Shaping Colour:

Density, Light and Form in Solid Glass Sculpture

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Copyright statement

Abstract

In transparent glass, colour occurs through the absorption of certain wavelengths of light, and transmission of other wavelengths. In thicker sections of glass, more light is absorbed than in thinner sections, making the thicker sections appear darker, and sometimes a different hue. This phenomenon is called *volume colour* by Joseph Albers, and together with the optical properties of glass as a denser material than air, leads to remarkable possibilities for glass artists, to work with form to achieve light accents and/or different hues in solid object made from a single transparent glass colour. Artists in the Czech republic have explored this potential in cast glass since the 1960s, working directly with colour factories, and passing on gained knowledge through teaching. Elsewhere, it is difficult for artists to explore these possibilities for two reasons: Firstly, the lack of literature on volume colour, and the difficulty of translating theoretical information on optics into practical application. Secondly, on the practical side, it is unusual for artists to work with factories to develop their glass colours. Instead, colours are available in a limited range of hues, and casting colours are developed for small to medium sized objects around 5 cm thickness, therefore often appear very dark or black when used for larger solid casts of more than 10 cm thickness. To explore the relationship between colour, form and light in glass sculpture, artists need to be in control of colour hue and value. To achieve control, they have to either work with a factory, or colour their own glass. This research contributes to the practice of kiln casting through the development of methods to produce homogenous transparent colours in a studio environment, using ceramic crucibles in a kiln. Visual and written guidelines about basic colour results using single colouring agents provide a starting point for development of bespoke hues and densities. Drawing on physics texts and through a thorough study of existing glass sculpture, the optical properties of glass are explained in relation to practical application.

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Author’s declaration

During the period of registered study in which this thesis was prepared the author has not been registered for any other academic award or qualification.

The material included in this thesis has not been submitted wholly or in part for any academic award or qualification other than that for which it is now submitted.

Heike Brachlow
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1. Introduction

1.1. Motivation

Colour can be a problem for glass artists; contrary to ceramicists, they generally don't make their own. Instead, coloured glass is bought from a small number of suppliers, who have a limited number of hues and values available. Colour in a transparent solid behaves differently to surface colour: it changes not only in different lighting conditions, but also depending on form and size of object. Joseph Albers called this phenomenon "volume colour, which exists and is perceived in 3-dimensional fluids".[1] The most obvious characteristic of volume colour is that it appears darker with more volume or thickness, but it can also change in hue, for example from orange to red or from yellow to green.

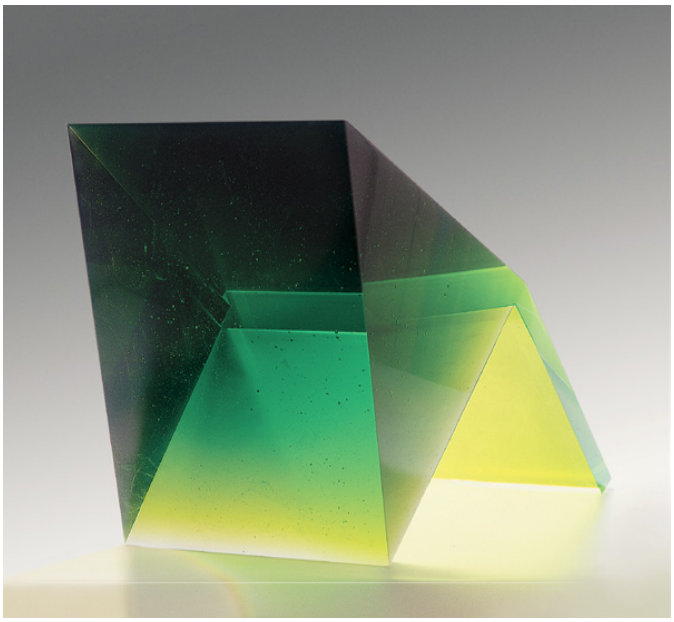

Figure 1: Colour change from thick to thin in *Metamorphosis IV*, 1984-86, by Stanislav Libenský and Jaroslava Brychtová. H: 65 cm, W: 35 cm.

[1] Josef Albers, *Interaction of Color* (New Haven & London: Yale University Press, 1963), 45.

I encountered volume colour during my MA, when I started scaling up my glass sculpture. The glass in sample form appeared light and luminous, while the finished casts looked dark and dull. Colouring glass in the college furnace, I finally achieved, after many failed attempts, the 'right' colour value for the forms I was casting. Each attempt involved at least 25 kg of glass batch mixed with colouring agents, melted over night at 1240ºC, cast into blocks the next day and annealed, again over night, and finally evaluated. If the colour was too dark, batch was added, if it was too light, a small amount of batch mixed with colouring agents was added. The process was uneconomical in regards to both time and energy. The following questions emerged: How is it possible to predict colour hue and density to prevent failure? How can glass be coloured in a kiln if a furnace is not available?

1.2. Aims

The following research aims evolved:

- Development of a feasible process for studio-based glassmakers to melt homogenous transparent coloured glass in a kiln.
- Development of a range of bespoke glass colours, including subtle variations and polychromatic colour (colours that appear different in different light sources).
- Investigation of the relationship between colour and volume in a transparent body, and development of a way to calculate the amount of colour needed to achieve desired results.
- A body of work in dialogue with this research, both testing results and pushing investigations in new directions.

The first aim, the development of a feasible process for studio-based glassmakers to melt homogenous transparent coloured glass in a kiln, was central for the development of the project and all further aims, therefore had to be addressed first. In-depth colour testing and the

creation of a bespoke palette would not have been possible within the time limit without a method to create multiple samples in a single firing.

The investigation of the relationship between colour and volume in a transparent body was addressed on several levels. It was found that volume colour is not featured in colour theory except for a small number of short mentions. However, literature about glass artists Stanislav Libenský and Jaroslava Brychtová addresses the issue from the viewpoint of form and light in solid transparent coloured glass, and their body of work provides a starting point for visual investigation. This led to the study of optics, and to empirical inquiry through making, which in turn led to the creation of a body of work.

The research was driven and defined by the need for coloured glass for creative studio work. It is rooted in a studio context, has been carried out in a studio environment (the Department of Ceramics and Glass at the Royal College of Art), and the resulting processes and findings are intended for use in a kiln caster's workshop. Based on a combination of empirical investigation and theory, the research was conducted using a maker's approach. Decisions are made intuitively, based on knowledge of material and on experience. Visual evaluation is central, and "living with" an object or a process, taking time to reflect, is important. An experimental approach often results in unexpected outcomes, which can open up new avenues. The maker is receptive to the possibility of improvement and adaption during the making. Skill, the physical ability do something well, frees the mind from having to concentrate exclusively on the process, providing opportunity to come up with alternative possibilities and solutions. Making skills are transferable; if someone is accomplished in working with one material, skills in other materials and processes will come more easily. The approach is not planned out in detail from the beginning; during the making, one thing leads to another, and understanding happens on many levels.

1.3. Literature

It is difficult to find useful literature on the subject of glassmaking and colouring. While there are many books about processes like glassblowing, casting, fusing, and lampwork, little is available on the making and colouring of glass. The major work on colouring glass, *Coloured glasses* by W. A. Weyl,[2] provides ample information, but is written for scientists or technologists, and hard to understand/translate. Recipe books like Henry T Hellmers' *Batch book of glass formulae*[3] and Wilhelm Schmidt and Finn Lynggaard's *Recipe book for practical glass melting* [4] provide full recipes for making coloured and plain glasses, but lack simple guidelines about single oxides and the approximate quantities needed. Being out of print, they are difficult to acquire. Vague guidelines are provided in Henry Halem's *Glass Notes*[5] and Charles Bray's *Ceramics and Glass: A Basic Technology*.[6] Frederic and Lilly Schuler provide slightly more detailed, but still brief guidelines in *Glassforming: glass making for the craftsman*.[7] Some suppliers of colouring oxides offer advice on the amount of oxide needed for glass blowing, but this is much more difficult for glass casting, because the colour density depends on form and size of the object to be cast.

Several artists have conducted research into different aspects of colouring glass. Sylvie Vandenhoucke completed a Master of Philosophy

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[2] Woldemar A. Weyl, *Coloured Glasses* (Sheffield Eng.: Society of Glass Technology, 1967).
[3] Henry Hellmers, *Henry T. Hellmers Batch Book of Glass Formulae* (Kevil, KY: J. W. Courter, 2002).
[4] Wilhelm Schmidt and Finn Lynggaard, *Recipe Book for Practical Glass Melting* (Cider Press, 1998).
[5] Henry Halem, *Glass Notes: a Reference for the Glass Artist*, vol. 4th (Kent , OH: Franklin Mills Press, 2006).
[6] Charles Bray, *Ceramics and Glass: a Basic Technology* (Sheffield: Society of Glass Technology, 2000).
[7] Frederic Schuler and Lilli Schuler, *Glassforming: Glass Making for the Craftsman* (London: Pitman, 1971).

at the Royal College of Art in London in 2003, investigating the results of colouring clear glass frit with metal oxides at temperatures of 800ºC.

Max D. Stewart's PhD research at Edinburgh College of Art (2007-2010) focused on recreating the forgotten pâte de verre colour palette and methods of French artist Amalric Walter. A comprehensive study of colouring lead crystal frit at casting temperatures, using metal salts, was conducted.

Teresa Almeida completed her PhD at the University of Aveiro, Research Unit VICARTE *Glass and Ceramic for the Arts,* which is a multidisciplinary research and development centre for the study of glass and ceramics in Portugal. She studied the making and use of luminescent glasses, created by adding oxides of the rare earth elements europium, terbium, cerium, dysprosium, thulium and samarium to soda lime glass. The objects created have no colour in normal illumination, but appear coloured and luminescent under UV light. Like mine, Almeida's research involves making transparent, homogenous coloured glass, but her starting point is not batch, but finely ground glass frit. The project is set in a scientific context, rather than a studio context, and does not include methods of melting glass in an artist's workshop. However, her results can be applied by a studio artist, restricted only by the expense and lack of availability of the rare earth oxides.

1.4. The thesis

The outcomes of this PhD project include a written thesis, a series of colour tests and a body of creative work. The thesis begins with a selective history of glass. In a survey of glassmaking and colouring, literary and archaeological evidence of processes and materials is assembled. A study of glass casting processes shows that while casting was the first glassforming method, the process was almost completely discarded after the discovery of glassblowing, to re-emerge over 1500 years later in France, as pâte de verre.

The third chapter examines the appearance of colour in glass. Factors influencing the interaction of form, colour and light, as well as optical principles as pertaining to glass are discussed, with volume colour taking centre stage. The chapter ends with a short history of polychromatic glasses, definitions, as well as motivations for their development and use.

The fourth chapter covers material and process research. The development of methods for testing and making coloured glass in a kiln is described, as well as aims and results of colour testing, methods of recording and criteria of evaluation.

The creative work is discussed in the fifth chapter. It is placed in a fine art, applied art and studio glass context. The thought and making processes leading to creative outcomes are discussed, and the development of tests into artwork is explained.

The conclusion summarises accomplishments and explains changes in direction. Areas for further research and possibilities for creative work are identified.

The appendices contain the colour test databases and the colour chart used to describe hue. Information on suppliers, materials, and firing cycles is provided, as well as a project summary for artists interested in using the newly developed processes for their own work.

2. History of glassmaking, colouring and casting

2.1. Introduction

This is a personal history of glass, which focuses on the processes I use in my studio work and research. In the writing of this history, I have attempted to compile as much data as possible, in form of object interpretation and literary evidence, but some of the account is speculation at least in part. The history of glass is a history of objects, objects that have been found in archaeological excavations, on sunken ships, or in locations unknown, and dated by various methods, such as radiometric dating, seriation (sequence dating) and cross-dating (the placing of the object in an already established sequence). The method of dating is either relative, where the age of an object is estimated by its relationship to the containing deposit or associated objects, or absolute, where the object, or its containing deposit, is dated by internal evidence, as in radiocarbon dating. Context, place of manufacture and place of use of an object are often unclear, and although methods of dating and analysis are improving, many findings are by no means certain, and in some cases superseded by later research. Some literary sources are available, for example glassmaking recipes on cuneiform tablets, household inventories, administrative texts, and books, for example Pliny the Elder's *Natural History*[8] and Theophilus' *On divers arts*[9].

[8] Pliny, John Bostock, and Henry T Riley, *The Natural History of Pliny, Vol. VI* (London,H. G. Bohn,, 1857), http://www.biodiversitylibrary.org/item/34003.
[9] Theophilus, *On Divers Arts: The Foremost Medieval Treatise on Painting, Glassmaking and Metalwork*, vol. 1st (New York ; Dover Publications ; London: Constable, 1979).

2.2. Glass melting and colouring

2.2.1. Ancient glassmaking

There is some uncertainty about the beginnings of glassmaking, but it is believed to have developed in the Bronze Age, during the third Millennium BC, in Western Asia, probably Mesopotamia, most likely as a result of experimentation with vitreous pottery glazes[10] or Egyptian faience.[11] It was in all probability an accident, for example glaze pooling on a kiln floor, or a faience bead that was forgotten in a furnace, fusing into glass, that prompted a craftsperson to experiment further. A story about the beginnings of glass told by Pliny the Elder is based on an accident: Phoenician merchants suspended their cooking cauldrons on blocks of their cargo, which was nitre (potassium nitrate, sodium nitrate, potassium carbonate or sodium carbonate, i.e., a flux) in the sand on the seashore. The cooking fire is supposed to have melted the soda and the sand together into glass. The story is thought unlikely, because sand does not melt so easily. [12]

Finds of very early glass include a fragment of translucent blue-green rod from Tell Asmar, Mesopotamia (now Iraq), whose excavation context has been dated to the 23rd century BC, and a lump of very bubbly opaque blue glass found at Eridu (now Iraq) from the 21st century BC.

The oldest known glass items are non-transparent beads, dated to the late 4th millennium BC, which were found in Egypt. Glass*making,* the production of glass from raw materials, and glass*working,* the fabrication of glass objects, seemed to have been separate industries from early on, with glassmaking centres in resource-rich areas, most likely in

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[10] David F. Grose, *Early Ancient Glass: Core-formed, Rod-formed, and Cast Vessels and Objects from the Late Bronze Age to the Early Roman Empire, 1600 B.C. to A.D. 50* (New York: Hudson Hills Press in association with the Toledo Museum of Art, 1989), 45.

[11] Egyptian faience is a non-clay ceramic consisting of a solid mixture of powdered quartz, lime and alkalis, and displaying surface vitrification.

[12] Pliny, Bostock, and Riley, *The Natural History of Pliny, Vol. VI*, 379.

Mesopotamia (Modern day Iraq as well as some parts of north-eastern Syria, south-eastern Turkey and south-western Iran) and Egypt. Glassmakers were exporting glass ingots and frit to the surrounding areas to be used by glassworkers. There are numerous finds indicating glass workshops in Egypt from the 14th to the 12th century, as well as several possible glassmaking sites, namely at Malqata on the west bank of the Nile at Thebes, at Amarna on the east bank of the Nile, and at Quantir.[13] The site at Quantir Pi-Ramesse, about 60 miles north-east of Cairo, is an important find that had workshops for various crafts including high-temperature technologies like bronze casting and glassmelting. From the study of glassmaking crucibles, the conclusion was drawn that the glass was made in relatively small batches of a few litres volume in ceramic crucibles lined with a lime-based parting layer. It has been shown that the parting layer was partially absorbed into the glass, thereby increasing the lime content of the glass ingots considerably.[14] Even so, it is surprising that Bronze Age Egyptians managed to successfully separate the ingot from the crucible, without leaving residual clay on the glass surface.

To date, no glassmaking sites have been found in Mesopotamia.[15] Evidence of the trade of glass as a material to be worked into objects are ingots found on sunken ships, as in a discovery near Ulu Burun off the south coast of Turkey, of a ship that sank in the late 14th or early 13th century BC. It carried over a hundred ingots of mainly blue glass, weighing about 2 kg each.[16]

In 1956, a large slab of opaque, glassy material, measuring 1.98 m by 3.35 m by 45.5 cm and weighing about 9 tons, was discovered in Beth

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[13] Andrew Shortland, "Glass Production," *UCLA Encyclopedia of Egyptology.* (UC Los Angeles, 2009).
[14] Thilo Rehren and Edgar B. Pusch, "New Kingdom Glass-Melting Crucibles from Qantir-Piramesses," *The Journal of Egyptian Archaeology* 83 (1997): 127–141.
[15] Shortland, "Glass Production."
[16] Yael Israeli, Dan Barag, and Na'ama Brosh, *Ancient Glass in the Israel Museum: The Eliahu Dobkin Collection and Other Gifts* (Jerusalem: The Israel Museum, 2003), 35–36.

She'Arim in Galilee. This is thought to be a glass melt from the end of the 4th century A.D, which was meant to be broken up for the use of glassworkers. It was most probably left in place, because it had been spoiled by an excess of lime (calcium carbonate), most likely from the furnace walls. Chemical analyses shows the lime content to be near 16% instead of 8%, as was common in glasses of this time. The extra lime caused the glass to devitrify[17] and turn opaque as it cooled. The size of the slab is truly astonishing and rivalled only by the giant telescope mirrors of the 20th century. Roughly 11 tons of raw materials would have been heated to 1100°C for 5 - 10 days, using about 20 tons of wood![18]

2.2.1.1. Ingredients and processes

The basic raw materials of ancient glass are the same as today: silica, lime and a flux, of which only silica and the flux were acknowledged ingredients. Sand or river pebbles were pounded or crushed to obtain the silica, and sometimes the sand contained seashells, thereby providing the lime. Plant ashes, which also sometimes contained lime, provided the flux. The ingredients were weighed and mixed, then heated in two stages. In the first stage, the mix was introduced to a furnace which was pre-heated to a temperature sufficiently high to lead to granulation, but not high enough to lead to complete fusion, and stirred or raked continuously, to produce *frit*. In the second stage, additional ingredients, for example colouring agents or decolourisers, are added to the prepared frit, then it is melted until a homogenous glass is achieved. This two-step process was probably necessary because the temperatures required for melting and fining glass from raw materials (1300º - 1500º) could not be reached. Another advantage is the reduction of the number of times a

[17] Crystal formation in the glass, most often on the surface, which renders the glass opaque and can introduce strain.
[18] "The Mystery Slab of Beth She'Arim - Resource on Glass - Corning Museum of Glass," *Corning Museum of Glass*, n.d., http://www.cmog.org/dynamic.aspx?id=9420.

crucible has to be charged during the final melting process, thus reducing the heat loss.[19] The process seems to have been practised from the very beginning of glassmaking until into the 19th century. An in-depth study of crucibles found at a glassmaking site at Wadi el-Natrun, Egypt, which was dated to the period of 30 BC to 359 AD, showed that different crucibles were employed for fritting and melting. For fritting, the crucibles only needed to withstand temperatures of about 900ºC, and were made from friable materials, to allow for easy removal of the frit. The specimens investigated had volumes of about nine and five litres, and were of a rectangular shape, which has not been found at other sites. The material was coarse-grained and brittle, giving rise to the conclusion that it was only used once, and broken off the frit after the process was finished. The crucibles for the melting stage, on the other hand, were fairly small and made of a fine fireclay body. They needed to withstand temperatures of approximately 1000ºC to 1100ºC. Saleh Ahmed Saleh et al. suggest that the frit was ground to a fine powder, before mixing it with more flux for the final melting process.[20]

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[19] J. W. Smedley, C. M. Jackson, and C. A. Booth, "Back to the Roots: The Raw Materials, Glass Recipes and Glassmaking Practices of Theophilus," in *The Prehistory & History of Glassmaking Technology*, ed. Patrick (W Patrick) McCray (Westerville, Ohio: American Ceramic Society, 1998), 163.

[20] Saleh Ahmed Saleh, Adel Wageih George, and Fatma Mohamed Helmi, "Study of Glass and Glass-Making Processes at Wadi el-Natrun, Egypt in the Roman Period 30 B.C. to 359 A.D. Part 1. Fritting Crucibles, Their Technical Features and Temperature Employed," *Studies in Conservation* 17, no. 4 (November 1972): 143–172.

2.2.2. Literary evidence of ancient glassmaking processes

Amongst the earliest evidence of glassmaking recipes are a series of Mesopotamian clay tablets with recipes in cuneiform script dated between the 14th and the 12th century BC, from the library of Assurbanipal in Nineveh (now Ninawa, Iraq).

Figure 2: Babylonian clay tablet with recipe for making red glass, 1400-1200 BC. L: 8.25 cm, W: 5.23 cm. British Museum.

At that time, the glassmaking process was surrounded by ritual: "When you set up the foundation of a kiln to make glass, you first search in a favourable month for a propitious day…you make a sheep sacrifice…"[21] The two-step heating process is described as follows: *frit* is produced by heating crushed silica and the ashes of the naga plant for a long time at low temperatures of about 850ºC or "the colour of ripe grapes", until sintered. After cooling, the frit was ground, then fired again at a

[21] A. Leo Oppenheim, Robert H. Brill, Dan Barag, and Axel von Saldern, *Glass and Glassmaking in Ancient Mesopotamia* (Corning, N.Y.: Corning Museum of Glass Press, 1970), 32–33.

temperature of about 1050ºC or "heat which glows golden yellow" until melted. Three different types of furnace or kiln are described, used for sintering, melting and casting respectively.[22] Crucibles also differed in composition, shape and size depending on which process they were intended for.

In his *Natural History*, published in the first century AD, Pliny the Elder also describes a two-step process, where white sand from specific locations is pounded in a mortar and pestle, mixed with nitre, and fused, then transferred into a second furnace, where the mass is melted into glass.

> "It is melted, like copper, in contiguous furnaces, and a swarthy mass of an unctuous appearance is the result. Of such a penetrating nature is the molten glass, that it will cut to the very bone any part of the body which it may come near, and that, too, before it is even felt. This mass is again subjected to fusion in the furnace, for the purpose of colouring it; after which, the glass is either blown into various forms, turned in a lathe, or engraved like silver."[23]

Pliny the Elder was obviously not a craftsman; much of his writing on glass production is inaccurate or incomplete.

Fritting and melting processes are described in detail by Theophilus, a Benedictine monk who is thought to have been a practising craftsman, probably near Cologne (Germany), in his manuscript *Artibus Diversibus*, most likely written in the early 12th century AD.[24] He gives a description of the furnace and kilns needed, as well as of the preparation of

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[22] E. M. Stern and Birgit Schlick-Nolte, *Early Glass of the Ancient World: 1600 B.C.-A.D. 50; Ernesto Wolf Collection* (Ostfildern, Germany: Verlag Gerd Hatje, 1994), 20.
[23] Pliny, Bostock, and Riley, *The Natural History of Pliny, Vol. VI*, 360.
[24] Theophilus, *On Divers Arts: The Foremost Medieval Treatise on Painting, Glassmaking and Metalwork*, vol. I.

ingredients and of the different processes.

In 1612, Florentine monk and glassmaker Antonio Neri published a glass recipe book, L'Arte Vetraria, which was translated into English and published with observations and notes of the translator, Christopher Merrett, in 1662.[25] It was also translated into Latin, German, Spanish and French, found widespread interest amongst glassmakers and provided a basis for further innovation. Considering the secrecy that surrounded Venetian glassmaking, with penalties (including death) for revealing knowledge, the impact of Neri's book on the further development of glassmaking can be imagined. In the text, much attention was given to the preparation of ingredients, but knowledge of furnaces was mostly taken for granted; Neri does mention variations in crucible size depending on the quantities required for different operations; lead glasses were usually melted in amounts of twenty to thirty kilograms, enamels in amounts from two to three kilograms, and heavy lead glass for gems were melted in quantities of a few hundred grams[26] in a potter's kiln.[27] In his *Observations*, Merrett adds descriptions of furnaces and equipment to Neri's account.

When comparing the different texts, improvements in equipment, preparation of ingredients, and processes are notable. The cuneiform tablets from Nineveh, for example, don't mention stirring during the fritting process, but the frit had to be ground to a fine powder in between steps; Theophilus' description of fritting requires stirring for "a night and a day", whereas Neri's instructions only require 5 hours of mixing with a rake. Neither description requires grinding of the frit. Merrett, in his *Observations* added to Neri's manuscript, describes improvements and mechanisations for the preparation of ingredients, for example a horse-drawn mill with millstones made of hard marble to grind ashes,

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[25] Antonio Neri and Christopher Merrett, *The Art of Glass* (Sheffield: Society of Glass Technology, 2001).
[26] Original: "in quantities of ounces".
[27] Neri and Merrett, *The Art of Glass*, 31.

manganese, zaffre[28], cullet etc., which must have speeded up preparation time and reduced the required labour considerably. Regarding colouring agents, in Theophilus' times, colouring seems to have occurred by accident due to varying quantities of manganese and iron present in the ingredients, and their state of oxidation. Neri provides detailed instructions on purification of materials and preparation and addition of colouring agents.

2.2.3. Early glass colouring

Most early glass that has survived until today is opaque and bright in colour, probably because it was produced and used as a substitute for precious stones such as lapis lazuli and turquoise. Also, it was difficult to achieve transparency because many microscopic bubbles remained in the glass due to low melting temperatures. There is some evidence of early transparent glass; for example the earlier mentioned rod of translucent light blue-green glass from the 23rd century BC.[29] Transparent glass became more common in the 15th century BC, but the colours produced were often too dark to transmit light. With the advent of the core forming technique around 1550 BC, polychrome designs such as marbling emerged, and at roughly the same time, use of cane for mosaic work became common. A high level of technical experimentation must have accompanied the use of polychrome glass in core forming and mosaic vessels, to achieve compatibility[30], which is still an issue for today's glassworkers!

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[28] Alternative spelling: zaffer. Impure cobalt oxide, used to colour glass or ceramic glazes. From Italian *zaffera;* probably related to Latin *sapphīrus* sapphire. "Zaffer | Define Zaffer at Dictionary.com", n.d., http://dictionary.reference.com/browse/zaffer.

[29] Dan Barag and Veronica Tatton-Brown, *Catalogue of Western Asiatic Glass in the British Museum* (London: The Museum in association with Magnes Press, Hebrew University, Jerusalem, 1985), 35.

[30] Compatible glasses have similar coefficients of expansion. If glasses with different expansion coefficients are fused, they will crack after cooling. Colouring oxides can affect the coefficient of expansion.

Figure 3: Mosaic inlays, Egypt, 1st century BC. . L: 2.9 cm, W: 2.8 cm; L: 2.2 cm, W: 1.6 cm. British Museum.

The use of decolourisers, for example antimony and manganese, to achieve a transparent colourless glass, is documented from the late 8th century BC in western Asia. The glassmakers of this time were imitating rock crystal rather than lapis lazuli and turquoise, and the techniques used for fashioning objects were the same grinding and polishing techniques as employed for rock crystal. Pliny the Elder wrote that "the most highly priced glass is colourless and transparent, as closely resembling rock crystal as possible."[31] And also, "Vessels of glass have been brought to a marvellous degree of resemblance to crystal."[32] The colours Pliny mentions include an opaque red, a "dead" white, hyacinthine, sapphire, "and every other tint."[33]

Theophilus describes how to achieve several colours:

> If you see a pot changing to a saffron yellow colour, heat it until the third hour and you will get a light saffron yellow. Work up as much as you want of it […]. And if you wish, let it heat until the sixth hour and you will get a reddish saffron yellow. […] But if you

[31] Pliny, Bostock, and Riley, *The Natural History of Pliny, Vol. VI*, Book XXXVI, 382.
[32] Ibid., Book XXXVII.
[33] Ibid., Book XXXVI, 382.

> see any pot happening to turn a tawny colour, like flesh, use this glass for flesh-colour, and taking out as much as you wish, heat the reminder for two hours, namely from the first to the third hour, and you will get a light purple. Heat it again from the third to the sixth hour and it will be a reddish purple and exquisite. [34]

These colour changes take place because of the varying percentages of colouring agents in the ingredients, and their state of oxidation. It is surprising that the author writes: "If you see [the glass in] a pot changing colour…" In my experience, it is extremely difficult to make any colour judgements from a pot of hot glass, which always glows orange to yellow. Possibly Theophilus didn't mean it literally, but was talking about the observing a colour change while working the glass into objects, and letting a sample of it cool naturally to judge the colour.

Theophilus doesn't seem to have any knowledge about purposefully colouring glass. He writes about others who do, mentioning "the French, who […] even melt blue in their furnaces."[35]

Neri, on the other hand, provides detailed accounts on different batches and colours, describing in minute detail how to prepare the colouring oxides, often in several different ways. He also describes how the colour is to be added to the glass, in some cases taking into account colour density, i.e. the variation in value needed for different size objects, as in the recipe for sea-green described in his chapter XXII. He also recommends to "put in rather too little than too much, for the colours may be easily heightened."[36] In the introduction to the third book, Neri gives general instructions regarding melting coloured glass:

> The colour must be made fuller or lighter according to the works you employ them for, and to heighten them, put in more of the colour, but to make them lighter put into the pot more Fritt. Take

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[34] Theophilus, *On Divers Arts: The Foremost Medieval Treatise on Painting, Glassmaking and Metalwork*, Vol. 1, p. 55.
[35] Ibid., Vol. 1, p. 55.
[36] Neri and Merrett, *The Art of Glass*, 97.

> some metall (molten glass) out of the pot, and you shell see whether you have your desired colour; put in your colours little by little lest they overdo.
>
> Put your colour to the Fritt, and not to the metall, when melted, for then it neither takes the colour so well, nor so good a colour.[37]

The first reference to glassmaking in Venice was recorded in 982. Even though the area is not resource-rich, Venice is a port, facilitating import of raw materials, for example plant ashes from Syria. Venice became the most important glassmaking centre of the Middle Ages.

A recipe book on Venetian glassmaking, somewhat similar to Neri's, was published in 1986, in Italian, with English introductory essays. It is Venetian glassmaker Giovanni Darduin's notebook, started by his father Nicolo, and finished by an anonymous glassmaker. Darduin also copied two further notebooks onto the pages. The complete manuscript spans almost 200 years, from 1523 to 1712 approximately.[38] The book gives nearly 300 colour recipes, sometimes repeated, and exact details on preparation of materials, as well as instructions on controlling furnace temperatures and atmosphere. It confirms that a two-stage process is needed for the production of glass from raw materials because temperatures in excess of 1200ºC could not be reached. To melt a soda-lime glass from batch, temperatures of 1300ºC to 1400ºC are necessary. A process to purify the glass, i.e. eliminate insoluble salts, and render it more homogenous, involved repeatedly casting the molten glass into water before re-melting it. Darduin adds a caution to the reader: "In everything, experience is more necessary than science."[39] Several potash-lead crystal recipes are included in the notebook, the earliest of which is dated 1697. The invention of glass where lead becomes the main flux is attributed to George Ravenscroft of England, who patented it in

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[37] Ibid., 147.
[38] Luigi Zecchin and Rosa Barovier Mentasti, *Il Ricettario Darduin: Un Codice Vetrario Del Seicento Trascritto e Commentato* (Venezia: Arsenale, 1986).
[39] Ibid.

1674. Ravenscroft had spent some time in Venice and probably studied glassmaking there.

2.2.4. Glass colouring for pâte de verre

In the late 19th century, an ancient form of glass casting using glass frits and powders was re-discovered in France and came to be called pâte(s) de verre or pâtes de crystal (50% lead crystal). Pioneers of the process included Henri Cros, Albert Dammouse, Georges Despret, François-Émile Décorchemont, Gabriel Argy-Rousseau, and Amalric Walter, and the objects produced were mostly vessels and sculptures with multi-coloured figurative designs. In order to cast with coloured glass frits, said frits had to be manufactured. A good account of pâte de verre production, including the manufacture of coloured frits, is preserved in Argy-Rousseaus notebooks[40], which the Argy-Rousseau family donated to the Rakow Library in Corning, NY in 1976. The manuscript was translated into English in 1978. It contains recipes of composition of glasses used to make pâte de verre, instructions on preparation of ingredients, methods of founding, many colour recipes for borosilicate and lead glasses, as well as notes on mouldmaking processes, preparation and application of frits, and firing. For melting small quantities of glass, Argy-Rousseau describes the use of a Perrot[41] gas furnace with a crucible. The crucible is charged[42] several times in the early stages of the melting process until almost filled. After about five hours, the glass is checked to make sure it is completely melted. If it is, the crucible is removed from the furnace and the glass pulled out with tools (as described for the borosilicate glass, which must have been fairly viscous at melting temperatures of around 1250ºC) and placed in water to break it up into frit. Some of the colour recipes are similar to the results I have achieved with small tests,

[40] Gabriel Argy-Rousseau, "The Notebooks of Gabriel Argy-Rousseau. The Production of Pate-de-Verre."
[41] See section 3.1.9
[42] Adding raw material mixture

but most are quite different, as the base glasses are of different compositions. The percentages of oxides employed are calculated to yield mostly strong (dark) results, as the colours are meant to be ground into fine powders, usually to be used as an outer colouring layer, which appears translucent or opaque.

Antoine and Etienne Leperlier have been making use of their grandfather François Décorchemont's technical notes. In a similar, but much less detailed fashion to Argy-Rousseau, they describe a three-step process in 1982: Firstly the colouring of the glass, secondly the modelling, and lastly the casting.[43] The melting of the glass takes place in refractory crucibles made in a plaster mould, with a capacity of 5-10 kg. The melting process differs in several aspects: crushed crystal mixed with metal oxides is placed in crucibles, which are fired in a kiln (12 at a time) between 1200ºC and 1300ºC. After cooling, the crucibles are broken off the glass, and the glass is crushed by hand in a cast iron bell jar, and sieved.

I do not know if some of the pâte de verre pioneers melted their glass in crucibles in a kiln, or if they used large glass furnaces for industrial size melts, and Perrot furnaces for small quantities, as Argy-Rousseau describes. But Cros et al. worked mostly in ceramic factories, therefore it is not too far-fetched to assume that they would have used ceramic kilns for their melts.

2.2.5. Recent history

Until the 20th century, glassmaking and working happened in factories, usually situated in resource-rich areas, for example in the Black Forest in Germany (from the 12th century at least), in Bohemia (now Czech Republic) and Silesia (now Poland) from the 13th century, in the Bavarian Forest in Germany from the 15th century, in Stourbridge in England from

[43] Antoine Leperlier and Etienne Leperlier, "The Techniques of Pate De Verre," trans. Diana Hobson, *Revue De La Ceramique Et Du Verre* 6 (October 1982): 14–15.

the 17th century onwards, et cetera. In the 19th and 20th centuries, many innovations were introduced and new processes were invented. An example is Pilkington's development of new processes for making window glass, which culminated in the float glass process, developed between 1952 and 1959. Important research about components of optical glass was begun by Dr. Otto Schott in 1879, and led to the founding of the Glastechnisches Laboratorium (Glass Technology Laboratory) in 1884 by Otto Schott, Ernst Abbe, Carl Zeiss and Roderich Zeiss in Jena. Later, it was renamed Jena Glasworks.

Glassmaking was established in America in 1739 (after failed attempts in Jamestown, Virginia, in 1608 and 1621), when Caspar Wistar built a glassmaking plant in what is now Salem County, New Jersey. This plant operated until 1780. In the early 19th century, Sandwich Glass Company, founded by Deming Jarves in 1825, and the Bakewell, Page, and Bakewell Company of Pittsburgh, Pennsylvania, began to make pressed glass.[44] The Corning Glass Works, now Corning Inc., were founded in 1851 in Brooklyn, New York, and later moved to (and took the name of) the city of Corning, New York. In 1918, the Corning Glass Works purchased the Steuben Glass Works, which had been founded by Frederick Carder of Stourbridge, England, and Thomas J. Hawkes in 1903.

To supply the glass industry with coloured glass, Farbglashütten (colour glass works) were established, for example the Farbglashütte Reichenbach (founded in 1866), located in East Saxony, and the Friedrich Farbglashütte GmbH (now merged with Kugler Colours), which was founded in the S*udetenland*, the German speaking part of what is now Czech Republic, and moved to Neugablonz in Germany after World War II. They supply customers all over Europe, North and South America, India, Japan and China.

With the establishment of the studio glass movement, which started in

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[44] Steve W Martin, "Historical Facts About Glass!", n.d., http://www.texasglass.com/glass_facts/history_of_Glass.htm.

the early 1960s, another market opened up: Glass art supplies for the studio artist, and later, the hobbyist. In the USA, several companies were started to supply this particular market: Uroboros was founded in 1973 by glass artist Eric Lovell, and the Bullseye Glass Co. started in 1974, both in Portland, Oregon. Both supply glass for stained glass artists as well as for fusing and slumping, and later for casting.

Figure 4: Bullseye billets and sheet glass at the factory. Portland, Oregon.

Gaffer Coloured Glass Ltd. was founded in 1993 by John Croucher and John Leggott in Auckland, New Zealand. They supply colour rods and frits as well as casting billets.

The Friedrich Farbglashütte has begun the development of glasses for casting as recently as 2007; the product has been for sale since September 2008. Clear glass for the European studio artist is supplied by Schott, but in England, many artists sourced their casting glass from crystal factories, for example Stuart Crystal (founded in 1883) in Stourbridge and Waterford (founded in 1783) in Ireland. With the closure of these factories, new sources had to be found. The most commonly used casting glasses are Gaffer's lead crystal and Bullseye's Soda-lime billets. Czech colour company Banas offer a wide range of more affordable colours, however, compatibility is not assured.

In a studio environment, glassblowers occasionally experiment with colour melting in their furnace; literature to provide a starting point is

sadly lacking. Recipe books like *Henry T Hellmers' batch book of glass formulae*[45] and Fritz Lynngaard's translation of a German recipe book[46] provide full recipes for making coloured and plain glasses, but lack simple guidelines about single oxides and the approximate quantities needed. Vague guidelines are provided in Glass Notes[47] and Ceramics and Glass: A Basic Technology.[48] Frederic Schuler[49] provides slightly more detailed, but still very brief guidelines in his book *Glassforming: glass making for the craftsman*. Suppliers of colouring oxides provide advice on the amount of oxide needed for glass blowing, but this is much more difficult for glass casting, because the colour density depends on form and size of the object to be cast. Ideally a guide to colouring glass for artists should contain detailed descriptions of effects of different amounts of oxides at different glass thicknesses, as well as visuals.

2.3. History of glass casting

Glass casting had its peak before the invention and in the early times of glass blowing, between the 15th century BC and the middle of the first century AD. After the fall of the Roman Empire, casting stopped almost completely, although the mould pressing of small seals and medallions continued. Casting was revived and re-developed in the 19th century in France in a process called *pâte de verre*, and also for the manufacture of mirrors. From the early 20th century onwards, gigantic telescope mirrors were cast in America. A leap in development of glass sculpture was attained in the 1960s in Czechoslovakia, where castings of ever increasing size and volume were attempted and achieved. From the late 20th century onwards, casting has been pushed in scale as well as breadth of process, and increased enormously in popularity.

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[45] Hellmers, *Henry T. Hellmers Batch Book of Glass Formulae*.
[46] Schmidt and Lynggaard, *Recipe Book for Practical Glass Melting*.
[47] Halem, *Glass Notes: a Reference for the Glass Artist*, 4th:21–24.
[48] Bray, *Ceramics and Glass: a Basic Technology*, 198–214.
[49] Schuler and Schuler, *Glassforming: Glass Making for the Craftsman*, 83–85.

2.3.1. Ancient history

2.3.1.1. Casting process

Before 1500 BC, the predominant glassworking technique was almost certainly casting. The processes used were derived from the much older metalworking techniques, where molten metal was poured into clay-based or stone moulds. Glass objects from this time include beads, inlays, rods and other small items. One or both of the following processes have probably been utilised: Glassworkers heated a chunk of glass until viscous and used tools to press it into a simple open mould made from clay or soapstone (steatite). Alternatively, chunks of glass could have been placed in the mould and heated together with the mould until softened, then pressed into the mould. Tool marks on the back of plaques and pendants suggest these procedures, which were used because small amounts of glass require much higher temperatures than larger amounts to completely fill the details of the mould, or extra weight or pressure, which was applied using tools. Frequently, the glass either overfilled or did not quite fill the mould. In the latter case, additional layers of glass, often different in colour, were fused to the back of the inlay. Most early glass was opaque and brightly coloured, probably because it was used to replace precious stones like lapis and turquoise. Objects were finished using lapidary techniques when cold.

Figure 5: Ancient Egyptian plaques. British Museum.

2.3.1.2. Mould release

With the first casting method described, which is similar to what is now referred to as *hot casting,*[50] the difference in temperature between mould and glass would have prevented the glass from adhering to the mould. Using the second method, similar to kiln casting, clay moulds would have required a release agent, for example corundum (aluminium oxide), traces of which were found on Greek clay moulds from the 5th and 4th centuries BC. Alternatively, the composition of the clay could have been such that no release agent was needed, as is sometimes observed when leftover glass in a terracotta flowerpot, used as a reservoir, releases cleanly after cooling. Steatite moulds most probably do not require a separate release agent, as soapstone's main component is talc, which works as a release agent. Ancient castings were probably taken out of the mould while still hot, and annealed in a bed of ashes.

[50] The pouring of molten glass from the furnace into a metal, graphite or refractory mould. The glass object is removed from the mould after stiffening, at approximately 550ºC, and annealed.

2.3.1.3. Mould materials and casting techniques

Conclusions about mould materials and casting processes have been reached mostly by studying the objects made in such moulds, and also the moulds themselves where possible. Stone moulds were much more likely to survive and be found than re-usable clay moulds, which again were more likely to survive than friable one-piece-moulds, which had to be broken of the glass object after casting. Early Egyptian moulds dated to the 14th century BC are made of clay; however, it is not clear if they were used for faience, for glass, or for both.[51] Mycenaean moulds for beads and inlays, made from Steatite, were used for glass as well metal casting.

Figure 6: Moulds for a faiance ring (L: 3.2, W: 3 cm) and a bead, 1349–1336 BC, found in Amarna, Egypt. Museum of Fine Arts, Boston.

Techniques of casting metal into stone moulds are considerably older than glass: The earliest known metal casting is a copper frog made in

[51] Stern and Schlick-Nolte, *Early Glass of the Ancient World: 1600 B.C.-A.D. 50; Ernesto Wolf Collection*.

Mesopotamia around 3200 BC.[52] Lost wax casting has been used as early as during the 3rd millennium BC in Sumeria, and again from the 16th to the 13th century BC in Egypt, which means the technique was already known when glass was discovered/developed. It is difficult to ascertain when plaster-based waste moulds were first used for glass, but it is known that plaster as a building material was employed well before the discovery of glass. It is known to have been used as a mould material in Egypt for items such as the death mask of King Teti around 2400 BC, and was employed extensively during Greek times around 400 BC, when sculptors perfected the technique of piece-moulding[53] to create portraits, and even more in Roman times to make copies of Greek items. Pure plaster does not work for glass or metal casting, because the heat causes it to crack. Schuler[54] suggests that a plaster/sand mix was used for glass moulds, but doesn't cite any evidence. No indication of dumping grounds for plaster containing waste moulds has been found near glassmaking sites.

2.3.2. Mosaic bowls

The first glass vessels were made using the core forming technique before or in the mid 15th century BC. The earliest cast glass vessels, mosaic bowls, followed in the mid 14th century BC and continued to be made until the Imperial Roman period.

The initial stage in making a mosaic vessel is the manufacture of glass rods (mosaic cane). These were monochrome and opaque when mosaic bowls were first made, and later polychrome with patterns in a range of different styles. The canes could have been made at the furnace, but a recent study of Mosaic bowls during the Hellenistic and Imperial Roman

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[52] Nick Brooks, *Mouldmaking and Casting: a Technical Manual* (Ramsbury: Crowood, 2005).
[53] Use of multi-part moulds.
[54] Frederic Schuler, "Ancient Glass Making Techniques, the Moulding Process.," *Journal of Glass Studies* (1959).

periods suggests it is more likely that the widely used spiral and star patterns were made by fusing and manipulating sheets of different coloured glass.[55] The resulting rods were broken into pieces of similar length.

Figure 7: Hellenistic mosaic bowl, 200 -100 BC. Diameter: 13.2 cm, H: 7.5 cm. British Museum.

Axel von Saldern and many other sources suggest that two-part clay moulds were used for making mosaic glass vessels.[56] Pieces of plain and/or multi-coloured glass rod were arranged around a core. This was covered by an outer mould, and fired until the glass was fully fused. After cooling, the bowl was ground and polished inside and out. During the 3rd century BC, both mosaic and monochrome bowls were produced by slumping (or sagging). For mosaic bowls, sections of glass were fused into a circular slab on a flat surface, probably made of clay and coated with a release agent. Then the slab was slumped into or over a convex mould or into a ring mould.[57] The heat needed for slumping causes a fire

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[55] Susan Dawes, "Hellenistic and Roman Mosaic Glass: A New Theory of Production," *The Annual of the British School at Athens* 97 (2002): 413–428.
[56] Axel von Saldern in Oppenheim, Robert H. Brill, Dan Barag, and Axel von Saldern, *Glass and Glassmaking in Ancient Mesopotamia*, 206.

[57] Susan Dawes was successful in replicating the manufacture of mosaic bowls using clay moulds, first with china clay or talc as a release agent, and later using unfired clay, which eliminated the need for a release agent.

polish to the surface that doesn't touch the mould, eliminating the need for polishing. This method explains why many Hellenistic mosaic bowls are fire polished on the outside and of uneven thickness, which is characteristic of the slumping process, causing the bowls to be thinner in the base. The spiral network mosaic pattern in some bowls, as well as the frequently occurring network cane rim suggest that glassworkers manipulated the blank with tools in a hot state. Taking this into account, the slumping could have been a hot process also, as suggested by William Gudenrath.[58]

Figure 8: Network mosaic bowl, Hellenistic, 200 - 100 BC, found in Crete. Diameter: 11.4 cm H: 6.5 cm. British Museum.

Marianne Stern suggests that rotary scratches on vessels are caused while the vessel is being removed from a mould[59], but this does not seem plausible, especially when considering that some bowls have the rotary scratches both on the inside and the outside. The proposal that the exterior scratches were caused by rough particles in the clay, which secured the piece to the wheel, seems improbable to anyone working with glass. The scratches are more likely caused by grinding while the

[58] Hugh Tait, *Five Thousand Years of Glass* (London: Published for the Trustees of the British Museum by British Museum Press, 1995), 221.
[59] Stern and Schlick-Nolte, *Early Glass of the Ancient World: 1600 B.C.-A.D. 50; Ernesto Wolf Collection*, 48.

object is attached to a lathe or a pottery wheel.

2.3.3. Sculpture and other solid objects

Figure 9: Portrait of King Amenhotep II, 1450-1400 BC. H: 4 cm, W: 2.9 cm, D: 3.4 cm. Corning Museum of Glass.

While a multitude of ancient glass vessels survive, glass sculpture is extremely rare. The oldest known portrait is of Amenhotep II and has been dated to 1450-1400 BC. It was probably cast using the lost wax process:[60] A wax model, which possibly included a reservoir to be filled with cold glass before firing, was made. Then a mould, most likely made from clay, was build around the model. The wax was melted out, probably during the firing of the mould. The inside surface could have been coated with a separator, or maybe the composition of the clay was such that the glass didn't stick to the mould. Glass was stacked in the reservoir and/or the mould, fired, and annealed. After cooling, the mould was broken off the glass object.[61] Objects such as this attest to highly developed casting and finishing methods in the 15th century BC.

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[60] "Corning Museum of Glass - Portrait of King Amenhotep II", n.d., http://collection.cmog.org/detail.php?t=objects&type=all&f=&s=head&record=95.

[61] Stern mentions the possibility of soft clay models being used instead of wax, however, as the mould material of ancient times was most likely clay, it would have been nearly impossible to neatly remove a soft clay model from a clay mould.

High relief castings, such as pendants of Astarte, the Assyrian and Babylonian goddess of love and war, are more frequent. Like beads and inlays, they are made by pressing or casting glass into open moulds made from stone or pottery.[62]

Figure 10: Mould-cast glass plaque of female figure, possibly Astarte, 1550BC-1400BC. Excavated at Tell Atchana, northern Syria. H: 8.5 cm, W: 2.4 cm, D: 1.8 cm. British Museum.

