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ANCIENT REPRESENTATIONS of wood-fired glassworking furnaces of the Roman period are limited to three oil lamps from the first century A.D.[1] and a small fired clay statuette from the first or second century A.D.[2] Archeological remains of Roman furnaces are incomplete, often with only the fire chamber found in situ, along with a few tantalizing glimpses of the scattered superstructure.

The furnace with a rounded fire chamber is the most common Roman type. Examples have been discovered in the western provinces of the Roman Empire, including Britain, France, Germany, and Switzerland. This form of furnace became the focus of our reconstruction experiments.

To explore how such furnaces may have functioned, in 2005 we built two furnaces under a shelter: (1) a pot furnace, which held several terra-cotta pots, and (2) a tank furnace with an attached lehr, which we then fired for three weeks. A year later, we demolished the superstructure of the tank furnace and its lehr, and then constructed a small furnace over the fire chamber of the tank furnace, as well as a new, free-standing lehr. These too were fired, together with the pot furnace, for three weeks. Throughout both firings, we recorded fuel consumption and temperatures.

This article will concentrate on the furnaces and lehrs. The vessel and waste glass produced during the experiments, and their scientific analyses, will be the subject of another article.

CONSTRUCTION AND INITIAL FIRING

Furnace Design Considerations

The combustion process for wood[3] involves the burning of volatile gases released from the surface of the wood, in the presence of oxygen, resulting in the generation of heat and the creation and expansion of waste gases. Removal of

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1. A lamp from Asseria, in the Museum of Archeology, Split, Croatia (1094-30); a lamp from Voghenza, in the National Museum of Archeology, Ferrara, Italy (52196); and the recent find from Spodnje Škofije, in the Piran Archeological Museum, Slovenia (PN A 270), which shows the clearest detail.
2. The British Museum, London (GR 1986.10-3.2).
3. Michael Vogel, "Heating with Wood: Principles of Combustion," Montana State University Extension Service: www.montana.edu/wwwpb/pubs/mt8405.html, 2005. Greater detail is found in F. L. Browne, *Theories of the Combustion of Wood and Its Control: A Survey of the Literature*, report no. 2136, U.S. Department of Agriculture, Forest Service, Forest Products Laboratory, Madison, Wisconsin, 1958.

the gases through exit holes creates a draft that sucks air into the combustion chamber to replenish the oxygen. Charcoal formed during this process will burn at a lower rate, and it will finally form ash, a waste product that can be discarded.

The rate of combustion is determined by the size of the air intake, the size of the combustion chamber, and the size of the exit holes. The size, shape, and condition of the wood are other factors. As wood burns from the surface, an entire log will emit its heat energy at a lower rate than the same log split into smaller pieces. Therefore, large logs will provide a slow burn and small logs a fast burn because a greater surface area is exposed. Dry, seasoned timber is essential; otherwise, heat energy is lost in removing water. Finally, for a furnace, longer logs are better for adjusting the rate of burn and controlling the heat.

A modern wood-burning pottery kiln will accomplish this process by having a large firebox leading into the kiln chamber, with the wood burning on a grate to allow the ash to fall onto the floor of the firebox, and the air directed over the ash and through the grate to preheat it. The chimney at the back of the kiln chamber facilitates the draft through the firebox into the chamber. Both its length and its cross-sectional area have an important effect on its ability to remove the waste gases and to draw in new air. If the exit hole is restricted, airflow will be slow and combustion will be retarded.[4]

For a Roman glassworking furnace, these considerations must be taken into account. The lack of evidence in the archeological record for fire bars or a grate, as well as the presence of stokeholes or chutes, implies that the wood is burned in the circular fire chamber, directly beneath the glass melting chamber. This idea is reinforced by the representation of the furnace on the oil lamps, which also appears to lack a chimney, showing instead the exit of flames through the gathering holes. For these reasons, chimneys were omitted from our designs, and the stokeholes were large enough to allow the combustion of several logs at a time with a good air supply.

The fire chambers of several Roman furnaces, such as a fourth-century A.D. furnace at Cesson-Sévigné, France,[5] have a horizontal stokehole with a tile floor set into the ground, while others have a steeply sloping chute floored with a large stone, such as several first- to third-century A.D. furnaces at Augst.[6] This is reflected in the design of the fire chamber and stokehole for each of our furnaces.

