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A REVIEW OF MID-SECOND MILLENNIUM B.C. EGYPTIAN GLASS TECHNOLOGY AT TELL EL-AMARNA

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INTRODUCTION

In 1891 and 1892 Sir Flinders Petrie excavated glass in various stages of processing from the palace dumps at the fourteenth century B.C. site of Tell el-Amarna, a city built by artisans practicing the highest quality possible in their crafts in order to adorn the new capitol of Tutankhaman and thereby legitimize his rule(1). In order to learn more about the making and working of this glass, we analyzed samples in several stages of processing for composition, processing temperature, viscosity, extent of crystal growth and microscopic evidence of forming methods. Our findings accord with microscopic evidence from complete vessels, an unpublished manuscript on glass finds by the excavator, Sir Flinders Petrie(2) and previous work of the British glass technologist, W.E.S. Turner(3).

The technology of melting glasses at Tell el-Amarna involved multiple step, batch processing of small amounts of material in both fritting and melting operations. However, at no time was the glass fluid enough to pour. The forming processes involved low temperature operations which utilized high viscosities similar to those used in forming warmed, but still solid, wax to make rods, strips and vessel walls in Ashanti lost wax casting(4). An examination of tool impressions in the glass artifacts and Ashanti manufacturing elements and vessels reinforces the similarity of tool kit and operations. Modern glasses typically are melted in the range of 10 Exponent 1.5-2.5 poise and represent values similar to olive or machine oil at room temperature. For comparison, glass at room temperature has a viscosity of about 10E25 poise. Modern glasses are formed in the viscous range from glycerol to cold honey, 10E4-7.6, where 10E7.6 is defined as the softening point (a glass will barely flow under its own weight within a given time). We will show that Egyptian glasses were formed at higher viscosities than modern glasses, similar to forming taffy, 10E7-9, or even cheddar cheese, 10E9 but in a more fluid condition than lead, 10E10, the range of annealing glass, 10E12.5-13.4 or the glass transition range, 10E11-13.

GLASS SAMPLES

Petrie reported finding 3 or 4 glass factories and 2 glaze workshops (2). However, industrial waste distributed in extensive trash heaps provided samples with information about the practice of glass crafts that had accumulated during the 15 years the complex was active. They were dug in 1891 and 1892 to recover artifacts and not microexcavated to reconstruct deposition. That glass and faience activity was extensive is indicated by the tremendous distribution of finds. Petrie found a "palace waste heap" with considerable evidence of glass technology to the southeast of the palace which he mapped as being 800 ft across (2a, pl.35). He found another dump area to the southwest of the palace complex which he describes as 600x400 feet with a depth of 1-4 feet where he found pottery molds for faience products and some 750 glass fragments which he calculated to represent perhaps 150 glass vessels (2a,p.16-17). In addition a ditch-like depression to the south probably contained manufacturing debris which he described as 3x3x300 feet long. The mold waste heap area did not seem to contain only industrial residue expected during palace construction and decoration when the molds were primarily used for faience architectural inlay, but also broken glass vessels which presumably could, and probably would, have been recycled to make other glass objects. Thus, the two prime refuse areas probably did not have separate functions, but may have been multilayered deposits which were separated by temporal or other criteria.

Our sample consisted of six fragments from the craft or palace dumps at Tell el-Amarna excavated by W.M.F. Petrie. Two core vessel fragments were analyzed; one was an opaque, copper blue (no.1) similar in appearance to turquoise and having a thin, white parting layer inside (about 0.5 mm) and a porous, red, ferruginous ceramic (similar to the clay body called Nile mud) on the interior of the white layer that functioned as the core or support during building up of the glass. The other, a translucent dark cobalt-like blue (no.3), similar in appearance to lapis lazuli, had a thin grayish white interior layer of about 0.4 mm. Rods of white and yellow glass were inlaid into each vessel fragment and combed or deformed into a pattern of festoons, prior to annealing. Other samples are a copper blue spherical bead (no.2) with white interior layer and a fragment of a crucible of translucent, dark blue glass (no.4) and two white parting layers (one between the glass and the crucible, and another white layer which had floated about 1 mm. into the glass). The crucible consisted of a quite vitreous, coarse, dark reddish brown ceramic. Two translucent frits, one dark (no.5) and the other light blue (no.6),

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with a somewhat friable, light brown crucible adhering to one side of each were also analyzed.

