Excavating the Wear Flint Glass Works, Lisburn Terrace, Sunderland

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SUMMARY

In 2011, an open-area excavation was undertaken on the site of the Wear Flint Glass Works, Sunderland. This glassworks operated throughout the late nineteenth and twentieth centuries, and was initially engaged in the production of pressed-glass vessels and then, from 1921 onwards, PYREX goods. The excavation exposed the remains of seven glass furnaces, which reflect both the historical development of the works and, more generally, the technological advances in glass-furnace design during the latter half of the nineteenth and early part of the twentieth centuries. Detailed scientific analysis of glassworking debris has provided insights into the manufacture of twentieth-century glass.

INTRODUCTION

THE WEAR FLINT GLASS WORKS lay to the west of Sunderland town centre (NZ 38359 57345; fig. 1), and represented a significant late nineteenth/twentieth-century industrial site engaged in the manufacture of both pressed-glass and PYREX. Pressed-glass first appeared in the 1830s and was used to produce cheap glass vessels and ornaments that imitated those made of cut glass.[1] In Sunderland, however, this industry emerged in the latter half of the nineteenth century, when English pressed-glass manufacturing effectively shifted to the North East (Latimore 1979, 32). During this period, the Sowerby glassworks at Gateshead was of central importance to the pressed-glass industry, though several other glassworks also emerged, such as the Wear Flint Glass Works, which were established by men who had gained their knowledge of the trade by working at Sowerbys (Thompson 1989). In contrast, PYREX, the well-known heat-resistant borosilicate cookware glass, was patented in America just before the First World War and was manufactured in this country during the twentieth century, under licence from American manufacturers Corning & Co. (Evans 1983).

Given the importance of the Wear Flint Glass Works to both the region's pressed-glass and borosilicate glass industries, prior to a recent scheme of redevelopment, this former glassworks was subjected to a developer-funded excavation, in order to satisfy several planning conditions, which had been placed on the site by Sunderland City Council. This work was informed by an archaeological desk-based assessment (Under Construction Archaeology 2009) and a later scheme of evaluatory trenching (cf. OA North 2017), and included the excavation of two separate open-area trenches (Areas 2 and 3) within the boundaries of the glassworks (fig. 1). One of these (Area 2), measured approximately 1877 m², and focused on the western and south-eastern parts of the Wear Flint Glass Works, whilst the other measured approximately 250 m², and comprised an east/west-aligned trench, which targeted the south-eastern portion of the works.

In addition, another open-area trench (Area 1) was excavated to the north-west, to investigate a second industrial site that lay within the area earmarked for redevelopment. This was

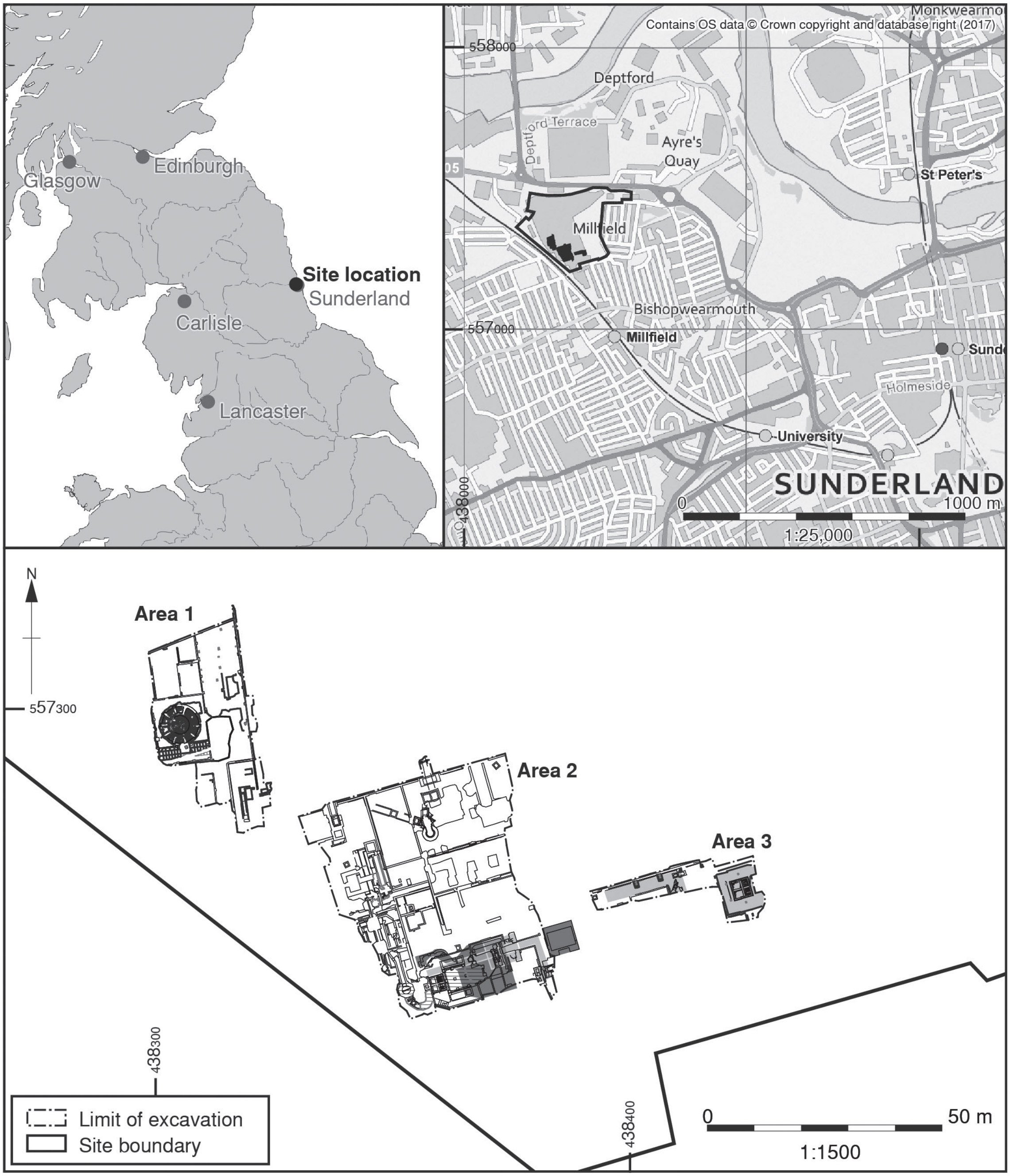

Fig. 1 Site location and the areas subjected to open-area excavation.

the site of the Wearside Pottery, which was in operation between 1913 and 1957. Significantly, the excavation uncovered a series of remains associated with this twentieth-century pottery, including the base of a pottery kiln, which are detailed in a separate publication (Miller 2014).

HISTORICAL BACKGROUND

The Wear Flint Glass Works was established by Henry Greener, who had previously been involved in the manufacture of blown and press-moulded glass, with James Angus at the Harrison Street Glassworks, also in Sunderland (Latimore 1979, 74–87). Greener had previously been an employee of Sowerbys, and following Angus' death in 1869, he expanded operations and established the Wear Flint Glass Works, which at this time housed five ten-pot furnaces. Greener's glassworks rapidly became one of the largest of Sowerby's rivals (Ross 1982), and produced a large range of goods, patenting several important new production techniques, including a method of producing glass letters for shop windows and the manufacture of glasses with angular prisms for use as carriage-roof lamps (Thompson 1989). From 1878, however, the company put more effort into making less-intricate items, such as pavement lights and slabs of glass, and this may have been driven, in part, by a spate of strikes that beset the company during this period.[2]

Henry Greener died in 1882, leaving his company in financial difficulties (Ross 1982). His son, Edward Greener, was among the executors and honoured his request to keep the factory in the family. However, with falling sales and increasing debts, and further strikes amongst the workforce,[3] the firm was taken over in 1886 by James Augustus Jobling, a wealthy Newcastle chemical merchant (Baker 1983, 7). With this change of ownership, although the registration mark was modified, the range of products remained largely the same, and the main emphasis was on press-moulded colourless and coloured domestic glass (Latimore 1979, 74–87).

An advertisement dating to the late nineteenth century includes a useful illustration of the Wear Flint Glass Works (fig. 2). This depicts a large, rectangular glasshouse with five large conical flue-structures protruding through the roof. These structures were designed to generate draught to the furnaces, whilst also dispersing fumes, and presumably they related to the five ten-pot melting furnaces. A smaller chimney, clearly for industrial use, is also shown at the south-western corner of the glasshouse, whilst a larger chimney is shown immediately to the north of the buildings. The illustration also depicts a probable office and warehouse, on the eastern side of the works, whilst its northern part was largely given over to a single-storey structure, which could have been used for the inspection and packaging of products, or perhaps as an area where melting pots were made and stored. The general layout of the works is also partly confirmed by the Ordnance Survey 1:2500 plan of 1897 (fig. 3).

Although James Jobling continued to register new designs, he did not spend the time required to grow the company and, as such, financial problems beset the firm towards the end of the nineteenth century. These were overcome in 1902, when Ernest Jobling Purser, nephew of James Jobling, joined the firm (then renamed James A. Jobling & Co.) and immediately introduced technological improvements from Germany and America (Ross 1982). After the First World War, the firm began to produce an opalescent pressed-glass called Opalique which imitated Lalique (Notley 2000, 37).

The form of the glassworks in the early twentieth-century is depicted on the Ordnance Survey 1:2500 map of 1919. This shows that the layout of the works was largely comparable

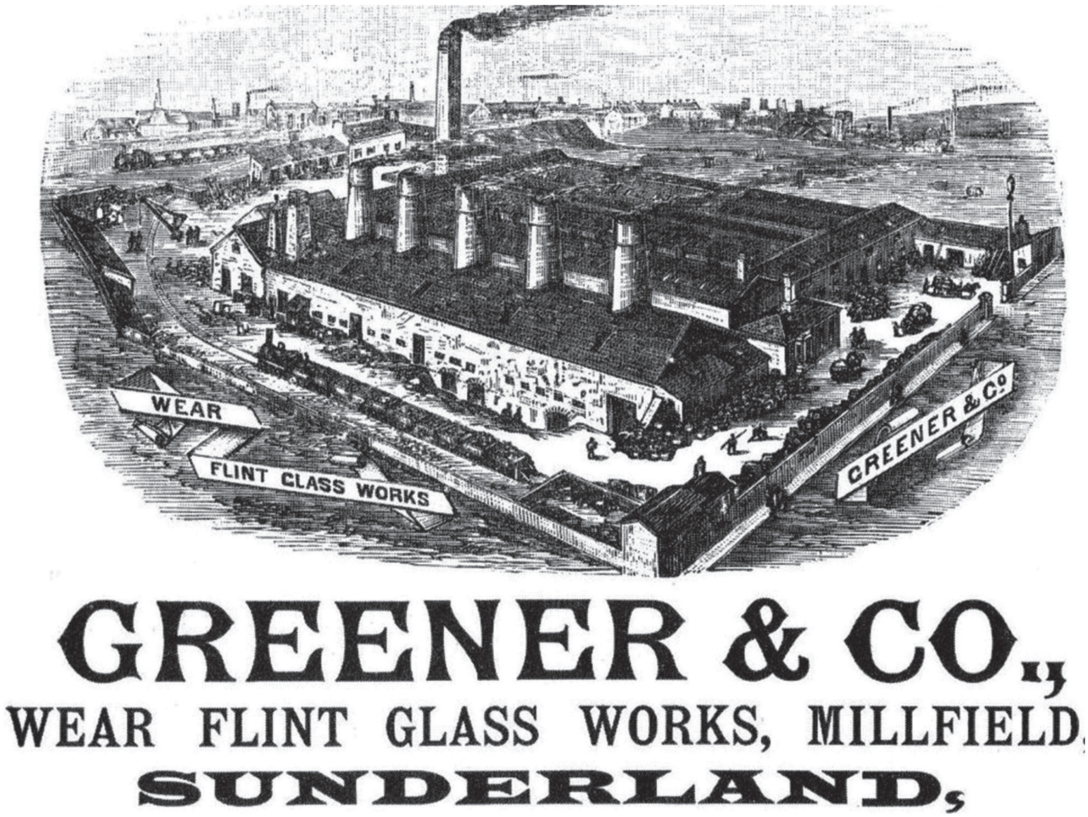

Fig. 2 A late nineteenth-century advertisement for the Wear Flint Glass Works.

to that of the late nineteenth century (see above). It is notable, however, that this map only depicts four flues along the southern part of the glasshouse, suggesting that at least one of the melting furnaces had gone out of use by the time of the publication of this map.

