. Degrees C	Soak Time
80	520	1 hour
80	671	2hrs
FULL	830	1 hour
FULL	590	0
40	548	3hrs
75	150	end

This test result confirmed the 'cut vent theory': The vent channels had sealed, after evacuating most of the air from the waterjet cut channels which were subsequently sealed by the increasing heat. The softening top (outer) surface trapped the air that remained in the cut-outs. Based on this observation, it was proposed that varying the size of the vent channels would affect the amount of air released from the cut-out.

The waterjet cut vent was the same depth as the cut-out channel (4mm) and the width of the cutting jet (+/_0.75mm). A smaller vent channel would potentially seal sooner in the firing process. Adjusting the channel size offered a route to controlling the amount of air retained or evacuated.

New tests were developed using different methods of cutting finer vents. Testing routes included engraving, diamond-wheel cutting, and using sections of smaller glass pieces (here titled '*section venting*') to cover the upper surface, whereby fine gaps between the glass sections acted as vents. Vertical and horizontal vents were tested, as well as combinations of types of vent channel.

A vertical firing was again tested, this time with diamond-wheel mitre cut (v-shaped profile) vents, again in a flat-bed kiln (K19) with ceiling elements. The results showed that more entrapped air had stayed in the cut-out channels with the mitre cut vents and the air bubbles had again risen to the heads of the figures and expanded them, whilst the figures' legs contracted. A small amount of air pooling had occurred around the head of one figures but the remaining majority were successful.

Figure 128: ‘Legion’ artwork trial piece, vertical firing. Air can be seen to have risen into the upper part of the figures, and slight air pooling visible in one of the rear figures.

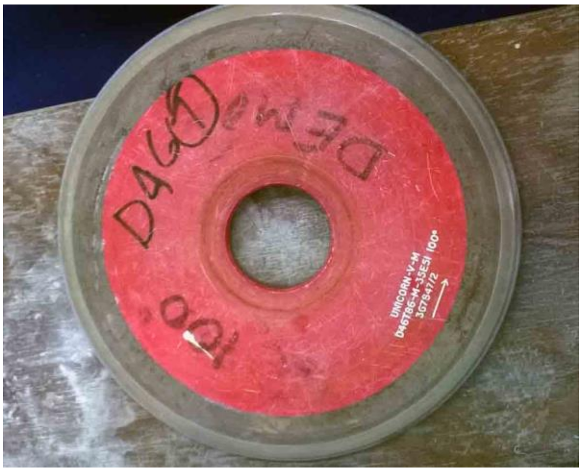


Figure 129: Diamond mitre wheel used for fine cut vents.

The results supported the theory that the edges near the heat source were becoming visco-elastic and sealing first and that some parts of the component reach the visco-elastic stage before others. It also showed that the air was travelling upwards in the glass as it softened, rising into the hotter, more liquid area.

Tests were undertaken firing the design horizontally. It was supposed that firing the layers horizontally would allow an even distribution of air across the design. All the results using this method successfully contained the air entrapment within the intended design. The most successful method of venting to release sufficient pressure for accurate design retention was with the diamond mitre wheel cut vent, fired horizontally. Cut to an approximate depth of 0.5mm, it produced a fine v-shaped groove which sealed during the firing, leaving a very subtle veil and retaining sufficient air entrapment in the contours with no air pooling. Firing horizontally meant that the air entrapment was evenly distributed in the cut-out channel, with excess air evacuated through the vent and sealed from the outer edge. This theory was successfully replicated using wheel cut vents in numerous small scale tests.

Figure 130: Testing the 'Cut Vent Theory': various successful scale and glass thickness figure test with diamond wheel-cut vents

After identifying the successful 'cut vent' method of controlling air entrapment with repeated test tiles with a specific kiln and test conditions, it was necessary to repeat the test in different kilns, and analyse the results, in order to make the research transferable.

The reason for repeating the test in various kilns was to calculate what adjustments might need to be made to account for new variables such as variations in temperature measurement and heat distribution from one kiln to the next, and the size and positioning of the work inside the kiln in relation to the thermocouple. It was found that if the kiln temperature was accurately calibrated, the method could be successfully applied to numerous kilns with minor adjustments to account for the height of the glass in relation to the thermocouple.

Figure 131: Testing the 'Cut Vent Theory' with expanded variables: scaling up to multiple cut-out air entrapment layers.

The method was tested and successfully repeated in various kilns. The variables for the design were then expanded, changing the quantity of cut-out layers, to find a process which could be used to develop different configurations of artwork with air entrapment in multiple layers, and in order to scale up the work.

The challenge in applying the cut vent technique to scaled up artwork lay in the variables which changed with the form of the work. For example, in scaling up the figurative form as an air entrapment, the variables of air volume, glass sheet size, proximity to heat source, and distance from air void to edge all then changed.

Figure 132: Increasing scale of cut-out contour and glass shape with the 'Cut Vent Theory'.

To investigate applying the successful technique from the test tiles into artworks, a new question was posed and then tested:

- Would numerous waterjet cut sheets fire uniformly when stacked within an artwork of multiple layers? :
- How might air entrapment be affected when the volume of the air void was increased?
- What would happen if the same design was scaled up?
- Could combinations of sandblasted and waterjet-cut contours be fired successfully in the same piece?

Figure 133: Testing multiple layers of air entrapment and various scale pieces using the 'Cut Vent Theory'

The technique was applied to ideas for the development of the body of artworks in which components could be repeated. Successful results proved the 'Cut Vent Theory' was a replicable method for controlling air entrapment using various forms and artwork compositions with minor modifications to the kiln programme for variations in position in relation to the thermocouple or alternative kiln (when using a previously untested kiln it is recommended that the accuracy of the temperature reading is determined in advance, through pilot tests or via a probe.)

Variations in glass tint (blue tinted float, grey, bronze and Optiwhite low iron float glass) were successfully tested with adjustments to the firing schedule based on Pilkington annealing data, and variations to the top fuse temperature based on observation of the bubble formation.

6.10.2 **Testing the 'Section Venting Theory'**

The venting theory was further tested using alternative methods of cutting the channel. The idea of breaking up sections of glass which would then re-seal at the fuse temperature, is a method of expelling bubbles from a piece of fused glass documented by Lundstrom (1983). The connection was made between this and the wheel cut channels as a means of venting air pressure. Further literature on cutting glass into sections to avoid trapping bubbles in fused work was later found in Bullseye Tech Notes which supports the theory.

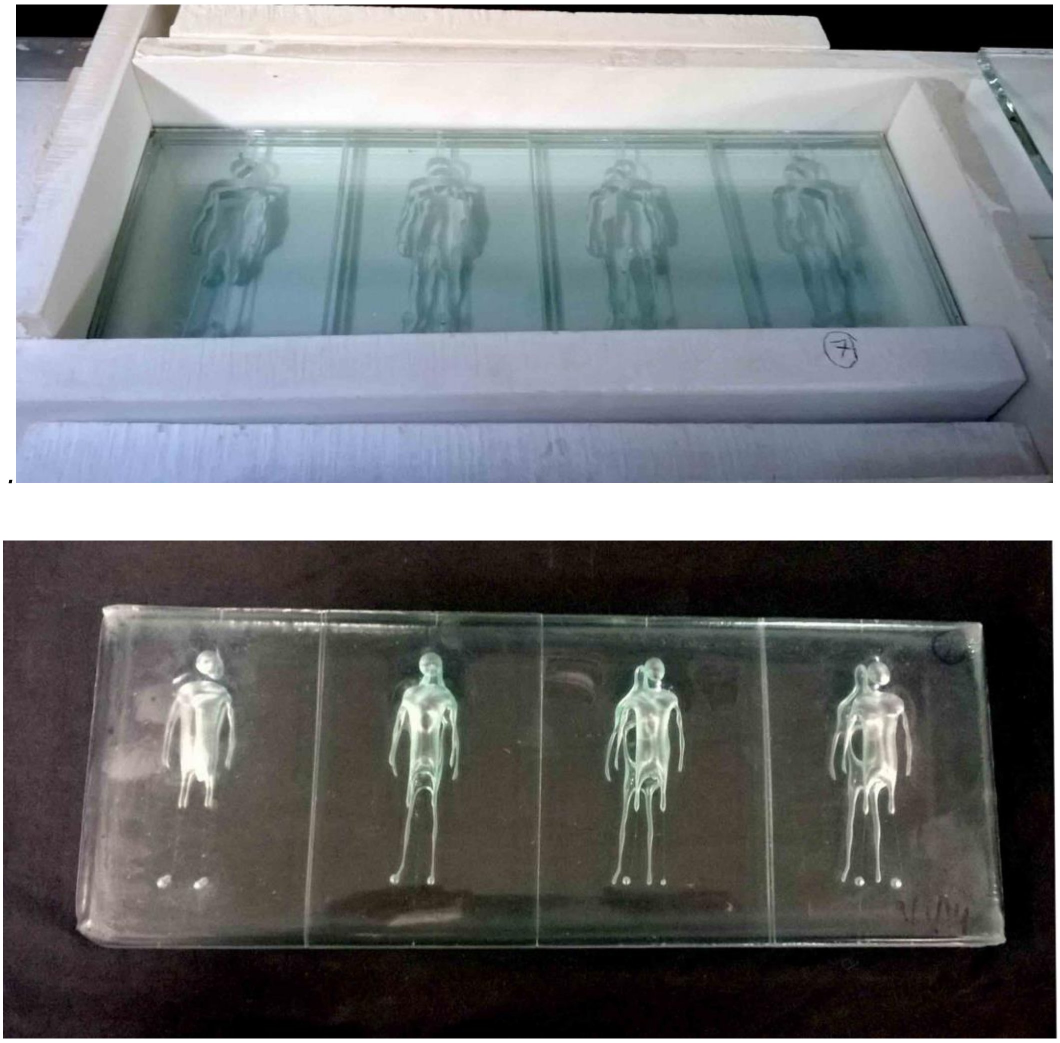


Figure 134: Testing combined Wheel Cut Vent and Section Vent tests, double layered air entrapment with sections of glass applied above the cut-out layer.

The successful outcomes of the technique on small scale pieces led to further testing of the technique on an increased scale. A three layer piece was made, using the 50cm cut-out design based on the multi-layered artwork *Host* (see Chapter 8). The middle layer contained the waterjet cut contours whilst the base layer was cut into sections of approx. 7cm in area and pieced back together like a jigsaw in the kiln.

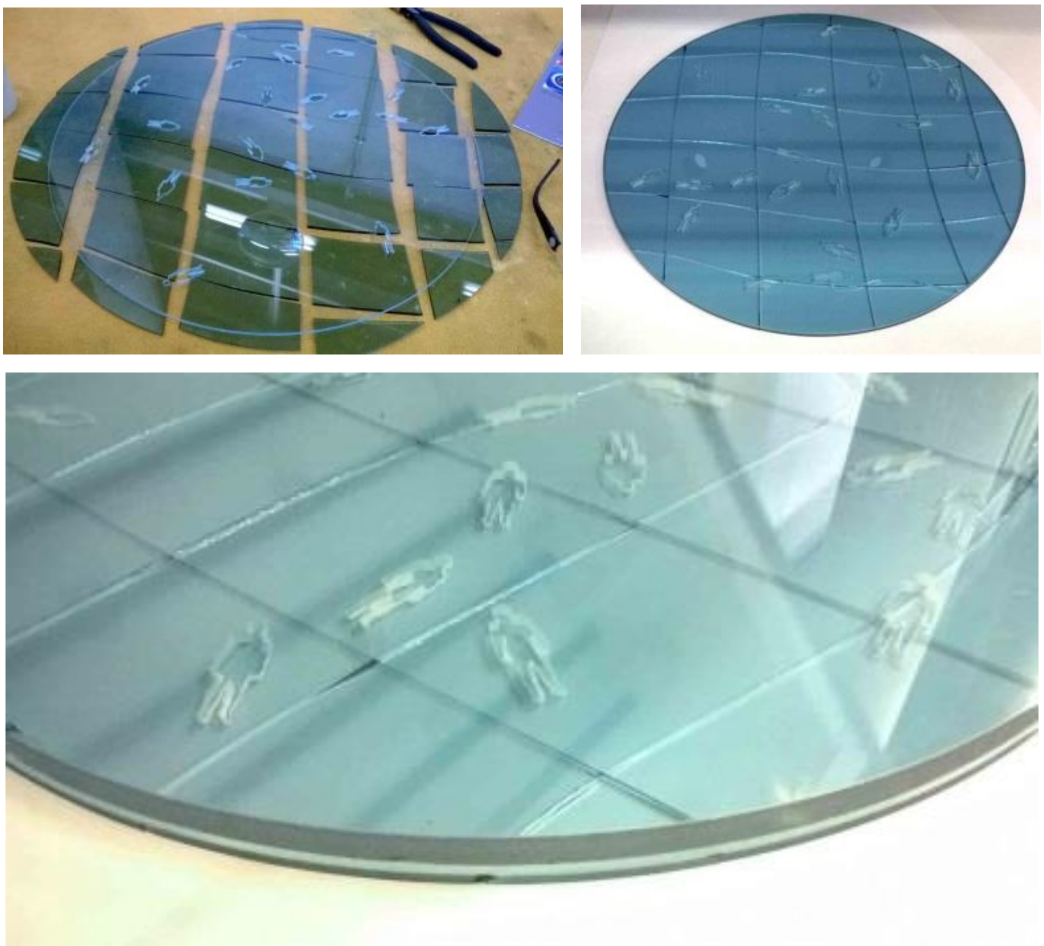


Figure 135: 'Section Vent' testing for circular architectural glass panel – 3 layers (10mm top layer on 4mm cut-out layers and sectioned base layer).

Figure 136: Section vented flat-plane piece in the kiln and post-firing

Figure 137: Fired flat panel and air entrapment detail

The middle cut-out layer and plain top layer were placed on top and fired. The outcome demonstrated that air entrapment succeeded where the cut-out motifs intersected with the sectioned vents, evacuating the excess expanded air in the same way as the wheel cut vents. Future research would further investigate whether the sections are most effective on the top or base layer.

This avenue offers several new options for large area flat plane work where high slump venting is not viable because of the kiln dimensions, or monumental sculptural pieces in which glass sheets are larger than can be cut using a diamond wheel. The original waterjet cut venting test had released a significant amount of air from the design, leaving an ethereal ‘veil’ effect which, with more investigation, could also be used as an interesting aesthetic development of these ‘cut vent’ and ‘section venting’ techniques.

Waterjet cut vents in particular applied to large-area flat plane air entrapment designs, with relatively large area cut-out channels, is an avenue which has great potential for the future in terms of designs cut on the waterjet for architectural applications. This needs further exploration and would require significant safety testing.

6.10.3 **Testing the ‘High-Slump Theory’**

Successful testing of samples over convex moulds and concave slumping indicated that air pooling could be avoided through a gradual slump of the upper layers to ensure that the outer edges fused last, thus minimizing the opportunity for excess expanded air to be trapped between the layers.

Experiments were undertaken which would further confirm the theory that excess trapped air caused by expansion was the cause of the ‘air pooling’ problem. This led to the hypothesis that related to the ‘bubble-squeeze’ starting point: employing the natural ‘slump’ or bend of the glass sheet (c.671C) to expel air bubbles. The High Slump hypothesis was that when the upper layer of glass is suspended and heated to full fuse to bend from the central point outwards, the trapping of excess air is avoided by suspending the outer edges of the glass so that they cannot seal as the piece heats.

Figure 138: Left to right: testing the ‘High Slump Theory’ (before/after firing).

The ‘High-Slump’ method was achieved by using kiln-shelf walls to raise the top layer(s) of sheet glass to a substantial height, which would ensure a bend in the glass as it slumped expelling excess air concavely. This method is particularly applicable for the creation of flat-plane pieces, for panels and architectural applications.

The test samples were gradually scaled up and layers and glass thickness for the slump layer explored. Single and double layers of 4mm and 6mm float as well as tests using 10mm sheet were investigated. The added weight of the two sheet of glass in the slump layer or using thicker sheets correlated with the success of the slump. Increasing the wall height also increased the success rate of the air entrapment.

Figure 139: Successful air entrapment tests investigating the ‘High Slump’ theory.

The outcomes of the tests supported the ‘High Slump’ theory. This hypothesis was consistent with anecdotal methods used by glass fusers of *avoiding* unwanted bubbles in sheet glass, in which slivers of compatible glass are added as edge supports to slightly raise the top layer and release air. The theory also correlated with the principle behind the ‘bubble-squeeze’ soak in glass fusing.

Whilst tests based on bubble squeeze and edge support procedures had initially been misleading due to unsuccessful results in initial tests, gaining an understanding of the thermal conductivity of glass and air and the behaviour of the air expansion led to critical thinking to modify the process in order to account for the added variable of the air entrapment layer.

Figure 140: Name plate flat plane high slump tests exploring scaled up design and increased slump height.

Figure 141: Kiln-controlled precision air entrapment detail using high-slump method

The ‘High-Slump’ technique of air entrapment is particularly suited to flat plane pieces with single-layer cut-outs. The high slump method offers an alternative solution to cut vent channels, which is useful for those without wheel-cutting facilities or skills, and in pieces in which channels cannot be feasibly wheel-cut. It also is applicable where the slight veiling effect from the cut vents would be an issue, perhaps in applications such as architectural glass panels and signage. Combinations of the new methods can also be applied depending on the specifics of the application.

6.11 Findings from Stage 6 Tests

The venting hypotheses are consistent with observations of outcomes of tests with frit, intermediate layers, ground surfaces and textured glasses (rough or textured surfaces) as an aid to vent air. (An explanation for the tests that successfully fused without these measures, proposed by Gelder, was that at a microscopic level, random striations on the glass surface in some sheets of glass, resulting from the float process, might vent the air in a similar way, whilst unsuccessful tests probably did not have these striations.)

The anomalies of the successful unvented air entrapment tests cannot be *fully* explained scientifically because at the intermediate temperature range (the temperature range of glass processing), modelling the behaviour of glass becomes difficult, as the thermal history rather than just the instantaneous temperature is important in the structure of the glass, and thus its physical properties (Cooke & Howells, 1998, p.3). This leads to scientific ‘unknowns’ in the structural behaviour of the glass as it changes from a solid to a liquid, meaning all scientific variables cannot be measured.

