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WENTWORTH CASTLE CONSERVATORY, STAINBOROUGH, SOUTH YORKSHIRE
CHEMICAL ANALYSIS OF THE FLAT GLASS

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David Dungworth and Roger Wilkes

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CHEMICAL ANALYSIS OF THE FLAT GLASS

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SUMMARY

The analysis of 55 fragments of flat glass from the Wentworth Conservatory was undertaken to determine the composition of the glass originally installed during its construction in 1877. A visual examination of the glass during collected suggested that much of the glass was later replacements of float glass from after 1960. The chemical analysis of the glass showed that the vast majority of it contains levels of magnesium that are consistent with manufacture after the introduction of automatic drawing techniques c1930. Four fragments (two of which are joining fragments) have very low levels of magnesia and are compositionally consistent with manufacture between c1830 and c1930. It is likely that this glass represents the glass originally installed at Wentworth in 1877.

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INTRODUCTION

The analysis of fragments of flat glass from Wentworth Conservatory forms part of a much larger project undertaken to investigate the chemical composition of window glass produced and used in Britain during the past five centuries. Samples of glass have been selected from archaeological excavations (including glass production sites) and from historic buildings. These have been analysed to determine their chemical composition. A comparison of the chemical composition with the available dating evidence shows that a series of changes in window glass manufacturing took place during this period. The aim of this research is to provide a technique to date the manufacture of individual panes of glass in historic buildings. This knowledge will allow architects and others to make more informed judgements about which glass to retain and which can be replaced (Clark 2001).

Wentworth Castle (originally Stainborough Hall) was built in the early 18th century for the Earl of Strafford. The gardens were used as a theatre for competition with another branch of the Wentworth family (Charlesworth 1986). The Conservatory, which was constructed in 1877 by Crompton and Fawkes of Chelmsford, allowed the cultivation of exotic plants which formed an important means of establishing and maintaining social status among aristocrats and gentry in the 19th century (Kohlmaier and Sartory 1986).

The Wentworth estate went into decline in the early 20th century and, following the death of last member of the family in 1948, it was sold to Barnsley Corporation. The estate was split up: the house was used as a teacher training college and later an adult education centre, while the gardens were allowed to deteriorate. Nevertheless some replacement of the Conservatory glass was carried out by Barnsley Corporation (Michael Klemperer personal communication). In 2002 the management of the heritage assets of the Northern College and Barnsley Metropolitan Borough Council were transferred to the newly established Wentworth Castle and Stainborough Park Heritage Trust which undertook a programme of restoration. Wentworth Castle Gardens are a Grade I Listed Gardens and Parkland and contain 26 individually listed structures. The Conservatory is a Listed II* structure and plans have been drawn up for its restoration.

THE GLASS

Fifty-five fragments of glass from Wentworth Conservatory were selected for analysis. All of the glass was broken and recovered from the interior of the surviving structure. Most of the fragments of glass exhibit near perfect plane surfaces which suggest that they were not produced using crown, cylinder or drawn techniques (Cable 2004). Plane surfaces can only be achieved by polishing sheet glass (plate glass) or by floating the cast glass on a bath of molten tin (float glass). Plate glass was produced in Britain from the 18th century but the float process was invented in the late 1950s and was only produced commercially from 1960. The cost of plate glass makes it rather unlikely that this sort of glass was used for a structure the size of Wentworth Conservatory. Therefore, before analysis was

undertaken, it was suspected that most of the Wentworth glass samples analysed represented float glass installed by Barnsley Corporation after 1960.

Each fragment of glass was examined to determine the thickness and glass tint. The glass varied from 2.5 to 3.9mm in thickness with few samples exhibiting any measurable variation in thickness. The uniformity of thickness also indicates that much of the surviving Wentworth Conservatory glass represents relatively recent replacements. All of the glass was almost colourless and a faint blue-green tint was often only detectable when the glass was placed on a white background. Any attempt to group fragments of glass by their tint was undermined by variations in the thickness of the glass.

METHODS

Samples of each of the fragments of glass were mounted in epoxy resin, then ground and polished to a 3-micron finish to expose a cross-section through the glass. The samples were inspected using an optical microscope (brightfield and darkfield illumination) to identify corroded and uncorroded regions. None of the Wentworth Conservatory samples exhibited any substantial corroded surfaces. The samples were analysed using two techniques to determine chemical composition: SEM-EDS and EDXRF. The energy dispersive X-ray spectrometer (EDS) attached to a scanning electron microscope (SEM) provided accurate analyses of a range of elements while the energy dispersive X-ray fluorescence (EDXRF) spectrometer provided improved sensitivity and accuracy for some minor elements (in particular manganese, iron, arsenic, strontium and zirconium) due to improved peak to background ratios (Table 1).