The most beneficial of the improvements introduced by Ernest Jobling Purser was the licence to produce and sell PYREX to Britain and the Empire (except Canada), which he gained in 1921. The manufacture of PYREX proved to be highly successful and a 60-ton tank furnace was constructed in 1927 with automated presses (Baker 1983, 8). This allowed the firm to expand this suite of glass products throughout the depression years, when other companies were suffering. Indeed, between 1926 and 1940, 42 designs were registered, many of which facilitated the production of dinner sets to match the ovenware (Hibberd 2007). In 1938, Flameware was introduced, which could be used in the oven and also on top of the stove. The form of the works during this period is depicted on the Ordnance Survey 1:2500 plan of 1941, which indicates that by this date the glassworks had nearly doubled in size (fig. 4).

Following the outbreak of the Second World War, the focus shifted entirely to the production of PYREX goods and, in 1949, Ernest Jobling Purser sold the company to Pilkington Brothers. The 1950s saw the development of an opaque white PYREX (Opalware, later called Tableware), which was even more resistant to changes in temperature. Opalware was used

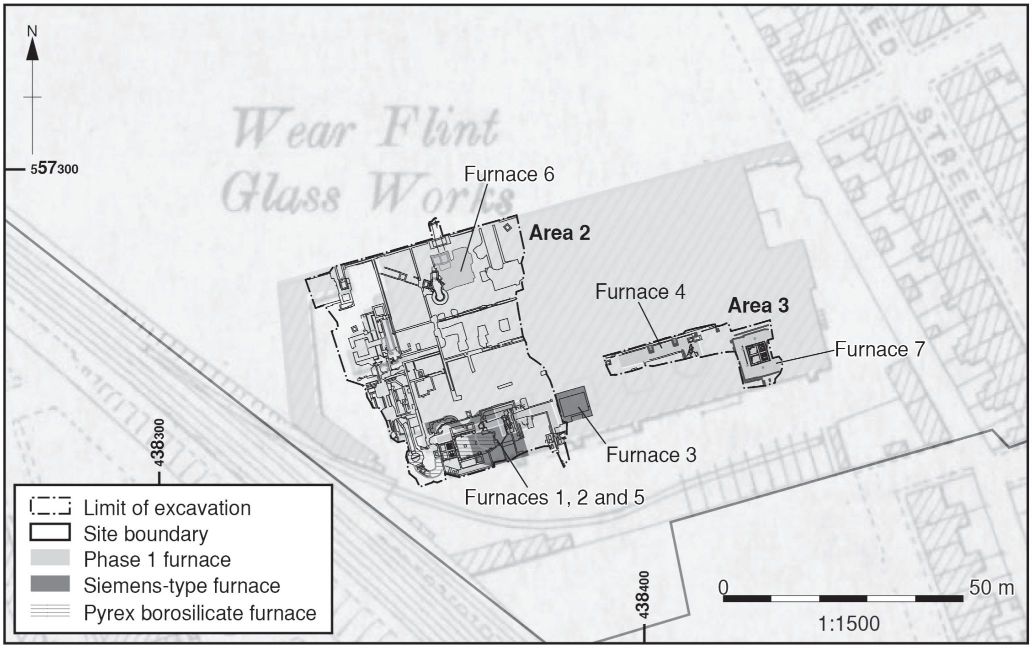

Fig. 3 Excavation areas superimposed on the Ordnance Survey, 1:2500 map, Second Edition 1897, Durham sheet VIII.14.

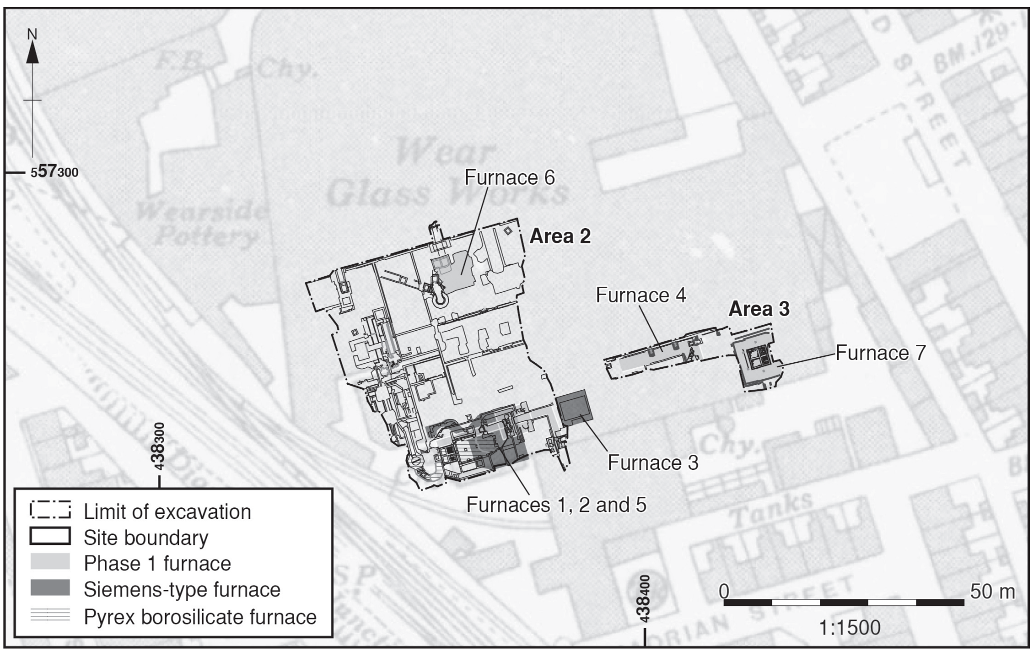

Fig. 4 Excavation areas superimposed on Ordnance Survey, 1:2500 map, Revision of 1941, Durham sheet VIII.14.

extensively for the production of dinner sets, and these were produced increasingly with screen-printed enamel patterns (Hibberd 2007; Mauzy 2002). Pilkington eventually sold 60% of its shares to Thomas Tilling, and 40% to Corning & Co., and then, in 1973, Tilling sold his shares to Corning & Co., and the company was renamed as Corning Ltd. In 1994, the glassworks was sold to Newell Ltd, and then to Arc International,[4] and production ultimately shifted to France in 2007, marking the end of glass manufacture in Sunderland.[5]

TECHNOLOGICAL BACKGROUND

The Wear Flint Glass Works was operating within a period characterised by rapid advances in the technology associated with glass production, specifically that connected with the development of glass-melting furnaces and the raw materials used to produce glass. The following discussion focuses on those developments which have specific relevance to the remains encountered during the excavation, and also the types of glass that were produced at the works.

GLASS-MELTING FURNACES

Initially, during the early and mid-nineteenth century, most glassworks utilised direct coal-fired pot furnaces, and these were probably the type of furnace that was initially in operation in the Wear Flint Glass Works. Based on nineteenth-century descriptions, such furnaces normally comprised a square or rectangular brick-built structure, which was arched over with stone. The furnace base was normally divided into three compartments, the central one containing the grate, whilst on either side of this were firebrick seats (sieges), upon which the pots rested (Ure 1838, 580). When the furnace was in operation, coal was shovelled onto the grate, through a fire hole, and once combusted, the smoke/hot gases would be directed around the sieges, heating the pots. The exhaust gases would then travel up small vertical flues attached to the furnace. The furnace was also provided with either single or multiple flues, which allowed air to be drawn into it, to aid combustion (Crossley 2003, 173). Other features associated with these types of furnaces included an iron bar that was used to bind the walls of the furnace, to prevent it from swelling, and, in some instances, stone abutments and/other iron fittings that were wrapped around the exterior, which again were used to hold the furnace together (Ure 1838, 581).

In the mid-nineteenth century, glass production was radically transformed following the development of the gas-fired regenerative pot furnace by William and Frederick Siemens, which was patented in 1861.[6] The gas-fired regenerative pot furnace worked by using the hot exhaust gases produced by the furnace to preheat incoming combustion gases in chambers known as regenerators, which were positioned beneath the furnace (Bell 2002, 10). The chambers were packed with a checker work of unbonded bricks (known as the 'checker') stacked in a way that allowed hot gases to pass through, and hot exhaust gases leaving the furnace flowed downwards through one pair of regenerative chambers, imparting heat to the checker, on their way to the chimney. Once the bricks were sufficiently hot (after about 30 minutes), the direction of gas/air flow in the system was reversed (by the use of the 'switch room') and this allowed the checker to heat up the gas and air entering the furnace via the other pair of chambers, whilst the exhaust gases reheated the opposing pair of chambers (Hodkin and

Cousen 1925, 336). After another 30 minutes, the checker would be cooler and so the gas/air flow would be reversed and the cycle would start again.

A gas-producer unit supplied the required gas to the regenerative furnace. Within this unit a hopper fed coal onto a brick ramp, which led to an inclined grate. A fire on the grate produced heat, and an arch of firebrick above the grate also imparted heat to the coal as it travelled down the brick ramp, beginning the decomposition process before the fuel reached the grate itself. When mixed with air rising through the grate, these gases formed carbonic-acid gas (H_2CO_3), which then rose through the partially decomposed material above, onto which droplets of water were added via a small pipe, the resultant gases comprising carbon monoxide (CO) and hydrogen. The gas then rose into a flue that was linked to the regenerative chambers of the furnace (Douglas and Frank 1972, 117).

