REPRINTED FROM JOURNAL OF GLASS STUDIES VOLUME 50 • 2008

Sarah Paynter

Experiments in the Reconstruction of Roman Wood-Fired Glassworking Furnaces: Waste Products and Their Formation Processes

Copyright © 2008 by The Corning Museum of Glass, Corning, NY 14830-2253

Experiments in the Reconstruction of Roman Wood-Fired Glassworking Furnaces: Waste Products and Their Formation Processes

Sarah Paynter

Based on experiments conducted by Mark Taylor and David Hill

I N 2005 AND 2006, Mark Taylor and David Hill built two experimental glassworking furnaces based on archeological remains and representations from the Roman period. Over several weeks in each of these years, they used these furnaces to melt and work soda-lime-silica glass. Later, the appearance of the waste materials and structures was carefully recorded, and some of them were sampled for scientific analysis.

This article describes the various types of waste produced in the experiments, including their characteristics and their formation processes. This experimentally produced material is compared with archeological glassworking waste, with the aim of facilitating the interpretation of the latter. Details of the experimental work and the materials used can be found in the accompanying article by Taylor and Hill (see pages 249–270). All of the materials examined in this study were taken from the first firing in 2005, unless stated otherwise.

BACKGROUND

Structures

Two small furnaces (a pot furnace and a tank furnace) and a lehr (annealing oven) were constructed in the first firing in 2005. These structures were built from daub, made from a mixture of clay, sand, grit, and chopped hay.

The pot furnace had an internal shelf that held a number of ceramic pots (also known as crucibles) full of glass. The shelf (W. about 0.3 m when fired) inclined slightly downward toward the center of the furnace. The furnace had three gathering holes: (A) to the left of the stokehole, (B) to the right of the stokehole, and (C) at the rear of the furnace (Fig. 1). There was also a small hole in the top of the furnace. Two small pots (1 and 2) were placed in front of gathering hole A, two large pots (4 and 5) were placed in front of gathering hole B, and one large pot (3)was placed in front of gathering hole C. Pot 3 failed, and so gathering hole C was usually left closed, while gathering holes A and B were generally left open.

The tank furnace had an integral tank for holding the melted glass. A lehr, for annealing the glass vessels, adjoined the tank furnace, and the two were separated by a removable damper. As the tank within the furnace failed, the furnace was operated at a lower temperature for the remainder of the experiment and was used only to heat the lehr.

Acknowledgments. This study is based on material produced by Mark Taylor and David Hill during their experimental work. Watching the furnaces in operation and the glass being made was a valuable and enjoyable learning experience, and I thank them for their considerable assistance with this article. Thanks also to Roger Wilkes for his help in preparing and examining samples, and to Sarah Jennings for general support with the project.



FIG. 1. Plan of pot furnace, showing position of gathering holes A, B and C; two small pots (1 and 2); three large pots (3–5); and gathering iron.



FIG. 2. Small pot after use, showing glossy glaze on left side of rim, matte opaque yellowish brown glaze on right side of rim, and black mark left by gathering iron.

Pots

Ceramic pots were used to hold the glass in the pot furnace. Each was a terra-cotta vessel with a thick gray external daub layer. During the firing, the daub layers partly pulled away from the pots, leaving a gap between the two (Fig. 2).

Fuel

The furnaces were fired with a mixture of seasoned ash and beech wood, and lesser amounts of holly, chestnut, cherry, walnut, and yew. When wood is burned, the water and volatile organic components are lost as gaseous oxides, so only a small amount of ash is produced from a relatively large quantity of wood (about 0.5 wt %).¹ The composition of the ash produced is highly variable, and it depends on such factors as the type of wood burned, the geology of the area in which the plant grew, the parts of the plant burned, the amount of adhering soil, and the temperatures and atmosphere during the burning. For these reasons, the compositional data for the wood ash discussed in this article are treated as approximate. Some previously published data for the composition of ashes from beech wood (by convention, presented as oxides, even though the compounds are largely carbonates) are given in the middle part of Table 1. The ash from these plants is dominated by calcium carbonate.²

The minerals in ash undergo transformations and reactions as they are heated, causing the composition of the ash to change. Calcium carbonate decomposes to the oxide between 650° and 900°C.³ At higher temperatures, potassium carbonate and sodium compounds decompose to form the oxides, which volatilize.⁴ The sulfates (such as calcium, magnesium, and potassium sulfates) dissociate. The sulfur, sodium, and potassium content of the ashes therefore decreases as these reactions take place. The amount of boron, copper, and zinc in the ash also decreases. The volatile products are carried through the furnaces and the lehr in the waste gases, where they come into contact with the surfaces of the structures, the pots, and the glass before they are lost to the atmosphere.

Glass

The glass melted in the furnace had a sodalime composition similar to glass of the Roman period (Table 2). Most of the glass used in the experiment was premelted in a modern gas-fired furnace and introduced into the experimental wood-fired furnaces as cullet. The ingredients were weighed out into pots in batches of about 15 kilograms and premelted in the gas-fired furnace for two and a half hours at 1250°C, followed by 1100° for another 21 hours. The temperature was then reduced to 1070°C so that gathers of glass could be removed, plunged into cold water, and broken into small lumps. The resulting cullet was stored damp until it was needed at the wood-fired replica furnaces. This 24-hour cycle resulted in a moderately bubbly glass with a few small inclusions.

During the experiment, the pots in the pot furnace were repeatedly filled, almost to the rim, with the prepared cullet, using a small, custommade shovel, which was inserted through the gathering holes. The cullet was heaped centrally in each pot. It gradually melted at temperatures of about 1050°C or less, over two days before it was used. The cullet tended to spit as it was heated. The glass appeared greener in the wood-fired furnace than in the modern gas-fired furnace because of the greater oxidizing atmosphere in the former.

^{1.} W. E. S. Turner, "Studies of Ancient Glass and Glass-Making Processes. Part V: Raw Materials and Melting Processes," *Journal of the Society of Glass Technology*, v. 40, no. 194, June 1956, pp. 277T–300T, esp. p. 289T.

^{2.} *Ibid*. See also D. C. W. Sanderson and J. R. Hunter, "Compositional Variability in Vegetable Ash," *Science and Archaeology*, v. 23, 1981, pp. 27–30, esp. p. 28.

^{3.} M. K. Misra, K. W. Ragland, and J. A. Baker, "Wood Ash Composition as a Function of Furnace Temperature," *Biomass and Bioenergy*, v. 4, no. 2, 1993, pp. 103–116, esp. p. 107.