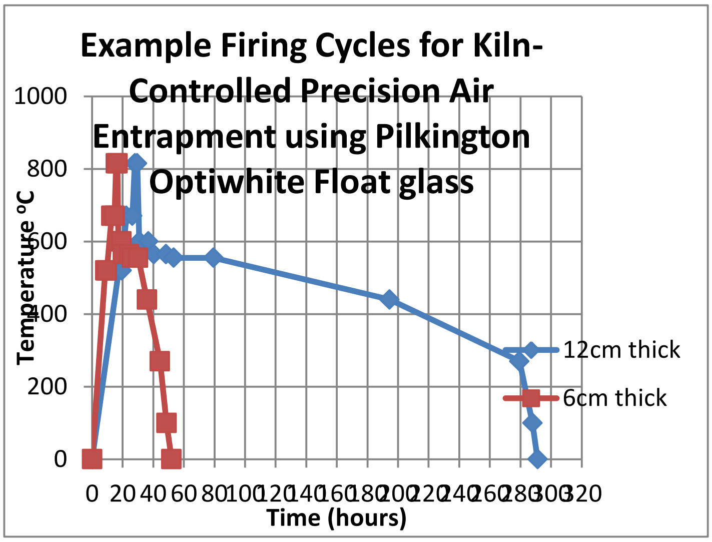
The thermal conductivity of glass is equal in all directions, but the thermal conductivity of air is lower. The heat transfer rate through layers of air/glass will be slower than through solid glass. The time taken for the glass temperature to reach tack fuse (layer bond) temperature will be less through the thinnest dimension and therefore the rate of heating needs close control to aid air evacuation before the edges are sealed. This was achieved by slowing the ramp speed, along with the additional measures to ensure the evacuation of expanded air, as outlined in this chapter.

Below are a series of practical outcomes which were found to facilitate the process of Kiln-Controlled Air Entrapment in order to successfully create and replicate precision air-voids using the kiln:

- Fine vents applied between the cutout and the edges of the glass evacuate excess air which expands during the heating process, and seal upon full fuse, trapping sufficient air to create the air entrapment design.
- Slumping upper the layer(s) above the cut-out in flat plane work avoids the problem of encapsulating expanding air by fusing from the centre

outwards, letting the edges seal last, but retaining sufficient air in the cutouts for the air entrapment design.

- Fused float glass over the size of approx. 7cm square in area must be vented, slumped or sectioned to avoid air pooling.
- A minimum number of layers of the same thickness as the contoured layer are required above the contoured layer to contain expansion.
- Moderate ramp to 520C is advantageous (the required heating rate is variable dependent on glass thickness as a whole).
- A soak at 520C is beneficial (length of soak time is relative to the overall size of the piece) to ensure even heat throughout the glass before advancing through the bend/softening range.
- A slow ramp between 520C and 671C (max 50C/hour) is advantageous in multi-layered firings, reducing the temperature differential through the piece, to minimize air pooling.
- A ‘bubble squeeze’/ tack fuse soak at 671C assists the successful fuse.
- Varying the top fuse temperature and soak time above between 740C and 820C allows the modification of bubble characteristics.



6.12 Kiln-Controlled Precision Air Entrapment Techniques

The '*Cut Vent'* method, whereby:

- Assisting the air evacuation process through pre-prepared wheel-cut cut vents which seal as the glass is heated, after releasing expanded air.

The Cut Vent method is suited to multiple-layered air entrapment work for thick fuses. This offers the opportunity to cleanly fuse float glass layers, with only fine veil lines as a residue, preferable in many applications than 'air pooling' trapped between the glass sheets. A by-product of this technique is its application to produce deeply layered, plain float glass fuses without air entrapment.

The '*Section Venting'* method, whereby, similarly:

- Assisting the air evacuation process by hand-cutting the glass into sections and reassembling them to create vents which seal as the glass is heated, after releasing a percentage of the expanded air from the air entrapment design.

The '*High Slumping'* method, whereby:

- Supporting the upper layer(s) of sheet glass on high walls to create a sufficient gap between the cut-out layer and upper layers, and applying heat to slump the upper layer(s) onto the layers below from the centre outwards, thus avoiding edge-sealing until after the point at which excess air is trapped.

7. Application of the Technical Investigation towards Artworks

Having established and tested a series of transferable hypotheses for controlling air entrapment in the kiln, routes for application of the findings into a variety of types of artwork were then investigated, with the aim of discovering the potential of the technique in artistic terms. Specific applications in kiln glass were explored: multiple-layered forms in which the interior of the glass is exploited; 3D contouring through digital processes; large area, flat plane objects, and hot glass roll-ups. The following sections document the process of development from test outcomes to the articulation of artistic ideas.

7.1 The Development of Air Entrapment from Single to Multiple-layered Assemblages

To explore the potential of the Kiln-Controlled Precision Air Entrapment technique in sculptural applications, emphasis was put on the incorporation of air as 'form' within solid, spatial, three dimensional artworks. Following resolution of the technical issue of 'air pooling' and the successful transfer of the technique between kilns, multiple firings were undertaken for the artwork series *Figures within Space*. The aim of the work was to create a clear glass space through fusing multiple clear layers and a single air entrapment figure, which could be repeated at different points within the artwork.

Figure 142: Single air entrapment contours within clear glass space, repeated firings - development of Figures within Space Series of artworks

The Cut Vent method was applied to multiple layers of air entrapment within a single piece, to test an idea for an artwork entitled *Host*. Increasing scale of both the cut-out of air entrapment to 4mm and 6mm cut-outs and the glass sheet size, cut-out and layer quantity was successfully pursued.

Figure 143: Preparatory work scaling up multiple layered pieces using the Cut Vent technique for the artwork 'Host'.

Figure 144: Image showing the increase in scale from the first 'Host' test piece at11cm diameter to the maquette for the largest at 50cm diameter.

Various firings for artworks of up to 14 layers in depth with three intermediate cut-out layers were developed, gradually increasing size. The tests proved that the technique was effective in pieces of numerous and various scales. The method was successfully tested in different kilns which became necessary as the scale of the work was increased and casting kilns were used. The technique was further developed for multiple, stacked horizontal cut-out layers incorporating the air figure to develop artwork *Legion*.

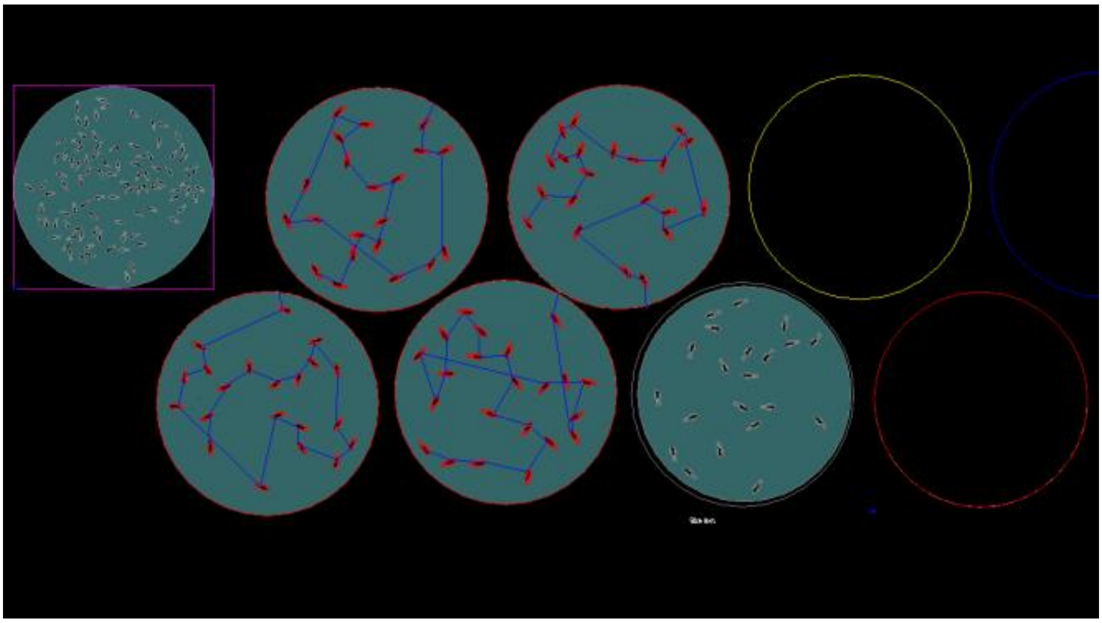


Figure 145: Programme for five air entrapment cut-out layers in IGEMs software for *Host II*

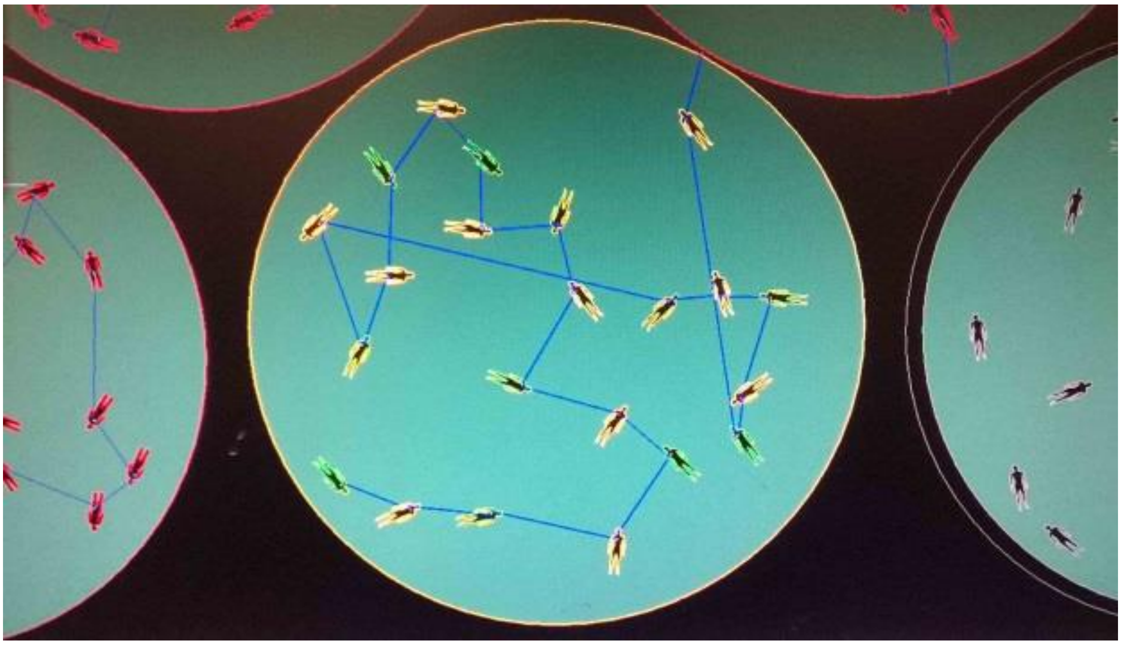


Figure 146: Host air entrapment cut-out layers programmed in IGEMs waterjet software (detail)

Figure 147: Grinding and polishing Host II on the air tool

The multi-layered pieces were ground and polished using conventional coldworking methods once annealed. Alternatives to standard float glass were also tested to explore colour options in the artworks: Pilkington Optiwhite Low Iron float glass was successfully fired with adjustments to the kiln programme based on slightly higher annealing and fusing temperatures, and used in the final body of work, as were Pilkington blue and grey tinted float glass.

Figure 148: Left-right: Host I and Figures in Space artworks. Blue tinted float and multi-layered using Cut Vent technique.

The tests were repeated in separate kilns successfully to create multiples of the same design to develop the *Legion Series* artwork. *Legion* and *Host* incorporated the possibilities of multiple and repeated cut-outs using waterjet technology to create identical rows of air figures within a single artwork. Legion Series was made up of three units separately fired in different kilns.

Figure 149: Left: Loading kiln for Legion Series: horizontally fired multiple layered cut-vent artworks, in top loader kiln (K19); Right: firing a replicated Legion Series piece, transferred into casting kiln 1.

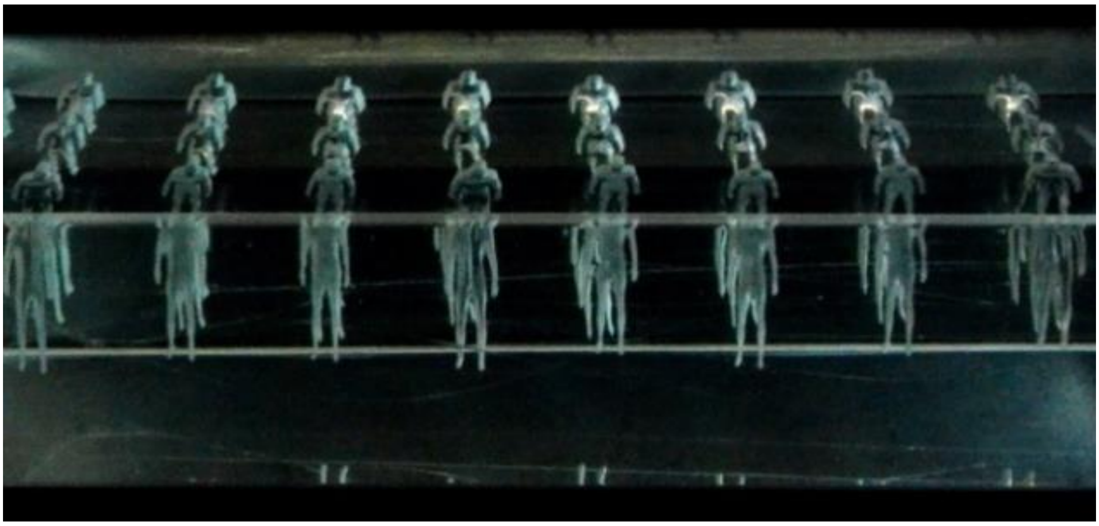


Figure 150: Detail of trial piece multiple cut-vent firing for Legion Series (Pilkington Optiwhite Low Iron glass).

The method was gradually retested, adapted and extended to create multiple cut-out layers in a single firing on a large scale, extending the technique to a sculptural scale and depth so that the interior space of glass could be explored for creative expression in the artworks.

Figure 151: Legion Series in progress - multiple repeated application of the cut-vent firing process fired in various kilns (Pilkington Optiwhite Low Iron glass).

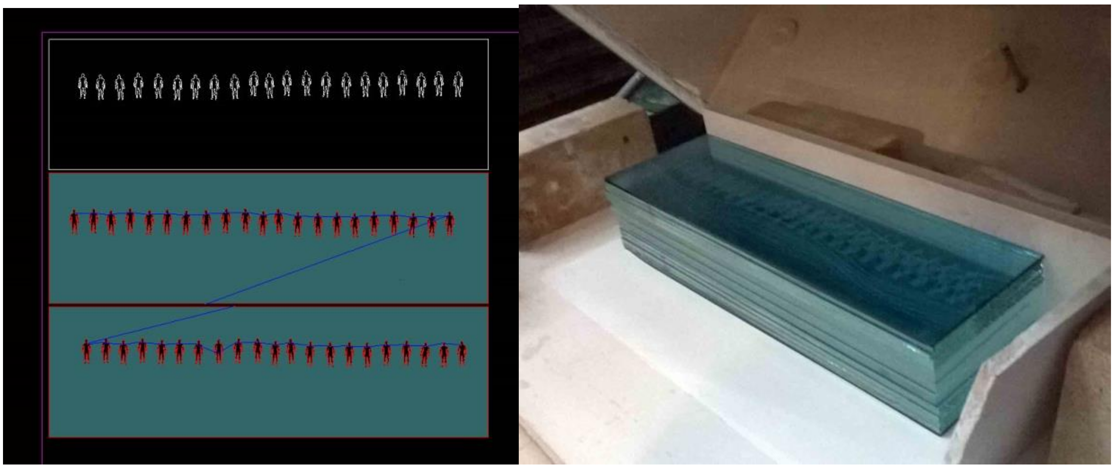


Figure 152: Left: Legion AutoCAD design programmed in IGEMS showing separate cut-out contour layer designs. Right: Scaled up stacked multiple layered Legion artwork loaded for firing.

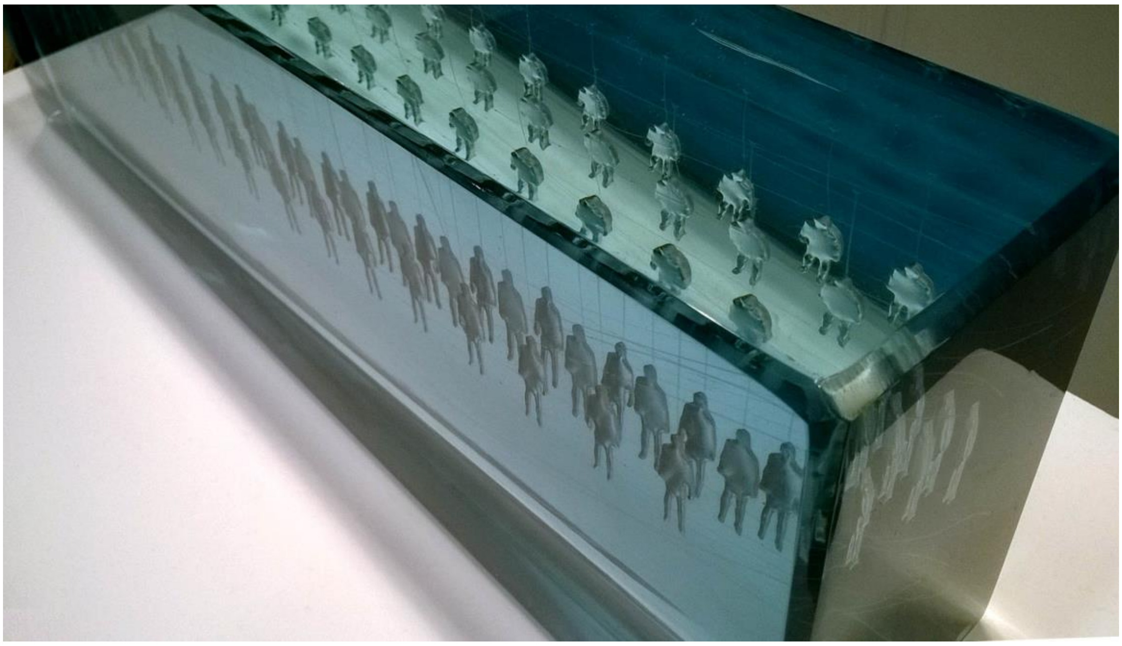


Figure 153: Detail of fired and cold worked artwork 'Legion' (2015) 50cm x 10cm x 15cm

The Cut Vent method in multiple layers can be seen in the artworks, *Host I, II and III*, and the *Legions* Series of pieces. These artworks demonstrate the transferable kiln-controlled precision air entrapment with varying sheet thickness, increasing scale and increased cut-out complexity.