Table 1. Minimum Detection limits (MDL) and analytical errors for each oxide

	SEM-EDS			EDXRF	
	MDL	Error		MDL	Error
Na_2O	0.1	0.1	V_2O_5	0.02	0.03
MgO	0.1	0.1	Cr_2O_3	0.02	0.03
Al_2O_3	0.1	0.1	NiO	0.02	0.03
SiO_2	0.5	0.2	MnO	0.02	0.03
P_2O_5	0.2	0.1	Fe_2O_3	0.02	0.03
SO_3	0.2	0.1	CoO	0.02	0.02
Cl	0.1	0.1	CuO	0.02	0.01
K_2O	0.1	0.1	ZnO	0.02	0.01
CaO	0.1	0.1	As_2O_3	0.02	0.01
TiO_2	0.1	0.1	SnO_2	0.1	0.05
BaO	0.2	0.1	Sb_2O_5	0.15	0.07
			Rb_2O	0.005	0.005
			SrO	0.005	0.005
			ZrO_2	0.005	0.005
			PbO	0.02	0.02

The SEM used was a FEI Inspect F which was operated at 25kV with a beam current of approximately 1nA. The X-ray spectra generated by the electron beam were detected using an Oxford Instruments X-act SDD detector. The quantification of detected elements was achieved using the Oxford Instruments INCA software. The EDS spectra were calibrated (optimised) using a cobalt standard. Deconvolution of the X-ray spectra and quantification of elements was improved by profile optimisation and element standardisation using pure elements and compounds (MAC standards). The chemical composition of the samples is presented in this report as stoichiometric oxides with oxide weight percent concentrations based on likely valence states (the exception being chlorine which is expressed as element wt%). The accuracy of the quantification of all oxides was checked by analysing a wide range reference materials (Corning, NIST, DGG and Newton/Pilkington). A number of elements were sought but not detected in any of the Wentworth samples: phosphorus, chlorine, cobalt, vanadium, chromium, nickel, manganese, copper, zinc, tin, antimony and barium.

RESULTS

The 55 fragments of glass from Wentworth Conservatory are all soda-lime glasses (Figures 1 and 2; Table 2; full data in Appendix) but have been divided into several groups based on small variations in their chemical composition. Group 1 comprises just four samples but is clearly distinguished from all the others samples by its high lime and low magnesia content (Figure 2). After the chemical analysis had been undertaken and the compositional groups identified, the glass fragments were re-examined and this revealed that two samples from Group 1 (#41 and #46) were joining fragments.

Table 2. Average chemical composition of the Wentworth glass

Group	Na_2O	MgO	Al_2O_3	SiO_2	SO_3	K_2O	CaO	Fe_2O_3	SrO
1	11.9	0.4	0.7	71.5	0.24	0.28	14.3	0.28	0.026
2	13.3	3.8	1.4	72.5	0.19	0.66	7.9	0.22	0.007
3a	13.0	3.8	1.1	72.7	0.19	0.58	8.4	0.15	0.005
3b	13.6	3.8	1.1	72.1	0.20	0.56	8.4	0.15	0.005
3c	13.8	4.1	1.1	71.9	0.19	0.57	8.1	0.19	0.010

Group 2 comprises 33 samples which are distinguished by their slightly higher levels of alumina (Figure 3). Group 3 comprises 18 samples with slight less alumina and more lime than Group 2. Group 3 has been subdivided into three sub-groups: 3a has the lowest sodium oxide content and 3c has the highest magnesia content..