^{4.} L. Etiégni and A. G. Campbell, "Physical and Chemical Characteristics of Wood Ash," *Bioresource Technology*, v. 37, 1991, pp. 173–178, esp. p. 174.

TABLE 1

Compositions of Ash and Powdery Deposits*, Compared with Published Data for Plant Ashes

Ash	Na_2O	MgO	Al_2O_3	SiO_2	P_2O_5	SO_3	K_2O	CaO	TiO_2	MnO
Pot furnace (from sides, compacted)	bd	2.7	bd	10.4	1.3	bd	7.2	77.2	trace	0.1
Pot furnace (surface layer)	bd	9.7	bd	10.5	3.0	0.4	5.1	69.7	trace	trace
Pot furnace (bottom layer)	bd	12.3	bd	10.5	4.5	0.1	5.5	66.2	trace	0.1
Tank furnace (from sides, compacted)	bd	5.1	bd	10.6	2.5	0.2	4.9	76.2	trace	0.1
Tank furnace (surface layer)	bd	6.3	bd	11.4	2.8	0.3	3.2	75.4	trace	0.1
Tank furnace (bottom layer)	bd	6.8	bd	10.7	2.7	0.3	3.2	73.9	trace	0.1
Literature Data for Ash	Na ₂ O	MgO	Al_2O_3	SiO ₂	P_2O_5	SO ₃	K_2O	CaO	TiO_2	MnO
Beech trunk, Turner [note 1]	3.60	10.90		5.40	5.40	1.80	16.40	56.40		
Beech brush, Turner [note 1]	2.40	10.60		9.80	12.20	0.80	13.80	48.00		
Beech, Sanderson and Hunter [note 2]	8.00	2.17					27.42	57.16		4.28
Powdery Deposits	Na ₂ O	MgO	Al_2O_3	SiO ₂	P_2O_5	SO ₃	K ₂ O	CaO	TiO ₂	MnO
Pot furnace (hole in top)	bd	7.9	0.5	14.6	3.3	1.6	5.8	62.0	0.1	0.1
Pot furnace (from collar of gathering hole A)	3.7	6.6	2.7	30.3	4.5	0.1	6.6	43.0	0.6	0.1
Pot furnace (inside door to gathering hole C)	14.5	1.8	1.8	13.1	1.6	18.9	32.4	14.8	0.1	trace
Tank furnace (gathering hole door)	4.4	1.6	bd	13.9	2.1	24.3	20.7	31.1	0.1	0.1
Lehr (furnace side of damper)	7.5	1.4	0.8	11.6	1.6	20.9	35.9	19.3	0.1	trace
Lehr (top of wall facing inlet from tank furnace)	7.1	1.6	0.6	11.3	1.7	21.4	31.4	20.8	trace	trace

*Normalized and corrected; average of two XRF analyses. Trace = present, but at less than 0.1 wt %; bd = below detection limit.

TABLE 2

Raw Materials Used to Make Glass Batches, and Predicted
and Measured* Compositions of Final Glass

Fe_2O_3	СиО	ZnO SrO Raw Materials				Prec Comp (wi	licted position t %)	Mea Comț (w:	Measured Composition (wt %)			
0.1	trace	bd	trace	SO	70.48	SO	70.48	SO	67.83			
0.1	trace	bd	trace	$\operatorname{Na}(\Omega)$	32.15	$N_2 O$	18.8	$N_2 O$	18.1			
0.1	trace	bu	trace		0.099	1420	10.0	14420	10.1			
0.1	trace	bd	trace	K.CO.	1.28	K ₂ O	0.88	K ₂ O	1.73			
				CaCO ₂	11.20	CaO	6.6	CaO	6 87			
0.2	trace	bd	trace	MgCO ₂	1.78	MgQ	0.85	MgO	1.76			
				Al ₂ O ₂	1.4	Al ₂ O ₂	1.4	Al ₂ O ₂	2.73			
0.3	trace	bd	trace	Fe_2O_3	1	Fe_2O_3	1	Fe_2O_3	0.98			
0.1	trace	bd	trace	*Normalized;	*Normalized; average of seven SEM-EDS analyses.							
Fe ₂ O ₃	СиО	ZnO	SrO		Glass wa iron, which hole (Fig. 1	s gathered (was inserte). Mark Ta	on the end d through	of a blowi the gatheri orted the ir	ing ing on			
0.84	0.05	0.07			against the door of the gathering hole, and with the end dipped in the glass, he rotated the iron toward the supporting wall of the gathering hole. As the iron was withdrawn through the door, some glass dripped or trailed from the gather. On one occasion, glass was produced directly							
Fe_2O_3	СиО	ZnO	SrO									
1.7	trace	0.1	0.1		from batch ingredients in the pot furnace. This is discussed below.							
1.6	trace	trace	trace		METHODOLOGY							
0.4	trace	0.4	trace		SEM-EDS	Analysis						
0.9	trace	0.2	trace		An energ tached to a	y-dispersive Leo Stereos	e spectromo scan 440i s	eter (EDS) scanning el	at- ec-			
0.4	trace	0.2	trace		the analyses	scope (SEM 5. This techr) was used nique perm	its samples	to			
0.2	trace	0.7	trace	be examined at high magnification and selected areas or phases to be analyzed simultaneousl Samples for analysis were mounted in resin an polished to obtain a flat surface. The EDS sy tem used an accelerating potential of 25 kV. Star								

dard glasses of known composition (Corning ref-



FIG. 3. Broken neck of vessel, where external surface became dull while glass was annealed in lehr (photographed on light box).

erence glasses A, B, and D; potash- and lime-rich glasses YM144 and YM149; soda-lime glasses London 1 and 2; Sheffield 620; and a mixed-alkali glass, SRM710) were repeatedly analyzed with the archeological samples throughout the study (Table 3). The detection limits for most elements measured by SEM-EDS was 0.1 wt %, but higher (about 0.2 wt %) for Na₂O, P₂O₅, and SO₃.

XRD Analysis

While the other techniques provide information on chemical composition, X-ray diffraction (XRD) analysis gives information on crystal structure. XRD analysis facilitated the identification of crystalline phases in the samples. A Philips PW 1830/40 diffractometer was used, with a tube voltage and current of 40 kV and 40 mA respectively. Samples were ground into a fine powder before they were presented for analysis. The multiple compounds in each sample were identified by comparison with an ICDD database.