Glass was also used to fashion items such as axe blades and mace heads, which had traditionally been made from stone. Two-part or multi-part moulds were used as early as the 8th century BC for small Babylonian sculptures, gaming pieces and tools. Castings of knucklebones (Astragaloi) with a mould seam provide evidence of possibly re-usable

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[62] Tait (1991) speculates that these pendants were produced by pressing a mould into hot glass already poured onto a marver. I think this is unlikely, because heat would be lost on the marver, which means that much higher temperatures would have to be reached than for pressing the hot glass straight into a mould; also material would be wasted, and, to me as a maker, it seems a complicated way to go about making a pendant.

two part moulds in the Hellenistic period. Greek and Roman gaming pieces have been made in many different materials; a display in the British museum shows knucklebones made of onyx, rock crystal, agate, bronze, glass and lead respectively and marbles made of clay, stone and glass.

There are many examples of cast elements from Egyptian inlays, often with fine detail, but complete figures are rare. One such figure, dating from the 3rd to 1st century BC, can be seen in the Corning museum of Glass. It may have been used for decoration for furniture. The inlay is made with dark and light blue, red-orange, yellow, and a dark olive-green glass that appears to be black.

Figure 11: Inlay figure, 3rd-1st century BC. H: 21.5 cm. Glass, Plaster. Corning Museum of Glass.

An example of a three-dimensional Egyptian sculpture is of a ram, dated to approximately 600 BC, which was cast using opaque turquoise glass in a one-piece waste mould. It appears like a three-dimensional relief, as the material between the ram's legs has not been removed.

Figure 12: Egyptian sculpture of a ram, ca. 600 BC. L: 10.2 cm, W: 8.8 cm, D: 2.4 cm. British Museum.

Roman sculptures include a statuette of Venus, dated to 1st to 2nd century AD. The figure is incomplete; circular holes in the arm stumps indicate attachment of such as the example in figure 14.

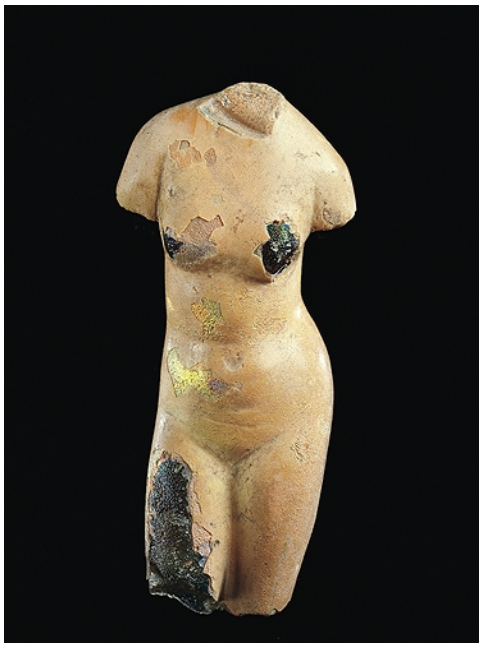

Figure 13: Statuette of Venus, 1st - 2nd century AD, Italy
1st-2nd century. H: 9.4 cm, W: 4.5 cm. Corning Museum of Glass.

Figure 14: Hand and Forearm from Composite Statuette.
Probably 1st -4th century AD, Roman Empire. L: 4.8 cm; Hand W: 1.2 cm.
Corning Museum of Glass.

Ancient glass sculpture found to date is always small. Larger sculptures might have been assembled, possibly in combination with other materials. Amongst the larger cast objects is a medallion from the 1st to 2nd century AD, made of translucent wine-coloured glass and overlaid with opaque bright blue, showing the head of Jupiter Ammon. It measures 15 cm in diameter and was cast (or pressed) into an open mould.[63]

2.3.4. Assyrian cast vessels

During the 9th century BC, a luxury glass industry emerged in Assyria. Objects produced include thick walled vases and heavily coldworked bowls, their shape often based on popular metalware forms. An example is the Sargon Vase, now in the British Museum.

[63] "British Museum - Medallion", n.d., http://www.britishmuseum.org/research/search_the_collection_database/search_object_details.aspx?objectid=466140&partid=1&searchText=moulded+glass+medallion&numpages=10&orig=%2fresearch%2fsearch_the_collection_database.aspx&currentPage=1.

Figure 15: *The Sargon Vase*, 702-705 BC. Diameter: 6.2 cm, H: 8.5 cm. British Museum.

Solid blanks for thick monochrome vessels as well as hollow blanks for drinking cups were probably cast in closed, single part moulds using the lost wax process.

2.3.5. Grinding and polishing

The casts, especially the solid blanks, had to be coldworked extensively. For this, lapidary techniques used for the carving of stone vessels were adapted. The inner cavity was drilled, probably using a bow drill with a copper rod, and loose emery as the abrasive. Emery is a rock containing the minerals corundum (Al_20_3, Mohs hardness of 9) and magnetite (FeO Fe^2O^3), which has been used for cutting, grinding and polishing since the third millennium BC. Most likely, oil was used as a lubricant; it was found that emery with oil drills four times faster than emery with water. The outside surface was also ground and polished, probably using emery as

well.[64]

Stone workers were used to starting out with a solid block for carving. Would they have used solid blocks of glass to carve vessels from, just as they did with rock crystal? Or maybe they asked glassworkers to produce blanks, recognising the advantages of a mouldable material?

2.3.6. Achaemenian, Hellenistic and Imperial Roman cast vessels

The luxury glass industry continued during the Achaemenian (550-330BC), Hellenistic (323-146 BC approximately) and into the Imperial Roman (44 BC-476 AD) periods. Glass blanks were heavily coldworked. Were the blanks cast by the lost wax process, in core moulds, or slumped like mosaic bowls?

Figure 16: Skyphos, eastern Mediterranean, circa 225BC to 200BC, Diameter: 11 cm, H: 11 cm, and Conical glass bowl, made in a Syro-Palestinian glasshouse between about 150-50 BC. Diameter: 16 cm, H: 8.8 cm. British Museum.

Typical of 5th and 4th century BC Persia are shallow colourless glass bowls

[64] W. Heimpel, Leonard Gorelick, and A. John Gwinnett, "Philological and Archaeological Evidence for the Use of Emery in the Bronze Age Near East," *Journal of Cuneiform Studies* 40, no. 2 (Autumn 1988): 195–210.

with cut petal designs, a shape derived from Persian silver and bronze vessels. These bowls were highly prized and widely exported.

Figure 17: Persian bowls, 4th century BC. Glass, diameter: 17.2 cm, H: 3.9 cm, and silver, diameter: 30.7 cm, H: 4 cm (right). British Museum.

2.3.7. Hellenistic and Roman ribbed bowls

Many ribbed bowls can be found in museums today; a considerable number must have been produced, mostly between 50 BC and 50 AD. The first Hellenistic ribbed bowls (around 50 BC) have asymmetrical uneven ribs with irregular spaces, sat at different angles. These were probably made by pouring a blob of hot glass onto a slab of stone, possibly on a turntable, impressing ribs with a metal or wooden implement, then slumping the still-hot glass over a convex former mould. Later examples of ribbed bowls have evenly spaced, tapering, more shallow ribs. These were probably produced using a press mould, rather than a single tool, to impress the ribs into a hot gather poured onto a marver. The impressed disc is then picked up and placed on top of a former mould. The rim was in many cases finished by rotary polishing, possibly by fixing it onto a pottery wheel using wet clay, centering it, then using metal tools and a loose abrasive to grind the vessel.

Figure 18: Ribbed bowl, Roman, circa 50 BC- 50 AD. Diameter: 14.3 cm, H: 4.3 cm. The Metropolitan Museum of Art, New York.

Pliny suggests the grinding and polishing was done on a lathe, but was the vessel was fixed to a lathe, centred on a pottery wheel, or was the process similar to modern glass engraving, where the glass is held to a rotating metal wheel? The technology was available; wheel engraving has been known since at least the mid second millennium BC.[65]

During the Imperial Roman period, glassblowing slowly replaced all other techniques, probably due to its speed and possibilities. Cast blanks were replaced by blown blanks to be finished using the same coldworking techniques; in fact, a number of coldworked vessels that until recently had been thought to be cast proved to be mould blown. One such example is a large round box (phyxis), 40 cm in diameter, in the collection of the British Museum; it would have been an amazing technical feat had it been cast. The making method is determined by analysis of the bubbles in the glass: if they are perfectly round, the object is cast or slumped; if they are elongated, indicating that the glass

[65] Margaret Sax, Nigel D. Meeks, and Dominique Collon, "The Early Development of the Lapidary Engraving Wheel in Mesopotamia," *Iraq* 62 (2000): 157–176.

was worked while cooling, the object is blown.

Figure 19: Cylindrical glass box, said to be from near Rome, Italy, probably made around 50 AD. Diameter: 39.5 cm, H: 11.8 cm. British Museum.

2.3.8. The decline of casting

While the pressing of small medallions and similar items continued beyond Roman times, casting processes seemed to have been all but forgotten after the fall of the Roman empire. Mould blowing replaced the casting of blanks for luxury vessels. Very few cast objects are found after 400 BC. Small sculptures were cast during the Tang period (618 – 906 AD) in China; one wheel-cut Islamic bowl from the 9th to 10th century in the Corning Museum of Glass is labelled as slumped over a mould.[66]

[66] "Corning Museum of Glass - Bowl Islamic; Western Asia; Perhaps Iran 9th-10th Century", n.d., http://collection.cmog.org/detail.php?t=objects&type=related&kv=3593.

Figure 20: Bowl, Islamic; Western Asia; perhaps Iran, 9th-10th century, H: 7.6 cm, W: 17.8 cm. Corning Museum of Glass.

Literary references such as the mention of low relief glass tiles in Filarete's *Trattato di architettura* (Treatise on Architecture)[67] around 1460 are rare, and we can only guess how they were made; probably by stamping or pressing, using hot glass from a furnace.

2.3.9. Re-occurrence in 17th and 18th century France

Casting re-emerged briefly around 1675 in the factory of Bernard Perrot (1640-1709), who developed a casting process to produce hollow relief figures, busts, medals, inscriptions and coats of arms. From his production, seven large cast medallions of Louis XIV in hollow relief, made in three different moulds, survive today.

[67] Filarete, *Filarete's Treatise on Architecture: Being the Treatise by Antonio Di Piero Averlino, Known as Filarete. Originally Composed in Milan C. 1460 - C. 1464. Translated by John R. Spencer*, 2 vols. (New Haven: Yale University Press, 1965).

Figure 21: Medallion with Portrait of Louis XIV. France, glasshouse of Bernard Perrot, about 1675-1685. H: 35.5 cm, W: 29 cm. Corning Museum of Glass.

Unfortunately the process was lost when Perrot died. It is not known whether his objects are cast with molten glass from a furnace or kiln cast. Perrot also attempted to patent a method of casting mirrors, but another French company beat him to it.

A little later, around 1716, a process for production of large medallions emerged in Germany. Four plaques with philosopher's heads in raised relief survive in Kassel. It is speculated that these were pressed or hot cast, because of the mention of a "peculiar invention", involving steel for "medallion dies", by chronicler Johann Just Winkelmann[68]. The considerable differences between the French and German processes of casting suggest that they are unconnected. This is further supported by the fact that both were restricted to a brief period of time. Glassmaking

[68] Dedo von Kerssenbrock-Krosigk, *Glass of the Alchemists* (Corning, N.Y.: Corning Museum of Glass, 2008), 226.

processes have a history of being treated as secrets, which was likely to result in the knowledge vanishing after the inventor died.

Relief glass was not mass-produced until the early 19th Century in the United States, as *pressed glass*. It is manufactured by pouring molten glass into multi part metal moulds, with a "stamp" coming down in the centre to form the vessel cavity. This method could be derived from ceramics processes or could be a development of early casting processes.

2.3.10. Pâte de verre

As discussed in section 2.2.4, p.37, a form of kiln casting called pâte de verre developed around 1880 in France. Henri Cros (1840-1907), looking for a more permanent way to render his wax figures while keeping the qualities of subtle colouration and translucence, turned researcher, rediscovering and further developing ancient casting techniques. His father, an Egyptologist, appears to have translated ancient texts on the subject. At the same time, Albert Dammouse (1848-1926) is said to have developed his own version of the process. Pâte de verre was taken up by many French artists. The process was associated with, and carried out in, glass and ceramics factories, usually by the artists/craftsmen who worked there. Notable pâte de verre artists include Georges Despret (1862-1952), François-Émile Décorchemont (1880-1971), Gabriel Argy-Rousseau(1885-1953), and Amalric Walter (1870-1959). Walter joined the Daum factory in 1903 and was given his own workshop and a substantial fee in return for his knowledge of the pâte de verre technique. Between 1906 and 1914 Walter created with Henri Berge many dishes and sculptures of small animals, insects, and reptiles.

Figure 22: Amalric Walter and Henri Bergé, pin tray. Diameter: 12.5 cm, H: 5 cm, circa 1920. Chameleon, W: 17 cm, circa 1900.

Pâte de Verre was defined by Antonin Daum of the Daum Brothers in 1925 as follows:

> Glass crushed into powders of different colours is mixed with a liquid binder to form a paste of ground glass and binders, which is brushed or stamped onto the interior relief surface of a fireclay mould formed upon a wax model. The pâte de verre shell is then covered, according to the thickness desired, with additional layers of vitreous paste. After drying, it is placed either in its mould or bare, as with soft porcelain, inside the muffle furnace for the re-fusing of the glass. After firing, the mould, which has become friable, falls to dust, allowing the piece to reappear with its colours, solidity, and details all scrupulously conforming to the model. It then has only to be cleaned and polished as desired. [69]

Strangely, Daum refers to a fireclay mould, which "falls to dust" after firing, reminiscent of ancient casting processes. This might be a mistranslation and probably should read "*refractory* mould". Argy

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[69] Janine Bloch-Dermant, *The Art of French Glass, 1860-1914* (New York: Vendome Press, 1980), 152.

Rousseau's notebooks describe a plaster-silica mixture for the making of pâte de verre moulds, and a process, which would not appear out of place in a contemporary book on kiln casting. However, in a marked difference to contemporary glassmaking, the process did not begin with crushed glass powders, but with making the coloured glass, as discussed in section 2.2.4.

2.3.11. American cast and pressed glass - Frederick Carder

In the late 1920s, Steuben Glass Works in Corning, NY, began producing what they called "decorative architectural cast glass". One of their earliest interior installations was the lighting frieze in the elevator lobbies in the Empire State Building in New York City. The panels were hot cast at Steuben into iron moulds, using Pyrex glass.

The company was founded in 1903 by Frederic Carder (1863-1963), an immigrant from England. Carder, an artist competent in all aspects of glassworking as well as bronze casting, was inspired by Henri Cros, and spent long years exploring and developing processes for glass casting using the lost wax method. Always pushing his materials and techniques, Carder sought to prove that the lost wax process was suitable for large castings, and in 1929 cast an Indian head using 360 kg of Pyrex glass. It stands 117 cm high, with a thickness at the nose of 30 cm. This was the largest sculpture Carder cast using lost wax. Unfortunately, the Indian head, now in the Rockwell Museum of Western Art in Corning, is cracked, allegedly due to it having been removed from its mould too early.[70]

[70] Paul Vickers Gardner, *The Glass of Frederick Carder* (New York: Crown Publishers, 1971).

Figure 23: Frederic Carder's *Indian Head*, 1929. H: 117 cm, D: 30 cm. Rockwell Museum of Western Art, Corning, New York.

2.3.12. Optics: cast telescope mirrors

The largest cast glass items in existence today are telescope mirrors. The first large reflecting telescope with a glass mirror was built by French Physicist Leon Foucault in 1864. In the early 20th century, astronomer George Hale endeavoured to build bigger and bigger telescopes. His first attempt at a mirror telescope was equipped with a 1.5 m diameter, 19 cm thick mirror cast in France by the Saint-Gobain Glassworks, and supposedly annealed in manure. Hale's second telescope, the Hooker telescope with a mirror of 2.5 m diameter and 33 cm thickness, went into operation in 1917. In 1934, the Corning Glassworks succeeded in casting a 5-meter mirror blank, weighing over 20 tons, on the second attempt. It was used to build the Hale telescope for the Palomar Observatory, which was the world's largest telescope for almost 45 years.[71] In 1995, Corning Inc. cast the largest monolithic telescope mirror to date for the Subaru telescope of the National Astronomical Observatory of Japan. It measures 8.3m in diameter, is 20 cm thick and weighs 22.5 tons. It took 3 years to

[71] "Corning Life Sciences | Glassware Selection Guide | CORNING, PYREX® and Telescopes", n.d., http://www.corning.com/lifesciences/us_canada/en/technical_resources/product_guid/glass/corning_pyrex_telescopes.aspx.

make. The Subaru telescope went into operation in 1999.[72] Videos of the process are available on the website of the Corning Museum of Glass (http://www.cmog.org/telescopes/).

2.3.13. Casting in the Czech Republic

A country famous for its monumental glass castings is the Czech Republic, former Czechoslovakia. Glassmaking was an important industry under the communist regime, and artists worked with glass factories as a matter of course. Divided from the west by the iron curtain, Czech artists, led by husband and wife team Stanislav Libenský and Jaroslava Brychtová, began to develop cast glass as a sculptural medium. The development of new casting and annealing techniques made possible the casting of large solid glass forms. While elsewhere glass artists were mostly working with the vessel, here, a tradition of fully-fledged sculpture and large-scale architectural work was established.

The Czech way of casting employs massive open block moulds, often assembled, screwed together or wedged in, using plain plaster/silica mould mix, sometimes with wire for extra strength. The glass is generally placed directly into the mould. The West first saw evidence of the monumental Czech glass castings at the 1957 Triennial in Milano and the 1958 Expo Brussels, where Libenský and Brychtová won the first Grand Prix for their *Wall of Glass Animals*. The husband and wife team have produced a large body of work during their 48-year collaboration. With many clear glass architectural features and sculptures, they have extensively explored the optical properties of solid clear glass, gaining knowledge, which they have applied to great effect in their coloured work. Libenský and Brychtová are best known for their large-scale cast glass sculptures. They have won many international awards and were awarded honorary doctorates in glass by the University of Sunderland in

[72] "Corning Museum of Glass | Telescopes and Mirrors", n.d., http://www.cmog.org/telescopes/.

1999. Libenský also holds an honorary doctorate from the Royal College of Art, awarded in 1994. In the course of their long career, Libenský and Brychtová have developed an intuitive understanding of the interaction of colour, form and light.

A contemporary of Libenský, Vaclav Cigler, has also studied at the Academy of Applied Arts in Prague, in the glass atelier under Prof. J. Kaplicky. During the 1960s, Cigler made geometrical cut solid optical glass objects, exploring the phenomena of reflection and refraction. Today, he creates mostly installations, which still concerned with optics, but only occasionally contain glass. Instead, he uses other transparent materials like water.

Another Czech glass artist whose works display mastery of transparent colour and exploration of optical properties is Frantisek Vizner. Following a similar path of education as Libenský and Cigler, Vizner initially worked as a glass designer. From 1977, he worked mostly in his own studio, cutting geometrical forms, usually vessel-shaped, from glass blocks.

Stanislav Libenský', as an educator, has greatly influenced generations of Czech glass artists. Amongst his students are many notable artists, for example Jaroslav Matouš, Václav Machač, Jiří Šuhájek, Aleš Vašíček, Marian Karel, Ján Zoričák, Ivo Rozsypal, Jaromír Rybák, Jan Exnar, Gizela Šabóková, Milan Handl, Stanislava Grebeníčková, Břetislav Novák Jr., Ivana Šrámková, Markéta Šílená, Marian Volráb, Michal Machat and Zdeněk Lhotský, who now runs a glass casting factory named *Mold Melted Glass Studio* in Libenský and Brychtová's home town of Železný Brod. The studio offers many services, from modelmaking to casting to coldworking and laminating. They will use any glass the artist specifies, but usually work with a nearby factory, Banas Glass. Banas produce a colour range of 110 hues, as well as custom colours (minimum quantity 150 kg). Many Czech and international artists have their work realised there, amongst the Peter Bremers and Karen LeMonte.

2.3.14. Casting in studio glass

The studio glass movement began in the United States of America in 1962, with Harvey Littleton, a ceramics instructor, building a glass furnace in a garage on the grounds of the Toledo Museum of Art. The aim was to conduct a workshop to explore "ways artists might create works from molten glass in their own studios, rather than in factories." For the first three days of the workshop, all attempts to fuse molten glass failed, but with the help of Dominick Labino and Harvey Leafgreen, a retired glassblower, the melting and blowing of glass from the small furnace was achieved.[73]

Casting did not play a large role in the early studio movement, although several individuals, for example Frances and Michael Higgins of Chicago and Cleveland sculptor Edris Eckhardt (1905-1998), adopted the pâte de Verre process in the 1950s. Eckhardt taught a kilnforming class at the University of California, Berkeley, in 1962, a fact, which is mostly ignored in the history of studio glass. She is believed to have been the first American artist to mix and melt her own glass batch.[74]

In the 1960s and 70s, interest in glass casting was on the rise in Europe, with several artists researching and developing the process.

In France, the history of pâte de verre continues unbroken until today. Antoine Leperlier assisted and learned from his grandfather François-Émile Décorchemont from 1968 and continued to work in his grandfather's studio after Décorchemont's death in 1971. His brother Etienne Leperlier started working with the pâte de verre process in 1981.[75] The Leperlier brothers published several articles on pâte de verre technique and helped many international artists with the technique.

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[73] "Studio Glass Movement « The Toledo Museum of Art", n.d., http://www.toledomuseum.org/glass-pavilion/glass-at-tma/studio-glass-movement.
[74] "Eve Page", n.d., http://www.nbmog.org/EvePage.html.
[75] Susanne K. Frantz and Museum of American Glass, *Particle Theories: International Pâ te De Verre and Other Cast Glass Granulations* (Millville N.J.: Museum of American Glass at Wheaton Village, 2005), 33.

In Great Britain, one of the instrumental figures in the studio glass movement is Keith Cummings, who has been working with glass since the late 1950s, and teaching since 1967. Currently professor of glass studies at the University of Wolverhampton, Cummings has extensively researched glass history, glassmaking processes, and contemporary practice. His first book *The Technique of Glass Forming*, published in 1997, became an important reference work for a new generation of glass artists. It was followed by *A History of Glassforming* in 2002, and *Contemporary Kiln-formed Glass* in 2009. Cummings' personal interest lies in the pate de verre technique, and the combination of metal with glass. In 1976, a symposium held at the Royal College of Art in London included a presentation on mould making for kiln-fired glass by the College's Head of Glass, Martin Hunt. In 1978, Keith Cummings and Stuart Garfoot organised a seminar on pâte de verre at the same venue. Another symposium with the theme of kilnforming took place at the Royal College in 1980. At the time, the glass department had a copy of one of Argy-Rousseau's notebooks on loan from the Library of the Corning Museum of Glass.[76]

Another British glass casting practitioner and educator is Tessa Clegg, who started working with the pâte de verre technique in the 60s, creating translucent textured bowls. Later, her work changed to solid geometric forms with internal voids. Her forms often contain voids, into which smaller glass forms are fitted. Sadly, Clegg retired from glassmaking in 2010.

Diana Hobson, who studied jewellery and silversmithing at the Royal College of Art, was inspired to combine glass with her metalwork at the 1978 symposium. She went to France in 1982 on a research grant from the Crafts Council of Great Britain and Camberwell School of Art to study pâte de verre objects and meet Noel Daum and the brothers Antoine and Etienne Lepelier.[77] She went on to develop a similar process to create

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[76] Ibid., 32.
[77] Susanne K. Frantz and Museum of American Glass, *Particle Theories:*

small, asymmetrical, translucent vessels (in the region of 10 cm x 12 cm x 15 cm) with intricate colour designs.

In the USA, glass casting rose in popularity in the 1980s, with Howard Ben Tre pioneering hot casting of glass as a sculptural medium, and Daniel Clayman kiln-cast glass. Ben Tre graduated from the Rhode Island School of Design with a MFA in 1980. Working mostly with hot casting, Ben Tre has completed many public and private commissions, often of architectural-scale, and is represented in numerous museums worldwide. His forms frequently reference architectural forms like spires and obelisks.

Figure 24: Howard Ben Tre, *Column 36*, 1999. Cast glass, copper, patina. H: 246cm, W:83 cm, D: 36 cm (l). Benches for Claude, II*,* 1992. Cast glass, brass, and patina. Each section H: 49 cm, W: 137 cm, D: 68 cm. Collection of The Toledo Museum of Art, Ohio. Museum Commission. (r)

Clayman, also a graduate of the Rhode Island School of Design (BFA,1987), kiln-casts large-scale glass sculpture, always working with volume and light. While his volumes are rarely solid, they have expanded in size, prompting Clayman to find solutions to the issue of casting large

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International Pate De Verre and Other Cast Glass Granulations (Millville N.J.: Museum of American Glass at Wheaton Village, 2005), p.33.

forms. He custom-builds kilns, sometimes around a mould, or assembles his forms.

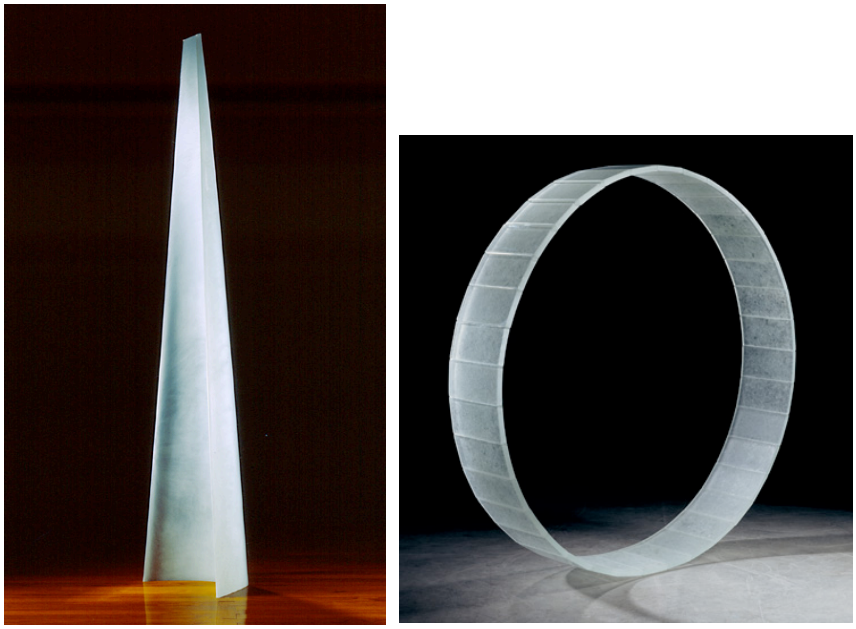

Figure 25: Daniel Clayman, *Pel* 2004. Glass, H: 272 cm, W: 50 cm, D: 30 cm (l). *Clear Volume*, 2010. Glass, H: 165 cm, W: 165 cm, D: 30 cm (r). Photography: Mark Johnston

In New Zealand, Ann Robinson, a sculptor with knowledge of bronze casting processes, turned to glassblowing, and later, glass casting. She developed her own processes derived from bronze casting. Completely different from Czech mould making, she shapes her moulds in multiple layers around her waxes, making sure the mould is of an even thickness all over. The first coat is a plaster/silica face coat; to the remaining coats, fine and coarse washed grog as well as paper pulp are added to strengthen the mould. The glass is placed in a flowerpot, which has been sealed with a plug. The plug is connected to a nichrome wire, by which it is pulled out from above at top temperature to allow the glass to flow into the mould. Initially, Robinson used furnace glass for her castings. In the early 1990s, she developed a 40% lead crystal casting glass together with Gaffer Glass.

Kilnforming arrived in Australia with glassmaker Klaus Moje, who emigrated from Germany in 1982 to become the founding Head of the

Glass Workshop at the Canberra School of Art. He taught at the school for 10 years until 1992. Moje is famous for his vessels and tiles made by fusing many different coloured strips of glass. With Kirsty Rea and Scott Chaseling, he developed the Australian Roll-up technique, where fused blanks are picked up on a blow pipe and shaped into vessels. Moje worked closely with Bullseye Glass in developing a range of compatible coloured glasses.

Amongst Klaus Moje's students was Richard Whiteley, who is now head of the Glass Department at the Australian National University in Canberra. Whiteley has done extensive research on the annealing process of cast glass objects, setting up monitoring systems with multiple thermocouples to determine the heat differential between the coldest and the warmest point in the glass ("Delta T"), and thus anneal the glass exactly as long as it needs. Whiteley casts large-scale sculptures, often assembled, using transparent colours and clear glass.

2.3.15. Art and design research today

Historically, material and process development in art and design took place in industry or in artist's studios. As mentioned in the previous chapter, this still carries on today. In addition, a new platform for innovation has emerged about 30 years ago with the advent of practice based research degrees in art and design in Australia, Europe, Japan, and New Zealand. Universities provide the researcher with support in form of supervision, facilities, research methods training, and a creative environment. In 1996, Czech artist Zora Palova took up the position of research professor at the University of Sunderland. She has commissioned the largest casting kiln in the country, which is now situated at the University, and thus facilitated large-scale casting. In 2004, Czech Glass artist Alena Matejkova used this kiln for her research project *Magic Carpet,* to create one of the largest castings executed in Britain. Ray Flavell completed a two-fold PhD in 2001; his research encompassed creative effects achieved with air inclusions in blown glass

as well as the development of methodologies for practice based research in the applied arts. Angela Thwaites, who studied with Professor Libensky in Prague from 1983 to 1985, spent several years on a research project 'Investigation and comparison of contemporary working methods and mould making materials for use in the kiln forming of glass', which was funded by the Arts and Humanities Research Board, at the Royal College of Art (1999 – 2003). Kevin Petrie carried out PhD research into glass and print, and Vanessa Cutler studied the creative possibilities of waterjet cutting.

Recent research carried out in the field of colouring glass include Sylvie Vandenhoucke's and Max Stewart's studies into use of oxides as colouring agents for pâte de verre, and Teresa Almeidas research into luminescent glasses, as mentioned in the introduction. Sylvie Vandenhoucke's research in 2003 addressed the colouring of clear glass frit with metal oxides at temperatures of 800ºC. In a similar fashion to this research, the test shapes used were not simple tiles, but intricate repetitive textures, which developed into a body of creative work.

Max Stewart's PhD research at Edinburgh College of Art (2007-2010) initially focused on recreating the forgotten pâte de verre colour palette and methods of French artist Amalric Walter. During practical experimentation, new avenues and ideas arose, and Stuart's research transformed into a comprehensive study of colouring lead crystal frit at casting temperatures, removing the necessity of creating glass colours at melting temperatures, and thus making the process particularly suitable for contemporary studio practice.

Concurrent with this project, Teresa Almeida researched the making and use of luminescent glasses, created by rare earth oxides to soda lime glass. Her colours appear clear in normal illumination, and luminescent colours under UV light. Working at the University of Aveiro in the Research Unit VICARTE *Glass and Ceramic for the Arts,* her project is set partly in a scientific context, and does not include methods of melting glass in an artist's workshop.

3. The appearance of colour in glass

3.1. Colour in general

'It's obvious that colour as material and colour as light are extremely different. Colour almost always seems applied, except for raw materials and they're seldom bright', observes minimalist artist Donald Judd, about an exhibition by Dan Flavin[78].

Glass could be seen as a material that allows colour to take form, a material that merges colour, form and light. However, discussion of colour is difficult, colour vocabulary scarce and not always understood. Even the most basic terms are interpreted subjectively. In Part I of his *Interaction of Color*, Joseph Albers begins: "If one says '*Red'* (the name of a color) and there are 50 people listening, it can be expected that there will be 50 reds in their minds. And one can be sure that all these reds will be very different."[79] Clearly, even a simple discussion of colour poses difficulties; how, then, does one discuss colour in glass, with its many different modes of appearance and its many contributing factors?

Judd discusses colour in the following manner:

> After a few decades the discussion of color is so unknown that it would have to begin with a spot. How large is it? Is it on a flat surface? How large is that? What color is that? What color is the spot? Red. If a second spot is placed on the surface, what color is it? Black? What if both spots were red, or black? How far away is the black spot from the red spot? Enough for these to be two

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[78] Donald Judd, *Complete Writings 1959-1975 : Gallery Reviews, Book Reviews, Articles, Letters to the Editor, Reports, Statements, Complaints*, 2005 ed. (Halifax N.S.: Press of the Nova Scotia College of Art and Design, 2005), 200.
[79] Albers, *Interaction of Color*, 3.

> discrete spots, one red and one black? Or near enough for there to be a pair of spots, red and black? Or apart enough for this to be uncertain? What if the red and black spots are next to each other? And of course, which red?[80]

A discussion on colour in glass would have to begin with a simple, 3-dimensional form, for example a cuboid. How large is it? Is it transparent or opaque? Are there variations in thickness? What about the surface? Is it textured? Polished? Matt? What colour is it? Where does the illumination come from? How strong is it? What type is it? How does the colour change when the type of illumination changes? What happens if the direction of illumination changes?

Presumably, Albers' and Judd's reds are opaque; the colour of a surface, which is the appearance of colour discussed in the majority of literature. Other types of colour – transparent colours - are, if at all, mentioned briefly, with differing definitions. For articulation of modes of appearance of colour, psychology, physiology (studies in perception) and physics offer some possibilities; although artists empirically engage with colour, they do not often articulate their findings.

One of the biggest differences between glass and most other materials is its transparency. And if a solid lump of this transparent medium is coloured, and the colour is transparent as well, this colour appears very different to opaque or surface colour. This transparent coloured material could be a thin layer, containing empty volume, like in a blown vessel. It could be clear glass with a film of colour. This film could be partly opaque, obscuring the view to the inside, or thinning out and merging into clear, revealing glimpses of the interior, as can be found in many of Dale Chihuly's objects, for example. Or it could be a solid transparent object that is coloured throughout its mass.

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[80] Donald Judd, "Some Aspects of Color in General and Red and Black in Particular," *Artforum* 32, no. 10 (Summer 1994): 70–79, 110, 113.

How can these different modes of colour be described? Johann Wolfgang von Goethe called the appearance of a volume of transparent colour "dioptric",[81] but this expression did not catch on. The two most common terms used for transparent colour that is not surface colour are *volume colour* and *film colour*. Albers explains volume colour using the example of a coloured liquid: Tea in a spoon will appear lighter than tea in a cup; the blue of a swimming pool will appear darker in deeper water.[82] Gestalt psychologist David Katz describes volume colour as "colours which are seen as organized in and filling a tri-dimensional space".[83] For him the true property of volume colour is expressed only when these colours are genuinely transparent. Film colour, according to Albers, appears as a thin, transparent, translucent layer between the eye and an object. Katz describes it as the colour experience one gets when looking through "a piece of smoked glass of medium transparency or a piece of coloured gelatine, held at arm's length in such a way that its boundaries are invisible."[84] A Dictionary of Psychology defines it as "a misty appearance of colour without any fixed distance that is experienced when there are no lines or edges present in the visual field."[85]

I understand film colour as an appearance of colour without a definite location or boundaries. Volume colour is the colour of a transparent or translucent solid or liquid that is coloured throughout its mass – for example the homogenous colour of a solid mass of transparent glass. A major consideration in the discussion of colour and glass are surface quality and form – the surface can be matt or glossy, textured or smooth; each of these properties will impact differently on the way light

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[81] Johann Wolfgang Goethe, *Theory of Colours* (Cambridge Mass.; London: M.I.T. Press, 1970).
[82] Albers, *Interaction of Color*, 45.
[83] David Katz, *The World of Colour*, trans. R. B. MacLeod and C. W. Fox (New York: Johnson Reprint Corp, 1970), 21.
[84] Ibid., 17.
[85] Andrew Colman, *A Dictionary of Psychology*, 3rd ed. (Oxford; New York: Oxford University Press, 2009).

is transmitted, reflected, refracted, diffused, and scattered. Form has a considerable impact on the appearance of colour – and vice versa. The relationship between colour and perceived size is demonstrated by Lois Swirnoff in her book *Dimensional Color*. Shown are examples of objects appearing larger or smaller, closer or farther away than they really are depending on their colour.[86]

3.2. Colour in glass - volume colour

My interest lies in Volume colour, the colour of a transparent 3-dimensional object, which is coloured throughout its mass. Volume colour in transparent glass is a relatively new problem: most pre-20th century glass objects are small or fairly thin-walled. Volume colour became an issue only with development of ways to cast large objects, and while large castings such as the 5-meter diameter mirror for the Hale Telescope at Palomar were done for scientific purposes in the late 19th and early 20th century, it was not until the mid 20th century, initially in Czechoslovakia (now Czech Republic), that glass was used for coloured large scale sculpture.

In the Czech republic, the situation was ideal for experimentation with colour: many artists worked directly with factories to make their work, and therefore had the opportunity to control the colours they use. When talking to Jaroslava Brychtová about the subject (personal communication, May 22, 2009), she explained how she evaluates colour samples, made to contain thick-thin variations, by looking through lengthwise and blocking out the light falling in from the sides. She would then ask the factory to make adjustments. (Along the lines of: just a bit lighter, and a touch more blue, please…)

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[86] Lois Swirnoff, *Dimensional Color* (New York; London: Van Nostrand Reinhold; Chapman and Hall, 1992), 52–53.

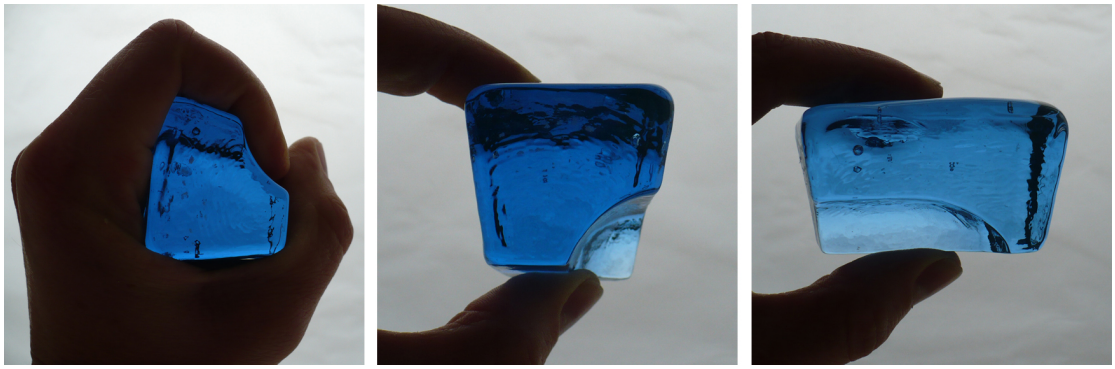

Figure 26: Judging colour density using a Banas colour sample as shown by Jaroslava Brychtová.

In the west, glass casting is mostly practised by studio artists in their own studios, who buy coloured glass off the shelf. For them, dealing with the phenomenon of volume colour is more difficult. For many glass artists, colour decisions are secondary to form, or they handle the matter as they deal with many other restrictions: the available colours are taken as a given, and the work is designed with these colours in mind. Another restriction every glass artist has to deal with is size of object in relation to annealing, thus forms tend to be large only in two dimensions; with the third dimension under 10 cm, the density of many standard casting colours would be adequate.

New Zealand glass caster Ann Robinson, who developed her own casting methods derived from bronze casting, asked her friends and colleagues John Leggot and John Croucher of the Gaffer Glass Company to develop casting colours for her. Ann specialises in large, thick-walled vessels, and while Gaffer casting colours include light options, they are not formulated for large solid objects. In fact, only a few people cast large solid objects, and many of the ones that use homogenous coloured glass are working in Czech republic and consult with factories on their colours.

My own investigation into the relationship between colour and volume in a transparent glass body began with museum and gallery visits, which was partly accomplished on visits to the Corning Museum of Glass and to Czech Republic. Studying artist's approach to colour in glass lead to writing about the appearance of colour in glass, which in turn lead to the study of optics, essential in the exploration of interaction of form, colour

and light. The study into colour density for solid glass objects resulted in a list of the factors influencing the relationship between colour and volume in a transparent glass body:

1. Form of object
2. Size of object in relation to amount of colouring agent
3. Surface finish of glass
4. Scattering of light through bubbles and inclusions
5. Wavelength and intensity of light (especially with polychromatic colours)
6. Angle of incident light

3.2.1. Form of object

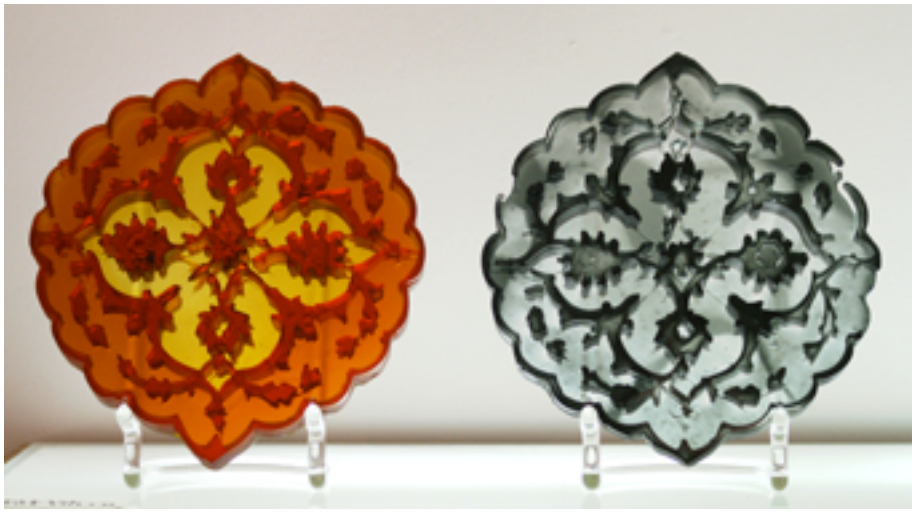

Figure 27: Purnima Patel, from the *Decaying Perfection* series, 2009. W: 23 cm, H: 25 cm.

Form and size of object have an enormous impact on the appearance of its colour. If the same coloured glass is used for a large and a small object, the large object will appear darker. If there are variations in volume within the same object, thinner areas will appear lighter, and sometimes differ in hue. Purnima Patel's work (figure 27) is a prime example; the piece on the left is made from red glass, which appears red,

orange and yellow depending on the thickness of the glass. This form contains three definite, clearly visible thicknesses. Generally, the change in form is more gradual, and so is the change in hue, as in Libenský and Brychtová's Red flower/heart (1976). This sculpture is made in two parts, which are

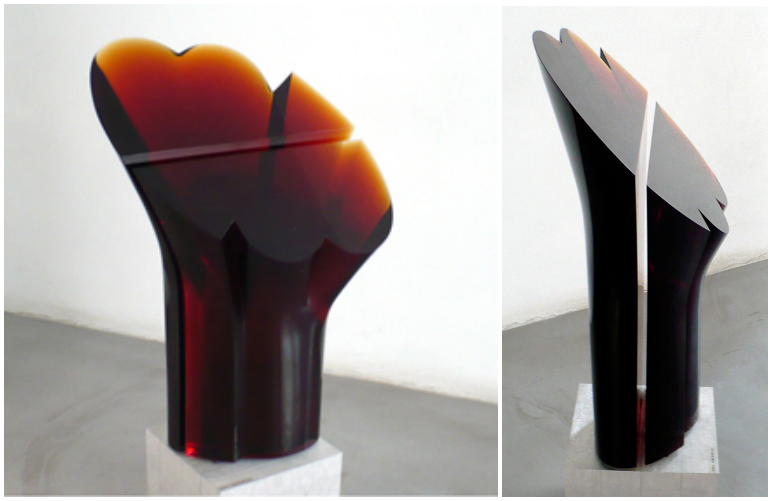

Figure 28: Libenský & Brychtová, *Red Heart-Flower*, designed in 1973. H: 120 cm, W: 60 cm. Town Museum, Železný Brod.

displayed about two centimetres apart, but appear as a single form. This is an ingenious solution to the problem of colour density; the central void allows light to enter the form and cuts the actual thickness in half. On the technical side, it allows the form to be made in two open casts. A central void as part of a single form, which Brychtová calls a "light cavity"[87], has been used in many of Libenský and Brychtová's sculptures, and grew larger in the later stages of their career. They have extensively explored optics in clear glass in many large architectural installations as well as object sculpture. Their most interesting work from a perspective of volume colour was made in the 80s and 90s. Sculptures like Arcus, Green Eye of the Pyramid, Silhouettes of a Town, and Space I to V show mastery of colour, light and form.

[87] Robert Kehlmann, *The Inner Light: Sculpture by Stanislav Libenský and Jaroslava Brychtová* (Tacoma Wash.; Seattle: Museum of Glass International Center for Contemporary Art; University of Washington Press, 2002), 74.

3.2.2. Size of object

The effect of object size in relation of colouring agent should be simple: larger objects appear darker than smaller objects if made of the same glass. However, if the colour is very light or very dark, the difference can be subtle. A strong change in value is observed only at the density threshold (a point where the colour density reaches certain saturation, resulting in considerable changes in value with increase or decrease of glass thickness),[88] or if the difference in size is extreme.

3.3. Optics

In glass, to understand the impact of form, surface finish and scattering of light through bubbles and inclusions, a basic knowledge of optics is essential.

When light reaches a solid material, several things can occur, including (but not limited to) the following:

- Reflection
- Refraction
- Transmission (with some change to the speed and direction of the light)
- Scattering from the surface of the solid
- Scattering from features inside the solid
- Absorption by the solid

[88] This is discussed in detail chapter 4.9 *Colour testing: aims and results*

3.3.1. Reflection and refraction

When light reaches the surface of a solid, some of it will be reflected. If it is a transparent solid, some of it will be transmitted. Generally some light is reflected at every boundary.

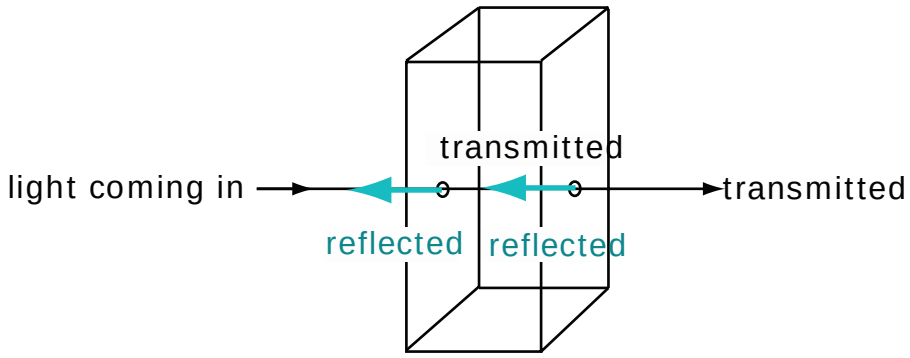

Figure 29: Reflection and transmission

How much is reflected usually depends on the wavelengths of the incoming light, the nature of the solid and the condition of the surface. The amount reflected is also dependent on the angle at which the light hits the surface. The angle of incidence equals the angle of reflection. When light passes from one material (for example air) to another material of different density (for example glass) at an angle, the light changes speed, causing refraction. The ray of light proceeds through the second medium in a straight line, but in a changed direction (figure 30). The amount of the change in direction (the "refractive index") depends on the density of the solid. If the second medium is denser than the first, the ray of light will slow down, and its direction will change towards the normal (normal is a term for perpendicular to the surface). When the ray of light passes into a less dense material (from glass to air), it will speed up, and its direction will change away from the normal. No change in direction occurs if the light impact is perpendicular to the surface (figure 29).