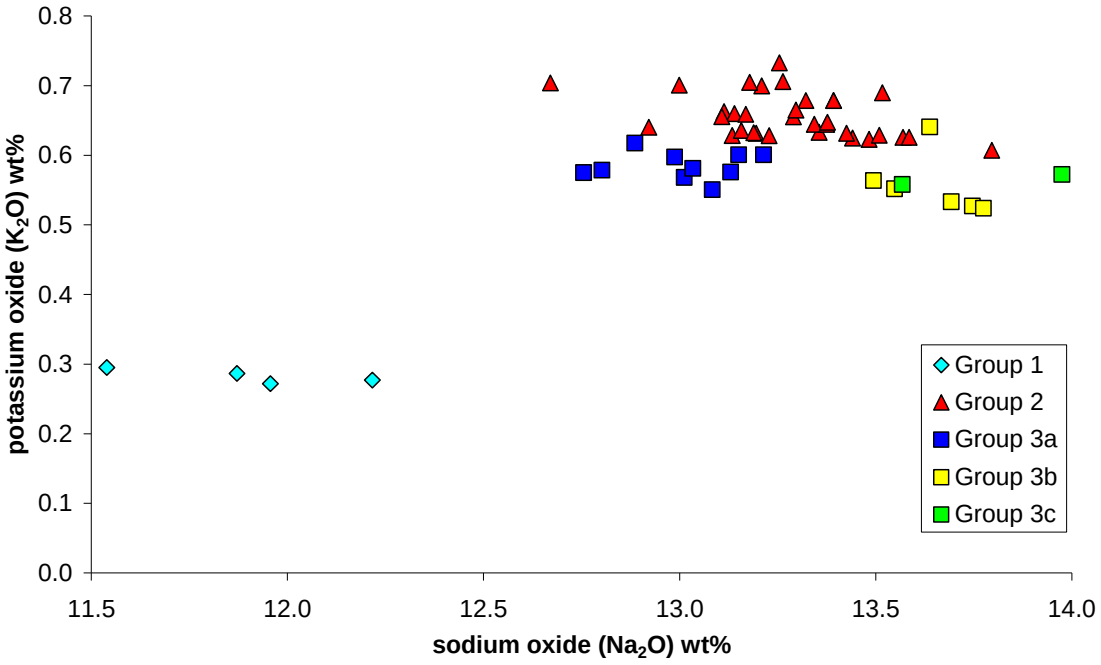

Figure 1. Plot of sodium and potassium oxide concentrations of the Wentworth glass