Six other ancient glass samples were analyzed for comparison: the Corning glass standard B (no.6), two Roman blown glass fragments, one 0.3 mm clear wall fragment from Samaria, West Bank (no.10, ca. 3rd to 4th century A.D., Harvard Semitic Museum) and another mold blown base from the Belus River delta, Israel (no.9, Margaret and Charles Withers Coll.) with 5mm base and 0.3mm wall. Four other, roughly contemporaneous fragments were analyzed, only one of which is reported, a transparent, dark cobalt-like blue bead, press molded, which was excavated from Mycenae, Greece (no.7, Trustees of the British Museum). One crucible from Memphis, Egypt, consisted of a coarse dark, reddish brown ceramic crucible, 17 mm thick with a white parting layer about 0.6 mm. An opaque blue frit (19 mm thick) which is strong blue at the outer surface but which shades to bluish white toward the interior contained too much lime (35% CaO) to melt as a glass before the crucible melted (University College). We assume this melt was a mistake; it is not further reported. The two others were an opaque, copper blue medallion and transparent, cobalt blue bead from Nuzi, Iraq reported previously (5, Harvard Semitic Museum).

COMPOSITIONS

Glasses were analyzed using SEM with EDS, wavelength dispersive microprobe analysis, PIXE, XRD, DTA, replication melts and attempts to measure viscosity. The microprobe compositions (Table I) were prepared as fresh fractures 1 mm from any surface (except nos. 5 and 10), and then ground and polished in less than 3 minutes to avoid alkali loss. Surfaces are typically weathered and have undergone network breakdown, even in a seemingly recent cross sectional break (Fig. 1). In SEM backscattered emission, a polished cross section of this bead (Fig. 2) has a roughened outer surface (upper left) in which the glass network has broken down to a depth of 10-20 microns and a near surface layer of 40-80 microns (dark gray) that has undergone cycles of hydration and drying with attendant outward diffusion of alkalies (gray area current total $Na_2O+K_2O=1.4\%$) and propagation of shrinkage cracks. The glass to be analyzed, in order to obtain the composition of the original product, lies beneath this layer, the thickness of which must be experimentally determined even in these relatively well preserved 3500-year-old specimens.

Glasses were analyzed by P. Vandiver on the Smithsonian Department of Mineral Sciences' A.R.L. 9-spectrometer wavelength-dispersive microprobe using a 10-micron defocused beam and counting for 10 sec. to avoid alkali loss. Each sample was analyzed 30-45 times and compared to mineral standards of hornblende, rhyolite, copper metal and manganite. Corning glass standards A and B were used as working standards to check for possible instrument drift.

Table 1. Wavelength-dispersive microprobe analyses are reported as mean (standard deviation in parentheses). Low totals indicate other elements (such as colorants and impurities) are present which were not analyzed. Inclusions were identified by x-ray diffraction and were not intentionally included in the probe analyses.