Another major advance in glass-furnace technology was made in the late nineteenth century with the development of the continuous-tank regenerative furnace, which allowed the continuous working of the furnace (Cable 1999–2000). The initial design for this type of furnace was initially patented by the Siemens in 1870,[7] and had been perfected by 1872, when a further patent was granted for the continuous-tank furnace.[8] The tank was constructed of refractory bricks and had two compartments, separated by a floating barrier, which comprised a melting end and a semi-circular working. The superstructure below the tank was essentially comparable to a regenerative pot-furnace, with two pairs of regenerative chambers (see above), although the continuous-tank furnaces possessed an additional passage, known as a 'cave', which was normally placed at the centre of the furnace, with the regenerative chambers on either side of it (cf. Rosenhain 1908, 71, fig. 7).

One disadvantage of the Siemens-type regenerative furnace was that the horizontal movement of air within the regenerative chambers did not produce an even distribution of heat (Hermansen 1929, 166). In order to combat heat loss, vertically set regenerative furnaces were therefore developed, which had the regenerative chambers built together in a vertical stack with well-insulated side walls (*ibid*., 1929, 170). Although in plan these regenerators were smaller in size than the Siemens-type horizontal regenerators, they were often deeply set into the basement of the buildings in which they were housed. Thus, a similar surface area for heat exchange could be created within a vertical regenerator, for a much smaller footprint, and with a more efficient flow.

An alternative glass-melting furnace, similar to the regenerative furnace, for reusing exhaust gas, was the recuperator furnace. The principle of the recuperator is simpler than the regenerative furnace, whereby cold air *en route* to the furnace passes adjacent to conductive tubes of hot exhaust air flowing towards a chimney, with heat being passed between the two. This simple process requires no switching mechanisms, with the intake air being constantly heated by the exhaust. Given their relative simplicity, the earliest recuperators pre-dated Siemens' regenerative furnace, and used cast-iron pipes (*ibid*., 1929, 177). However, these were susceptible to leakage, and many subsequent attempts to increase the reliability and efficiency of recuperators ended in failure. In the early twentieth century, however, gas-fired recuperator furnaces were developed that were made of refractory material, being thus less prone to leakage, and these offered a viable alternative to the Siemens-type furnace. These early twentieth-century recuperator furnaces included the Stein furnace, the Hermansen furnace and the Teisen furnace, which had two recuperative chambers, placed on either side of the furnace (Hodkin and Cousen 1925, 365–72), and end-port furnaces, which had a recuperative chamber positioned at one end of the furnace (Trier 1989).

THE GLASS

During the early nineteenth century, when production of press-moulded glass began in the Midlands, it probably used essentially the same glass recipe (potash, lead oxide and sand) that had been used in the blown lead-glass sector (Dungworth and Brain 2009; 2013). However, with the shift of the press-moulded glass industry to the North East in the later nineteenth century, it has been suggested (Latimore 1979, 32) that at least some of the success of this industry rested on its use of semi-lead glass, which contained less lead and a proportion of sodium and barium (cf. Angus-Butterworth 1948, 36). Latimore (1979, 32) has also suggested that while American and European manufacturers succeeded in using soda-lime-silica glass (presumably of a similar composition to that used for window glass and, from the later nineteenth century, increasingly for bottle glass), in England this recipe was deemed insufficiently durable for press moulding. The recent analysis of debris from a nineteenth-century glass house in Manchester suggests that a great variety of glass recipes were used, including ones with less lead and more sodium (Willmott *et al*. 2012), and also suggests that the traditional lead-crystal recipe (Dungworth and Brain 2009; 2013) was increasingly restricted to free-blown vessels (Willmott *et al*. 2012). Much of the press-moulded glass produced in Manchester was essentially a soda-lime-silica glass, although this usually also contained small amounts of lead.

The technical aspects of both the early production of PYREX and later developments are incompletely understood. PYREX was initially a borosilicate glass, and later specifications (e.g. PYREX 7740; Corning Glass Works 1987) indicate a silicate glass with 13wt% boron oxide (B_2O_3), 4wt% soda (Na_2O) and 2.3wt% alumina (Al_2O_3). While it is often assumed that all PYREX glass is a borosilicate, this is not always true. Borosilicate glasses have a very low rate of thermal expansion which allows them to be taken from an oven straight to a table without cracking, but during the early twentieth century, methods of tempering glass were developed which allowed for the production of toughened glass (Phillips 1941, 228–30). It would appear that PYREX for use in the home is now largely toughened soda-lime-silica glass; however, it is not clear when the change from borosilicate glass occurred. Both Flameware and Opalware achieved their heat resistance through tempering rather than the use of a borosilicate glass. Shaw and Evans (1983, 16) suggest that Flameware was an aluminosilicate glass (cf. Baker 1983, 10), but they describe Opalware as having a 'complex composition consisting of about 60% silica combined with many other constituents' (Shaw and Evans 1983, 17). The glass-ceramic materials such as Pyroceram produced from the 1950s were often lithium-aluminium-silicate (spodumene) glasses, but a range of other elements were introduced (e.g. magnesium, zinc, titanium and fluorine; Vogel 1985). The heat treatment of these glasses could lead to devitrification (crystallisation) or to microphase separation. In the latter case, two immiscible glasses form and separate, but the separation is usually at the 1 μm scale (*ibid*.).

EXCAVATED REMAINS

The excavated remains relating to the nineteenth- and twentieth-century glassworks were present in Areas 2 and 3 (figs 3 and 4). Significantly, these could be divided into three main phases of activity, which relate to the known history of the site and concomitant adoption of improved/specialised glass-melting furnaces within the glassworks.

PHASE 1. THE POT-FURNACE WORKS: *C.* 1869 (GREENER GLASSWORKS)

Evidence relating to the primary phase of the glassworks was exposed in both Areas 2 and 3, and comprised the fragmentary remains associated with a pot furnace (Furnace 1; fig. 3) and several lengths of walling, which defined both the exterior of the glassworks and interior rooms. All of these remains were probably built in *c*.1869, when the glassworks was established by Henry Greener, and they largely dictated the functional use of space within the glassworks throughout its working life.

Internal Layout

Within Areas 2 and 3, several Phase 1 red-brick walls were present, laid in a three-stretcher English Garden Wall bond, which were set on irregular sandstone-block foundation plinths, bonded with lime mortar. Of these, wall [249] formed the northern external wall of the Phase 1 glassworks, whilst wall [251] was a substantial north/south-aligned internal division across the complete width of the works (fig. 5). The area to the west of wall [251], at a later date at least (Phase 3), appears to have been associated with the power plant and an annealing house (see below), whilst the area to the east housed the glasswork's furnaces, and preparation and storage areas. Inside the glassworks, the furnaces (see below) were to the south of wall [245], whilst the preparation and storage areas were to the north.

This latter area was associated with seven rooms (Rooms A–G), on either side of a 33 m-long, north/south-aligned wall, [246], which returned eastwards at its southern end to link with wall [245]. Rooms E–G were to the east of wall [246] and were generally larger, with Room E having a width of 15.2 m (50 ft), and Rooms F and G being 7.62 m (25 ft) wide. Room G was also divided into two by north/south-aligned wall [247] (keyed into wall [248]), which divided it from Room F.

Rooms A–D were to the west of wall [246], and all were 7.62 m (25 ft) wide, with Rooms B and C being separated by a 0.7 m (2 ft 3 in)-wide passageway defined by walls [252] and [253]. Room B contained post-sockets and the shadows of machine bases, along with a slot, [207], which may have marked the position of a small flywheel, whilst Room D contained three small chambers, [209–11], one of which, [209], had a sloping floor.

Furnace 1

Furnace 1 was defined by two sections of 1.21 m (4 ft)-wide, handmade red-brick walling, [222] and [229], on either side of a wide flue, [226] (fig. 6). Both walls had been cut into the natural clay and also had projecting returns on their western faces, each containing large quantities of broken bricks within their 'core'. Significantly, these return walls overlay heat-affected natural clay, which indicated that the main body of the pot furnace lay to the west of the extant walls.

The centrally positioned flue [226] was a sub-surface feature, 1.68 m (5 ft 6 in) wide. As with the other remains associated with Furnace 1, it was fragmentary and had originally been constructed of handmade red brick, laid in a four-stretcher English Garden Wall bond. Initially, the flue ran out eastwards from Furnace 1, and then turned through a right-angle to continue in a southward direction. The bull-nosed inner return of the wall survived, but the outer return had been removed for almost its entire length following the insertion of a later furnace (Furnace 3; see below). At its southern end, part of the crown of the flue did, however,

Fig. 5 High level view of the excavated remains in Area 2.

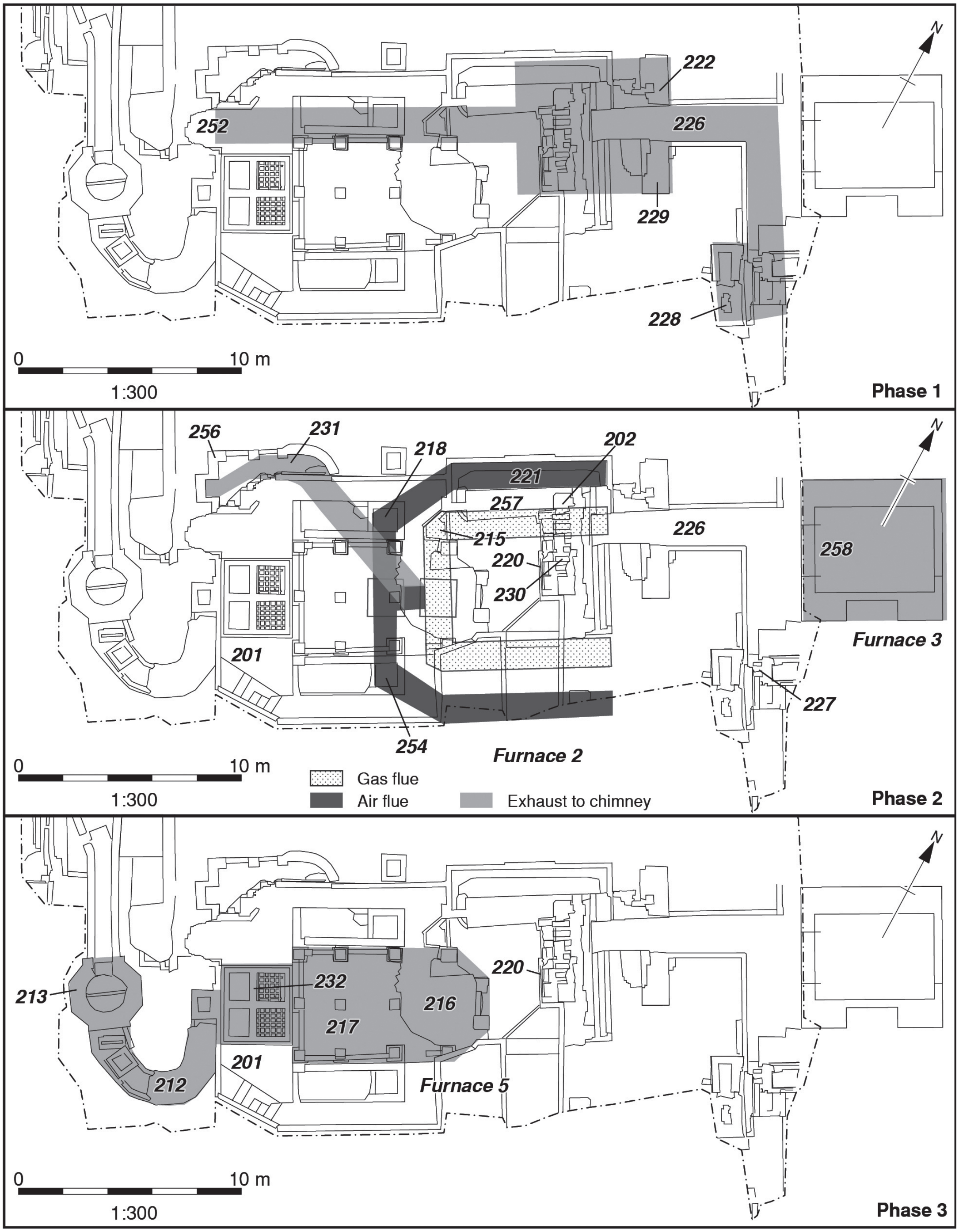

Fig. 6 The excavated furnaces in Area 1.