XRF Analysis

An Edax Eagle II spectrometer was used for X-ray fluorescence (XRF) analysis, with a tube voltage of 40 kV and current of about 500 μ A, depending on the sample. A series of standards of known composition were also analyzed, in-

cluding the glass standards noted above and several mineral standards, and the results for each element were plotted against the known composition. These linear graphs were used to calibrate the XRF results for each element, and the totals for each sample were normalized. The detection limits of the Eagle XRF were very good (generally less than 0.1 wt %) for heavier elements, such as manganese, copper, zinc, and strontium, but poor for light elements, such as sodium. Therefore the detection limits were ~ 3 wt % for soda, ~ 0.5 wt % for alumina, and ~ 1 wt % for magnesia. The results for elements present in amounts less than 0.1 wt % have not been quantified, but a "trace" was recorded if they were detected.

RESULTS

Glass

Numerous samples of glass from the experiment were examined. Previously prepared cullet was used for most of the glassworking, but in the 2006 experiment, one batch was also melted directly in the pot furnace. Samples of this batch were taken at intervals to investigate changes in the homogeneity and composition of the glass over time.

The glass vessels produced in the experiments were annealed in the lehr, but many of them developed dull surfaces (Fig. 3). These were examined to determine why this change had occurred.

During the glassworking, trails, drips, moils, and broken fragments of glass were deposited around the pot furnace (Fig. 4). Large lumps (Fig. 5) and small blobs (Fig. 6) of glassy waste were also recovered from inside the pot and tank furnaces after the experiment had been completed. These different types of waste are described and characterized.

Changes in the Glass over Time. In the second firing (in 2006), approximately two kilograms of weighed batch materials was placed directly into a large pot in the pot furnace (without any previous heating or melting in the gas-fired furnace). Samples were taken from this pot, using



FIG. 4. Fragments of glassworking waste around pot furnace.



FIG. 5. Large lump of glass waste recovered from within pot furnace.

a gathering iron, after 14, 29, 54, 76, and 90 hours (as well as at some point after five days), and examined. The pot leaked slowly, but it was not refilled. Not surprisingly, the glass gathered in the earlier stages had more visible imperfections than the glass that was heated for longer periods (Fig. 7). The gathers at 14 and 29 hours contained occasional undissolved particles, predominantly grains of quartz but also potassium feldspar, zircon, and spinel, and more numerous



FIG. 6. Small blobs of glass waste recovered from ashpit of pot furnace. From top: yellowish green, with rough surface, brown, and blue-green.

TABLE 3

Standard	Na_2O	MgO	Al_2O_3	SiO_2	P_2O_5	SO ₃	K_2O
Corning A known	14.30	2.66	1.00	66.93	0.13	0.10	2.87
Corning A measured (20)	14.18	2.61	1.06	66.64	0.17	0.22	2.92
Glass Waste from Within the Furnaces	Na_2O	MgO	Al_2O_3	SiO_2	P_2O_5	SO ₃	K_2O
Small brown blobs (11)	11.23	1.42	8.16	66.36	bd	0.27	5.90
Small blue-green blobs (6)	16.51	1.54	2.65	68.65	bd	bd	2.56
Small rough-surfaced blobs (5)	12.66	1.62	4.32	65.85	bd	bd	8.56
Large lump from tank furnace (6)	18.24	1.49	2.45	68.24	bd	bd	1.60
Large opaque lumps from pot furnace (15)	13.51	2.71	2.83	56.90	1.04	bd	5.46
Pots	Na ₂ O	MgO	Al_2O_3	SiO ₂	P_2O_5	SO ₃	K_2O
Daub layer fabric (7)	0.64	0.54	20.03	72.97	bd	bd	2.26
Terra-cotta pot fabric (3)	0.45	1.04	22.11	67.10	bd	bd	1.33
Terra-cotta pot rim: yellowish brown section, lower layer (2)	1.80	0.99	21.23	50.97	bd	bd	19.66
Terra-cotta pot rim: yellowish brown section, middle layer (3)	5.26	1.27	19.87	43.85	0.44	bd	18.93
Terra-cotta pot rim: yellowish brown section, upper layer (3)	4.05	4.08	8.62	36.29	4.41	bd	7.65
Daub rim: yellowish brown section, lower layer (1)	0.62	0.41	27.05	45.91	bd	bd	23.56
Daub rim: yellowish brown section, daub layer, upper layer (3)	3.65	2.43	9.89	45.50	1.08	bd	10.93
Terra-cotta pot rim: glossy section (3)	16.20	1.51	4.98	66.13	bd	bd	3.10
Daub rim: glossy section (3)	9.58	1.24	12.33	62.57	0.28	bd	6.52
Daub pot walls: glaze on surface (3)	9.38	0.78	12.91	63.31	bd	bd	8.87
Daub pot walls: transparent glaze streak (3)	9.33	1.28	9.15	67.17	bd	bd	6.10
Furnace	Na ₂ O	MgO	Al_2O_3	SiO ₂	P_2O_5	SO_3	K_2O
Pot furnace internal glaze (2)	4.59	0.60	9.79	66.37	bd	bd	14.40
Tank furnace internal glaze (8)	8.55	0.81	9.97	60.07	bd	0.39	15.73
Pot furnace fabric (1)	0.42	0.68	21.45	70.54	bd	bd	4.09
Tank furnace fabric (7)	0.91	0.63	23.14	68.23	bd	0.26	2.82

SEM-EDS Results for Corning Glass Standard A (Compared with Certified Known Composition) and Waste Materials from the Experiment*

*Normalized; average. Number of SEM-EDS analyses in parentheses; areas of different sizes were ana-

lyzed, depending on the size of the feature. bd = below detection limit.