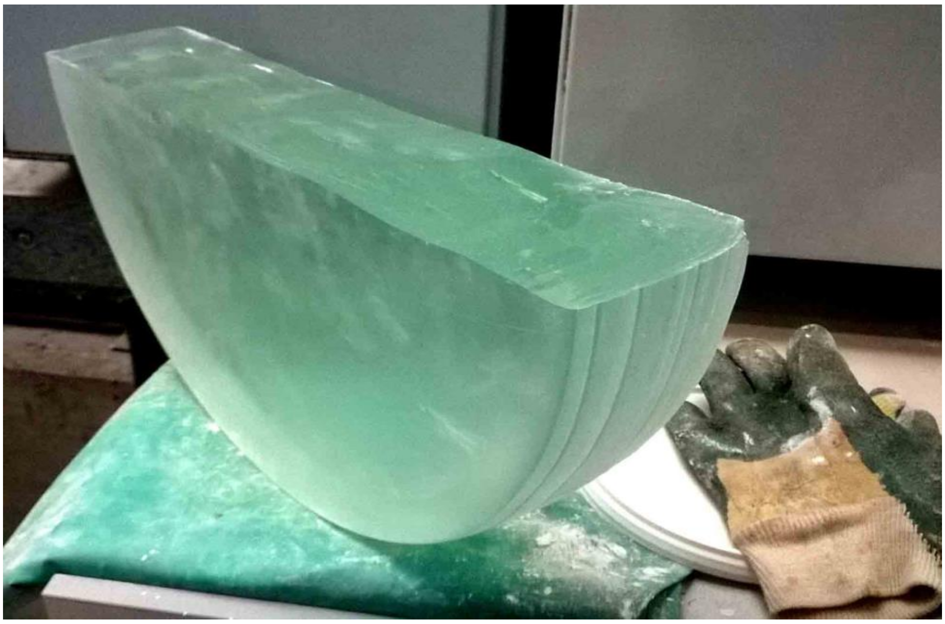


Figure 154:Multi-layered Optiwhite float glass air entrapment artwork Corpus in progress, 50cm wide x 25cm high x 12cm depth

Corpus (above in progress) represents the largest scale artwork achieved during the research, at 50cm diameter and 12cm glass thickness with six cut-out layers of air entrapment using the Cut Vent method. It takes the technique forward in a large sculptural configuration.

7.2 Development of Air Entrapment for Fine Detail (Sandblasting)

Finely detailed air entrapment using multiple sandblasted layers was explored for the artwork *Secret Diary*; and in a single-layer small scale flat plane in the artwork *Memory Echo.* All the testing results were successful using the Cut Vent air evacuation method, with air entrapment retained within the design contours and no air pooling.

A series of tests were undertaken to determine the relative heat and soak time necessary for very fine sandblasted air channels, and the kiln programme refined accordingly for the two x 3mm layer *Memory Echo* and six x 6mm layer *Secret Diary*.

Figure 155: Digital image of scanned postcard for sandblast air entrapment

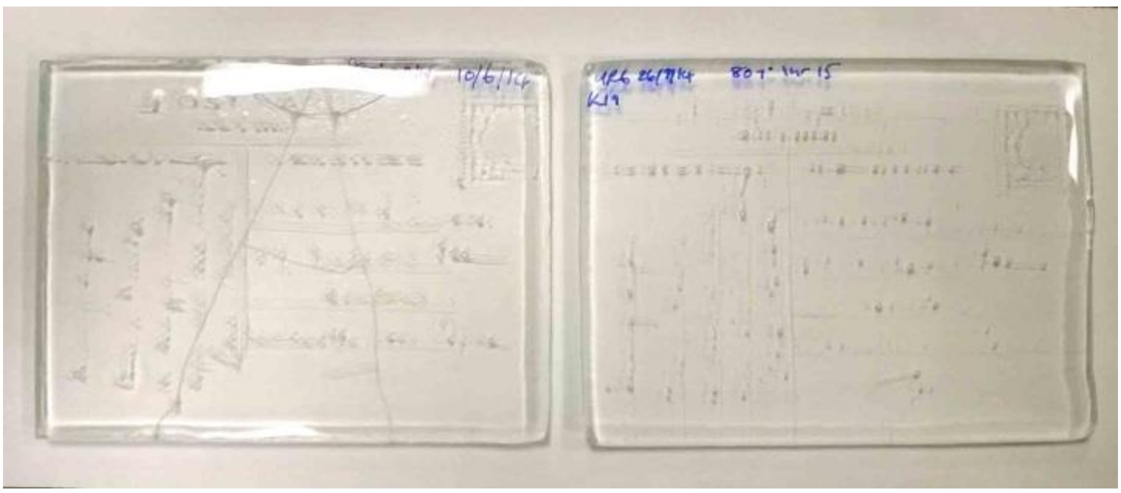


Figure 156: Test pieces determining the correct firing cycle for fine detail air entrapment in optiwhite glass

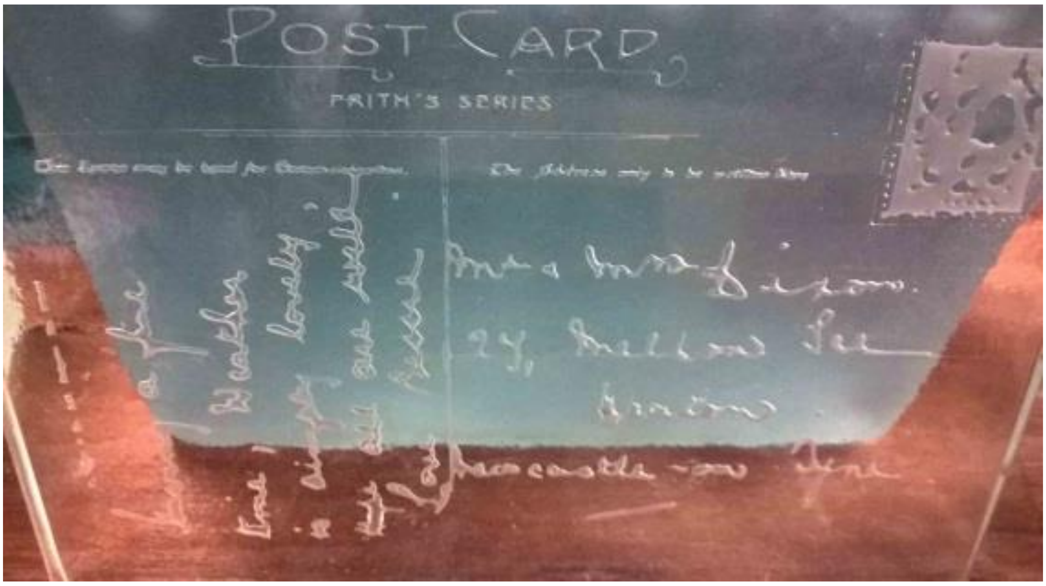


Figure 157: Developing single-layered fine detail sandblasted air entrapment for 'Memory Echo' artwork - 'Cut Vent' technique (size 15cm high x 10cm wide x 6mm deep), low iron float.

Figure 158: Development of multiple-layered sandblasted air entrapment for Secret Diary artwork ('Cut Vent' technique), low iron float glass.

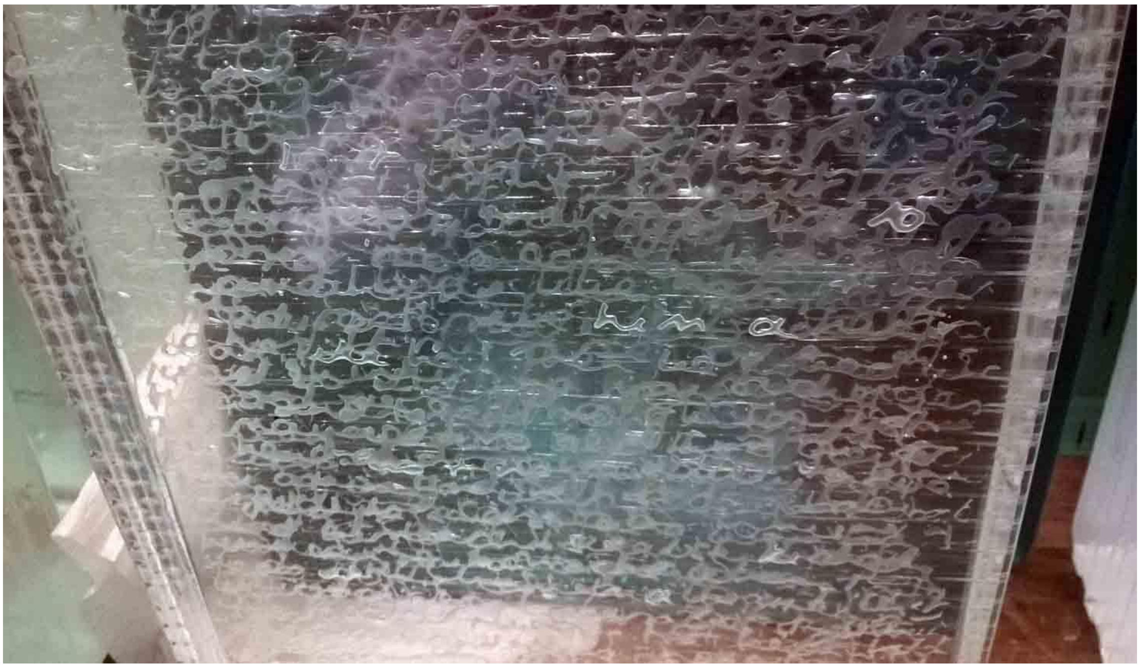


Figure 159: Detail of multiple-layered sandblasted air entrapment for Secret Diary artwork (‘Cut Vent’ technique.)

For future application of the technique when increasing/decreasing the scale of the cut-out channels, or indeed changing kilns, initial tests to determine the correct firing temperature are necessary (as in the application of any studio glass kiln programme).

The extension of the air entrapment from single and multiple-layer cut-outs to three dimensional void contours was a significant advancement in the technique. This led to the possibility of working with the internal transparent mass of the glass sculpturally. This progression is discussed in the next chapter.

7.3 Development of Air Entrapment in Three-dimensional Void Contours

A progressive technical advancement made possible by the use of the waterjet is ‘three dimensional void contours’. *Three-dimensional void contours* are cut-out layers assembled without intermediary layers, to create a shaped 3D void space for air entrapment. This represented a significant jump in the scale and air volume of air entrapment within the body of a glass piece. With the method of stacking cut-out sheets directly on top of one another, and the Cut Vent air evacuation method, the creation of large bubbles with three-dimensional internal contours became possible.

Similar to 3D printing innovations whereby products are built up through laminated layers, the research takes a similar approach to creating three-dimensional cut-out voids by effectively laminating the *negative* contours of layered cut-outs. The intention was to develop highly detailed three-dimensional air bubbles. The thinner the glass layer and more detailed the cut-out, the more detail could be incorporated into the three dimensional bubble form.

Initially tested on a small scale, three-layer, 3D void contours were developed, to explore ideas for the *Deconstructed Being* artwork series (below).

Figure 160: 3D Contoured air entrapment figures for 'Deconstructed Being' after firing.

Figure 161: Development of three-dimensional void contours for the artwork 'Deconstructed Being'.

The three-dimensional void contour enabled more detail in the air figures such as front and back, knees, calves, feet, neck, face, and so on. The thinner the glass sheet, the more detail and layer quantity could be applied to the void contour.

The *Entity* artwork series emerged from the development of this technique. Initial pieces used three assembled layers of 4mm sheet cut-outs, with three layers of plain 4mm glass above and below the cut-out contours. Vents were wheel cut from the shortest distance from the cut-out to the outer edge, usually the head and feet of the figure. Gradually the scale of the figures was successfully increased to test the technique with larger air entrapments. Top fusing temperature and soak time were adjusted to increase or decrease the inflation of the figure.

Figure 162: Entity II and III in progress, Triple-layered 3D void contour air entrapment.

Figure 163: Entity III in progress. Variations in top fuse temperature allowed control of inflation of the figure. Triple-layered 3D void contour air entrapment before grinding and polishing.

Figure 164: Precision Kiln-controlled Air Entrapment 3D figure realised artwork.

The scale, colour and layer quantity was further progressed using a combination of blue tinted and Optiwhite float glass in the piece below. After firing, the outer shape was cut on the waterjet. This is at the limit of the depth of cut for glass using the 3-axis waterjet cutter at the University of Sunderland, at approximately 4cm thick, however the potential for further shaping air entrapment artworks using new 5-axis waterjet technology has much potential for future development.

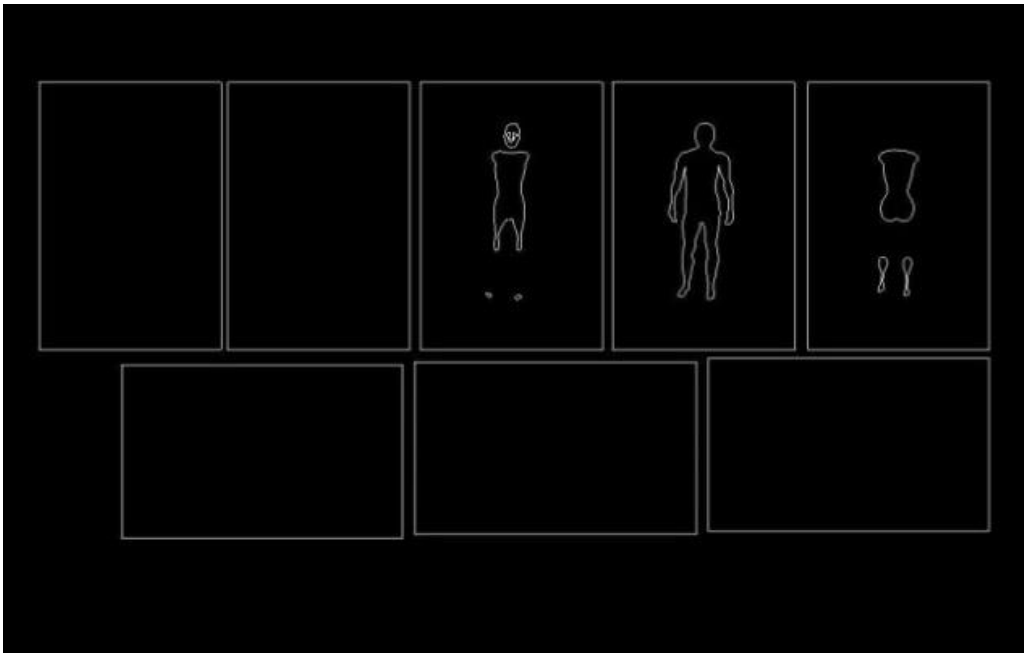


Figure 165: Three-layer 3D Void Contour design in AutoCAD

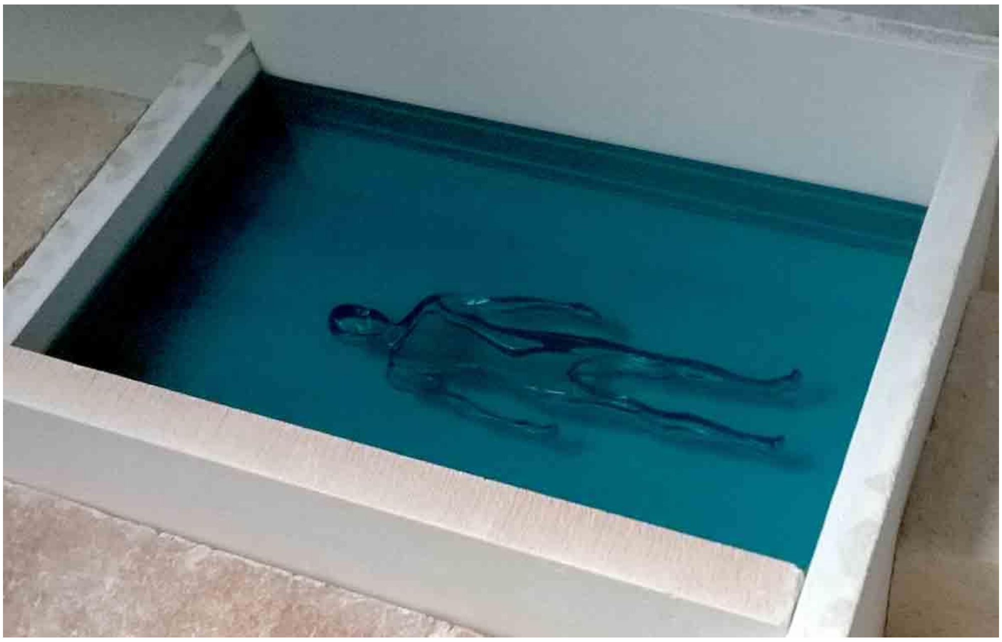


Figure 166: Kiln-controlled Air Contoured 3D figure after firing.

The technical development of three-dimensional void contours, made possible by the Cut Venting method, expanded the air entrapment achieved in the kiln beyond the original expectations of the research project. The level of scale and detail of the air entrapment accomplished using this method took the options for artworks beyond the level of recognisable lettering and sophisticated imagery that *Ariel* had previously reached, to 3D forms with front and back elevations.

Figure 167: Precision Kiln-controlled Air Entrapment 3D figure after firing (right) and after secondary waterjet cutting to create the outer shape: front view (left) and reverse view (right). Size: H28cm x W14cm x D4cm.

Further exploration was undertaken moving on from formal geometric shapes in the outer form of the artworks. The piece below considers containment of the air figure within an outer solid figurative form. This area has much scope for further exploration through the incorporation of waterjet cutting and cold working to develop the shape and forms of the artworks after kiln firing.

Figure 168: Idea for artwork in development: waterjet-cut outer form with internal 3D air entrapment figure.

The new multiple-contoured air void technique generated new creative avenues for three-dimensional air-forms within the body of a glass artwork. The 3D figure produced at this stage was designed using AutoCAD software by drawing the layers the contours individually, designed by the researcher to create the detail of the figure.

To further increase the intricacy and scale of the figures for *3D Void Contoured* air entrapment, it was envisaged that a computer modelling programme could be used to map a 3D object in detail, taking more accurate contours from it for the cut-out layers. Rhinoceros was identified as the software to achieve this, a programme available at Sunderland University of which the researcher had some previous experience. The digital mapping possibilities of Rhinoceros software allow a *three-dimensional* form to be designed and modelled to scale. This gave the opportunity of modelling an accurate scale drawing of a potential figure and slicing its form into 4mm cut-out contours for the waterjet. The results of this inquiry are discussed in the Chapter 7.5, Development of Air Entrapment using 3D Scanning and Digital Modelling.

7.4 Development of Air Entrapment Combining Multiple Methods

Artworks with combined layers of sandblasted and waterjet-cut 2D and 3D contoured air entrapment were also successfully produced using the *Cut Vent* method. Application of colour-tinted float glass was investigated successfully using blue, bronze, Optiwhite, grey and green float and combinations of colours.

Figure 169: Artwork development combining three-dimensional contoured figure and fine sandblast detail in standard Pilkington float and blue-tinted float.

Figure 170: Developments combining three-dimensional figure and two-dimensional digital text in Pilkington Optiwhite and blue-tinted float.