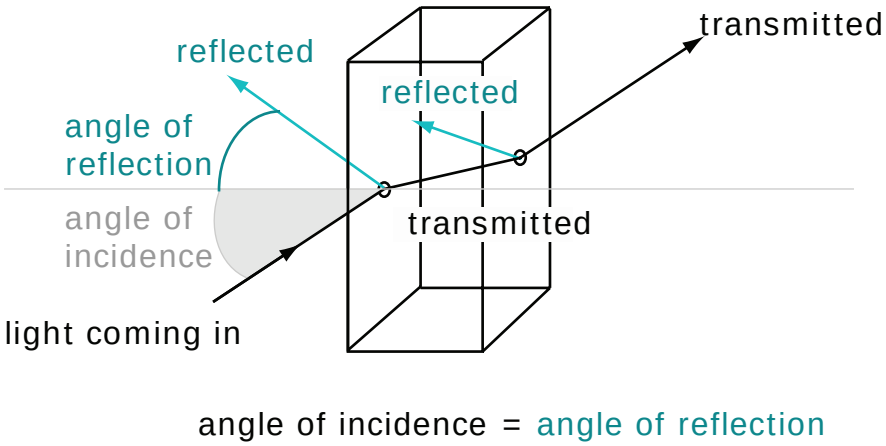

Figure 30: Reflection and refraction

The index of refraction of glass ranges between 1.47 (borosilicate glass) to approximately 1.8 (Lead glass, 71% lead). Soda-lime glasses have an approximate index of refraction of 1.52. (For comparison, the refractive indices of water and diamond respectively are 1.33 and 2.42).[89] The high refractive index of lead crystal gives the glass more brilliance, especially when angles are cut into it.

The amount of refraction also depends on the frequency of a wave of light, which is why white light can be split into its component spectral colours when directed through a prism. The white light entering the prism is a mixture of different frequencies (or wavelengths). Each wavelength bends slightly differently. Blue light slows down more than red light and will thus bend more than red light.

[89] "List of Refractive Indices - Wikipedia, the Free Encyclopedia", n.d., http://en.wikipedia.org/wiki/List_of_refractive_indices.

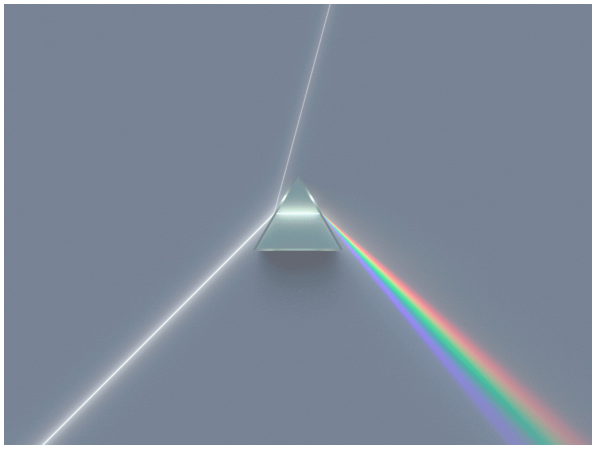

Figure 31: Light dispersion in a triangular prism

Prisms are also used to reflect light, for example in binoculars and cameras.[90]

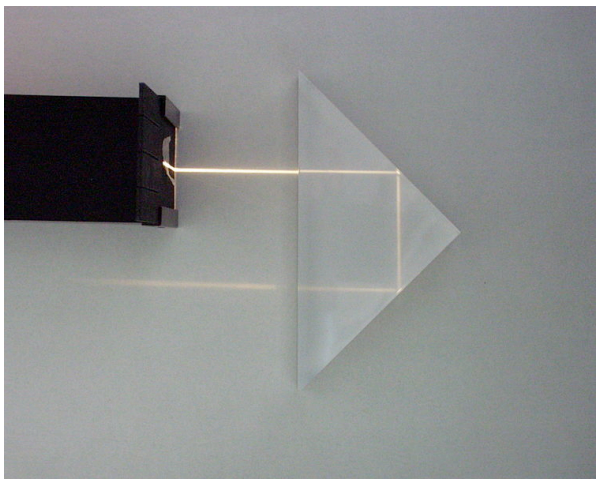

Figure 32: Reflection of light in a Porro Prism

When a ray of light exceeds a certain angle (always measured from the normal) in a denser material, it skims along the surface of that material. This is called the critical angle (for glass around 42º). If the angle is above the critical angle, all light is reflected. This is called total internal reflection.

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[90] "Prism (optics) - Wikipedia, the Free Encyclopedia", n.d., http://en.wikipedia.org/wiki/Prism_(optics).

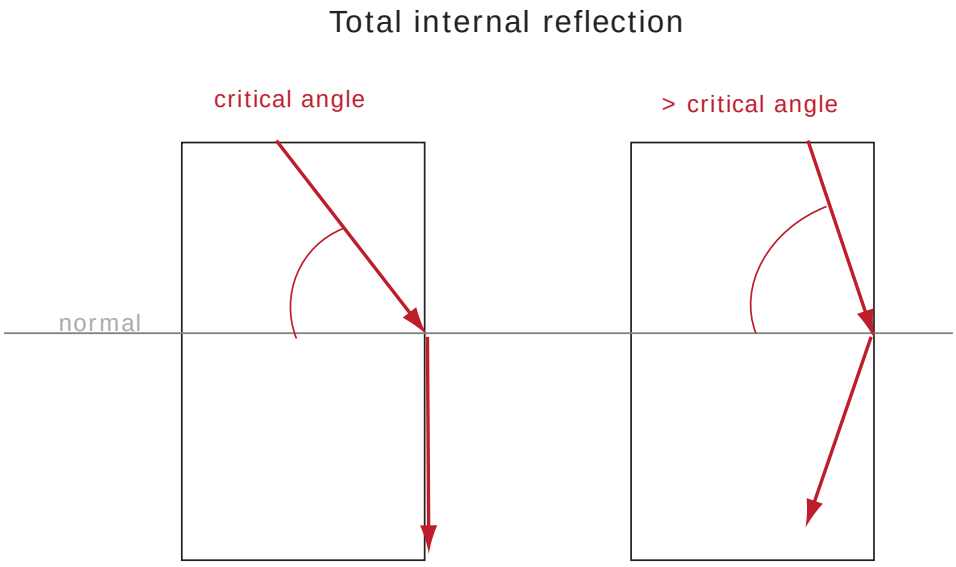

Figure 33: Total internal reflection

A practical example of total internal reflection is a work by Jun Kaneko which is in the collection of the Victoria and Albert museum. Light is reflected from the coloured sections within the piece, resulting in the clear glass appearing to be coloured along one side.

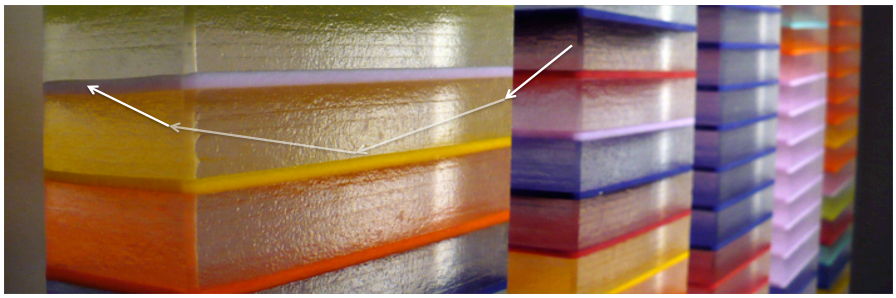

Figure 34: Reflection of colour, Jun Kaneko, *Colourbox 1-5*, 2006. W: 84 cm, H: 208 cm, D: 20 cm. Victoria & Albert Museum, London.

Martin Rosol, a Czech-trained glass artist living in the USA, uses this phenomenon extensively in his work. He glues two or more clear optical glass elements with coloured epoxy. As one walks around the work, the colour seems to invade the object and then retreat again. There is no

volume colour in Rosol's work, but from certain angles, it appears as such.

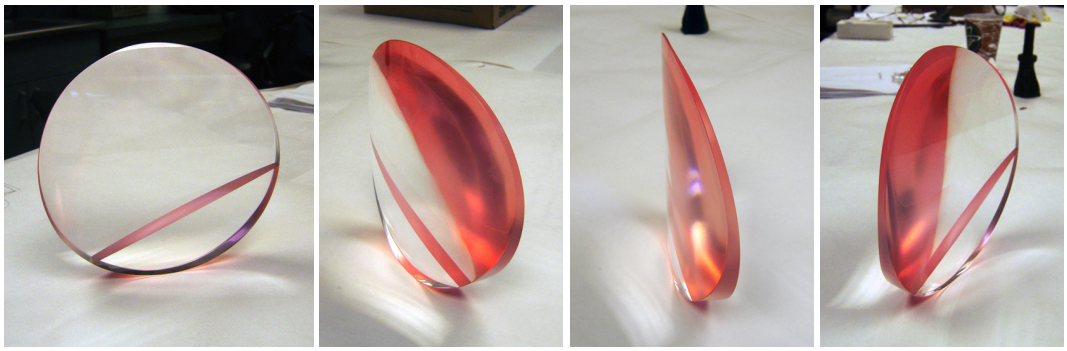

Figure 35: Two pieces of clear glass were joined with red glue, then coldworked. Work by a student in Martin Rosol's class at the Studio of the Corning Museum of Glass in 2007.

Total internal reflection is responsible for an interesting effect in a narrow, long prism shape: due to the angle of the walls, light entering the long sides of the prism is refracted away from its tip. Only the light entering through the short side is visible from near the tip, due to total internal reflection.

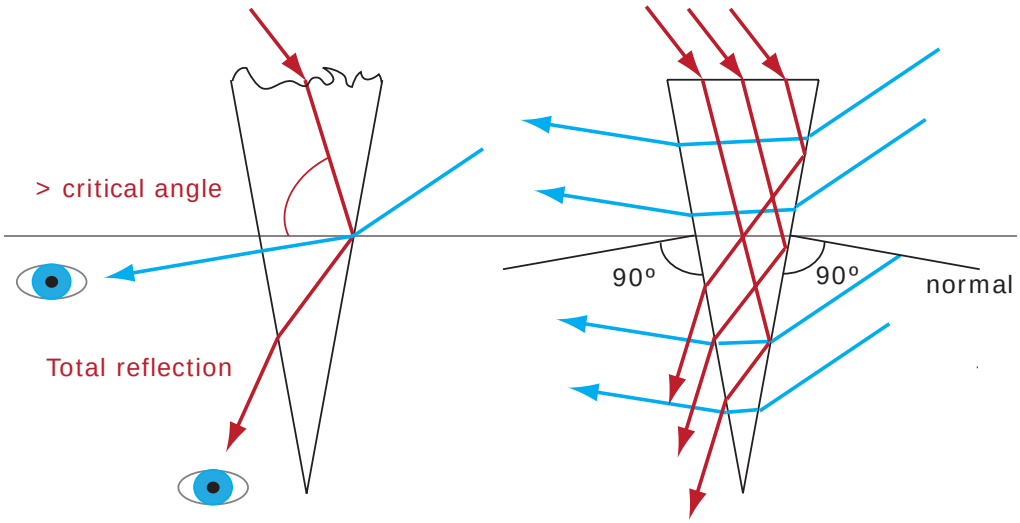

Figure 36

Colin Reid uses this phenomenon extensively in his work, texturing the short side of his prism forms, so a perfect reflection is visible at the side when viewed from the tip.

Figure 37: Colin Reid, *Untitled form with books*, 2008. H: 66 cm.

I have always been intrigued by Frantisek Vizner's *bowl with point* forms. Why is the point dark, even though it is a fairly thin part of the form? The reason became clear while studying optics: because of the angle of the point, light cannot exit the glass through the sides, due to total internal reflection. In the course of my research, I arranged for the Victoria and Albert museum's example to be placed on a light box to observe the effect. The point was still dark, which in retrospect makes sense, because if illuminated from underneath, the point is the thickest section of the object.

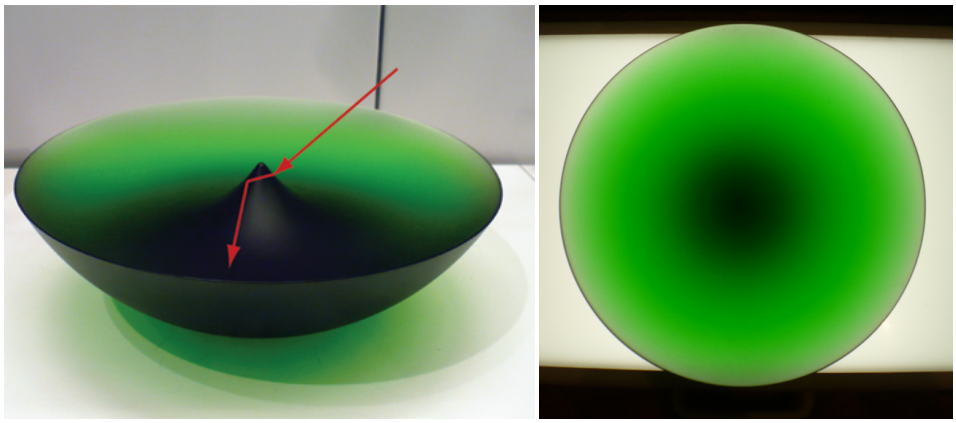

Figure 38: Frantisek Vizner, *Bowl*, 1984. Diameter: 28 cm, H: 9 cm. Victoria & Albert Museum.

3.3.2. Scattering from the surface and from features inside the solid

If the surface of the solid is not perfectly smooth, some reflection and refraction of the light will occur on a very small scale. If light interacts with features inside the solid, which have dimensions close to the wavelength of the light, scattering will occur. This will generally spread the light out and reduce its intensity.

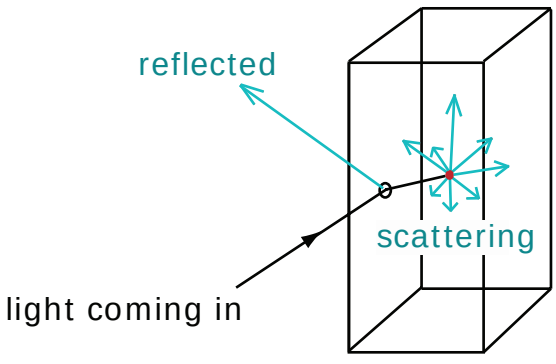

Figure 39: Scattering of light

Most cast glass contains some bubbles. If the bubbles are considerably larger than the wavelength of the light, the ray of light will pass through the bubble and continue on its way. Only if the size of the bubble is close

to the wavelength of the light, scattering occurs, as in figure 40.

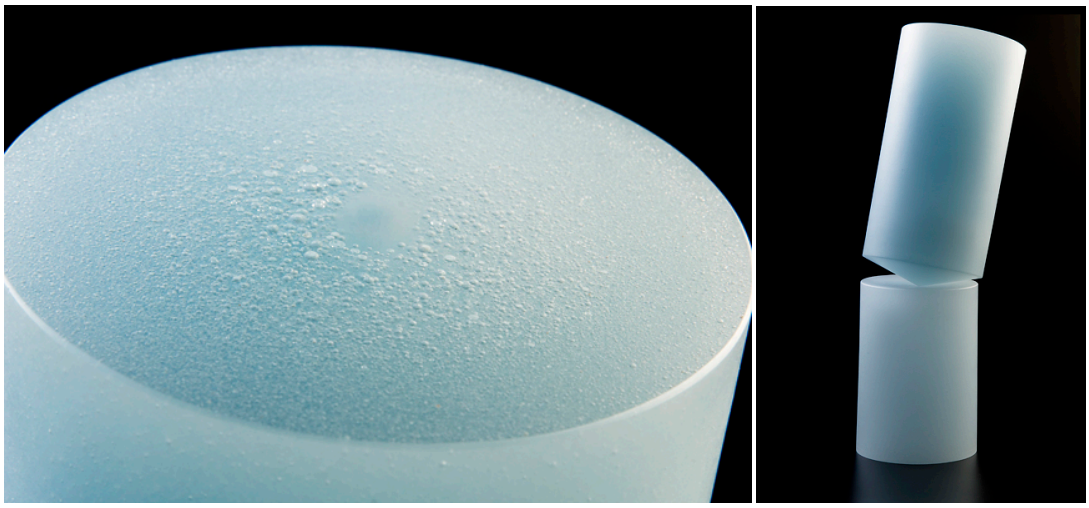

Figure 40: Heike Brachlow, *Waiting IV*, 2007. Diameter: 16.5 cm, H: 51 cm.

3.3.3. Absorption of light

When light passes through a solid, some of its energy will be absorbed. The more material (thickness, t) the light passes through, the more energy (E) is absorbed. This is described by the Beer-Lambert Law, also called Beer's Law:

$E = E_0 / e^{\gamma t}$

E_0 is the energy of the incident light. Euler's constant e = 2.71828. Absorbance (γ) is a constant which is characteristic of the solid.[91] Although absorbance is a constant for the material, this only applies to one wavelength.

So for a specific red wavelength, for example 800 nm, for a certain type of glass, there will be one unique value of absorbance. However, for

[91] Eugene Hecht and Alfred Zajac, *Optics* (Reading Mass.: Addison-Wesley Pub. Co., 1974), 85.

other wavelengths, the absorbance will be different. This is the reason glass can change in hue as well as in value due to variations in thickness.

A spectrometer can generate light at different wavelengths (colours) and compare the energy generated to the energy transmitted. The difference between those two can be related to produce a quantity, which is characteristic of the glass. This quantity will depend on the composition of the glass.

In short, using a spectrometer, an absorbance graph can be produced for coloured glasses by measuring the absorbance of light of all wavelengths within the visible spectrum. The graphs generated will be different for glasses of different compositions. In practice, this means that it is impossible to generate a formula for general prediction of absorbance of light in coloured glass. A formula for each composition (i.e. colour) of glass is required. Consequently there is no easy mathematical solution for the problem of prediction of colour density.

3.4. Polychromatic glass

3.4.1. Definitions and terminology

The most common term for colour changing glass is *dichroic*. Dichroism (Greek dikhroos: two-coloured) is a term with two meanings. One refers to polarization by absorption, which occurs in several crystalline materials, for example tourmaline. This phenomenon can cause a change in colour when the material is viewed from different directions. This only occurs in materials with a crystalline structure and therefore cannot occur in glass, which is amorphous.

The second meaning refers to the ability of a material (or coating) to split a beam of light into two beams of different wavelengths. While the term *dichroic* is sometimes used for all types of colour changing glass, it is most commonly used for glass coated with metal oxides. Here, the colour appearance changes when the object is viewed from different directions,

as well as in transmitted and reflected light. A different type of colour changing glass shows one of these effects and is also referred to as dichroic: glass coloured with colloidal metals i.e. gold, silver and copper. This glass is homogenously coloured throughout its mass rather than coated, but also shows a different colour appearance in transmitted and reflected light. The effect is due to the development of nanoparticles of a certain size in the glass, which scatter and reflect the light, and even today extremely hard to control. It is also referred to as the Lycurgus effect, after its most famous example, the Lycurgus cup in the British Museum. This late roman cage cup appears transparent red in transmitted light and opaque green in reflected light[92].

Figure 41: The *Lycurgus cup* in reflected and transmitted light. H: 15.9 cm, Ø13.2 cm. British Museum.

The third colour change effect in glass is the alexandrite effect. The name originates from the mineral alexandrite, a type of chrysoberyl, which changes from green in daylight to red in incandescent light. In glass, the effect is most commonly achieved by adding the rare earth element neodymium to the melt. Glass coloured with neodymium oxide changes

[92] Ian Freestone et al., "The Lycurgus Cup - A Roman Nanotechnology," *Gold Bulletin. The Journal of Gold Technology, Science and Applications.* 40, no. 4 (February 1, 2008), http://www.goldbulletin.org/.

from purple in daylight to reddish purple in incandescent light to pale blue in fluorescent light. In combination with other colouring agents, different hue changes can be achieved. The effect is due to interaction between the absorption spectrum of neodymium glass and the emission spectrum of the illumination.[93] Any given light source, for example the sun, an LED, a fluorescent or an incandescent light, can only generate certain range of wavelengths. A graph can be generated for each light, showing which wavelengths it can emit (figure 42).

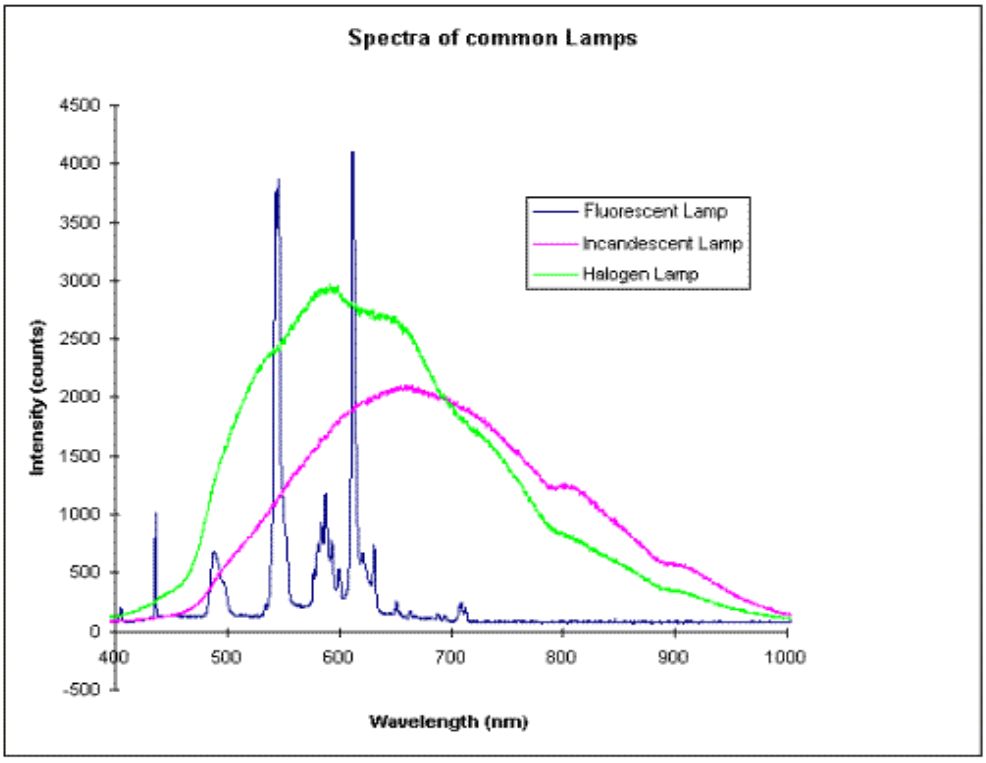

Figure 42: Spectra of common lamps. (http://www1.union.edu/newmanj/lasers/Light%20Production/LampSpectra.gif, accessed 09/05/09)

Because of extremely narrow absorption bands in the yellow region, glass coloured with neodymium absorbs almost all the yellow light (around 580nm) and therefore appears yellow's complimentary colour, purple, if

[93] Brad Amos, "Birefringence for Faceters 4: Gemstones That Change Colour," *UK Facetcutter's Guild Faceters Stonechat* November/December 2005, no. 64 (n.d.): 11–16.

illuminated with light that displays a continuous spectrum, such as daylight. Incandescent light contains more yellow than daylight, therefore the hue of neodymium glass shifts towards reddish. Fluorescent light has sharp peaks in the red, green and blue regions. Neodymium glass does not interfere much with the peaks, and the result is a pale blue appearance.

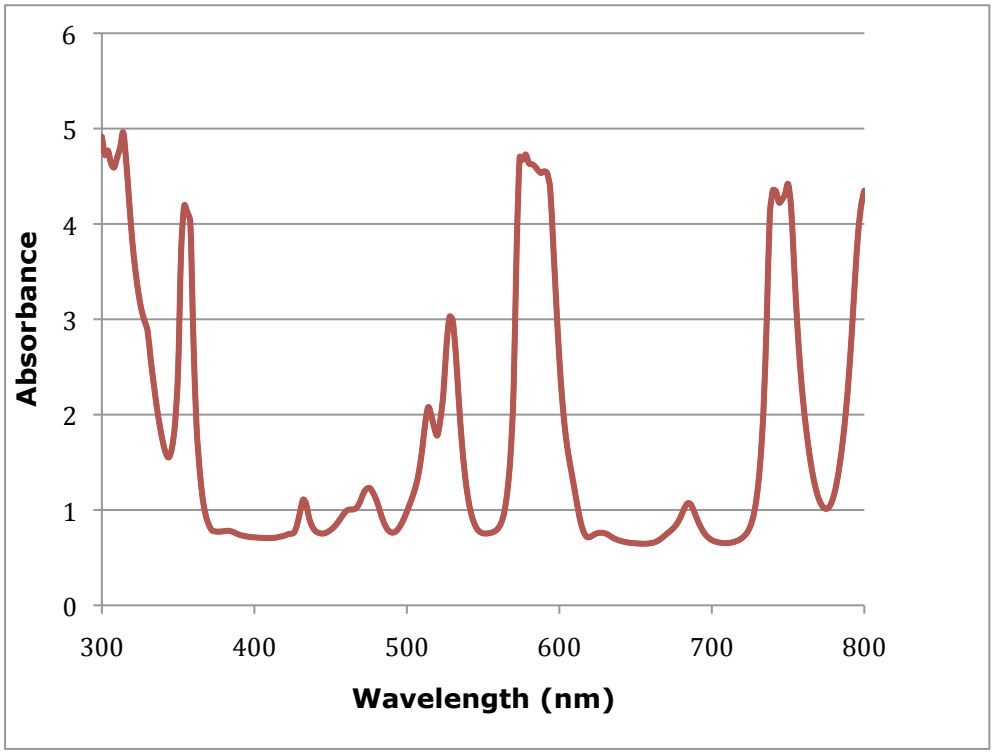

Figure 43: Absorbance of 4% neodymium glass. The graph was generated using a spectrophotometer at Imperial College, with the help of Dr. Ruidong Xia.

Although also sometimes referred to as dichroic glass, both the cause and the appearance of colour change are different to the previously discussed phenomena. Throughout this text, I refer to glass coloured with neodymium oxide (by itself or in combination of other colouring agents) as polychromatic glass, to distinguish from other colour changing glass. Neodymium doped glass can appear many different colours depending on illumination.

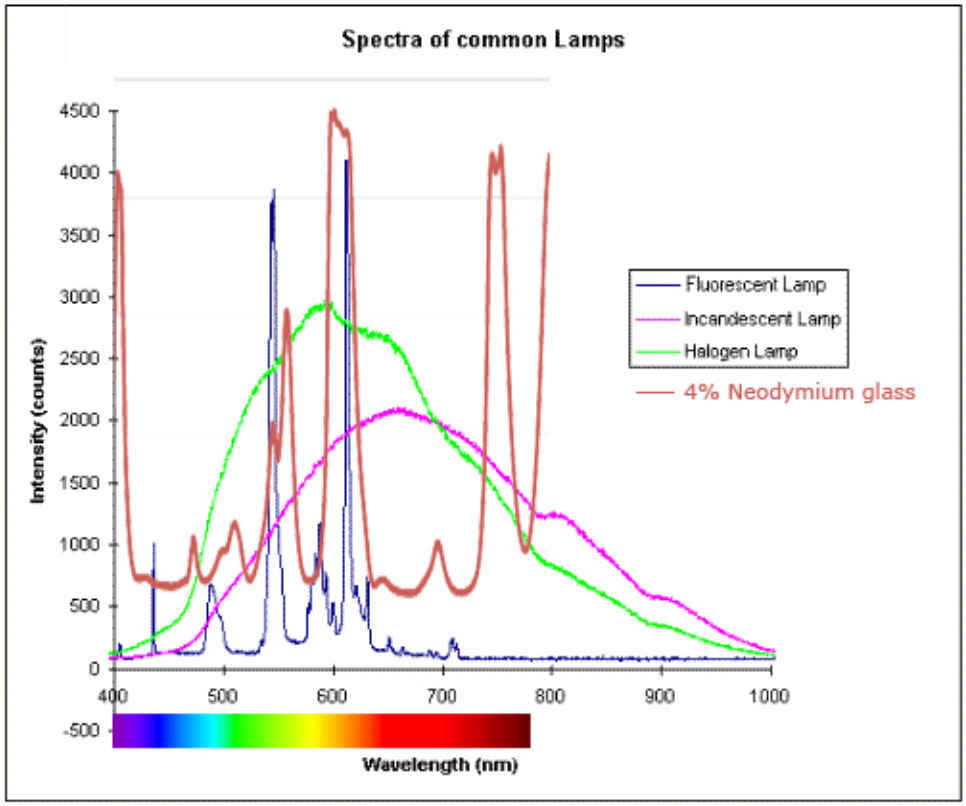

Figure 44: Interaction between absorption spectrum of 4% neodymium glass and emission spectrum of fluorescent, incandescent and halogen lamps.

3.4.2. History of neodymium glass

Neodymium was discovered in 1885 by Austrian chemist Carl Auer von Welsbach, who separated the material didymium, previously thought to be an element, into two elements, which he named praseodymium (Pr) and neodidymium, later to be called neodymium (Nd)[94]. It is best known for its application in permanent magnets and lasers. The Bohemian glass company Ludwig Moser & Söhne, under the leadership of Leo Moser, was the first to experiment with neodymium to colour glass around 1920, when rare earth oxides[95] became commercially available. The result was

[94] "Neodymium - Wikipedia, the Free Encyclopedia", n.d., http://en.wikipedia.org/wiki/Neodymium.
[95] See periodic table in Appendix V.

a range of glass colours of which the best known is *Alexandrit*, coloured with 4%-5% of neodymium oxide, appearing blue violet to red violet in daylight and incandescent light, and pale bluish-violet in fluorescent light (although the colour appearance in fluorescent light would have been unknown at the time, as fluorescent lighting did not become commercially available until 1938.)[96] Other rare earth glasses included *Didym* (Nd, Pr), *Heliolit* (Nd, Pr, lanthanum [La]), *Latr* (Nd, Pr), *Praseamit* (Pr) and *Royalit* (Nd, selenium [Se]). The change in colour of these glasses depends on both thickness of the glass and illumination.[97] Moser is one of the few companies who still produce rare earth glasses now. American glass companies started using neodymium glass in the late 1920s; A. H. Heisey and Company, Morgantown Glass Works and Boyd's Crystal called it Alexandrite, the Fostoria Glass Company, Fenton Art Glass Company and Steuben Glass Works named it Wisteria, the Tiffin Glass Company called it Twilight or Dawn, the Cambridge Glass Company, Heatherbloom, Lotton Art Glass named it Neo-Blue or Neodymium Glass. Most of these companies produced neodymium glass for a short period only; the items are now sought after collector's items.

Glass artists know neodymium glass from Bullseye's Neo-Lavender, Rhubarb, and most recently Lavender-green-shift colours, Gaffer's Rhubarb and Semillon, and many of Banas' glass colours. Unfortunately none of these companies show the colour change in their promotion materials; Bullseye alone calls the colours "shift tint", but does not include images in fluorescent light.

3.4.3. My interest in polychromatic glasses

Polychromatic glasses have been one of the focal points of this research from the beginning. My work focuses on movement and change, and the

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[96] "Neodymium - Wikipedia, the Free Encyclopedia."
[97] Gary Baldwin and Lee Carno, *Moser-artistry in Glass, 1857-1938* (Marietta Ohio: Antique Publications, 1988).

potential of colour change adds an extra layer of transformation and ambiguity. Transparent coloured glass always changes with the illumination, but in polychromatic glasses, this change is much stronger, especially in combinations of neodymium oxide with praseodymium oxide, iron oxide or cerium and titanium oxides, which change from reddish to green. The glass is transformed to the point where it appears as a different object. Although the most obvious change is, for example, from pink to green, several different greens are apparent in different fluorescent lights, yellow in certain LED light, blue in gas discharge light. Working with this glass – or wearing or carrying it – challenges one's perception and conveys that colour is a property of the light, not the object.

A wide range of unusual colours can be achieved with neodymium oxide combinations. Many colours are ambiguous shades, which are difficult to understand or describe, for example certain neodymium-chromium combinations appear a purplish green, and neodymium-cerium-titanium combinations can appear greenish red. Also, polychromatic glasses usually show a strong colour change from thick to thin, which is inspiring to work with and can enhance the form of an object. Polychromatic colours are discussed in detail in chapters 4 (*Process Development and Material Testing*) and 5 (*The Creative Work*).

4. Process development and material testing

4.1. Introduction

The technical aims for this research are twofold: Firstly, establishment of a method for colouring glass in a kiln, to allow glass artists control over hue and colour density. Secondly, judgement of the amount of oxide to be added to the glass to achieve a desired colour result for a given volume.

This research is set in a studio context; it has been carried out in a studio using an artist's approach and is intended for use in a kiln caster's studio. While artists tailor their studios to their specific practice, and one cannot speak of a typical studio, most kiln casting studios contain certain pieces of equipment, for example kilns and grinding and polishing machinery, as well as a mould-making area, possibly with an extraction system. For the purpose of melting glass, a kiln has to be capable of reaching temperatures of 1240-1280ºC, whereas for kiln casting, temperatures above 1000ºC are not required. However, many glass artists use pottery kilns capable of a maximum temperature of 1300ºC, and if necessary, a small pottery kiln can easily be acquired. For the weighing of materials, scales with a capacity of at least 3 kg, and with increments of 0.01 g are required; I am using 3 pairs of scales: jeweller's scales capable of 100 g with increments of 0.01 g, scales capable of 5 kg with increments of 0.1 g, and for weighing ingredients for furnace melts, scales capable of 50 kg with increments of 1 g. Certain health and safety equipment is also likely to be available in a kiln caster's studio, for example a high-quality dust mask to be worn when dealing with silica dust, ear defenders and safety glasses. Many artists have an area for drawing and writing in their studios, and keep notebooks and/or sketchbooks that they often refer to. A studio artist's approach to research relies heavily on experience, be it general making experience or more specific experience, for example in evaluation of colour. The approach includes iterative testing leading to

the making of larger or more refined objects, with slowly evolving objectives, and consideration given to shifting aims that evolve through the making. Evaluation is mainly visual, because the results will also be visual.

There are scientific methods for measuring colour density, but they are neither easily accessible nor practical for artists. I am trying to develop a way to create coloured glass and judge colour density in a kiln caster's studio.

Contrary to the field of ceramics, where glaze testing is a part of studio practise with established procedures, glass artists usually obtain their coloured glass from commercial suppliers such as Bullseye, Gaffer, Kugler, etc. There is no established format for colour testing in glass, therefore a functional method of testing had to be developed. Far from being a by-product, the process for testing is central to this research, answering one of its aims by providing processes for testing and making coloured glasses in a kiln. To obtain large amounts of coloured glass, a melt in a furnace is still the obvious method, but for smaller amounts up to two kilograms, a method for melting colour in the kiln has been developed.

While recognising the need for as many constants as possible in the testing programme, changes are inevitable because the approach is being tested as much as the glass. Where significant parameters have changed, some tests are repeated to ascertain continuity.

Two separate colour tests have been developed: a simple test for colour hue, and a test for density, which also developed into a series of work. In addition, a process for making colour in a kiln has been developed and tested.

4.2. Classification of glass

Glasses have the mechanical rigidity of crystals, but the random disordered arrangement of molecules that characterises liquids. Glass is generally formed by melting crystalline materials at very high temperatures. When the melt cools, the atoms are locked into a disordered state before they can form into a crystal arrangement.

Glasses are usually composed of formers (the basic ingredient), fluxes (which allow the former to be melted at lower temperatures), and stabilisers (to keep the glass structure, which is weakened by fluxes, intact).

Glass formers are silicon dioxide (silica sand SiO^2), boric oxide (B^2O^3), and phosphorus pentoxide (P^2O^5).

Soda ash (sodium Carbonate Na^2CO^3), potash (potassium carbonate K_2CO_3) and lithium carbonate (Li_2CO_3) act as fluxes.

Stabilisers are limestone (calcium carbonate $CaCO^3$), litharge (lead oxide PbO), alumina (aluminium oxide Al^2O^3), magnesia (magnesium oxide MgO), barium carbonate ($BaCO_3$), strontium carbonate ($SrCO^3$), zinc oxide (ZnO), and zirconia (zirconium dioxide ZrO^2).[98]

The most common and least expensive type of glass is soda-lime glass, usually containing 60-75% silica, 12-18% soda, 5-12% lime, and small amounts of other fluxes and stabilisers. It is used for making float glass, bottles and other containers, table and decorative glassware. It is used by many studio glass artists.

Lead glass contains a high percentage (20-40%) of lead oxide. Due to its high refractive index, its low softening temperature, and its softness, it is often used for expensive tableware and cut and engraved glass. Studio glass artists use it for casting and glassblowing.

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[98] "The Glassy State - Resource on Glass from The Corning Museum of Glass", n.d., http://www.cmog.org/dynamic.aspx?id=5640#.TuDOY0qGYy4.

Borosilicate glass is any silicate glass, which contains at least 5% of boric oxide. It is highly resistant to temperature change and chemical corrosion. Light bulbs, photochromic glasses, laboratory ware, and bake ware are examples of borosilicate products. Some studio glass artists use borosilicate glass for outdoor sculpture.

Other glass types are aluminosilicate glass, 96 percent silica glass, and fused silica glass. These are far more difficult to make than soda-lime, lead and borosilicate glasses and are used for specialist applications in industry.[99]

4.3. Base glass

As colour results can significantly differ between different types of glass, it was decided to use a single type of glass throughout the project. A choice had to be made between soda-lime and lead glass, the two types generally employed for casting. Several factors were taken into account: Firstly, lead glass is much heavier than soda- lime glass, with a specific gravity of approximately 3.6 versus soda-lime at approximately 2.5. This can become an issue for cold-working larger sculptures. Secondly, I had been using soda-lime glass for my previous castings, and had already gained some experience with colouring this glass. Lastly, Glasma pelletised batch, a soda-lime glass, is melted in the college furnace, which means the material is readily available at the college.

Several soda-lime glasses were employed during the testing. The bulk of testing was done using Glasma pelletized batch (Glasma Studioglass MRJ 702 A)[100], and some tests were completed using two other glasses, a batch made from raw materials, and Bullseye frit, to evaluate the comparative merit of using glass frit, prepared batch, and batch made

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[99] "Corning Museum of Glass | Resource on Glass | Types of Glass", n.d., http://www.cmog.org/dynamic.aspx?id=5658#.TuDgu0qGYy4.
[100] The mixed raw materials from which glass is melted are called *batch*.

from raw materials, and assess the differences in colour hue, which proved to be negligible in most cases. This allows for a choice of base glass in reproduction of the experiments.

Glass melting from batch should not be attempted without sufficient extraction, due to the gasses released during the melting process.

4.3.1. Glass batch made from raw materials

This batch, a soda-lime glass made from raw materials, is the most economical option. The glass composition is known and consistent, and so the tests will be repeatable. Better colour results can be achieved by adjustment of the formula for certain colours, for example for manganese purple, where the replacement of antimony with cerium oxide allows for a much deeper tone. The glass can be formulated especially for casting, i.e. it with higher viscosity at lower temperatures, and a lower annealing point. However, the formulation of such a recipe proved difficult. The early recipe, provided by external advisor Richard Golding, worked well for initial hot cast tests but showed strong devitrification when kiln-cast.

Devitrification, the formation of crystals on the glass surface, which appear as a whitish scum, is most likely to happen at temperatures between the softening point and the melting point of the glass. During the casting process, the glass is held at temperatures between 800ºC and 900ºC for a considerable amount of time, therefore prone to devitrification.

Figure 45: Devitrification in RG2 Glass coloured with 0.01% chromium oxide. Diameter: 4.5 cm, L: 6.5 cm.

In a furnace, the glass is less likely to devitrify, because it is kept at higher temperatures, and it is being moved around during the glassblowing process (which will inhibit the phenomenon). Blown items are cooled down to annealing temperature quickly. Casting glasses are formulated to avoid the devitrification. This can be achieved by replacing part of the lime (calcium carbonate) percentage with other stabilisers, for example barium and magnesium oxides, and adding a small amount of alumina, which has the property of suppressing devitrification.

In an attempt to avoid this problem, the batch formula was adjusted several times, and finally replaced by a recipe supplied by Gaffer Glass, "Gaffer Batch Lithium Carbonate". This is still slightly more prone to devitrification than Glasma pelletized batch.

Another issue with manufacturing batch is that more storage is needed for the raw materials, especially for the silica sand, where the minimum commercially available quantity is 1000 kg. A set up for measuring and mixing the ingredients, with an extractor fan, is required. The process of measuring and mixing the ingredients takes more time and effort, especially for small colour tests: because it is difficult to get a homogenous mix of materials, the ingredients have to be measured out separately for each melt. The increased contact with raw materials also

increases the health and safety risks. For these reasons, it was decided to use Glasma pelletized batch instead.

4.3.2. Glasma pelletized batch

Glasma pelletized batch is a premixed, pelletized batch formulated for glass blowing. It is less economical than self-mixed batch, but more economical than Bullseye frit. Pelletized batch doesn't produce much dust as the materials are bound. Less storage space is needed, and the set up for measuring and mixing can be basic. Due to the homogenous mix of materials, the melting temperature is slightly lower and the melting time less than for batch mixed from raw materials.

Because its formula cannot be adjusted, certain colours are not achievable. The exact formula is unknown. The glass shows slight surface devitrification when used for casting.

When heating pelletized batch or batch mixed from raw materials to 1240-1260°C, all gases, except fining gases,[101] are liberated. The mixture consists of a melt with suspended refractory particles and gas bubbles. Frothing takes places because of the bubbles, which provide

stirring (self-mixing) of the ingredients and, if colouring agents are present in the mix, helps achieve a homogenous colour.

For larger melts in the kiln, Glasma frit has been used to avoid frothing of the batch. If Glasma frit cannot be obtained, a commercially available glass frit such as Bullseye could be used.

[101] Fining agents, for example antimony or arsenic, are added to the glass to remove seed bubbles. Fining agents create large bubbles, which take the small bubbles with them as they rise to the surface of the glass.

Glasma pelletized batch (Glasma Studioglass MRJ 702 A)		
<60%	Sand	
<20%	Sodium	NaO
<2%	Sodium hydroxide	NaOH
<20%	Potassium	KO
<10%	Limestone	CaO
<7%	Barium	BaO
<3%	Zinc oxide	ZnO
<4%	Borax	BO
<1%	Antimony oxide	SbO
820g glass from 1000g batch **Glass weight x 1.22 = batch weight** **Density = 2.54 kg/dm^3 ± 0.01 kg/dm^3** **Refractive index n = 1.520±0.005** **Recommended Melting Range 1250-1400ºC** **Recommended Annealing Temperature: 510 ± 5ºC**		

Figure 46: Specifications for Glasma pelletized batch.

4.3.3. Bullseye glass frit

Bullseye frit is the least economical option. The glass is formulated for fusing and casting, i.e. fairly resistant to devitrification. Frit doesn't froth as batch does, allowing more glass to be melted in a crucible. This is crucial for melts larger than 1.5 kg. However, care needs to be taken that the colouring agents are mixed well with the frit, as the lack of large gas bubbles means that the glass does not mix as well during the melting process. The glass needs to be held at top temperature longer, and/or the top temperature has to be increased, to avoid seed bubbles.

It has been found that an addition of 20% of Glasma pelletized batch solves the difficulties with stirring and seed bubbles by introducing fining agents to the mix.

Because the formula cannot be adjusted, certain colours are not

achievable.

A furnace trial was carried out with Bullseye cullet during a residency at the Studio of the Corning Museum of Glass in November 2007. The oxides didn't sufficiently mix with the glass, and the resulting colour was not homogenous. As the results were unsatisfactory, frit was employed instead.

The composition of Bullseye glass is not available. Tests showed that the colour results are similar to Glasma and RG glass.

4.4. Colouring glass

There are two types of glass colours: Ionic (solution) colours and colloidal colours (colours produced by particles).

The most common colouring ions are those of the transition metals cobalt (Co), chromium (Cr), copper (Cu), manganese (Mn), and iron (Fe).

Colour in glass can also be caused by atomic solution, as in the case of selenium (Se), and by colloidal precipitation of very small metallic particles, such as those of gold (Au), copper Cu), or silver (Ag). Such particles develop when glass of suitable composition, which is melted under reducing conditions, is subjected to a secondary or extended heat treatment. The re-heating causes the metal crystals to grow, producing colour caused by light absorption of certain wavelengths by the metal nanoparticles. This process is called 'striking'. The particle size is critical, between 5 and 60 nm, as larger crystals give rise to reflection and scattering, causing a muddy brown colour. A "good colour" (red in the case of gold and copper) is achieved only when particles of a smaller size than one-quarter of a wavelength are obtained, and the colour is caused by absorption, not reflection.[102] Temperature and heating/cooling rates are critical for the melting of ruby glass.

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[102] Weyl, *Coloured Glasses*, 331–379.

4.4.1. Polychromatic colours

Dichroic glasses can be achieved in glasses coloured with colloidal gold, copper or silver when particles grow considerably larger than the desirable range (for example to 200-500 nm). Particles of this size, as mentioned before, scatter and reflect the light, causing the glass to appear a different colour in transmitted and reflected light. A famous example is the Lycurgus Cup in the British Museum.[103]

Glasses coloured with neodymium oxide (a polychromatic solution colour; the reason for the colour change is explained in section 3.4.1), by itself or in combination with other colouring agents, are an important part of this research; I am interested in the additional aspect of transformation that colour changing glass can bring to my creative work. Polychromatic glasses also complicate the research, because neodymium oxide behaves very differently from oxides of the transition metals. Moser refer to glasses coloured with rare earth oxides as rare-earth doped glasses, because of the relatively large amounts of oxide required to achieve intense colours. I have experimented with up to 15% neodymium oxide, which gives a strong red-purple, but is not significantly different in colour appearance from glass coloured with 8% of neodymium oxide. High percentages of oxide change the characteristics of the glass, and in theory, the recipe should be adjusted; in the case of neodymium oxide, which acts as a flux, this is achieved by using accordingly less sodium carbonate. In practice, the batch recipe cannot be changed when using ready-made batch or frit.

When combined with oxides of transition elements like nickel, cobalt, copper, iron and chromium, less neodymium is needed to achieve

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[103] "British Museum - Lycurgus Cup", n.d., http://www.britishmuseum.org/research/search_the_collection_database/search_object_details.aspx?objectid=61219&partid=1&searchText=lycurgus+cup&numpages=10&orig=%2fresearch%2fsearch_the_collection_database.aspx&currentPage=1.

saturated colours; however, the ratio of neodymium to those oxides lies between 100:1 and 1000:1.

4.4.2. Colouring agents

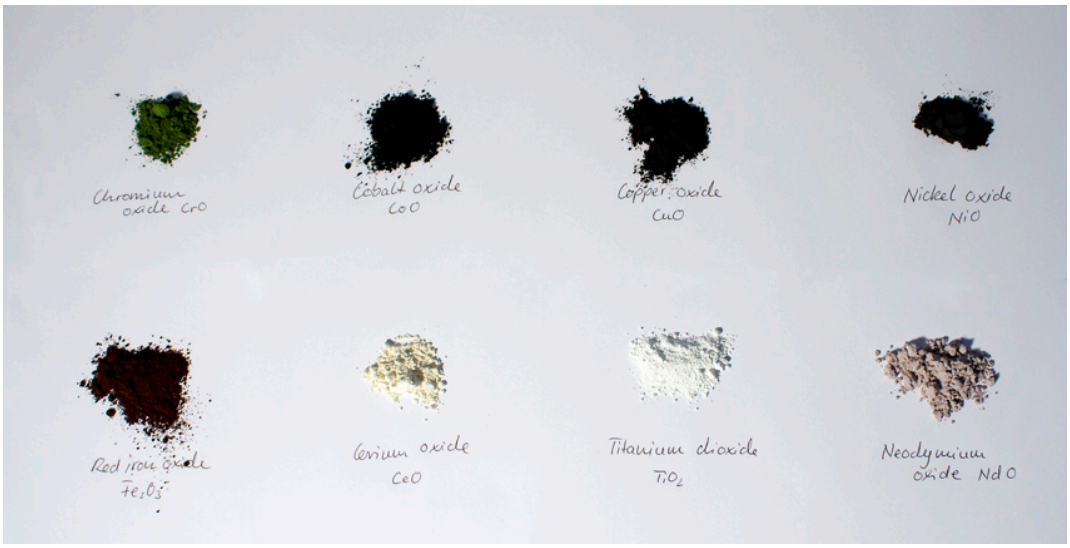

Figure 47: Oxides used in the course of this project.