SiO_2	Al_2O_3	CaO	MgO	K_2O	Na_2O	Fe_2O_3	CuO	MnO	Total	
Glass fragments from Tell el-Amarna waste heap										
1a. Translucent Turquoise Blue Vessel										heterogeneous, bubbly glass; SiO_2 & $CaMgSi_2O_6$
65.71(0.78)	0.55(0.05)	7.13(0.14)	2.47(0.12)	1.69(0.82)	19.44(2.29)	0.31(0.03)	1.49(0.10)	0.10(0.01)	98.41	
1b. Opaque Yellow Threaded Decoration										homogeneous, few bubbles, opaque; $PbSb_2O_4$,$CaMgSi_2O_6$
62.16(0.77)	0.74(0.09)	8.84(0.17)	3.53(0.12)	2.50(0.10)	18.38(0.48)	0.45(0.03)	0.14(0.06)	0.03(0.01)	96.15	
2. Opaque Turquoise Blue Bead										homogeneous, few bubbles, opaque
64.75(0.70)	0.62(0.31)	7.23(0.16)	2.53(0.10)	1.66(0.06)	19.43(0.19)	0.31(0.02)	1.55(0.15)	0.02(0.01)	98.10	
3a. Translucent Dark Blue Vessel										homogeneous, nonbubbly glass; $CaMgSi_2O_6$ inclusions
63.12(0.72)	2.68(0.14)	7.32(0.16)	0.50(0.04)	0.86(0.05)	16.64(0.15)	0.23(0.03)	0.10(0.01)	0.05(0.02)	91.35	
3b. Opaque White Thread on Dark Blue Vessel										heterogeneous, few bubbles, opaque; quartz, $CaSb_2O_4$
62.04(0.90)	2.08(0.21)	5.18(0.15)	3.83(0.27)	4.27(0.12)	20.78(0.39)	0.71(0.06)	0.08(0.05)	0.03(0.01)	99.00	
3c. Opaque Yellow Thread on Dark Blue Vessel										heterogeneous, few bubbles, opaque; cristobalite
61.44(0.89)	0.65(0.09)	9.12(0.24)	3.50(0.11)	2.39(0.08)	18.33(0.55)	0.4(0.046)	0.18(0.05)	0.03(0.01)	95.44	
4. Dark Blue Glass in Crucible										heterogeneous, few bubbles; diopside ($CaMgSi_2O_6$)
61.54(0.77)	0.68(0.06)	6.08(0.09)	6.66(0.18)	4.74(0.08)	18.43(0.24)	0.25(0.20)	1.16(0.08)	0.03(0.02)	99.58	
5. Dark Blue Frit										heterogeneous, porous; SiO_2 & $CuCaSiO_4$ inclusions
58.36(1.57)	0.56(0.64)	13.26(6.01)	0.2(0.19)	0.86(1.35)	8.38(2.51)	0.28(0.30)	13.98(2.5)	0.11(0.14)	97.89	
6. Light Blue Frit										heterogeneous, porous
60.30(1.39)	0.89(0.54)	7.62(0.24)	3.49(0.14)	1.6(0.08)	18.63(0.53)	0.39(0.04)	1.42(0.12)	0.01(0.01)	94.34	

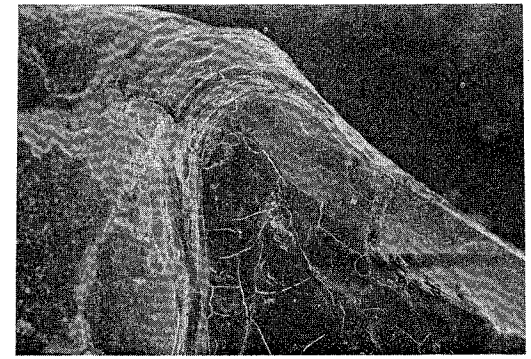

Fig. 1. Cross section of miniscus of blue bead with lime plaster parting layer on hole interior (no. 2), 100x.

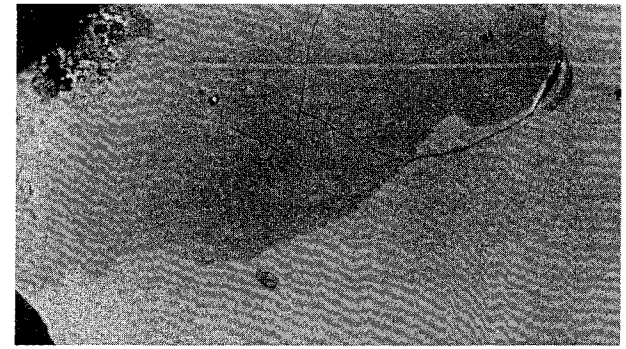

Fig. 2. Polished cross section with network breakdown at surface (upper left), below which is alkali-depleted, 100-micron thick weathered layer which has shrunk and cracked during environmental cycling (1000x).

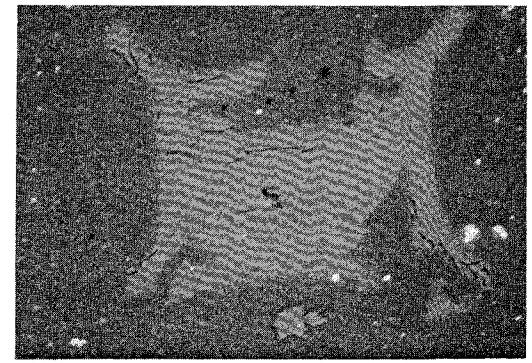

Fig. 3. Diopside inclusion showing evidence of crystal growth morphology, 5000x.