The tile wall of the pot furnace's fire chamber (Fig. 1, left), bonded and coated with daub (a mixture of clay and hay used for construction), continues upward and corbels inward to form a circular shelf or siege, while that of the tank furnace (Fig. 1, right) stops at ground level. (Corbeling is evident on two furnaces in France, one at Lyons[7] and the other at Besançon.[8]) The surrounding walls of both furnaces form a dome, into which are set gathering holes, with a single hole at the apex (the "top hole"). A small stoppered hole in the side of the pot furnace is included as an interpretation of the use of stoppers found on sites such as at Hambach[9] and Avenches.[10] Shelves for resting collars and doors are an integral part of each structure, as is the tank for the smaller furnace.

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4. Frederick L. Olsen, *The Kiln Book: Materials, Specifications, and Construction*, 2nd ed., Radnor, Pennsylvania: Chilton Book Co., 1983, chaps. 3 and 8.

5. 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, p. 55.

6. Andreas Fischer, *Vorsicht Glas: Die Römischen Glasmanufakturen Äussere Reben*, Forschungen in Augst, v. 37, in press.

7. Christine Becker and Michèle Monin, "Fours de verriers antiques des Subsistances, Lyon," in *Echanges et commerce du verre dans le monde antique: Actes du colloque de l'Association Française pour l'Archéologie du Verre*, ed. Danièle Foy and Marie-Dominique Nenna, Monographies Instrumentum, v. 24, Montagnoc: Editions Monique Mergoil, 2003, pp. 297–302, esp. p. 300.

8. Claudine Munier and Gaël Brkojewitsch, "Premiers éléments relatifs à la découverte récente d'un atelier de verrier antique à Besançon," in *ibid*., pp. 321–337, esp. p. 327.

9. Wolfgang Gaitzsch and others, "Spätrömische Glashütten im Hambacher Forst: Produktionsort der ECVA-Fasskrüge. Archäologische und naturwissenschaftliche Untersuchungen," *Bonner Jahrbücher*, v. 200, 2000, pp. 83–241, esp. p. 102.

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, p. 88.