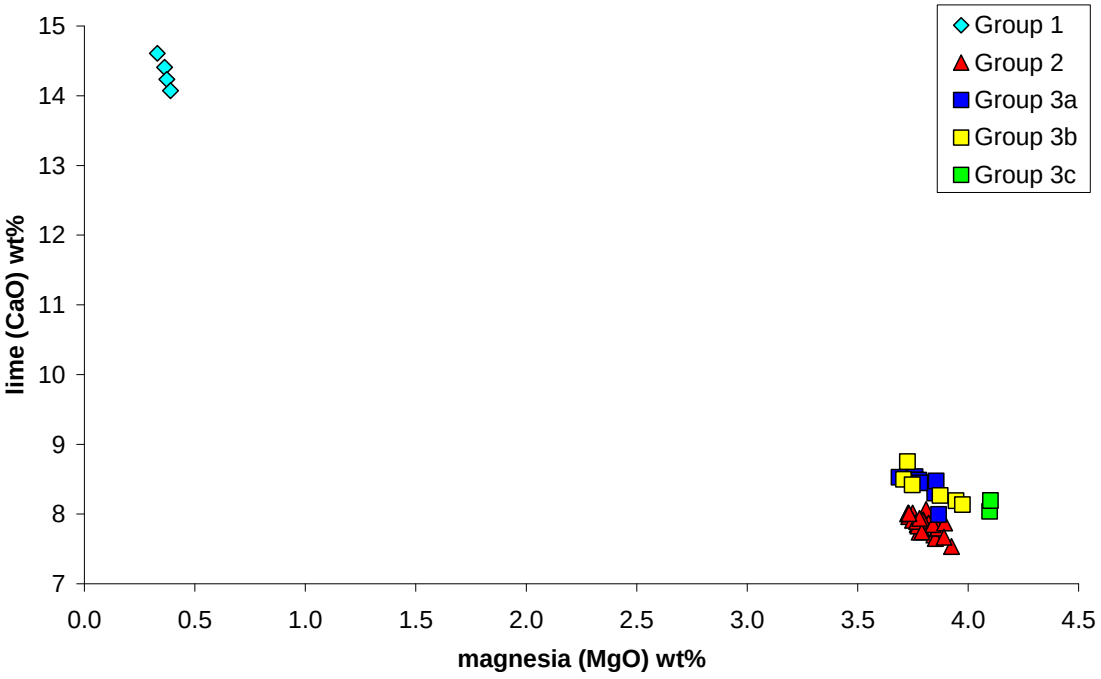

Figure 2. Plot of magnesia and lime concentrations of the Wentworth glass

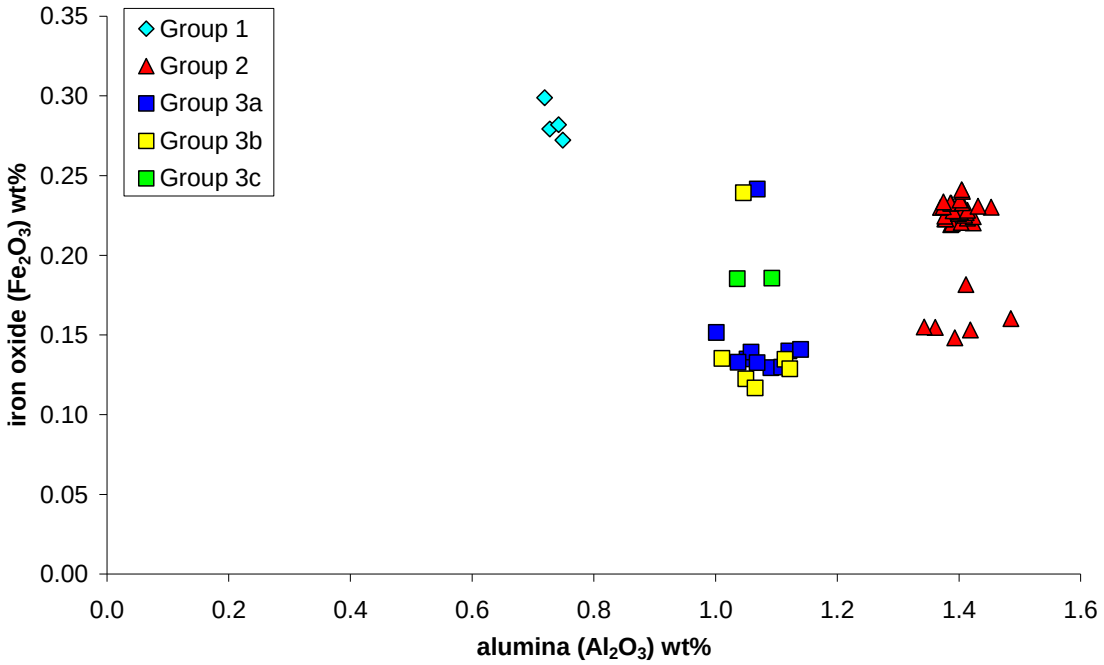

Figure 3. Plot of alumina and iron oxide concentrations of the Wentworth glass

DISCUSSION

All of the Wentworth glass is of the soda-lime type introduced to Britain c1830 following the development of the Leblanc technique for the production of sodium carbonate (or sodium sulphate) from common salt (sodium chloride). With some modifications, the same basic glass type has remained the most commonly used in the manufacture of window glass since then (Table 3).

Table 3. Chemical composition of some 19th- and 20th-century flat glass (Sources: 1 = Dungworth 2009; 2 = Hatton 2004; 3 = this report; 4 = Dungworth 2010a; 5 = Dungworth 2010b; 6 = Smrcek 2005, nr = not reported)

	Source	Date	Na_2O	MgO	Al_2O_3	SiO_2	SO_3	K_2O	CaO	Fe_2O_3	As_2O_3	SrO
Chatsworth	1	1837–40	14.0	<0.1	0.7	70.3	0.34	<0.1	14.1	0.20	0.41	0.015
Nailsea	2	1830–70	13.1	0.2	0.8	68.9	0.60	0.1	13.5	0.33	0.22	0.022
Wentworth 1	3	1877	11.9	0.4	0.7	71.5	0.24	0.3	14.3	0.28	<0.02	0.026
Welch Road	4	1895	11.6	0.1	1.5	72.5	0.30	0.6	13.1	0.20	<0.02	0.019
Fort Cumberland	5	1940	14.3	2.9	0.3	72.5	0.25	<0.1	9.4	0.13	<0.02	0.008
Drawn	6	1930–60	14.6	2.1	1.0	72.0	0.45	0.1	9.8	0.12	nr	nr
Wentworth 2	3		13.3	3.8	1.4	72.5	0.19	0.7	7.9	0.22	<0.02	0.007
Wentworth 3	3		13.3	3.8	1.1	72.4	0.19	0.6	8.4	0.15	<0.02	0.006
Float	6	1960–99	13.8	4.1	1.1	71.9	0.19	0.6	8.1	0.19	nr	nr

The Wentworth glass has been divided into three main chemical groups (with some sub-groups in the third group). A comparison of the average compositions of each group with

available data from other sites suggests that only Group 1 is likely to be original, while the remaining groups are likely to represent later replacements.

The Original Glass

Wentworth Group 1 (comprising only four samples — and two of these from joining fragments) represents the only glass from the Conservatory which, on compositional grounds (low magnesia and high lime content), is likely to have been made before 1929. It is probable that these four samples represent the glass installed at the time that the conservatory was constructed in 1877.

The Wentworth Group 1 glass shares almost exactly the same chemical composition as the window glass used in Welch Road, Portsmouth (Dungworth 2010a) within a decade or so of the erection of the Wentworth Conservatory. The glass from both Wentworth and Welch Road contains slightly lower levels of sodium oxide than window glass of the earlier 19th century and slightly higher levels of silica and potassium oxide (Table 3). The slightly lower sodium oxide content might have been a deliberate response to the adoption of regenerative furnaces in the glass industry from 1860 onwards (Cable 2000). Regenerative furnaces were capable of achieving higher temperatures and so of melting glass with a lower alkali content. The melting temperature of the Chatsworth and Nailsea glasses would be 1400–1420°C, while the melting temperature of the Wentworth Group 1 and Welch Road glasses would be 1440–1460°C (Fluegel 2007). Bontemps suggests that the alkali accounted for about half of the cost of all raw materials used in making window glass (Cable 2008, 310). As the alkali was the most expensive ingredient, there would be some incentive to reduce this as much as possible. Savings in alkali might be offset, however, by increased fuel costs. The sulphur content of the Wentworth and Welch Road glass, which would have been made with sodium sulphate, is not higher than the Chatsworth glass which was probably made with either sodium carbonate or a combination of carbonate and sulphate. This suggests that the sulphur content of glass is governed by SO_3 solubility factors (Papadopoulos 1973). The SO_3 solubility in soda-lime-silica glasses is increased as the sodium oxide concentration is increased but decreases with temperature.