CaO	TiO_2	MnO	FeO	CoO	СиО	ZnO	SnO_2	Sb_2O_5	BaO	PbO
5.03	0.79	1.00	0.98	0.17	1.17	0.044	0.19	1.75	0.56	0.12
5.16	0.81	1.10	1.02	0.18	1.27	0.06	0.17	1.69	0.48	0.02
CaO	TiO_2	MnO	FeO	CoO	СиО	ZnO	SnO_2	Sb_2O_5	BaO	PbO
4.91	0.29	bd	1.55	bd	bd	bd	bd	bd	bd	bd
7.00	bd	bd	0.90	bd	bd	bd	bd	bd	bd	bd
5.86	0.17	0.12	0.86	bd	bd	bd	bd	bd	bd	bd
6.97	bd	bd	0.85	bd	bd	bd	bd	bd	bd	bd
16.39	0.13	bd	1.01	bd	bd	bd	bd	bd	bd	bd
CaO	TiO_2	MnO	FeO	CoO	СиО	ZnO	SnO_2	Sb_2O_5	BaO	PbO
0.83	0.72	bd	1.80	bd	bd	bd	bd	bd	bd	bd
0.48	1.22	bd	6.01	bd	bd	bd	bd	bd	bd	bd
0.19	0.69	bd	4.31	bd	bd	bd	bd	bd	bd	bd
6.11	0.51	bd	3.65	bd	bd	bd	bd	bd	bd	bd
30.74	0.60	0.10	3.39	bd	bd	bd	bd	bd	bd	bd
bd	0.67	bd	1.70	bd	bd	bd	bd	bd	bd	bd
24.90	0.36	bd	1.18	bd	bd	bd	bd	bd	bd	bd
6.66	0.18	0.15	0.98	bd	bd	bd	bd	bd	bd	bd
5.68	0.42	bd	1.22	bd	bd	bd	bd	bd	bd	bd
2.06	0.49	bd	1.38	bd	bd	bd	bd	bd	bd	bd
4.67	0.38	bd	1.65	bd	bd	bd	bd	bd	bd	bd
CaO	TiO_2	MnO	FeO	CoO	СиО	ZnO	SnO_2	Sb_2O_5	BaO	PbO
2.29	0.43	bd	1.35	bd	bd	bd	bd	bd	bd	bd
2.82	0.41	bd	1.18	bd	bd	bd	bd	bd	bd	bd
0.38	0.74	bd	1.58	bd	bd	bd	bd	bd	bd	bd
0.94	0.77	bd	2.13	bd	bd	bd	bd	bd	bd	bd



FIG. 7. Backscattered SEM image of heterogeneous gather of glass after heating batch for 14 hours in pot furnace.



FIG. 8. Plot showing EDS results for concentrations of potash in gathers of glass taken at intervals from otherwise undisturbed (but leaking) pot.

bubbles. Analyses also found that the gather at 14 hours had quite a variable composition. Glass that had been heated for more than 50 hours contained occasional bubbles but few inclusions, and it was compositionally more homogeneous.

However, the compositions of the gathers also differ slightly from one another, suggesting that the composition of the glass in the pot changed over time. Initially, three random areas (each about 2.5 mm²) of the glass samples were analyzed, including undissolved particles when these were present, but additional analyses of several samples were made at a later date. Figure 8 shows the results for potash. Although there is scatter in



FIG. 9. SEM image of dull surface of glass vessel in Figure 3, showing small depressions covering surface.

the data points because of factors such as the heterogeneity of the samples, the small areas analyzed, and the reproducibility of the technique, the concentrations of potash appear to have increased over time. Concurrently, the concentrations of silica decreased between the first and final samples (by roughly 2 wt % overall), noticeably diluted by the increased levels of alkali. (Changes in the concentrations of other elements were too small, relative to the scatter, to suggest any trend.)

This observation suggests that the alkali-rich waste gases in wood-fired glassworking furnaces can affect the composition of the glass when it is heated over prolonged periods. This results in increased concentrations of alkali, potash in particular. Some instances in which similar observations have been made with archeological material are discussed later in this article. In gas-fired furnaces, by contrast, reduced concentrations of alkalis caused by volatilization, especially for soda, are often noted.

Mark Taylor and David Hill also observed fine layers of ash from the fuel settling on the surface of the glass in the pot furnace after stoking, which were gradually absorbed. However, the incorporation of the lime-rich ash did not cause significant changes to the composition of the glass in the pots.

Dulling of the Glass. The external surfaces of some of the glass vessels annealed in the lehr became dull. Figure 3 shows the neck of a glass vessel that was accidentally overheated in the lehr, causing it to droop. Where the glass has stretched, the thin surface layer of dulled glass has broken in places, and so bands of dulled glass alternate with fresh glass. XRF analysis of the dulled surface of the vessel neck detected increased levels of sulfur and zinc relative to fresh glass from the fractured edge of the same vessel, which contained little sulfur and no detectable zinc. SEM images of the glass (Fig. 9) show that the dulled glass had a pockmarked appearance. These depressions (D. about 1-3 µm) scatter light at the surface of the glass, causing it to appear dull. Increased concentrations of sulfur and zinc were also detected in deposits from inside the furnaces and lehr, and in the glaze covering the inside of the furnaces (see below). These elements originated from the fuel, but they became volatile in the heat of the firing chamber. Therefore, the waste gases from the fuel, in particular the sulfur compounds they contain, play an important role in the dulling process.

Glassworking Waste Deposited outside the Furnaces. Much of the waste glass generated during each glassworking session was broken up by plunging it into a bucket of cold water, and it was then reused. However, some waste from gathering, blowing, and working the glass fell on the floor around the pot furnace (Fig. 4). This included drips and trails, broken fragments of vessel and window glass, and moils (small collars of glass from around the blowing iron). The composition of most of this glass waste was not significantly different from that of the original glass. Some of the moils, however, had small flakes of black iron oxide scale from the blowing iron adhering to their inner surface, and these flakes had started to react with the glass.

Glass Waste within the Furnaces. Glassy waste was also recovered from inside the furnaces after the first firing. The tank furnace failed, so a large spill of glass was found in the firing chamber. One of the pots in the pot furnace also failed, causing the contents to flow into the firing chamber. In addition to these large spills, small glass blobs were recovered from the ash when the firing chamber of the pot furnace was emptied. Some of these were brownish, some had rough surfaces, and others were blue-green, similar to the original glass (Fig. 6).

The larger lumps of glass tended to be from pot or furnace failures early in the experiment, and so they had been in the firing chambers of the furnaces, surrounded by lime-rich fuel ash (see below), for prolonged periods at high temperatures. Some samples, such as the large spill from the tank furnace, had charcoal adhering in places and had not wetted the fuel ash to any great extent. These samples were fairly unaltered compositionally in relation to the original glass, except around the edges, where there were lime-rich crystals, such as akermanite or melilite, tetrasodium-calcium-trisilicate, and numerous bubbles from reaction with the surrounding fuel ashes.⁵ Occasionally, crystalline phases were present in the bulk of the sample, including disodium-dicalcium-trisilicate and some dissolving particles of quartz. The latter may be the remains of sand that was added by Mark Taylor and David Hill in an attempt to stop the leak from the furnace tank.

Other large lumps of glass had obviously been altered to a greater extent because they were

mainly opaque and the surfaces were discolored (Fig. 5). Some ash still adhered around the edges, and the glass had yellowish white or opaque brown outer surfaces and patches of opacity within. A significant amount of ash had been incorporated in the glass, reacting to produce the observed changes in composition and microstructure. These lumps were often greatly enriched in lime, magnesia, and phosphorus (Table 3). A sodium-calcium-phosphate-silicate phase was occasionally present at the surface, similar to that seen on the yellowish section of the pot rims (see below). Disodium-dicalcium-trisilicate, melilite, and wollastonite were common, especially near the surfaces. Samples with particularly high concentrations of lime contained the disodium-dicalcium-trisilicate phase throughout (Fig. 10).