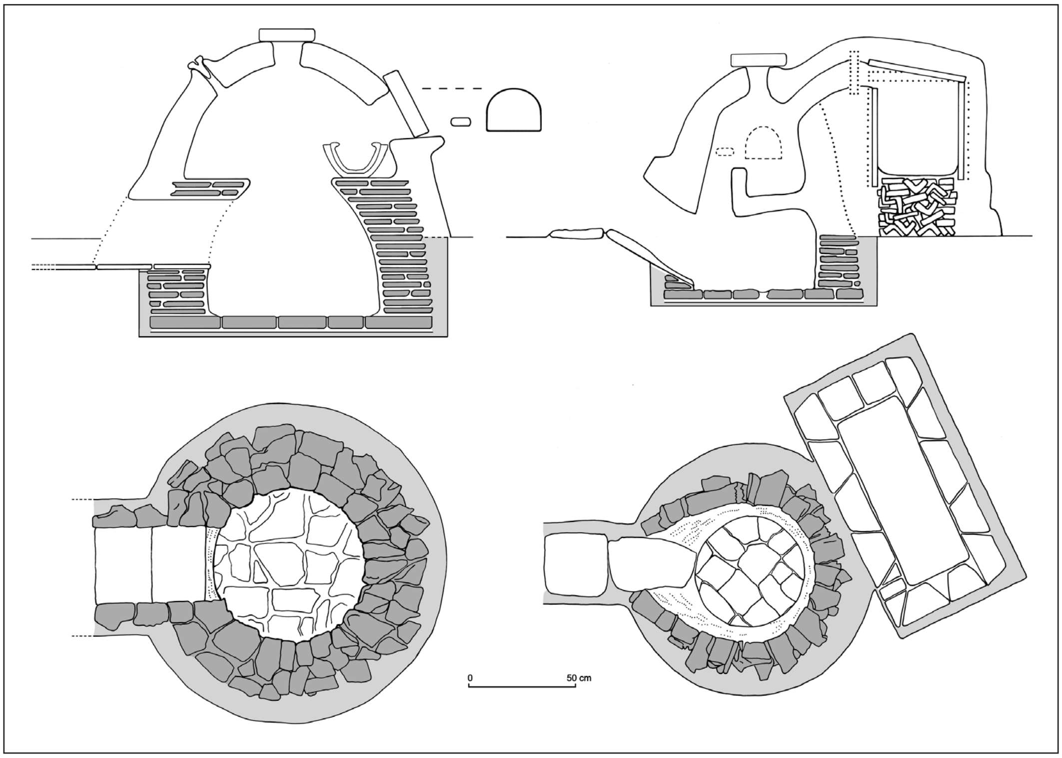


FIG. 1. *Composite sections and plans (at ground level) of pot furnace* (left) *and tank furnace with attached lehr* (right).

There is no archeological evidence for this period concerning the arrangements for supporting pots or other methods of holding molten glass in circular furnaces. Methods have therefore been improvised, including the use of corbeling to form a shelf. An integral tank would also appear to solve this problem.

The design for the lehr is more problematic because our interpretation of the scant archeological evidence is tentative. Perhaps the best candidate is the small rectangular tile structure on a shelf at Lyons.[11] It is associated with a small circular fire chamber at ground level, which appears to be its heat source. This inspired our original plan for a rectangular, tile-lined lehr using waste heat from the tank furnace, with a damper in the channel between the two structures to control the heat transfer (Fig. 1, right). Several large rectangular structures that appear to have their own heat source have been interpreted as lehrs,[12] and a small free-standing lehr, although it does not conform to these designs, was constructed for the second firing.

The small furnace (Fig. 2, left and center) reuses the fire chamber and stokehole of the tank furnace. The daub superstructure has sloping walls and a separate domed roof, with a small warming hole. One gathering hole is cut in a D shape, while the other is circular, and lined with a fired terra-cotta cylinder inspired by pot fragments from Avenches.[13] Four large tegula fragments are set into the walls in the interior of the furnace to act as brackets for a shelf.

11. Becker and Monin [note 7], pp. 300–301 (La Manutention, no. 3).

12. Munier and Brkojewitsch [note 8], p. 329 (Besançon, Furnace 3151); Fischer [note 6] (Augst, Of 17B01.Dc1.11 and Of 17B01.Dc3.13).

13. Large fragments of two pot rims in the Musée Romain, Avenches, Switzerland (8257). One rim is blackened on the inside surface, and the other has fired clay adhering to it; in addition, the part farthest from the rim has been darkened by high temperatures.

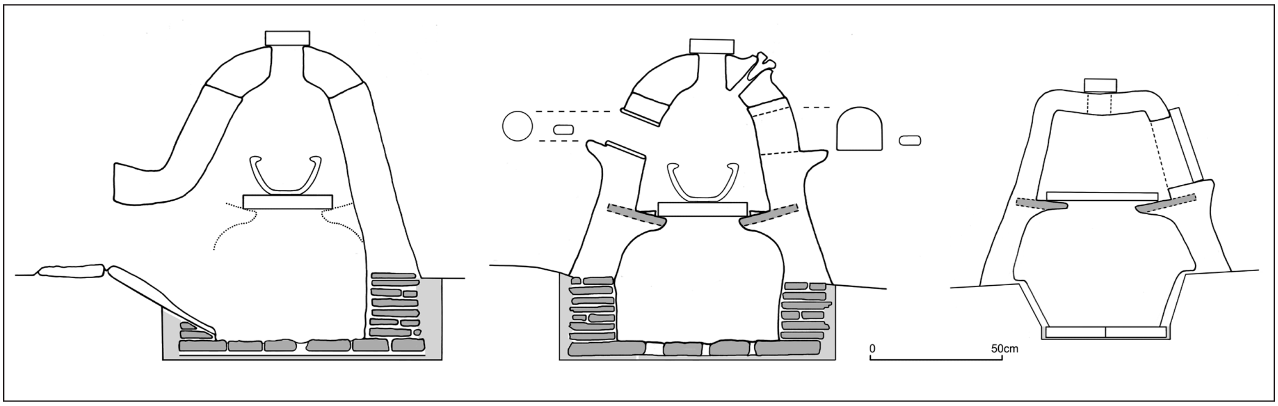


FIG. 2. *Composite sections of small furnace and free-standing lehr after firing.*

The free-standing lehr (Fig. 2, right), which is rectangular in plan, has daub walls sloping inward to a flat roof, with three holes at the top. There is a large stokehole at each end, and two large entrance holes on one side of the annealing chamber, the modern tegula floor of which is supported on Roman tegulae fragments.