A second small but significant difference between the earlier and later 19th-century glasses is their arsenic content (Table 3). Arsenic appears to be present in most window glass produced from c1830 until some time before 1877. The deliberate addition of arsenic is mentioned by most 19th-century sources (eg Cable 2008; Powell *et al* 1883; Ure 1844) as well as some early 20th-century sources (Marson 1918; Rosenhain 1919). Two reasons are commonly advanced for the addition of arsenic to window glass: to decolourise the glass and/or to refine the glass. Arsenic oxide (As_2O_5) is an oxidising agent and will reduce the colouring effect of iron by converting Fe^{2+} to Fe^{3+}. The use of arsenic in this way to decolourise a glass does not appear to be consistent with the use of sodium sulphate. The substitution of sodium sulphate for sodium carbonate in glass making was only successful when the sulphate was added with a reducing agent (usually coal). The coal reduced the sodium sulphate to sodium sulphite which would react with

the silica to form a melt (Rosenhain 1919, 84). The simultaneous addition of an oxidising agent and a reducing agent is difficult to accept, and was described by Powell *et al* (1883, 107) as a 'manifest inconsistency'. Arsenic oxide has also been added to glass as a refining agent, that is a material which will help to remove bubbles from molten glass (Cable and Haroon 1970). At high temperatures the As_2O_5 will tend to form As_2O_3, releasing gas which will form bubbles: the intention being to form relatively large bubbles which will readily absorb smaller bubbles and rise more quickly than smaller bubbles (Stokes' Law). The refining potential of As_2O_5 would not be realised if it was included with all of the batch ingredients — it would give up its oxygen long before a molten glass was formed. It could only really be used as a refining agent if it was added after the glass had been melted (Rosenhain 1919, 86). Added at this stage As_2O_5 would also serve to oxidise any remaining carbon in the glass.

The analysis of 19th-century window glass suggests that arsenic was widely used from the introduction of Leblanc soda (c1830) but that its use was largely abandoned after a few decades. Arsenic has not been found in any of the Wentworth or later window glass. It is likely that the arsenic was added principally as a refining agent during the later stages of glass melting. The disappearance of arsenic from window glass in the last half of the 19th century is accompanied by a small increase in potassium concentration (Table 3). Several 20th-century sources recommend the use of potassium nitrate as a refining agent (Angus-Butterworth 1948, 40; Marson 1918, 7; Rosenhain 1919, 83). Thus it would appear that arsenic was used as a refining agent for several decades after 1830 but was then discontinued in favour of potassium nitrate. The potassium content of early 20th-century glass is generally lower than that of the later 19th century which indicates that potassium nitrate was probably replaced by some other refining agent.

The Group 1 glass fragments have surfaces which show very little distortion either when viewing a transmitted or reflected image. This suggests that the glass has been polished. As the glass is thinner than conventional plate glass it is likely that this glass was initially produced as cylinder glass and then polished using a process similar to that patented by Chance in 1838 (Barker 1977, 63). Chance's original process used a bed of damp leather to hold the sheet glass while it was polished. The damp leather would accommodate the slight undulations inherent in cylinder glass, thereby avoiding the need to grind away a substantial thickness of glass. Polished sheet glass was widely used in prestigious buildings of the 19th century, including the Crystal Palace of the Great Exhibition of 1851. Polished sheet glass was more expensive than cylinder glass and it probably did not offer significant practical advantages over cylinder glass in a greenhouse. Its use in the Wentworth Conservatory probably reflects the fact that the structure was used as a status symbol.

The Replacement Glass

Most samples of Wentworth glass (Groups 2 and 3) have compositions which suggest that they were made after c1929. At the time that the Wentworth Conservatory was constructed almost all flat glass was produced by flattening mouth-blown cylinders (Cable 2004). Such cylinder glass was made using sand, sodium sulphate and chalk (Powell *et al* 1883, 101). The early 20th century saw the adoption of a number of mechanised techniques for forming flat glass (Cable 2004). The first of these, the Lubbers process, used compressed air and machinery to lift much larger cylinders than could be formed by human labour. There does not, however, seem to have been any significant change in the chemical composition of the glass. On the other hand, the various techniques for drawing flat sheets direct from molten glass implemented in the 1920s did lead to a small but significant change in glass composition (Cable 2004). Attempts to draw large flat sheets were initially hampered by glass devitrification but it was found that the substitution of some of the lime by magnesia (typically 3wt% MgO) provided a glass with suitable viscosity characteristics but which would not devitrify under normal circumstances (Cable 2004; Smrcek 2005). The adoption of techniques for drawing flat glass led to the abandonment of cylinder glass (whether mouth-blown or Lubbers). Drawn glass was a considerable improvement over cylinder glass but still could not produce sheet glass with a perfectly plane surface. Before the late 1950s the only way in which perfectly plane glass could be produced was to polish sheet glass. The development of float glass by Pilkington Brothers in the 1950s, in which molten glass flowed onto a bed of molten tin, finally allowed the high-volume low-cost production of sheet glass with two perfectly plane parallel surface (Cable 2004, 38). The float technique required a glass with similar chemical composition to that used in the drawn processes, that is with magnesia replacing a proportion of the lime (although it appears that float glass usually contains slightly more magnesia than drawn glass).