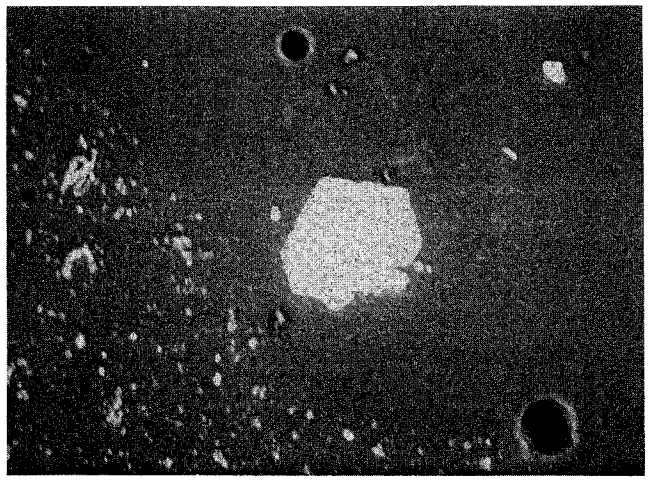

Fig. 4. Cristobalite needles next to 5 micron lead-antimonate particle in yellow glass (upper right) and fine dispersion of calcium antimonate particles in white glass thread (lower left) 5000x.

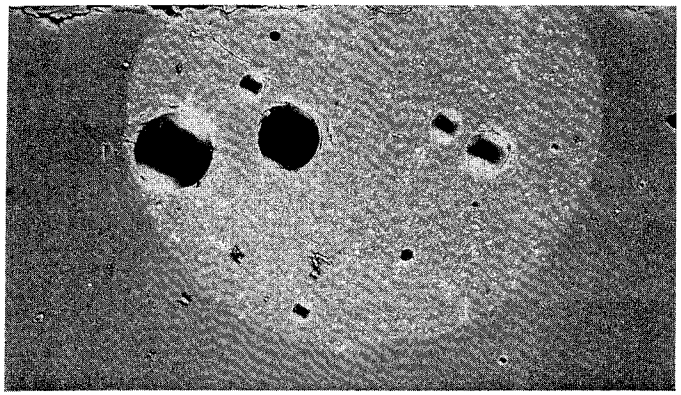

Fig. 5. White thread inlay with quartz and calcium antimonate particles embedded in blue glass vessel (no. 1), 800x.

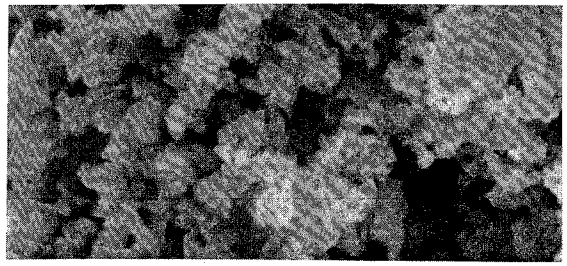

Fig. 6. Lime plaster parting layer inside blue bead, 7500x.

Comparative glass compositions:

7. Corning Glass Standard B used as working standard
68.54(0.05) 1.69(0.17) 8.99(0.97) 0.02(0.02) 2.54(0.24) 6.80(0.71) 0.31(0.14) 6.51(0.59) 0.02(0.02) 96.42

8. Mycenaean Transparent, Dark Blue Press-Molded Cord, no inclusions TiO2 Bead
69.08(0.84) 2.53(0.34) 4.86(0.09) 2.60(0.24) 0.67(0.06) 17.23(0.44) 0.61(0.05) 0.13(0.02) 0.22(0.08) 99.64

9. Roman, Belus River, Israel, Clear Transparent Homogeneous Wall Fragment of Blown Glass Vess
69.63(0.61) 2.43(0.12) 7.92(0.07) 0.60(0.06) 0.66(0.06) 17.09(0.31) 0.31(0.03) 0.06(0.02) 0.90(0.04) 99.60

10. Roman, Samaria, West Bank, Greenish Clear Homogeneous, Some Cord, Blown Base of Bowl
70.70(0.87) 2.68(0.11) 8.98(0.12) 0.52(0.05) 0.98(0.06) 15.25(0.37) 0.30(0.03) 0.07(0.03) 0.12(0.02) 99.6