Building Materials

The choice of building materials was based, in part, on evidence provided by excavations, and included Roman tile fragments from excavations (unwanted material donated by archeological units), as well as a daub made from powdered clay (with a low iron content), chopped hay, builder's sand, and grit.

Daub Mixes

The mix used for the first construction (by volume) was 42% clay, 13% sand, 13% grit, and 32% chopped hay. The sand and grit were included to decrease the shrinkage. The chopped hay was added to increase the "green strength" of the daub and to leave small air pockets in the material after it had been fired, adding to its insulating properties. The grit contained small shells, which caused spalling on the doors and collars after they had been fired. For this reason, grit was omitted from the recipe for the second firing.

In order to determine whether the insulation properties would change, the mix used for the second construction (by volume) was 65% clay, 15% sand, and 20% chopped hay.

It was important to allow the superstructures to dry as they were built. The daub needed to harden in order to withstand forces applied during the hand-building process, as well as to support the added weight of subsequent layers. Cracks that appeared in the later stages of the drying of the attached lehr, and on the surface of the shelf in the pot furnace, were caused by the shrinkage of the daub backing the tiles.

The First Construction

The pits for the two fire chambers were dug, and their floors and walls were lined with tile fragments bonded with daub. The stokeholes were constructed at the same time (Figs. 3 and 4). The daub was added in handfuls, with the naturally occurring small gaps left unfilled, adding to the insulation (Fig. 5). The inner and outer surfaces were molded and smoothed by hand, and surfaces and holes were cut and shaped with the use of a builder's trowel and wooden sticks. The positions of the gathering holes were adjusted during the construction to allow the glassworker comfortable access from a seated position.

It took 30 days to build all three structures (19 days for the pot furnace, eight for the tank

FIG. 3. *Fire chamber of pot furnace.*

FIG. 4. *Fire chamber of tank furnace reused for small furnace.*

FIG. 5. *Pots in partly built pot furnace.*

FIG. 6. *Tank furnace and attached lehr.*

FIG. 7. *Small furnace.*

FIG. 8. *Free-standing lehr.*

furnace, and three for the lehr), working about four hours per day. Most of the time was devoted to the laying of the tiles, while the construction of the daub walls was comparatively fast.

The structures were allowed to dry for 12 days under the shelter, assisted by the wind. During this period, cracks that occasionally appeared were filled (Fig. 6).

The Second Construction

The superstructure of the small furnace was built over the reused fire chamber of the tank furnace (Fig. 4) by applying handfuls of daub, and molding and cutting as necessary. Only two days were required to construct it. The cylinder and four large tegula fragments were set into the walls, and the undersides of the tegulae were reinforced with daub. The removable roof was separated from the walls with newspaper, and the small warming hole was pushed through after the furnace had dried for a few days (Fig. 7).

It also took two days to build the lehr (Fig. 8). The floor of the shallow fire pit was lined with modern fire bricks, and a sloping stokehole at each end was floored with a large modern tile. Large tegula fragments were set into the daub walls to support the three shelf tiles, and the structure was roofed using a lattice of interwoven sticks set into the top of the walls to support the daub. The stokeholes, front holes, and top holes were shaped and cut as necessary. Both structures were left to dry for seven days before firing.

The pot furnace was repaired by fitting a new shelf under one of the gathering holes. This was keyed in by cutting a dovetailed wedge into the daub, packing in new daub, and extending a shelf from it. Cracks that appeared as it dried were filled.

The First Firing

To prevent the furnaces from heating up too quickly, the fires were started just outside the entrance to the stokehole. The pot furnace drew well from the outset, although it took a little time to establish the best settings. A temporary tunnel built from small slabs of sandstone helped to direct the fire, and the top hole and the gathering holes were opened. As the fire took hold and the furnace heated, the draw increased, and it had to be controlled to prevent the temperature from rising too quickly. The roof of the tunnel was removed after an hour or so, when the draw was well established.

At first, the tank furnace did not draw, even with a short tunnel. Blocking the top hole and the gathering hole, and channeling the waste gas through the lehr to achieve the maximum draw length, finally worked. Once a draw was established, there was no real problem.