As the scope of colouring glass is enormous, this research has been limited to solution colours produced in an oxidised atmosphere, as colloidal colours (striking colours) are much more difficult to control, particularly in a studio environment. Of the colouring agents listed by Weyl in his classical work *Coloured Glasses,*[104] oxides of the transition elements chromium, cobalt, copper, iron, manganese, nickel, titanium and vanadium, as well as oxides of the rare earth elements cerium, erbium, neodymium, and praseodymium are employed in the initial testing stage. Of these, the oxides of chromium, cobalt, copper, iron, nickel, titanium, cerium, praseodymium and neodymium have been employed throughout the project. Tests with vanadium, erbium and manganese have been discontinued because the hue produced with

[104] Weyl, *Coloured Glasses*.

vanadium is not significantly different to the colour produced by chromium, erbium is a weak colouring agent, producing a light pink, which does not substantially alter the colours produced by other elements, and manganese is also quite weak in soda-lime glasses.[105]

With few exceptions, these oxides are consistent in colour result, i.e. the results don't change with changes in melting time, temperature, or small variations in batch composition. Due to health and safety considerations, the oxides of cadmium, selenium and uranium are not used.

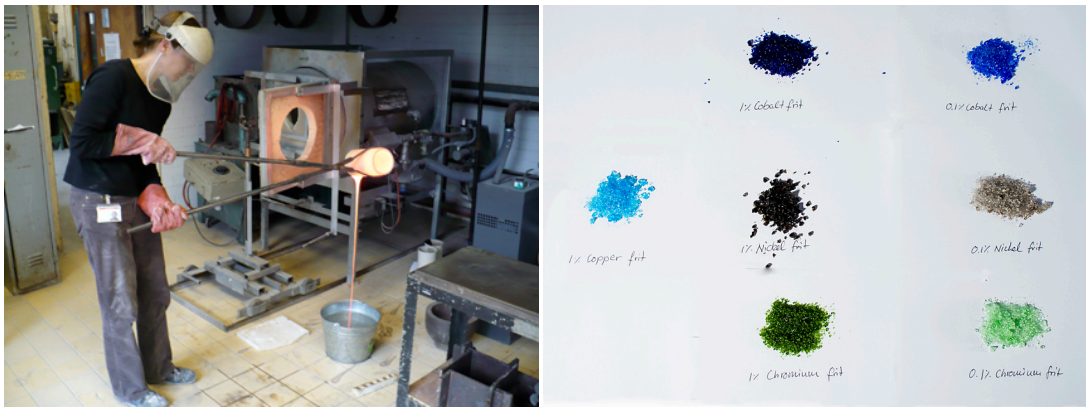

Figure 48: Hot glass is poured into water to produce frit.

For producing small tests, sometimes extremely small quantities of oxide are needed. As it is difficult to weigh out very small quantities, for example 0.001g, a frit was made containing 1%, and 0.1% of oxide, for the oxides of cobalt, copper, chrome and nickel. 1300 g of batch containing 1% or 0.1% of oxide was melted in a 2.3 litre crucible in a kiln, removed with tongs at top temperature and poured into a metal bucket filled with water to frit the glass. The resulting frits ensured that exact quantities of very small amounts could be weighed out as shown in figure 49.

[105] A periodic table of elements can be found in Appendix V.

oxide	1% frit	0.1% frit
1 g	100 g	1000 g
0.1 g	10 g	100 g
0.01 g	1 g	10 g
0.001 g	0.1 g	1 g
0.0001 g	0.01 g	0.1 g

Figure 49: Oxide amount to frit amount conversion.

4.5. Basic hue tests

4.5.1. Process development

To develop a process for glass colour testing in a kiln, many factors had to be considered: firstly crucible material, making method, form and size, firing times and temperatures. Secondly, firing temperatures and cycles for the glass melt, and the amount of glass required. Thirdly, how to remove the glass from the crucible for shaping into desired forms.

4.5.2. Requirements

The main purpose of basic tests is to show the colour hue of the glass, to allow choosing of appropriate compositions for either further testing or making. They should also give a basic idea of colour density, allowing judgement of the quantity of oxide to be employed in follow-on tests. The principal requirement is visibility of colour hue. Ideally, the outcome should be a transparent sample, which can be viewed in different lighting conditions and in front of a white background. Also, the testing should

require as little energy and time as possible: ideally, multiple tests should be done at the same time, in a single firing, with no or little coldwork required.

4.5.3. Crucibles

Initially, wide and squat stoneware crucibles were made on the Jigger-jolly, using B17C white stoneware (obtained from Valentine Clays Ltd). On recommendation of Richard Golding, a low, wide form was chosen. However, the form proved unsuitable because the colouring agents didn't mix homogenously with the glass. The layer of batch at the bottom of the crucible was too thin to allow for self-mixing through bubbles during the melting process. Narrower, rounded crucibles, measuring approximately 10 cm in diameter and 5 cm in height, were tested, with the colouring agents mixed with the glass batch by shaking for at least twenty seconds in a sealed container. This was successful; a more compact volume allows rising bubbles to stir the mix.

Figure 50: Initial stoneware crucibles, later to be used as trays to guard against spillage, and small porcelain crucibles.

The initial aim was to produce colour samples that could be taken out of the mould. Some time was spent trying to find a separator, or mould release agent, to coat the crucibles with. The removal of samples from the crucible as if from a mould would allow re-use of the crucible.

Different kiln-wash recipes, a plaster-silica mould mix and fibre blanket were used. However, while all of these work at casting temperatures around 850°C, they did not stop the glass from adhering to the crucible at 1240 - 1260°C, apart from the fibre blanket, which adhered to the glass and caused it to crack. A suitable separator was not found.

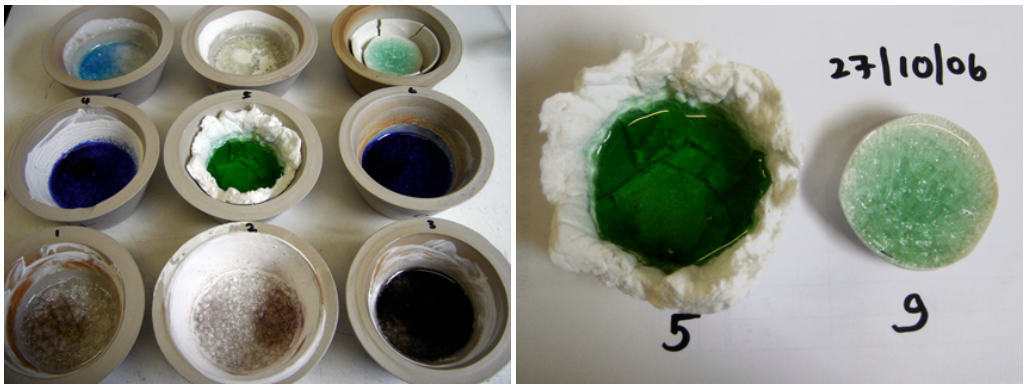

Figure 51: First colour and separator tests.

Several options were considered: hot casting, kiln casting, or accepting that the glass will adhere to the crucible.

The most important factors for basic hue tests were speed of making and energy efficiency, therefore it was accepted that the glass adheres to the crucible. Small, near hemispherical slip-cast crucibles made from Valentines porcelain[106] were used for their colour, so the hue could be judged on a near white background. Disadvantages are inconsistency in appearance, with some samples shattered and some whole, and instability of the samples, some of which tended to explode at any time, most often during the first two days after the firing. This is due to the differences in thermal expansion of the porcelain and the glass.

100g of batch or glass per test were used. When thin crucibles pre-fired to 1240° were used, some of the samples did not crack. When unfired

[106] Obtained from Valentine Clays Limited.

crucibles were used, all samples cracked, but the process was faster and more energy efficient.

Figure 52: Unpredictable results when firing small colour tests.

The initial stoneware crucibles were used as trays, to protect the kiln in case the thin porcelain cracked during firing. At a later time, lighter and smaller trays were slip cast to maximise kiln space.

Approximately 190 tests were carried out in this way and recorded in a database named *Colour Tests 1*.[107]

The development of *crucible casting* for larger tests, discussed in section 4.6.4 p. 126, allowed for improvement of the process for small hue tests to provide a sample that is not attached to a crucible. The process is carried out in the following manner:

Figure 53: initial set-up for casting small hue tests. Diameter: 5 cm.

150g of glass is melted in a stoneware crucible (cast in the same mould

[107] See Appendix VII

as the initial porcelain crucibles), and cooled down. Then the crucible is suspended above a ceramic mould coated with a separator (Bullseye kiln wash was found to work best) and fired to 840°C, to cast the sample. Initially, hemispherical porcelain crucibles were used as ceramic moulds, but any clay is suitable at casting temperature of 840°C. The moulds can be re-used, but have to be coated with the separator before every firing. The use of unfired crucibles was tested for the melting process; this would eliminate one firing. However, the results showed occasional occurrence of scum in the glass. Using bisque fired crucibles is preferable. The mould shape was later changed to produce rectangular samples, as the lens shape of the initial samples made it difficult to observe colour hue and density accurately. The new sample shape allows for viewing at two thicknesses to help judge colour density. The moulds are taller and allow for easy positioning of the crucible-reservoir for casting. They take up less space in the kiln than the initial set-up.

Figure 54: Improved set-up for casting small hue tests.

This process allows for consistent tests that provide more information, easier evaluation and easier storage.

Figure 55: Improved small hue samples. H: 1.5 cm, W: 5 cm, D: 5 cm (each sample).

4.5.4. Firing cycles

A typical firing cycle employed for 100g colour tests in porcelain shells, using Glasma pelletized batch:

200º/h -> 600ºC (3 hours)
213º/h -> 1240ºC (3 hours)
HOLD 30 min
END

It was found that the pelletized batch melts faster and at lower temperatures than batch mixed from raw materials. A different firing cycle was adopted for tests made with batch mixed from raw materials.

Typical firing cycle employed for 100g colour tests in porcelain shells, using batch mixed from raw materials:

200º/h -> 600ºC (3 hours)
220º/h -> 1260ºC (3 hours)
HOLD 1 hour

END

Due to the circumstances of this research (in a college ceramics and glass department), different kilns were used for the tests, depending on availability. The kiln used most frequently is a rectangular Kilns & Furnaces Ltd. front loader with the dimensions 38 cm x 37 cm x 42 cm, with a Stafford Instruments ST314A controller. Other kilns used have different controllers, some of which require an adjustment of the firing cycle. Exact records of firing cycles have been kept in the testing notebooks.

4.5.5. Recording

Test set-up and results are recorded in a database, which contains all relevant information as well as photos of each sample. Because part of this research focuses on polychromatic colour, samples are photographed in two to three different lighting conditions, incandescent light, fluorescent light and daylight or an approximation of daylight. Daylight is light reflected from the sky (not direct sun light, which contains more yellow.) As daylight isn't consistent, two 150 W tungsten bulbs with a daylight filter were used initially. This proved an unsatisfactory solution, because the glass appears quite different in actual daylight. Some of the samples are photographed in sunlight, but the difference in hue between daylight and incandescent light is in reality much more obvious than it appears in the images. For incandescent light, one 300 W or two 150 W tungsten bulbs were used, and for fluorescent light, one 28 W or two 20 W "cool white" bulbs were used.

Camera and settings: A Canon 40 D digital camera was used. White balance was adjusted for Daylight for the tungsten with daylight filter, incandescent, and fluorescent light. F-stop and shutter speed was set on automatic, the ISO on 100. The camera was suspended 50 cm above the test sample. Manual focus was used. Other than the aforementioned

illumination, the room was dark.

Printed and screen representation of colour is always a problem, and seldom accurate. In the case of representing volume colour, which is transparent and 3-dimensional, in printed form, which is opaque and 2-dimensional (in effect, surface colour), it is even more difficult; accurate colour representation has not been achieved. A photographic colour chart has been included in each photo to allow visual judgement of colour accuracy, but even with the chart, accurate judgement of hue using images is in some cases impossible. It was found that the differences between daylight and incandescent light did not show well in the images. Some colours show a considerable divergence from image to actual. This means that the images in the database give a rough idea of hue, but cannot be used instead of samples. The actual glass needs to be viewed for colour judgements.

As there are not many colour names in common use, which are universally understood, names from the Wikipedia web colour chart[108] (see appendix) were used to describe hue and value in the database. The descriptions are approximates only, because often, no exact match is available, especially for small variations in hue or value.

Figure 56: Sample no. 29-10 (3% neodymium oxide, 0.0075% chromium oxide) in fluorescent light, incandescent light and daylight. W: 5 cm.

[108] "Web Colors - Wikipedia, the Free Encyclopedia", n.d., http://en.wikipedia.org/wiki/Web_colors.

4.5.6. Basic hue testing

The aim for hue testing was firstly to establish oxide amounts to achieve a desired colour value, and secondly to mix oxides to create a personal colour palette. Tests were produced employing a single colouring agent, using oxides of chromium, cobalt, copper, iron, manganese, nickel, titanium, vanadium, cerium, erbium, neodymium, and praseodymium in different percentages. Then, tests were produced using two or three colouring agents, with focus on combinations containing neodymium oxide, exploring colour change. Here, the aim was to produce glass exhibiting a strong colour change, as well as pleasant or interesting hues. Difficulties were experienced with judgement of colour density as well as subtleties of hue from the initial basic hue test with the glass adhering to the porcelain crucible; repeated larger tests had to be carried out to find a concentration that produces a transparent saturated colour. With the improved testing processes, the tests became more useful for judging both hue and colour density. Once basic guidelines on the amounts of oxides required had been established, creating colour became simple and intuitive, with only occasional unexpected results. It was found that by overlapping two samples in transmitted light, conclusions could be drawn about appearance of a mixture of the oxides contained in both samples. However, visual evaluation of light colour tones in transmitted light is difficult, as is the recording (photography) of colour. In this study, the making of samples was the key to understanding colour in glass, and evaluation was done visually using the samples themselves rather than photographs thereof.

4.6. Process development for 1000g colour melts in the kiln

For evaluation of colour density, larger tests with thick-thin variations needed to be produced. The following issues had to be addressed:

- Crucible material and making method
- Crucible size and form
- Amount of glass
- How to remove the glass from the crucible
- Test size and form

4.6.1. Crucible material and making method

Because of possible colour contamination, each crucible can only be used once; ease and speed of making as well as cost efficiency are important. Slip casting was chosen as the making method for these reasons. Initially, two materials were tested for crucibles: The material used for basic hue test crucibles, Valentine's porcelain, and fine fireclay sanitary ware casting slip supplied by Ideal Standard.

Figure 57: Slip-casting of crucibles.

All porcelain crucibles broke off at the glass line after firing, while the sanitary ware crucibles proved suitable. They slip cast easily to about 6-8mm thickness and have excellent thermal properties. These crucibles were used for larger melts, with trays made of the same material underneath to protect the kiln in case of crucible failure or glass overflow. When the supply of casting slip ran out, the material could not be obtained again, as it is not commercially available.

Trials with commercially available slips Valentines HT stoneware slip and Earthstone Q-Cast resulted in breakage of the crucibles after firing.

Figure 58: Porcelain crucibles (left) and HT Stoneware crucibles after firing.

Several slips were made from plastic clay, using crank, stoneware B17, and a crank-stoneware mixture.[109] These functioned for melting, but initially only cast to 4-6 mm thickness. Below 5 mm thickness, crucibles sometimes crack and break off just above the glass line after firing. At times the base part with the glass attached also breaks into several pieces, which makes it hard to use the glass for casting, with contamination by bits of fired clay likely. For scaling up to allow the casting of medium sized objects directly from a crucible, a way to cast thicker crank crucibles needed to be found. This was achieved by adding 5% of molochite dust. However, trials with larger crucibles holding 4.5 kg of glass frit failed: the crucibles split during melting, the glass spilled into the tray and onto the kiln shelf during both attempts. Several possible ways to solve this problem will be tested: slabbing or press moulding the crucibles using crank, or Earthstone Handbuilding White ES20. Due to time restrictions, only one possibility was tested: the press moulding of a crucible using Earthstone Handbuilding White ES20, with a wall thickness of 1 to 1.5 cm, together with a large tray, made the same way, to avoid leakage in case of crucible failure. The crucible was filled with 4.5 kg of Glasma frit[110] mixed with 0.01% cobalt oxide. Both crucible and glass

[109] The recipes can be found in Appendix VI, section C.
[110] Frit was used instead of batch to avoid overflow, because the frit does not

shattered during cooling.

Figure 59: Earthstone handbuilding white ES20 crucible with Glasma frit before (left) and after firing.

The problem may be that larger amounts of material experience more thermal shock, i.e. expansion and contraction. It is possible that the crank casting slip used for smaller crucible would work on a larger scale, if the cooling process were slowed.[111]

4.6.2. Amount of glass

Usually, when glass is melted in a furnace, the batch is added in stages. Only when the first quantity of batch is partially melted, and therefore reduced in volume, is the next quantity added. Because it is impractical to add batch to a small crucible in a kiln, the crucible had to be large enough to take the required amount of glass in a single, initial charge. Empirical testing showed that the batch can more than double in volume during the melting process. This depends mostly on the amount of batch; small amounts expand much less than larger ones. For basic tests using 150g of batch, the crucible is filled almost to the rim without overflow. Amounts of 2 to 4 kg of batch expand approximately 2 to 4 times in

increase in volume during the melting process.

[111] Conversation with Professor Dr. Rees Rawlings of the Materials department at Imperial College, London, 07/12/2010.

volume. Another possible factor is the shape of the crucible; wide and squat crucibles can hold more batch in relation to volume than tall and narrow ones. The colouring agents can be partly responsible; some, notably vanadium pentoxide, cause the batch to expand more during the melting process.

The resulting glass is about a third of the volume of the initial batch. For 1 to 1.5 kg melts in tall, cylindrical crucibles, the crucible has to hold about six times the volume of the required glass. In a crucible with a volume of 1.7 litres (when fired to 1260°C), 1300 g of pelletized batch can be melted. This results in roughly 1100 g of glass, 390 ml in volume. Two crucible sizes were used: the smaller is 19 cm high and 12 cm in diameter, the larger 21 cm tall and 11 cm in diameter at the base, widening to 15 cm diameter at the top.

For attempts to melt 4.5 kg of glass in a larger crucible, glass frit instead of batch was used to avoid overflow due to expansion of the batch during melting. This aspect of scaling up the kiln melts was successful.

Figure 60: Glass overflow.

Weight loss:

Tests have shown that the loss in weight during the melting process is

approximately 16% when melting 800 g of Glasma pelletized batch in tall crucibles (Glasma states that it is 18%). The loss of glass during the crucible casting process is approximately 21%. This means that the loss of weight from batch to finished cast is circa 33%.

4.6.3. Removing the glass from the crucible: hot casting

Initially, the following method was used to remove the glass from the crucible: The glass was melted in a crucible in a kiln, then picked up with tongs at 1120°C and cast into graphite moulds to form billets. After several trials with lower temperatures, it was found that a casting temperature of approximately 1240º was most successful. About a quarter of the glass stays in the crucible, because the temperature falls quickly, causing the viscosity to increase.

The following firing cycle was employed:

150º/h -> 600°C (4 hours)
165º/h -> 1260°C (4 hours)
hold 3h
AFAP -> 1000°C (as fast as possible)
hold 3h
AFAP -> 1240°C
hold (casting temperature)

Melting glass generates a large amount of bubbles. To force these to rise to the surface, the temperature is dropped and held at 1000°C to force small bubbles, called *seed bubbles*, to rise, before being brought back up to working temperature. This process is called *squeezing*.

4.6.4. Crucible kilncasting

When kiln casting glass into plaster/silica moulds, terracotta flowerpots can be used as a reservoir to contain the glass. The glass melts and pours through the hole in the base of the pot into the mould.

As the crucibles used for melting glass are not dissimilar from flowerpots, experiments were conducted using crucibles containing previously melted glass as reservoirs. The batch is coloured, melted in a crucible, cooled down. Then the cold crucible containing glass is turned upside down and balanced on top of a plaster/silica mould, returned to the kiln and fired. After overcoming initial difficulties, this course of action proved successful, reducing the process by one step, as well as yielding more glass, because during the casting process, most of the glass from the crucible runs into the mould, whereas when hot pouring, a larger quantity of glass remains in the crucible. Several problems were encountered with this process: Initially, the crucible was suspended too close to the mould, causing it to be encased in or adhere to the glass, which resulted in cracks in the glass due to different rates of expansion of the crucible material and the glass. This was resolved by insertion of plaster/silica and later soft firebrick spacers between the crucible and the mould (figure 61).

Figure 61: The crucibles adhere to the cast, causing the glass to crack (left). The crucible is suspended above the mould (right).

The second difficulty lies in the composition of the crucibles, as explained in section 4.6.1 p. 120 (*Crucible material and making method*).

Before the crank slip was improved by the addition of molochite dust, many crucibles cracked above the glass line after the initial firing. Props were made to allow suspending the cracked crucible above a mould, but depending on the severity of the cracks, small bits of the crucible sometimes spoiled the glass cast.

Figure 62: The broken crucible is suspended upside-down over the mould using custom-made ceramic props.

The typical firing cycle employed for melting 800g to 1000g of Glasma pelletized batch in stoneware crucibles, to be used as reservoirs for plaster-silica moulds, is as follows:

200º/h -> 600ºC (3 hours)
165º/h -> 1260ºC (4 hours)
HOLD 2 hours
END

When using Gaffer batch for the same process, the firing cycle is slightly modified to allow for a higher melting temperature:

150º/h -> 600ºC (4 hours
167.5º/h -> 1270ºC (4 hours)
HOLD 2.5 hours
END

The firing cycle employed for kiln casting the glass straight from the crucible into a mould has been modified significantly over time. The initial annealing cycle[112], adapted from the Bullseye annealing chart[113] for 40mm, proved too short due to the complicated shape with extreme thick-thin variations. The annealing cycle employed towards the end of this research is adapted from the Bullseye annealing chart for 62mm:

50ºC/hour -> 220º (4.4 hours)
HOLD 2-4 hours [to dry moulds]
50ºC/hour -> 680º (9.2 hours) [slow through the quartz inversion point]
100º/hour -> 840º (1.6 hours)
HOLD 5 hours [for casting]
AFAP[114] -> 480º
HOLD 8 hours [annealing]
2º/hour -> 430º (25 hours) [annealing]
4º/hour -> 360º (17.5 hours) [annealing]
14º/hour -> 80º (20 hours) [annealing]
END

[112] See appendix: annealing cycles
[113] "Bullseye: Education", n.d., http://www.bullseyeglass.com/education/.
[114] As fast as possible

4.7. Density testing

The purpose of density testing is the investigation of the relationship between colour and volume in a transparent body, and the development of a way to calculate the amount of colour needed to achieve desired results.

As a starting point, to get a visual impression of colour density (or volume colour), a bar of coloured glass melted in the furnace, measuring 5 cm by 5 cm in cross section, was cut into segments of incrementally increasing length. For one series, the cross-sections were polished, and for the second series, ground to an even matt finish. Light was prevented from entering through the side using black tape. The segments were then placed in sequence on a light box. In this way, the visual effect of volume colour can easily be perceived. An attempt was made to measure transmittance of light with a light meter; however, the readings were inaccurate because firstly, the light source used was not strong enough, and secondly, the light meter was not sensitive enough.

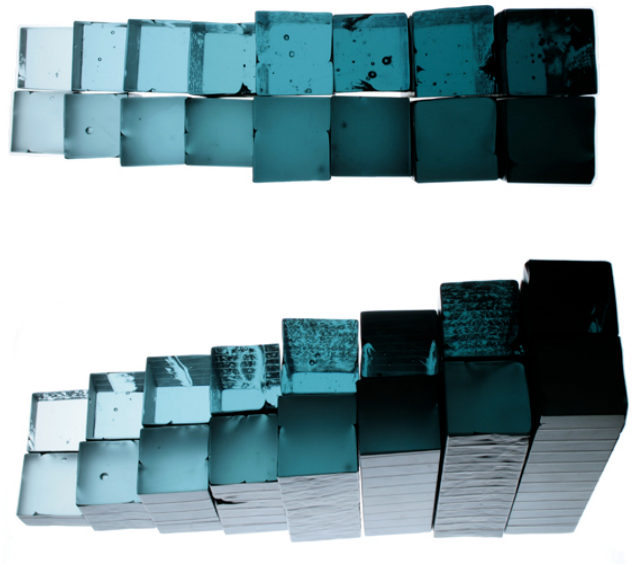

Figure 63: First attempt to visually evaluate colour density. W: 4.5 cm, L: 4.5 cm, H: variable (each element).

This experiment required a fairly large amount of glass. For the purposes

of this research, establishment of a method to make test forms from coloured glass melted in a kiln was needed.

Using 1.5 kg crucibles, bars measuring 2.5 cm x 3 cm, in different lengths, were hot-cast into graphite moulds, with the aim of producing samples to be measured in a spectrophotometer. During this process, oxide quantities needed to achieve a transparent sample were determined by iterative testing.

Links to the physics department at Imperial College were established to gain access to a spectrophotometer. After meeting Dr. Ruidong Xia, who agreed to help, a format was set up.

The following aims were established:

1. To learn if density and volume are directly related.

2. To learn if the density of glass coloured with more than one oxide can be predicted from the measurements gleaned from glass coloured with single oxides.

The first stage of the test is conducted with single colouring agents. The transmittance is measured for three samples of the same glass at different thicknesses, and plotted on a graph. Then the transmittance is measured for three samples of constant thickness, with increasing amounts of the same colouring agent, and plotted on a graph. If the graphs overlap, density and volume are directly related.

4.7.1. Method

To produce glass bars for absorption measurements, 1300 g of glass were melted in 1.5 litre crucibles, picked up with tongs from the kiln at 1240°C, and poured into pre-heated graphite bar moulds, removed from the mould after stiffening, and annealed.

Figure 64: Test bars hot-cast into graphite moulds (left) and cut and polished for spectrophotometer measurements (right). W: 2.5 cm.

The bars were then cut to required thickness and polished at both ends. Initially, 10 unpolished bars were measured, and graphs produced, to allow judgement of sample thickness. The spectrophotometer will take samples of a maximum thickness of 64mm with the guide in place, and 110mm with the guide removed. To achieve a useful reading, samples of different thicknesses are required for different colour densities: if the glass is too dark, too much light is absorbed and the resulting graph will be off the scale. If the sample is too light, almost all light is transmitted and the graph will be flat, not yielding much information.

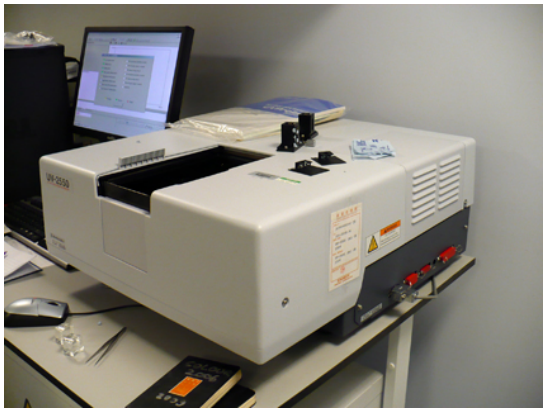

Figure 65: The spectrophotometer at Imperial College.

4.7.2. Results

Absorption measurements of 52 samples were taken and recorded with the thickness of the sample and the amount of colouring agent(s). After producing graphs in Microsoft Excel, it became obvious that every colouring agent or mixture of colouring agents produces a different absorption graph. Evaluation of the graphs proved difficult. While in some instances, it is possible to measure light absorption of a small sample and calculate absorption of this glass in different dimensions using Beer's law, the exceptions to this law include oxides of iron and nickel[115]. But even for glasses that obey Beer's law, it is impractical for practising artists with no access to scientific equipment and advice to follow this route. The determination of amounts of single oxides required to achieve certain density results for glass of different thicknesses would be a project to be pursued by a scientist, or an art/science collaboration. The determination of amounts of oxide(s) required to achieve specific densities for colours made using two or more oxides is even more complex; there are countless possibilities for colour mixing, and each mixture would require a separate spectrophotometer reading.

For this project, it was decided to discontinue this line of investigation, and instead attempt an empirical, visual method of evaluating and predicting colour density.

4.8. Test form

Development of a form for larger hue/density tests began in March 2008. The purpose of this form was to give information about colour density and hue. Practical requirements were thick-thin variation, flat planes for ease of polishing, and ease of mould making.

Prompted by the objective to understand the colour change caused by

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[115] Weyl, *Coloured Glasses*, 104, 204.

use of neodymium oxide in a visceral way, small shapes to be carried around were made. They were moulded to the inside of my hand. The top surface was polished to provide a window to the inside.

Figure 66: *Carry-on* form in incandescent light (left) and fluorescent light. W: 6.5 cm.

The forms were suitable for the purpose of being carried around for observing colour behaviour in different light conditions, and they contained thick-thin variations, but colour density was difficult to evaluate due to the amorphous shape. A more formal, systematic approach was adopted, starting with a cube. Part of the cube was removed to create thick-thin variation.

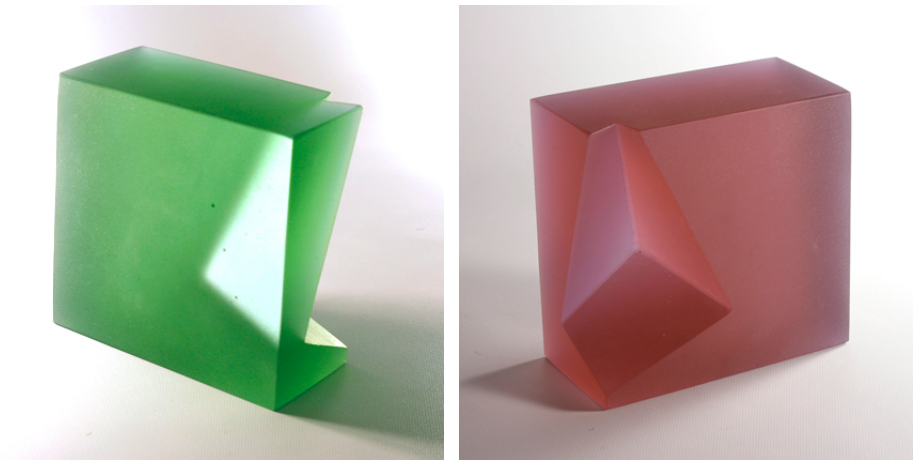

Figure 67: First model of a cube with a section removed, in fluorescent (left) and incandescent light. H: 12 cm, W: 15 cm, D: 4.5 cm.

Several preliminary models were taken through the casting process to finished test piece. A 6 cm^3 cube with an offset partial cube shaped void was chosen as a form for iterative tests. The shape has substantial thick-

thin variations and flat surfaces for ease of polishing. Silicon rubber models of three variations of the shape have been created for taking repetitive plaster/silica moulds. Part of the attraction of this form is its versatility: it can be shown in many different ways, for example stacked up or lined up. This is discussed in detail in Chapter 5 (*The Creative Work*).

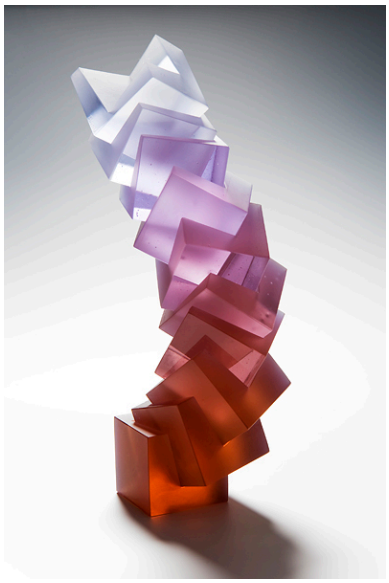

Figure 68: *Theme and Variations I* (2009) in different arrangements. Each element: 6 cm^3.

4.9. Scaling up and down

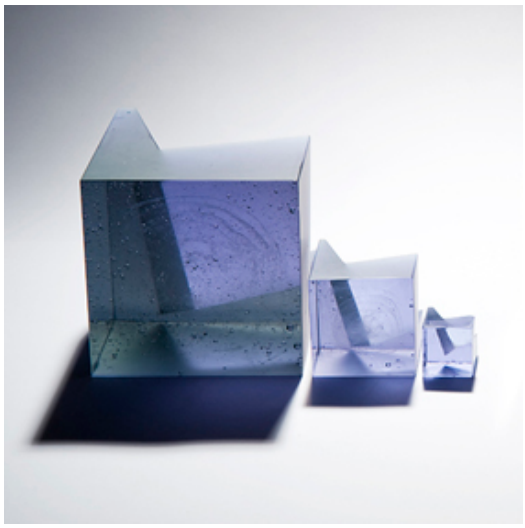

Figure 69: scaling up and down. Glass coloured with 2% neodymium and 0.005% chromium oxide. 12 cm^3, 6 cm^3, 3 cm^3. Photograph: Ester Segarra.

To understand and evaluate the impact of volume on colour density, scaling of objects was essential. The dimensions of the cube shape were doubled from 6 cm to 12 cm, and doubled again to 24 cm. Two attempts to cast a 24 cm^3 cube failed due to annealing difficulties. It was decided to scale down to 3 cm^3 instead. As time was restricted, only six of the 12 cm^3 cubes were cast. Polychromatic colours were used for all but one, and due to the nature of neodymium oxide, the colour density was too light to result in considerable changes in colour value for the size and thickness of the test objects.

4.10. Colour testing: aims and results

The aims for colour testing were twofold: firstly, the establishment of amounts or single oxides required to achieve a certain colour value, to serve as a starting point for the creation of mixed colours. In the case of transparent colours, colour value (or density) is dependent on the

thickness of the object; therefore ideally, oxide amounts should be stated for several thicknesses. In this project, 3 cm and 6 cm samples have been employed. For the oxides of cobalt, copper, chromium, nickel, red iron, and neodymium, as well as for a combination of cerium oxide and titanium dioxide in the ratio 1:1, the results below:

Oxide, glass thickness	**clear with a touch of colour**	**very light**	**light**	**medium light**	**medium**	**medium dark**	**dark**	**Very dark**
Cobalt oxide, 6cm	0.00025%	0.0005%	0.001%	0.0025%	0.005%	0.01%	0.025%	0.1%
Cobalt oxide, 3cm	0.0005%	0.001%	0.0025%	0.005%	0.01%	0.025%	0.05%	0.1%
Copper oxide, 6cm	0.01%	0.05%	0.1%	0.25%	0.5%	1%	1.5%	2%
Copper oxide, 3cm	0.025%	0.1%	0.2%	0.5%	0.8%	1.5%	2%	
Chromium oxide, 6cm	0.001%	0.005%	0.01%	0.025%	›	0.1%	0.25%	0.5%
Chromium oxide, 3cm	0.0025%	0.01%	0.02%	0.05%	0.75%	0.2%	0.5%	
Nickel oxide, 6cm	0.0025%	0.005%	0.01%	0.02%	0.03%	0.04%	0.05%	0.1%
Nickel oxide, 3cm	0.005%	0.01%	0.02%	0.035%	0.05%	0.075%	0.1%	
Red iron oxide, 6cm	0.1%	0.2%	0.3%	0.5%	1%	1.5%	2%	3%
Red iron oxide, 3cm	0.2%	0.3%	0.5%	1%	1.5%	2%	2.5%	
Neodymium oxide, 6cm	0.25%	1%	2%	3%	4%	8%	10%	15%
Neodymium oxide, 3cm	0.5%	2%	3%	4%	6%	15%		
Cerium & Titanium oxides 1:1, 3cm	1%	1.5%	2%	3%	4%	5%	6%	

Figure 70: Oxide amounts for 3 and 6 cm thickness.

Visual guidelines for single oxide amounts have been produced, in the form of line blends.

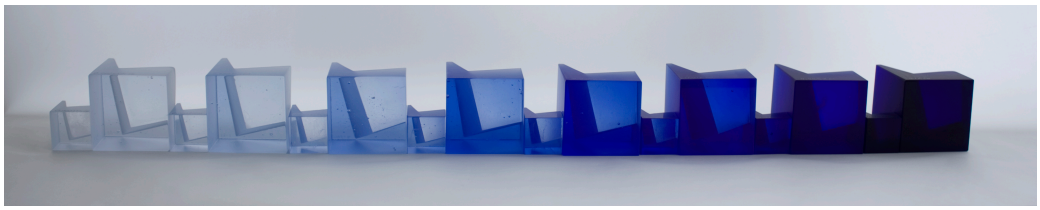

Figure 71: 3 cm^3 and 6 cm^3 cubes coloured with cobalt oxide. From left: 0.00025%, 0.0005%, 0.001%, 0.0025%, 0.005%, 0.01%, 0.025%, and 0.1%.

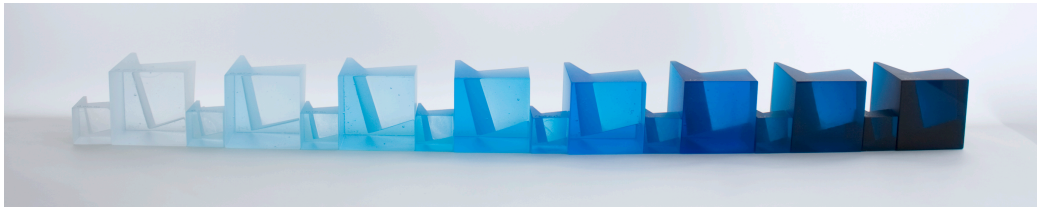

Figure 72: 3 cm^3 and 6 cm^3 cubes coloured with copper oxide. From left: 0.01%, 0.05%, 0.1%, 0.25%, 0.5%, 1%, 1.5%, and 2%.

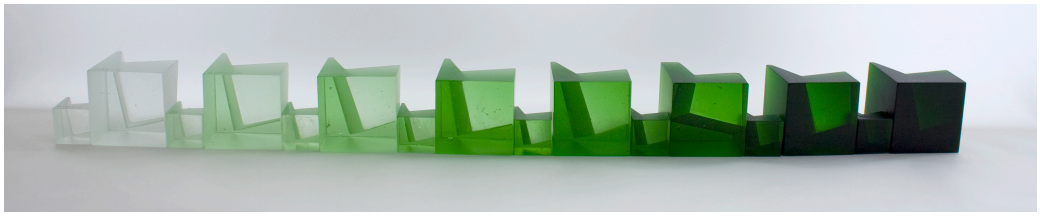

Figure 73: 3 cm^3 and 6 cm^3 cubes coloured with chromium oxide. From left: 0.001%, 0.005%, 0.01%, 0.025%, 0.05%, 0.1%, 0.25% and 0.5%.

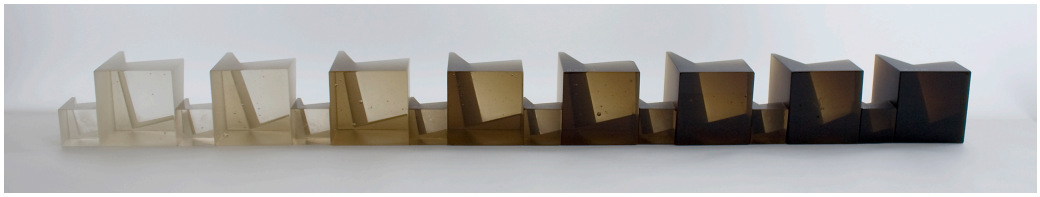

Figure 74: 3 cm^3 and 6 cm^3 cubes coloured with nickel oxide. From left: 0.0025%, 0.005%, 0.01%, 0.02%, 0.03%, 0.04%, 0.05%, and 0.1%.

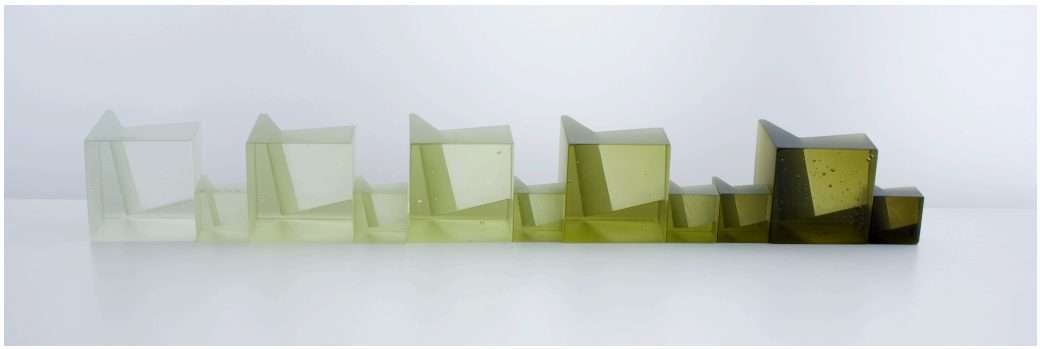

Figure 75: 3 cm^3 and 6 cm^3 cubes coloured with red iron oxide. From left: 0.1% (6cm^3 only), 0.3%, 0.5%, 1%, 1.5% (3 cm^3 only), 2% and 3% (3 cm^3 only).

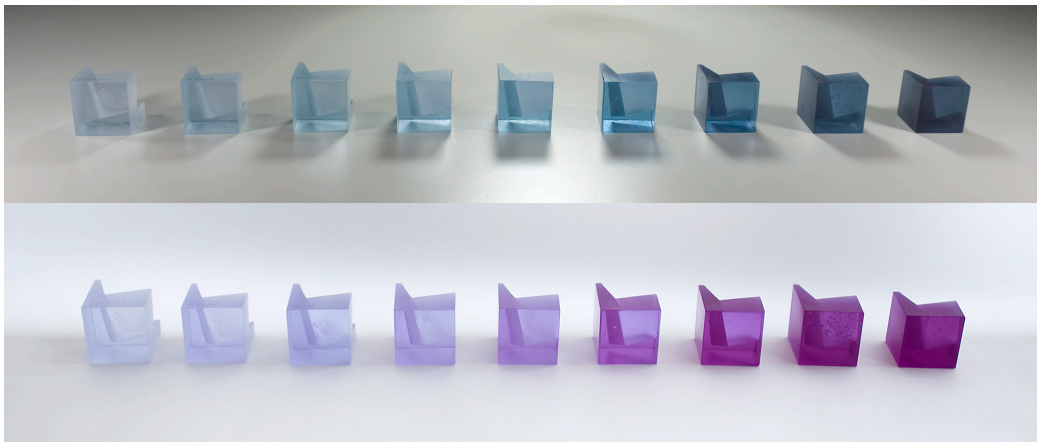

Figure 76: 3 cm^3 cubes coloured with neodymium oxide, in fluorescent light (top) and incandescent light. From left: 0.25%, 0.5%, 1%, 2%, 3%, 4%, 8%, 10& and 15%.

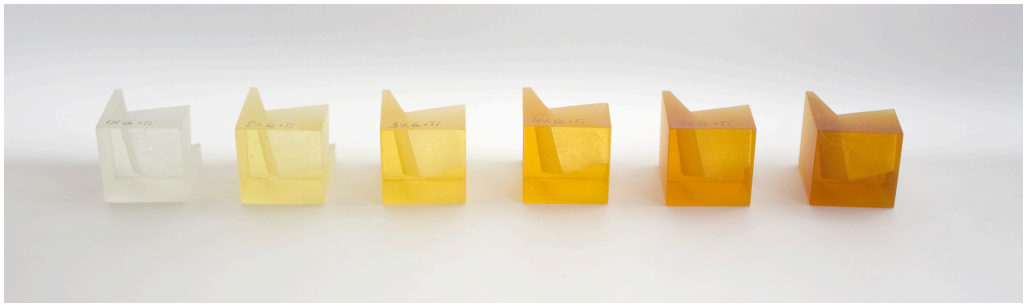

Figure 77: 3 cm^3 cubes coloured with cerium oxide and titanium dioxide in the ratio 1:1. From left: 1%, 2%, 3%, 4%, 5%, and 6% of each oxide.

Evaluation of colour density brought to attention the point where colour variation is strongest between thin and thick sections of the test form.

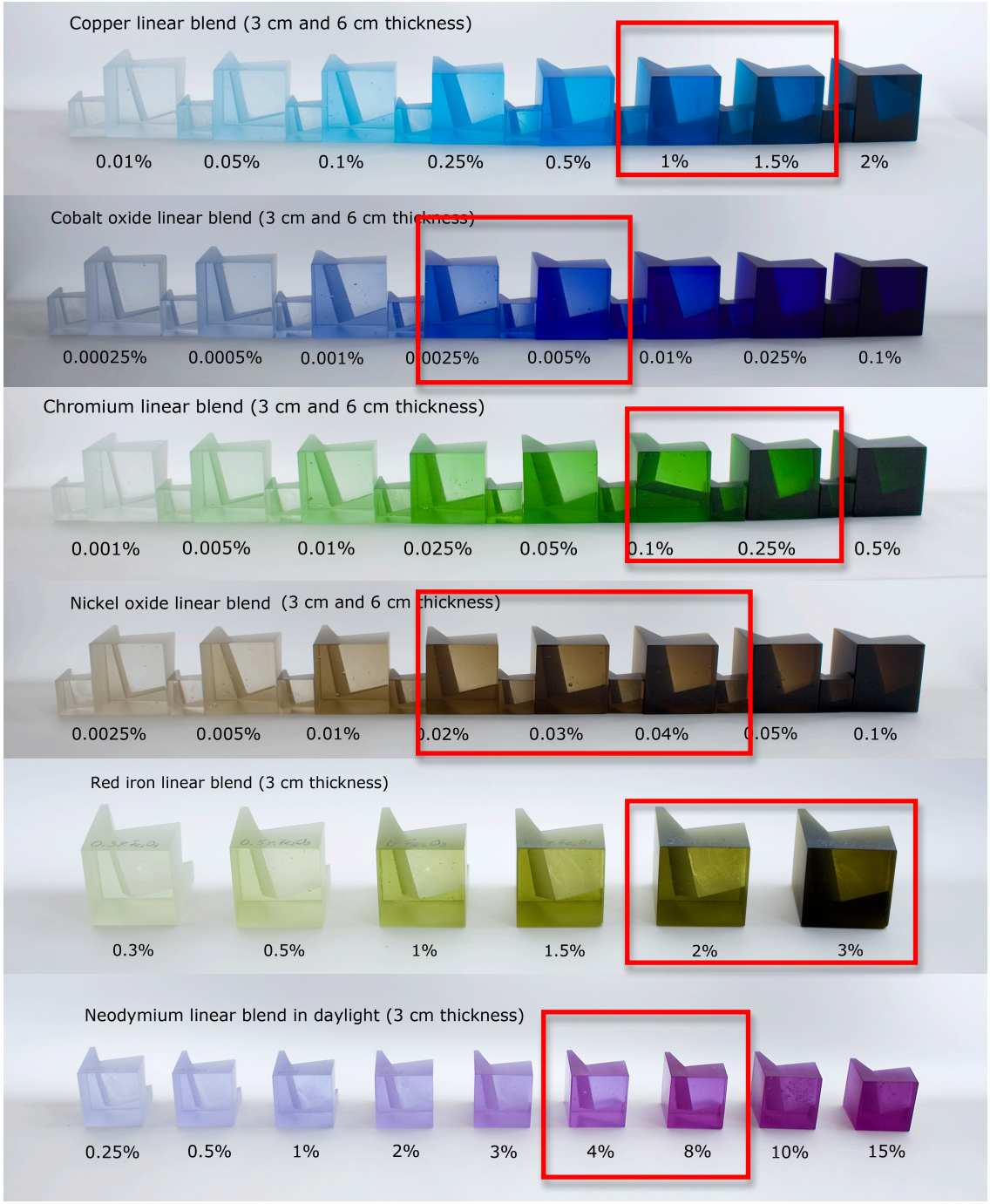

Figure 78: Density thresholds for glass of 6 cm and 3 cm thickness. Cobalt oxide: 0.005%-0.01%; copper oxide: 0.5%-1%; chromium oxide: 0.05%-0.1%; nickel oxide: 0.02%-0.04%; red iron oxide (3 cm): 2%-3% and neodymium oxide (3 cm): 4%-8%.

This territory was identified as a density threshold, or tipping point. Objects made within this area display strong changes of colour density between thick and thin areas. When scaling up, it is important to note that the colour darkens quickly with more thickness at the density threshold. However, when choosing the amount of colouring agent for scaling up from 6 cm^3 to 12 cm^3, too much caution was employed. 0.001% of cobalt oxide were chosen, and proved too far from the density threshold to darken considerably at double thickness.