Sufficient heterogeneities are present in the ancient glasses to promote nucleation, but the extensive crystal growth expected at these relatively low working temperatures was prevented by inclusions (such as quartz, diopside, cristobalite and ceramic crucible fragments) whose partial dissolution inhibited crystallization by increasing local concentration of Ca, Al, Si, etc. at liquid-solid boundaries (shown by probe analyses) and also possibly by the presence of many trace impurities which served to inhibit liquid-phase diffusion (Table 2). The compositions lie in the phase field of devitrite, sodium disilicate and quartz. Devitrite (Na_2O-3CaO-6SiO_2), which commonly forms at the melt line of glasses with similar composition, undercooled and allowed to stand about 12 hours, was not found in any of the ancient glasses; instead diopside ($MgCaSi_2O_4$) solid solution phases showing evidence of crystal growth are common (Fig. 3). Sodium disilicate is soluble in water and nondurable and would not be found; cristobalite was found in some samples crystallized from the melt as well as residual, rounded quartz from batch materials (Table 1 and Fig. 4).

To test whether the presence of a high trace element concentration prevents crystal growth and increases viscosity, PIXE was used by C. Swann to analyze fresh fractures of the same samples that were probed (Table 2). These were analyzed according to procedures published by Swann and Fleming(6) and show that a large number of elements are present in trace quantities, such that the properties of the glasses may well be affected. Totals of trace element concentration are shown with values for colorants and major glass forming constituents (Si, Al, K, Na, Ca, Mg, Sb and Co) subtracted. To test our hypothesis we had planned to melt one glass with a full trace element suite and another of the same composition without according to the parameters reported below; however, we have had problems making our two data sets agree.

Table 2. PIXE Analyses (standard deviation below).

	SiO_2	Al_2O_3	CaO	MgO	K_2O	Na_2O	TiO_2	Fe_2O_3	P_2O_5	PbO	SnO	MnO	CoO	Cl_2O	V_2O_3	As_2O_3
1.	64.02	4.44	9.05	1.42	1.08	17.36	.0795	1.121	.2011	.0115	.0076	.1837	.0037	.6732	.0134	.0038
	0.26	0.35	0.12	0.47	0.05	0.69	.0084	0.035	.0014	.0014	.0017	.0101	.0074	.0259	.0062	.0008
2.	61.10	1.14	6.47	3.19	1.34	15.78	.0628	1.289	.2051	.0312	.3530	.3217	.0472	1.036	.0171	.0162
	0.18	0.13	0.07	0.19	0.04	0.46	.0101	0.037	.1103	.0029	.0392	.0085	.0134	.0228	.0057	.0018
3.	63.63	2.63	9.22	5.25	1.63	1.86	.2280	1.938	.3245	.0423	.5061	.0646	.0591	1.207	.0151	.0303
	0.30	0.42	0.13	0.49	0.06	0.62	.0097	0.026	.2051	.0050	.0674	.0057	.0222	.0396	.0396	.0029
4.	48.56	5.16	10.2	7.16	0.52	16.05	.2509	2.174	.2802	.0161	.0431	.6377	1.123	.8063	.0051	.0100
	0.24	0.34	0.13	0.59	0.05	0.88	.0128	0.039	.1583	.0030	.0435	.0178	.0265	.0318	.0084	.0018
8.	75.61	4.81	5.45	5.20	0.72	1.67	.2122	2.253	.1188	.0045	.0349	.6098	.3560	1.201	.0042	.0045
	0.34	0.46	0.12	0.54	0.06	0.77	.0093	0.034	.2223	.0024	.0390	.0147	.0228	.0399	.0063	.0014
9.	64.02	4.44	9.05	1.42	1.08	17.36	.0795	0.832	.2012	.0115	.0076	.1837	.0037	.6733	.0134	.0038
	0.26	0.35	0.12	0.47	0.05	0.69	.0084	0.024	.1661	.0014	.0173	.0101	.0074	.0260	.0062	.0008
10,	65.95	4.09	9.56	1.38	0.78	12.61	.1025	1.145	.2333	.0029	.1104	2.628	.0390	.8464	.0053	.0039
	0.31	0.41	0.14	0.53	0.06	0.77	.0084	0.032	.2038	.0028	.0368	.0304	.0130	.0338	.0061	.0016