During this early stage, a creosote deposit built up on the interior of the furnaces. The deposit was caused by tar droplets from the wood condensing on the cooler surface of the furnaces' melting chambers. This burned away as the furnaces warmed up.

The furnaces were held at about 100°–150°C for the first two days to allow them to dry out thoroughly. Over the next two days, the temperatures were increased by about 30°C/hour to a maximum of 1050°C, the temperature at which the pots and the tank were to be charged with cullet. After several hours of learning how to keep the fire going steadily, and "trimming" the furnace vents, this became easier. The logs could be preheated in the tunnel/chute, and added at a relaxed rate to maintain a gradual increase in temperature.

The pot furnace was used for glassworking throughout the firing (Fig. 9), but the tank furnace quickly developed a problem, so it was used only to heat the lehr (Fig. 10). During the night, it was allowed to cool down, which saved fuel.

FIG. 9. *Pot furnace in use.*

FIG. 10. *Tank furnace in use.*

The Second Firing

Once again, the pot furnace was taken up to 1050°C over two days, but the small furnace was held at 100°C to dry out for two days before its temperature was elevated to 1050°C. The experience gained in the previous firing made the task straightforward, and the initial draw on the small furnace appeared to be better than that on the tank furnace. Short tunnels were constructed in front of the stokeholes to shelter the fire from the wind, and, with occasional adjustments, they were left in place throughout the three weeks (Fig. 11).

A creosote deposit appeared inside the small furnace while it was at low temperatures, but none was detected in the pot furnace because it heated steadily, without the need to dry out and fire at a low temperature.

Both furnaces were continuously used for glassworking, and the lehr underwent a daily cycle of heating and cooling (Fig. 12).

FIG. 11. *Small furnace in use.*

FIG. 12. *Lehr in use.*

PERFORMANCE AND DURABILITY OF MATERIALS AND FURNACE STRUCTURES

The tapering, domed superstructure of each furnace proved to be a strong shape, which had been easy to build. Although cracks appeared upon drying and firing (particularly on the inside, where it was also coated with a thin glazing), it maintained its strength. The areas of greatest wear were around the entrances to the stokeholes, where the unfired daub fell away. The tiles themselves stood up well to the heat, and there was no noticeable distortion.

FIG. 13. *Inside of pot furnace after second firing, showing glass attack.*

Other wear and tear was only superficial, and the cracks caused no problems. Atmospheric attack on the inside walls, aided by glass cullet spattered against the upper walls, resulted in glazed surfaces. This attack was more noticeable on the pot furnace after the second firing. Proof of spattered glass is provided by two small spots of cobalt blue glass at the top of the dome of the small furnace, one of which is inside the top hole. This can have come only from cullet, since blue glass had been placed in a small pot in that furnace.

Glass attack was detected where molten glass had directly contacted the furnace materials. This was visible on the thin daub veneer on the shelf of the pot furnace and the wall of the fire chamber below (Fig. 13), where it had peeled away, leaving the tiles exposed. This attack had been accelerated by the higher temperatures in this area.

Firing of Daub

A later cross section of the walls of the tank furnace revealed the colors caused by the gradation of firing: from a very hard interior region (brown), behind the blue-gray glazed surface, through a thin yellow-brown layer, a thick pale yellow layer, and a thick terra-cotta red layer, blending into a final thick layer of unfired, very dry gray-brown daub. The hay has been burned out, leaving tiny holes in all areas except the unfired brown outer layer. The grit and sand are also visible (Fig. 14).

In areas exposed to greater heat, such as the gathering holes and the top holes, the area of firing extended along the wall of the hole toward the outer surface of the furnace for as much as half the thickness.

In the entrance to the stokehole, the area exposed to the least heat, the surface was reddened, and this continued about halfway through the thickness of the wall. As the stokehole extended inward, the effects of the heat grew stronger, leading to the color changes described above.

Shrinkage, Insulation, and Refractory Properties of Daub

Upon firing, the daub superstructures shrank by up to nine percent. This caused extensive cracking on the inside walls, especially where prefired ceramics (such as tile fragments and the cylindrical gathering hole surround of the small furnace) were in contact with daub. Some cracks extended to the outside, where they were not as large.