While the use of neodymium oxide to create colour change fed into my personal practice, it also led to difficulties – being a weak colouring agent, neodymium oxide acts completely differently from the oxides of cobalt, copper, chrome, nickel and iron. For neodymium oxide to appear dense, percentages of 8% to 10% have to be used (more than 10% does not change the appearance significantly), whereas cobalt will appear almost black at 1%. Colour density of glass doped with neodymium oxide slowly increases between 0.25% and 10%, but stays fairly constant above 10%. In contrast, colour density of glass coloured with cobalt rapidly increases between 0.0001% and 0.05%, and colour density of glass coloured with nickel oxide increases exponentially between 0.01% and 0.1%, at a thickness between 1 cm and 6 cm. When using neodymium mixtures to explore increase of colour density with size of object, only subtle changes are visible. I realised only very late in the research that this was due to the nature of neodymium, and that any other oxide would yield different, more obvious results.

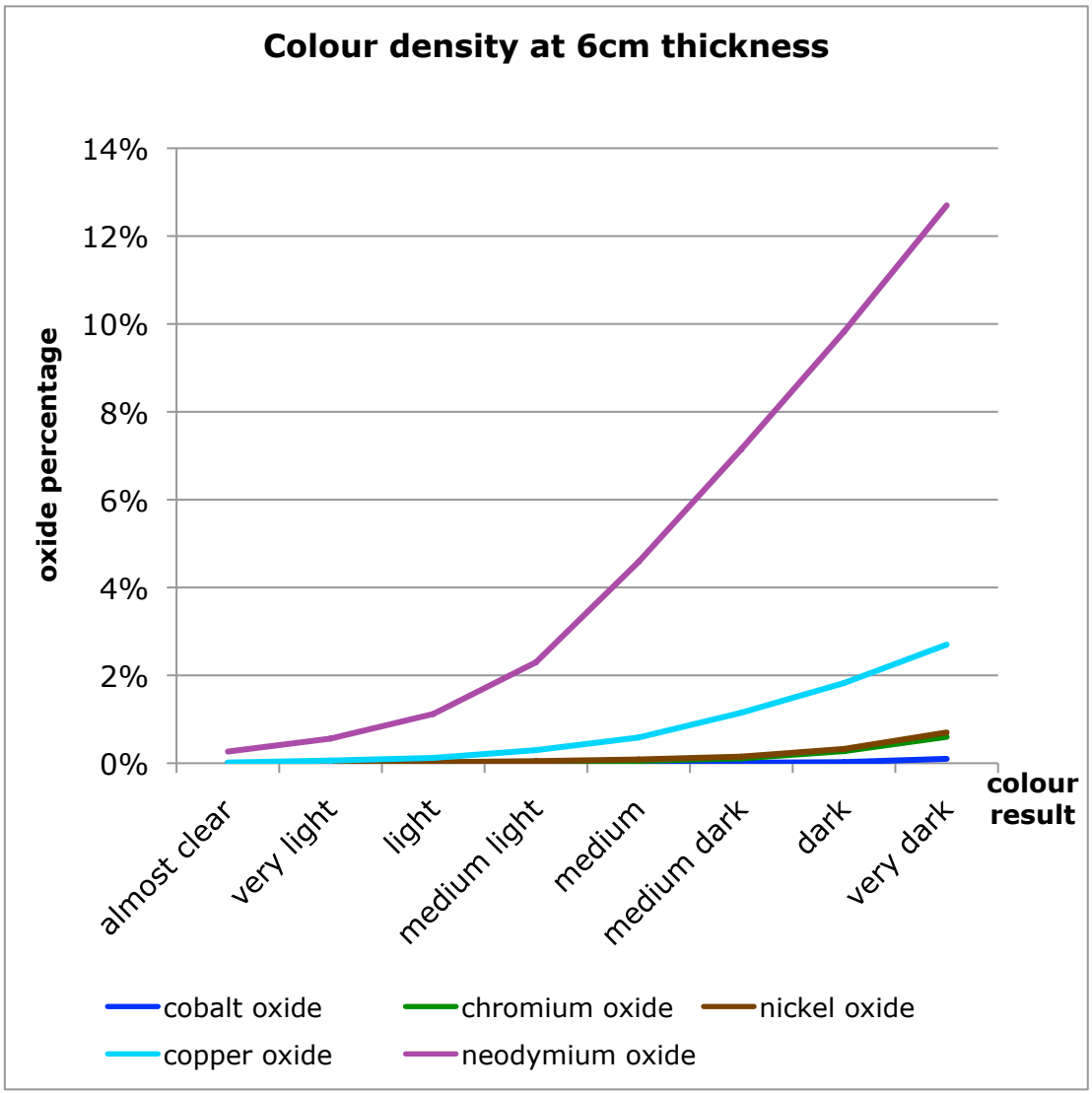

Figure 79: Illustration of amounts of colouring agent required to achieve specific values.

The second testing aim was the development of a colour palette consisting of mostly polychromatic colours, to be used for sculptural objects. The criteria used were attractiveness of hue and strength of colour change between fluorescent and incandescent illumination, as well as strength of colour change within a line blend. Developed using small hue tests followed up by larger tests, the following oxide mixtures have been chosen:

Neodymium, cerium and titanium oxides in the ratio 2:1:1, coloured in a line blend from a very pale pink-purple to a deep brown-red in

incandescent light and from very pale green to deep green-brown in fluorescent light.

Neodymium and chromium oxides in the ratio 600:1, coloured in a line blend from pale lavender to deep greenish purple in incandescent light, and from pale jade green to deep jade green in fluorescent light.

Neodymium and copper oxides in the ratio 100:1, pale purple to deep blue-purple in incandescent and pale turquoise to deep turquoise in fluorescent light.

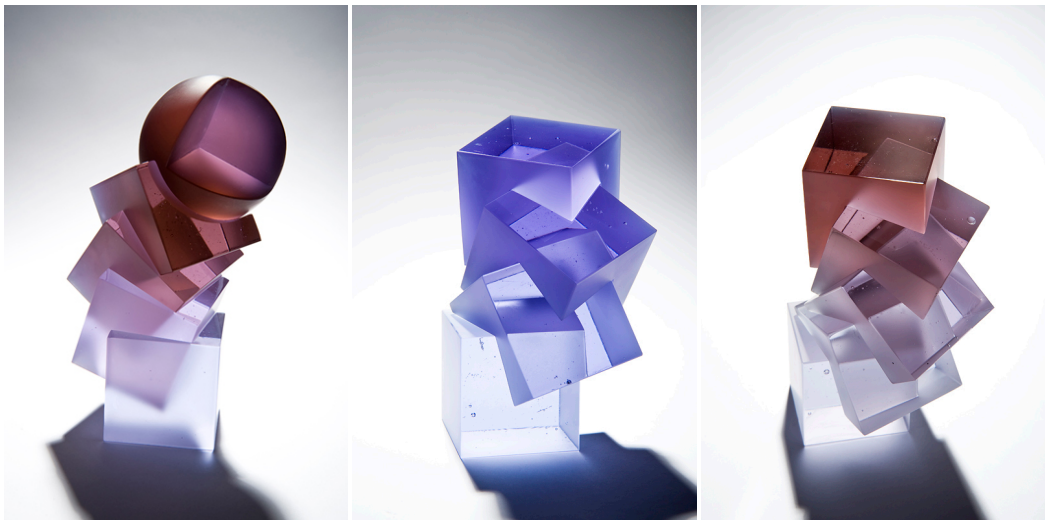

Figure 80: *Theme and Variations V (*neodymium and red iron oxides), *Theme and Variations VI (*neodymium and copper oxides) and *Theme and Variations VIII* (neodymium and nickel oxides). Each element: 6 cm^3.

Neodymium and praseodymium oxides in the ratio 5:1, pale pink to deep magenta in incandescent and pale jade green to deep green in fluorescent light.

Figure 81: *Theme and Variations III* (neodymium and praseodymium oxides) in incandescent (left) and fluorescent light. Each element is 6 cm^3.

Neodymium and nickel oxides in the ratios 200:1 and 300:1, pale pink to brown-purple in incandescent and pale grey-green-blue to deep grey-green-blue in fluorescent light.

Neodymium and red iron oxides in the ratio 10:1, very pale pink-purple to a deep brown-red pink in incandescent light and from a very pale green to deep green-brown in fluorescent light.

Using 6 cm^3 cube tests, the effect of an increase of colouring agents was explored. A single oxide or a combination of oxides was chosen, and a series of tests with incrementally increasing amounts of this constant oxide combination was produced.

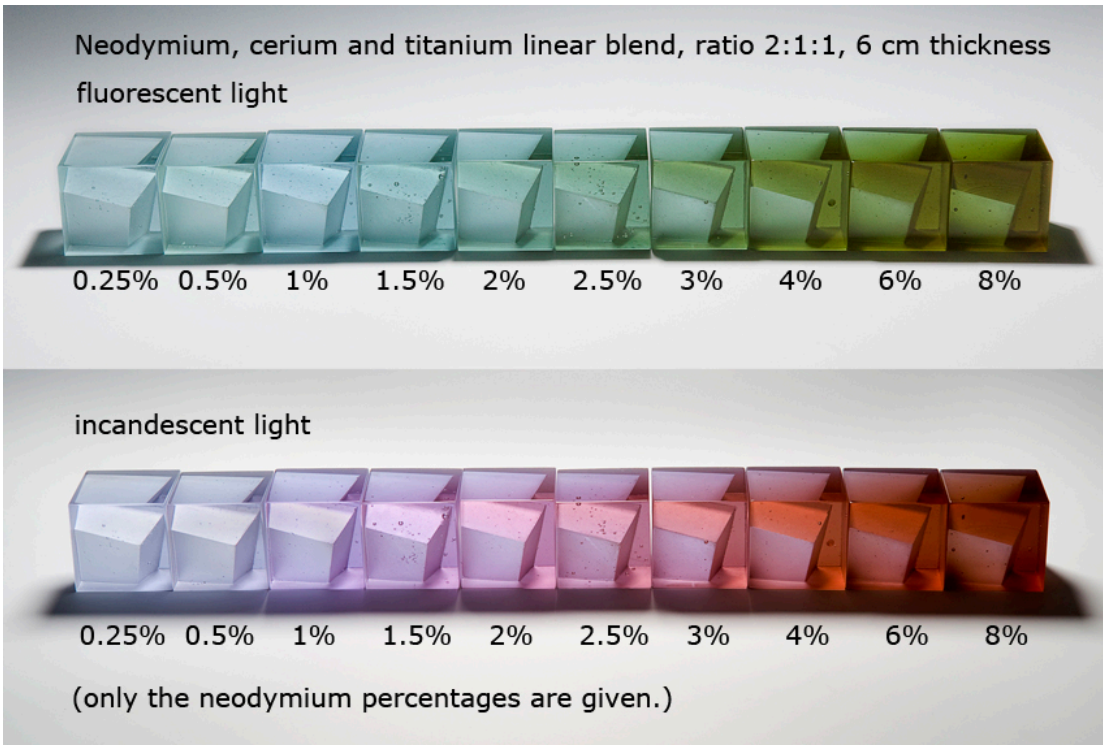

Figure 82: *Theme and Variations I* in fluorescent and incandescent light. Each element is 6 cm^3. Oxide percentages from left to right: 0.25% NdO, 0.125% CeO, 0.125% TiO^2; 0.5% NdO, 0.25% CeO, 0.25% TiO^2; 1% NdO, 0.5% CeO, 0.5% TiO^2; 1.5% NdO, 0.75% CeO, 0.75% TiO^2; 2% NdO, 1% CeO, 1% TiO^2; 2.5% NdO, 1.25% CeO, 1.25% TiO^2; 3% NdO, 1.5% CeO, 1.5% TiO^2; 4% NdO, 2% CeO, 2% TiO^2; 6% NdO, 3% CeO, 3% TiO^2; 8% NdO, 4% CeO, 4% TiO^2.

The first line blend, coloured with a combination of neodymium, cerium and titanium oxides in the ratio 2:1:1, produced an unexpected result: the colour hue as well as the colour tone change with increase of oxide amounts, as well as depending on thickness, and depending on the type of illumination. The reason is that the cerium-titanium yellow strengthens faster than the neodymium purple/blue with an increase in oxide amounts. This phenomenon is strongest in combinations of neodymium with cerium and titanium, or iron, or praseodymium, i.e. combinations of purple with yellow or yellow-green.

4.11. Conclusion

Most practitioners rely on experience and intuition for judgement of colour density. While transmission of light through glass can be measured using a spectrophotometer, this route is not practically accessible to studio artists. As each oxide has an individual colour density curve, no general formula can be applied to calculate colour density, instead the calculation for each oxide and combination of oxides is different. The most practical method remains visual evaluation, combined with background knowledge, which can be gained through experience and/or written and visual guidelines.

The understanding of volume colour and the relationship between form, colour, and light, can be furthered by visual examples, demonstrating amounts of single oxides needed to achieve a medium colour value in different thicknesses of glass. This provides a simple starting point for colouring glass. Different oxides behave differently, which means that visual examples of glass coloured with each oxide in different colour densities are required to make informed density judgements. Initially hard to define, the area where glass darkens quickly with more thickness was identified as the density threshold, or tipping point. Colour judgements have been made on a visual basis. Because of size restrictions in kiln melts, most research on volume colour has been carried out at dimensions of 3 cm^3 and 6 cm^3, with a small number of examples at 12 cm^3. This is not ideal, because for judging volume colour, an example that has the largest dimension in common with the proposed piece is best. Bullseye billets (12.5 x 25 x 1.9 cm), for example, are useful for judging colour density because they are rectangular with a large difference between the three dimensions, and because of the large size of the long dimension. My recommendation to glass companies like Bullseye and Gaffer would be to provide guidelines to their customers, showing the colour value of each colour in their range at different thicknesses.

Ideally, all samples should be viewed physically rather than as

photographs, as true reproduction of colour is always difficult, and especially problematic where volume colour is concerned. Albers writes that "film and volume colour might be considered tricks of nature"[116], and certainly the appearance of transparent colour in a volume is difficult to pin down, its hue and intensity depending on thickness, light, background and position, to name a few factors. Volume colour is, quite literally, three-dimensional, and thus harder to visualise. Guidelines can be helpful, for example if a colour is likely to contain nickel oxide, it will darken quickly with more thickness, the density threshold of glass coloured with nickel oxide being situated in a very small area (0.2% to 0.5% at 1 to 6 cm thickness). Yellow is a good colour for large castings, because yellow glass darkens slowly with more volume, and also glass coloured with neodymium oxide, for the same reason. Generally, to achieve a luminous effect in very large casts, much less colouring agent than expected is required. Because glass blowing has been the primary glass forming method since its invention in the first century AD, and more recently because studio glassblowers, having access to a furnace, are more likely to make their own colours than casters, most colour recipes are formulated for glass blowing rather than for casting. Unfortunately, blowing colours are usually too dark for casting. For a light casting glass, a small sample needs to appear almost clear to the eye. However, for a casting glass that is tailored to show thick-thin variation in colour density in a certain size object, judgement of density is much more difficult, and several attempts at producing this glass may be necessary. For this, the making of larger samples is essential. This could be achieved either through an up scaling of crucible size for kiln melts, or by melting glass in a furnace. The sample needs to be the length of the thickest part of the object and the width or height of the thinnest part. To achieve a luminous glow in a large solid glass object is much simpler; a very light colour tone can be chosen.

While still in its infancy, the process for colour tests and small colour

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[116] Albers, *Interaction of Color*, 46.

melts in a kiln allows adjustment of colour tone and opens up exciting prospects, making possible the use of multiple colours, including subtle variations of hue and value.

5. The creative work

5.1. Introduction

This chapter is divided into two parts: part one is about the creative work that instigated this research, the Movement Series of kinetic solid glass objects, exploring actual movement as well as transformation brought about by colour and light. The second part describes the Theme and Variation Series, which comprises of modular cube shaped objects that were initially conceived as colour tests, then turned into a body of work.

To clarify the terminology, *the work* is a term referring to the objects an artist or craftsperson creates. It is more explicit with the prefix *body of*, and maybe *artwork* would be a better expression as an umbrella term encompassing paintings, drawings, sculptural objects, decorative objects, and installation, but the term is also used for functional objects like cups, plates and furniture with no ambitions of being regarded as art. Therefore, *work* is a blanket term used by artists to describe a wide range of outcomes of their labour. Some artists have invented new terminology to define their work, for example Donald Judd employs the term '*specific objects*'.

One of my research aims was to produce a body of work in dialogue with this research, both testing results and pushing investigations in new directions. This final aim closes the circle that began with the starting point and reason for this investigation: a series of solid glass objects created during my MA studies at the Royal College of Art, which raised my awareness of the subject of volume colour and the problems in choosing the appropriate colour density for a given form and size of object. The aim included both the creation of forms to explore the effect of volume on colour, and the creation of colours to emphasise form and explore the interaction with light. My starting point was a vocabulary of basic geometric shapes, somewhat similar to forms used by Czech glass artists like Stanislav Libenský and Jaroslava Brychtová, Frantisek Vizner, Pavel Trnka, and Marian Karel, to investigate the interaction of form,

colour and light. The investigation was approached from two directions: colour and form.

5.2. Form

5.2.1. The Movement Series

The reason and starting point of my colour research was a body of work I called the *Movement Series*. It was developed during my MA studies at the Royal College of Art, and it was the first time I made sizable solid glass objects.

Figure 83: *Mirror Movement* 2006. H: 30cm, Ø 16cm and H: 16.5cm, Ø 33.5cm. Dan Klein & Alan J. Poole (Private Collection). Photograph: Simon Bruntnell

The basis of the *Movement Series* is a cylinder on a conical base, which allows the object to rotate around its centre. This initially unexpected motion, together with weight, solidity, and the material, glass, with all its connotations, caused a physical impact on the viewer, manifesting as a jolt of adrenalin, shock, or expectation of a collision or crash. Colour, in these objects, is not a reflection of surface light only, but is present

throughout the transparent solid, as volume colour. The hues used initially are subtle: blue-grey, brown-grey, green-grey and salmon in different shades. The colours come to life in light, preferably sunlight. In daylight, transformation can take place in a static glass object, as sun and clouds modify the quality of light. The light enters, bends, bounces off internal bubbles, rebounds off the inside of the matt exterior skin, causing an interior glow and a bright spot in the point of the conical base. The technical difficulties in achieving an appropriate colour density showed the necessity for further study and have been the starting point for my doctoral research. In a different approach to the problem of colour density, frit tints (clear glass frit mixed with small amounts of coloured glass powder) were employed. This technique, which is called frit casting or pâte de verre, renders the object semi-translucent, trapping the light in thousands of small bubbles contained within the glass. However, homogenous transparent colour, the object of this research, cannot be achieved using this process.

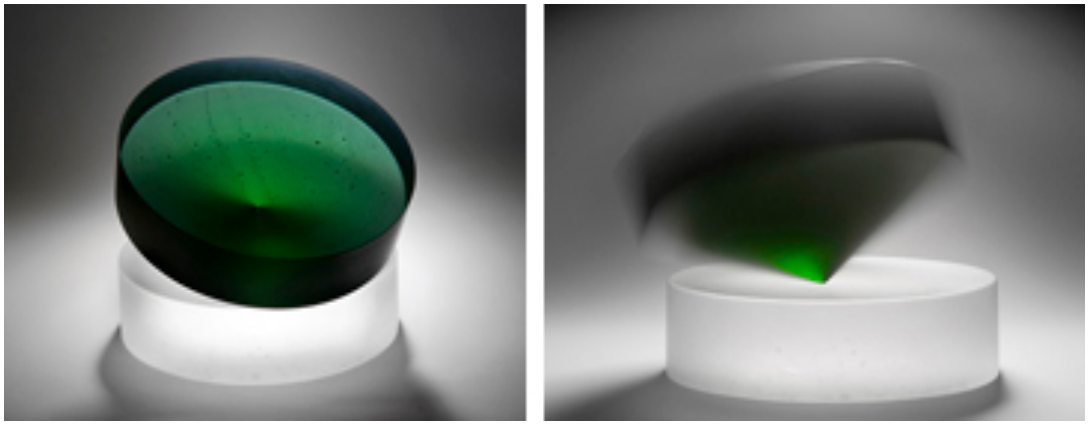

Figure 84: On Reflection IV 2009. H: 27cm, Ø 29cm. Photographs: Ester Segarra.

"Movement" is comprised of two cylinders placed next to each other, with enough space in between to allow for full rotation without contact. "Waiting" and "On Reflection" are comprised of a cylinder with a conical base sitting on top of one with a flat base. Initially, the bases had flat, polished tops. This was extremely precarious, with the top cylinder

tending to slide when set into motion. Consequently the base was given a shallow conical indentation to prevent the top cylinder sliding off.

While "Movement" and "Waiting" truly are precarious, other sculptures, for example "On Reflection I" consist of a single cylinder and invite playful touch. Due to the shorter cylindrical form, the centre of gravity is low; it would be difficult to push over. "Rocky", a tall cylinder that sits straight on a rounded base, is also grounded. Its movement is a rocking motion, with no centrifugal force to endanger the equilibrium. These objects are all solid and cylindrical in form, with a polished, flat top surface, while all other surfaces are matt. Illumination is best from above, as the light enters through the polished top.

When I embarked on my colour research, the forms changed to encompass thick-thin variation in the glass. In Passing I is the first such attempt; this cylinder has an opening in the base, which narrows towards the top.

This form is more complex, with the outside base only 1.5 cm thick, widening to 17 cm at the top. The centre of gravity is higher, which necessitated adjustment of the angle. The variation in form can be observed through the polished top, while mostly obscured by the matt surfaces. This form allows the use of darker colours, but is only the first step in a search for a form that includes colour change through thick-thin variation in form. This piece is one of very few single objects in this body of work; usually I work with pairs or groups, where objects relate, and create tension both in stillness and movement.

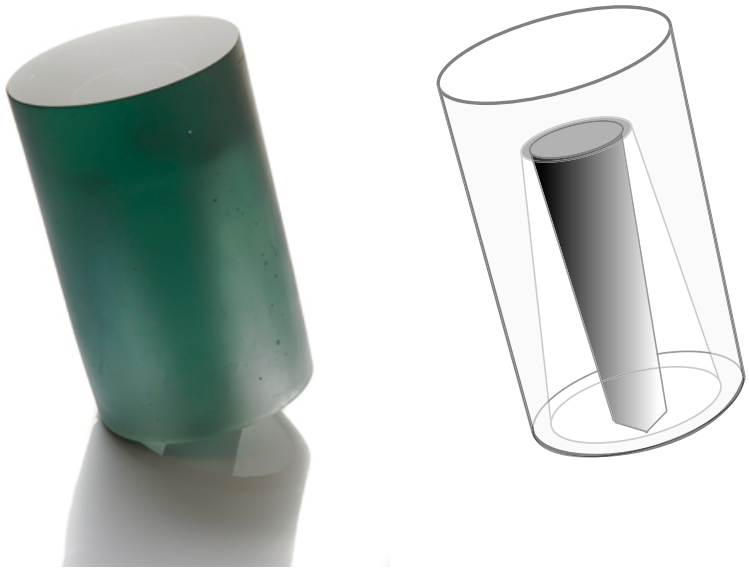

Figure 85: *In Passing I*, 2008. H: 34 cm, Ø 19 cm. Photograph: Ester Segarra.

The next step in the search for a form to investigate colour density was the *Orbit Series*, where for the first time I included scale in the investigation. This series consists of four short cylinders with cylindrical voids at different angles, varying in scale.

Figure 86: *Orbit Series* 2008 in incandescent and fluorescent light. Ø 28 cm – Ø 5.5 cm. Photograph: Ester Segarra.

It was made during a residency at the studio of the Corning Museum of

Glass. At this point I was not advanced enough in my development of processes to test colour density, I used the opportunity to do several colour melts in the studio's small colour furnace to explore colour density in polychromatic glass made using the rare earth oxides of neodymium and praseodymium. Reddish-pink in sunlight, pink in incandescent and green in fluorescent light, this work contains the potential for transformation within the glass. As I later found out, fairly high percentages of rare earth oxides are needed to achieve a medium colour density. For this reason, my initial colour melts are fairly light, and the visual difference in density between the large and small objects in the series is slight. To show an obvious difference due to scale, a darker glass would be needed. The same is the case for achieving a colour variation from thick to thin, but this could also be accomplished by a change in form; as a goblet that was made from this glass attests, if the thin part of the form is thin enough, a colour change from pink to blue can be observed in daylight.

The Orbit series is the link between my kinetic work (while not obviously kinetic, the cylinders are sitting on a curved surface, and move when touched), and my test forms, which are discussed later in this chapter.

In a return to the movement series, models were made of cylinders with conical base with different shaped voids. However, the thick thin variations in the forms were not pronounced enough to produce a discernible colour variation. The resolution came in the shape of conical forms, a long cone moving on a flat conical base, with *double cone* as the working title, later renamed *Careful*.

5.2.2. Kinetic work: the Careful Series

The Careful Series is a continuation of the Movement series. It retains the same characteristics, as well as simplicity of the form. The difference lies in the variations in thickness within the form, and the possible variations in colour caused by this. Using colours made with a combination of neodymium and chromium oxide, and neodymium and nickel oxide,

causes the colour to change hue in lights of different spectra, and also between thick and thin sections of form. The cone shape changes in thickness gradually, therefore the change in hue caused by colour density is gradual and subtle. The form ends in a sharp, thin tip, which can be seen as fragile, or as aggressive. Because of the lower centre of gravity, these forms are still stable when leaning strongly, and appear even more precarious than the cylinders of the *Movement Series*. However, the cones lack the sheer mass and weight of the cylinders, reducing the sense of physical presence. When exhibited at the Royal College of Art graduation show in 2010, three cones of slightly different sizes, angles and colours were exhibited as a group, inducing fear of a three-way collision when set into motion.

Figure 87: The *Careful Series* 2010. H: 44 cm, H: 40 cm, H: 33 cm. Photograph: Ester Segarra.

A problem presents itself regarding exhibiting the colour-changing properties of polychromatic work: how does one show, in an exhibition, that the glass can change in hue from pink to green, depending on the light? I have tried different ways of addressing this issue. As exhibition lighting is generally incandescent, a viewer-activated fluorescent lamp was trained on the polychromatic objects in the Ceramics and Glass Work in Progress Show 2008 at the Royal College of Art. The lamp became part of the piece, and as a result the exhibit somewhat resembled a science experiment. It has potential as an interactive exhibit, but more thought

needs to be put into the lamp used, as it is an integral part of the work. In the subsequent Ceramics and Glass Work in Progress Show (2009), the objects were backlit with a fluorescent lamp on a timer, switching on for 60 seconds, then off for 60 seconds. The fluorescent lamp was concealed to avoid visual distraction, and the result was that viewers were inclined to see the colour change as a property of the light rather than the glass.

For the Royal College of Art graduation Show 2010, the issue was addressed in a more complex way: a glass pendulum was created, which moved past a constantly lit fluorescent tube. The form is a cone ending in a hemisphere, with the point of the cone only two centimetres above the floor at the mid point of the pendulum's path. The pendulum idea had been in my mind for several years, and two small test pieces had been made in 2008. The glass used was a neodymium/vanadium mix made in Corning using Weyl's[117] guidelines, but unfortunately the vanadium percentage is too high for the volume of the object, resulting in the glass remaining green in daylight instead of changing to purple. The first successful pendulum was made in 2010. The glass used was a neodymium/iron mixture, which changes from light green to pink-purple. The concept works, but most visitors don't notice the colour change until it is pointed out.

5.2.3. Transformation

While transformation is always present in 3-dimensional objects, with shifting views as the spectator walks around the object, in the *Movement* Series and its continuation, it is taken further, away from the static nature of the craft object and traditional sculpture. In this work, the objects are poised precariously, evocative of movement. The weight and solidity and the expectation of a static object make the surprisingly smooth and effortless movement, once achieved, unexpected, a physical

[117] Weyl, *Coloured Glasses*.

shock. But is the unexpected still unexpected the second, third, or tenth time it happens? Certainly not, but the material's connotations of fragility and preciousness, together with mass, weight and solidity even then achieve a physical impact, a sense of angst, as soon as movement commences. "If two objects are close together they define the space in between", writes Donald Judd in *Some Aspects of Color in General and Red and Black in Particular*. Here, space is defined by the orbit of the objects as well as by the juxtaposition, and space as well as time is physically felt through movement. Originally based on the vessel, the container's void exists only metaphorically within the transparent solid of a cylinder, and vanishes altogether in the conical forms.

5.3. Context

Far from trying to compare my work directly to that of the artists discussed in this section, I am using the example of movement and colour in fine art as an inspiration and food for thought, and as a point of reference, as critical writing in the field of craft has been lacking throughout much of craft's history. Arguably, a critical discourse on contemporary craft is underdeveloped, and often focussed on the placement of craft in a wider visual field. In this section, I am discussing examples from historical sculpture and modern art, which relate to my practice.

My sculptural work shares a fundamental element with traditional sculpture from ancient Egypt to the 20th century: mass. In Egyptian Sculpture, the mass was total, with removal of as little as possible by the sculptor – in effect, a relief around mass. During the High Archaic period in Greece, space was introduced into sculpture, and during the Classical and Hellenistic periods, forms became more life-like and evocative of movement. While traditional sculpture is figurative with emphasis on the human figure, my work employs geometric form in the tradition of Brancusi, who "…provides a […] point of reference for functionless,

formal, abstract sculpture."[118] The relationship of mass and space changed in the second half of the 20th century, with artists like Alexander Calder, David Smith, Donald Judd and many contemporaries establishing new relationships between objects and their surroundings. The new sculpture was constructed rather than carved or modelled; the previous mass in space becomes enclosure or description of space. "If two objects are close together they define the space in between. […] The space between can even be more definite than the two objects which establish it; it can be a single space more than the two objects are a pair"[119], observes Judd.

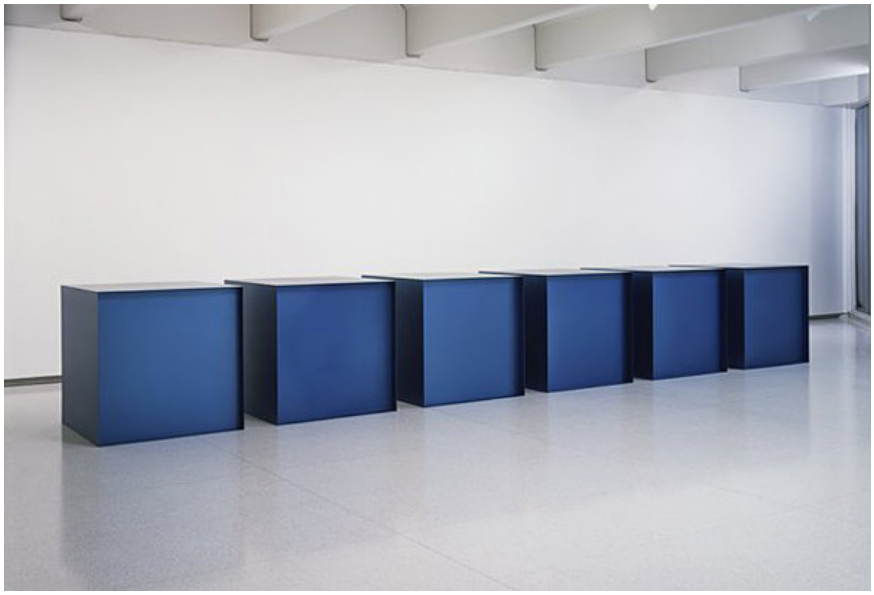

Figure 88: Donald Judd, *Untitled*, 1971, anodized aluminum, H: 122 cm, L: 122 cm each of 6 boxes. Walker Art Center, Minneapolis.

My work shares with minimalism a preference for simple geometric form, and the absence of a narrative or image. It doesn't refer to anything else. "It is what it is[…]".[120] Judd, Flavin, and Morris have called their work

[118] Glenn Adamson, *Thinking Through Craft*, English ed. (Oxford; New York: Berg, 2007), 14.
[119] Judd, "Some Aspects of Color in General and Red and Black in Particular."
[120] Michael Gibson, "The Strange Case of the Fluorescent Tube," *Art*

direct, straightforward, and simple. Judd's concern for colour, evident both in his objects and his writing, is interesting; the reason he prefers cadmium red light is that "the red, other than a grey of that value, seems to be the only colour that really makes an object sharp and defines its contours and angles."[121] His concern is how surface colour emphasises or changes form, while I am concerned with the interaction of volume colour and form. Judd and other minimalist artists worked at the forefront of fine art, creating a new tradition where the work is often fabricated or readymade, like Carl Andre's brick assembly "Equivalent VIII", and the emphasis is on manipulation of space as much as the objects. My own work is grounded in the tradition of craft, it is made by me, by hand, with one specific material, glass, exploring the material's properties, especially transparency, optical effects, and volume colour. On a very much smaller scale, my work is also about sensing the objects and the immediate space around them, which is delineated by their movement.

5.3.1. Movement

Regarding movement, one of Marcel Duchamp's "Readymades" strikes a chord: his *Bicycle Wheel* (1913), a bicycle fork and wheel screwed upside down on a kitchen stool.

International, no. 1 (Autumn 1987): 105.

[121] Judd, "Some Aspects of Color in General and Red and Black in Particular."

Figure 89: Marcel Duchamp's *Bicycle Wheel* at MOMA in New York.

While Duchamp didn't take the concept of actual movement in his work any further than his "Rotary Glass Plaques" powered by an electric motor in 1920, Alexander Calder exhibited his first "Mobiles" in 1932, and, after initially using small motors, developed his first unpowered Mobiles, which rely solely on air movement, in 1933. He continued making "Mobiles" as well as "Stabiles" throughout his career. Sartre describes Calder's Mobiles as "a small local feast, an object defined by its movement and which does not exist independently of it, a flower that fades the moment it stops, a pure play of movement just as there are pure plays of light."[122]

[122] Jean-Paul Sartre, *Alexander Calder: Mobiles, Stabiles, Constellations* (Paris: Galerie Louis Carré, 1946), http://calder.org/historicaltexts/text/13.html.

Figure 90: *Mobile* by Alexander Calder exhibited at the Royal Academy in London in 2009.

A survey of this new element in sculpture was conducted at Denise René Gallery in Paris in 1955. The exhibition "Le Movement" (The Movement)[123] featured work by Yaacov Agam, Pol Bury, Calder, Duchamp, Robert Jacobsen, Jesus-Raphael Soto, Jean Tinguely and Victor Vasarely. Vasarely's and some of Agam's works do not in themselves move, but rely on the shifting viewpoint of the observer. Vasarely's "Large Aluminium Mural panel" for the University Centre of Caracas is constructed of strips slanted in two directions, presenting three distinctly different views: from one side, head on, and from the other side. Agam's relief paintings, composed of basic geometric forms, also offer three distinct views and a number of in - between compositions.

Calder's work, after some early motorised experiments, relies solely on natural or viewer intervention, as do Agam's later work with transferable elements, Bury's wall planes and Jacobsen's steel sculptures with movable parts, while Tinguely's machines are carefully motorised to achieve continuous but irregular movement, constantly transforming. The idea of movement, be it optical, physical, or mechanical, is the basis of these works, unstable, uncertain, not fixed, and involving the factor of

[123] *Le Movement: The Movement Paris 1955* (Paris, New York, Düsseldorf: Editions Denise Rene, 1955).

time.

Other than Jacobson's, none of these works consist of mass. Only the transformability, the fact of movement, is a constant factor that my own work shares.

Peter Fischli and David Weiss' film *Der Lauf der Dinge* (*The way things go* 1986-7) documents a chain reaction of bouncing, rolling, colliding and exploding everyday objects like chairs, tyres, buckets, bottles and planks. The genre of film is not included in this survey, because it is two-dimensional and illusionary. However, I refer to this particular film, because it documents the movement of objects, where precariousness and balance change to chaos once the reaction is set into motion. Fischli and Weiss' still images of balanced household items and tools, named *Equilibres*, are photographs of transient, but nonetheless real sculptures which create an extraordinary amount of tension as one imagines what has gone before and come after the moment the image has been taken.

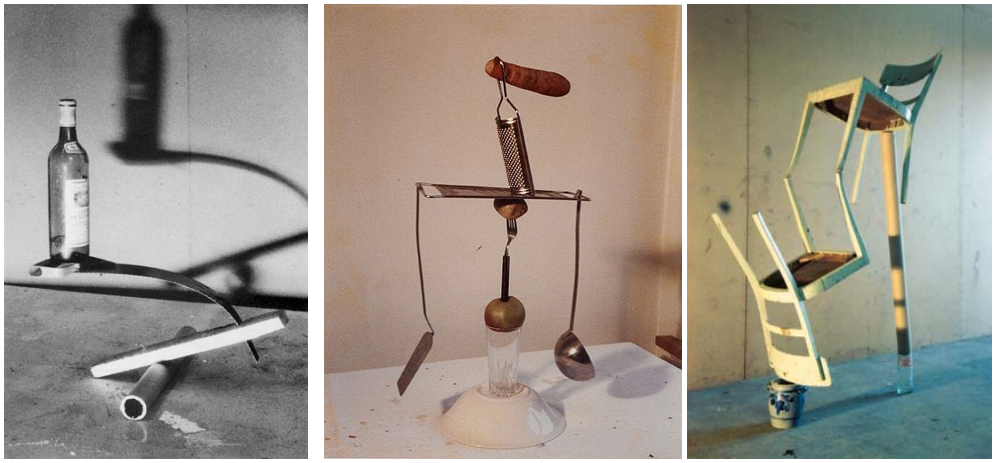

Figure 91: Peter Fischli and David Weiss, *Equilibres; The Egoist* (left), *The Maid* (middle) and *The Lawless* (right).

In Cornelia Parker's "Cold Dark Matter: An Exploded View" (1991, Tate Collection), parts of an exploded garden shed are suspended from the ceiling around a single bare light bulb, as if frozen in time. But this installation is not static: the pieces rotate slowly, casting moving shadows on the walls, turning the room into a place of contemplation, in

a marked contrast to the violent nature of the event portrayed. Danish artist Jeppe Hein exhibits interactive fountains, vibrating cubes, falling ceramic plates, moving walls and attacking flames. Curator, writer and critic Francesco Bonami calls Hein's approach "that of a designer of an amusement park, but a wicked amusement park…" The works are uncanny and explosive, subtle or obvious, always involving the (willing or unwilling) participant.

Figure 92: Jeppe Hein: *Appearing Rooms*. W: 700 cm, L: 700 cm, H: 230 cm. South Bank, London.

Another type of movement is used by James Turrell. His skyspaces, which he began in the 1970s, frame the movement of the sky for the viewer. They rely on nature for movement, and this movement is mostly subtle and slow, contemplative, but also can be fast and dramatic, with racing shadows as clouds obscure the sun, or raging storms. Turrell's material is light, both natural and artificial, and hence encompasses colour. He is interested in how we see and how we perceive. After his early cross corner projections, where he created illusions of three-

dimensional forms across the corner of a room, the object as subject was abandoned entirely to work with light in a more architectural manner. "In working with light, what is really important to me is […] to make the quality and sensation of light something really quite tactile. It has a quality seemingly intangible, yet it is physically felt, often people reach out and try to touch it."[124]

In many of Turrell's works, for example the "Wedgeworks", space is delineated by light. I am working with objects, and on a much smaller scale, the motion of these objects also delineates space, and is felt on a physical level. Glass, because of its transparency, has the potential of drawing light into itself. In polychromatic glass, transformations take place: as the quality of light changes, so does the colour of glass. Turrell's 'skyspaces' bring the light directly to the viewer, calling attention to the astounding changes, particularly at dusk and dawn, while at the same time imparting a feeling of tranquillity and otherness.

Many of Anish Kapoor's works are concerned with colour and visual perception. He uses surface colour rather than light, and frequently incorporates mirrors. "Untitled 2008", exhibited at Frieze 2008 by the Lisson Gallery, is a bowl shape with an opening of approximately 1 meter across, fixed to the wall with the centre roughly at eye height.

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[124] Craig Adcock, *James Turrell: The Art of Light and Space* (Berkeley: University of California Press, 1990), 2.

Figure 93: Anish Kapoor, *Untitled 2008*.

When stepping close, the surface curvature draws the eye in until it can find no reference as to where the concave surface is located. This creates an illusion of a haze of colour, similar to Turrell's space division pieces, where light fills a defined area, also perceived as a haze of colour. The appearance is close to volume colour, and closer to what phenomenologist David Katz calls *film colour*, colour of indefinite location. Both Kapoor's and Turrell's pieces are located at the limits of human perception and tend to cause disorientation. Kapoor's *Ishi's Light* 2003 is a large concave egg shape with a reflective maroon surface on the inside. When entering this form, it simultaneously opens up and closes in, enveloping and disorientating the viewer with appearing and disappearing reflections and echoing sound.

My work shares some concerns about movement, space and transformability with these artists, but differs in scale and placement. While modern sculpture jumped off its plinth to exist around and on the same plane as the viewer, then dematerialised into light and spatial environment, my work is object based and only slightly above domestic scale, and exhibited on plinth in white cube galleries and glass or craft exhibitions. Because my work is focused on a single material, glass, and

largely developed through making, its likely context is craft, or, to narrow it down even more, contemporary studio glass.

5.3.2. Transformability and movement in the applied arts

Applied arts is a designation encompassing material based craft disciplines, for example textiles, metalwork, woodwork, ceramics and glass. Applied artists generally know their material and use the making process as a tool in development of work. Colour and transformation are recurring themes in the applied arts. Ceramicist Martin Smith's concerns, for example, include perception of colour and form. His piece *Wavelength*, a site-specific, 17-meter long installation for an exhibition at the Tate St Ives in Cornwall in 2001, consists of ten thick-walled truncated cones made of brick clay, with platinum leaf covering the rim and the inside surface.

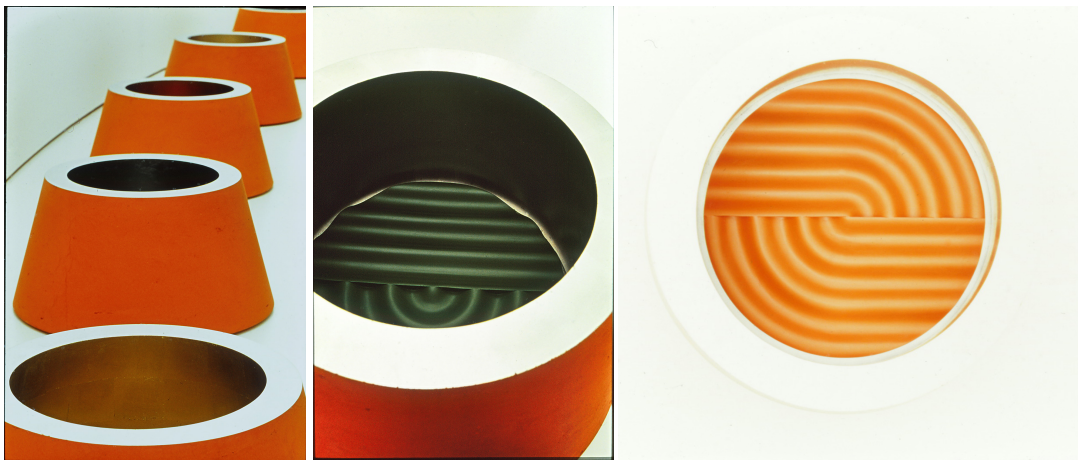

Figure 94: Martin Smith, *Wavelength*, 2001, site specific installation at Tate St Ives. Red earthenware, underglaze colour, Platinum leaf, aluminium. Individual elements H: 50 cm, Diameter: 65 cm; overall length: 10 meters.

The colours (other than the terracotta red of the brick clay body) are introduced as separate elements, coloured disks with different wave textures that sit inside the cones. When viewed from the side, colour is

only visible in reflection from the platinum-leaved inside surface. As the light changes, so does the coloured glow. On a sunny day when the tide was out, the colour tone would shift towards yellow at the site at Tate St. Ives, but when the tide was in, towards blue. The installation is the first piece of a continued exploration of the effects of reflection of colour and texture.

In his quest to explore the container, ceramicist Michael Eden is concerned with inside/outside relationships, illusion, shadows, and reflections. During his MPhil studies at the Royal College of Art (2006-2008), he produced ambiguous forms with no beginning or end. *Event Horizon* (2008) picks up colour from its surroundings, and shows distorted reflections of the environment. The shape is a torus, which Eden had CNC milled to achieve a perfect form to take a mould off.

Figure 95: Michael Eden, *Event Horizon*, 2008, Diameter: 47 cm.

Inspired by the unwoven warp threads on a loom, textile artist and designer Laura Thompson creates colour graduations using cotton and silk threads, which she encapsulates in acrylic to create three-dimensional objects. The visual effect of placing the threads varying distances apart can create the illusion of different colour values.

Figure 96: Laura Thomas, *Loose Threads* midnight blues, 2007, and *Loose Threads – Flame*, 2008. Cotton and silk encapsulated in acrylic. H: 30 cm, W: 12 cm, L: 10 cm.

Many applied artists have made objects with the capability of movement. Moving functional objects are usually whimsical commentaries on object making, inspiring and humorous, as silversmith Chris Knight's tea sets, for example. The teapot is an iconic pottery item, and in applied art often used for its connotations of home and hearth and Britishness. Ceramicist Lucy Whiting also makes tea sets, in their traditional material, but with conical bases that put teapots and cups on an angle and allow movement. Drinking tea is transformed into an adventure.

Figure 97: Lucy Whiting, *Porcelain teapot and cups,* and *diplomat porcelain teapot* (2006).

5.3.3. Transformability and movement in studio glass

Due to the fragility of the material, moving glass sculptures are rare. The optical properties of glass, on the other hand, provide ample opportunity to create transformable works.

Colin Reid, for example, makes optical glass sculptures that are transformed by a changing field of vision as the viewer walks around the work. A polished glass surface on a three-dimensional transparent object will show two distinctly different scenes, depending on the viewing angle. This phenomenon is similar to Vasarely's wall reliefs, but the cause is different: In Reid's work, the shifting views are caused by the optical properties of the glass, reflection and refraction of light.

Another way of animating glass is the inclusion of other materials, for example fluids as in RCA graduate Gaea Todd's work. Borosilicate tubes are drawn into long and elegant funnels and filled with viscous liquids like honey or molasses, evocative of body fluids, as in *Utopia*, where honey forms a puddle on the floor and attracts insects*, or Reveberations*, long, thin tubes filled with wine, curving out from white walls, which has been exhibited in the British Glass Biennale 2010. The liquid will over time drip into another tube or on the floor. The time–based and ephemeral nature places this work with installation art.

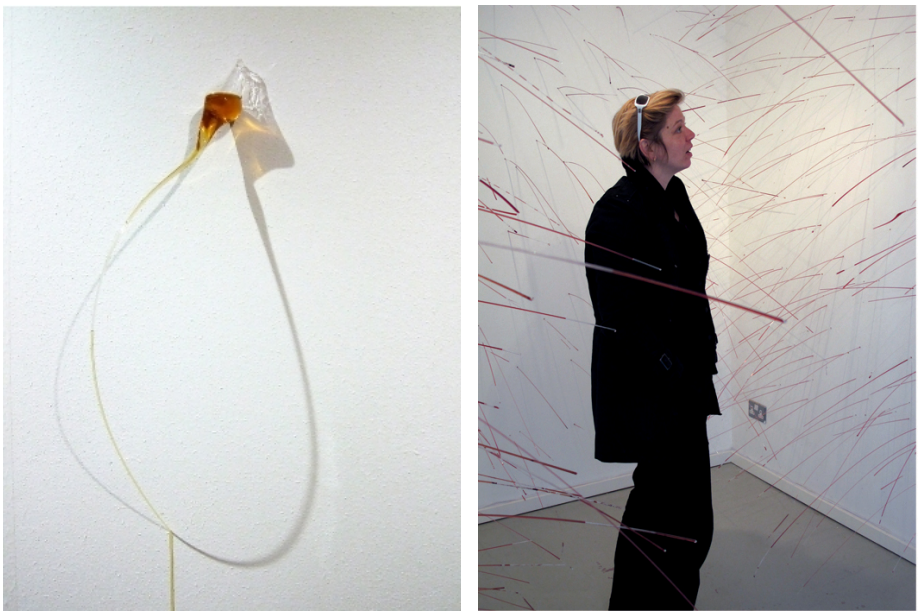

Figure 98: Gaea Todd, *Utopia* (2006) and *Reveberations* (2010). Photos by Lisa Byrne.