The extent of the reaction between the glass lumps and the fuel ash was extremely variable, but one of the most important factors was probably where the glass fell in the firing chamber, which would have affected not only the temperature but also how often the glass was disturbed during the stoking and removal of ash. A greater reaction would be expected with increased time and temperature in the furnace, and larger, thicker pools of glass would be more likely to contain some unaltered glass.

The small blobs of brown glass (Fig. 6) were higher in alumina, potash, iron oxide, and titania relative to the original glass composition (Table 3). They contained crystals of wollastonite, meli-

^{5.} The phases referred to in this article include akermanite, Ca₂MgSi₂O₇; melilite, (Ca,Na)₂(Mg,Fe₂+,Al,Si)₃O₇; leucite, KAlSi₂O₆; kalsilite, KAlSiO₄; wollastonite, CaSiO₃; portlandite, Ca(OH)₂; sodium-calcium-phosphate-silicate, Na₂Ca₄(PO₄)₂SiO₄; arcanite, K₂SO₄; aphthitalite, KNaSO₄; calcite, CaCO₃; and dipotassium-calcium-carbonate, K₂Ca(CO₃)₂. Two forms of sodium-calcium-silicate were present: the most common was disodium-dicalcium-trisilicate (Na₂Ca₂Si₃O₉), but small amounts of an unstable cubic phase, thought to be tetrasodium-calciumtrisilicate (Na₄CaSi₃O₉), were occasionally present. See W. A. Deer, R. A. Howie, and J. Zussman, *An Introduction to the Rock Forming Minerals*, Harlow, Essex, U.K.: Longman, 1992. This note should be referred to throughout the following discussion.



FIG. 10. Backscattered SEM image of large lump of glass waste from ashpit of pot furnace, which has become highly crystalline.

lite, and tetrasodium-calcium-trisilicate, as well as iron-rich droplets, particularly near the surface. The rough-surfaced glass blobs were higher in potash and, to a lesser extent, alumina. They contained crystalline phases, again concentrated near the surface, including akermanite or melilite, as well as both types of sodium-calciumsilicate phase, and numerous bubbles. The phosphorus-rich phase was present at the surface.

The compositions of the brown and roughsurfaced blobs (Fig. 6 and Table 3) indicate that they were formed from the glassy material that dripped from the furnace walls or shelf, or from the exterior of the pots. This glassy material was a mixture of soda-lime glass and aluminaand potash-rich glaze from the pots and the furnace walls. The higher concentrations of iron resulted in a brownish color, and the rough surfaces may be related to the high concentrations of alumina, resulting in greater viscosity. In the firing chamber, the droplets of glass also started to react with the lime-rich fuel ashes, resulting in the precipitation of the lime-rich crystalline phases noted previously.

The small blue-green glass blobs (Fig. 6) recovered from the ashpit of the pot furnace had compositions similar to that of the original glass (Table 3). Some reaction with lime-rich ash had occurred in the firing chamber, however, resulting in very fine sodium-calcium-silicate crystals toward the surface. These blobs of glass were formed from the glass that spattered out of the pots when they were refilled with cullet. Although drips of glass were also lost during the gathering, these tended to fall between the pot and the gathering hole, rather than over the firing chamber, because the gathering iron was not extended that far.

Pots

Pots 1 and 2 from the first firing were sectioned and examined. The terra-cotta fabric contained considerably more iron oxide than the daub layer, accounting for the strong color of the former, but otherwise the materials had similar bulk compositions (see Table 3). A backscattered SEM image of the terra-cotta pot fabric (Fig. 11) shows quartz grains and occasional iron-rich inclusions surrounded by a fine, compact matrix. The pale daub fabric (Fig. 12) also contained a large number of quartz grains and many elon-



FIG. 11. Backscattered SEM image of section from rim of terra-cotta pot, showing highly crystalline microstructure of opaque yellowish brown glaze on surface.



FIG. 12. Backscattered SEM image of section from rim of daub layer from around pot, showing homogeneous glossy glaze on surface.

gated voids that resulted from the addition of hay as an organic temper. Among the inclusions were occasional fragments of shell (introduced with the grit used to make the daub mixture) and spinels.

Walls. Although the pots were originally unglazed, a glaze developed on the outer walls and rims during use. The glaze on the external daub layer was semiopaque pale green and finely crazed. In contrast, thick vertical streaks of transparent colorless glaze were noted down the outer face of the daub layer on the side of the pots that had faced into the furnace (Fig. 13). There were also greenish glassy deposits between the outer layer of daub and the terra-cotta vessel within (Fig. 2). Only the bases of the pots re-



FIG. 13. Large pots (4 and 5) by gathering hole B, viewed through gathering hole A, showing glazed internal surfaces of furnace, glazed external surfaces of pots, and streaks of more transparent glaze running down pot walls and under furnace shelf.

mained unglazed because these were in contact with the furnace shelf and were thus protected.

The glaze on the outer surface of the daub layers was glassy and homogeneous. However, a layer of crystalline phases, consisting of leucite and kalsilite, had formed at the interface between the glaze and the daub, because of the high concentrations of alumina and potash in those regions (Fig. 12). These small crystals scattered light, and so made the glaze appear semiopaque. This glaze had formed mainly from the reaction of the daub with fluxes in the waste gases from the burning fuel. The glaze was therefore rich in compounds found in the daub, such as alumina, silica, titanium, and iron (the latter imparted the slight green color to the glaze). It also contained high concentrations of potash and soda that had volatilized from the fuel ashes, but it had little lime or magnesia.

The thick, transparent, vertical streaks of glaze down the surface of the daub layers had different compositions, higher in lime and lower in alumina, from the rest of the external glaze (Table 3). These streaks formed when glass ran down from the rim of the pot. The furnace shelf was inclined slightly downward toward the center of the furnace, and the glaze streaks on each pot faced in this direction. The streaks were transparent because there were very few crystalline phases in them (Fig. 13). They were also likely to have a lower viscosity than the rest of the external glaze because of their composition (Table 3), especially the lower levels of alumina, accounting for the more pronounced flow in these areas. It is likely that drips from these glaze streaks became the previously described small blobs of brown glass consisting of a mixture of glass and the glaze from the pot walls.