The small furnace developed a large crack at the top of the entrance to its stokehole. When the furnace had been in use for several days, the crack was plugged with fresh daub, which fired in place, and thereafter it caused no problems. Shrinkage in the tank furnace was more serious, and this will be discussed later.

The daub bonding the tile siege of the pot furnace was also affected by shrinkage. After both firings, the siege, which had originally been horizontal, sloped down several degrees toward the center of the furnace.

Both daub mixes provided a high level of insulation, with hot-face temperatures of 1000°–1050°C and temperatures between 150°C and 200°C on the cold face. There were no signs of disintegration and weakening because of heat, apart from shrinkage and cracking. These were offset by the strength imparted by the firing of the interior of the wall, and the daub would probably withstand temperatures close to 1250°C.

Because both lehrs were worked at lower temperatures, the daub did not fire to form a hard inner shell, although cracks caused by shrinkage appeared on drying (Fig. 12).

FIG. 14. *Close-up of fired daub section.*

Daub Furniture

Daub furniture included arched collars and doors (Th. about 3–4 cm), small triangular-sectioned iron rests, and rectangular and circular tiles of various dimensions. All of these were regarded as throwaway items because of the thermal shock, uneven heating, and hard usage they would experience (Figs. 15–17).

Some of the doors and collars, along with the pipe rests and the tiles, were fired to about 1050°C. The unfired items, including the larger bricks, were used as they were, relying on the bonding properties of the hay in the mix. All of them performed adequately, although several doors and collars broke and were discarded. The high proportions of hay, sand, and grit in the daub enabled the unfired doors to withstand

FIG. 15. *Daub furniture in use.*

FIG. 16. *D-shaped gathering hole with collar in use.*

FIG. 17. *Circular gathering hole in use.*

FIG. 18. *Fired tank showing cracks.*

the thermal shock and the effects of uneven shrinkage, as well as partial firing in front of the gathering holes, for a reasonable length of time. One or two of these doors lasted only a week or so, but others survived both firings.

Tank Furnace Failure

The daub floor and the walls of the tank began to crack early on in the initial drying and firing stage. This eventually led to large cracks that allowed molten glass to leak out and fall into the fire chamber below (Fig. 18). The unevenness and speed of the firing, and the fact that the tank fired more completely and at a greater rate than the main furnace walls, pulled the tank apart. This highlights the problems associated with incorporating integral structures inside a furnace, and it argues against these particular types of structures.

Small Furnace and Interior Shelf of Free-Standing Lehr

Large fragments of Roman tegulae, embedded horizontally into the walls of the small furnace and free-standing lehr, and reinforced underneath by daub, formed supports for the tile shelves. By the end of the three-week firing, all of them had sloped downward toward the center of the furnace, but they were still held very solidly by the walls and so performed well (Fig. 19). The tiles in the furnace changed from terra-cotta red to brown on their top surfaces, with, particularly on their edges, a speckled glaze of dark green, a color caused by the high proportion of iron oxide in the tile. Those in the lehr retained their original color.

Gathering and Warming Holes and Shelves

The D-shaped gathering holes on all of the furnaces functioned well (Fig. 16), although cracks opened along both angles between the floor and the sides. Their dimensions (W. 15–20 cm) limited the size of the vessels made.

The circular gathering hole lined with a ceramic cylinder worked well for the making of small vessels and objects (Fig. 17). The unglazed terra-cotta cylinder turned yellowish brown on its outer end and acquired a glaze over virtually all of its exposed surfaces. The terra-cotta-colored fragments at Avenches,[14] on which it was based, do not show this coloring and glazing, suggesting that lining a gathering hole was not their function.

The warming holes for the irons worked very well, but the holes could have been made wider to accommodate more irons. On both the pot and the tank furnace, they were positioned to the left of the gathering holes (a possible interpretation of a small hole to the left of the gathering hole in the depiction on the oil lamps), but on the small furnace, they were situated to the right. Both sides had their advantages, but it is more convenient for the glassworker if they are on the right (Fig. 17).

The unfired, integrated daub shelves at the level of the gathering-hole floors, which extended along either side of the holes, were very strong (Figs. 15 and 17). These shelves were used mainly for supporting the collars and doors, although the replacement shelf on the pot furnace was built wider than its predecessor, and it had an extension in front of the gathering hole to accept a rest for the blowing and gathering irons. They were not intended as marvers, which were placed as separate units in front of the gathering holes.