British artist Helen Maurer creates movement through projection, as does American artist Therese Lahaie. Maurer's glass tableaus are motionless, but projected light creates moving images on the wall. A sense of calm, combined with uneasiness, is achieved. Lahaie employs a combination of glass, steel, motors, and fabric to attain slow, repetitive movement in imitation of water and air. She projects the texture of slumped glass panes onto fabric or the wall, with either the fabric, the glass, or the light in motion.

Former printmaker Mark Zirpel creates kinetic installations using glass and multimedia objects, sometimes motorized, as in 'viewer activated greeting device, 2005', where a motion sensor activates an air pump that blows up a latex glove attached to a glass tube into a gesture of greeting. His works include social commentary, humor, time, and sound.

Figure 99: Mark Zirpel, *Viewer activated greeting device*, 2005. Latex, blown glass, air. H: 48 cm, Diameter: 9.5 cm.

Paul Marioni, one of the early American studio glass protagonists, makes surreal and figurative, often humorous cast glass objects, for example masks or body parts, that aim at carrying out a rocking motion for the longest possible time. His objects are solid mass in space, and the motion is triggered by viewer participation, as it is in my own work.

A different kind of transformation, a change through colour and light, is explored by Czech husband-and-wife team Stanislav Libenský and Jaroslava Brychtová, whose monumental sculptures demonstrate the distinctive ability of cast glass to capture light. "Time and kinetic activity are integral to their pieces. They like it best when the sculptures are seen in natural light that alters the way they look throughout the course of the day", and "Implicit in any discussion with them about their work is a sense of lively interaction between viewer and object", writes American artist and writer Robert Kehlmann.[125]

[125] Kehlmann, *The Inner Light: Sculpture by Stanislav Libenský and Jaroslava* Brychtová, 13.

5.3.3.1. Transformation through colour, light and material

Transformation can be found within the glass itself; optical movement as the viewer walks around the work, as in Reid's sculptures, and colour shifts, depending on either the thickness of the glass or the type or direction of light (i.e. daylight or fluorescent light; transmitted or reflected), as in many of Libenský and Brychtová's sculptures.

Figure 100: The Libenský/Brychtová Gallery at the Museum of Železný Brod, 2009.

As a transparent solid, glass is coloured throughout its mass, and transforms in value and hue with changing volume and changing illumination. Certain glasses vary in hue in different light conditions, for example glasses containing neodymium oxide change from purple in daylight and incandescent light to blue in fluorescent light. Different hue changes can be achieved with neodymium in combination with other oxides. Soda glasses containing Nickel, usually brown, show a purple hue in strong sunlight. Some glasses coloured with gold, silver and/or copper can appear different in transmitted and reflected light; the Lycurgus cup in the British museum is one famous example. Use of such polychromic glass adds an aspect of transformation to otherwise static objects: These

works change in response to the environment, a transformation that can be subtle or obvious, slight or considerable. As these transformations don't involve physical movement, they are easy to miss. Even strong changes don't initially register on the viewer, because they are unexpected and therefore difficult to perceive. "Perceptions are an interaction of 90% or more stored knowledge, plus sensory information gained by rules based on previous experience", writes neuropsychologist Richard L. Gregory. The result this has on a viewer seeing a glass object change colour is disbelief; unless the effect can be observed repeatedly, the viewer quickly convinces himself that his eyes have deceived him. Use of polychromic glass adds a new element to my work, a transformation independent of physical movement, a touch of the uncanny.

5.3.4. Kiln casting and colour

An approach that takes colour into account from the beginning can be found in Czech glass, with Stanislav Libenský and Jaroslava Brychtová leading the way. Most of their sculptures are made from a single glass colour, which displays subtle to striking differences in value and sometimes hue due to differences in thickness. The development process for each project began with Libensky's large-scale drawings, which show the form as well as the envisaged behaviour of the light. Brychtova then built a model, most often using clay. The artists would consult extensively with each other throughout the process. Libensky's predictions did not always prove correct, as the drawing for *Green Eye of the Pyramid* shows.

Figure 101: Stanislav Libensky, study for *Green Eye of the Pyramid*, 1993

The drawing places the darkest part of the sculpture vertically through the centre, following the thickest part of the sculpture. In the glass form, however, the central "eye" is outlined in bright light, while the darkest part is situated in the base third of the sculpture, with a darker area central in the top third, above the "eye".

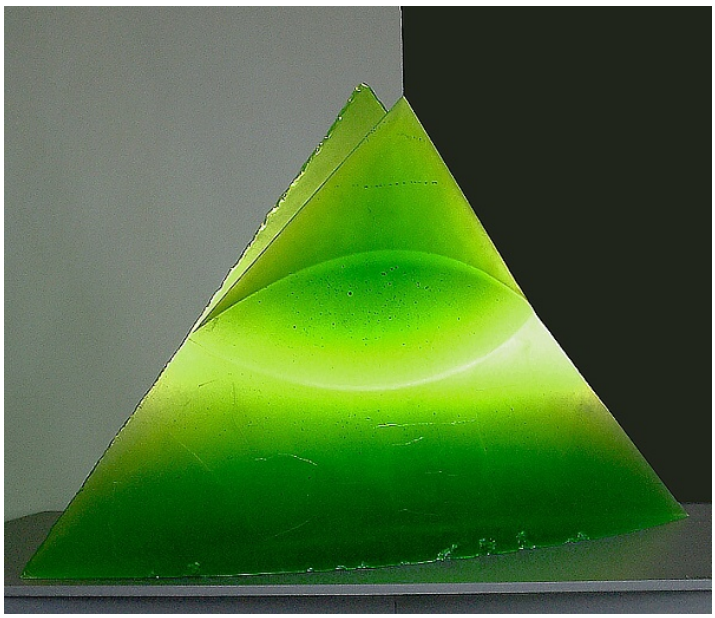

Figure 102: Stanislav Libensky and Jaroslava Brychtova, *Green Eye of the Pyramid.* H: 75 cm, W: 117 cm, D: 17 cm.

This is due to reflection and refraction of light and would have been hard to predict; the effects of illumination in the glass are certainly more dramatic than Libensky's visualisation.

Forms were often realised on different scales, starting with a very small version as a model. The smaller sculptures, for example *Red Pyramid* (1993, H: 83.4 cm, W: 119.3 cm, D: 28.2 cm) in the Corning Museum of Glass, are cast in one piece, while larger objects, for example *Imprint of an Angel I* (H: 234cm, W: 111cm, D: 43 cm) in The Museum of Fine Arts, Houston, are made in several pieces (three in this case) and assembled. Assemblages are done with great sensitivity to appear to be an integral part of the sculpture rather than a solution to a problem.

Figure 103: Libensky and Brychtova, *Imprint of an Angel I* 1998-99. H: 234

Often, variations in form are explored through a series of sculptures with the same basic shape, as in *Green Eye of The Pyramid*. The work exists in three different versions: Firstly a pyramid shape with two peaks. Secondly, a pyramid shape with the peak protruding from a square vertical base, and thirdly, the simple version, a single pyramid shape. Again, the larger versions are cast in several pieces.

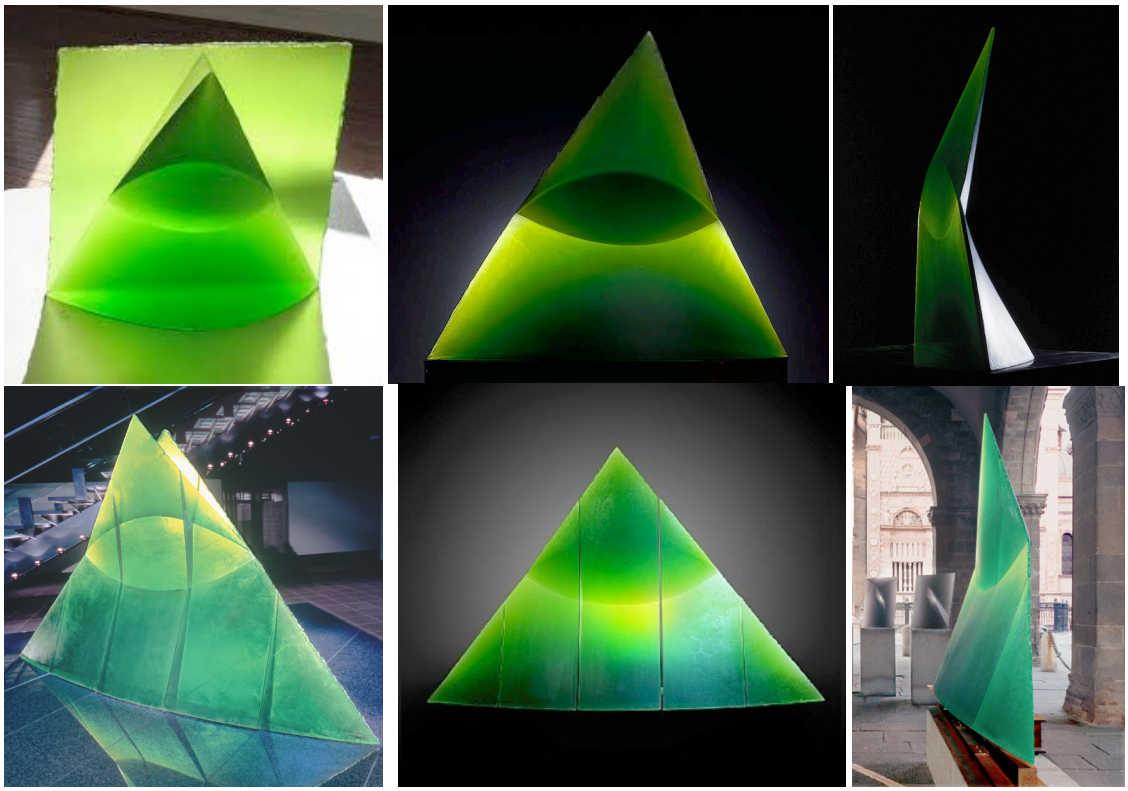

Figure 104: *The Green Eye of the Pyramid* in its different incarnations, 1993 - 2009. Sizes range from 84 x 102 cm to 167.6 x 274.4 cm.

Late in the husband and wife team's career, their colour palette changed from fairly bright hues to subdued greys, grey-blues and grey-purples and the forms became softer and more figurative.

Their forms are developed with a profound understanding of colour and light in solid glass, and colours are chosen with great care for the specific form and size of object, in fact, from the early wall reliefs to monumental 'angels', their whole body of work can be seen as an in depth investigation of the subject. This work and Libenský's teaching has led Czech glass into an understanding of the subject far ahead of the rest of the world. As in most craft-based practises, the documentation of process has been sparse, and while many articles and books have been written about Libenský and Brychtová's work, their approach to colour is difficult

to express. Phrases like "The way crystalline surface channels light into a work affects the colour saturation of nearby areas."[126], and "The sculptural and colour manipulation creates spatial colouration"[127] attempt to give words to the visual and convey the complex tacit knowledge that feeds into the work.

Another Czech artists who addresses volume colour in his work to great success is Frantisek Vizner, who cuts geometric vessel forms from solid glass blocks. Vizner's deceptively simple forms often thin out to almost nothing along the rim, while displaying a rich, deep colour in the thicker areas. He often uses very light hues, to display voids within an object, sometimes through a matt outer surface, causing the inner voids to appear diffused, almost ghostly. Vizner has created many versions of his

Figure 105: Frantisek Vizner, *Bowl with Peak*, 1986. Optical glass, cut and polished. Ø 31 cm (top left). *Bowl with Point,* 2000. Cut, sandblasted and polished Ø40 cm (top right). *Bowl,* 1998, cut, sandblasted and polished. Ø 28 cm. (bottom left) *Bowl,* 2000. cut, sandblasted and polished. Ø 42 cm (bottom right).

works, exploring differences of colour, form and surface finish.

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[126] Ibid.
[127] Ibid., 91.

Working with colour in a different way is Pavel Trnka. In his *Spectrum* series, he explores reflection and refraction, and the effects that can be obtained by overlapping coloured blocks or wedges.

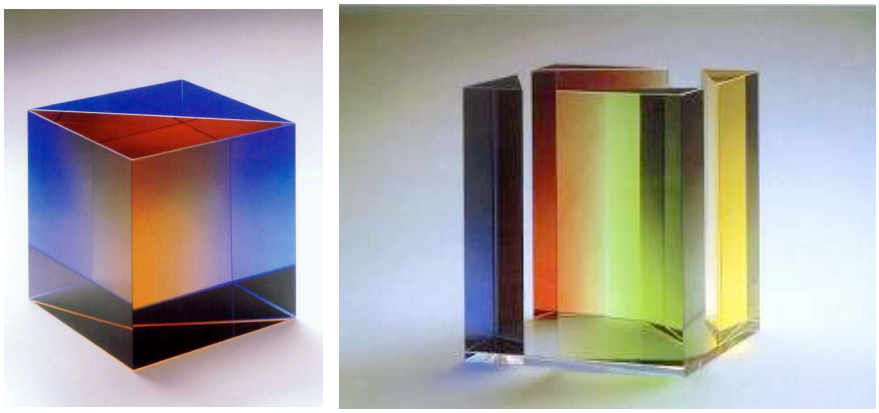


Figure 106: Pavel Trnka, *SPECTRUM*, cut polished glass, series 1985, 10 x 10 x 10 cm (l), 1990, 7.5 x 7.5 x 7.5 cm (r)

The latest generation of Czech artists has learned from these examples, and contemporary Czech cast glass, as for example in *Connections* (2009) at the exhibition hall Mánes in Prague, displays very deliberate use of colour density to emphasise shape, and great control in doing so.

Figure 107: Vladimíra Klumperová, *After Rain* (2007), H: 84 cm, L: 64 cm, D: 23 cm, and Vlastimil Beránek, *Orange One* (2005), H: 53: cm, L: 66 cm, D: 47 cm, at the Connections exhibition in Prague in 2009.

Elsewhere, it is more difficult to achieve control of colour density, and working directly with glass factories is unusual and generally expensive. To benefit from the knowledge and experience Czech glass artists have gained in the past decades, interested artists have the option of studying in the Czech republic, as for example Angela Thwaites has done in the early 1980s. There, she was introduced to Banas glass, which she has continued to use after her return to Britain.

Most glass casters work with commercially available colours, and design their forms accordingly. This is increasingly difficult when making larger forms, as available glass colours tend to be too dark. One of the few glass artists who works with a factory outside of Czech Republic is Richard Whiteley, head of the glass department at the Australian National University. Whiteley casts large-scale sculptures, generally around 10 cm thick, using mostly Bullseye glass. Because of the difficulties to source glass colours light enough to transmit enough light through his forms, Whiteley works closely with the Bullseye factory to achieve the desired colour density for some of his objects, ordering batches of Bullseye colours that have been modified to lighter colour densities. For his sculpture *Subvert* (2010, H: 29 cm, W: 60 cm, D: 10.5 cm) for example, he used a Bullseye grey, which contained half the usual amount of colouring agents, with striking results: The object shows strong hue differential between thick and thin areas, and displays strong colour changes when viewed in different light conditions.[128]

[128] Several conversations with Richard Whiteley, June 2011.

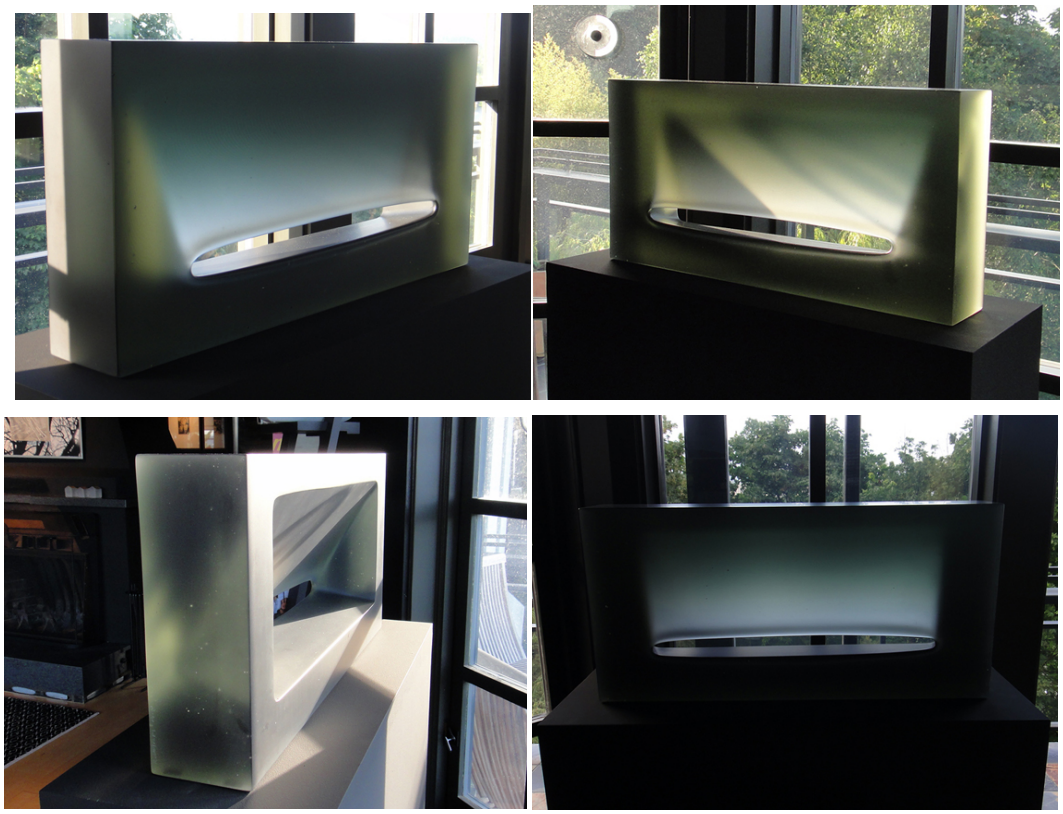


Figure 108: Richard Whiteley, Subvert 2010 in different light conditions. H: 29 cm, W: 60 cm, D: 10.5 cm.

As mentioned in the history section (2.3.14 p. 70), New Zealand glass caster Ann Robinson solved the problem of colour by working closely with Gaffer Glass in New Zealand, to produce suitable glasses for her vessels, benefitting artists all over the world.

In England and America, glass artists mostly use existing glass colours, but different ways of achieving individuality and custom colours and densities have been developed, for example the frit-tinting process, where colour powders are mixed with glass frit. American glass caster Steven Easton works extensively with this method. In his installation Shades of Sunlight, he created translucent colour blends, which are comparable to my Theme and Variations series (discussed in the next section of this chapter). Completely transparent colours are nearly impossible to achieve with this process, usually the result is a translucent to opaque appearance.

Figure 109: Steven Easton, *Shades of Sunlight*, 2009. H 21.5 cm, W 183 cm, D 58 cm.

In Britain, glass artist Bruno Romanelli has recently turned to the frit tinting process for elements in his assembled sculptures. In his early career, Romanelli mostly used optical clear glass for figurative sculptures, often cast as a negative. Around 2006, he turned to abstract geometrical vessels, which almost always incorporate colour. As a way to deal with the limited range of casting colour, he has started to use frit in his larger sculptures, introducing internal movement to the severely geometric forms, and creating bubbles, which reflect the colour of an enclosed element of the sculpture. In his latest work, he has further developed the process to include frit tinted with colour powders. This is a good example of how problems during the making (here the limited range of available glass colours) impel the artist to find different ways of working, often opening up unexpected possibilities.

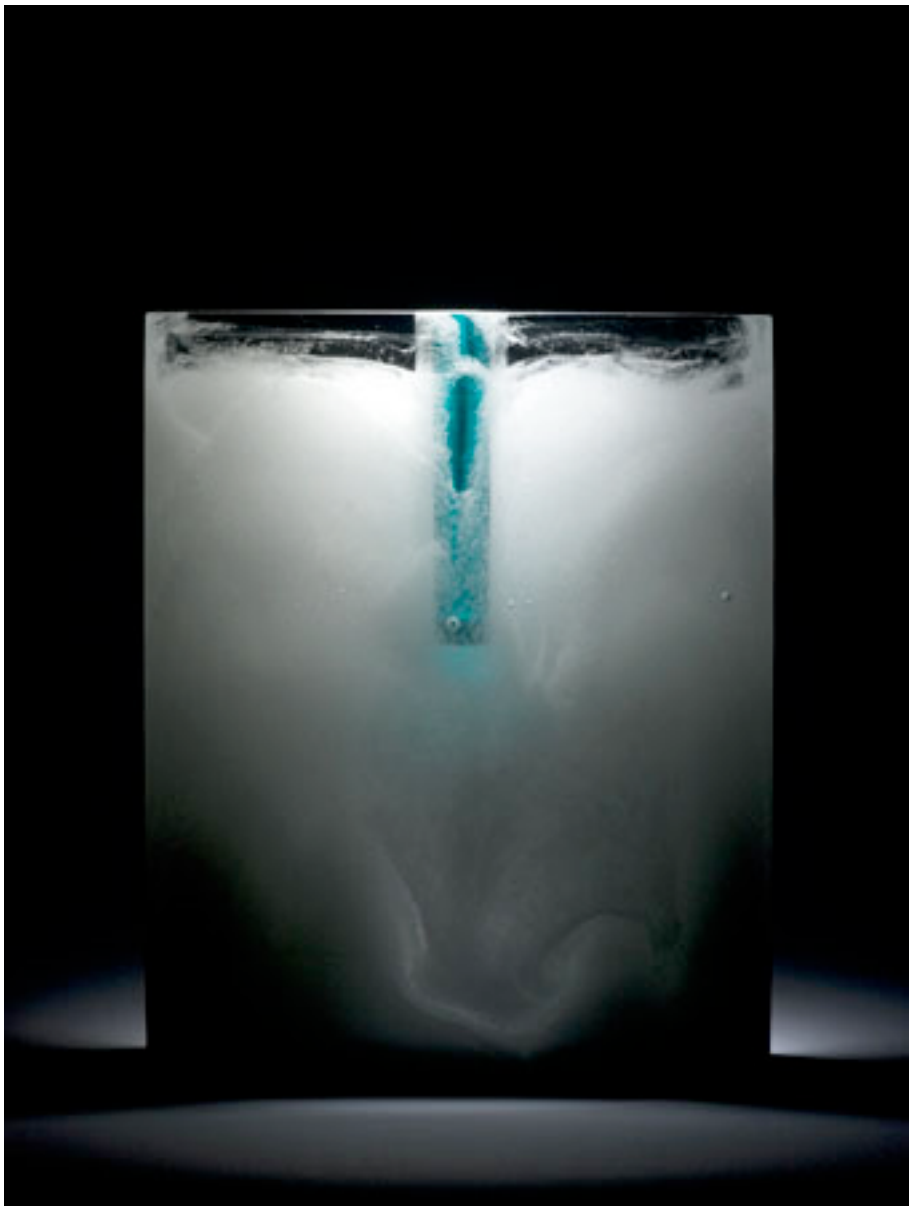


Figure 110: Bruno Romanelli, Sirius, 2010. H: 43.5 cm, W: 35 cm, D: 8 cm.

The process of frit tinting does give the artist colour control and the ability to mix colours with fairly homogenous results, but it is not suitable for producing transparent colours.

5.4. Colour

5.4.1. Starting with colour

Although the idea of colour as the basis of a body of work fed into the title of my research (Shaping Colour), I did not initially know how to go about putting this approach into action. But colour was the starting point in pursuing the research aims of developing a way to melt transparent homogenous colour in a kiln, and developing a personal palette of glass colours. As testing and making processes were developed and improved, test forms also developed and improved. The final form for medium sized tests was a cube with a slightly offset cube-shaped void, designed to show how colour density is affected in different thicknesses of glass, to be aesthetically pleasing, and to be assembled in many different ways in puzzle-like configurations. This last attribute is an almost unconscious development, a way to insure change and transformation is part of the piece.

Once the form was established, I started making a line blend using neodymium, cerium and titanium oxides in the ratio of 2:1:1. The result was unexpected: not only the colour value changes with higher oxide percentages, but also the hue. In daylight, the hue changes from a very light airy blue to a deep orange red; in fluorescent light, from a subtle, very light jade to a deeply saturated grass green. The overall effect is a subtle colour shift in many steps, and the emergence of an artwork in its own right from a series of objects initially intended as colour tests.

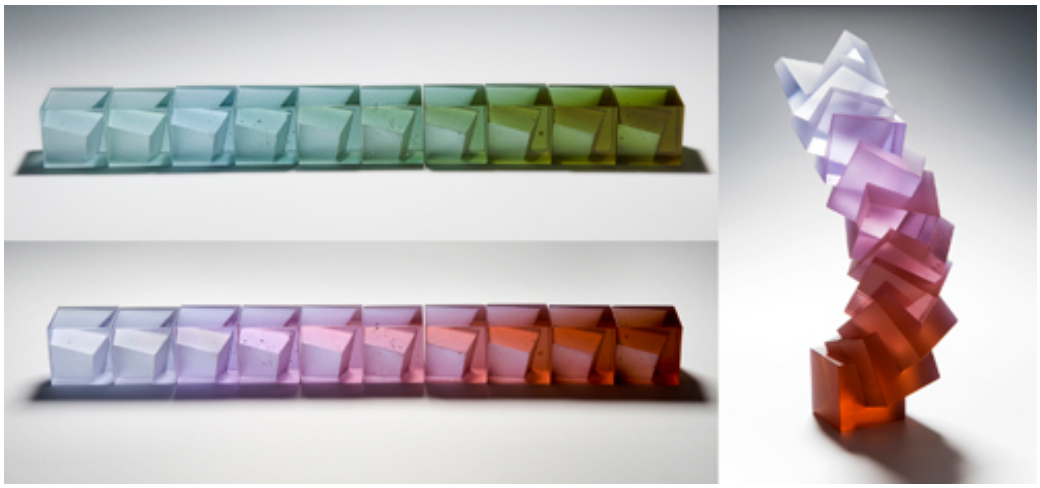


Figure 111: *Theme and Variations I* 2009 in fluorescent and incandescent light, and stacked. Each element: 6 cm^3. Photographs: Ester Segarra

Of course this is not the first time a cubic form has been used for the exploration of colour and form; it is ideal as a simple form to explore optical properties of glass and has been used as such by Libenský and Brychtová in "sphere in a cube" (1970), "cube in a sphere" (1980), and "cube in cube" (2000), all made from colourless glass[129]. Trnka, who studied under Libenský at the Academy of Applied Art in Prague, assembles wedge forms into cubes in his spectrum series, and Vizner has used coloured cube forms for his small vases, for example "green vase" (2007), a cuboid with two cylindrical voids.[130]

5.4.2. How do tests transform into creative work?

While the cube-with-void shape was referred to as *colour test* from its conception, the resulting glass objects were intriguing as single objects and carry many possibilities as puzzle-like modular assemblies. The form

[129] Milena Klasova, *Libensky/Brychtova* (Praha: Gallery, 2002).
[130] "Frantisek Vizner on Artnet", n.d., http://www.artnet.com/artist/103831/frantisek-vizner.html.

is neither straightforward, with the angled void reflecting and refracting light in odd directions, nor easy to make, as is true for most kiln casting. The simple hot cast bars initially used for density tests were designed to show hue and density for different thicknesses of glass, faster to make and requiring less energy and much less coldwork, while still providing the necessary information. On the other hand, they were not aesthetically pleasing due to their slightly amorphous form, rounded edges and broken-off trails from the casting. The bars showed colour only, without specific form. While approaching making from a colour point of view (every object starts with the melting of a crucible of coloured glass), as soon as that glass is given form, this form becomes as important to the object as the colour. The severe geometrics of the cubes allow for a much improved visual impact and exploration of optical results achieved through sharp angles and thick-thin variations. They also give a more realistic idea of colour appearance in a sculptural form with different surface treatments. In contrast, the test bars simplify visual results by minimising reflection and refraction, are easier to read, and are a means to an end only, without the possibility of transformation into work.

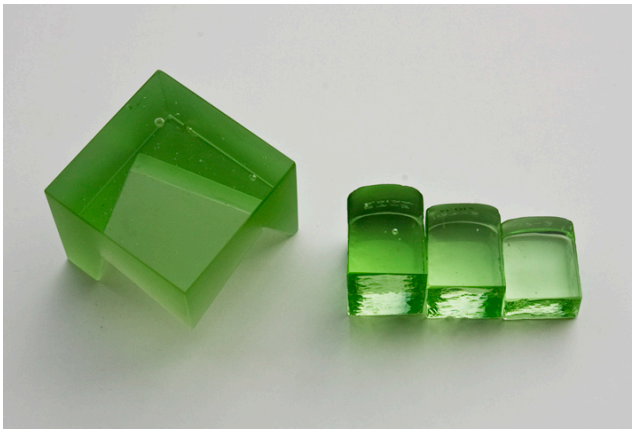


Figure 112: glass coloured with 0.01% chromium oxide. Cube: 6 cm^3. Thickness of bars: 4 cm, 3 cm and 2 cm.

The decision to use the cube form rather than bars for tests was carefully considered. Using a studio artist's approach, understanding happens on

different levels, and subjective response is as important as objective evaluation. During the making process, one thing naturally leads to another, and evaluation of the finished object or series of objects feeds back into the making, as does reading on the subject and critical writing. As inherent beauty was part of the initial requirements, the more complex form was chosen.

While the cube form stayed almost the same after its initial conception and refinement, the thinking and the designation changed over time. Making line blends turned separate objects into groups of objects. Playing with the cubes identified many different, aesthetically pleasing, intriguing and sometimes precarious assemblies. In a slow making process, the visual gaps in a line blend were progressively filled, then assigned a specific assembly, which could be a stacked high or sitting in a row, and sometimes included a full cube or a sphere. During this last step, my thinking about the objects changed, and the bestowing of a name (for example "Theme and Variations III") completed the transformation from test to work. Or maybe expansion from just "test" to "test and work" would be a better description, because the objects still function as tests as long as they remain accessible – and even if not, the records, including photos in different types of light and with a colour chart for comparison, remain. Of course there are problems with the accuracy of colour representation in a photo, and this seems to be more of a problem with three-dimensional transparent coloured glass than with most other materials. This means that a number of cube tests, especially the single oxide line blends, need to be constantly available as reference items. The designation was changed back from "work" to "tests" only, or, more practically, these objects cannot be for sale.

Why not make the same line blend in the basic test form, a smaller, much simpler form cast into ceramic moulds? These have all the usual attributes of tests: designed for one specific purpose only, easy to make, faster, with less energy consumption, needing hardly any coldwork.

The answer is simple: the processes for making basic tests were developed during the course of the research and not sufficiently refined

to provide the required information until the last year of the project, by which time the cube form had been developed and used in making line blends. From the time the process was available, basic tests were used to judge hue and value, and promising colour combinations were repeated in cube form, which provides more information. The effort in making the cubes is many times that of making the basic tests, but exactly this effort, the time expended working on each cube, provides intimate knowledge of each cube, each colour, hue and value, and the changes in different types of light. The cube tests turned into objects for contemplating and learning from.

After the first time a line blend of cubes changed designation from test to work, part of the process changed: The planning for further pieces of work was begun by choosing an arrangement, planning the hues, then making the whole piece. Then the process changed again to making a comprehensive line blend, to be arranged as and when needed.

All cubes have reference numbers, linking back to my notebooks. Even the assemblies designated as “work” keep this allusion to their origins. Variations in form were conceived through playing with models: the cut-out form, scaled up, was used as a base to display a single cube, for example. While using a single form for modular assemblies focussing on colour was exceptional in its simplicity, a full cube, a spherical shape with cube-shaped cut-out and a cube shape with spherical cut-out, allowing the sphere to be added into stacked assemblies, were added. The full cube allows for variations in stacking the modules, acting either as a base, or to finish off the assembly at the top. These extra forms originated with an investigation into the effect of form on colour appearance.

Figure 113: Objects from the *Theme and Variation* Series. Each element: 6 cm^3. Photograph: Ester Segarra

5.4.3. Polychromatic colours leading to jewellery

Polychromatic colours are one of the focal points of my research. I am interested in the aspect of change, the fact that an object can be completely transformed by an external occurrence like a change in illumination. As discussed in chapter 3 (*The Appearance of Colour in Glass*), there are different types of polychromatic glass – glass that appears a different colour in reflected and transmitted light, and glass that changes colour in different types of illumination, usually achieved by using neodymium oxide, which is the type I have experimented with. Working with polychromatic glass, for example glass coloured with neodymium and praseodymium oxides, is a challenge to perception: when working on it in the cold shop, which is illuminated by fluorescent lighting, it is green, and when taking it into daylight, it is pink, appearing as a different object. I use a goblet made of this glass; it is pink/blue (depending on thickness) by day and green by night (the house has fluorescent lighting). This glass changes colour depending on where it is and what time it is. As it is difficult to comprehend this colour change, I made small objects designed to fit in the hand to carry around with me. Green on the Underground, a different green at the station, blue in a street light, yellowish-salmon under white light emitting diodes (LED),

deep reddish pink in incandescent light, pink in daylight. But how can this change be exhibited? Stationary objects were discussed earlier in this chapter, but the obvious solution is jewellery: objects that are carried on the body.

Figure 114: *Change!* Pendant. 2.5 cm^3. Photograph: Ester Segarra

Again, tests turned into something else: the 3 cm^3 cube made for density comparison was turned, with small modifications, into a pendant. But while the colour change can be observed by others, the wearer cannot easily see it due to the location of the item. Bracelets or rings are a more practical option, so the cube form was further scaled down, and had a silver ring fitting designed to fit it. The result functions as personal adornment and also allows the wearer to observe the colour change of the glass. The wearer comes to terms with the fact that colour is a property of the light, not the object.

In conclusion, the main reasons for the transformation of these objects from test to work were intent and designation (since Duchamp, anything can become art by the simple act of designation), but the seed was in place from the conception of the cube form. The extra element that allowed this to happen was colour, subtle blends from one hue to the next, from light to dark. These works are about colour, not only in the sense of being colourful, but also from the point of view of the maker exploring the characteristics of the colouring agents. In "Theme and Variations I", the change in hue happens because the cerium-titanium

yellow strengthens faster with higher oxide percentages than the neodymium purple. This result was unexpected but welcome, and the effect became part of my colour vocabulary. This, as well as the approach of starting with colour and the development from test to work came into fruition through making in a craft tradition. During the making, while some decisions are made through thinking, certain decisions are made in an almost automatic fashion, lead by the hand. Ideas and different avenues open up by working on objects, changing something during the making, handling the object, the thinking starting from the concrete rather than the abstract. As Richard Sennett explains in *The Craftsman*, the meaning of the term 'to grasp something' is to understand a concept, but the word implies that we physically handle something.[131] All results, positive or negative, contribute to the final outcome, and sometimes the unexpected results are more important than expected results in the development of something new.

5.4.4. Development

In developing my work, the importance of material and (hand-) making cannot be overstated. The making plays an essential role. Initial ideas and concepts are a starting point, but forms and weight/balance relationships change and develop during model making. Optical effects and density are difficult to predict through tests, and can only be seen on the finished object. For me, making involves an element of experimentation: "Every experiment is a situation in which the end is unknown; it is tentative, indeterminate, something that may fail. An experiment may produce only a restatement of the obvious or yield unexpected insight. The indeterminacy of its outcome is part of its excitement", states Stanley Milgram in "*The individual in a social world"*.[132] I don't know if a form or a concept will succeed until I try it,

[131] Richard Sennett, *The Craftsman* (London: Allen Lane, 2008), 153–154.
[132] Stanley Milgram, *The Individual in a Social World : Essays and Experiments*,

and in making, it sometimes changes completely, as if taking on a life of its own.

5.5. The creative work - conclusion

Through writing about the work, I have realised how important an *actual* ability of transformation and movement is. Objects suggestive of movement, objects that seem to be waiting to spring to life, but are unable to do so, are in an entirely different category to objects capable of actual movement. The first category expresses a tension that is never resolved, whereas objects capable of movement provide a resolution, only to build up a different kind of tension. Once the unexpected has happened, it ceases to be unexpected. But the movement of pieces in the *Movement, Waiting and Careful* Series, even when expected, doesn't lose its physical impact, because the cylinders and cones can and will fall over, due to centrifugal force, when pushed too fast. Breakages at exhibitions attest to this fact. Although just above the domestic object in scale, the weight of *Movement*, at approximately 40 kg, more than half the weight of an average person, allows for a physical presence far more pronounced than the size would suggest. It is further aided by the material connotations attached to glass: preciousness and fragility. Physical intervention by the viewer manifests a jolt or shock or induces a sense of impending disaster when the piece is set in motion. Seeing the work in motion attracts attention, but even when still, the pieces are evocative of movement. When the work is motionless and accessible, it strongly appeals to the sense of play, tempting to touch - especially if forbidden. The use of polychromatic colours and line blends has added an additional aspect of transformation to the work; the colour changes in different kinds of illumination, and, in the case of line blends, a subtle transformation, from light to dark, or from one hue to another, is present within the piece.

3rd ed. (London: Pinter & Martin, 2009).

6. Conclusion

As most practice-based art and design research, this project was driven by the researcher's need for specific knowledge, in this case, the need to understand and control transparent colour in glass. As discussed in section 2.3.15, p.72, several other research projects in the past years have engaged with this issue. Sylvie Vandenhoucke's and Max Stewart's research provides solutions to colouring glass during the casting process, while Teresa Almeida's project promotes working with scientists or factories to achieve luminescent colour results. My research is bringing a part of the making process, which was traditionally sited in a factory into the artist's studio, as well as providing guidelines for colour making and evaluation. These projects were lead by the researcher's own creative work, developing processes which extend the scope of a particular area of making. In all cases, the researcher is also a maker, and the starting point of the project is practical experience, or *tacit knowledge*, defined by Peter Dormer as craft knowledge, which can be unconscious or unknown knowledge.[133] This allows the researcher to explore the issue at hand experientially, through practice as well as theory. In this manner, part of the thinking is a manual process, which can lead to unexpected avenues and results, often rooted in serendipitous accidents.

This research has made possible the creation of bespoke transparent colours in a kiln, allowing for the exploration of colour transformation, in both hue and value, in different lights and through variations in form.

Process development and improvement proved to be an extensive undertaking and has continued throughout this project. Methods have been developed to create crucibles and to melt glass for multiple small colour tests in a single firing, as well as to melt amounts of coloured glass up to 1.5 kg in a kiln. Development of the *crucible kiln casting* process allows the glass to be cast into moulds straight from the crucible

[133] Peter Dormer, *The Art of the Maker* (London: Thames and Hudson, 1994), 13–20.

in a separate firing. For casting basic colour samples, re-usable ceramic moulds have been designed to hold the glass-filled crucible suspended on top of the mould during the firing to simplify and speed up the process.

A step-by-step description of the processes developed in the course of this project, as well as guidelines for colour melting, have been added in *Appendix II: Summary of results for practical application.* This is available on www.heikebrachlow.com as a resource for artists who are interested in creating their own colours.

Over 600 colour tests have been completed, using oxides of cerium, chromium, cobalt, copper, iron, neodymium, nickel, praseodymium and titanium, singly or in various combinations, to create an evolving colour palette. Colour testing focussed on line blends from light to dark, to explore colour density, and on polychromatic colours achieved by addition of neodymium oxide.

While my interest in polychromatic colours to use for glass sculpture grew throughout the project, I realised that exploration of colour density had to begin with the basics, that colour results achieved with single oxides had to be the starting point for all further investigations. A series of line blends in two sizes, 3 cm^3 and 6 cm^3, was created using single oxides, to provide a visual starting point for hue and density judgement. As light absorption is different for each oxide or mixture of oxides, a simple formula for estimating colour density at a given thickness does not exist. Therefore visual and written guidelines mapping hue and colour density are an important resource, providing a starting point for experimentation, which will allow artists to gain the experience and knowledge to make informed colour judgements.

During the project, I have realised that there is a general need for better visual guidelines on volume colour; most glass companies provide only a single image for each colour. Density judgement could be greatly facilitated by images showing the glass at, for example, 1 cm, 5 cm, and 10 cm thickness. The same problem exists for polychromatic colours; they are mostly shown in incandescent light only. A second image in fluorescent light should be added.

This research has enabled me to develop my creative work into new directions, both in use of colour and the assembly of multiples to create larger sculptures. Test forms with thick-thin variations, which have been created to explore the interaction of colour and form, evolved into a new body of work, with simplicity of form emphasising delicate colour graduations.

The use of polychromatic colours has added an additional element of transformation to my work, transformation that doesn't depend on movement, but on light. My previous body of kinetic work has developed into conical forms highlighting colour change due to variations in thickness as well as in different lights, creating transformation on several different levels. The piece *Pendulum III* tackles the difficulties of exhibiting colour changing glass by swinging past a stationary fluorescent light under otherwise incandescent or daylight illumination, changing colour at every pass.

The experimentation with colour blends opens up exciting possibilities for the development of future work.

6.1. Areas for further research

Process development and improvement continued throughout the project and is ongoing. There is need for further work on crucible materials, for example, because occasionally pieces of loose clay contaminate the glass and sometimes, the crucibles crack across the base.

Could the processes be rendered more energy efficient? How can the melting temperature or hold time at top temperature be reduced? One possibility is the addition of glass frit to the batch; the glass industry always uses a certain percentage of waste glass to render the melt more efficient.

One of my initial questions could be taken up again: Is it possible to melt glass in a crucible and remove the glass from the crucible after cooling down, thereby eliminating one step of the basic testing process? A different approach would be adopted, building on the evidence that in ancient Egypt, friable melting crucibles were broken off the glass after cooling down, resulting in glass ingots.

At this point, only relatively small amounts of glass can be melted in a kiln, and so the crucible casting process is restricted to objects using less than 1.5 kg of glass. Further research into up scaling of crucibles to allow for melting amounts of up to 4.5 kg would considerably widen the scope of the process. Use of glass frit instead of batch would allow melts of up to 2.5 kg in standard crucibles, but this needs testing to ensure that the crucibles can hold larger amounts of glass without cracking. Slow cooling may be necessary to reduce thermal shock. The colour research has been restricted to solution colours, using a limited range of oxides; widening the range of oxides and experimenting with colloidal colours can extend this.

The most interesting area of further research lies in the further exploration of volume colour. Relatively early in my research it became clear that the colour density curve of each oxide is unique, and a single formula for calculating the amount of oxide needed to achieve a certain

result does not exist. Only in the last months did I identify the territory within a range of transparent colours that I am interested in, the density threshold, or tipping point, where the colour darkens quickly with relatively small changes in volume. During this project, I have gained the necessary experience, or tacit knowledge, to start an informed investigation of volume colour, an exploration of changing colour appearance due to form, using glass colour at its density threshold.

Appendices

Appendix I: Plates

A gallery of images, showcasing the work that was exhibited at the Royal College of Art Graduation Show, *The Show One*, 2010. All photos are by Ester Segarra.

Plate 1: *Careful I, III* and *IV* in incandescent light. Ø 15 cm, H 33 cm (l), 40 cm (m), 44 cm (r).

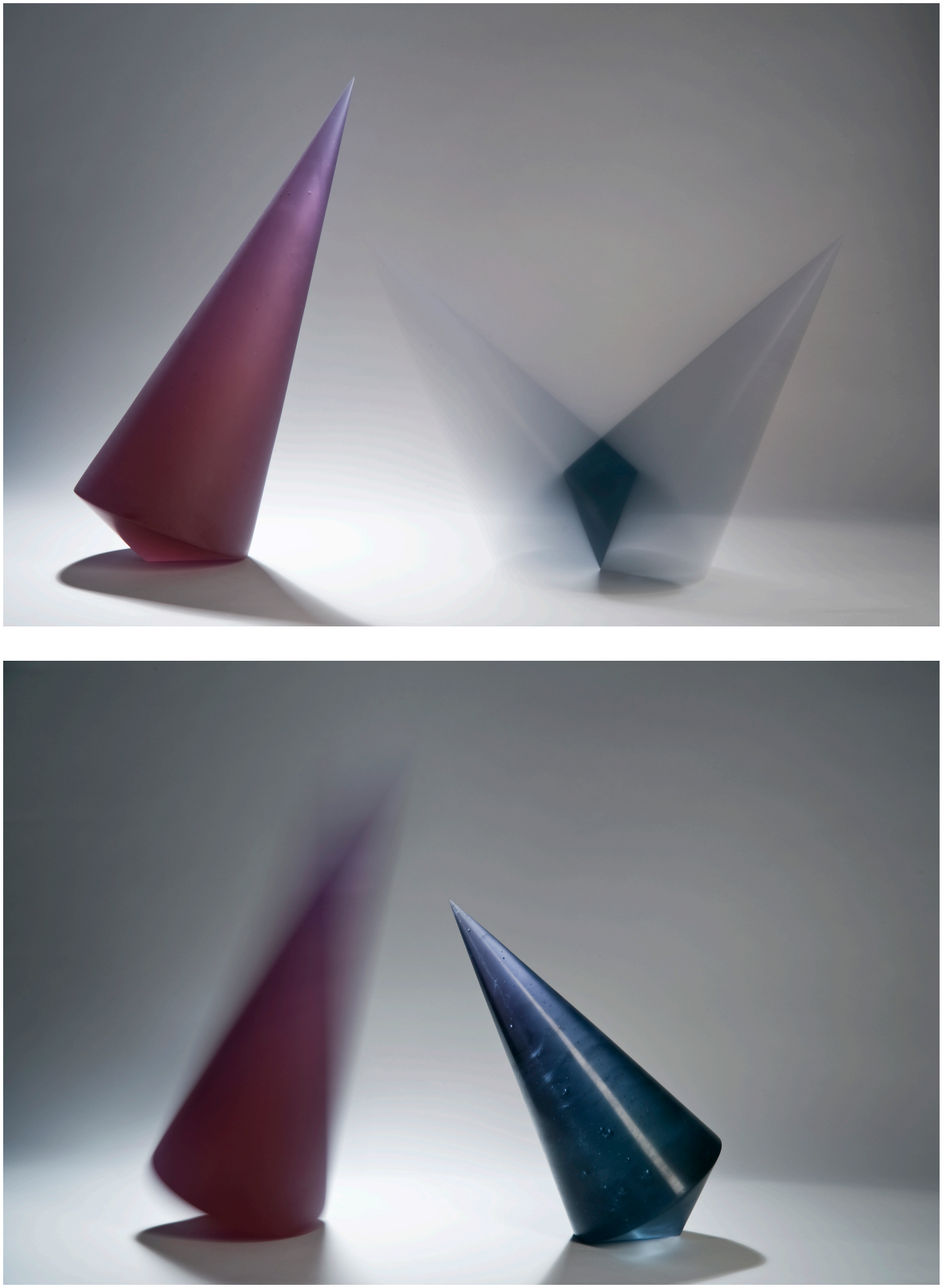


Plate 2: *Careful I* and *IV* in incandescent light. H: 33 cm, 44 cm, Ø 15 cm

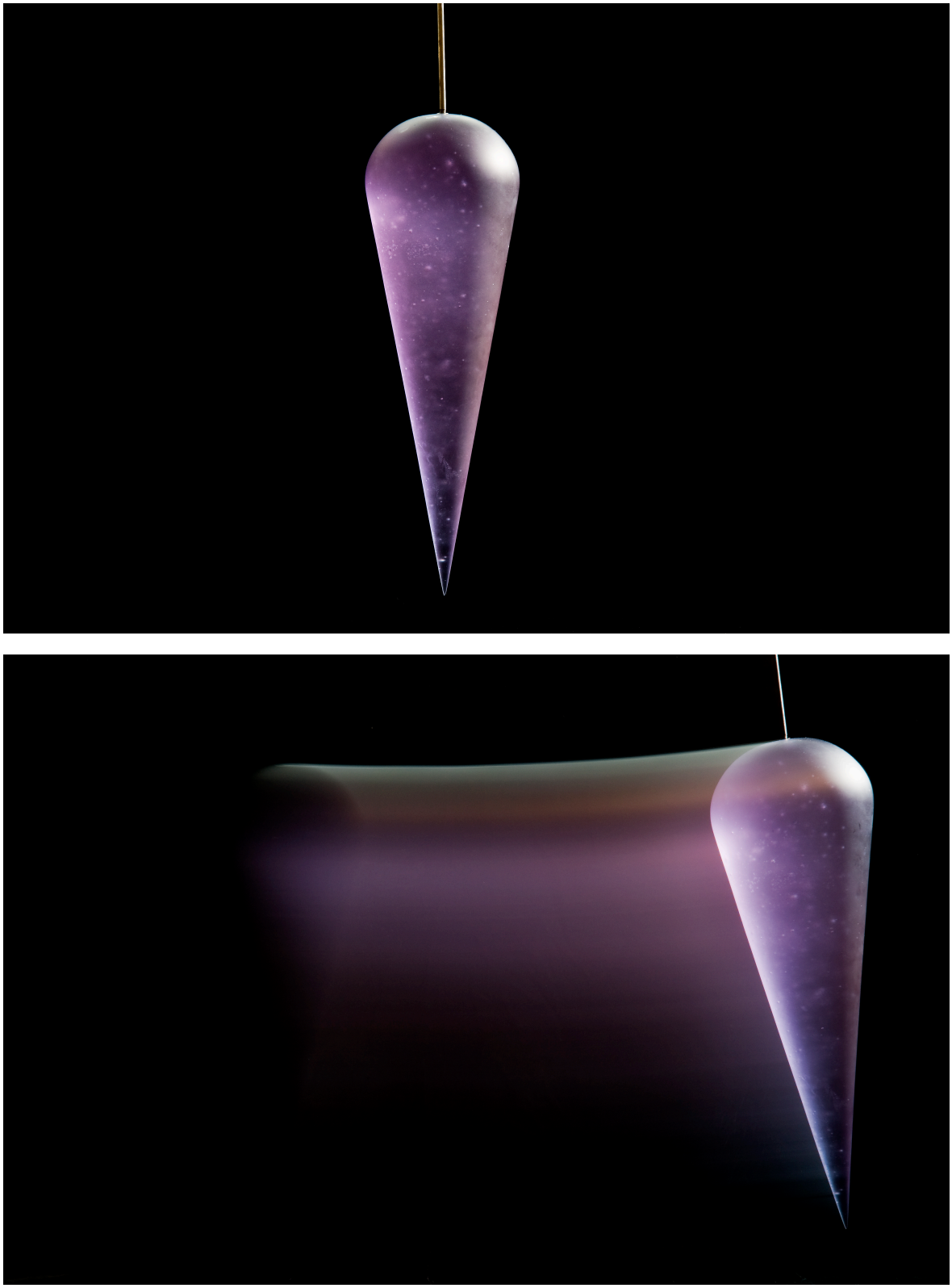


Plate 3: *Pendulum III* in incandescent light. H: 44 cm, Ø 15 cm.