	Rb_2O	Y_2O_3	MoO	BaO	SO_3	Cr_2O_3	NiO	ZnO	Br_2O	SrO	ZrO_2	Ag_2O	Sb_2O_5	CuO	Trace	Total
	.0067	.0021	.0099	.1625	.0949	.0004	.0026	.0059	.0029	.2107	.1110	.0071	.0056	.0477	1.79	
	.0009	.0015	.0033	.0542	.0380	.0054	.0002	.0009	.0008	.0032	.0044	.0080	.0186	.0017		
	.0057	.0020	.0020	.2392	1.606	.0162	.0248	.0802	.0309	.3856	.0221	.0237	.0950	5.330	3.86	
	.0020	.0027	.0066	.0797	.0401	.0054	.0045	.0061	.0017	.0063	.0087	.0152	.0317	.0205		
	.0100	.0034	.0126	.0306	.7663	.0108	.0253	.0680	.0040	.3949	.0173	.0901	4.437	5.510	3.85	
	.0028	.0005	.0129	.2041	.0644	.0036	.0066	.0097	.0027	.0085	.0121	.0026	.1593	.0275		
	.0057	.0165	.0251	.3832	.2314	.0012	.6634	1.029	.0125	.2844	.0610	.0354	3.947	.2901	4.21	
	.0021	.0034	.0084	.1277	.0500	.0066	.0133	.0092	.0020	.0061	.0092	.0196	.1266	.0077		
	.0033	.0092	.0215	.0924	.2841	.0118	.2092	.3972	.0054	.2435	.0334	.0410	.0457	.3453	2.81	
	.0019	.0031	.0072	.1519	.0542	.0039	.0088	.0062	.0017	.0059	.0086	.0137	.0550	.0071		
	.0067	.0021	.0099	.1625	.0949	.0004	.0025	.0059	.0029	.2108	.0111	.0071	.0560	.0477	1.69	
	.0009	.0009	.0033	.0054	.0380	.0055	.0021	.0009	.0008	.0032	.0044	.0080	.0186	.0017		
	.0078	.0082	.0184	.4685	.4259	.0043	.0082	.0160	.0138	.3387	.0015	.0279	.1557	2.071	5.25	
	.0024	.0027	.0111	.1562	.0520	.0059	.0049	.0025	.0023	.0076	.0010	.0212	.0519	.0032		

GLASSWORKER'S TOOL KIT

Petrie illustrated various manufacturing elements including rolled glass rods, flattened glass strips, drawn glass threads and tubes, beads still on copper wires, small blobs of glass with impressions of pincers, and glass ingots or blanks which had been removed from a crucible (2a, Pl.13). One rod was illustrated as having been made by rolling under a paddle which was run diagonally along its length until it was reduced to a rod or cane about 1/8th-inch thick (2a,Pl.13).

Study in the Egyptian Dept. of the British Museum in 1974 using a low-power binocular microscope with continuous magnification adjustment from 10 to 270x (Bausch and Lomb), a needle, loup and penlight for glancing light revealed evidence of the tools used to form these elements and allowed reconstruction of their use in diverse forming methods and sequences of manufacture. Included in this glassworker's tool kit were pincers with opposing jaws used to pull glass. Small rods and tubes were drawn, but blowing of glass was not evidenced. Rods also were rolled between a paddle and flat plate, shown by a spiraling indentation continuing the length as well as a rods each made of two twisted rods differently colored in which the outer surfaces are flat rather than rounded and the depressions remain rounded (7,p. 125). Blocks of glass were rolled and paddled to shape and often rods were cut by abrasion; some only partially cut have a 0.4 mm wide indentation. There is no evidence of knicking and snapping of rods. Amazingly, blocks of glass which had been flattened by rolling into strips less than 0.5 mm thick were then reheated and folded lengthwise in thirds, so that the folds still can be seen. Holes remain at the folds, such that this double-holed rod could have been used to make spacer beads. Forming such fine elements requires considerable mechanical force and negligible rounding due to surface tension. In making replicas of core vessels (as we did each semester for 12 years in an undergraduate lab at M.I.T.) using rods we had drawn and a small modern glass furnace, the results were never satisfactory because the glass had the appearance of being overheated, such that much of the detail became softened by being too liquid. In replicas the added rods tend to spread out and melt into the surface; in cross sections of Amarna glass quite viscous rods were pressed into the more molten glass which flowed around them (Fig. 5), indicating a low-temperature process. The fineness of manufacture, sharpness of details and use of processes in which mechanical force rather than temperature is determinate, all indicate low-temperature forming, as distinct from the blowing technology practiced glassworkers from Roman times to the present.