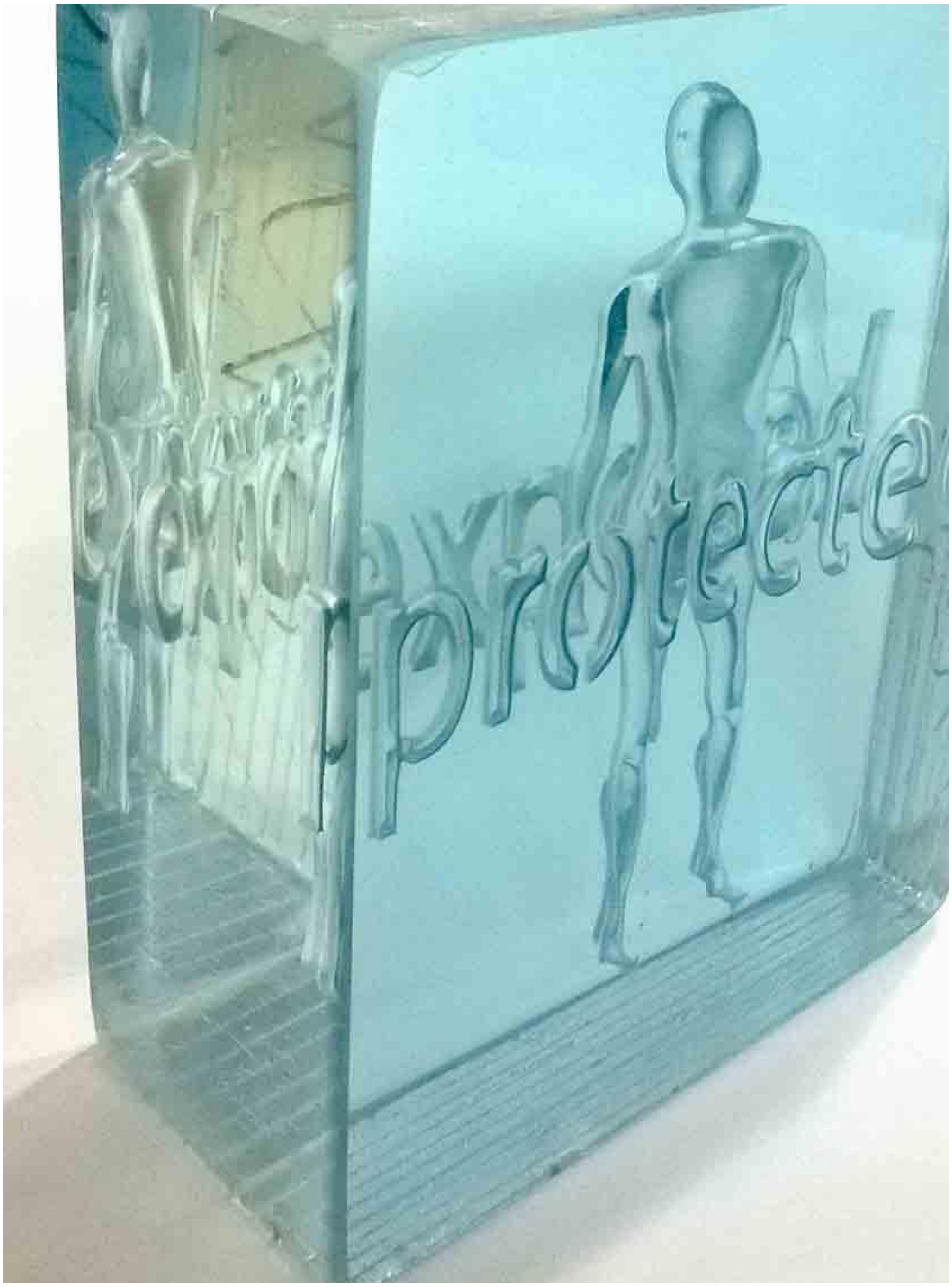


Figure 171: Detail of artwork development: three-dimensional contoured figure and two-dimensional digital text (Pilkington Optiwhite and blue-tinted float.)

7.5 Development of Air Entrapment using 3D Scanning and Digital Modelling

A further avenue leading from the three-dimensional air void contours, made possible by the cut-venting method, was the possibility of a significant progression in highly detailed three-dimensional precision air entrapment, using 3D modelling software. Whereas the first 3D figure's void contours were designed free-hand in three or four layers in AutoCAD; 3D modelling and 3D scanning technology offered the opportunity to scan physical objects directly from life. The digital mapping possibilities of Rhinoceros software allowed a three-dimensional form to be modelled accurately and to scale, and used to create highly intricate multiple-layered cut-out contours.

3D Scanners scan across and around an object's full surface, collecting digital points, from which a triangulated surface mesh is generated to construct a 3D model. It is used to capture models of forms that would be difficult and expensive to generate from scratch using CAD (Shillito, 2013, p94).

From the artistic inquiry exploring the subject of self and concept of humanness, the idea had developed to visually represent the inner 'self' using air. To develop an air entrapment, kiln-contoured self-portrait, a 3D photographic portrait was initially attempted using 3D photo-meshing modelling program 123D Catch which was unsuccessful in knitting together the 3D image. A discussion with visiting Newcastle artist Joseph Hillier brought the opportunity to create a personal head and shoulders 3D Scan using his portable scanner. The resulting 3D head self-scan was digitally modelled in Rhinoceros software at 0.5 scale (see image below).

Figure 172: 3D modelled scan of the researcher's head as triangulated surface mesh in Rhinoceros software

The head scan was then vertically 'sliced' into 4mm sections, the same thickness as the float glass sheet. With assistance from supervisor Colin Rennie, the sections were 'unrolled' into 4mm layers using *Grasshopper* software. The 4mm layers were then imported into the waterjet's IGEMS software and programmed individually as cut- contour CNCs for the waterjet.

Figure 173: Cut-contours in IGEMS: 'unrolled' head sections ready to waterjet cut from 4mm float glass sheet

Once waterjet cut, cut-out layers were vent-cut on each layer using the diamond wheel and assembled to form the negative 'head space' as air entrapment ready for firing.

Figure 174: Assembled cut-out contours of researcher's 3D digitally scanned head. Complex 3D void for air entrapment before cut venting and firing.

Figure 175: 3D Void Contour self-portrait reverse view.

As the largest scale individual air entrapment attempted to date, it was unknown how the volume of air would react to the firing schedule. The piece was fired over 12 days. The resulting form incurred some distortion due to the contraction of the air bubble, however the air entrapment appeared otherwise very successful.

Figure 176: 3D scan self-portrait air entrapment in progress after firing, before polishing.

More development would fully resolve the idea as an artwork; however the technical progress of air entrapment from 3D scanning technology is a substantial move forward for the research with exciting possibilities for the future.

The transfer of a real physical object (or person) into an intangible air entrapment form has huge potential for artistic development in the view of the researcher. The results generated innovate and hold potential for future investigations in the combined fields of digital technology and kiln-formed glass.

Figure 177: 3D Void Contour air entrapment self-portrait after polishing, detail.

The incorporation of 3D scanning technology with the new technique of Kiln-Controlled Precision Air Entrapment has opened opportunities for creating highly complex air contour sculptures based on real-life artefacts and animate objects, from direct scans. Future technical experimentation into air-bubble control at this scale will yield further learning on the behaviour and control of the air void at this volume and layer quantity.

7.6 Development of Flat Plane Air Entrapment for Hot Shop Roll-ups

The successful development of air entrapment forms latterly inspired another avenue of exploration beyond the original scope of the project: the possibility to combine the new process of kiln-controlled precision air entrapment with roll-up forms, to return to air entrapment in hot glass. Fused flat-plane air entrapment panels, with a maximum of 4 layers, are thin enough to be manipulated on a blowing iron. By pre-fusing the panel in the kiln to the point at which the air entrapment has formed and edges have sealed (not to the full fuse temperature); the panel can be picked up from the kiln on an iron and rolled-up into new forms. This new method revisits air entrapment in its conventional *vessel* incarnation, but with the development of a new lightweight form and thin-walls.

The first kiln-contoured roll-ups trialled used 3mm Spectrum S96 glass due to its relatively low working temperature and theoretical compatibility with the furnace glass used in the University of Sunderland hotshop, which also has a CoE (see Glossary) of 96. Triple-layered waterjet cut air entrapment panels using the Cut Venting method were pre-fused to 671c with a 2hr soak. They were then reheated in the hotshop kiln to 600c (to avoid thermal shock when removed from the kiln), and picked up, shaped and manipulated on the blowing iron by glassblowing technician James Maskrey.

The vented air entrapment panels successfully retained their intended forms. The first attempt was made into a simple cylinder, the second expanded into a spherical vessel. The Spectrum S96 glass showed substantial seeds due to its texture, as in the original Spectrum kiln-formed tests.

Figure 178: Rolling up a flat plane air entrapment panel

Figure 179: Kiln-controlled precision air entrapment thin-wall roll-ups using Spectrum S96 glass with figurative imagery. Waterjet-cut Spectrum S96 glass, (glassblower James Maskrey).

Integrating the kiln-controlled air entrapment and hot shop process established an opportunity to develop thin-walled air entrapment forms with a large internal space. The waterjet-cut fused air entrapment panel, rolled up and manipulated on the blowing iron, developed a different visual aesthetic than that of the *Ariel* blown vessel: a more finely blown form with space to ‘contain’; and brought the use of digitally-generated text and imagery into the work.

Ideas for hollow forms as roll-up vessels emerged based on the theme of ‘protection and exposure’ using text. In ensuing attempts, to attain the desired level of clarity, 1mm float glass layers were tested using framer’s glass offcuts, and also revisiting the enamel flashed float glass of the early air entrapment pilot tests. The clarity of the float glass was superior to the Spectrum S96. The enamel-flashed glass created some interesting colour effects which have generated several ideas for future avenues of development.

Figure 180: Air entrapment text designs in Adobe Illustrator before waterjet cutting

Figure 181: Fused panels in the kiln prior to rolling up (waterjet cut float glass)

Figure 182: Thin-walled float glass air entrapment roll-up 'Shellcase' vessels, kiln-formed and blown float glass, 4mm thick.

Figure 183: Exploratory air entrapment roll-ups using framers float glass (left); and enamel-flashed float (right)

The method was refined with by torching the rolled up form to soften the join, and applying a thicker outer layer in the pre-fuse to avoid popping of the air entrapment when in contact with the direct heat of the glory hole. The control of text, its transparency and the clarity of the float glass were deemed satisfactory by the researcher for the technique to be applied in future artworks. Full resolution of the planned artwork is planned for future development using bronze tinted float glass. Both the *Cut Venting* and *Section Venting* methods can potentially be used in the pre-firing of panels for roll-up work.

7.7 Development of High Slump Air Entrapment for Flat Plane Work

Development of the Kiln-Controlled Precision Air Entrapment technique in architectural applications focussed on pieces which maximised the use of the flat plane with single layer cut-outs, which could be developed for wall-based artworks, installations, or site specific environments such as windows, doors or signage.

Figure 184: Name plate cut-out layer on the waterjet bed

The ‘high slump’ method was tested successfully, avoiding excess air via slumping to create a name plate panel using text, and then developed to produce the flat panel artwork *I.D.* using the figure. More research time would have allowed for larger scale artworks; however the pieces produced in the body of work show the opportunities for making larger works with this technique.

Interest has already been shown following exhibition of the work at *New Designers, London,* from potential clients for personalised signage using this technique.

Figure 185: Flat plane piece using ‘high slump’ method. Outer form waterjet cut and ground and polished after firing.

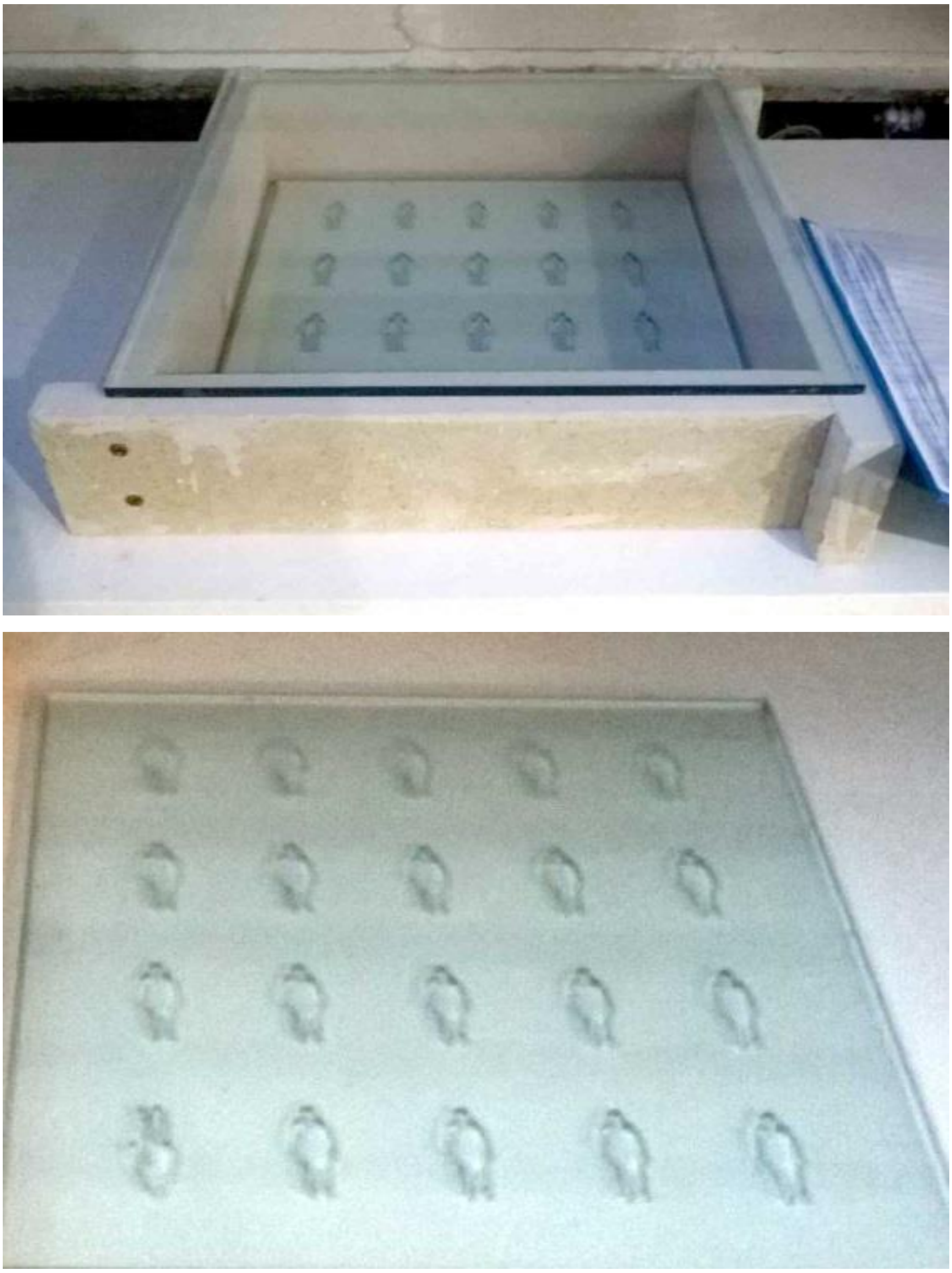


Figure 186: Wall piece 'I.D.' made using 'high slump' method. Outer form waterjet cut, and surface sandblasted after firing.

The artworks developed in the research (shown above) using this method demonstrate the beginning of possibilities for future development of High Slump air entrapment in flat-plane work as a method for creative expression in architectural glass art.

8. Creative Possibilities

This chapter documents the possibilities of Kiln-Controlled Precision Air Entrapment when applied to the making of a body of artworks to contribute to the advancement of glass art practice. It relates to the objective: 'to produce a body of work in order to articulate and demonstrate the creative potential of the research, and extend air entrapment into new directions in sculptural and architectural glass.'

This chapter illuminates the ideas which developed out of the inquiry and discusses them through description and evaluation of the body of artwork. The process of decision making, critical analysis, and reflection in practice which formed the artistic direction is explained.

8.1 The Body of Artwork

For the approach to the creation of artworks in this research, the relationship between the material, the process and the artistic ideas was critical. The medium forms part of a continuous reflective dialogue, both conscious and intuitive, between concept, technique and developing artwork.

One of the research objectives was to develop artworks using the new precision kiln-controlled air entrapment techniques in practice, and it was important that the artistic intentions could be met with integrity. This was achievable when a level of comprehension of the material's behaviour in the combined processes was reached through making, allowing for some kind of visualisation of the outcome determined by the chosen making process. That is not to say that the intention could not change upon critical reflection during an artwork's development, but a level of insight through practical competence had to be reached.

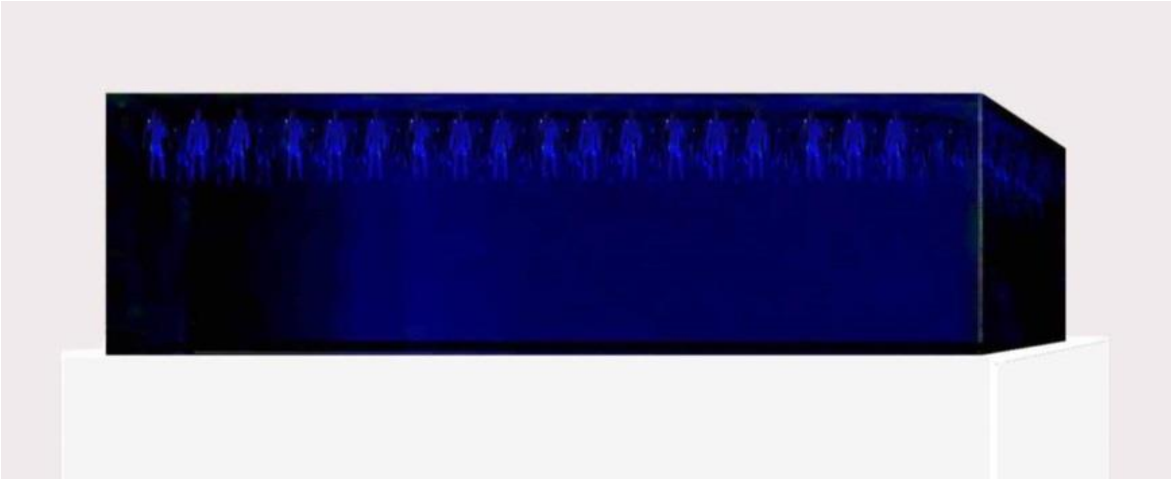


Figure 187: Adobe Photoshop rendering of the idea for *Legion*

Due to the uncharted nature of the investigation, a substantial period of the research was undertaken in the technical development of the kiln-controlled precision air entrapment technique. This then engendered both a familiarity with the process through which artistic ideas could be expressed, and the emergence of ideas from observation and reflection on the outcomes of the experimental investigations, both serendipitous and anticipated. With the successful transfer of the techniques between kilns, it was possible to develop the process towards the body of artworks in various configurations.