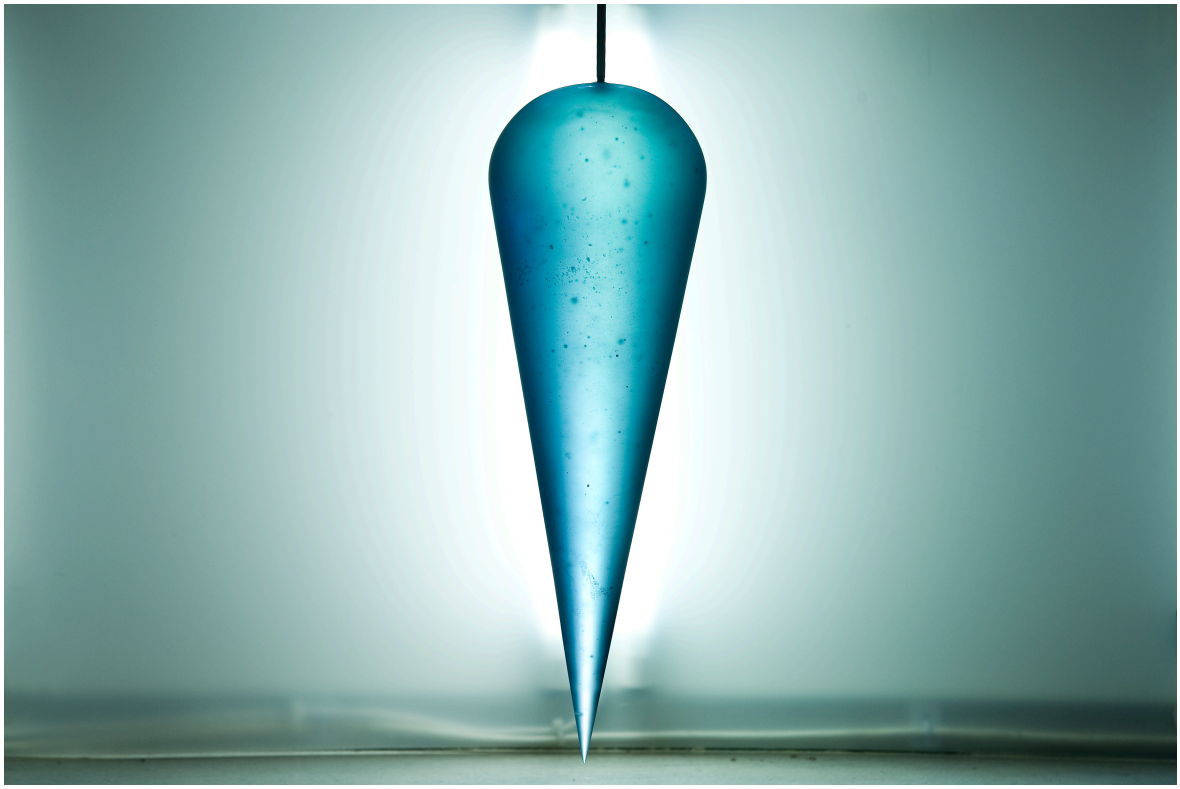


Plate 4: *Pendulum III* in fluorescent light. H: 44 cm, Ø 15 cm.

Plate 5: *Theme and Variations I* in fluorescent (top) and incandescent light. Each element: 6 cm^3.

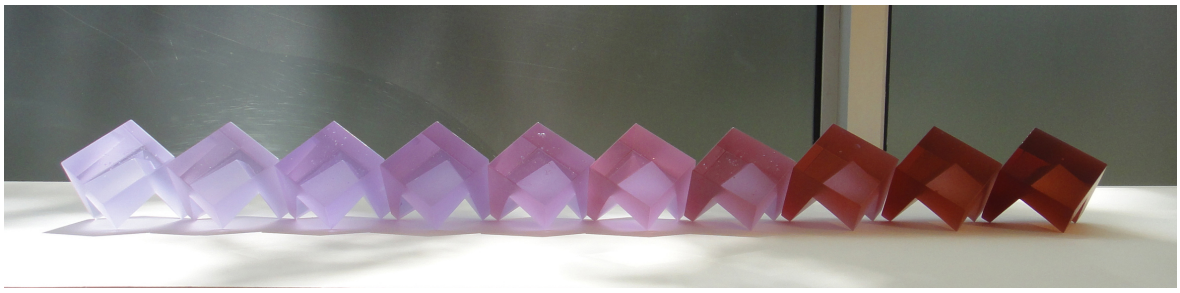


Plate 6: *Theme and Variations I* in incandescent light, as exhibited at the Royal College of Art Graduation Show 2010. Each element: 6 cm^3.

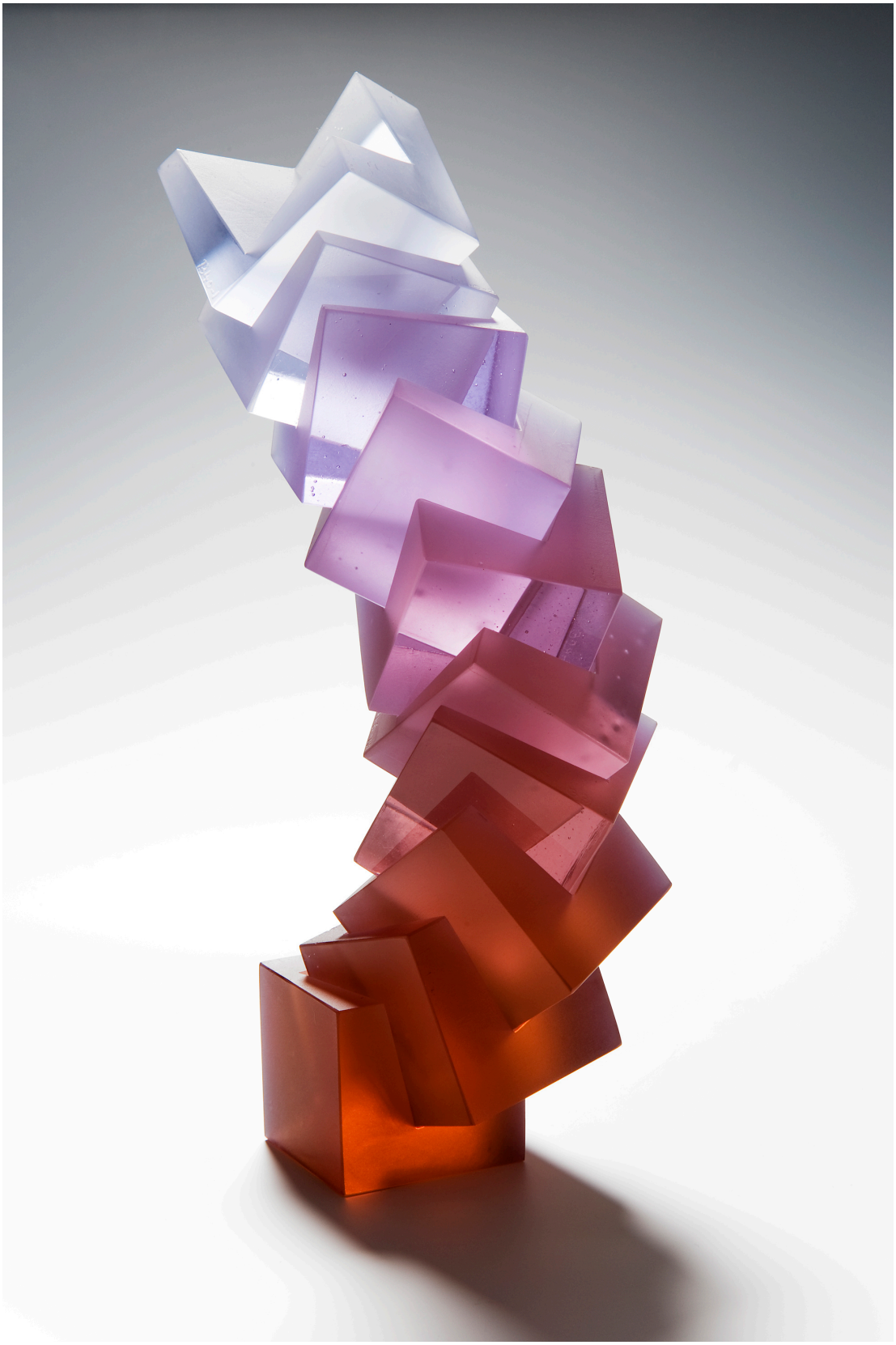


Plate 7: *Theme and Variations I* in incandescent light. Each element: 6 cm^3.

Plate 8: *Theme and Variations III* in incandescent (top) and fluorescent light. Each element: 6 cm^3.

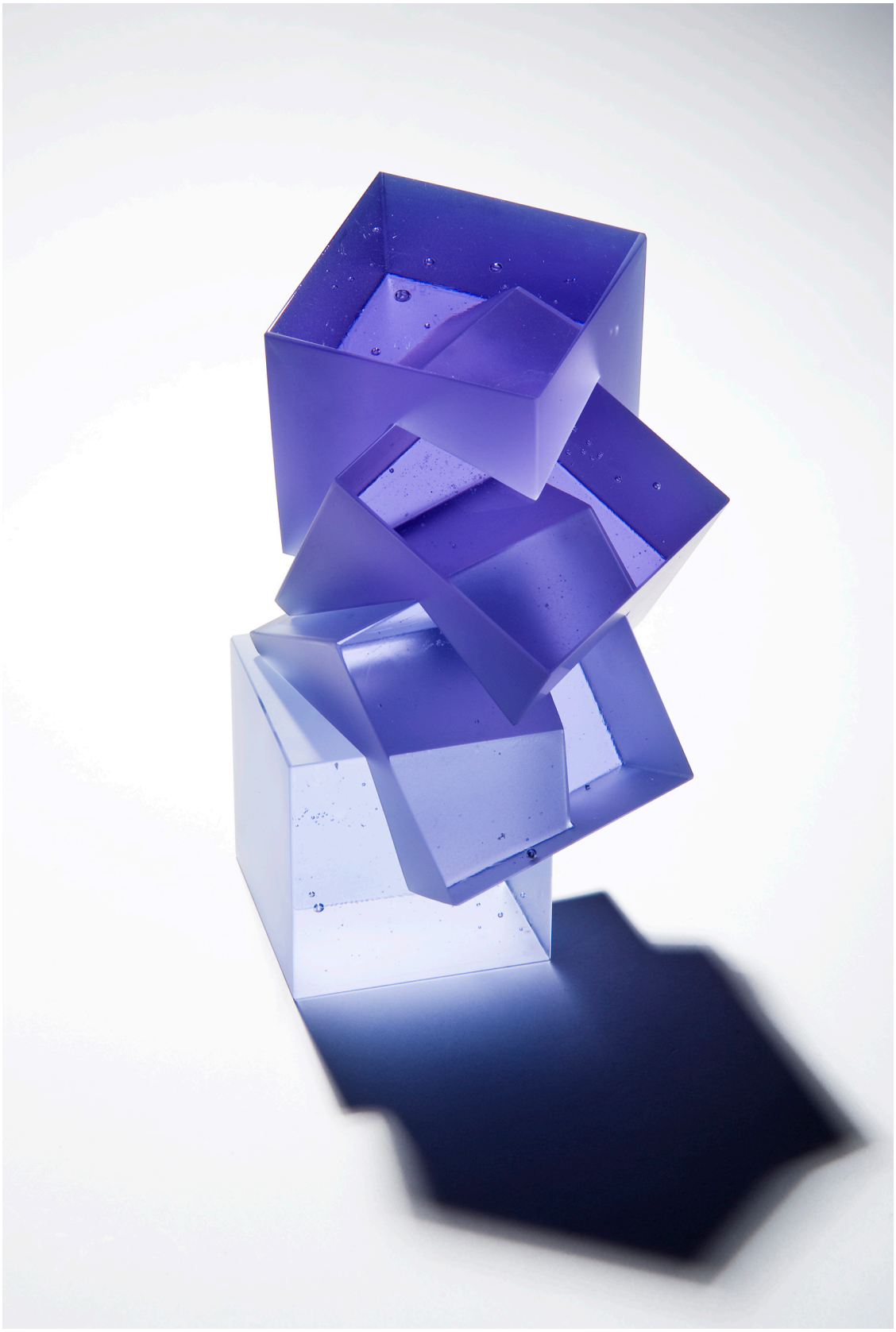


Plate 9: *Theme and Variations VI* in incandescent light. Each element: 6 cm^3.

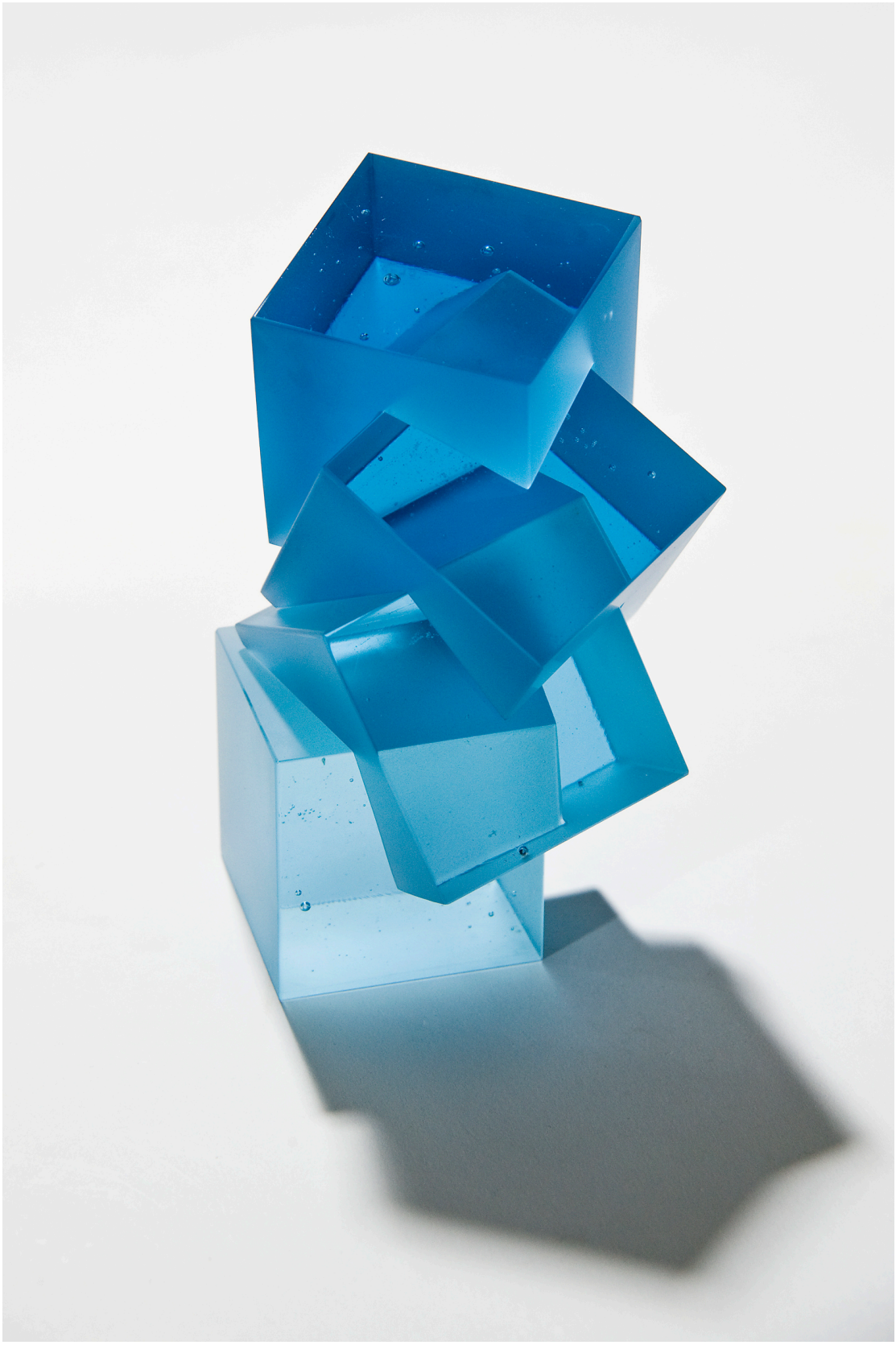


Plate 10: *Theme and Variations VI* in fluorescent light. Each element: 6 cm^3.

Plate 11: *Theme and Variations VIII* in incandescent light. Each element: 6 cm^3.

Plate 12: *Theme and Variations VII* and *VIII* in fluorescent light. Each element: 6 cm^3.

Plate 13: *Theme and Variations VII* and *VIII* in incandescent light. Each element: 6 cm^3.

Plate 14: *Theme and Variations V* in incandescent light. Each element: 6 cm^3.

Plate 15: *Theme and Variations V* in fluorescent light. Each element: 6 cm^3.

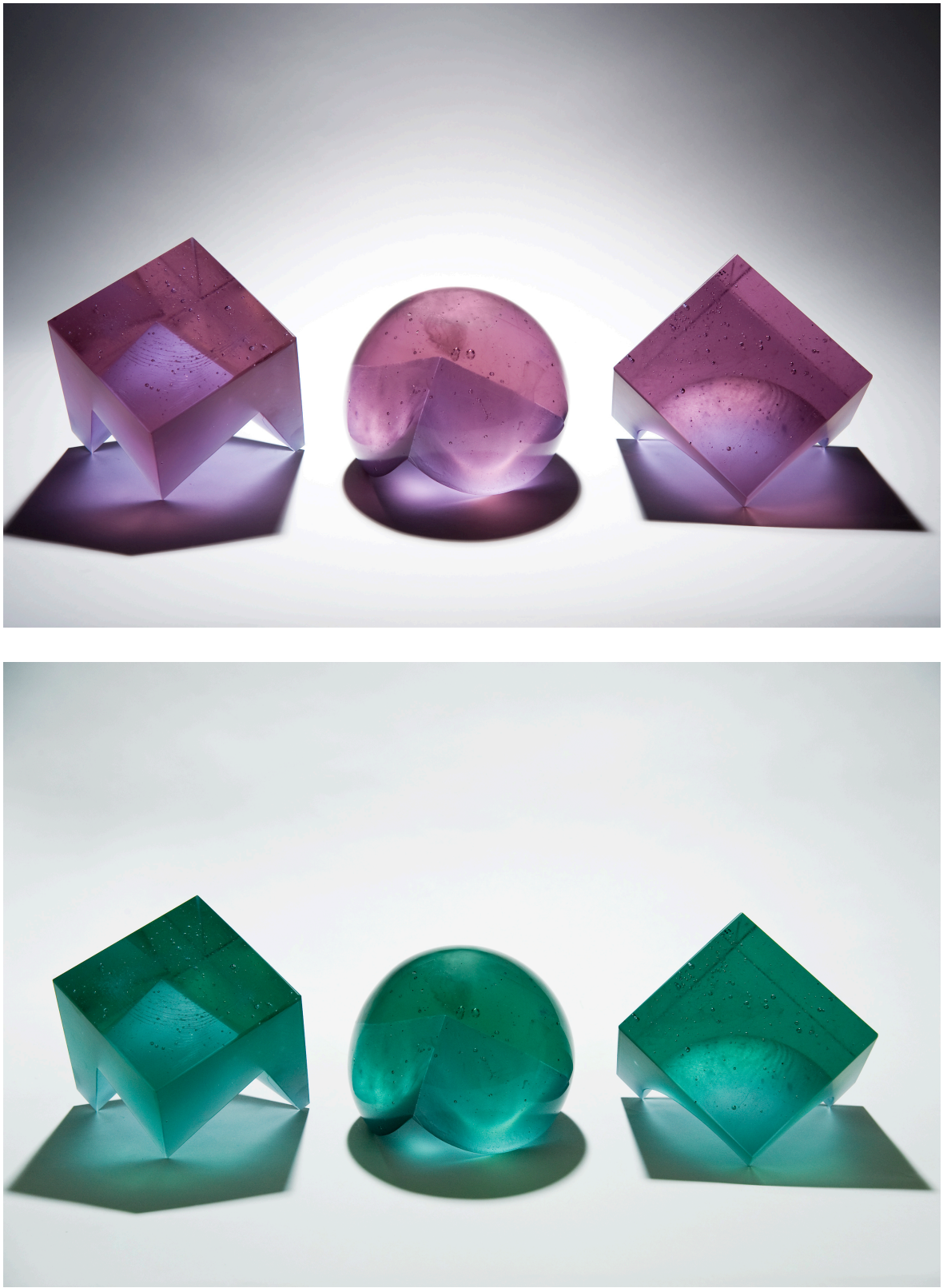


Plate 16: *Theme and Variations XII* in incandescent (top) and fluorescent light. Each element: 12 cm^3.

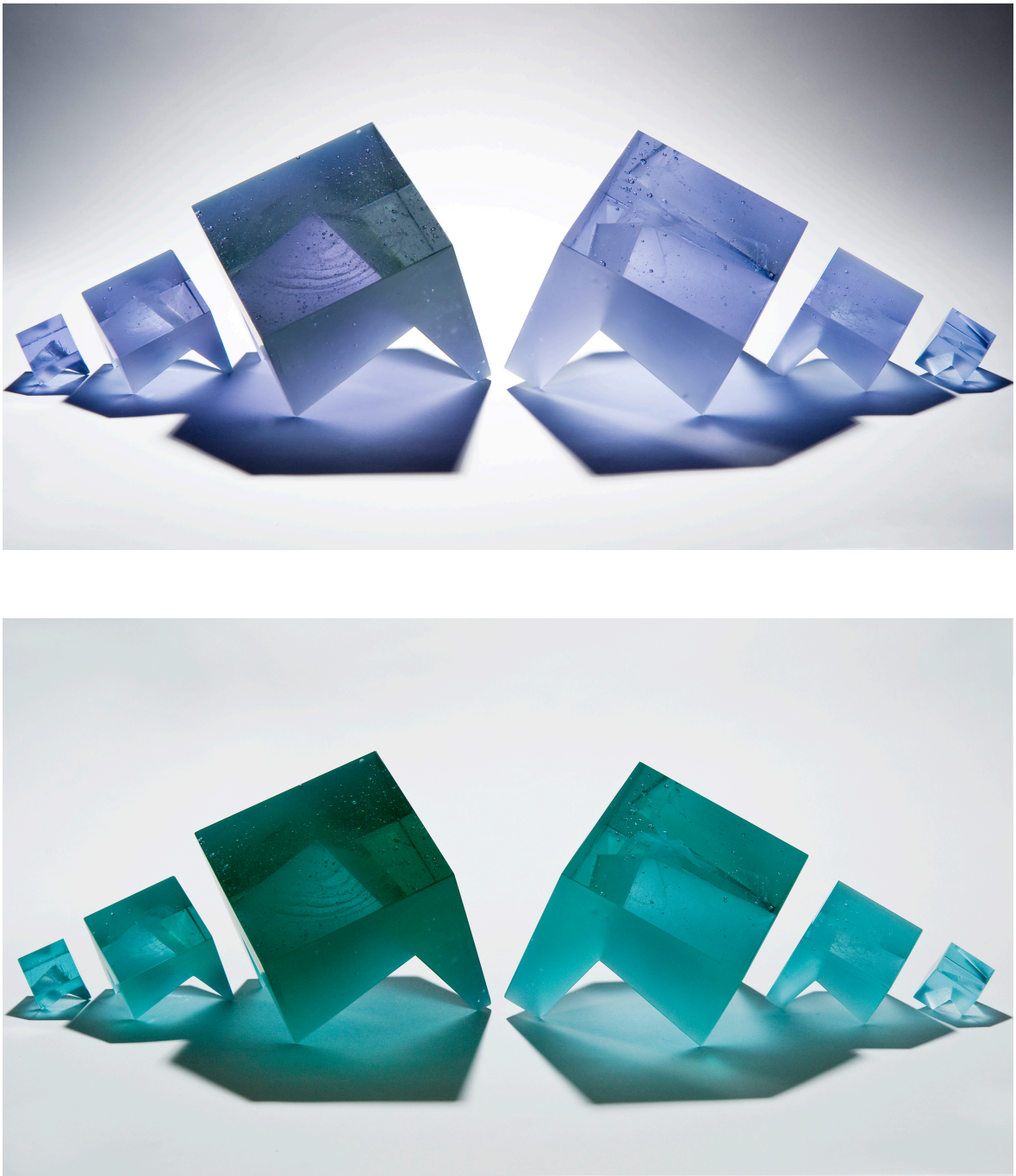


Plate 17: *Theme and Variations XV* in incandescent (top) and fluorescent light. 3 cm^3, 6 cm^3, 12 cm^3.

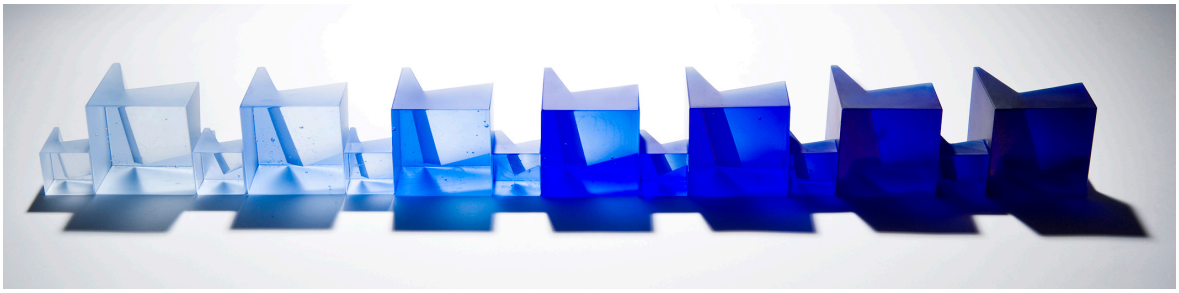


Plate 18: *Theme and Variations XIV*. Large cubes: 6 cm^3, small cubes: 3 cm^3.

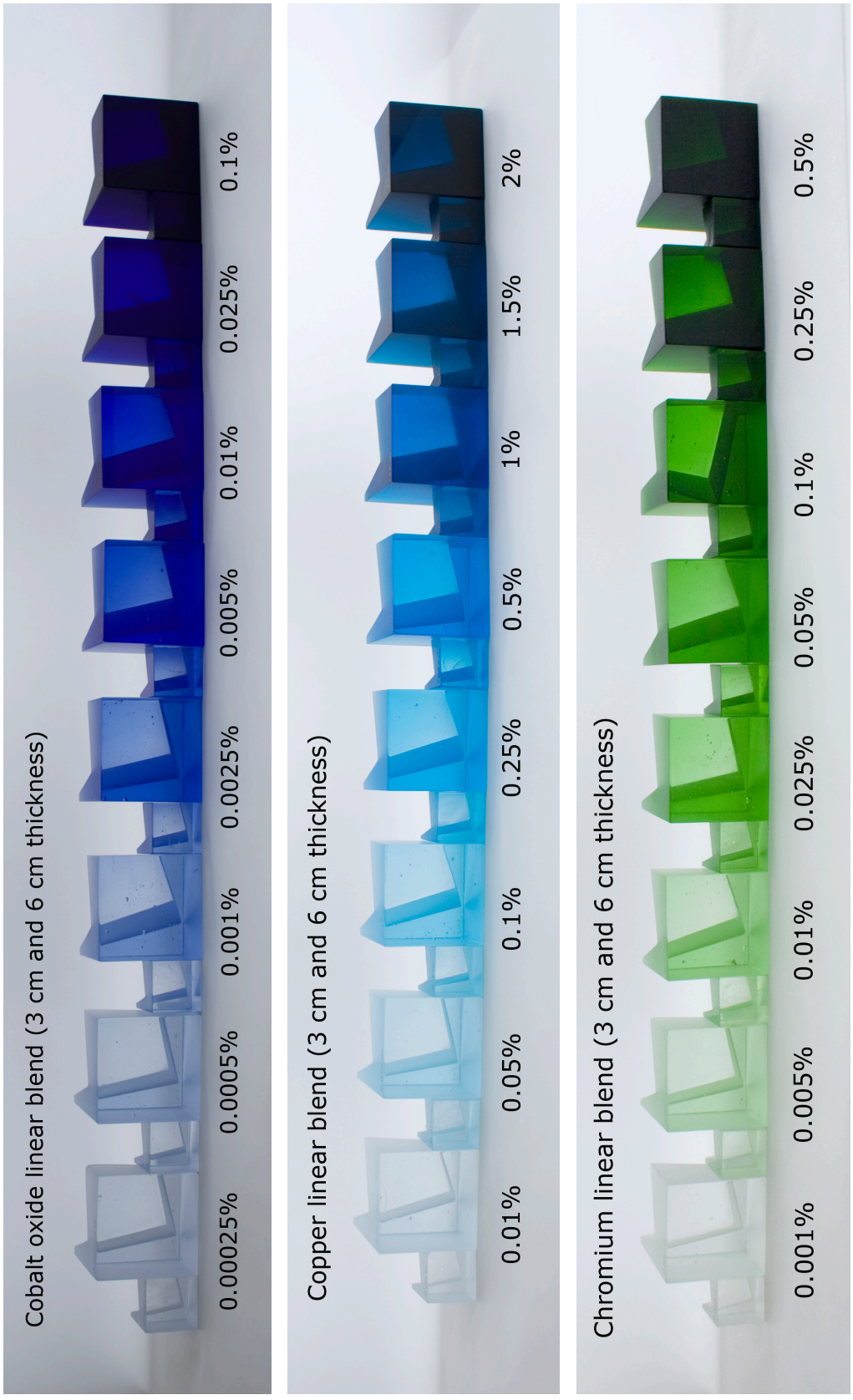


Plate 19: Cobalt, copper and chromium oxide linear blends.

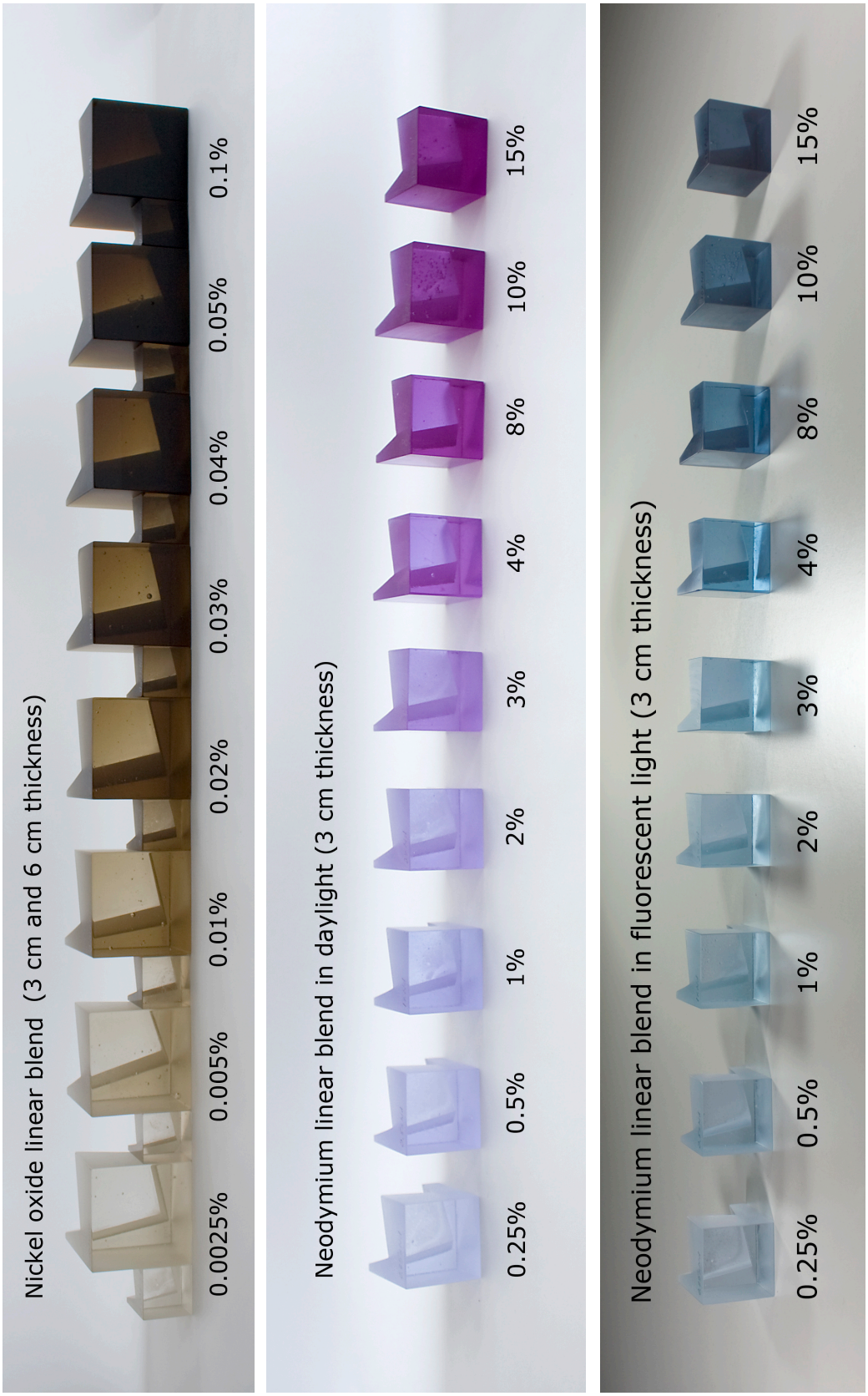


Plate 20: Nickel oxide and neodymium oxide linear blends.

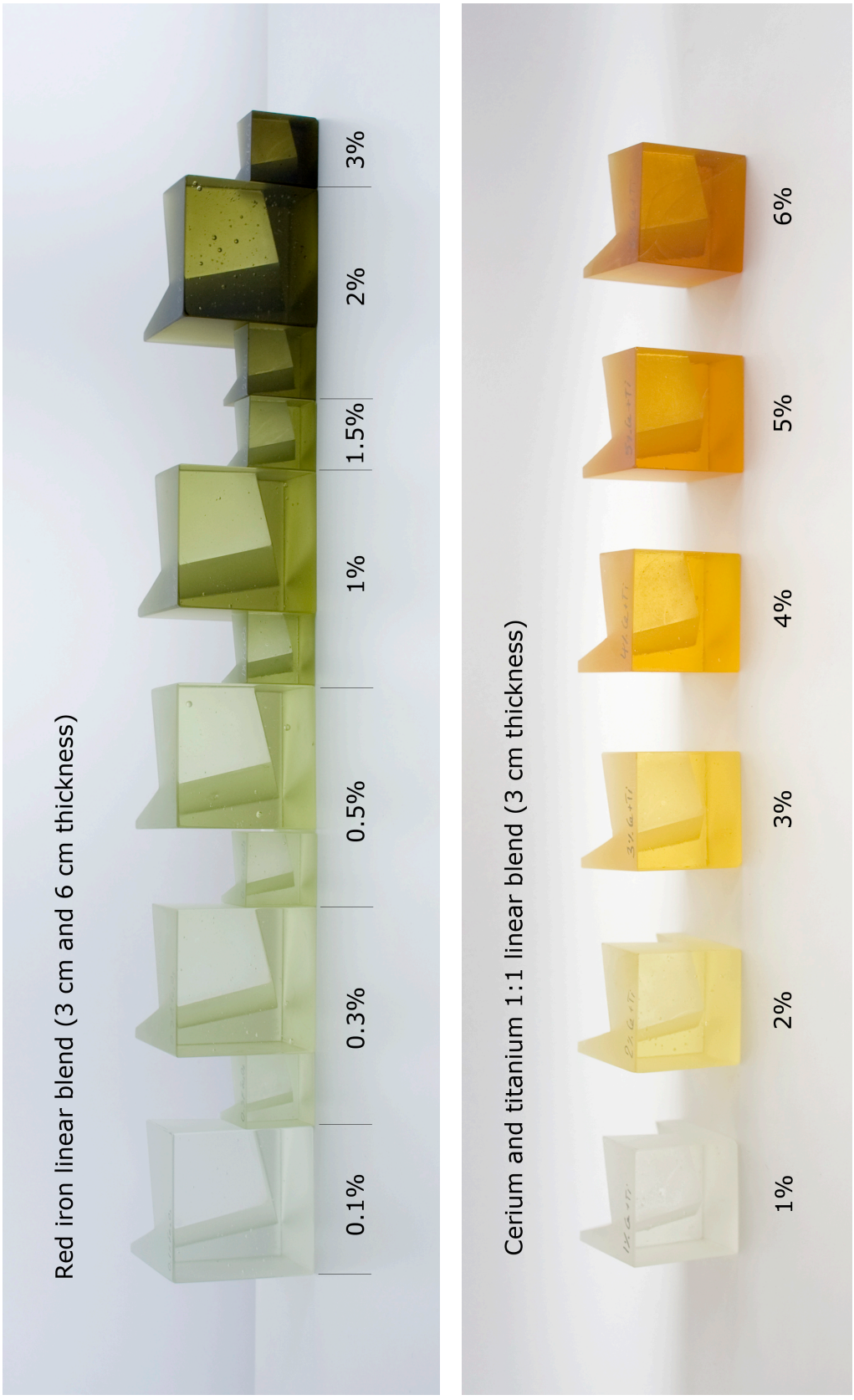


Plate 21: Red iron oxide linear blend; cerium and titanium oxide linear blend, ratio 1:1.

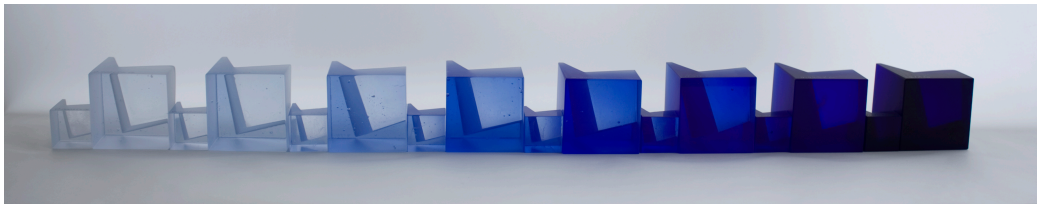
Appendix II: Summary of results for practical application

In the course of this project, I have developed a practical method for melting multiple samples of coloured glass, in amounts from 100 g to 1500 g, in a kiln. The coloured glass can be used for hot casting straight from the crucible, or for kiln casting by suspending the inverted glass-filled crucible as a reservoir above a refractory mould. This summary is a description of the processes required for melting coloured glass in a kiln and using it for kiln casting. It includes a chart with images, detailing oxide amounts required to achieve basic colour results using a single colouring agent, to provide a starting point for development of a bespoke colour palette.

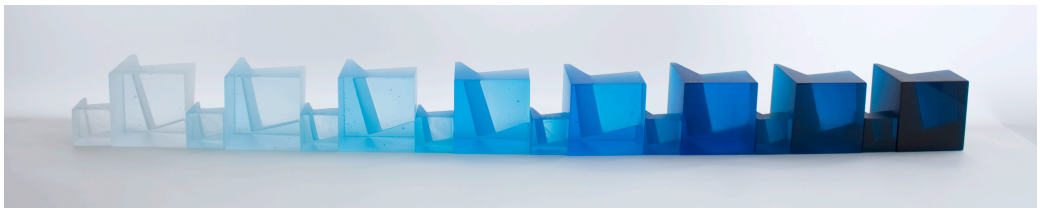
A. Melting coloured glass

When melting coloured glass, the first step is deciding on the required colour and estimating the oxide percentages. The following table and images provide a starting point.

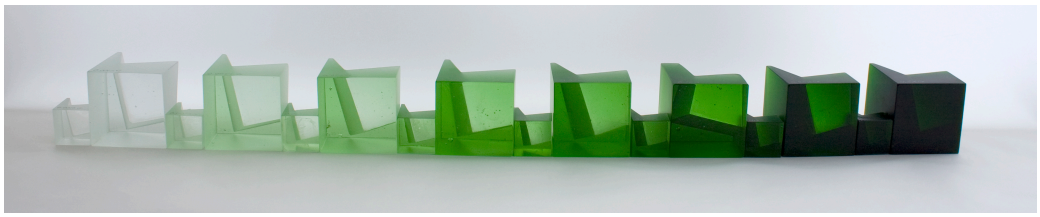
Oxide, glass thickness	very light	light	medium	dark
Cobalt oxide, 6 cm	0.0005%	0.001%	0.005%	0.025%
Cobalt oxide, 3 cm	0.001%	0.0025%	0.01%	0.05%
Copper oxide, 6 cm	0.05%	0.1%	0.5%	1.5%
Copper oxide, 3 cm	0.1%	0.2%	0.8%	2%
Chromium oxide, 6 cm	0.005%	0.01%	0.05%	0.25%
Chromium oxide, 3 cm	0.01%	0.02%	0.75%	0.5%
Nickel oxide, 6 cm	0.005%	0.01%	0.02%	0.05%
Nickel oxide, 3 cm	0.01%	0.02%	0.04%	0.1%
Red iron oxide, 6 cm	0.1%	0.5%	1%	2%
Red iron oxide, 3 cm	0.3%	0.75%	1.5%	2.5%
Neodymium oxide, 6 cm	1%	2%	4%	8%
Neodymium oxide, 3 cm	1.5%	3%	6%	15%
Cerium & Titanium oxides 1:1, 6 cm	1.5%	2%	3%	5%
Cerium & Titanium oxides 1:1, 3 cm	2%	2.5%	4%	6%



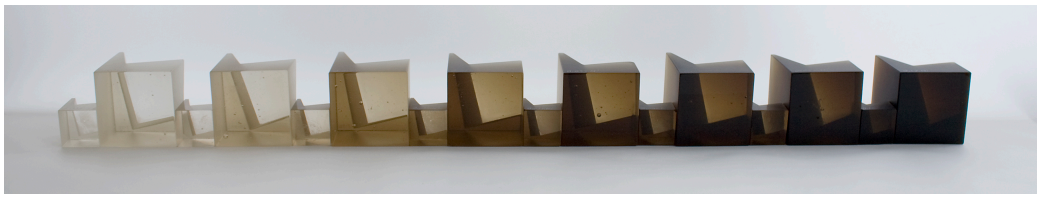
3 cm^3 and 6 cm^3 cubes coloured with cobalt oxide. From left: 0.00025%, 0.0005%, 0.001%, 0.0025%, 0.005%, 0.01%, 0.025%, and 0.1%.



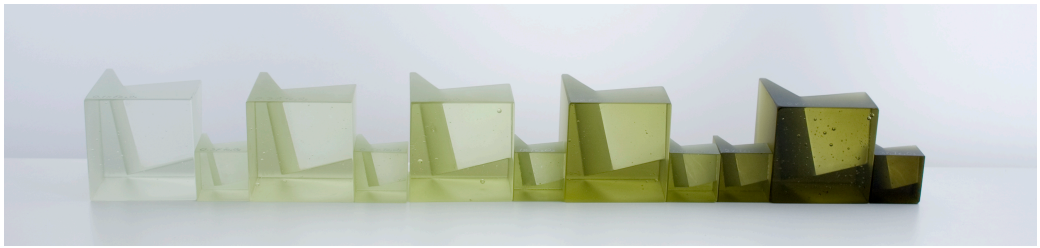
3 cm^3 and 6 cm^3 cubes coloured with copper oxide. From left: 0.01%, 0.05%, 0.1%, 0.25%, 0.5%, 1%, 1.5%, and 2%.



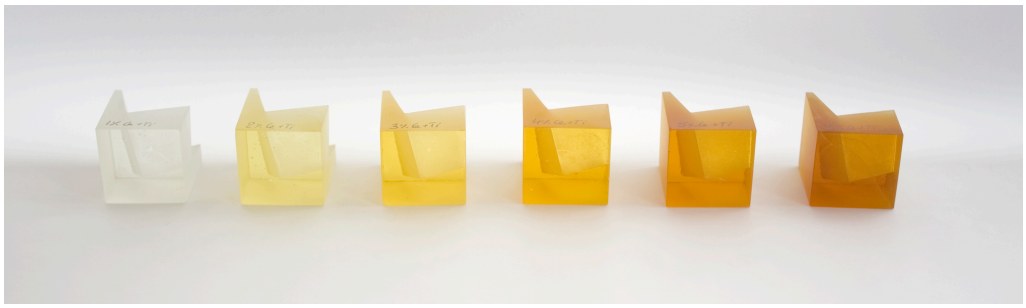
3 cm^3 and 6 cm^3 cubes coloured with chromium oxide. From left: 0.001%, 0.005%, 0.01%, 0.025%, 0.05%, 0.1%, 0.25% and 0.5%.



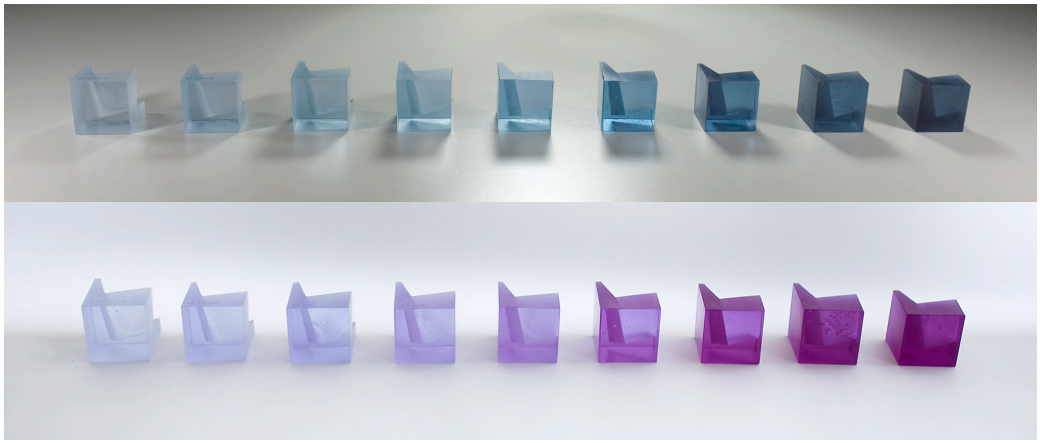
3 cm^3 and 6 cm^3 cubes coloured with nickel oxide. From left: 0.0025%, 0.005%, 0.01%, 0.02%, 0.03%, 0.04%, 0.05%, and 0.1%.