The pots were damaged by the progressive reaction of the fabric with drips of glass and the waste gases from the fuel. The advantage of the daub layers applied to the pots in this experiment was that they were sacrificial and provided the pots with some protection from this chemical attack, although Taylor and Hill suspect that the primary function of the daub layer was to make the pots more stable while they were on the furnace shelf (see page 261). This may be one reason why similar layers were sometimes applied to pots in antiquity.

Rims. As described by Taylor and Hill, roughly half the rim of each pot (both the external daub layer and the terra-cotta pot within) was covered with a smooth, glossy, and transparent glaze, whereas the opposite half of each rim appeared matte, yellowish brown, and opaque (see page 261). The yellowish brown deposit had formed on the part of the rim that had been near the furnace wall during use. On each terra-cotta pot rim, an opaque black mark (in the newly formed glaze) indicated where the gathering iron had been placed (Fig. 2). A black trail of dissolved iron oxide could also be seen in the glaze on the internal wall of the pots.

The composition of the glossy regions of glaze on the rims of the daub layer and the terra-cotta pot, and also in the gap between the two, tended to be close to that of the glass being melted in the pot (Table 3). Therefore, the glaze in these areas was formed largely from spills and splashes of this glass (Fig. 12). Increased concentrations of compounds such as alumina, however, indicate some reaction with the pot and daub fabrics. Slightly increased concentrations of potash suggest some reaction with fuel vapors as well. Occasional crystals of wollastonite were present.

In contrast, the opaque yellowish brown sections of glaze on the pot and daub rims were highly crystalline and microstructurally complex. The composition, and therefore the type of crystalline phases that had precipitated, varied with depth. The concentrations of potash, alumina, and silica were highest in the bottom layers of the crystalline glaze, whereas lime dominated toward the surface, together with increased magnesia and phosphorus (Table 3). These compositional data indicate that the crystalline glaze was formed with a significant contribution from fuel ash. The distribution of these yellowish brown patches shows that fuel ash settled on the rims near the furnace wall but not on the portion of the rims facing the center of the furnace. The

strong draft in that region carried the fuel ashes past the pots and out of the furnace with little chance to settle, while more turbulent airflow would be expected near the furnace walls.

A backscattered SEM image of the complex microstructure of the yellowish brown glaze on the terra-cotta pot is shown in Figure 11. At the surface were small amounts of an alkalicalcium-phosphate-silicate phase, in addition to kalsilite and melilite. Beneath these were regions rich in wollastonite and, moving lower, increasing amounts of kalsilite in a glassy matrix. The upper layers of the microstructure on the daub also contained numerous phases, including wollastonite and melilite surrounded by soda-rich glass. The lower layers consisted of large, elongated wollastonite crystals, as well as melilite in a glass matrix.

Furnace

During use, each of the furnaces developed a glaze over the interior surfaces, and some glass was also spattered or spilled on these surfaces, particularly on and beneath the shelf (Fig. 13). However, circular unglazed patches were left on the shelf when the glass pots were removed. The top hole of the pot furnace became visibly corroded during the experiment.

A powdery pinkish brown deposit was present on many of the pot furnace surfaces, particularly around the gathering holes and on their doors and collars, in the top hole, and on the internal shelf at both the front (over the stokehole) and the back (by the closed gathering hole C). A similar deposit was observed in areas of the tank furnace and the lehr, and samples were taken from all of these areas for analysis.

Glaze. Few samples were taken from the pot furnace because it was reused in a later experiment, but more were removed from the tank furnace and the lehr. Each of the samples included a section of daub fabric with some of the covering glaze.

In each case, the glazes were rich in alumina because they formed from the reaction of the daub with fluxes. The major fluxes were potash

and, to a lesser extent, soda (generally, there was little lime or magnesia in the glazes). Soda and potash fluxes from the burning fuel traveled through the furnace as vapor. The composition and thickness of the glazes, and the crystalline phases that precipitated, varied from region to region, influenced by the types of inclusions in close proximity-for example, from lime-rich shell fragments and silica-rich quartz grains to iron-rich spinel particles (see Table 3). However, common crystalline phases were kalsilite and leucite. In a sample taken from near the gathering hole of the tank furnace, increased levels of sulfur were also detected, concentrated in an alkali-rich phase with a dendritic structure in the glaze. This phase is likely to have been aphthitalite, which was also present in powdery residues removed from the walls of the furnace and the lehr (see below).

Powdery Deposits. Pot furnace samples, both from the collar of gathering hole A and from the hole in the top of the furnace, were dominated by deposits of calcium, with magnesium, phosphorus, and potassium also present in significant amounts (Table 1). XRD analysis detected calcium carbonate and portlandite in both samples, and dipotassium-calcium carbonate was also found in the sample from the gathering hole. These samples therefore consisted mainly of fuel ash that was carried through the furnace by the drafts and deposited around apertures as the gases exited the furnace.

Samples were also taken from the door to gathering hole C in the pot furnace, from the door to the gathering hole in the tank furnace, from inside the lehr at the top of the wall facing the inlet from the adjoining tank furnace, and from the furnace side of the damper between the lehr and the tank furnace. The composition of each of these samples was dominated by potassium, sulfur, calcium, and sodium (Table 1), and XRD analysis identified the phases arcanite, aphthitalite, and calcite. Some zinc and, to a lesser extent, copper were present in all four samples.⁶ These deposits have formed predominantly from compounds in the burning fuel that had volatilized in the furnace and then condensed on cooler surfaces. Some lime-rich fuel ash was also incorporated in the deposits.

Ash

Large quantities of ash were produced in the firing chambers of both furnaces. The ash from the lower layers was darker gray, containing a larger amount of charcoal because the conditions were slightly less oxidizing. In the upper layers, the ash was white and contained very little charcoal. A layer of cream-colored compacted ash was found around the sides of the firing chamber, where it had been consolidated by stoking and raking.

XRF analyses indicated that, although the ash was compositionally variable, calcium compounds were consistently the major component.⁷ This would have been expected because of the type of wood burned (mainly ash and beech). Potassium, magnesium, and phosphorus compounds were also present in significant amounts. Small quantities of sodium, aluminum, and silicon were detected, along with minor amounts of manganese, iron, titanium, and strontium (Table 1). XRD analysis of ash samples from the top, bottom, and compacted side layers of the firing chambers showed that calcium carbonate, portlandite, and, to a lesser extent, lime were dominant. Dipotassium-calcium carbonate was also detected in ash samples from the top and compacted side layers of the pot furnace.

Wood ash undergoes numerous transformations at high temperatures.⁸ The calcium in the ash formed at low temperatures is largely in the form of the carbonate, but this decomposes to the oxide as it is heated. When the oxide is left to stand, however, it absorbs water from the atmosphere to form portlandite.⁹

^{6.} Misra, Ragland, and Baker [note 3], esp. p. 116.