Artistic evaluation and interpretation of the outcomes extended the researcher's ideas for artworks beyond those initially envisaged. In this way, the material and making process come together, as 'conduits through which ideas are shaped and expressed, partners in the whole act of thinking and making' (Cummings, 2009, p.15), which forms glass practice. An on-going reflective conversation was applied through the process of creative development; evaluating each work and audience response to it retrospectively, and taking forward this new knowledge into further work.

The artworks were evaluated using a practice-based approach, combining artistic discourse, experiential learning (Kolb, 1984, p.41), reflection 'on' and 'in' action, (Schön, 1983, p.49), and describing and evaluating (Gray & Malins, 2004, p.113) and later in the research, through exhibition in the field of practice. Reflective methods used development of the artwork included a visual diary and journal; and dialogical encounters in the form of peer-review and supervisory conversation and discussion, and dissemination and review in a professional context. Out of this formed a conscious understanding of the artwork and its impact beyond the internal, which informed the critique of personal practice.

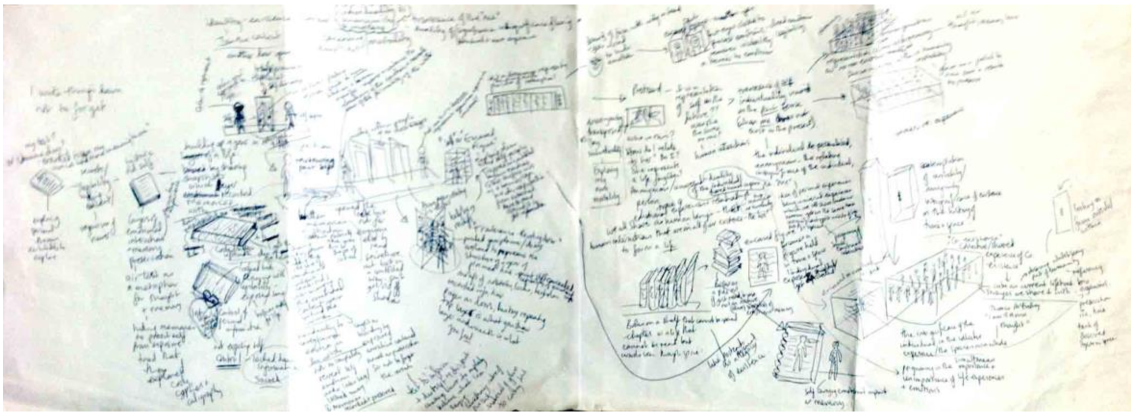


Figure 188: Creative mind map - sketched critical thinking to visualise the creative process.

The creative possibilities of the investigation were developed in symbiosis with new technical discoveries as they emerged and illuminated new pathways for exploration. New techniques supplement the repertoire of processes and skills, and extend the visual language, on which the glass artist can draw in the development of artwork; and developing them also can be a catalyst for new artistic ideas. As Markuu Salo, speaking in 2013 at Glass Skills CGS Annual Conference, explained of his creative methodology:

> *[Creating new techniques] in itself creates new forms of expression. Often, it is true that a new technique creates a form of dialogue which gives the work new content' (Salo, 2013).*

The use of air entrapment as text was initially borne of utilitarian purposes as a legible control to test for the precision of the bubble formation. Through reflection, this exploratory testing inspired the application of personal text in the artworks to express individual thought and memory using the ethereal quality of trapped air. *Control* of the air entrapment's ambiguity also became part of the artistic exploration as a subject and as a form of expression.

Both air and glass possess the distinctive qualities of transparency and translucency, making them appear both physically present and visually absent.

The use of air entrapment to represent aspects of the intangible and impermanent, and the glass containing it to represent physical space or indicate momentary time, was explored in the artistic direction.

The possibility of kiln-formed air entrapment artworks with internal depth through the accumulation of layers, to create solid blocks of glass, inspired ideas using both the material's interior and external form and surface. The transparency of float glass, when cleanly fused, allows a view into, onto and through the artefact simultaneously. The successful realisation of the new technique permitted creative avenues for the body of work which utilised the internal space of the material for expression in the way that it is often used in kiln cast glass art.

Metaphorical connections were made between the material properties of glass in its highly transparent state in terms of its visibility and clarity, and visceral associations both in nature: air, water, ice; and in its more contemporary references: as a lens or window - a means of exposure and protection. The subtexts generated by the material characteristics were explored in the development of the content of the artworks.

Air entrapment was first explored as externalised thought and memory, and presented as an indicator of individual identity glimpsed through text. An unknown relationship's brief interaction is memorialised in *Memory Echo (2014)*.

Figure 189: Memory Echo (2014) Joanne Mitchell. Optiwhite float glass, sandblasted kiln-controlled air entrapment, sandblasted reverse imagery.100 x 130 x 6mm

In *Secret Diary (2015)* text is merged in transparent layers to disrupt legibility, making it purposefully difficult to read and attain the meaning of the words. Glass and air's transparency both reveals and conceals its contents through the indistinct layers. The book limits access to the personal narrative, exerting some control over the self-exposure of the author.

Figure 190: Secret Diary (2015) Joanne Mitchell. Optiwhite low iron float glass, sandblasted kiln-controlled air entrapment, glass and wood case, ribbon, key.

In the development of *Secret Diary*, standard float glass was originally used. The glass's inherent green tint (caused by its iron content) was intensified with multiple layering, reducing the ethereal quality of the glass and visual transparency. Low iron float glass was used as an alternative, which retained a clarity similar to clear crystal, resolving the production of the work. The work explores the voyeuristic interest of the audience in the artist. An undertone in this artwork is cultural preoccupation with individualism and self-focus, and the significance placed on self-narrative in western art.

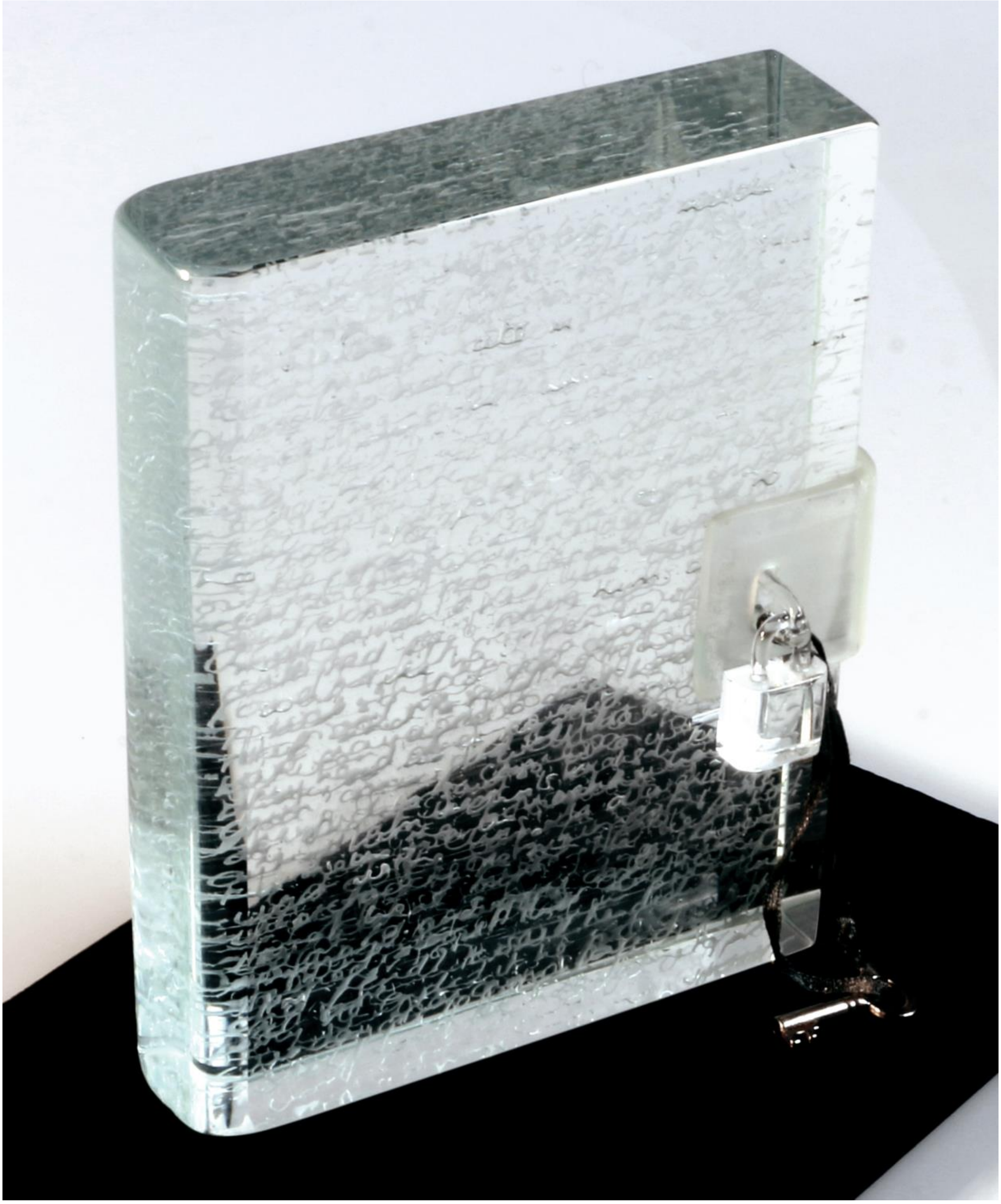


Figure 191: Secret Diary (detail) 2015, Joanne Mitchell

The cultural differences in ‘self’ as an individualistic or collectivist identity (Jen, G. 2013, p76), and self-identification with others became of interest. The air entrapment figure was explored initially as personification of the ‘inner self’.

The development of effective air-venting fusing methods created a new level of transparency of the material in deeply layered float glass blocks. This inspired a series of work portraying the individual as the figure and the ethereal quality of clear glass to represent time. The series '*Figures within Space'* was the first artwork to be resolved once the technical and aesthetic intentions were allied.

Figure 192: Figure within Space (2014) Joanne Mitchell. Blue tinted float glass, kiln-controlled air entrapment

The resolved techniques made it possible to incorporate deliberate air entrapment forms without interference from unintentional air-bubbles. This created a new aesthetic for the expressive use of air in solid float glass. Air is used in ‘figure’ form in this work to embody physical presence and implicit absence: the uninhabited, un-grounded form is used to suggest the impermanence of the body. The idea was taken further using multiple figures to explore existence within a moment in time as a common binding thread between individuals in *Figures within Space Series* (2015).

Figure 193: Figures within Space series (detail) (2015) Joanne Mitchell.

The researcher’s personal circumstance as a quadruplet was a point of reflection for exploring the notion of personal identity and individuality. The ideas touched upon in *Memory Echo* and *Figures within Space* led to consideration of connecting human experiences – humanity and the individual, both separate and immersed within it. These themes were further explored in *Legion* series of artworks.

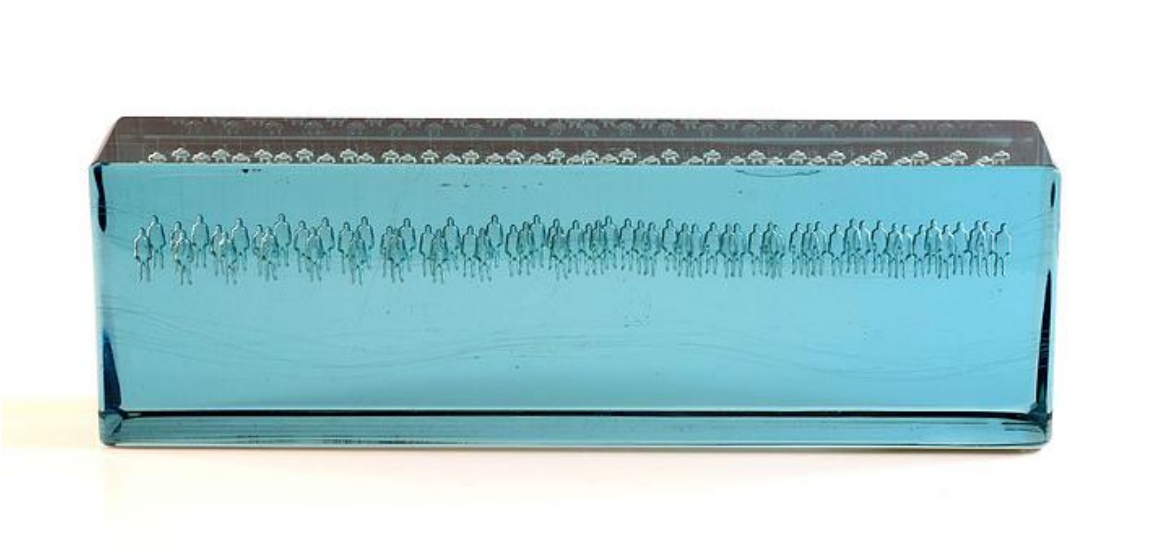


Figure 194: Legion (2015) Joanne Mitchell. Blue and optiwhite float glass, waterjet cut kiln-controlled multiple layered air entrapment.

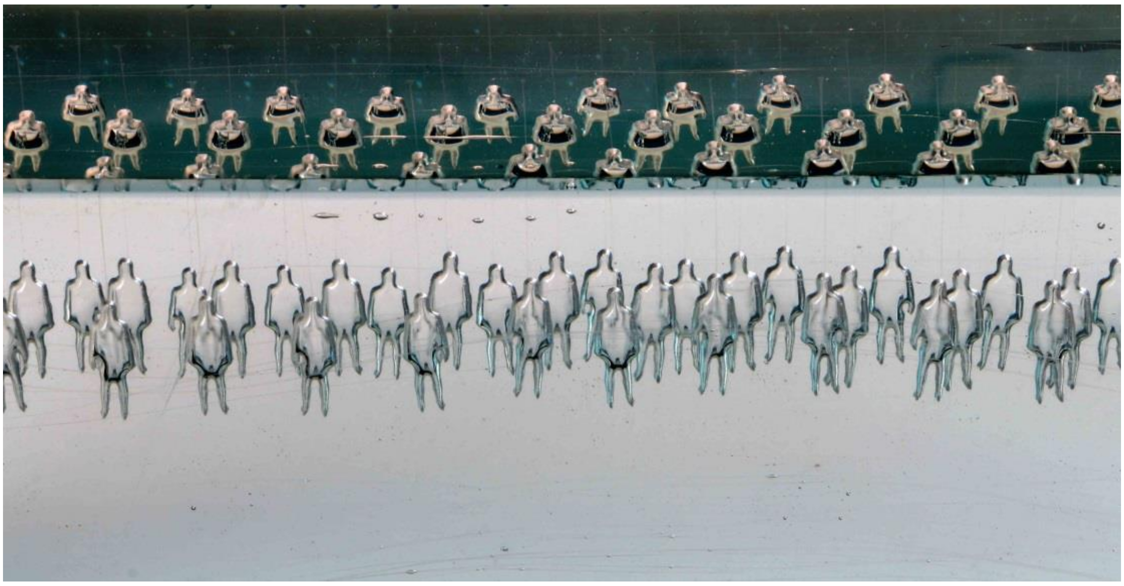


Figure 195: Legion detail (2015)

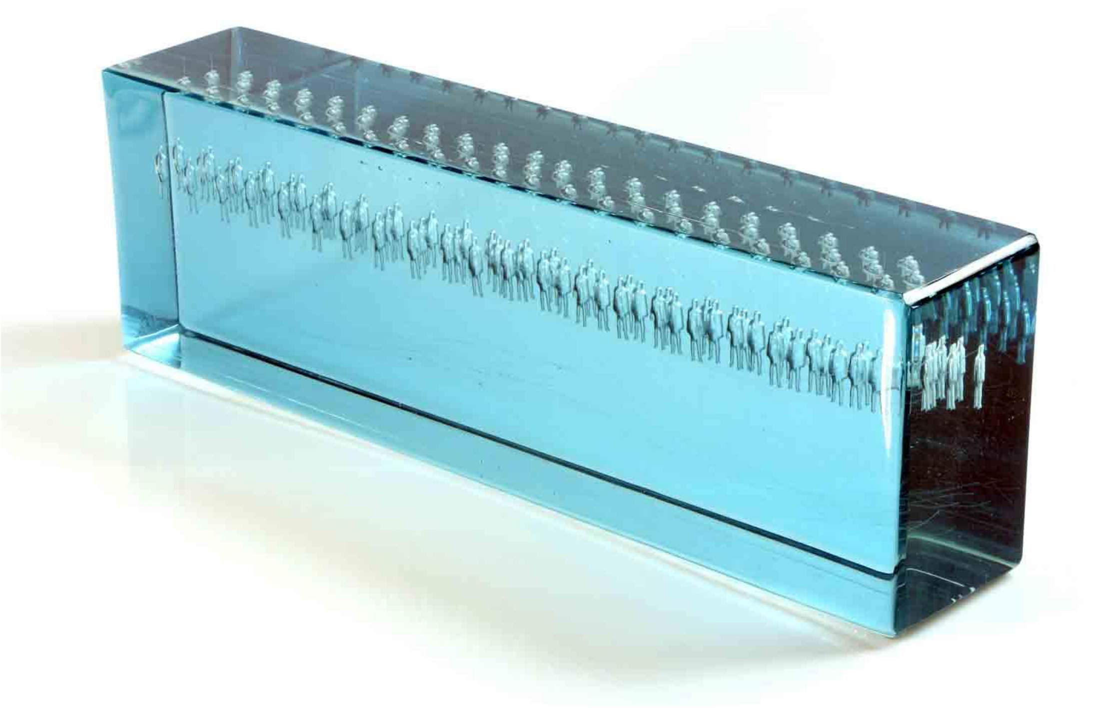


Figure 196: Legion (2015) 500 x 100 x 120mm. Blue and optiwhite float glass, waterjet cut kiln-contoured multiple layered air entrapment.

Legion (2015) explores the duality of human connectedness and isolation. This theme was also explored as a flat-plane piece *I.D. (2015)*.

Figure 197: Legion Series (2015) Joanne Mitchell. Optiwhite float glass, kiln-controlled precision air entrapment.

One of the objectives of the inquiry was to develop the scale and configuration of possible air entrapment artworks in new directions to advance the field of glass art. *Legion Series (2015)* advanced the formation of the artworks as a triptych and demonstrates the possibilities of repetition using the new technique.