FIG. 19. *Fired shelf of small furnace (seen from below).*

Small Warming Hole

A hole (D. about 5–6 cm) was placed high up in the wall of the pot furnace, and another in the dome of the small furnace. Each had a stopper, based on finds such as those from Avenches[15] and Hambach.[16] We tried to use them as warming holes for flattening the tips of "stirring rods," but because an insufficient amount of heat emerged from them, it took a long time to reheat each end. This appears to have been caused by the design of the hole: a long, narrow tunnel through the daub wall. A better design might be to make a funnel-shaped tunnel with a much wider opening on the inside wall of the furnace.

Stokeholes and Fire Chambers

Fire chambers must be well built in order to withstand high temperatures and constant wear and tear. Digging and lining a pit creates a strong construction, and it takes advantage of the natural insulating properties of the ground.

14. See note 13.

15. Amrein [note 10], pp. 88–90. The author reconstructs these as stoppers placed in holes in the roof or the walls of the furnace.

16. Gaitzsch and others [note 9], p. 102.

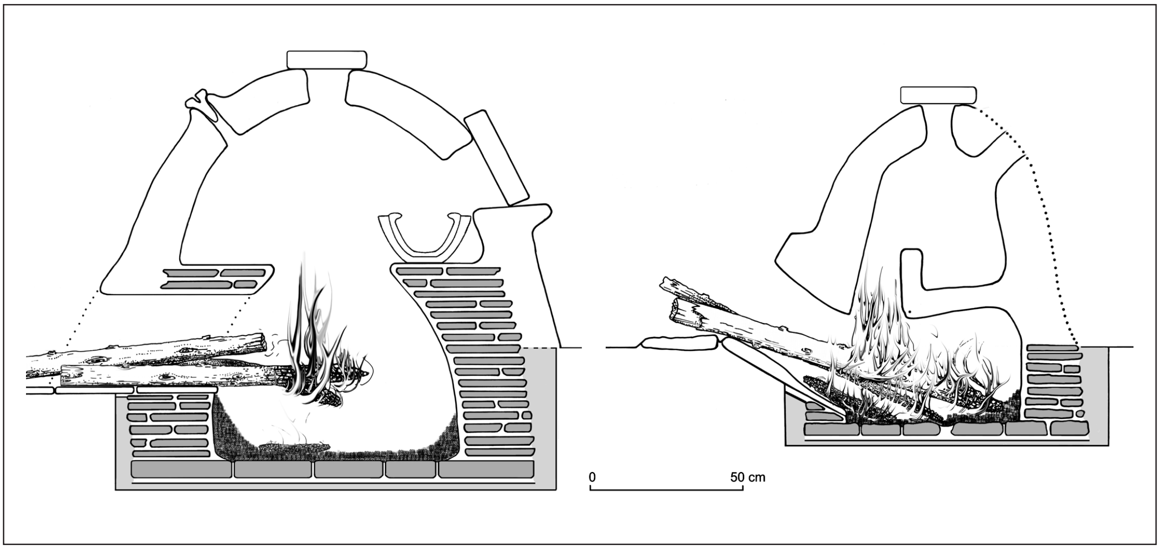


FIG. 20. *Sections showing the function of two designs of Roman fire chambers.*

It also increases the length of the flow of air without the need to build a taller superstructure, and it allows the glassworker to work comfortably when seated while maintaining a reasonable height for the chamber. This, in turn, allows more room for combustion and its associated increase in the volume of waste gas.

Both types of stokeholes appear to have been developed for cordwood up to four feet long and up to six inches in diameter. Of the two types, the horizontal one is easier to use, particularly with lump wood, because the wood does not fall freely into the fire chamber and its tunnel allows cordwood to hang in midair within the fire chamber (Fig. 20, left).

The steeply chuted stokehole allows cordwood to rest on the floor of the fire chamber (Fig. 20, right). The steeper the chute, the larger the space for air to circulate under the log, which may account for the almost vertical chutes of many Roman furnaces. It is also a little easier to remove charcoal from the sloping stokehole.