Fig. 7 Flue [226] (right) and tunnel [228] (left).

survive, which was directly adjacent to contemporary tunnel [228], parallel with the flue (figs 6 and 7). The tunnel had a westward return and it probably allowed access to the main floor level within the glassworks, either via stairs, or more likely a ramp, in order for coal from the yard to be delivered to the furnace, as well as the raw materials needed for glass production.

To the west of Furnace 1, placed against the original external wall of the glassworks, was a further vaulted passage, [252] (fig. 6). This was of similar size and construction to flue [226], but retained its full-brick-thickness crown at its western end. It clearly formed part of the same flue as [226], providing the furnace with a through draught as well as additional access.

PHASE 2: SIEMENS-TYPE CONTINUOUS TANK FURNACE WORKS: LATE NINETEENTH/ EARLY TWENTIETH CENTURY (JAMES A. JOBLING & CO. GLASSWORKS)

The excavated remains indicate that at some stage in the late nineteenth/or early twentieth century the glassworks was remodelled in order to house Siemens-type continuous tank regenerative furnaces, two of which (Furnaces 2 and 3) were uncovered in Area 2. The precise date of this remodelling is difficult to ascertain, though it must post-date the early 1870s (see above). Moreover, based on the known history of the site, it is possible that the installation of these improved furnaces related to specific changes in the ownership of the works. For instance, in 1886 the works was taken over by James Jobling (see above), and one possibility is that some continuous tank furnaces were installed during his ownership. Tellingly, however, James Jobling did not fully invest in the glassworks, which may suggest that he was not responsible for the installation of a complete suite of new furnaces. Indeed, the complete 'modernisation' of the works probably fell to his nephew, Ernest Jobling Purser, who joined the firm in 1902 and introduced new technological improvements (see above). Given this, it is possible that the excavated continuous tank furnaces date to either the late nineteenth and/or early twentieth century.

Apart from the regenerative furnaces in Area 2, several other Phase 2 structures were identified. These included a gas producer, also in Area 2, supplying Furnaces 2 and 3, and fragmentary remains which may have formed elements of another regenerative furnace (Furnace 4) in Area 3.

Furnace 2

Within Area 2, the piecemeal remains of a Siemens-type regenerative furnace were encountered (fig. 6). These comprised a large 0.91 m (3 ft)-thick wall [230], surviving to a similar height, with a basal course of red brick and an upper course of refractory brick. The central 3.65 m (12 ft)-long basal section of the wall was, however, covered with 0.76 m by 0.23 m by 0.13 m (2 ft 6 in by 9 in by 5 in) refractory blocks, placed transversely across the wall, with 0.18 m (7 in)-wide air gaps between. Above these were two courses of mixed refractory and red bricks, below a further row of blocks, which were capped with a surface of heavily degraded refractory slabs, measuring *c.* 0.91 m by 0.3 m (3 ft by 1 ft). Several of these slabs were covered with vitreous splashes, suggesting that this represented the working floor-level of the furnace.

The blocks beneath the slab floor butted the rear of another wall [202], formed of large refractory blocks, which formed the end of the tank furnace, with chamfered blocks in the upper course representing 'tuckstones', forming the interface between the tank base and side walls (cf. Trier 1989, 22–3). In the centre of this tank wall, a 0.91 m (3 ft)-wide column rose above the wall on either side. The inner face was heavily corroded and glazed by glass metal and, although its exact purpose remains unclear, it possibly related to the framing of a gathering port, several of which would have been placed around the working end of the tank. The surface of this pier was also coated with pools of vitreous waste, possibly as a result of spillage during gathering.

A passage, [221], on the north side of the furnace (fig. 6), almost certainly represented the remains of the furnace's northern air flue, whilst the northern gas flue appears to have reused the central flue [226] of the earlier furnace (see above), which had been narrowed for use within the regenerative furnace. In addition, the southern side of air flue [221] was overlain by a machine-made, red-brick wall, [257], with a return at its eastern end, and this appeared to have formed the outer wall of the tank furnace. It had 2.3 m (7 ft 5 in)-wide, rebated double relieving arches in both the north and east faces (fig. 8), and presumably it originally continued around the southern and western side of the furnace, with similar arches to each face, those on the east/west alignment almost certainly forming a central cave, given the positioning of the gas and air flues.

To the east of the main furnace body, three apertures, [215], [218] and [254], were present, which probably formed the switch room access hatches associated with Furnace 2. The two

Fig. 8 External wall [257] of Furnace 4, and its northern relieving arch.

square chambers, [218] and [254], were placed to the rear of the smaller, angular hatch, [215], and represent the access into the air flues, which ran along the outer sides of the narrower gas flues. Flues would have led from the eastern side of both openings, on an angle demonstrated by the western side of [215], which represented the northern of a pair of access hatches for the gas flues. Short flues would have led from each pair to a further central aperture, that would have housed the switching valves/dampers, allowing the flow of air and gas to be reversed between each pair of flues.

Other features associated with Furnace 2 comprised a flue and chimney base. The flue was defined by a curving refractory brick wall, [231], which led northwards from the switch room to chimney base [256]. This base would have supported a 1.21 m (4 ft)-wide, square-sectioned chimney.

Furnace 3

The remains relating to a second Siemens-type regenerative furnace (Furnace 3) were also encountered, immediately to the east of Furnace 2, the construction of which had entailed the destruction of part of flue [226], associated with the earlier pot furnace (Furnace 1; see above). These remains were, however, only recorded in plan, as they lay beyond the excavation area

Fig. 9 Furnace 5 and its cave opening.

(fig. 6). The remains comprised wall [258], defining a rectangular structure, which had narrowed in one section, indicating the presence of an arch at its southern side. The wall was faced externally with red brick, with piers of yellow refractory brick placed in the south-western and south-eastern corners. On the eastern side of this furnace, an arched opening for a centrally positioned passageway was also visible (fig. 9). This marked the position of the furnace's cave, which was accessed from flue [226], once associated with the now redundant Furnace 1 (see above). Other features connected with this furnace included a series of joist sockets within its western elevation, and fragments of 0.05 m (2 in)-thick refractory tile at its south-eastern corner that were probably associated with a floor level.

Furnace 4

Within Area 3, the piecemeal remains of another potential Phase 2 furnace were exposed, though the main body of this appears to have been to the south of the excavation trench. These remains included a small flue and wall, [304] (fig. 10). The wall was of refractory and red-brick construction, and may have formed the northern side of a furnace that had a length of 8.23 m (27 ft). A flue, [302], was immediately to the east, and probably served this putative furnace. It was made of refractory bricks and was capped with square flags of refractory

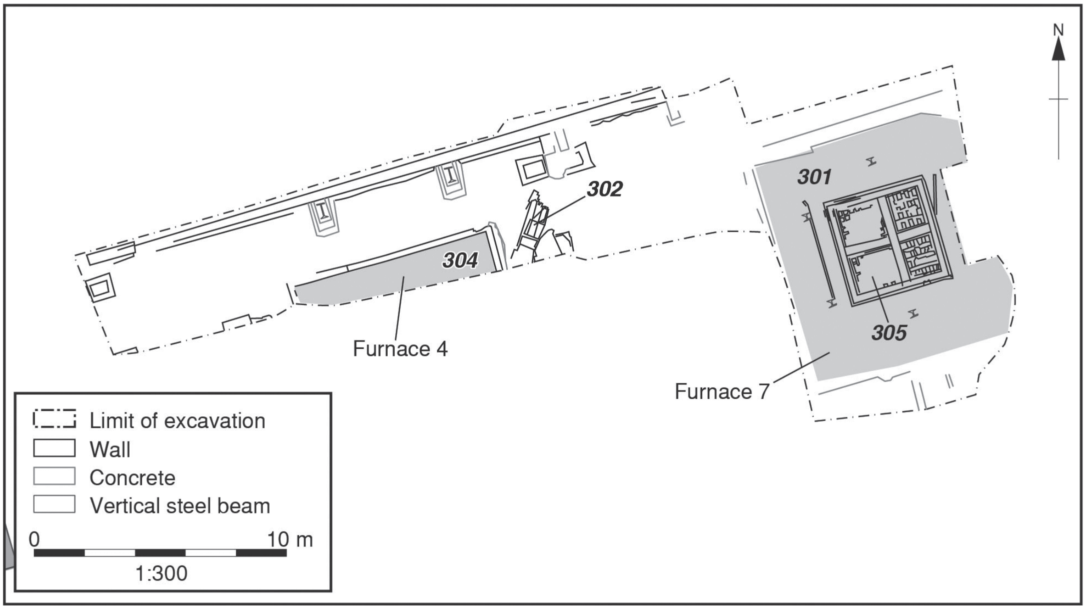

Fig. 10 Furnaces 4 and 7 in Area 3.

material. The refractory bricks were stamped with 'NHC', possibly the stamp of the North Hetton Coal Company, owners of Moorsley Colliery, where an extensive firebrick works was in production in the early 1890s (Kelly 1890), suggesting that this furnace was constructed when James Jobling was running the glassworks.

Gas Producer

The remains of a gas producer were encountered in Area 2, which probably supplied the gas required by Furnaces 2 and 3 (fig. 6). This lay to the south of these furnaces and had been inserted into flue [226] (associated with Furnace 1; see above). The structure was only partially revealed within the side of the trench, but comprised a vertical, 1.21 m by 0.91 m (4 ft by 3 ft) chamber, [227], with two flues above its southern side. The chamber was braced with vertical steel I-section stanchions, with transverse and lateral tie rods between, incorporated into the construction of the refractory-brick-lined walls. The inner faces of the chamber were covered in a fine tar-like residue, which thickened towards the base, whilst the bottom was filled with fine clinker, indicating that it was a coal- and water-fired producer. The front wall, which had almost entirely collapsed, probably housed an inclined grate, and beneath this, a pan of sheet iron would have been placed, within the ash pit, providing the water vapour to induce the optimal reaction.