METHODS OF GLASSMAKING AND GLASSWORKING

Although Petrie said that the workrooms had almost vanished, he published drawings of a brickwork furnace which he stated came from a "glazing" factory (2,Pl.42). The ovens were small, 2 or 3 feet across (2b,p.117) and contained a special placement of dishlike crucibles, 4-5 inches across, on inverted cylindrical pots as supports. The cylindrical pots had glaze only on the exterior and dripping from the foot to the rim. The glass fragments from the crucibles, about 1 cm high, have a bun-shape from having been in such a dish-shaped crucible(7). The crucible, when cool, was chipped away from the glass, according to Petrie (2b,p.124). Flat tops are observed which are bubbly, sometimes frothy or scummy, with miniscuses at the edge. The rounded sides were against crucible surfaces as can be determined by chisel marks and bits of residual crucible and lining which still adhere to the glass. Petrie stated that the glass had been prepared as a paste in the shape of the crucible prior to a melt, which implies that it had previously been ground as a powder and mixed with a fluid, preformed, and then melted. That the melt was carried out at a very low temperature (below 1000oC) is attested by the lack of wetting of the crucible by the glass and by the extent of the miniscus which sometimes has a curvature of 1 cm diameter, which in fact may reflect the shape of the preform. At such low temperatures, fuse may be a better term than melt. Melt temperatures between 900 and 1000oC are shown on the soda-lime-silica phase diagram for the glass compositions simplified from Table 1.

Frits and glasses were melted in heavily grogged, sometimes fiber-tempered crucibles which deform when fired to 1100oC and which turn a darker color at 1050oC than the original samples. Many crucibles have a white layer between the glass and ceramic crucible. Cores inside vessels were reported by Brill composed of a mixture of ferrugenous clay and fibrous organic inclusions (8); Bimson(9) found two-layer vessel cores consisting of clay coated with a lime wash. We found mainly two-layer structures on fritting and melting crucibles, and both single and double structures inside core vessels, but the materials used for the parting layers varied from lime plaster to gypsum mixed with calcareous clay, and ground limestone mixed with fine quartz. In the blue bead (no. 2, Fig. 6) a rounded submicron, homogeneous lime plaster structure was found as a 0.2-0.4 mm parting layer; this is the earliest date for a lime plaster in Egypt. Reasons for using lime-rich parting layers are high temperature stability without the creep which characterizes Nile mud clays and a closer thermal expansion match. Lime also acts as a temperature indicator because these glasses do not wet lime until above 800oC when at least the surfaces of particles decompose to CaO. Particles of limestone tend to flake apart much more than a previously formed lime plaster.

Additional curious evidence of multiple-stage processing are several quartz pebbles, some as much as 5 mm long with blue frit adhering to one flat surface (7), which are evidence of a fritting operation, as are crucibles containing frit (nos.5,6). Some crucibles containing frit are clearly for production of Egyptian blue (no. 5 contains Egyptian blue by XRD and has a higher lime and copper composition than any glass); however, Egyptian blue may have been used as a colorant in glass as it would provide an evenly dispersed, particulate source of colorant. Frits were mixed with faience bodies to give diverse colors at this time (10) and several examples of bun-ingots contained bits of a glass of a different color, e.g. purplish blue in a white glass, which had deformed perhaps three times their diameter of 2 mm, indicating mixing of a about 3 mm bits of powdered, fritted glass. Other crucibles contain coarsely ground frit of a composition similar to the glass vessels and bead (nos.6,1 & 2). Thus, we are sure that a multiple stage fritting process was used to melt or fuse the glass, just as described in later glass texts (11).

Many glass objects were finished by considerable grinding, polishing, and even engraving of surfaces, for use as inlays in furniture or weapons, or as jewelry, amulets, small sculptures, etc. Even the outer surfaces of many core-formed vessels have scratch marks from polishing and exhibit bubbles partially open by a grinding operation. However, no associated archaeological evidence of such a workshop has been recognized for this stage of manufacture.

RECONSTRUCTION OF THERMAL HISTORY

To determine melting temperatures of Amarna glasses, W.E.S. Turner refired the crucible fragments and found that at 1200oC, they formed a glass(3). At 1150oC the amount of vitrification was considerably more than that found in the fragments before refiring. He gave 1100oC as the upper limit of glass melting. Petrie (2b,p.121) alluded to the low temperature of forming Amarna glasses saying they are easily visually distinguished from Roman glass "by the direction of streaks and bubbles in it...The early glass is all wound (with rods), with lines running around; the Roman glass is all drawn out and nicked off with lines running along" diagonally.