Wentworth Groups 2 and 3 are characterised by high magnesia content (Figure 2; Table 3) and so are likely to have been produced after the development of drawn glass techniques. According to Smrcek (2005), British manufacturers did not adopt drawn glass until 1929. Therefore Groups 2 and 3 were probably manufactured after 1929. Given the financial circumstances of the Wentworth family it is unlikely that any of this glass was installed between 1929 and the sale of the estate in 1949. In addition, the near perfect plane surface of most of this glass and the relatively high magnesia content suggest that most of this is float glass produced after 1960 (cf Table 3).

Melting and forming characteristics of 19th- and 20th-century glass

As mentioned above, modelling the temperature-viscosity relationship of the glasses represented in Table 3 shows that late 19th-century glasses required an additional 40°C for their melting (Fluegel 2007). This trend does not, however, appear to continue into the 20th century, where all glasses require a melting temperature of 1430–1450°C. The working range of these glasses, here taken at the temperature at viscosity 2 log(n) minus the temperature at viscosity 7.6 log(n), does show an upwards trend with time (Figure 4). Increasing the working range of these glasses would provide glassworkers (or their machines) with more time to manipulate the glass before it became solid. This would have been increasingly important as the flat glass industry mechanised and sought to produce glass on an ever-increasing scale. While Figure 4 appears to indicate a gradual increase in the working range of 19th- and 20th-century flat glass, it is perhaps more likely that the increase occurred in a series of steps in line with other developments in the industry (reverberatory furnaces, Lubbers' mechanised cylinder glass, drawn glass, float glass, etc).

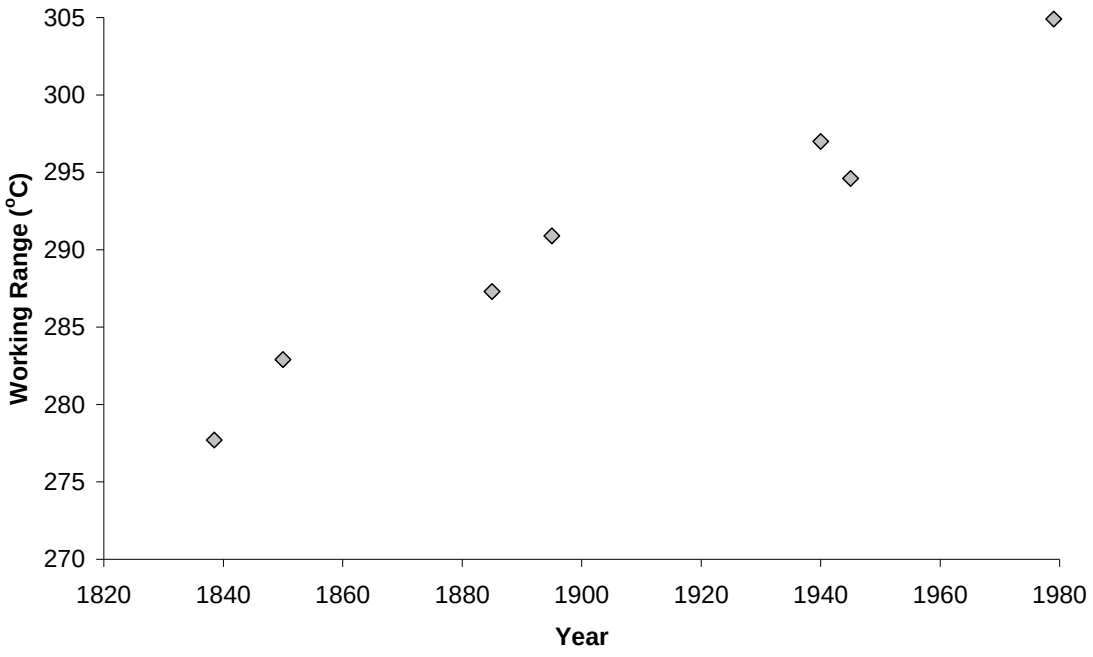

Figure 4. Working range of 19th- and 20th-century window glass (calculated from compositions in Table 3)

CONCLUSIONS

The chemical analysis of 55 fragments of flat glass from the Wentworth Conservatory has shown that only 4 fragments are likely to be original glass (1877). The remaining 51 samples represent later replacements probably made after 1960. The chemical composition of the original glass is very close to that used for the windows installed in Welch Road, Southsea in 1895. Wentworth and Welch Road appear to indicate that late 19th century window glass can be distinguished from that made earlier in the century by the lower sodium content and the absence of arsenic. The lower sodium content would have required a higher temperature to melt the glass. It is likely that the lower sodium content was a response to the introduction of reverberatory furnaces which enabled higher temperatures to be achieved.