The gas produced by this structure rose into a central rear flue, which was placed on a concrete base, carried on steel beams across earlier flue [226]. Moreover, the short length of the gas flue from the producer, and an apparent rear wall on its southern side, suggest that the flue rose vertically, probably into an iron-sheet flue, which could feed flues leading to the switch rooms of the furnaces.

Fig. 11 Columns supporting the tank of the PYREX furnace.

PHASE 3: THE PYREX GLASSWORKS (JOBLING/CORNING LTD GLASSWORKS): 1921–2007

The final phase of activity associated with the operation of the glassworks dates from the 1920s until the latter part of the twentieth century, and relates to the period when the works was engaged in the production of PYREX goods. The remains relating to this phase included three furnaces, two (Furnaces 5 and 6) in Area 2, and the other (Furnace 7) in Area 3.

Furnace 5

The construction of Furnace 5 entailed the near-complete removal of the earlier Siemens-type regenerative furnace (Furnace 2; see above) in this part of the glassworks. A new room was also created around Furnace 5, with its floor placed at approximately the level of the bottom of the tank of the earlier Siemens furnace, with associated walls of both red brick and concrete shuttering inserted.

The surviving remains associated with this furnace indicated that it formed a continuous borosilicate, end-port, recuperative furnace (fig. 6). These remains included 13 brick piers, which supported the furnace tank (fig. 11). The piers consisted of two-brick, 0.46 m

Fig. 12 Detail of recuperator tubes.

(18 in)-square, refractory-brick columns placed on a three-course tiered base, and nine piers, set in a 4.87 m by 4.72 m (16 ft by 15 ft 6 in) rectangle, which formed the 'melt end' of the furnace. The four remaining piers forming the rounded 'working end' of the furnace.

The piers, and the furnace outline they defined, overlay an 0.21 m (8 in)-thick floor of heavily burnt and oxidised refractory tile, [216] (fig. 6). For the majority of the melt end of the furnace, this was bounded by two to three courses of refractory brick, which formed a boundary wall to a large flow of glass metal, [217], which covered most of floor [216]. This appeared to represent the standard procedure for emptying the tank above, although it presumably held less metal, when emptied for maintenance, than it did after its final firing.

The other main element of Furnace 5 was a vertical recuperator stack, [232], measuring 3.35 m by 2.90 m (11 ft by 9 ft 5 in), which lay to the west of the tank. This structure comprised four vertically set chambers of refractory-brick construction within an outer skin of red brick, which was bound by vertical iron stanchions and rails. The two eastern chambers, nearest the tank, were 1.21 m (4 ft 2 in) square, whereas the rear two were slightly smaller, measuring 0.91 m (3 ft) across, on the east/west axis. Although the rear two chambers were empty, the front chambers did retain vertically set, square-section ceramic pipes, on a five by five grid, each having its internal corners rounded, to aid the flow of air (fig. 12). Access ports into the recuperator tubes were observed in the southern face of the external wall, with an area of rebuilding below, suggesting the replacement of a leaking tube.

The base of the recuperator was not identified during the excavation, as this was placed below the limit of excavation. This is to be expected, however, as the chamber of a recuperator stack normally penetrated ground level to a considerable depth (cf. Trier 1989, 13). Although the base of the stack was not observed, as this lay beneath the water table, concrete steps positioned to the south would have afforded access to both it, and the cellar level of the furnace. The furnace was also associated with a concrete floor, [201], and a drain, [220], which contained glass waste (this was subjected to chemical analysis; see below).

The recuperator of Furnace 5 was connected to an octagonal-shaped chimney [213], via flue [212] (figs 5 and 6). This flue incorporated a square-shaped access manhole, into its crown, which may have housed a damper, intended to control the flow rate of exhaust entering the chimney. A similar access, placed immediately to the rear of recuperator [232], presumably regulated the exhaust flow from the furnace.

Furnace 6

Several Phase 3 structures were present to the north of Furnace 5 (fig. 5), and these appear to have formed elements of a vertically set regenerative furnace (Furnace 6). This was defined by a concrete base covering 7.5 m^2, and a twin-chamber rectangular structure, [225], which formed the remains of the regenerator. Significantly, within the rubble infill contained within the surviving chambers were several square-section refractory bricks, typical of regenerative checkers. The size of the surviving chambers also differed, with that on the western side being narrower, representing the gas intake to the furnace, whilst the wider would have supplied the furnace with air.

The regenerator, constructed in refractory brick, was externally faced on its southern and eastern sides with a skin of red brick, and its northern side was shuttered with concrete and metal sheeting. Some of the refractory bricks were also stamped with 'BURNAXE' and 'DOUGLAS-D', and these indicate that this furnace dates to the early twentieth century, when the works was operated by the Jobling family. For instance, those stamped with 'BURNAXE' were produced by the Burn Fireclay Co. at the Stobswood Brickworks near Morpeth, which commenced production in the 1860s using surface clay, although the modern fire-brick-making enterprise began in 1923, when the Stobswood Coal Company began making bricks at Stobswood Colliery, using clay extracted from beneath two of the coal seams in the colliery (Davison 1986). Similarly, those stamped with 'DOUGLAS-D' were also produced in the early twentieth century, by the Douglas Firebrick Co. Ltd of Dalry, Ayrshire, which was in operation by 1917, and remained in production until 1945 (*ibid*.).

Immediately to the south and north of the regenerator were several flues, which probably served Furnace 6. Two short, brick-built flues, [260 and 261], were located to the south and, of these, flue [261] was closed with an iron sheet, placed immediately behind an iron lintel, apparently representing the corroded remains of a butterfly valve. Both flues led to a circular red-brick chimney [203], lined with a single skin of refractory brick (fig. 13). Flue [263] ran directly from the northern side of the regenerator stack, measuring only 0.91 m (3 ft) wide, and 0.76 m (2 ft 6 in) high. It had an external skin of red brick to either wall, with a slightly cambered floor, and was at a lower level than flues [260] and [261], demonstrating that the depth of the regenerator was in excess of 5 m.

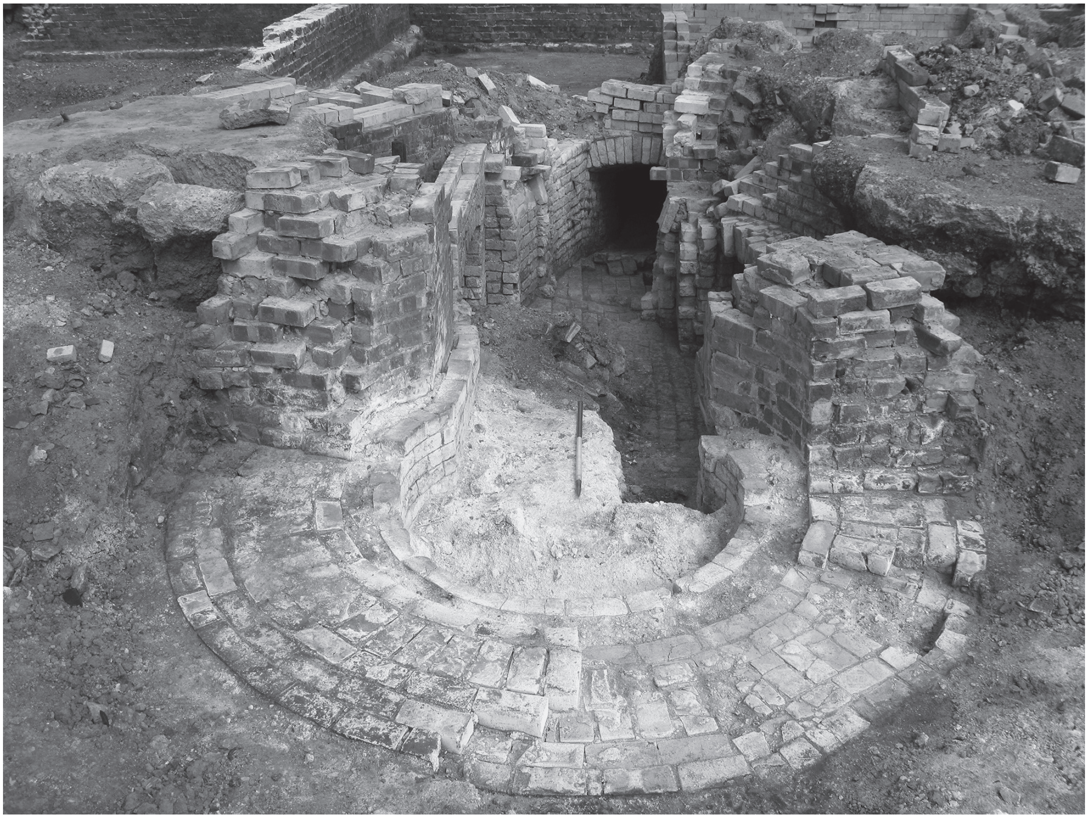

Fig. 13 Chimney [203] with flues [260] and [261] to the rear.

In addition, another flue, [206], extended in a north-western direction from chimney [203]. However, this was probably designed to emit exhaust gases produced in another part of the works. This flue contained two access hatches/damper housings and a probable iron-sheet butterfly valve, the position of which was denoted by a brick scar.

Furnace 7

The last furnace was located in Area 3 and formed a vertically set regenerative furnace associated with the twentieth-century works (fig. 10), contained within a concrete chamber, [301], and surviving to an exposed height of approximately 4 m (fig. 14). Its outer sides were made of red brick, bearing a 'CELL-O-BRICK' stamp, laid in three-stretcher English Garden Wall bond, with refractory-brick headers. The interior comprised four chambers built entirely of refractory tiles, many stamped 'DOUGLAS-D', implying that it was probably built at a similar time to Furnace 6 (see above). The lining of each of the four internal chambers, and the checker within, were constructed of edge-set refractory blocks, some of which bore the additional stamp '5'. Fragments of white PYREX glass were recovered from the fill of the chambers, one bearing the word 'Cornings'. The checker was supported by segmental arches

Fig. 14 Furnace 7.

from the north to south wall of each chamber, supported at the sides by angled springers set into the side walls, which related to flues supplying the furnace.

The whole structure was braced by horizontal steels, supported by four, vertically set, I-section steel joists. Two were placed on the west side of the furnace, with the other two set slightly wider, in the middle of the north and south sides. At the base of Furnace 7, steel doors placed on the outside of the north and south walls formed dampers, allowing control of the gas flow, and access to inspect the refractory chambers. They were set within rails, and were operated by sliding vertically. There was also a removable block observed in the south exterior wall of the south-east chamber, and as this was placed within the highest surviving part of the furnace, it is possible that such a feature may once have been present on all sides.

Ancillary Areas

In Area 2, whilst chimney [213] was linked to Furnace 5, it also served buildings to the north-west, evidenced by a flue, [214], extending from the northern side of this structure (fig. 5). Within the chimney base, this flue was separated from that serving the furnace by a central partition wall, which was probably intended to allow separately controlled exhaust from each flue, in order to avoid the mixing of waste gases.