^{7.} *Ibid.* See also Turner [note 1] and Sanderson and Hunter [note 2].

^{8.} Misra, Ragland, and Baker [note 3], esp. p. 116.

^{9.} See note 5.

DISCUSSION

Waste from Roman glassworking has been recovered from many sites in Europe,¹⁰ and it can be compared with the waste produced in these experiments. Waste from glassmaking and glassworking in other periods has also been studied.¹¹ The glass produced in the medieval and postmedieval periods was made from different raw materials and resulted in types of glass different from those of the Roman era. The raw materials used for furnace construction and for pots also varied from site to site and over time. Despite these differences, evidence from later sites is also discussed here because the furnaces used were wood-fired, and thus there are many similarities with the waste from the experimental Roman furnaces.

Taylor and Hill describe the weathering of the tank furnace, which was left in the open for a year after the first firing (see pages 269–270). The outer layers of the structure had not reached high temperatures, so they were friable and quickly disintegrated. This is consistent with the poor

survival of archeological furnace remains, and it also complicates efforts to deduce the original thickness of the furnace walls or the form of the superstructure.¹² However, the inner layers of the experimental furnaces, which were also glazed by reaction with vapor-borne fluxes, had been fired to reasonably high temperatures during use, and these proved to be more robust. Similar fragments of fired material (stone, daub, tile, or brick) with an adhering potash-rich glaze are found at glassmaking and glassworking sites of various periods, and they are likely to have come from the furnace structure. Blobs of glassy material from the glazed furnace walls and sieges have also been identified.¹³ However, similar potash-glazed waste can be produced by many processes in which plant matter is burned in contact with siliceous materials (for example, in a smithing hearth), and so interpretation is dependent upon the presence of other types of diagnostic glassworking waste.

At medieval and post-medieval glass production sites, the sieges, on which the glass pots stood, often survive. Like the pot shelf in Taylor

12. Foy and Nenna [note 10], esp. pp. 62–63; Hilary E. M. Cool, "Local Production and Trade in Glass Vessels in the British Isles in the First to Seventh Centuries," in *Echanges et commerce du verre dans le monde antique: Actes du colloque de l'Association Française pour l'Archéologie du Verre, Aix-en-Provence et Marseille, 7–9 juin 2001*, ed. Danièle Foy and Marie-Dominique Nenna, Monographies Instrumentum, no. 24, Montagnac: Editions Monique Mergoil, 2003, pp. 139–145, esp. p. 141.

^{10.} Heidi Amrein, L'Atelier de verriers d'Avenches: L'Artisanat du verre au milieu du 1er siècle après J.-C., Aventicum, v. 11, Lausanne: Cahiers d'Archéologie Romande, 2001; Danièle Foy and Marie-Dominique Nenna, Tout feu tout sable: Mille ans de verre antique dans le Midi de la France, [Marseilles]: Musées de Marseille, and Aix-en-Provence: Edisud, 2001; Caroline Jackson and others, "Roman Glass-Making at Coppergate, York? Analytical Evidence for the Nature of Production," Archaeometry, v. 45, no. 3, August 2003, pp. 435-457; Caroline M. Jackson, Hilary E. M. Cool, and Emma C. W. Wager, "The Manufacture of Glass in Roman York," Journal of Glass Studies, v. 40, 1998, pp. 55-61; Jackie Keily and John Shepherd, "The Glass," in Fiona Seeley and James Drummond-Murray, Roman Pottery Production in the Walbrook Valley: Excavations at 20-28 Moorgate, City of London, 1998-2000, MoLAS monograph 25, London: Museum of London Archaeology Service, 2005, pp. 178-184; K. Hans Wedepohl, Wolfgang Gaitzsch, and Anna Barbara Follmann-Schulz, "Glassmaking and Glassworking in Six Roman Factories in the Hambach Forest, Germany," Annales de l'Association Internationale pour l'Histoire du Verre, v. 15, New York and Corning, 2001 (Nottingham, 2003), pp. 56-61

^{11.} Caimin O'Brien, Jean Farrelly, and Sarah Paynter, *The* 17th-Century Glasshouse at Shinrone, Co Offaly, Ireland, Centre for Archaeology Report 39, Swindon: English Heritage, 2005; G. Eramo, "The Melting Furnace of the Derrière Sairoche Glassworks (Court, Swiss Jura): Heat-Induced Mineralogical Transformations and Their Technical Significance," *Archaeometry*, v. 47, no. 3, August 2005, pp. 571–592; Cath Mortimer,

[&]quot;Chemical Composition of Glass and Glass Waste at Little Birches, Wolseley, Staffordshire," in Christopher M. Welch, "Glassmaking in Wolseley, Staffordshire," *Post-Medieval Archaeology*, v. 31, 1997, pp. 38–43; David W. Crossley, "Glassmaking in Bagot's Park, Staffordshire, in the Sixteenth Century," *Post-Medieval Archaeology*, v. 1, 1967, pp. 44–83; Justine Bayley, "Saxon Glassworking at Glastonbury Abbey," in *Glass in Britain and Ireland*, *AD* 350–1100, ed. Jennifer Price, British Museum Occasional Paper 127, London: the museum, 2000, pp. 161–188 and 204; Oren Tal, Ruth E. Jackson-Tal, and Ian C. Freestone, "Glass from a Late Byzantine Secondary Workshop at Ramla (South), Israel," pp. 81–95 in this volume.

^{13.} For descriptions and some analyses of potash-glazed furnace structural materials, see O'Brien, Farrelly, and Paynter [note 11], esp. p. 14; Eramo [note 11], esp. pp. 581–589; Thilo Rehren and Elisa Perini, "The Glass Furnace Debris," in Seeley and Drummond-Murray [note 10], pp. 184–186, esp. p. 186; Tal, Jackson-Tal, and Freestone [note 11], esp. p. 85; and Bayley [note 11], p. 171.

and Hill's experiments, the sieges have a glassy coating consisting of spills of glass and a glaze formed by reaction with vapor-borne fluxes. The position of the pots can also be discerned by the marks left by their bases.¹⁴ Deposits of ash are sometimes recognized in archeological contexts, although only the less soluble compounds, such as calcium carbonate and siliceous components, remain, and their survival depends considerably on the post-depositional environment.¹⁵ Tal, Jackson-Tal, and Freestone (pages 81-95) describe small lumps of glass covered in a lime-rich deposit that may be ash.¹⁶ However, the deposits identified on the inside of the furnaces and the lehr in the experiments described here, such as sodium and potassium sulfate salts, together with traces of zinc and copper, would have been highly soluble, and no trace of them will remain archeologically.