3 cm^3 and 6 cm^3 cubes coloured with red iron oxide. From left: 0.1% (6cm^3 only), 0.3%, 0.5%, 1%, 1.5% (3 cm^3 only), 2% and 3% (3 cm^3 only).



3 cm^3 cubes coloured with cerium oxide and titanium dioxide in the ratio 1:1. From left: 1%, 2%, 3%, 4%, 5%, and 6% of each oxide.



3 cm^3 cubes coloured with neodymium oxide, in fluorescent light (top) and incandescent light. From left: 0.25%, 0.5%, 1%, 2%, 3%, 4%, 8%, 10% and 15%.

Many hues can be achieved by combining colouring agents. Most combinations are intuitive; a mixture of cobalt oxide (blue) and chromium oxide (green) will result in blue-green. Exceptions are combinations including neodymium oxide; a mixture of neodymium oxide (purple, changes to blue in fluorescent light) and praseodymium oxide (lime green) in the ratio 5:1 results in salmon pink in daylight, for example. This unpredictability of results, combined with its colour changing properties makes experimentation with neodymium particularly exciting. In the following example of a combination of neodymium, cerium and titanium oxides, not only the value (darkness) changes with an increase in oxide amount, but also the hue.

Glass coloured with mixture of neodymium oxide (NdO), cerium oxide (CeO) and titanium dioxide (TiO^2) in the ratio 2:1:1, photographed in fluorescent light (top) and incandescent light. From left: 0.25% NdO, 0.125% CeO, 0.125% TiO^2; 0.5% NdO, 0.25% CeO, 0.25% TiO^2; 1% NdO, 0.5% CeO, 0.5% TiO^2; 1.5% NdO, 0.75% CeO, 0.75% TiO^2; 2% NdO, 1% CeO, 1% TiO^2; 2.5% NdO, 1.25% CeO, 1.25% TiO^2; 3% NdO, 1.5% CeO, 1.5% TiO^2; 4% NdO, 2% CeO, 2% TiO^2; 6% NdO, 3% CeO, 3% TiO^2; 8% NdO, 4% CeO, 4% TiO^2.

I have been melting glass in the following amounts: 100 g to 150 g in small hemispherical crucibles, for small colour tests; 800 g to 1500 g in tall crucibles for small objects and for making frit; 25 kg to 75 kg in a furnace.

The process is roughly the same, except that for kiln melts, the whole amount of glass batch or frit mixed with oxides is placed in the crucible at once, whereas in the furnace, the glass is added in stages, just like it is done for melting clear glass.

The actual oxide amounts are calculated as in the following example for 540 g of light blue glass using 0.001% of cobalt oxide:

Because of the weight loss during the melt and the glass clinging to the crucible during the casting process (the combined loss of weight is

approximately 33%), the required batch amount is approximately 800 g.

800 g x 0.001% = 0.008 g of cobalt oxide. As this is almost impossible to weigh out, a prepared glass frit containing 0.1% cobalt oxide is used instead. 0.008 g oxide = 8 g 0.1% oxide frit. (The preparation and use of frit is explained in section E.1, p. 229.)

800 g batch are mixed with 8 g of 0.1% cobalt frit by swirling around in a closed jar for approximately 30 seconds. After an interval of approximately one minute to allow the dust to settle, the mix is transferred to a crucible with an approximate volume of 1.7 litres, which has been marked with an underglaze pen. (I keep a notebook just for colour melts. Every entry contains the date, glass and oxide amounts for each sample, the kiln ID if more than one kiln are used, and the firing cycle. Later, the results are added in red pen. My numbering system allocates a number for each firing and a number per sample, for example the fifth sample in the sixth firing would be no. 6-5. This number is marked on the crucible.)

Tall crucible with glass batch, and with glass after firing (left). Crucibles with batch are set up in a kiln on trays with calcined alumina, ready for firing (right).

The crucible is placed on a stoneware tray filled with calcined alumina, to avoid damaging the kiln in case of spillage (The alumina protects the tray in case of a small spillages.)

The following firing cycle is used:

°C	°F
200°C/h -> 600°C (4 hours) FULL -> 1260°C (4 hours) HOLD 2 hours END	360°F/h -> 1112°F (4 hours) FULL -> 2300°F (4 hours) HOLD 2 hours END

For 100 g to 150 g of batch, the soak (hold) time is reduced to 30 minutes.

Slip cast and bisque fired crucibles (left). Mixing batch with oxides. The crucibles are placed in trays for firing (right).

B. Crucible kiln casting

Colour melting in a kiln for kiln casting only became viable with the invention of *crucible kiln casting*, the use of crucibles full of glass as reservoirs for kiln casting. Initially, the glass that was melted in a small crucible in a kiln was left in the crucible for hue tests (which were not ideal for assessing colour, as they could not be viewed in transmitted light) or hot-cast as follows: the crucible was removed from the kiln with tongs at 1240°C (2264°F) and the glass was poured into graphite or steel moulds. The resulting blocks were then cold worked, or used for kiln casting. This process is suitable for hot casting, but uneconomical for kiln casting. Crucible kiln casting reduces the amount of steps required as well as the energy consumption: instead of casting and annealing blocks, the crucible is left to cool naturally in the kiln, then returned to the kiln for casting the glass directly from the crucible.

Crucible kiln casting. Before (left) and after the firing (right).

The **set-up** for crucible kiln casting is simple: the crucible is suspended upside-down on soft kiln bricks above the mould. In the images above, the crucibles are supported by the back wall of the kiln. Care needs to be taken to leave enough space between crucible and mould; if the crucible sticks to the glass, it will cause cracks.

The following firing cycle was used for 6 cm^3 cubes with angled cube-shaped voids.

ºC	ºF	
50ºC/hour -> 220ºC [4.4h]	90ºF/hour -> 430ºF [4.4h]	HOLD 2-4 hours (to finish drying moulds and remove chemically bound water)
50ºC/hour -> 680ºC [8.8h]	50ºC/hour -> 680ºC [8.8h]	slow through the quartz inversion point
100ºC/hour -> 840ºC [1.6h in theory – in practice longer, depending on kiln]	180ºF/hour -> 1544ºF [1.6h in theory – in practice longer, depending on kiln]	HOLD 4.5 hours (for casting)
AFAP -> 480ºC (as fast as possible)	AFAP -> 900ºF (as fast as possible)	HOLD 10 hours (annealing)
2ºC/hour -> 430ºC [25h]	3.6ºF/hour -> 800ºF [25h]	annealing
4ºC/hour -> 360ºC [17.5h]	7.2ºF/hour -> 680ºF s[17.5h]	annealing
14ºC/hour -> 80ºC [20h]	25ºF/hour -> 176ºF [20h]	annealing
END	END	

Length of cycle: approximately 100h (4.2 days; 5 days to cool down completely). The long annealing time is necessary because of the

extreme thick-thin variations within the shape.

For **small colour tests**, ceramic moulds have been designed to completely support the glass-filled crucible during the casting.

Plug for taking plaster mould off and resulting plaster mould for slip-casting clay kiln casting moulds for basic tests.

The shape of the mould is rectangular, 5 cm x 5 cm, widening towards the top to 10 cm x 10 cm. It is 10.5 cm tall. The plug for taking a plaster mould off is turned on a lathe and modified on a flatbed grinder. Multiple plaster moulds for slip-casting can be taken off the plug. Any stoneware or earthenware slip can be used, as the moulds are only fired to 850ºC (1562ºF) maximum. The moulds are re-usable and need to be coated with a separator (Bullseye kiln wash was found to work well) before each firing.

The crucible kiln casting process for small tests.

The following firing cycle was employed for kiln casting small tests (ca. 5 cm x 5 cm x 1.5 cm):

ºC	ºF
150ºC/h > 600ºC (4h) AFAP > 840ºC HOLD 2h END	270ºF/h > 1112ºF (4h) AFAP > 1544ºF HOLD 2h END

C. Equipment required for glass colour testing and melting

- A kiln capable of reaching temperatures of 1300ºC (2372ºF) with a controller with glass annealing capability. If batch is used for melting, air extraction is recommended.

- Scales with a capacity of at least 3 kg and increments of 0.01 g. (I am using 3 pairs of scales: jeweller's scales capable of 100 g with increments of 0.01 g, scales capable of 5 kg with increments of 0.1 g, and for weighing ingredients for furnace melts, scales capable of 50 kg with increments of 1 g.)

- A high-quality dust mask to be worn when working with glassmaking materials, oxides, or any sort of silica dust.

- An underglaze pencil for marking crucibles.

- A blunger or a drill with mixer attachment for making ceramic slip for crucibles.

- A light metal bowl for weighing oxides.

- Glass or plastic jars with lids for mixing glass with oxides.

D. Materials required for carrying out colour melting and testing in a kiln

D.1. Glass

Glasma pelletized batch (Glasma Studioglass MRJ 702 A)

and/or

Bullseye clear medium frit 1101-0002 (size 1.2 to 2.7mm) or 1101-0001 fine frit (size 0.2 to 1.2mm) or any other soda-lime glass frit.

D.2. Selected colouring agents

Cerium oxide (CeO) [Clear. Luminescent blue in UV light. Yellow in combination with titanium dioxide.]

Chromium oxide (CrO) [Green]

Cobalt oxide (CoO) [Blue]

Copper oxide (CuO) [Turquoise blue]

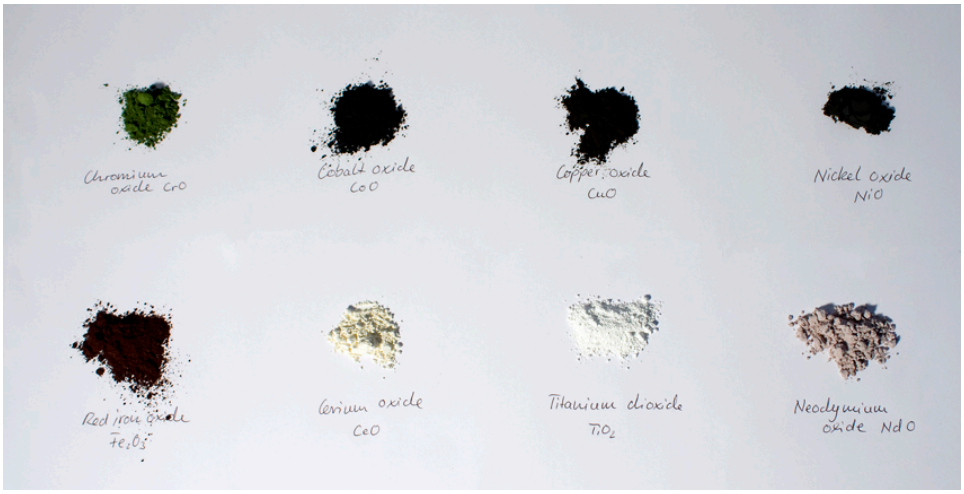
Neodymium oxide (NeO) [Purple in daylight and incandescent light, steel blue in fluorescent light.]

Nickel oxide (NiO) [Brown to black]

Praseodymium oxide (PrO) [Lime green]

Red iron oxide (Fe^2O^3) [Olive green]

Titanium Dioxide (TiO^2) [Clear. Yellow in combination with cerium oxide. Promotes devitrification.]



D.3. Other materials

Pottery plaster
Soft soap
Clay (Valentines stoneware crank, Valentines white stoneware B17C)
Calcined alumina
Molochite Dust
Molochite 120
Soda ash
Sodium silicate
Sodium dispex
Refractory mould mix, for example crystalcast (Gold Star Powders)

E. Processes

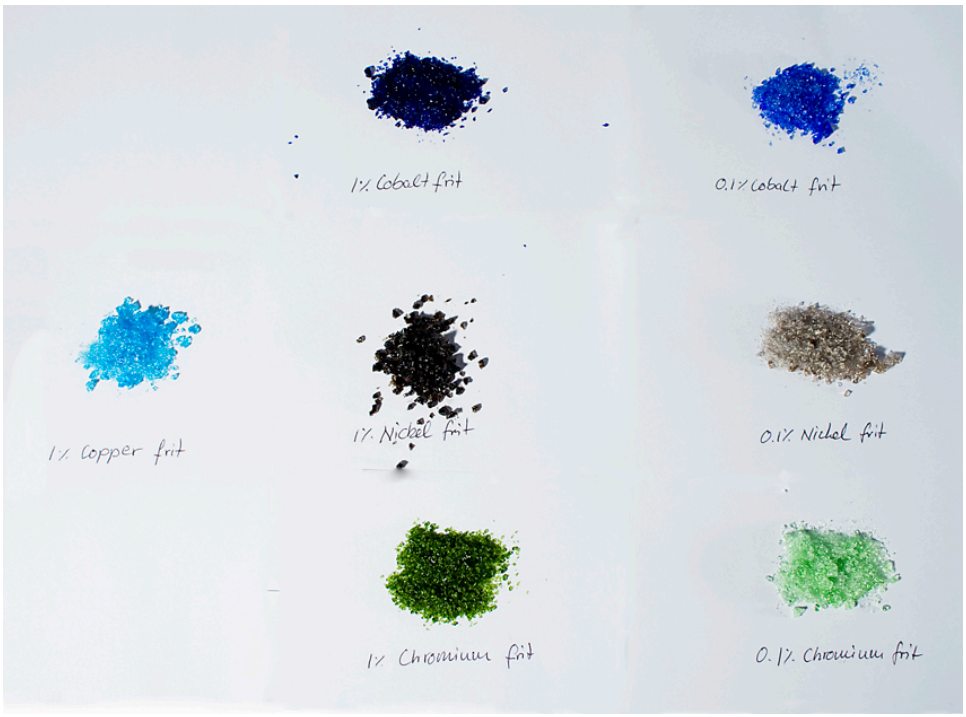
E.1. Making oxide frits to facilitate measuring of small amounts

In order to facilitate measuring small amounts of colouring agents, frits containing 1% and 0.1% of Chromium oxide (CrO), Cobalt oxide (CoO), Copper oxide (CuO) and Nickel oxide (NiO) need to be prepared:

The glass or glass batch is mixed with the required oxide amount and melted in a kiln, using the following firing cycle:

ºC	**ºF**
200ºC/h ->600ºC (in 3 hours) 1260ºC AFAP (as fast as possible) HOLD 2 hours 1240ºC AFAP HOLD for casting	360ºF/h ->1112ºF (in 3 hours) 2300ºF AFAP (as fast as possible) HOLD 2 hours 2264ºF AFAP HOLD for casting

The crucible is removed from the kiln with tongs and poured into a galvanised steel bucket filled with cold water. Heat-proof gloves and a face shield should be worn.



Oxide amounts are converted into frits using the following table:

oxide	1% frit	0.1% frit
1 g	100 g	1000 g
0.1 g	10 g	100 g
0.01 g	1 g	10 g
0.001 g	0.1 g	1 g
0.0001 g	0.01 g	0.1 g

E.2. Making crank stoneware crucibles

Materials:

Valentines stoneware crank
Valentines white stoneware B17C
Molochite Dust
Molochite 120
Soda ash
Sodium silicate
Sodium dispex

Crank slip recipe and instructions:

50 kg stoneware crank (4 bags)
100 g molochite dust
100 g molochite 120
100 g sodium silicate
50 g soda ash
¾ tsp sodium dispex
4600 ml filtered water

Weight of slip: 170 g - 180 g per litre

Use of a blunger is recommended, but a large bucket and a drill with mixer attachment will serve purpose.

Blunger and 1.7 litre crucible moulds.

Instructions:

Pour 4000 ml of water into the blunger. Cut the plastic clay into small lumps and add to the water. Turn on blunger after ca. 10 kg of clay, and keep mixing throughout. Stop adding clay when the mixture turns viscous; wait a few minutes before adding more. Add sodium silicate mixed with hot water (the rest of the total amount of water), and soda ash before mixture turns stiff, usually after about half the clay has been added. Add molochite in stages at the end. Adjust viscosity using sodium dispex.

Mix for ca. 2 hours. Leave the slip over night. (It will stiffen, but turn liquid again with renewed mixing). Mix again and weigh. Adjust the weight if necessary (more clay will render the slip heavier, more water, lighter). If required, adjust viscosity using sodium dispex. The slip should be ready for use.

Pour the slip into a dry, preferably warm plaster mould, leave for ca. 30 minutes for small crucibles, or ca. 1 hour for tall crucibles. Stir slip before pouring out to achieve an even wall thickness. Pour out half the slip, swirl around vigorously, then pour out the rest. (Because of the molochite dust, the slip is very viscous and will form ridges if not stirred and swirled). Small crucibles will come out of the mould after about an hour. I have found it best to leave the tall crucibles in the mould over night, covered with a plaster or wooden bat.

Crucible shapes and sizes:

Crucible moulds are made by turning a plaster plug (model) in the required size and shape on the lathe, then casting plaster moulds of the plug. A standard pottery plaster is used.

Crucibles for small tests are hemispherical, 10 cm in diameter, 5 cm high. These hold 100 to 150 g of glass batch or frit.

Crucibles for casting 6 cm^3 cubes are cylindrical, 19 cm high and 12 cm in

diameter. With a volume of 1.7 litres, they can hold 1 kg to 1.3 kg of batch. 1300 g of pelletized batch results in roughly 1100 g of glass, 390 ml in volume.

Slip-casting moulds with crucibles.

Slightly larger crucibles, capable of melting approximately 1.5 kg of batch, are 21 cm tall and 11 cm in diameter at the base, widening to 15 cm diameter at the top.

The crucibles can be used un-fired, but this is not recommended, as contamination of the glass with clay particles is more likely when using an un-fired crucible. Contamination is a problem in any case; care must be taken that no loose bits of clay are in the crucible when the batch or glass frit is added.

The following cycle was employed for firing dry stoneware crucibles:

100ºC/h -> 600ºC (6 hours)
AFAPº/h -> 1140ºC (or any temperature between 1120ºC and 1260ºC)
END

[180ºF/h -> 1112ºF (6 hours)
AFAP/h -> 2084ºF (or any temperature between 2050ºF and 2300ºF)
END]

F. End note

This research is still very much in progress. Processes are constantly being developed and improved. A big concern is the reduction of energy consumption, and a testing cycle exploring the lowering of top temperatures and shortening of firing cycles is in planning. Certain materials and processes need improvement; the crucible material, for example, is far from ideal: the glass shows contamination by clay particles at times, and the crucibles sometimes split at the base or crack at the glass line. Slower firing and cooling rates seem to minimize these occurrences, and further development of the material is planned.

There is much scope for further exploration of colour in glass. The investigation of volume colour is only at its beginnings; a good starting point for further work on the subject is provided in this document.

Appendix III:

A. Firing cycles

The factors that are usually considered in a melt cycle are size of the melt, temperature to which the furnace is heated prior to first charge, melting time and temperature, charging rate, rate of temperature recovery after each charge.[134] For melting in a kiln, the factors would be size of the melt, heating time and temperature, melting time and temperature, and cooling rate.

Typical firing cycle employed for firing stoneware crucibles for glass melting (when the crucibles are dry):

100º/h -> 600ºC (6 hours)
AFAPº/h -> 1140ºC (or any temperature between 1120ºC and 1260ºC)
END

Typical firing cycle employed for melting 100g glass colour tests in porcelain shells, using Glasma pelletized batch:

200º/h -> 600ºC (3 hours)
213º/h -> 1240ºC (3 hours)
HOLD 30 min
END

Typical firing cycle employed for melting 100g glass colour tests in porcelain shells, using batch mixed from raw materials:

---

[134] COMPATIBILITY OF GLASSES: EXPANSION DOES NOT EQUAL COMPATIBILITY, © Daniel W. Schwoerer Bullseye Glass Co., 1997, from http://www.cdvkiln.com/ris-bullseye.htm, accessed 28/04/08

200º/h -> 600ºC (3 hours)
220º/h -> 1260ºC (3 hours)
HOLD 1 hour
END

Typical firing cycle employed for making glass frits to facilitate measuring of small amounts of oxide, using 1500g of Glasma to be poured into water:

200º/h -> 600ºC (3 hours)
1260ºC AFAP (as fast as possible)
HOLD 2 hours
1240ºC AFAP
HOLD for casting

Typical firing cycle employed for melting 1500 g glass in stoneware crucibles, to be hot cast into graphite moulds:

150º/h -> 600ºC (4 hours
167.5º/h -> 1270ºC (4 hours)
HOLD 2 hours
1000ºC AFAP
HOLD 2 hours ("squeeze" to reduce bubbles)
1240ºC AFAP
HOLD – hot casting temperature

Typical firing cycle employed for melting 800g to 1000g of Glasma pelletized batch in stoneware crucibles, to be used as reservoirs for plaster-silica moulds:

150º/h -> 600°C (4 hours)
165º/h -> 1260°C (4 hours)
HOLD 2 hours
END

or

200º/h -> 600°C (3 hours)
AFAP -> 1260°C
HOLD 2 hours
END

Using Gaffer batch for the same process, the firing cycle is slightly modified to allow for a higher melting temperature:

150º/h -> 600ºC (4 hours)
167.5º/h -> 1270ºC (4 hours)
HOLD 2.5 hours
END

Using unfired crucibles, the initial heating ramp is reduced:

100º/h -> 600ºC (4 hours)
165º/h -> 1260ºC (4 hours)
HOLD 2 hours
END

Typical firing cycle for kiln casting small colour tests (L: 5 cm, W: 5cm, H: 1 cm to 1.5 cm):

150º/h > 600º (4h)
AFAP > 840º
HOLD 2h
END

B. Annealing cycles

Firing cycle employed for crucible kilncasting 6 cm^3 cubes from July 2008:

50ºC/hour -> 200º [4h]
HOLD 0-2 hours (to dry moulds)
80ºC/hour -> 680º [6h](slow through the quartz inversion point)
HOLD 0-2 hours
100º-160º/hour -> 840º [1-2h]
HOLD 3-4 hours (for casting)
AFAP -> 500º
HOLD 6-8 hours (annealing)
5º/hour -> 320º [36h](annealing)
6º/hour -> 220º [16h](annealing)
10º/hour -> 100º [12h](annealing)
END

Length of cycle: approximately 95h (4 days; 5 days to cool down completely)

Firing cycle employed for crucible kilncasting 6 cm^3 cubes from May 2010

50ºC/hour -> 220º [4.4h]
HOLD 2-4 hours (to finish drying moulds and remove chemically bound water)
50ºC/hour -> 680º [9.2h](slow through the quartz inversion point)
100º/hour -> 840º [1.6h in theory – in practice longer, depending on kiln]
HOLD 4.5 hours (for casting)
AFAP -> 480º
HOLD 10 hours (annealing)
2º/hour -> 430º [25h](annealing)
4º/hour -> 360º [17.5h](annealing)
14º/hour -> 80º [20h](annealing)
END

Length of cycle: approximately 100h (4.2 days; 5 days to cool down completely)

Firing cycle employed for crucible kilncasting 3 cm^3 cubes:

50ºC/hour -> 220º [4.4h]
HOLD 1-2 hours (to finish drying moulds and remove chemically bound water)
50ºC/hour -> 680º [9.2](slow through the quartz inversion point)
100º/hour -> 850º [1.7h in theory – in practice longer, depending on kiln]
HOLD 2 hours (for casting)
AFAP -> 480º
HOLD 5 hours (annealing)
11º/hour -> 430º [4.5h](annealing)
14º/hour -> 360º [5h](annealing)
60º/hour -> 80º [4.7h](annealing)
END

Length of cycle: approximately 43h (2 days to cool completely).

C. Bullseye annealing chart

(http://www.bullseyeglass.com/education/)

BULLSEYE
GLASS CO.

ANNEALING THICK SLABS

This annealing chart has been formulated for use with Bullseye clear glass. It is derived from Corning's method as shown in McLellan and Shand.* It is based on a flat slab of uniform thickness that is set up in such a fashion that it can cool equally from top and bottom.

If the piece is not set up in such a fashion that it can cool equally from top and bottom or is anything besides a flat slab of uniform thickness, select an annealing cycle for a piece that is twice the thickness of the thickest area of the piece. Even a very conservative annealing cycle may not work if the kiln is not capable of cooling the work uniformly.

For more Bullseye technical and product information see **www.bullseyeglass.com**

THICKNESS inches mm	ANNEAL SOAK TIME @ 900˚F @ 482˚C	INITIAL COOLING RATE ˚F/hr ˚C/hr	INITIAL COOLING RANGE ˚F ˚C	2nd COOLING RATE ˚F/hr ˚C/hr	2nd COOLING RANGE ˚F ˚C	FINAL COOLING RATE ˚F/hr ˚C/hr	FINAL COOLING RANGE ˚F ˚C	TOTAL MINIMUM TIME Hours
0.5 in	2 hr	100	900–800	180	800–700	600	700–70	~5 hr
12 mm		55	482–427	99	427–371	330	371–21	
0.75 in	3 hr	45	900–800	81	800–700	270	700–70	~9 hr
19 mm		25	482–427	45	427–371	150	371–21	
1.0 in	4 hr	27	900–800	49	800–700	162	700–70	~14 hr
25 mm		15	482–427	27	427–371	90	371–21	
1.5 in	6 hr	12	900–800	22	800–700	72	700–70	~28 hr
38 mm		6.7	482–427	12	427–371	40	371–21	
2.0 in	8 hr	6.8	900–800	12	800–700	41	700–70	~47 hr
50 mm		3.8	482–427	6.8	427–371	22	371–21	
2.5 in	10 hr	4.3	900–800	8	800–700	26	700–70	~70 hr
62 mm		2.4	482–427	4.3	427–371	14.4	371–21	
3.0 in	12 hr	3	900–800	5.4	800–700	18	700–70	~99 hr
75 mm		1.7	482–427	3.1	427–371	10	371–21	
4.0 in	16 hr	1.7	900–800	3.1	800–700	10	700–70	~170 hr
100 mm		0.94	482–427	1.7	427–371	5.6	371–21	
6.0 in	24 hr	0.75	900–800	1.3	800–700	4.5	700–70	~375 hr
150 mm		0.42	482–427	0.76	427–371	2.5	371–21	
8.0 in	32 hr	0.42	900–800	0.76	800–700	2.5	700–70	~654 hr
200 mm		0.23	482–427	0.42	427–371	1.4	371–21	

* McLellan and Shand (1984), *Glass Engineering Handbook*, 3rd Edition, New York, McGraw Hill.

WWW.BULLSEYEGLASS.COM

Appendix IV: Web colour chart

http://en.wikipedia.org/wiki/Web_colors

HTML name	Hex code R G B	Decimal code R G B
Red colors		
IndianRed	CD 5C 5C	205 92 92
LightCoral	F0 80 80	240 128 128
Salmon	FA 80 72	250 128 114
DarkSalmon	E9 96 7A	233 150 122
LightSalmon	FF A0 7A	255 160 122
Crimson	DC 14 3C	220 20 60
Red	FF 00 00	255 0 0
FireBrick	B2 22 22	178 34 34
DarkRed	8B 00 00	139 0 0
Pink colors		
Pink	FF C0 CB	255 192 203
LightPink	FF B6 C1	255 182 193
HotPink	FF 69 B4	255 105 180
DeepPink	FF 14 93	255 20 147
MediumVioletRed	C7 15 85	199 21 133
PaleVioletRed	DB 70 93	219 112 147
Orange colors		
LightSalmon	FF A0 7A	255 160 122
Coral	FF 7F 50	255 127 80
Tomato	FF 63 47	255 99 71
OrangeRed	FF 45 00	255 69 0
DarkOrange	FF 8C 00	255 140 0
Orange	FF A5 00	255 165 0
Yellow colors		
Gold	FF D7 00	255 215 0
Yellow	FF FF 00	255 255 0

LightYellow	FF FF E0	255 255 224
LemonChiffon	FF FA CD	255 250 205
LightGoldenrodYellow	FA FA D2	250 250 210
PapayaWhip	FF EF D5	255 239 213
Moccasin	FF E4 B5	255 228 181
PeachPuff	FF DA B9	255 218 185
PaleGoldenrod	EE E8 AA	238 232 170
Khaki	F0 E6 8C	240 230 140
DarkKhaki	BD B7 6B	189 183 107
Purple colors		
Lavender	E6 E6 FA	230 230 250
Thistle	D8 BF D8	216 191 216
Plum	DD A0 DD	221 160 221
Violet	EE 82 EE	238 130 238
Orchid	DA 70 D6	218 112 214
Fuchsia	FF 00 FF	255 0 255
Magenta	FF 00 FF	255 0 255
MediumOrchid	BA 55 D3	186 85 211
MediumPurple	93 70 DB	147 112 219
Amethyst	99 66 CC	153 102 204
BlueViolet	8A 2B E2	138 43 226
DarkViolet	94 00 D3	148 0 211
DarkOrchid	99 32 CC	153 50 204
DarkMagenta	8B 00 8B	139 0 139
Purple	80 00 80	128 0 128
Indigo	4B 00 82	75 0 130
SlateBlue	6A 5A CD	106 90 205
DarkSlateBlue	48 3D 8B	72 61 139
MediumSlateBlue	7B 68 EE	123 104 238
Green colors		
GreenYellow	AD FF 2F	173 255 47
Chartreuse	7F FF 00	127 255 0
LawnGreen	7C FC 00	124 252 0
Lime	00 FF 00	0 255 0

LimeGreen	32 CD 32	50 205 50
PaleGreen	98 FB 98	152 251 152
LightGreen	90 EE 90	144 238 144
MediumSpringGreen	00 FA 9A	0 250 154
SpringGreen	00 FF 7F	0 255 127
MediumSeaGreen	3C B3 71	60 179 113
SeaGreen	2E 8B 57	46 139 87
ForestGreen	22 8B 22	34 139 34
Green	00 80 00	0 128 0
DarkGreen	00 64 00	0 100 0
YellowGreen	9A CD 32	154 205 50
OliveDrab	6B 8E 23	107 142 35
Olive	80 80 00	128 128 0
DarkOliveGreen	55 6B 2F	85 107 47
MediumAquamarine	66 CD AA	102 205 170
DarkSeaGreen	8F BC 8F	143 188 143
LightSeaGreen	20 B2 AA	32 178 170
DarkCyan	00 8B 8B	0 139 139
Teale	00 80 80	0 128 128
Blue/Cyan colors		
Aqua	00 FF FF	0 255 255
Cyan	00 FF FF	0 255 255
LightCyan	E0 FF FF	224 255 255
PaleTurquoise	AF EE EE	175 238 238
Aquamarine	7F FF D4	127 255 212
Turquoise	40 E0 D0	64 224 208
MediumTurquoise	48 D1 CC	72 209 204
DarkTurquoise	00 CE D1	0 206 209
CadetBlue	5F 9E A0	95 158 160
SteelBlue	46 82 B4	70 130 180
LightSteelBlue	B0 C4 DE	176 196 222
PowderBlue	B0 E0 E6	176 224 230
LightBlue	AD D8 E6	173 216 230
SkyBlue	87 CE EB	135 206 235
LightSkyBlue	87 CE FA	135 206 250

DeepSkyBlue	00 BF FF	0 191 255
DodgerBlue	1E 90 FF	30 144 255
CornflowerBlue	64 95 ED	100 149 237
MediumSlateBlue	7B 68 EE	123 104 238
RoyalBlue	41 69 E1	65 105 225
Blue	00 00 FF	0 0 255
MediumBlue	00 00 CD	0 0 205
DarkBlue	00 00 8B	0 0 139
Navy	00 00 80	0 0 128
MidnightBlue	19 19 70	25 25 112

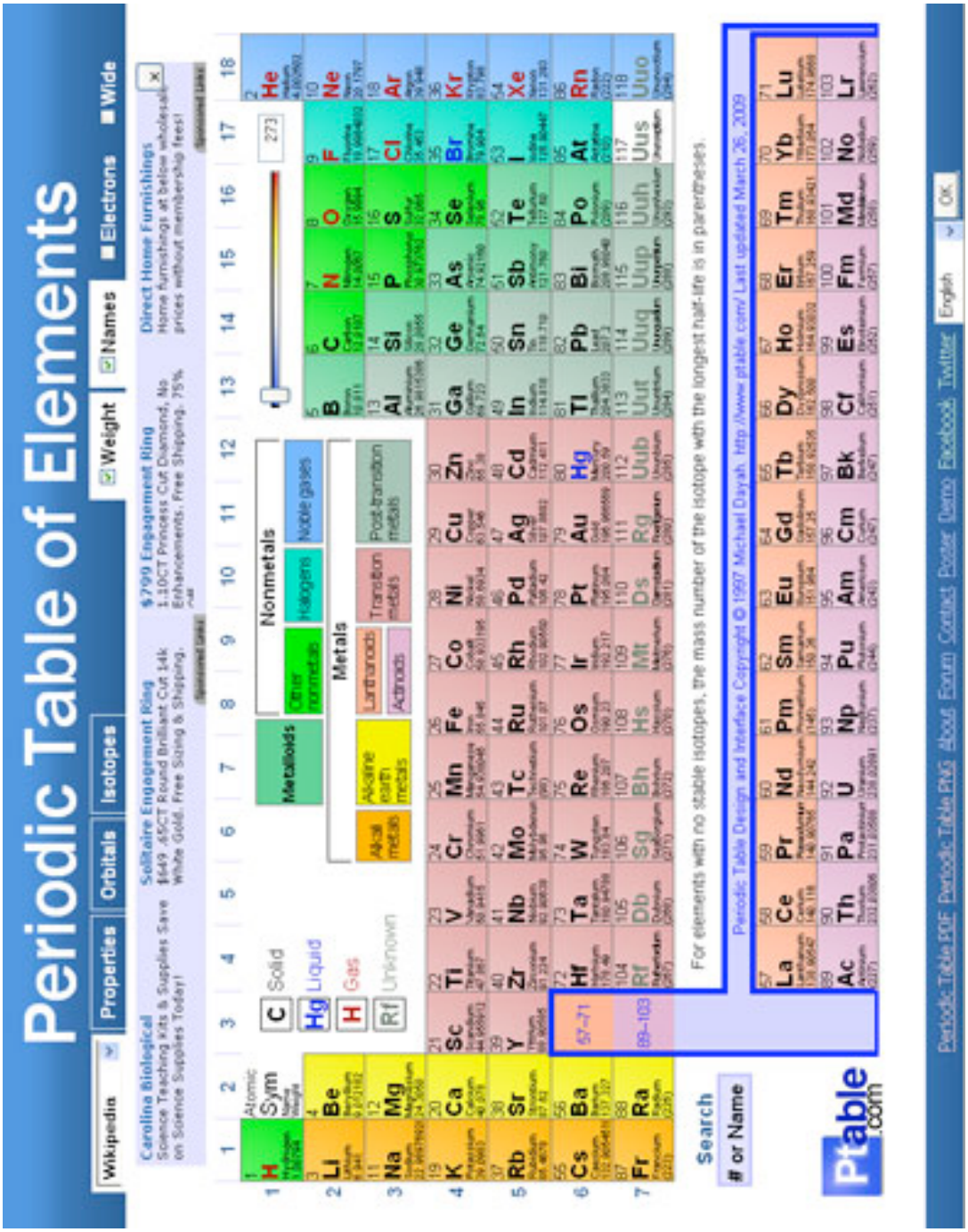
Brown colors		
Cornsilk	FF F8 DC	255 248 220
BlanchedAlmond	FF EB CD	255 235 205
Bisque	FF E4 C4	255 228 196
NavajoWhite	FF DE AD	255 222 173
Wheat	F5 DE B3	245 222 179
BurlyWood	DE B8 87	222 184 135
Tan	D2 B4 8C	210 180 140
RosyBrown	BC 8F 8F	188 143 143
SandyBrown	F4 A4 60	244 164 96
Goldenrod	DA A5 20	218 165 32
DarkGoldenrod	B8 86 0B	184 134 11
Peru	CD 85 3F	205 133 63
Chocolate	D2 69 1E	210 105 30
SaddleBrown	8B 45 13	139 69 19
Sienna	A0 52 2D	160 82 45
Brown	A5 2A 2A	165 42 42
Maroon	80 00 00	128 0 0

White colors		
White	FF FF FF	255 255 255
Snow	FF FA FA	255 250 250
Honeydew	F0 FF F0	240 255 240
MintCream	F5 FF FA	245 255 250
Azure	F0 FF FF	240 255 255

AliceBlue	F0 F8 FF	240 248 255
GhostWhite	F8 F8 FF	248 248 255
WhiteSmoke	F5 F5 F5	245 245 245
Seashell	FF F5 EE	255 245 238
Beige	F5 F5 DC	245 245 220
OldLace	FD F5 E6	253 245 230
FloralWhite	FF FA F0	255 250 240
Ivory	FF FF F0	255 255 240
AntiqueWhite	FA EB D7	250 235 215
Linen	FA F0 E6	250 240 230
LavenderBlush	FF F0 F5	255 240 245
MistyRose	FF E4 E1	255 228 225
Grey colors		
Gainsboro	DC DC DC	220 220 220
LightGrey	D3 D3 D3	211 211 211
Silver	C0 C0 C0	192 192 192
DarkGray	A9 A9 A9	169 169 169
Gray	80 80 80	128 128 128
DimGray	69 69 69	105 105 105
LightSlateGray	77 88 99	119 136 153
SlateGray	70 80 90	112 128 144
DarkSlateGray	2F 4F 4F	47 79 79
Black	00 00 00	0 0 0

Appendix V: Periodic table of elements

(http://www.ptable.com/)



Appendix VI: Materials & processes

A. Glasses

Glasma pelletized batch (Glasma Studioglass MRJ 702 A)

Bullseye clear medium frit 1101-0002 (or any other soda-lime glass frit)

Batch mixed from raw materials using the following recipes:

Richard Golding's batch recipe (RG1)		
71%	Silica sand	
16%	Sodium carbonate	Na_2CO_3
0.5%	Potassium nitrate	KNO_3
10%	Limestone	$CaCO_3$
0.5%	Borax (anhydrous)	B_2O_3
1%	Antimony oxide	Sb_2O_3
1%	Lithium carbonate	Li_2CO_3

Initial development of testing processes was undertaken using Glasma pelletized batch. After a discussion with Richard Golding on 20/04/07, RG1 batch was used for further tests, until it became obvious that it was not suitable as a casting glass. Further batch recipes were tested as follows: 100g of batch was mixed up, then fired in a kiln in a small crucible together with 100g of Glama pelletized batch as a control sample. The following firing cycle was employed:

200º/h -> 600ºC (3 hours)
AFAP ->1270º (as fast as possible)
HOLD 1 hour
235º/h -> 800ºC (2 hours)
HOLD 6 hours
END

Richard Goldings improved batch recipe (RG2)		
70.8%	Silica sand	
15%	Sodium carbonate	Na_2CO_3
0.5%	Potassium nitrate	KNO_3
12%	Limestone	$CaCO_3$
0.5%	Borax (anhydrous)	B_2O_3
0.2%	Antimony oxide	Sb_2O_3
1%	Lithium carbonate	Li_2CO_3

Richard Goldings improved batch recipe (RG4)		
69.3%	Silica sand	
16%	Sodium carbonate	Na_2CO_3
0.5%	Potassium nitrate	KNO_3
0.5%	Aluminum oxide	Al_2O_3
12%	Limestone	$CaCO_3$
0.5%	Borax (anhydrous)	B_2O_3
0.2%	Antimony oxide	Sb_2O_3
1%	Lithium carbonate	Li_2CO_3

Richard Goldings improved batch recipe (RG5) with advice from Glassworks services		
73%	Silica sand	
12%	Sodium carbonate	Na_2CO_3
3.8%	Potassium carbonate	K_2CO_3
0.5%	Potassium nitrate	KNO_3
2%	Aluminum oxide	Al_2O_3
7%	Limestone	$CaCO_3$
0.5%	Borax (anhydrous)	B_2O_3
0.2%	Antimony oxide	Sb_2O_3
1%	Lithium carbonate	Li_2CO_3

Gaffer batch lithium carbonate		
71%	Silica sand	
17.2%	Sodium carbonate	NaO
0.9%	Potassium nitrate	KNO_3
0.8%	Aluminum oxide	Al_2O_3
4.5%	Limestone	$CaCO_3$
2.5%	Zinc oxide	ZnO
2.6%	Borax (anhydrous)	B_2O_3
0.3%	Antimony oxide	Sb_2O_3
0.2%	Lithium carbonate	Li_2CO_3

All of the glasses show more devitrification than Glasma. Gaffer batch Lithium Carbonate, given to me by John Croucher of Gaffer Glass, shows the least amount of devitrification of the formulas tested. However, when 10 kg of this batch was mixed up and used in small portions, the results were erratic due to lack of homogeneity of the mix. To use this batch for small amounts, each of these small amounts would have to be mixed separately. Because of the time and effort involved in doing this, it was decided to use Glasma pelletized batch instead.

B. Clays used in the course of this research:

Valentines stoneware crank

Valentines white stoneware B17C

Valentines porcelain

Fine fireclay sanitary ware casting slip supplied by Ideal Standard

Earthstone Q-cast slip

Valentines HT stoneware slip

Earthstone handbuilding white ES20

C. Slips made from plastic clay:

For all slips, filtered water was used. The sodium silicate was dissolved in some of the required quantity of water heated to the boiling point before being added to the mix.

Generic slip recipe used as a starting point:

10 kg plastic clay
10-25 g sodium silicate
10 g soda ash
850 ml water
Crank slip (09/12/08):
10 kg stoneware crank
30-35 g sodium silicate
10 g soda ash
950 ml filtered water
weight of slip: 1789 g/litre
Result: thin casts; many crucibles cracked along the glass line after firing.

Crank/stoneware slip (23/03/09):

14 kg stoneware crank
6 kg white stoneware B17C
50 g molochite dust
50 g molochite 120
30-35 g sodium silicate
12 g soda ash
1700 ml filtered water
Result: slightly thicker casts; some crucibles cracked along the glass line after firing.

Stoneware slip (23/04/09):

20 kg white stoneware B17C
100 g molochite dust
100 g molochite 120
100 g molochite 30/80
500 g fine grog
70 g sodium silicate
30 g soda ash
2700 ml filtered water

Result: difficult to cast, very viscous; most crucibles cracked along the glass line after firing. Too much sodium silicate.

Crank slip (29/05/09):

16 kg stoneware crank
80 g molochite dust
36 g sodium silicate
15 g soda ash
1360 ml filtered water

Result: Successful. The molochite dust causes the slip to cast thicker. Slip needs to be stirred in mould, half tipped out, then swirled around for about 30 seconds before completely emptying mould of liquid slip, to avoid thickness variations in cast.

Crank slip (15/10/09):

80 kg stoneware crank
300 g molochite dust
200 g sodium silicate
72 g soda ash
7700 ml filtered water

Result: Reasonably successful. Only very few crucible breakages

Crank slip (20/01/10):

75 kg stoneware crank
12.5 kg white stoneware B17C
350 g molochite dust
210 – 240 g sodium silicate
80 g soda ash
8300 ml filtered water

Result: Successful.

Crank slip (15/02/10):

50 kg stoneware crank (4 bags)
25 kg white stoneware B17C (2 bags)
150 g molochite dust
150 g molochite 120
200 g molochite 30/80
200 g sodium silicate
90 g soda ash
7000 ml filtered water
weight of slip: 1720g/litre

Result: Successful.

Crank slip (06/04/10):

75 kg stoneware crank (6 bags)
150 g molochite dust
150 g molochite 120
150 g sodium silicate
80 g soda ash
1 tsp sodium dispex
7000 ml filtered water
Result: The sodium dispex causes the slip to cast much better. It is less thixothropic.

D. Crucible shapes and sizes

Crucibles for small tests are hemispherical, 10 cm diameter, 5 cm high. These hold 100 g – 150 g of glass batch or frit.

Crucibles for casting 6 cm^3 cubes are cylindrical, 19 cm high and 12 cm in diameter. With a volume of 1.7 litres, they can hold 1 kg - 1.3 kg of

batch. 1300 g of pelletized batch results in roughly 1100 g of glass, 390 ml in volume.

Slightly larger, capable of melting approximately 1.5 kg of batch, are 21 cm tall and 11 cm in diameter at the base, widening to 15 cm diameter at the top.

E. Weight calculations from batch to cast

B54: Kiln 19
Firing cycle:
30% -> 600
FULL -> 1260º
HOLD 2h
END

B54-1
weight crucible: 891.8g
with batch: 1720.2g (batch only: 828.4)
fired: 1582.7g (glass: 690.9g; loss: 137.5g = 16.6%)
cast glass: 559.9g (loss: 131g = 19%)
total loss: 268.5g = 30.1%

B54-2
weight crucible: 903g
with batch: 1752.5g (batch=849.5g)
fired: 1615.4g (glass: 712.4g; loss: 137.1g = 16%)
cast glass: 560.1g (loss: 152.3g = 21.4%)
total loss: 289.4g = 34%

B54-3
weight crucible: 1048.8g
with batch: 1918.2g (batch=869.4g)
fired: 1781.1g (glass: 732.3g; loss 137.1g = 15.77%)
cast glass: 576.4g (loss 155.9g = 21.3%)
total loss: 293g = 33.7%

B54-4
weight crucible: 1102.3g
with batch: 1934.4g (batch: 832.1g)
fired: 1796.8g (glass: 694.5; loss: 137.6g = 16.5%)
cast glass: no result

B55: Kiln 24
Firing cycle:
200º/h -> 600º
FULL -> 900º
HOLD 5h
100º/h -> 1260º
HOLD 2.5
END

B55-1
boiled over a little
weight crucible: 1481.9g
with batch: 3562g (batch only: 2080.1g)
fired: 3209g (glass: 1727.1g; loss 353g = 17%)
cast glass: no result

B55-3
weight crucible: 1044g
with batch: 1879g (batch=835g)
fired: 1742.5g (glass: 698.5; loss 136.5g = 16.35%)
cast glass: 567.9g (loss 130.6g = 18.7%)
total loss: 267.1g = 32%

B55-4
weight crucible: 1070.3g
with batch: 1902g (batch=832g)
fired: 1766g (glass: 695.7g, loss 136g = 16.35%)
cast glass: 565.6g (loss 130.4g = 18.7%)
total loss: 266.4g = 32%total loss: 266.4g = 32%

For 800g batch, average %
loss from batch to glass = 16.26%
loss crucible casting = 19.82%
total loss = 32.36%

For 800g batch, maximum %
loss from batch to glass = 16.6%
loss crucible casting = 21.4%
total loss = 34%

F. Health and safety

Safety glasses should be worn at all times when working with glass.

Respiratory protective equipment (RPE) with protection factor of at least 20 should be worn when working in an area where silica dust is

present (I.e. when mould making, de-moulding, mixing batch with oxides, fettling ceramics, etc.) Guidance on respiration equipment is available at http://www.hse.gov.uk/pubns/guidance/rseries.htm.

Exposure to Silica dust can cause silicosis, lung cancer and chronic obstructive pulmonary disease (COPD). To minimise the risks, regular vacuuming and wet sweeping of floors and machinery to remove settled dust is particularly important to stop dust being kicked back into the air. Work clothing should be vacuumed before removal. Under no circumstances should dry sweeping take place in areas where silica dust could be present. [135]

An **extraction system** is recommended for the kiln when melting batch, for mould making and de-moulding, and for mixing batch and oxides.

Heat-resistant gloves and a **face shield** should be worn when taking crucibles from the kiln with tongs, for producing frit.

Adhesive bandages should be available, because cuts while handling glass are inevitable (but rarely serious).

Guidance for health and safety regarding silica dust and other toxic/dangerous materials is provided at http://www.hse.gov.uk/pubns/guidance/crseries.htm.

Appendix VII: Colour test database on CD

[135] http://www.hse.gov.uk/pubns/misc830.pdf, accessed 14/12/2010

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