Flue [214] appears to have been connected to a pair of boilers housed in Boiler Room [236]. This room had certainly been a hot working area, incorporating refractory-brick floors, and the remains of several flue dampers and refractory-brick-built walls were reminiscent of the layout of a Lancashire-type boiler. The brick floors to the north, [237–9], also appeared typical of an annealing house, comprising several layers of unbonded brick, some of which appeared heat-damaged. Several rectangular structures with refractory-brick linings appeared to represent small heaters, designed to control the temperature within the annealing house. Within this area, the manufactured glass vessels would have been subjected to slow cooling in order to alleviate internal stresses in the fabric of the glass (Hodkin and Cousen 1925, 43). This area had been heavily remodelled, however, presumably as annealing technology and mechanisation increased, and also as the glassworks switched from pressed-glass to PYREX production.

Dumps of Waste Glass

Several areas and structures were identified that were associated with fairly sizeable dumps of twentieth-century glass waste, samples of which were subjected to chemical analysis. These dumps were associated with: flue [231] associated with Furnace 2 (fig. 6); flue [302], forming part of Furnace 4 (see above; fig. 10); floor [201] associated with Furnace 5 (see above; fig. 6); chimney [203] and stack [225] associated with Furnace 6 (see above; fig. 5); and chamber [301], containing Furnace 7 (see above; fig. 10). Other dumps were located between Furnaces 5 and 6, and included: a deposit of clinker and glass waste beneath the floors of connecting chambers [209], [210] and [211], in Room D; a dump within slot [207], in Room B; and a dump in Room F (see above; fig. 5).

GLASS ANALYSIS

The archaeological excavations recovered material evidence for the manufacture of a range of glass products. This material comprises a range of finished glass artefacts and waste (especially threads), as well as other categories such as clinker and possible raw materials. The types of waste and the range of finished glass artefacts suggest that most of the material recovered relates to the manufacture of twentieth-century utilitarian ware, as there were no clear examples of nineteenth-century glass.

METHODOLOGY

All of the material considered was examined visually following standard procedures, and was then sorted into categories based on colour and form (cf. Dungworth and Cromwell 2006; Paynter and Dungworth 2011). The visual examination of the glass and glass waste was also supplemented by qualitative chemical analysis on select samples.

The samples were prepared using standard metallographic procedures (Vander Voort 1984): all samples were embedded in epoxy resin and ground and polished to a 1 μm finish. Polished samples were examined using optical and scanning electron microscopes to determine the nature of any surface treatments, as well as any corrosion. Chemical composition was determined using a bench-top energy dispersive x-ray fluorescence (EDXRF) spectrometer and an energy dispersive x-ray detector attached to the scanning electron microscope (SEM-EDS). The former technique provides better sensitivity for a range of minor elements (e.g. arsenic and strontium), while the latter technique provides better sensitivity for light elements.

The EDXRF was used both to identify the major glass types, such as soda-lime-silicate and borosilicate, as well as the use of some elements to colour (or decolourise) the glass. In several cases the analysed glass or glass waste appeared to contain only silicon; these samples are almost certainly borosilicates.

MATERIALS EXAMINED

Raw Materials

A substantial (18.7 kg) sample was taken of a white to pale green crystalline, but rather friable material. This is soluble in water and EDXRF failed to detect any significant x-ray peaks. It is boron oxide used in the manufacture of PYREX.

Colourless Glass

Most of the material examined (35 kg) comprised colourless glassworking waste and artefacts. The limited range of artefact types and the recurrence of identical forms suggest that these represent items produced at this site. A few of the forms are repeated in coloured glass.

The forms of finished glass identified include oval casserole dishes of a type first introduced in the 1920s. This form continued to be popular and remained in production throughout the twentieth century (Evans 1983, 34). One example has a PYREX logo which bears a ligatured JP monogram; this may refer to Jobling Purser. The best known UK PYREX logo was the crown, introduced in 1953 (*ibid*.), but the chronology of earlier logos is poorly known.

The remaining colourless glass is dominated by small jugs or tankards (cylindrical, octagonal and fluted), and a wide variety of bowls and ash trays. Some bowls bear the legend, 'BRITISH MAKE', suggesting they were made for export to the USA between the World Wars. The simple nature of the form and decoration of most of these vessels suggests they were manufactured after the First World War. The assemblage also includes several large domed objects of uncertain function.

Coloured Glass

Coloured glass vessels and working waste (13 kg) were present in a wide variety of colours, including several shades of green, red, blue, opaque white, orange and black. Most of the coloured glass (8.3 kg) comprised large fragments of unstratified blue and green tank metal. Green glass was relatively abundant and the most commonly identified form was the ash tray. Many colours were represented by a relatively small number of rather small fragments (e.g. only 0.2 kg of red glass) and some uncertainty remains as to whether all of the coloured glass was actually produced at the Wear Flint Glass Works. The opaque white vessels and waste appear to be made examples of Tableware or Caterware.

Crucible and Tank-furnace Fragments

In total, 16.8 kg of crucible and tank-furnace bricks were examined. Several fragments have adhering glass (blue and colourless), while another has a friable vitrified surface, suggesting that it is a fragment of the roof (crown) of the furnace and that the vitrification has occurred through the action of volatile alkali (sodium).

Miscellaneous Vitreous Materials

A quantity of 9.5 kg of devitrified glass waste was examined. This material was probably produced (accidentally) during the manufacture of glass at the site, but it may have undergone a variety of reactions, which will have altered its chemical composition (e.g. glass-ceramic interaction; cf. Dungworth 2008).

In addition, 3.1 kg of clinker and other black vitreous materials were examined. These are likely to represent material which formed during the combustion of coal and may be related to the operation of a glass-melting furnace; however, this said, most glass-melting furnaces from the late nineteenth century onwards have been heated using gaseous fuels (Phillips 1941). One fragment of black slag also contains minor amounts of zinc and nickel and is unlikely to be waste from the glass industry.

Glass Produced Off-site

A total of 2.4 kg of finished glass was identified as not having been made at the Wear Flint Glass Works. This includes window glass, milk bottles and green glass bottles bearing maker's marks on the bases.

CHEMICAL ANALYSIS

The visual examination of the glass indicated some of the range of glass types that were manufactured at the Wear Flint Glass Works. This included some borosilicate PYREX, some Opalware and soda-lime-silica glass. Further details on the nature of the glass were investigated through the quantitative chemical analysis of select samples (Table 1).

It was anticipated that some of the samples would contain boron, and while considerable effort was expended in trying to measure the boron content of all samples directly, this was ultimately unsuccessful. Nevertheless, it is possible indirectly to assess the possible boron content of these samples. The analysis of a range of glass standard reference materials suggests that the difference between 100 wt% and the total of all detected elements is the boron oxide content. The analysed samples have been divided into a number of categories based on their glass composition.

Borosilicate Glasses

Twenty-two samples of borosilicate glasses were identified. Based on their chemical composition, these could be subdivided into two different categories (Borosilicate1 and Borosilicate2).

Borosilicate1 (LISB#1, LISB#3–6 and LISB#17)

Six samples contain high levels of silica (*c.* 80 wt%), small amounts of soda (*c.* 4 wt%; fig. 15) and alumina (*c.* 2 wt%), and analysed totals which are both sufficiently and consistently low to suggest that they contain boron (10–15 wt% of the oxide). The apparent composition of this

Table 1 Details of materials sampled for analysis (note: sample number LISB#49 was not used).

Context	Sample	Description	Glass Type
Floor [201] (Furnace 5)	LISB#28 & #29	Colourless press-moulded vessel	Soda-lime1
	LISB#30 & #31	Colourless waste (lump)	Soda-lime1
	LISB#32–#36	Colourless waste (thread)	Soda-lime1
Chimney [203] (Furnace 6)	LISB#01 & #03	Colourless waste (dribble)	Borosilicate1
	LISB#04	Colourless vessel (circular, mould number 168-B)	Borosilicate1
	LISB#37–#40	Colourless vessel	Borosilicate2
	LISB#41–#44	Colourless waste (lump)	Borosilicate2
	LISB#45–#48	Colourless waste (thread)	Borosilicate2
Slot [207] (Room B)	LISB#05 & #06	Colourless vessel (oval, casserole dish)	Borosilicate1
Glass dump below chamber [209] (Room D)	LISB#02	Colourless beaker with fluted walls	Soda-lime3
	LISB#07	Colourless press-moulded vessel (failed, waste)	Soda-lime3
	LISB#08	Colourless press-moulded vessel (base)	Ungrouped
	LISB#10 & #11	Colourless waste (thread)	Soda-lead crystal
Glass dump below chamber [210] (Room D)	LISB#09	Colourless press-moulded vessel	Soda-lime2
Glass dump below chamber [211] (Room D)	LISB#12	Blue waste	Ungrouped
Drain [220] (Furnace 5)	LISB#16	Colourless press-moulded vessel (dish)	Soda-lime3
	LISB#17	Colourless waste (droplet)	Borosilicate1
Glass dump in Room F	LISB#18	Colourless press-moulded vessel (ash tray)	Soda-lime2
Stack [225] (Furnace 6)	LISB#19 & #20	Colourless cone-shaped object (large)	Borosilicate2
	LISB#21	Colourless waste (thread)	Borosilicate2
Flue [231] (Furnace 2)	LISB#22	Green press-moulded vessel (ash tray)	Soda-lime3
Chamber [301] (Furnace 7)	LISB#13	Ceramic with adhering glass	Soda-lime3
	LISB#13c	Fragment of tank wall	Ungrouped
	LISB#13g	Glass adhering to tank wall (LISB#13c)	Ungrouped
	LISB#14	Blue glass adhering crucible (LISB#15)	Ungrouped
	LISB#15	Crucible with adhering blue glass (LISB#14)	Ungrouped
	LISB#23	Opaque white cup (base glass) + blue decoration	Opalware
	LISB#24	Opaque white cup	Opalware
	LISB#25	Opaque white waste (dribble)	Opalware
	LISB#50	Devitrified waste?	Ungrouped
Flue [302] (Furnace 4)	LISB#26 & #27	Colourless waste (thread)	Soda-lime2