Pot fragments with an external potash-rich glaze and glass within are also reasonably common archeological finds from the Roman and later periods.¹⁷ These are often heavily vitrified, and so they survive, although generally in a fragmentary state. The extent of this vitrification is sometimes used to estimate the temperatures achieved in the furnace, using refiring experiments.¹⁸ The interaction between the glass and the pot, at the interface between the two, is well documented.¹⁹ However, some unaltered glass often survives at a distance from this interface, which can be used to determine the original composition of the glass that was melted. Among the published archeological examples, there are no descriptions of the pot rims with glossy and crystalline glaze sections matching those observed in the recent experiments. However, some differences in the surface appearance of the opposing sides of post-medieval pots have occasionally been noted, such as streaks of glass down one side in particular.²⁰

Although some glass, in the form of lumps and blobs, was recovered from the furnace after these experiments, much of it had been chemically altered from its original composition. Thin layers of glass that were in contact with the pots and the furnace structure were contaminated by reaction with those ceramics and by the waste gases and fuel ashes passing through the furnace. Glass that fell into the firing chamber reacted, to a varying degree, with the lime-rich fuel ashes there. However, it was generally possible to make a visual determination of the samples that had been chemically altered, using indicators such as color, opacity, and roughness. Fragments or drops of unaltered glass remained fairly transparent, smooth, and blue-green. Most of the examples of unaltered glass were recovered from the working area around the furnace (as opposed to within the furnace), and a little remained within the pots (excluding the glass in contact with, or near, the ceramic itself). This has implications for sampling archeological material. However, the chemically unaltered glass waste from the working area around the furnace would be less likely to be recovered archeologically because in practice most of it was recycled. Glass moils with black iron oxide crusts on the inside surface, similar to those produced in these experiments, were found at Anglo-Saxon glassworks at Glastonbury Abbey.²¹

The results from part of the experiments, in which gathers of glass were removed from an

18. Richard N. White, "Appendix 3. Refractory Materials," in Welch [note 11], pp. 48–49; David Dungworth and Tom Cromwell, "Glass and Pottery Manufacture at Silkstone, Yorkshire," *Post-Medieval Archaeology*, v. 40, no. 1, 2006, pp. 160– 190, esp. p. 177; M. Tite and Y. Maniatis, "Scanning Electron Microscopy of Fired Calcareous Clays," *Transactions and Journal of the British Ceramic Society*, v. 74, 1975, pp. 19–22.

19. See, for example, Dungworth and Cromwell [note 18], pp. 177–178; and Jackson and others [note 10], pp. 449–450.

^{14.} For descriptions of furnace sieges, see O'Brien, Farrelly, and Paynter [note 11], p. 4; Crossley [note 11], p. 53; and Welch [note 11], pp. 7–16.

^{15.} Matt G. Canti, "Aspects of the Chemical and Microscopic Characteristics of Plant Ashes Found in Archaeological Soils," *Catena*, v. 54, 2003, pp. 339–361, esp. p. 355.

^{16.} Tal, Jackson-Tal, and Freestone [note 11], esp. p. 85.

^{17.} See, for example, O'Brien, Farrelly, and Paynter [note 11], pp. 14–15; Wedepohl, Gaitzsch, and Follmann-Schulz [note 10], p. 56; Amrein [note 10], pp. 81–85; Foy and Nenna [note 10], pp. 64–66; and Welch [note 11], p. 16.

^{20.} See, for example, Ruth Hurst Vose, "Excavation at the 17th-Century Glasshouse at Haughton Green, Denton, nr Manchester," *Post-Medieval Archaeology*, v. 28, 1994, pp. 1–71, esp. p. 43.

^{21.} Bayley [note 11], p. 170.

undisturbed pot at intervals, suggest that, in some circumstances, the alkali-rich waste gases in the furnace could significantly influence the composition of the glass being heated. This effect was more noticeable in the glass exposed to the waste gases for the longest time. This observation has significance for the archeological interpretation of glass analyses, particularly when it is suspected that the glass has been repeatedly recycled. Tal, Jackson-Tal, and Freestone (pages 81–95) detected unusually high levels of potash in some of the glass from a Byzantine glassworking site, which they attribute to contamination by fuel waste gases.

The composition of the ash from the firing pit is compared with published data in Table 1. The potash content of the ash from the experimental furnaces is considerably lower than that reported in the literature. The soda and sulfur contents of ash from the glass furnace are also lower. Changes in ash composition, such as these, which occur during heating, are well documented, and they were described earlier in this article. However, there are also implications for potential secondary uses of ash from the firing chambers of glass furnaces. From the late 16th century in England, and earlier elsewhere in Europe, the lime-rich ashes of wood such as beech were used to produce glass. The potash and soda in the ash, although present in much lower quantities than the lime, would have played an important role in the formation of the glass because these compounds are strong fluxes. It is often assumed that the fuel used to fire the furnaces would also have supplied much of the ash required to make the glass.²² However, the results of Taylor and Hill's experiments emphasize that the chemical changes in ash, when burned at high temperatures in a glass furnace, make it less suitable for glass production. Therefore, additional sources of ash burned at low temperatures and in considerable quantities would have been required to make this type of early post-medieval high-lime glass. Alternatively, different types of plant ash, richer in alkali, may have been used to supplement the alkali-depleted ashes from the furnace fuel.

CONCLUSIONS

These experiments provided information on the practicalities of building and operating wood-fired glassworking furnaces of different designs. Many of the characteristics noted here have also been described for archeological finds of the Roman period and later, when wood-fired furnaces were used to make and work glass (see Discussion, above). Other types of waste observed during the experiments, such as the alkali salts deposited throughout the furnaces, would not survive archeologically, but their identification is useful in understanding the reactions that take place. The main by-products from burning wood fuel in the furnaces are alkali- and sulfurrich waste gases and lime-rich ash. The results of these experiments have emphasized the importance of taking into account the reactions of these by-products when interpreting archeological material. For example, the alkali-rich waste gases cause the formation of potash-rich glazes on ceramic materials, such as the pots and furnace walls, and they can lead to potash enrichment of the glass, whereas the lime-rich ash reacts with any glass that falls into the ashpit. The results also indicate the types of glass waste that are more likely to have been altered from their original composition and so are less suitable for analysis.

^{22.} Eleanor Smith Godfrey, *The Development of English Glassmaking*, 1560–1640, Chapel Hill: University of North Carolina Press, 1975, p. 158.