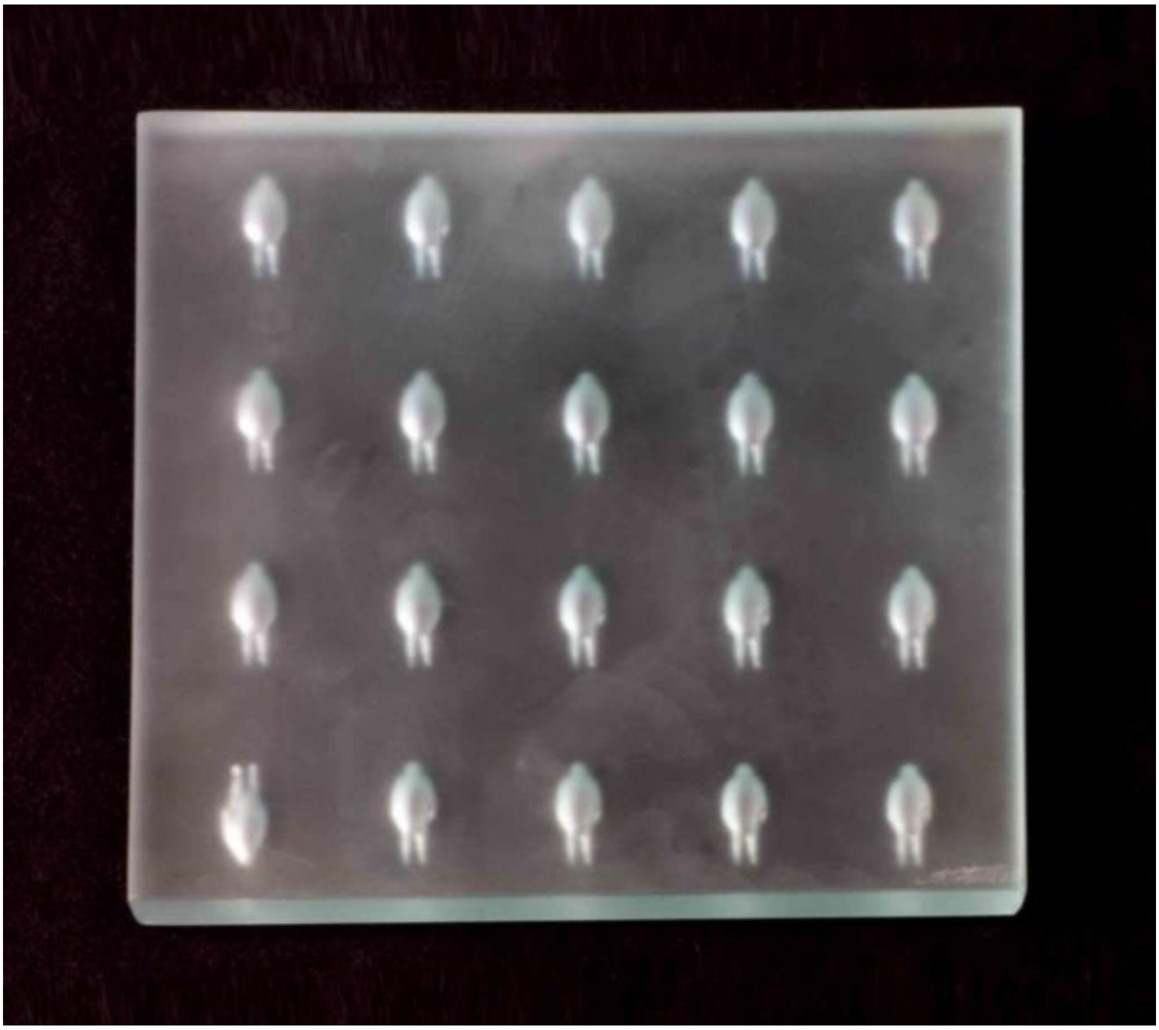


Figure 198: I.D. (2015) wall piece, 400mm x 380mm Optiwhite float glass, precision kiln-controlled air entrapment

Subsequent figurative pieces led to reflection on the subject of perception and the assumptions made of the air entrapment figure. This idea became of further interest following evaluation of one of the completed artworks, *Entity II*.

Peer discussion and evaluation of the figurative pieces *Entity I & II* suggested the figure could be perceived in various ways. This was the catalyst for new interest in the similarities and differences in the audience's subjective views of what the air-formed figure represented. Some identified the figure as an emerging, shadowy human which created a sense of unease; others saw specific gender; some perceived the air figure as non-human: alien or robotic, or spectral and ethereal. The viewer placed their own self-related contexts on the empty 'body'.

Figure 199: Entity II (Revised) (2015) detail. Kiln-controlled, three-dimensionally contoured air entrapment, standard float glass

Figure 200: Entity II (Revised) (2015) Joanne Mitchell. Three-dimensionally contoured air entrapment, standard float glass, optiwhite float glass and wood case.

Figure 201: Entity III (2015), detail. Joanne Mitchell

Figure 202: Entity III (2015), detail. Three-dimensionally contoured air entrapment, standard float glass, optiwhite float glass and wood case.

Curiosity in the interaction between artist, artwork and audience led to an interest in investigating work on bigger scale. Using solid, geometric blocks of glass as outer forms placed the visual focus on the inside acting as a literal, as well as symbolic, window to the interior space and place beyond the work. The role of the viewer and their own identification with the figure was evaluated.

A later observation of the artworks divulged the sometimes literal physical distance to the material during much of the act of making, the waterjet machine and kiln processes and clean, clinical polished finish - allowing minimal indicators of the hand of the maker in the work. This created a secondary suggestion of anonymity, emotional distance and protection in some of the artworks, themes that had appeared in *Secret Diary (2015)*.
In the final *Secret Diary* and *Entity II & III* artworks, the figure and the diary are

further ‘preserved’ and protected by an additional boundary in the form of a glass case.

Figure 203: Figures within Space series (2015) optiwhite float glass, precision kiln-controlled air entrapment mild steel. 800 x 650 x 220mm.

The investigation progressed with further exploration around identification and ‘humanness’. Interest developed in how recognition of ourselves in others influences our relationships with them. The propensity of human beings to ‘humanise’ or anthropomorphise forms and images, and what their interpretation reveals about the viewer as much as how the artworks communicate to the audience, developed as a subject of interest through the process of peer reviewing the artworks in progress.

Figure 204: Entity I (2014.) Grey and standard float glass, waterjet cut three-dimensionally contoured kiln-controlled multiple layered air entrapment.100 x 75 x 25mm

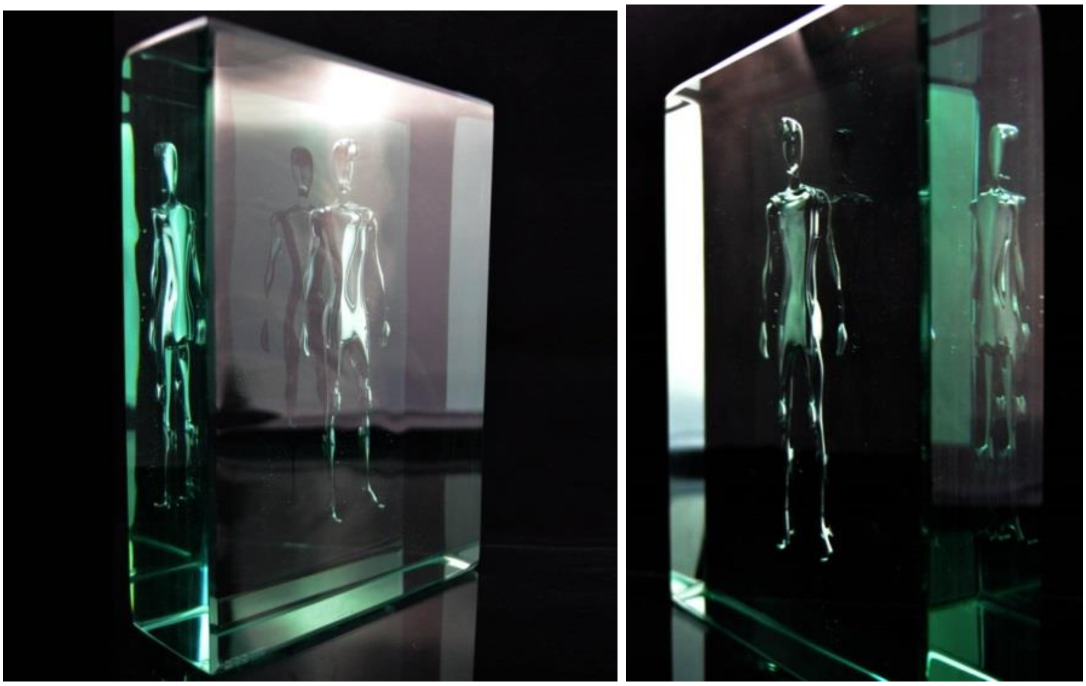


Figure 205: Entity II (2014) float glass, waterjet cut three-dimensionally contoured kiln-controlled air entrapment 200mm x 140mm x 50mm

Refining the technical aspects of the kiln-controlled air entrapment gave a level of control which allowed the opportunity to explore various stages of ambiguity of the figure and reflect on the resulting connotations in the development of the artwork.

Host II alluded to the resemblances between glass and water, to present the viewer with a reflection on the tension between personal individuality, anonymity within a multitude, and identification with others. In *Host II*, the air figures are expanded to a level of abstraction that they are devoid of most of their human characteristics.

The intention for the work was to create a sense of disordered and perpetual movement, but also create a sense of collective instinctive behaviour – like a shoal of fish. The concept was developed with increasing scales to evaluate how it was perceived as a more immersive piece. Glass's functional associations as a lens and petri dish inspired the circular form of the work.

Figure 206: Host II (2014) detail of anonymised figures

Figure 207: Host II (2014). Joanne Mitchell. Float glass, waterjet cut kiln-controlled air entrapment 300mm (diam.) x 80mm

Gaining the technical ability to successfully control the level of air expansion in the human form to the point of ambiguity led to interest in the subject of empathy. Personal interpretations resulting from the indistinctness of the softened air figure generated further reflection – is the figure an avatar for ourselves or an outsider? Is there an empathetic response?

These concepts evoked further ideas for content based on idea of 'humanness', and anthropomorphic responses to forms which possess an essentially human quality. Insight into perception of the figure and personification of the body and its influence in society developed during the inquiry. In an essay on 'Research and the Self,' Griffiths, (cited in Biggs & Karlsson, 2010) states that 'The world is understood through the body and also perceptions of our bodies constrain our relationships with others and ourselves' (Biggs & Karlsson, 2010, p168 [Accessed 1/10/14]).

Differences and commonality in individual frames of reference and assumptions made in interactions between people and others, leading to empathy or opposition became an area of interest. Recent research (Waytz, Cacioppo, &

Epley, 2010) has found that although people anthropomorphize in varying degrees, humanlike ‘agents’ seem to induce at least some anthropomorphism quite readily in most people. Individual differences in anthropomorphism predict the degree of moral care and concern afforded to an agent, and the extent to which an agent serves as a source of social influence on the self (Waytz, Cacioppo, & Epley, 2010 [Accessed 1/10/14]).

The cut-out human forms discarded on the waterjet bed following the glass cutting process had an inherent fragility and preciousness which in itself embodied meaning. An interest in the human propensity to personify inanimate objects and identify with others or to de-humanize them, developed in the inquiry.

Figure 208: Figures cut out on the waterjet. Right: work in progress exploring identification and anthropomorphism using waste cut-out void centres

Evaluation of peer reactions to a figure in various states of ambiguity was carried out to consider at what point the deconstructed figure still engendered an empathetic reaction in the viewer. Whilst it was acknowledged that the audience would make interpretations based on prior experience and a personal frame of reference, it was interesting to evaluate whether there might be a consensus of perception of whether a form was considered human, whether this reflected the personal intention in the work. The *Entity series (2014-15)* and artwork *Deconstructed Being (2015)* formed from this inquiry.

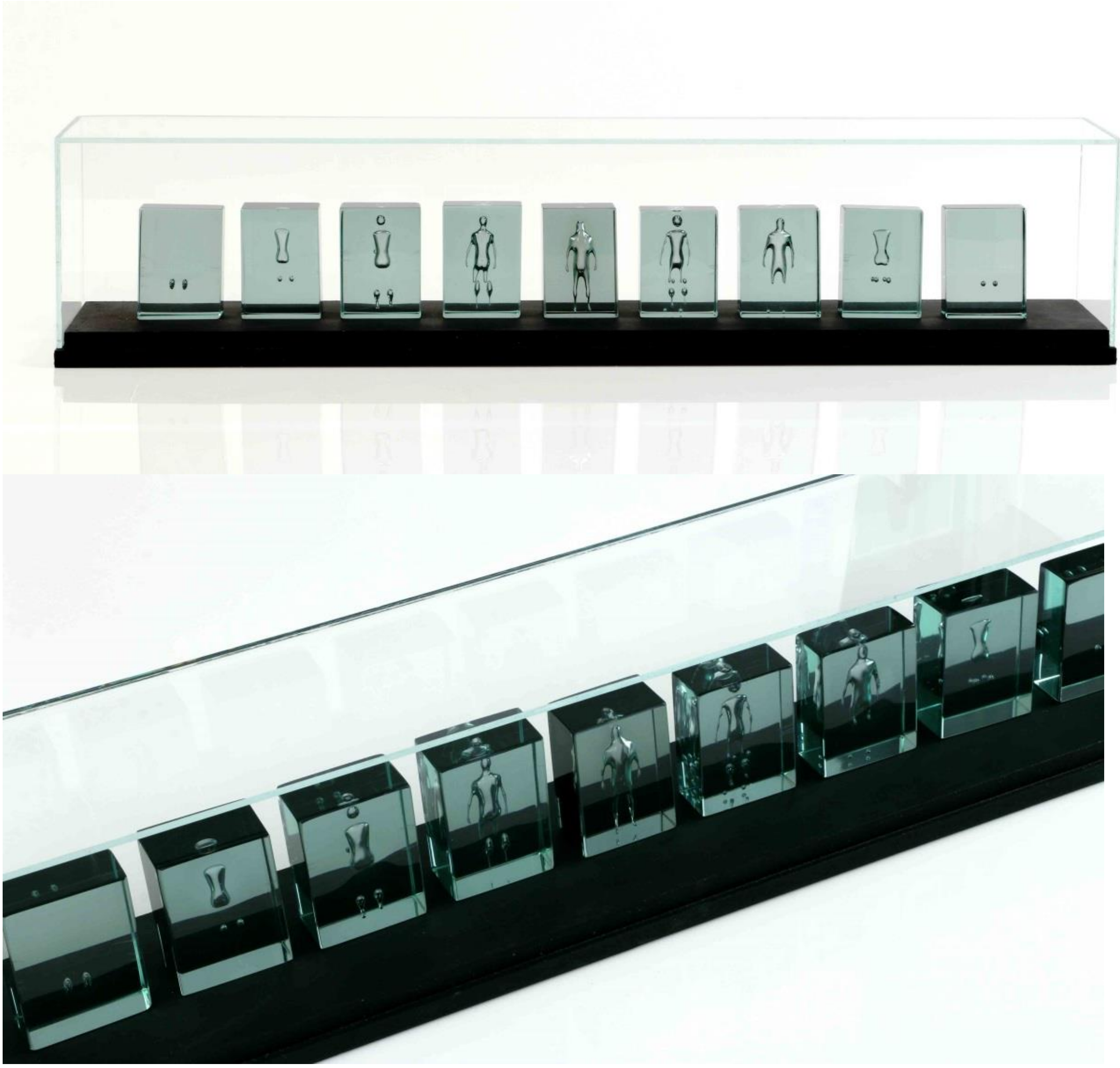


Figure 209: Deconstructed Being (2015) above & detail below. Joanne Mitchell. Standard and grey float glass, waterjet cut three-dimensionally contoured air entrapment, glass and wood case.

Corpus (2015) represents the new sculptural possibilities as largest scale piece using the kiln-controlled precision air entrapment technique.

The body of artwork represents the leap in creative possibilities of air entrapment in glass in forms beyond its previous incarnations as vessel or spheroid, and a new beginning in the expressive possibilities of precision air entrapment through applied digital and kiln technologies.

Figure 210: Corpus (2015) Joanne Mitchell. Kiln-formed optiwhite float glass, precision air entrapment 500mm x 250mm x 120mm.

Figure 211: Corpus (2015) detail

8.1.1 **Further Creative Developments**

An additional direction emerged out of the development of the roll-up vessel in the technical inquiry. An interest developed in the idea of the thin-walled vessel as protective container and a means of exposure inspired ideas for forms incorporated in the transparent vessel wall, with the possibility of further forms within it. Whilst ideas for final artworks were not fully resolved, this again is an interesting avenue for future investigation and takes the format of the air entrapment blown form beyond the heavy-walled Ariel vessel, into light-weight hollow forms offering a new language for expression incorporating digital imagery.

Figure 212: Experimental vessel hot glass rollup, 2015, Joanne Mitchell. Waterjet cut and kiln-formed Spectrum S96 glass, digital air entrapment imagery, blown by James Maskrey.

Figure 213: Experimental 'Shell case' hot glass rollups, Joanne Mitchell. (Waterjet cut and kiln-formed float glass, air entrapment digital imagery) blown by James Maskrey

Figure 214: Experimental cylinder figure form, 2015, Joanne Mitchell. Hot glass rollup (waterjet cut and kiln-formed Spectrum S96 glass, digital air entrapment imagery) blown by James Maskrey.

An interest in the tradition of transforming the ‘self’ as a physical representation in the self-portrait emerged, through the possibilities achievable in 3D scanning directly from life to create highly detailed three-dimensional forms of air - entrapment. Consideration of glass as a vessel for the intangible inner ‘self’ rendered in air, led to the development of this idea, a work-in progress on this theme using the personal physical form as the subject matter.

Figure 215: Kiln-controlled precision air entrapment self-portrait of the researcher, developed from 3D digital scan from life.

Although the above ideas were not fully resolved as artworks during the research period, they are avenues which the researcher sees great artistic value in pursuing as an avenue of further research in continuing personal practice, and possible post-doctoral research.

8.2 Artistic Evaluation & Findings

The artistic enquiry generated a new dialogue between subject, material, and making process, resulting in a transformation of direction in personal practice, demonstrated by the Body of Artworks. Throughout the development of the artistic enquiry, the emerging content drew on the intrinsic properties of glass, its implications and connotations, with its visual references and production methods acting as vehicles for personal expression. New knowledge gained from experimentation, analytical reflection, exhibition and peer evaluation opened up new avenues in critical thinking during the making process.

Analysis of the creative process found that technical inquiry was often the prompt for new philosophical ideas, whether through unexpected outcomes or simply observation and consideration of the material, or an unexpected quality of form, leading to artistic inspiration. The subsequent understandings gained, through the process of reflection-on and in-action, fed into decision making in the artistic development and onto the resolution of the body of work.