We have determined the glass transition range, Tg, of 5 glasses from Amarna (nos. 1-5) to be in the range of 670-780oC, although the amount of curve inflection is minor. Softening temperatures are in the range of 800-960oC determined using slumping of small ancient drawn fibers and modern-replicate rods. The ancient compositions depart from the norm for stable, durable modern soda-lime silica glasses (i.e., 70% SiO2, 15% Na2O, 10% CaO, 5% other) in being low in silica and high in alkali, and thus these ancient ones are more fluid at a given temperature. Two of the vessel glasses (nos.1 & 3) have DTA doublets at 229 and 260oC characteristic of cristobalite. The cristobalite has been identified also by XRD. Mackenzie has shown that DTA patterns of cristobalite in soda-lime silica glasses heated to 1100oC for 5 hours are characterized by a single peak(12). Formation of a doublet occurred at 14 hours, and a single peak was found again when heating for 21 hours. Replicate compositions (nos. 1a, 2) show a doublet at 1050oC for 14-16 hours, but not at 10 or 20 hours, giving a measure of the total duration of heat treatment in a finished vessel.

We had intended to plot temperature-viscosity curves by measuring viscosities using replicate glasses. Cranmer supervised procedures for melting modern replicate glasses at relatively high temperatures, above 1250oC, for which measurements of viscosities were much higher than expected. Compositional analysis showed a lack of alkalies; we believe these were driven off during the initial stages of melting. This experience pointed to the necessity of using appropriate technology to reconstruct ancient technology. Our work still remains to be completed.

GLAZES OR GLASSES?

During excavation Petrie reported finding sites for 3 and perhaps 4 "glass factories", and 2 large "glazing works" for the manufacture of "glazes". However, glazed ceramics at the time were mostly Egyptian faience, a soda-lime-silicate coated quartz paste which was primarily made by a self-glazing method in which effluorescent salts added to the body precipitated onto the surface and were melted during firing to form a glaze. In comparison, other uses of glass frits were minor and mostly related stone working. Glass frits sometimes were added as minor constituents to faience bodies to achieve special colors, for instance purple or lime green, or to make bodies dense and strong, for instance, in ring manufacture. Glazed steatite and schist were used for scarabs and small amulets, but this requires only small amounts of glaze materials. In addition, frits, as sintered powdered glasses, were shaped into objects. We suggest that Petrie retrospectively applied his knowledge of then-current ceramic glaze practice to ancient Egyptian practice, and that he was mistaken in believing he had found glaze factories. We propose instead that these glaze factories were for glass and frit preparation.

We suggest that, based on the evidence of industrial debris which consists of crucibles, glass bits with evidence of having been chipped out of a crucible, rods and bars of glass, and fragments and whole glass objects, that the industry was divided into two specialized crafts, one for the making of

frits and glass which Petrie mistakenly referred to as "glazing", and another for the manufacture of beads, vessels, inlays and other glass objects. A third step involved grinding of both raw materials and the intermediate fritted or fused products to fine particle size, cutting by abrasion of intermediate elements as well as the grinding and polishing of completed objects. This activity, comparable to a ground stone industry, lapidary, or mill, is not evident in the glass and faience debris and probably formed a third area of craft organization and specialization. If we argue that clear glasses could have been made, but are known in only one special case of a bolti fish now in the Brooklyn Museum, and that most Egyptian glasses resemble semi-precious stones, such as lapis and turquoise, and that even the some of the terms for glass/faience are similar to those for visually similar stones among other arguments (13), then a close connection to stone working seems even more likely.

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Note: Egyptian vessels were wound around cores which were built around a long armature, probably green wood or metal. Rods of different colors were wound around the base glass, much as one would wind thread around a spool. The glass was combed into various patterns, annealed and cooled. Then the cores were removed by scraping out the friable interior material. We made cores of Missouri fireclay mixed with about 1/3 by volume old coffee grounds, as the finest size, organic material which is commonly available around a university. Alternately, students ground insulating firebrick to shape and used high temperature cement to attach them to metal rods. K-20's seemed to work best; those with a lower K-value made with burned out sawdust caused the glass to crack as did those with a much higher K-value. A soft, friable material with fairly large pores which will yield during cooling or a specially formulated material which matches expansion coefficient of the glass (such as reported by D. Labino in J.G.S.) will both work.