RECOMMENDATIONS

The results of the chemical analysis of flat glass from the Wentworth Conservatory have identified that a small proportion of the glass may be original. This glass would have been produced initially as sheets of cylinder glass which were then polished to achieve a high-quality finish. Should restoration proceed it will almost certainly be necessary to replace a high proportion of the glass in the Wentworth Conservatory. Flat glass is no longer produced in exactly the same way as that originally installed, however, modern float glass has both a surface finish and a tint which is almost identical and it would make a suitable replacement material.

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APPENDIX

Chemical Composition of the Wentworth Glass

The following elements were sought but not detected in any of the Wentworth samples: phosphorus, chlorine, cobalt, vanadium, chromium, nickel, manganese, copper, zinc, tin, antimony and barium.

#	Th (mm)	Na_2O	MgO	Al_2O_3	SiO_2	SO_3	K_2O	CaO	TiO_2	Fe_2O_3	SrO	ZrO_2
1	2.7	13.26	3.79	1.39	72.6	0.18	0.71	7.78	<0.05	0.22	0.008	0.006
2	3.9	13.25	3.77	1.42	72.4	0.19	0.73	7.89	<0.05	0.15	0.011	0.014
3	2.6	13.32	3.77	1.41	72.5	0.18	0.68	7.83	<0.05	0.23	0.008	0.009
4	2.6	13.30	3.77	1.40	72.5	0.17	0.67	7.85	<0.05	0.23	<0.005	0.008
5	2.6	13.98	4.10	1.09	71.8	0.18	0.57	8.04	<0.05	0.19	0.008	0.013
6	2.8	13.11	3.87	1.39	72.4	0.22	0.66	7.95	0.06	0.22	0.009	0.005
7	3.0	13.15	3.87	1.07	72.8	0.20	0.60	7.99	<0.05	0.13	0.006	0.009
8	3.9	12.89	3.76	1.05	72.6	0.22	0.62	8.49	<0.05	0.13	<0.005	0.010
9	4.0	13.64	3.87	1.11	71.9	0.20	0.64	8.27	<0.05	0.13	0.008	0.012
10	2.6	13.17	3.75	1.40	72.4	0.23	0.66	8.01	<0.05	0.23	0.009	0.009
11	2.6	13.39	3.86	1.41	72.3	0.19	0.68	7.80	<0.05	0.23	0.005	0.006
12	2.7	13.39	3.86	1.41	72.3	0.19	0.68	7.80	<0.05	0.18	0.011	0.021
13	2.7	13.51	3.79	1.43	72.4	0.18	0.63	7.74	<0.05	0.23	<0.005	0.011
14	2.7	12.99	3.76	1.06	72.7	0.18	0.60	8.46	<0.05	0.14	<0.005	0.012
15	2.7	13.14	3.73	1.38	72.6	0.21	0.66	8.00	<0.05	0.22	0.008	0.007
16	2.6	12.92	3.73	1.42	72.8	0.18	0.64	8.02	<0.05	0.22	0.005	0.005
17	2.6	13.48	3.86	1.38	72.3	0.18	0.62	7.84	<0.05	0.22	<0.005	0.007
18	2.6	13.36	3.73	1.38	72.4	0.19	0.63	7.96	<0.05	0.22	<0.005	0.006
19	2.6	13.38	3.78	1.45	72.3	0.18	0.64	7.94	<0.05	0.23	0.008	0.009
20	3.8	13.13	3.78	1.11	72.5	0.20	0.58	8.45	<0.05	0.13	<0.005	0.009
21	2.6	12.80	3.76	1.07	72.8	0.17	0.58	8.53	<0.05	0.24	0.010	0.005
22	3.8	12.76	3.69	1.09	72.8	0.17	0.58	8.53	<0.05	0.13	<0.005	0.008
23	2.6	13.20	3.79	1.37	72.5	0.22	0.63	7.88	<0.05	0.23	0.007	0.010
24	2.9	13.00	3.84	1.34	72.8	0.17	0.70	7.86	<0.05	0.16	0.016	0.014
25	3.7	13.21	3.85	1.39	72.4	0.21	0.70	7.94	<0.05	0.15	0.016	0.013
26	3.9	13.21	3.86	1.14	72.3	0.20	0.60	8.47	<0.05	0.14	0.012	0.009
27	2.6	13.52	3.75	1.41	72.2	0.19	0.69	7.91	<0.05	0.23	<0.005	0.008
28	2.6	13.38	3.84	1.37	72.5	0.22	0.65	7.70	<0.05	0.23	0.007	0.006
29	2.6	13.59	3.84	1.41	72.1	0.19	0.63	7.85	<0.05	0.22	<0.005	0.008
30	2.5	13.19	3.81	1.39	72.4	0.15	0.63	8.07	<0.05	0.23	<0.005	0.007
31	2.6	13.11	3.78	1.40	72.6	0.19	0.66	7.92	<0.05	0.24	0.008	0.007
32	2.8	13.57	4.10	1.04	72.0	0.21	0.56	8.19	<0.05	0.19	0.012	0.013
33	2.7	13.23	3.80	1.39	72.5	0.17	0.63	7.91	<0.05	0.23	0.007	0.006
34	2.7	11.87	0.37	0.74	71.6	0.22	0.29	14.23	<0.05	0.28	0.027	0.013
35	2.6	13.43	3.78	1.41	72.5	0.15	0.63	7.74	<0.05	0.24	0.010	0.008
36	2.6	13.44	3.82	1.37	72.3	0.12	0.62	7.96	<0.05	0.23	<0.005	0.006
37	3.8	13.69	3.71	1.05	72.0	0.19	0.53	8.50	<0.05	0.12	0.009	0.012
38	3.8	13.75	3.75	1.07	72.1	0.16	0.53	8.42	<0.05	0.12	<0.005	0.010
39	3.8	13.55	3.97	1.01	72.3	0.20	0.55	8.14	<0.05	0.14	0.006	0.007