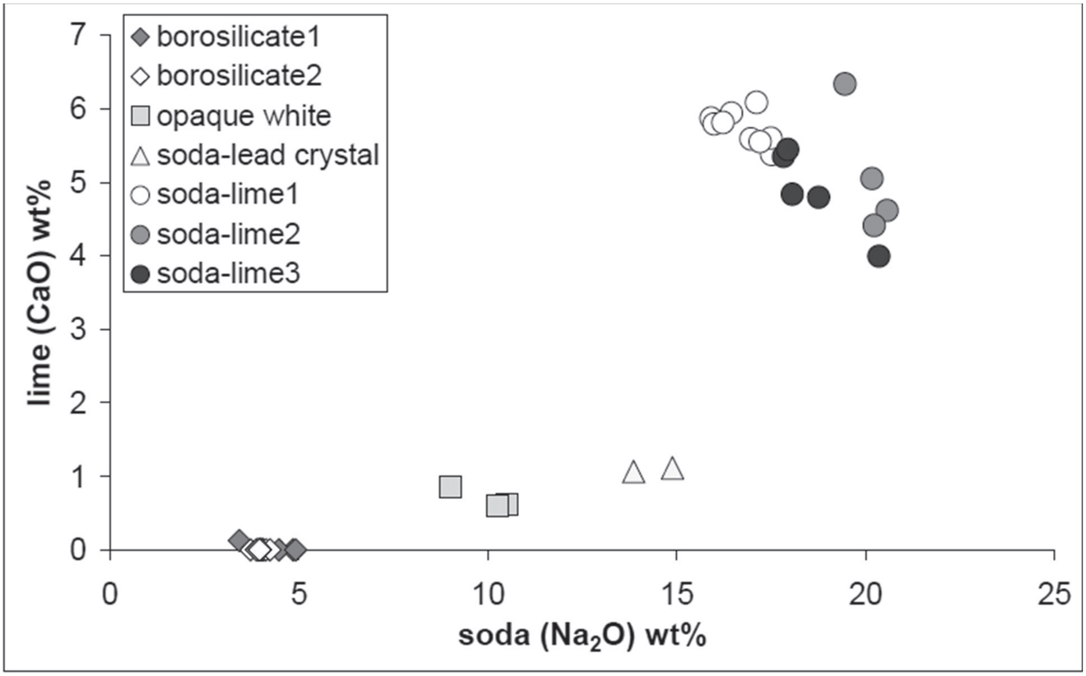

Fig. 15 Soda and lime content of the analysed glass and glass-working waste.

glass (Table 2) corresponds closely to PYREX 7740, developed in the early twentieth century and made at the Wear Flint Glass Works under licence from Corning & Co. (Corning Glass Works 1987).

The borosilicate1 glass samples are also characterised by very low levels of other elements, in most cases no other elements being detected. The glass contains small amounts of iron (fig. 16), although these are the highest levels of iron among all of the colourless glass samples analysed. The glass consistently contains small amounts of arsenic, which was presumably added deliberately to refine the glass (and possibly to reduce the colouring effect of the iron present). The vessel fragments that could be identified included the classic PYREX oval casserole dish. The form of the logo on the PYREX oval dish shows that this was manufactured prior to 1953.[9]

Borosilicate2 (LISB#19–21 and LISB#37–48)

In total, 15 samples of borosilicate2 were identified, with a composition which is similar to borosilicate1, but with less iron (fig. 16), no arsenic, but some zirconium (Table 2). The borosilicate2 glass includes fragments of production waste (threads, etc.) and a limited variety of vessel forms. Some of the vessel fragments were so small that it was difficult to propose what sort of vessel they were.

The only substantially complete objects were large cone- or bell-shaped objects of uncertain function. The low levels of iron in borosilicate2 compared to borosilicate1 suggest that this might be a slightly later recipe. The presence of the zirconium is not easily explained, some

Table 2 Average composition of the borosilicate1 and borosilicate2 glasses.

	B_2O_3	Na_2O	Al_2O_3	SiO_2	Fe_2O_3	As_2O_3	ZrO_2
Borosilicate1							
Mean	~12	4.2	2.0	77.5	0.17	0.28	<0.01
SD	–	0.6	0.3	1.8	0.02	0.15	–
Borosilicate2							
Mean	~12	4.0	2.2	79.3	0.08	<0.02	0.17
SD	–	0.1	0.1	0.8	0.01	–	0.19

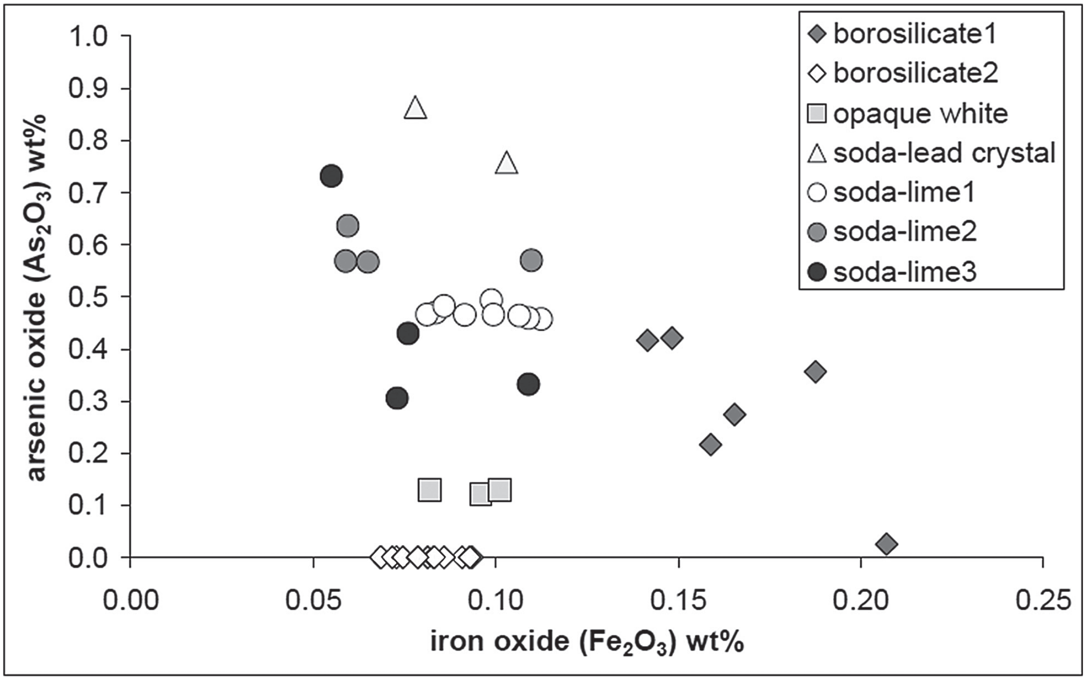

Fig. 16 Iron oxide and arsenic oxide content of the analysed glass and glass-working waste.

zirconium (*c.* 0.01 wt% ZrO_2) being present in most sands and glass, but the levels of this element in the borosilicate2 glass are much higher than normal. It is difficult to see why zirconium might be deliberately added to a glass, although small amounts would have undoubtedly eroded from furnace walls, and the twentieth century saw the development of zirconium-containing refractories; however, most twentieth-century glass contains negligible amounts of this element (Dungworth 2011; 2012).

Soda-lime Glasses

In total, 18 samples contain moderate amounts of silica (*c.* 70–73 wt%), significant proportions of soda (*c.* 16–20 wt%) and minor amounts of lime (*c.* 4.5–6 wt%). The analysed total for these glasses (*c.* 96–98 wt%) suggests that little or no boron is present, their composition conforming to soda-lime-silica glasses widely used throughout the twentieth century (Dungworth 2011; 2012). The soda-lime-silicate glasses have been divided into three sub-groups (soda-lime1, soda-lime2 and soda-lime3), based on very slight differences in their chemical composition (figs 15 and 16).

Soda-lime1 (LISB#28–36)

Soda-lime1 glass is represented by nine samples, of which seven are working waste and two are press-moulded vessels.

Soda-lime2 (LISB#09, LISB#18, LISB#26 and LISB#27)

Soda-lime2 glass is represented by four samples, of which two are working waste and two are press-moulded vessels (one of which is an ash tray). The glass is distinguishable from the other soda-lime-silica glasses by the presence of manganese (presumably added to reduce the colouring effect of the iron) and the high levels of arsenic (Table 3).

Table 3 Average composition of the soda-lime glasses.

	B_2O_3	Na_2O	Al_2O_3	SiO_2	SO_3	K_2O	CaO	MnO	Fe_2O_3	As_2O_3	BaO	PbO
Soda-lime1												
Mean	nil	16.8	0.2	73.9	0.2	–	5.7	–	0.10	0.47	<0.2	–
SD	–	0.6	–	1.0	–	–	0.2	–	0.01	0.01	–	–
Soda-lime2												
Mean	nil	20.1	0.1	70.3	–	<0.1	5.1	0.15	0.07	0.59	<0.2	0.4
SD	–	0.5	0.1	0.4	–	–	0.9	0.02	0.02	0.03	–	0.6
Soda-lime3												
Mean	nil	18.7	0.1	70.6	–	<0.1	4.7	0.17	0.21	0.5	0.7	0.5
SD	–	1.1		2.2	–	–	0.6	0.03	0.30	0.2	0.5	0.4

Soda-lime3 (LISB#02, LISB#07, LISB#13, LISB#16 and LISB#22)

Soda-lime3 glass is represented by five samples, of which two are working waste (glass adhering to a crucible (LISB#13) and a failed vessel LISB#07)) and three are press-moulded vessels (one of which is a green ash tray (LISB#22)). The relatively high average iron content of this group is the result of the inclusion of LISB#22. This sample is green and contains elevated levels of iron and copper to achieve this colour.

Opalware (LISB#23–5)

The three samples of opaque white glass proved to have just as complicated a chemical composition (Table 4) as suggested by Shaw and Evans (1983, 17). The glass has a silica base (and slightly more than that suggested by Shaw and Evans), which has been fluxed with soda

Table 4 Average composition of the Opalware glass samples.

	B_2O_3	F	Na_2O	Al_2O_3	SiO_2	K_2O	CaO	Fe_2O_3	As_2O_3	SrO
Mean	nil	6.3	9.9	7.3	70.0	1.2	0.7	0.09	0.13	3.4
SD	–	0.7	0.8	0.1	2.3	0.2	0.1	0.01	0.01	0.2

(the analysed total is sufficiently high to suggest that boron was not a part of the batch). The glass contains fluorine, and the proportions of fluorine and other elements suggest that it was added as AlF_3 (rather than as cryolite, Na_3AlF_6). The fluorine was probably added due to its tendency to promote microphase separation, the knowledge of which had allowed the production of opaque and opalescent glass since the beginning of the twentieth century. The glass also contains significant proportions of strontium, which would have helped the glass to devitrify (crystallise) during cooling.

Soda-lead Crystal (LISB#10 and LISB#11)

Two samples of glassworking waste contain soda and lead, with only very low levels of other elements (Table 5). This glass is a soda-lead crystal, rather than the more conventional potash-lead crystal. Soda-lead crystal glass was used in Manchester in the nineteenth century (Willmott *et al*. 2012).

Ungrouped (LISB#08, LISB#12, LISB#13c, LISB#13g, LISB#14, LISB#15 and LISB#50)

The remaining seven samples have compositions which do not match any of the groups described above. This includes two samples of refractory glass (one crucible (LISB#15) containing blue glass (LISB#14) and one fragment of tank wall (LISB#13c), or possibly crown, with adhering glass (LISB#13g)). These two samples are broadly similar to each other: the oxides of aluminium and silicon account for over 90 wt% of the material, with a range of minor oxides. The composition of this admittedly small sample appears to be rather conservative compared to some of the developments in glassmaking refractories discussed in contemporary literature (Phillips 1941). The zirconium content was unexceptional. Two samples of blue glass are both soda-lime-silica glasses; however, these do not share precisely the same chemical composition as any of the other soda-lime-silica glasses discussed above. These two were, however, coloured in quite different ways, one (LISB#12) with a combination of iron and copper, while the second (LISB#14) was coloured with cobalt. A third ungrouped soda-lime-silica glass has an exceptionally high soda content.