Evaluation led to consideration of scale and presentation, and the effect this had on the audience interaction with the artwork. New avenues of exploration in later work emerged through this reflection: individual subjectivity was expected, however it was interesting to note a general correlation between the personal intention and the viewer perception of the work. Where developmental work did not connect with the audience or the researcher to fulfil the artistic intention, the exploration was reframed and action taken to resolve the artwork, or a new direction taken.

Documentation of the artistic inquiry was instrumental in enabling critical evaluation of the work on a personal practice-based and contextual level. The investigation has transformed the researcher’s personal practice through the development of a new artistic focus, analytical skill, and contextual awareness. The body of technical knowledge generated by the research process has engendered new artistic directions and a more critical perspective on personal practice and the wider field.

Figure 216: Exhibition of artworks at New Designers 2015, Islington, London

The body of artwork demonstrates and articulates the value of the research to professional artistic practice. During the research period, artworks have been shown in exhibitions the UK, internationally and online, and submitted to relevant publications in order to review and validate the research in the context of the field of glass art practice. These professional outputs are listed in the Appendix 1.I Dissemination of the Artworks.

The initial set of criteria for personal evaluation of the body of artworks was based on their success and relevance within the researcher's practice in the context of the field of glass art, as follows:

- That when completed, the artwork embodied meaning in a way that resolved the aesthetic and conceptual goals of the practitioner.
- That it would be of interest to the sector in terms of gallery exhibitions, reviews and publication.
- That it would be of interest to a public audience interacting with the sector in terms of viewing and/or owning the artwork.
- That it would be technically interesting to others in the glass sector.
- That it developed and transformed technical knowledge, practical methodology and critical thinking to progress the researcher's personal

artistic practice.

- That it articulated new directions in air entrapment artworks for sculptural and architectural glass art applications.

The methods for evidencing these criteria were as follows:

- Peer review in the University Glass and Ceramics research environment.
- Peer review in the wider context of the University environment of art and design.
- Contextual Review through submission to relevant journals and competitions.
- Review through acceptance in gallery exhibitions/ outlets and online galleries.
- Success in terms of interest from the public through enquiries to buy/view.
- Interest through media and online dissemination.
- Acceptance of papers at relevant seminars/ conferences.
- Interest from the wider field of glass art in an international setting.
- Sector specific recognition and publication.

How the criteria for artistic intentions and aims and objectives in creative practice have been fulfilled and demonstrated are evidenced in Appendix 1.I. Dissemination of the Artworks.

9. Conclusions and Contribution to Knowledge

The contribution to knowledge centres on the origination of a series of techniques which establish new procedures to create and control precision air entrapment, through applied digital and kiln technologies and the documentation of the methods and their implementation in creative practice; to offer replicable methodologies for future studio glass applications. The body of work demonstrates the practice-based application of the new techniques to create glass artworks. The series of air entrapment techniques are titled collectively by the researcher as, 'Kiln-Controlled Precision Air Entrapment'.

9.1 Contribution to Knowledge

Previous to this research, in kiln-formed glass, only artworks incorporating basic air-bubble forms had been developed. No documentary evidence of kiln-formed air entrapment imagery at the level of refinement of the *Ariel* technique was available. No previous research for developing a replicable technique of precision air entrapment in glass in the kiln, or incorporating air entrapment in glass using digital technology could be found.

The research has cultivated new knowledge by the novel integration of kiln-forming processes, digital design and fabrication methods, in particular waterjet cutting, and cold-working techniques, via technical experimentation and creative inquiry; together with a parallel review and analysis of historical and contemporary antecedents in air entrapment and glassmaking innovation, on which this investigation builds.

A systematic methodology of experimentation, reflection and action was directed by the requirements of creative practice, from the perspective of the studio practitioner. The objectives were set within the scope and limitations of the glass studio, so that the research adds to the creative vocabulary of the artist working with glass. The development of the air entrapment process in the kiln has introduced a new aesthetic language into the field of kiln-formed glass, through intricately designed and controlled imagery and forms. The resulting body of artwork that the researcher has produced has demonstrated some of the range of applications beyond the conventional vessel into forms applicable to architectural glass and sculptural kiln-formed glass art.

Application of knowledge from technology in this research has built on and extended the possibilities of form, design and configuration of air entrapment as a vehicle for expression in artwork, beyond its innovative 20th century hot glass precedent of the Swedish *Ariel* technique, and research of Flavell (2001), highlighted in the Contextual Review (Chapter 3).

Digitally controlled Precision Air Entrapment differs from conventional methods of air entrapment by allowing more precision than the *Ariel* technique's hand-cut sandblasted stencils and a new level of complexity. The incorporation of digital technology contributed additional knowledge in creating air entrapment.

Though the introduction of new digital designs originated in CADCAM, and the use of waterjet, precise and complex forms can be accurately reproduced as bubbles and repeated. The shape, form and context of the possible artefacts extends configurations beyond the conventional vessel or spheroid. The research expands the creative vocabulary of the artist, designer and creative practitioner working in glass. Waterjet cutting technology exploration enabled the further innovative creation of three-dimensional void contours inside glass artwork, such as the 3D figure, an outcome beyond the original expectations of the research, which were to create recognisable lettering and imagery.

The extension of kiln-formed air entrapment into *hot* glass further extends the possibilities of artwork configurations, re-conceiving air entrapment as reduced-weight hot glass forms which can be blown and manipulated as thin-walled vessels, cylinders and hot-manipulated forms. This integration of kiln-formed air entrapment panels and the 'roll-up' technique is a pioneering advancement in hot glass.

In the area of kiln casting and multiple-layered fusing, this research provides new knowledge relating to the reduction and avoidance of unwanted bubbles. Conversation with peers and anecdotal evidence suggested that glass artists tend not to fuse sheets of float glass because of the significant problem of the occurrence of flat unsightly bubbles (here termed 'air pooling') which break up glass clarity and cause interference in the design. No existing technical documentation was found relating to deep, multiple-layered float-glass fusing.

The research re-evaluated float glass as a material for kiln-forming using multiple layers, advancing practical knowledge on how to eliminate unwanted air 'pooling' between layers of float glass, through the development of methods for releasing excess air, titled by the researcher:

- 'Cut–venting':
- 'Section-venting':
- 'High Slump Venting:

These methods offer a new level of control in the forming of air entrapment and additionally in the *removal* of unwanted bubbles, a benefit valuable to the general fusing of float glass for artists because it removes bubbles across the entire intersection. This expands the boundaries of glass fusing into deep sculptural forms, traditionally more allied with conventional kiln-casting processes. Once resolved, these methods were also applied to gain additional knowledge using different colour tints and thicknesses of Pilkington Float Glass.

A further creative avenue was developed by the use of the digital 3D scanner to derive the air-void structure from physical artefacts. This process takes air entrapment into a new level of intricacy, precision and scale, which sets a precedent for further research in an emerging cross-cultural area of glassmaking and digital technology. The artworks produced by these new processes demonstrate integration within the glass disciplines, and the wider digital media and applied arts sectors, and also within handcrafted and digital making processes.

A methodology for applying cross-fertilisation of technical knowledge between established disciplines has been documented; deconstructing the experimental exploration of air entrapment and contemporary technologies in digital fabrication; to innovate with and progress established processes.

This thesis documents and disseminates the application of the research outcomes to creative studio practice, and makes explicit the creative process involved in interpreting new technical knowledge from creative potential, into content, subject matter and a body of artwork. The elucidation of the methodology provides other practitioners with a demonstrable mode of practice, which might inspire new avenues for application of the techniques in the development of new work, and further advancement of the repertoire of artists' methods in the field of glass art.

9.1.1 **Contribution Summary:**

In summary, the key indicators of the contribution to knowledge can be evidenced as:

- A documented methodology for a series of techniques in glass art practice, entitled collectively as Kiln-controlled Precision Air Entrapment, and a mode of practice for its application into artworks.
- Production of a body of air entrapment artworks using applied kiln techniques and digital technology.

The new knowledge identified under the title *Kiln-controlled Precision Air Entrapment* is outlined as:

- The creation and control of complex text and image-based air entrapment in kiln-formed glass.
- The application of multiple-layered precision air entrapment in kiln-formed glass.
- The incorporation of CAD/CAM technology to air entrapment.
- The incorporation of digital imagery and photo-resist techniques in sandblasted air entrapment.
- The creation of three-dimensional air entrapment forms through multiple-layered waterjet-cut void contours in kiln-formed artworks.
- Development and documentation of modes of practice for scaling up air entrapment designs in volume of glass, complexity and number of contours.
- The investigation and application of float glass sheet as a viable material for kiln-formed air entrapment.
- Application of digital technology to create sophisticated kiln-formed air entrapment in ‘flat planes’ for architectural glass applications.
- Development of air entrapment roll-ups for thin-walled artworks and blown vessels.
- The introduction of 3D scanning technology to develop air entrapment in glass from physical objects.

- Production of multiple method combinations of air entrapment within a single artwork.
- Application of different colour tints and thicknesses of Pilkington Float Glass for multi-layered fusing.
- Comparative investigation of air entrapment in ‘fusing glasses’: Bullseye, Artista, and Spectrum S96
- Documentation of kiln programmes for control of various air entrapment forms in float glasses which can be replicated and modified to specific artworks.

9.2 Conclusions

The inquiry has developed and documented a synthesis of approaches, both technical and artistic, leading to a new technical methodology for a collective series of kiln-formed air entrapment techniques, entitled *'Kiln-Controlled Precision Air Entrapment'*. The Body of Artworks has demonstrated the application of these new techniques in creative glass practice.

The research has contributed to the advancement of artistic and technical knowledge in contemporary glass practice through discovery of innovative new methods for creating and controlling the form of air-bubbles in glass, which builds on and blends *Ariel* hot glass techniques, digital and waterjet processes and kiln fusing, casting, and cold-working knowledge.

The numerous technical difficulties in developing air entrapment using the kiln, digital technologies, waterjet and float glass were finally overcome through a process of intensive testing, evaluation and re-testing, and intuitive connection-making through tacit knowledge and thinking-in-action. The research has outcomes which offer new technical knowledge and a form of aesthetic expression for audiences in the wider glass sector.

The research offers a substantial body of knowledge that others might build upon, which has relevance to such sectors as glass art, glass design, processing and manufacture, and applications including sculpture, product design, architecture, interior design and signage. The outcomes may also be of interest to material scientists interested in examining the behaviour of air entrapment in glass.

The thesis documents a process of technical and artistic investigation as a creative practice-based methodology, which is transferable into further academic research and professional practice in glass. The body of artwork demonstrates the creative outcomes of the investigation in the context of the glass practice, which culminate as an extension of the previously documented possibilities of forms achievable in glass art incorporating air entrapment, thus extending the range and repertoire of the studio glass artist.

Through the Contextual Review, the research contributes a re-appraisal of conventional forms of air entrapment, and the collation of historical precedents for innovation in air entrapment for use by other artists and researchers, as well as a review of digital technology in glass, building on previous knowledge.

This investigation has advanced and matured the researcher's learning perspective via the development of a structured methodology in order to gain a deeper technical knowledge and critical awareness of glass. The contextual review generated a wider understanding of contexts within the field, and an ability to apply critical reflectivity in the generation of a body of artworks.

The researcher has also developed openness to alternative perspectives through peer review, exhibition, presentation and critical discourse, leading to the development of inter-subjective views. The process of the study has effected the capability to participate freely and fully in rational discourse, and willingness to accept and explore critical consensual validation as a mode of problem solving (Mezirow, 1991, P226).

This inquiry has constructed an interpretive synthesis of procedures which are coherent and congruent with an overarching theory (Schön 1983, p152) (the possibilities of *Kiln-Controlled Precision Air Entrapment* as a creative process) and, as such, has identified and disseminated revelatory and repeatable modes of practice, which are translatable into further academic research study and professional creative practice. This adds to the body of knowledge of practice-based research models, and a greater understanding of the process of creative thinking within practice-based research.

Making explicit the process of artistic inquiry in the context of the making of glass art, and the analysis of the body of artwork and documented application of the new technique of *Kiln-Controlled Precision Air Entrapment* in creative practice, it is hoped, has added value and contributed to advancement of the field in both professional glass practice and practice-led research.

Figure 217: Waterjet cut contours for 3D self-portrait in preparation for kiln-forming. Precision air entrapment work in progress (2015)

9.3 Areas for further research

- Further exploration of the Section Venting theory to comparatively investigate upper and base layer sectioning.
- Further exploration of waterjet cut vents applied to large-area flat plane air entrapment designs. This needs further exploration and would require significant safety testing.
- Application of venting techniques for air entrapment in kiln casting:

The research focuses primarily on float glass kiln-formed by fusing multiple layers. The methods documented also offer avenues for further research into the transfer of sophisticated air entrapment into kiln casting using alternative glass types, particularly with digital imagery and sandblasted channels.

- Air entrapment incorporating 5-axis waterjet cutting

This research has used a three-axis waterjet cutter to create contours cut on a flat plane. The potential for incorporating the latest 5-axis waterjet cutting technology to create three-dimensional void contours in glass seems to me an idea with much potential for future investigation.

- Air entrapment and neon:

The possibilities of investigating Kiln-Controlled Precision Air Entrapment to incorporate Neon is an area for future research.

- Air entrapment and enamel screen printing:

There are numerous possibilities for designs incorporating print between the layers of float glass and air entrapment.

- Monumental scale air entrapment:

The body of work evidences a significant development in the sophistication and scale of air entrapment shapes, and of the form of artworks which incorporate it; however this demonstrates the very beginnings of the potential of precision air entrapment through applied digital and kiln technologies. Increasing the scale of air entrapment artworks to an even larger size is an area for further research. This would require study into the behaviour of large amounts of trapped air under pressure, and the resultant stress issues in the glass.

Appendices

I. Dissemination of the Artworks

The body of artworks and their development through creative practice have demonstrated the application of the new knowledge of Kiln-Controlled Precision Air Entrapment to glass art practice, and substantiated the technical findings as artistic outcomes. Dissemination of the artworks via exhibition and review validates the relevance of the research and body of artwork in the in glass art sector and wider field.

Through the course of the research the developing artworks were exhibited in various sector-relevant settings. Artworks were shown in commercial art fairs and gallery exhibitions. The artist was represented by gallery ArtDog London at the Affordable Art Fairs in New York and Battersea in 2014, and in AAF New York, Buy Art Fair Manchester and Liverpool Contemporary Arts Fair in 2015; and in a curated multi-media PhD exhibition *Drawing?* at the Customs House Gallery, South Shields in May-July 2015.

The work was exhibited at the New Designers Exhibition at the Business Design Centre, Islington, London, in July 2015. Public, gallery and peer response to the work was very positive and the piece *Entity III* was purchased by a private collector. The work was awarded Highly Commended by The Contemporary Glass Society, and received the accolade Highly Commended: One to Watch from the applied art periodical Craft & Design magazine. A selection of pieces from the body of work were selected for a four-person mixed media exhibition, ‘An ‘in’ with a Stranger’ at Llantarnam Grange Arts Centre, Torfaen, Wales, January 2016.

Images of the artwork were disseminated in Craft & Design Magazine September 2015 and The Contemporary Glass Society Glass Network Magazine, September 2015 as part of the prizes won at the New Designers Exhibition. The body of work was also selected for inclusion in the UK Crafts Council Directory. Artwork was shown in the Contemporary Glass Society (CGS) *Wish You Were Here Exhibition* at the International Festival of Glass, Stourbridge 2015; online CGS Members Spotlight and *Strike a Balance* online exhibition.

In the glass art field, a solo show, *Form & Void*, at the National Glass Centre at the University of Sunderland in October 2015, following completion of the research, showed the final body of artworks in a public arts setting. Two of the artworks were acquired for public collections: *Legion (2015)* by the Shanghai Museum of Glass, China and *Memory Echo (2014)* by the Alexander Tutsek-Stiftung Foundation, Germany. *Figures Within Space* was selected for the international glass publication *New Glass Review 36,* published by the Corning Museum of Glass, New York. New Glass Review is an annual survey of glass in contemporary art, architecture, craft, and design, created in the previous year. The works are chosen by a changing jury of curators, artists, designers, art dealers, and critics.

The work was disseminated to the international glass sector via presentation at Pilchuck Glass School Summer Session 6, Stanwood, Washington, USA, September 2014 where the researcher was invited to present an artist talk to peers, international masterclass leaders and attendees as Teaching Assistant to American glass artist and masterclass leader Keke Cribbs.

The research was disseminated to the public, design professionals and technologists via various artists talks to: design delegates from Taiwan, October 2014; students and the public at the National Glass Centre, Sunderland, February 2015; the *Friends of The National Glass Centre* at 36 Lime Street Studios, June 2015; and the Society of Glass Technology at the *Glass Reflections* Conference*,* University of Cambridge Murray Edwards College, September 2015. An article about the research and images of the artworks were featured in online architecture/design/art/technology newsletter *Design Boom,* October 21st 2015.

The research was also featured in regional television programmes Our Creative North and The Lowdown, broadcast in April 2015. The National Glass Centre Artist Talk and Our Creative North programme are available to view online on the NGC and Creative North Channels on You Tube.

https://www.youtube.com/watch?v=wPQaEqx3Z9o and https://www.youtube.com/watch?v=OPDMj8b2510.

Online dissemination of artworks resulting from the research can be viewed at the following websites:

Crafts Council Directory: http://www.craftscouncil.org.uk/directory/maker/jo-mitchell;

The researcher's artist website www.jomitchellglass.com;

The Contemporary Glass Society website, at:

http://www.cgs.org.uk/member/1107

http://www.cgs.org.uk/exhibitions/strike-balance

http://www.ifg.org.uk/exhibitions/medallions.html

Society of Glass Technology Conference *Glass Reflections* website: http://www.glassreflections.sgt.org/Ab-JoanneMitchell.htm

36 Lime Street Studios website:

http://36limestreet.co.uk/creative/joanne-mitchell-glass-design/

Design Boom website:

http://www.designboom.com/art/joanne-mitchell-digital-tech-air-bubble-artworks-10-21-2015/

I.I Evidencing Criteria for Personal Evaluation of the Body of Artworks:

- *That it would be of interest to the sector in terms of gallery exhibitions, reviews and publication, evidenced by the following list:*
    - Selected for New Glass Review 36, 2015
    - Selected for Crafts Council Directory
    - Exhibition in CGS *Wish You Were Here* exhibition at the International Festival of Glass, Stourbridge, 2015
    - Selected for Contemporary Glass Society online gallery exhibition
    - Exhibition at Customs House South Shields 2015 & 2016
    - Exhibition at Llantarnam Grange Arts Centre, Torfaen, Wales, January 2016
    - *Figures Within Space* and *Host I* shown at Affordable Art Fairs Battersea, Hampstead and New York (2014) and Manchester Buy Art Fair, Liverpool Contemporary Arts Fair, AAF Battersea and AAF New York (2015) with ArtDog London Gallery
    - NGC Solo Exhibition, *Form & Void*, Research Space, October-November 2015
    - Invitation to exhibit with Coombe Gallery, Devon.
    - Invitation to exhibit with Mint Shop, London at London Design Festival 2015
    - Invitation to exhibit with the Craft & Design Centre Leeds
    - Invitation to exhibit with the Jed Malitz V2 Gallery in New Orleans
    - Invitation to exhibit at London Glassblowing

- *That it would be of interest to a public audience in interacting with the sector in terms of viewing and/or owning the artwork, evidenced by:*
    - Purchase of two artworks: *Secret Diary* and *Entity III* for private collections (2015).
    - Invitations to present talks for National Glass Centre (2015), Friends of NGC (2015) and Taiwan Design Delegation (2014).
    - Enquiries from public, galleries and sector professionals at New Designers Exhibition 2015.