#	Th (mm)	Na_2O	MgO	Al_2O_3	SiO_2	SO_3	K_2O	CaO	TiO_2	Fe_2O_3	SrO	ZrO_2
40	2.6	13.49	3.95	1.05	72.4	0.19	0.56	8.19	<0.05	0.24	0.007	0.008
41	2.8	11.96	0.36	0.73	71.3	0.19	0.27	14.41	<0.05	0.28	0.026	0.012
42	3.2	11.54	0.33	0.75	71.5	0.25	0.30	14.61	<0.05	0.27	0.024	0.011
43	3.9	12.67	3.73	1.49	72.8	0.21	0.70	8.01	<0.05	0.16	0.014	0.012
44	3.0	13.08	3.78	1.00	72.7	0.19	0.55	8.48	<0.05	0.15	0.015	0.013
45	2.6	13.80	3.92	1.40	72.3	0.16	0.61	7.53	<0.05	0.22	0.005	0.010
46	2.8	12.22	0.39	0.72	71.4	0.29	0.28	14.07	<0.05	0.30	0.029	0.009
47	2.6	13.16	3.89	1.41	72.4	0.22	0.64	7.87	<0.05	0.23	0.009	0.007
48	2.8	13.18	3.80	1.36	72.6	0.17	0.70	7.88	<0.05	0.15	0.022	0.016
49	2.9	13.01	3.81	1.12	72.6	0.18	0.57	8.45	<0.05	0.14	0.005	0.015
50	2.6	13.13	3.79	1.41	72.6	0.14	0.63	7.91	<0.05	0.23	0.008	0.008
51	2.8	13.34	3.85	1.39	72.6	0.21	0.64	7.65	<0.05	0.23	0.007	0.011
52	3.7	13.77	3.73	1.12	71.6	0.24	0.52	8.75	<0.05	0.13	<0.005	0.011
53	2.7	13.57	3.89	1.42	72.3	0.25	0.63	7.67	<0.05	0.22	0.005	0.007
54	2.7	13.29	3.82	1.40	72.4	0.21	0.66	7.87	<0.05	0.23	0.006	0.009
55	3.8	13.03	3.85	1.04	72.6	0.21	0.58	8.30	<0.05	0.13	<0.005	0.009






ENGLISH HERITAGE RESEARCH DEPARTMENT

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The Research Department provides English Heritage with this capacity in the fields of buildings history, archaeology, and landscape history. It brings together seven teams with complementary investigative and analytical skills to provide integrated research expertise across the range of the historic environment. These are:

* *Aerial Survey and Investigation*
* *Archaeological Projects (excavation)*
* *Archaeological Science*
* *Archaeological Survey and Investigation (landscape analysis)*
* *Architectural Investigation*
* *Imaging, Graphics and Survey (including measured and metric survey, and photography)*
* *Survey of London*

The Research Department undertakes a wide range of investigative and analytical projects, and provides quality assurance and management support for externally-commissioned research. We aim for innovative work of the highest quality which will set agendas and standards for the historic environment sector. In support of this, and to build capacity and promote best practice in the sector, we also publish guidance and provide advice and training. We support outreach and education activities and build these in to our projects and programmes wherever possible.

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