Table 5 Average composition of the soda-lead crystal glass samples.

	B_2O_3	Na_2O	Al_2O_3	SiO_2	P_2O_5	Cl	K_2O	CaO	Fe_2O_3	As_2O_3	Sb_2O_3	PbO
Mean	nil?	14.4	0.3	52.7	0.4	1.8	0.2	1.1	0.09	0.8	0.7	20.7
SD	–	0.7	0.1	1.6	0.1	0.1	0.1	0.1	0.02	0.1	0.1	0.5

OTHER FINDS

Apart from the glass materials, a small assemblage of other artefacts was recovered during the excavation. These included: 12 sherds of post-medieval pottery; three fragments of clay tobacco pipe; 18 stamped bricks; a single copper-alloy object; and 14 fragments of ironwork. Full details of these are contained in the archive report (OA North 2017). Following assessment, none of these items were deemed to hold any particular significance and they were not, therefore, subjected to any additional analyses.

DISCUSSION

THE GLASS RECIPES

A little over 40% of all the analysed material is a borosilicate glass. This appears to conform to Corning 7740 (Corning Glass Works 1987) and is likely to be the glass that was licensed to Jobling & Co. in 1921 (see above). The range of samples analysed unfortunately does not provide enough information to indicate when (if ever) the works switched to the production of glass ovenware based on tempered soda-lime-silica glass, rather than annealed borosilicate glass. However, the analysis of this glass has revealed aspects of the borosilicate which were not expected. There were clearly two different recipes in use: one with higher iron and detectable amounts of arsenic; and the other with lower iron and no detectable arsenic. It is not clear whether these were both in use at the same time, and it is possible that one recipe superseded the other, in which case it is plausible that the low iron and arsenic recipe would be the later. Curiously, the latter glass also contains appreciable amounts of zirconium, but the source of this and the intention (if any) behind its incorporation in the glass are unclear.

Soda-lime-silica glass was the second most abundant type represented in the analysed samples. Soda-lime-silica glasses have been used in most branches of the twentieth-century industry, including flat glass (Dungworth 2011) and containers (Dungworth 2012). One of the major advantages of this type of glass over the great variety of recipes used before the beginning of the twentieth century was that it produced a glass with particular properties that were suited to forming on a large scale using machines. The mechanisation of the bottle industry led to the adoption of soda-lime-silica glass, as this could (with relative ease) be made sufficiently fluid to fill moulds accurately. A relatively high soda content ensured the glass would be sufficiently fluid during forming (Turner 1926). The flat-glass sector tended to prefer a material with a slightly lower soda content and a higher calcium content, due to differences in the forming techniques used, such as continuous drawing of sheets of hot glass (Dungworth 2011; 2012). From the 1930s onwards, a proportion of calcium has been replaced by magnesium to prevent devitrification of flat glass during forming (Dungworth 2011). The soda-lime-silica glass produced by Jobling & Co. contains more soda and less lime than either contemporary window glass or bottle glass (cf. Dungworth 2011; 2012), and it is likely that the recipe was developed to match the nature of production.

In general, a high soda content would ensure a fluid glass, which would quickly and accurately fill a mould. The low lime content would encourage the glass to become stiff quickly as it cooled, which would allow moulds to be emptied quickly and so speed up production. The higher soda content and lower lime content, compared to contemporary bottle glass, may reflect the fact that Jobling & Co. produced relatively thin-walled and open forms which would lose heat quickly.

The material analysed also included a small proportion of Opalware, which proved to have a complex chemical composition, using raw materials which were rarely if ever used in other branches of the glass industry. The examples from the Wear Flint Glass Works are silicate glasses fluxed with soda, aluminium fluoride and strontium. The soda would help to reduce the melting temperature, while the aluminium fluoride might encourage microphase separation, which could contribute to an opalescent quality. The action of the strontium is less clear, although strontium and barium have been cited as helping to produce spontaneous glass-ceramics without the need for heat treatments (Vogel 1985).

GLASS-MELTING FURNACES

In terms of the structural remains at the site, by far the most significant relate to the sequence of glass-melting furnaces that, importantly, reflect the wider advances in glass-making technology, which occurred between the mid-nineteenth and earlier part of the twentieth century. The earliest excavated feature (Furnace 1) was a coal-fired pot furnace, probably constructed in *c.* 1869 when the Wear Flint Glass Works was first established by Henry Greener. Although by this date mechanical coal feeders had been introduced, specifically the Frisbie furnace feeder, patented in 1868 (Douglas and Frank 1972), there was no evidence that such devices were employed in Greener's late nineteenth-century glassworks. This furnace would therefore have required a 'stoker', who would have fed coal into the grate through a stokehole in the furnace wall. However, one disadvantage associated with the use of an open stokehole for fuelling was that it caused the temperature of the furnace to fluctuate (cf. Miller 2007, 19).

The surviving remains of Furnace 1 included a length of red-brick walling that probably formed the external wall of a square-shaped furnace. In form, this furnace was essentially comparable to those coal-fired pot-furnaces used in the earlier nineteenth century (cf. Ure 1838), even though by the latter part of the century, many glassworks utilised circular, coal-fired pot furnaces (Crossley 2003, 173), such as those found at the Percival, Vickers & Co. Glass Works, in Manchester (Miller 2007). Furnace 1 was also associated with a sub-surface flue that lay, centrally, beneath the furnace and extended out from its two sides. This flue would have incorporated a door, or shutter, placed within the passage to the east of the furnace, which had been intended to regulate the flow of air into the furnace. Closure of this shutter will have reduced combustion in the furnace to a minimum, allowing the melting pots to be filled with a fresh batch of raw materials. In addition, the flue would have provided sufficient room for the workmen, known as teasers, who cleared out ash and clinker from beneath the grate.

It is also known that the excavated furnaces at the Wear Flint Glass Works would have heated ten glass pots (see above). These crucibles could either be open or covered, with covered pots normally being used in the production of flint (lead-crystal) glass and optical glass, whilst open pots were used to produce other glass types (Rosenhain 1908, 56). However, as the precise glass recipes used in Greener's mid-nineteenth-century glassworks are unknown, it is unclear which pot types would have been employed.

The excavation indicated that the original pot furnaces were replaced in the late nineteenth and earlier twentieth centuries by Siemens-type regenerative tank furnaces, when the site was owned by the Jobling family. The remains clearly relating to two of these furnaces (Furnaces 3 and 4) were exposed and, in keeping with the standard design of continuous regenerative tank furnaces, these would have possessed four horizontal regenerative chambers, forming two pairs of gas and air regenerators, positioned on either side of a passage, or cave (cf. Rosenhain 1908, 71). This latter feature allowed access beneath the furnace and also created a 'buffer' of cooler air between the two pairs of chambers, which was designed to prevent the furnace from overheating (*ibid*.). The glass-melting refractory brick tank, covered by a crown, would have been set above the regenerators and would have had a filling hole at one end and a working hole at the other, where the molten glass was removed (*ibid*.). Such gas-fired furnaces would have allowed production at the Wear Flint Glass Works to be increased on a massive scale, reducing the manufacturing costs within a highly competitive industry. Moreover, they would have allowed for the more efficient production of mass-produced wares.

The remaining furnaces excavated (Furnaces 5–7) relate to the period when the works began to produce PYREX and, therefore, they post-date 1921, when Ernest Jobling Purser acquired the licence to produce vessels using this glass type (see above). Significantly, these furnaces also reflect the improvements that were made in glass-melting furnace design during the earlier part of the twentieth century.

One of these furnaces (Furnace 5) clearly represents an end-port furnace, provided with a recuperative stack, used to produce borosilicate glass (PYREX). The stack was situated immediately west of the furnace's tank, which was supported on piers, and heated by a U-shaped flame emanating from ports that were linked to the recuperative stack, with burner blocks below (Trier 1989, 8). The tank was probably constructed from a combination of clay blocks and cement and would have been covered by a crown (*ibid*., 16–17), whilst in terms of its layout, in common with other borosilicate glass furnaces, it would have included a melting and refining end that were separated by a weir (*ibid*., 13). In the case of Furnace 5, the melting end would have been positioned adjacent to the recuperative stack, and the batch (raw materials) would probably have been fed into the melting end from both sides of the furnace. Furnace 5's tank also possessed a rounded working end, which would have been separated from the melting and refining end by a throat. Moreover, in terms of borosilicate glass furnaces, it was also necessary to heat the working end separately, due to the high melting-end temperatures, and this was often achieved through the use of a small steel recuperator that was positioned directly above the working-end crown (*ibid*.). Other elements of this furnace, which were present, included a flue which ran from the recuperative stack to a chimney, depicted on the Ordnance Survey map of 1941 (fig. 4).

Although the details of Furnace 7 are difficult to ascertain fully, its position within the works indicates that it also represents an end-port borosilicate glass furnace. Indeed, it is highly likely that it actually represents the 60-ton tank furnace known to have been used in the works from 1927 onwards (see above). The cartographic evidence indicates that this furnace was linked to a chimney to the south, which is depicted on the 1941 map (fig. 4). Furthermore, apart from its suspected larger size, Furnace 7 differed from Furnace 5 in one major respect, in that it utilised a vertically set regenerative stack, as opposed to a recuperator, which would have heated its melting and refining ends.

Furnace 6 formed the other furnace that post-dates 1921. This also employed a regenerator stack that was probably linked to a chimney via flue [260] (fig. 5). It appears that this stack was also on the northern side of a glass-melting tank, which was situated on a solid concrete base. The position of the stack in relation to the base suggests that it formed a small side-fired tank furnace (cf. Trier 1989, fig. 2.1). Significantly, side-fired furnaces normally possessed two regenerative stacks (*ibid*.), positioned on either side of the tank, and given this, it is possible that another stack might have been on the southern side of the tank, which was perhaps linked to the nearby chimney via flue [261]. It is also quite possible that this small furnace was explicitly used in the manufacture of pressed-glass vessels. If this was the case, based on the known history of the site, it had probably been 'decommissioned' following the shift to the sole production of PYREX at the outbreak of the Second World War (see above), which may also explain the absence of its chimney on the Ordnance Survey map of 1941 (fig. 4).

CONCLUSION

The archaeological investigations on the site of the Wear Flint Glass Works have proved significant, both in terms of investigating the evolving technology and the products associated with a nineteenth- and twentieth-century glassworks engaged in the production of pressed-glass vessels and PYREX goods. Indeed, at a regional level, the site represents a significant addition to the study of Sunderland's historic glass industry, whilst nationally it also adds to the growing evidence for nineteenth- and twentieth-century glassmaking, derived from a handful of glassworks dating to this period that have been subjected to comparable programmes of archaeological investigation (*inter alia*; Krupa and Heawood 2002; Miller 2007).

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NOTES

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