- *That it would be technically interesting to others in the glass sector.*

- Acceptance of research paper for the Society of Glass Technology Conference 2015 and publication of abstract on SGT website.

- *That it developed and transformed technical knowledge, practical methodology and critical thinking to progress the researcher's personal artistic practice, evidenced by:*
    - Transformation of type and style of artworks made in personal practice through the artistic inquiry, evidenced by the body of artworks.
    - Futures Funding received to travel to international glass school Pilchuck based on submission of images of research.
    - Invitation work as technical assistant to Keke Cribbs at Pilchuck Glass School, Stanwood, USA.
    - Contemporary Glass Society Highly Commended Award for Artworks
    - Craft & Design Magazine Highly Commended: One to Watch for Artworks

- *That it articulated new directions in air entrapment artworks for sculptural and architectural glass art applications, evidenced by.*
    - The completed body of art works
    - Invitation to produce commissioned air entrapment signage for London Glassblowing
    - Acquisition of Legion (2015) for the Shanghai Museum of Glass Art Collection
    - Acquisition of Memory Echo (2014) by the Alexander Tutsek-Stiftung Foundation Collection

II. Glossary

- *Air entrapment*

Air intentionally trapped in voids, channels, cut-out contours, or as controlled bubbles in glass

- *'Air-lock' or 'Air-trap'*

The technique of making air-lock or air-trap glass patented in 1857 by Benjamin Richardson of the W.H., B. & J. Richardson Glass Company. To form a piece of glass with a decoration of air-locks or air-traps a gather of glass is taken and blown into a mould containing shaped protrusions to form the decoration. A second gather of glass is then put over the first, trapping air between the two layers of glass forming a pillow-like pattern.

- *Air Pooling*

Term coined by the researcher to define an unintended puddle of visible trapped air, pooled above or around the intended air entrapment contours or in between fused glass layers, compromising clarity of the design.

- *Air Trap*

An air-filled void, which may be of almost any shape.

- *Air twist*

Elongated spiral air bubble decoration found in goblet stems

- *Anneal*

The process of slowly cooling glass in a temperature controlled kiln to relieve internal stress

- *Ariel*

Hot Glass technique invented at Orrefors Glassworks in Sweden. To produce the *Ariel* design, a blown and cooled small 'blank' or 'parison' would be masked with a resist, and the intended design marked and cut-out by hand. The blank would then be etched, abrading the uncovered areas with deeply sandblasted channels to create an 'embryo'. The embryo would then be reheated in a kiln, until hot enough to be picked up on a blowing iron without breaking, but still rigid. A thin layer of glass called an 'overlay' is then applied over the embryo to trap air in the channels. A further layer of glass is then gathered over the piece and it is shaped, and returned to the lehr to cool.

- *Art Nouveau Glass*

In the late 19th Century, the glass of Art Nouveau elevated the status of glass to 'art', finding its expression in domestic objects enjoyed for their own beauty as contemplative pieces. The influence of its proponents Galle, Daum and Lalique spread throughout Europe and internationally, and the deeply carved cameo glass inspired by the natural world and its free-flowing style was imitated by many glassworks.

- *Bas Relief*

A slumping technique which incorporates elements of conventional casting, fusing, and slumping whereby glass is placed on a support (such as a vermiculite box-wall) over pre-fired plaster which has been impressed with a relief impression. When heated to a full fuse temperature the glass becomes viscous and takes the shape of the relief design. The higher temperature and support allow the glass to reach a semi-molten stage before slumping into the mould, creating a more 3D effect than conventional slumping.

- *Batwash*

A ceramic separator, sometimes called kilnwash or shelf primer, used in glassmaking to coat a surface such as a metal mould or ceramic kiln shelf, to stop the glass sticking to it.

- *Billet*

A block or glob of clear or coloured glass which has been hot cast from the furnace, used in kiln casting.

- *Bullseye Glass Co*.

Founded in 1974, Bullseye is based in Portland, Oregon and develops and produces hand rolled, tested-compatible glasses in many colours, specifically for glass artists. Bullseye glass is made in sheets for use in the kiln and for stained glass, as well as rods for flameworking and billets for kiln casting applications. Bullseye Glass runs educational and research programmes to further knowledge of kiln formed glass. They are highly involved with the glass art sector, also organising an international conference on kiln forming: BeCon; and Emerge: a juried exhibition for emerging artists working in kiln-glass.

- *CAD*

Computer Aided Design

- *CAM*

Computer Aided Machining/ Computer Aided Manufacture

- *CNC*

Computer Numerical Controlled

- *CoE (Coefficient of Expansion)*

COE, is a measure of how much a material will expand through a temperature range and can be an aid to assessing glass compatibility, along with viscosity tests. Different glasses have different approximate COEs. Bullseye glass Coefficient of Expansion is 90; Spectrum COE is 96; standard float glass ranges from around COE 84-87, depending on the manufacturer.

- *Cold Spots*

Cooler areas inside a kiln caused by a draught or insufficient insulation.

- *Cristallo*

Clear, colourless glass developed in 15th Century Venice, so named because of its resemblance to crystal.

- *Devitrification*

Surface crystallisation which occurs when the glass is cooled (or heated) too slowly (in temperature ranges around 600-700c in float glass) creating a cloudy effect.

- *Drawn glass*

In the Spectrum drawing process, raw materials are introduced into a tank furnace, displacing existing molten glass and forcing it, stream-like, down a channel called the forehearth. At the end of the forehearth the red-hot liquid pours into a deeper pool, the stirring bay, and on through a pair of water-cooled forming rolls, flattening into uniform thickness and becoming an endless ribbon of sheet glass. It is drawn directly into the annealing lehr to cool.

- *Fablab*

A Massachusetts Institute of Technology (MIT) initiative by inventor and scientist Professor Neil Gershenfeld which provides facilities and skills for rapid prototyping.

- *'Flashed' float glass*

A term for float glass with a pre-fired layer of enamel screen printed onto one surface and pre-fired, the name 'flashed' coming from its resemblance to 'flashed' hand-blown antique sheet glass which has a thin outer layer of coloured glass.

- *Float glass*

A soda-lime sheet glass that is manufactured predominantly for architectural purposes. In the float process, molten glass, at approximately 1000ºC, is poured continuously from a furnace onto a shallow bath of molten tin and forms a level surface. Thickness is controlled by the speed at which solidifying glass ribbon is drawn off from the bath. Most float glass products contain small amounts of iron oxide which produce a green tint usually only perceived when the glass pane is viewed 'on edge'.

- *Fourcault Process*

In the Fourcalt process, viscous glass that extrudes from a ceramic nozzle is gradually drawn up perpendicularly through a 'drawing machine'. Before it comes into contact with the rollers inside the drawing machine, the surface of the glass cools off and solidifies to the extent that it can no longer experience imprints or scratches (SCHOTT North America, Inc., 2011).

- *Frit*

Glass ground to a grain or powder consistency

- *Fusing*

A term used for heating two or more pieces of glass, usually in sheet form, so that they stick or 'fuse' together. A *'tack fuse'* is a fuse at the lowest temperature point where the surfaces stick fully. A *'full fuse'* means that the surfaces have been fully incorporated together into a single layer and edges have rounded off.

- *G-Code*

CNC Programming language for Computer Aided Manufacturing

- *Glory Hole*

Gas-fired re-heating chamber used in glassblowing.

- *Graal*

Innovative glassblowing technique invented at Orrefors Glassworks in Sweden in the1930s in which sandblasting was used to abrade the coloured surface of the glass to create a design, over which a clear layer was applied.

- *Hotshop*

Glassblowing studio

- *IGEMS*

Swedish CAD/CAM software used to programme the waterjet machining

- *Inductive Reasoning*

Reasoning in which the premises seek to supply strong evidence for (not absolute proof of) the truth of the conclusion.

- *Infrared pyrometer*

An infrared pyrometer is a non-contact thermometer with laser targeting

- *Juo Ltd*

Sunderland-based creative glass company run by co-founders and directors Joanne Mitchell and Jessamy Kelly between 2006 and 2012. Juo specialised in the design and production of high quality fused art glass, creating limited edition collections of wall panels and contemporary giftware for modern interiors, using kiln-forming techniques.

- *Kilncare*

UK company formed in 1982 by kiln engineer Brian Sherwin, Kilncare was primarily a kiln service company but soon expanded to include kiln design and manufacture and is a leading supplier of glass casting and fusing kilns in the UK.

- *Kiln Casting*

A method of melting glass into a mould at high temperature inside a kiln. Moulds are usually made from a plaster/silica or plaster/molochite mix. Examples of casting methods are:

  - *Open-mould casting:* broken up pieces or billets of glass are placed in an open mould and heated to 800 – 830 Celsuis (temperature depends on the type of glass used);
  - *Dribble or crucible casting*: This method is often used with the *lost-wax* method and semi-closed investment moulds. Pieces of glass are placed in a crucible with a hole in the base and placed above the mould. When heated, the glass becomes molten in the crucible, once liquid, is drips through the hole, filling the mould beneath.

- *Kraka*

Glassblowing technique developed by Sven Palmqvist in 1944. A wire mesh was placed over the blank which was etched to produce a net-like pattern of tiny bubbles (Dawson, 2000, p.131).

- *Lehr*

Annealing oven/kiln with temperature controller, used to cool glass slowly.

- *Low Iron Float Glass*

Iron Oxide aids the melting process and produces the very light green tint seen at the cut edge of a typical clear float glass. Pilkingtons Optiwhite Low Iron glass does not have this green tint.

- *Maurice Marinot*

Individual artist who pioneered glassmaking, as a medium for individual artistic expression, in France. Marinot developed his own tools and techniques to create vessels with deeply acid etched forms which he considered to be sculptural artworks.

- *Multi-layered Fusing*

Fusing numerous layers of sheet glass together in a single firing to make a thick glass piece, usually requiring a mould or supporting walls to avoid slumping of the glass.

- *Mykene*

Swedish glassblowing technique invented at Orrefors glassworks. Silicon carbide grit was mixed with water to paint a design onto a blank. When a glass overlay was added, the silicon carbide created gas which formed tiny bubbles trapped in the walls of the piece to form the design.

- *Overlay*

Hot glass technique in which a blown piece is overlaid with a 'cup' of clear or coloured glass which is heated until soft enough to apply, wrapping the blown piece, using gradual reheating and shaping.

- *Pate de Verre*

A technique using crushed glass frit or powder mixed with binder to form a paste which is applied into a mould to form a layer which fuses when fired to create a translucent to semi-opaque effect. The temperature of the fuse can be varied to create a sugar-like surface at a lower temperature, to a smoother, almost cast finish at a higher temperature.

- *Pate-de-verre*

Kiln-forming technique, in which grains of glass are mixed with a binder to a paste and fired in a mould.

- *Plate Glass*

A soda-lime-silica glass formed by rolling the hot glass into a plate that is subsequently ground and polished and used in large windows and mirrors. Sometimes used as an alternative name for Float Glass in the USA.

- *Pilkington*

Multinational glass manufacturer, founded in 1826. Headquarters in St. Helens, U.K. The invention of the float glass process, by engineer Alastair Pilkington (unrelated) in 1952 took away the need for grinding and polishing plate glass. Pilkington licenced the Float Process to manufacturers around the world, dominating the market. Pilkington Group Limited is a subsidiary of Japan-based NSG Group since 2006

- *Pilkington tinted float glasses*

Pilkington body tinted glass products are produced by small additions of metal oxides to the float glass composition to colour the glass bronze, green, blue or grey. They do not affect the basic properties of the glass. Additional iron oxide is introduced to standard float to produce green tint, cobalt oxide for grey tint, selenium oxide for bronze tint and cobalt oxide for a blue tint.

- *Pilkington Optiwhite*

Optiwhite is a low-iron float glass which is very clear. The low iron content reduces the green tint seen in standard float glass.

- *Polygon*

In computer graphics, a polygon is a formed by edges connected to each other by points in three-dimensional space

- *Ravenna*

A similar technique to Ariel, Ravenna, used powdered glass (frit) scattered into the sandblasted channels of a coloured blank before the top layer of molten glass was applied to seal in the decoration, trapping bubbles in the channels amongst the particles of glass powder.

- *Reticello*

Glassblowing technique which involves ‘rolling up’ canes of glass in two batches. The first batch is then twisted in one direction to form a spiral, and is opened into a cup and held at temperature. The second batch of canes is twisted in the opposing direction and then inflated into the original, creating a criss-cross lattice in which an air bubble is formed at each intersection.

- Sandblasting

A technique commonly used in all areas of studio glass as a means of abrading the surface. Sand, in the form of aluminium oxide abrasive ground to 80/120 grade grit, is blasted at the glass surface to erode it, using a compressed air gun at high pressure inside a cabinet. The air pressure can be altered for deep carving to create pattern and texture, or to lightly abrade the surface for a matt or semi-opaque effect.

- *Schott Artista®*

Optically clear low-iron sheet glass with subtle structured surface pattern for architectural glass. It has application possibilities for both interior and exterior use: as a full pane, in stained glass or as a fused glass, and is available as cast glass, thin glass and frits. Artista is produced using the Fourcault Process.

- *Slumping*

Often categorized within the discipline of fused glass, as it is often used in combination with the fusing technique. Glass is heated to reach its softening point, in order to bend and distort it. Glass can be slumped into or over a ceramic mould, batwashed[i] metal or plaster former, or through a former with a central hole, as in *freeform slumping.*

- *Soak*

To hold the kiln temperature for a period of time, usually to anneal a piece, or to ensure cast glass is sufficiently molten to run into a mould.

- *Spectrum Glass Co Inc.*

Manufacturers of System 96 glass for fusing, ‘antique’ glass for stained glass, as well as billets for hot glass, based in Woodinville, USA. Spectrum produce a fusible range of drawn glasses which are compatible with a coefficient of 96: System 96. These glasses are also compatible with Urboros System 96 glasses.

- *System 96*

A family of tested-compatible glass products designed and produced to work together, both technically and artistically, in Glass Fusing, Glass Kiln Casting, Glass Blowing, Glass Torchwork (System 96 website [Accessed 9/9/12]).

- *Thermal shock*

Cracking as a result of thermal stress caused by heat differential in an object making variations in expansion. (Usually from rapid heating or cooling of the glass).

- *Thermocouple*

A sensor used to measure temperature.

- *The Studio Glass Movement*

The emergence of the Studio Glass Movement in the 1960's was to have a profound effect on glass as an art form. The small furnace technology developed by artists Harvey Littleton and Dominick Labino made glass available in the studio environment for artists. Working directly with the material allowed artists to take charge of their process free from the factory environment, using glass for personal creative expression.

- *Tin Bloom*

*S*urface effect on fired float glass caused by oxidation of the tin surface, resulting in wrinkling and iridescent hazing. Can be minimized by firing the glass tin side down.

- *Tin Detector*

Ultraviolet lamp which shows the tin side of float glass when held against the surface. The tin side will fluoresce in the UV light.

- *Tin Side*

The 'tin side' of float glass is the surface which was in contact with the molten tin during the Float Process, leaving trace tin deposits.

- *Uroboros*

Based in Portland Oregon, manufactures fusible glass and 'art' glass sheet glass in various colours, styles and textures for stained/architectural glass applications and System 96 glass sheet, frit, billets and rods for fusing, casting and flameworking. Uroboros System 96 glasses have been developed to be compatible with Spectrum System 96 glass.

- *Vidriarte*

Established in 1980 making artisan engraved glass products. In 1986 began developing fused glass range and in 1994 began manufacturing 'Flosing' glass: coloured (flashed) float glass sheet, 2mm thick. Also manufactures an extensive range of float-compatible frits for fusers.

- *Viscosity*

The measure of a liquid's resistance to flow. At high temperatures glass in the liquid state has a low viscosity; at lower temperatures glass has a higher viscosity. A glass with low viscosity is sometimes said to be "soft." A glass with high viscosity is considered to be "hard" or "stiff." (Bullseye Tech Notes 5; www.bullseyeglass.com [Accessed 22/8/12])

III. Float Glass Brands & Manufacturers

Europe:

Pilkington
Saint Gobain Glass
AGC Glass Unlimited
Sisecam
Euroglass
Manfredonia Vetro/Sangalli,
Scheuten, GES

USA:

Pilkington USA & Canada
Guardian Industries
Cardinal Glass Industries
PPG Industries Corp

IV. Conferences, Seminars Attended & Collections Visited

The International Festival of Glass, Stourbridge, W. Midlands 2010, 2012 and 2015 (UK)

Dan Klein and Alan Poole Collection, National Museums Scotland, Edinburgh, 2011

Contemporary Glass Society Conference: Glass Skills: Exploring the Fusion of Art and Technique 12-13 October, 2013, National Glass Centre, Sunderland

Dan Klein and Alan Poole Collection , National Glass Centre, Sunderland 2013/14

Northlands Creative Glass, A selection of works from the North Lands Collection, 2014-15, National Glass Centre, Sunderland

Pilchuck Glass School Session 6, Stanwood, WA. (USA) 2014

Chihuly Garden and Glass, Seattle, WA, (USA) 2014

Glass Reflections: The Society of Glass Technology Conference, Cambridge, 2015

Broadfield House Glass Museum Collection, Kingswinford, W. Midlands, 2015

V. Institutions Visited

Broadfield House Glass Museum, Kingswinford, West Midlands, UK

Brooklyn Glass, Brooklyn, New York, USA

Chiluly Garden & Glass, Seattle, USA

Crafts Council, London, UK

National Glass Centre (now the National Glass Centre at the University of Sunderland), Sunderland, UK

National Museums Scotland, Edinburgh, UK

Pilchuck Glass School, Stanwood, WA. USA

Ruskin Glass Centre, Stourbridge, West Midlands, UK.

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