A stokehole, with its associated fire chamber, takes the place of a grate and allows air to circulate around the wood, leading to a more efficient burn and possibly to a slower accumulation of charcoal than we experienced in our use of lump wood.

Factors Affecting Draft

The design of the pot furnace created a better draw than on either of the smaller furnaces, making for easier temperature maintenance and control. There was no restriction to the airflow on this furnace. The restrictions on the airflow of both the tank and small furnaces created good conditions for turbulence, which would add to the difficulties in maintaining temperatures in these furnaces. Another limiting factor was the smaller volume of the fire chamber, which meant that it filled with charcoal faster, adversely affecting the air supply. None of these factors made either furnace unusable, but it did make the stoker's work harder, particularly when keeping the furnaces hot enough for glassblowing.

The draw of the tank furnace was affected by the attached lehr. Because the lehr depended on waste gases for heat, at least one of its doors was normally open partway, depending on the wind direction. This helped to draw the waste gases through both the furnace and the lehr.

The draw on all of the furnaces benefited from having the top hole at least partly open. Temporary, movable short tunnels (with or without a "roof") placed in front of the stokeholes helped to increase the airflow and to block unhelpful drafts caused by the wind.

POTS

The pots (Figs. 5 and 13), which were based on Roman glassworking pots from Hambach,[17] were heated in the furnaces to about 1050°C over two days before they were charged with cullet. Only two pots leaked. Both of them had pre-existing hairline cracks that were widened and elongated by the heating and the attack of molten glass.

There was little additional evidence of glass attack because the pots were in use for only three weeks, but their color changed from terra-cotta red to dark reddish purple. All surfaces, apart from patches on the base, were covered with a crazed glass coating that was dark green, a color produced by the iron oxide present in the clay body. The top surface of each pot rim had a rough yellowish brown layer bonded to it in the part that had been closest to the wall of the furnace, and a smooth glazed layer opposite, on the area pointing toward the center of the furnace. A smaller area, usually close to a junction between the rough and glazed areas, upon which blowing, gathering, and pontil irons rested while they were rotated to gather glass, was coated with a thin layer of black iron oxide from these irons (Fig. 13).

The pots used in the first firing (Fig. 5) were given a thick layer of daub in an attempt to emulate the clay layer sometimes found on original fragments, such as the late Roman pots from Hambach.[18] This may have been done in order to reinforce the pot wall and to give the pots a longer working life. When they were fired in the pot furnace, these layers of daub cracked and partly pulled away from the outer surface of the pots, rendering them unable to hold molten glass. It appears that this was not the intention for the layer. A probable explanation is that it was employed to support the pots in position in the furnace. This would have been particularly useful for pots with a narrow base, such as those from Sainte-Menehould.[19]

FIG. 21. *Attached lehr in use.*

LEHRS

Two lehr designs were tested: one using waste heat and one having its own heat source. Both successfully cooled the glass without breakages, but only the free-standing lehr annealed the vessels.

The attached lehr (Fig. 21) was heated from one side of the chamber, at the top, through a duct (D. about 15 cm) that channeled waste gases from the tank furnace. The duct was controlled with a sliding door made from daub. The gases exited at each end of the chamber, the exit holes doubled as the doorways to the chamber, and the position of the door controlled the draw. This created an uneven temperature distribution, with a hot spot at the top and a cold floor, which led to glass breakages for the first few days, until a shelf with a (modern) insulation layer was installed. The hot spot followed the path of the gases, and any glass placed too near it overheated and slumped. An improvement to this arrangement might have been to allow the gases into the lehr at floor level by elevating the lehr about one meter, which might have increased the draw on the furnace, but might still have resulted in hot spots.

17. *Ibid.*, pp. 111 and 181 (pot HA500 Gh28).
18. *Ibid.*, pp. 179–181.
19. Foy and Nenna [note 5], p. 65.

FIG. 22. *Free-standing lehr in use, showing dulling of outer surface of glass vessels.*

The free-standing lehr (Figs. 12 and 22) was fired, using the whole length of the pit underneath the floor of the annealing chamber, in which a level fire was made. The tile floor of the chamber became too hot for the glass, and the first batch of vessels slumped from their bases upward. This was easily corrected by placing another layer of shelves a few centimeters higher, creating an insulating air gap between them. The exit holes for the waste gases were built into the roof of the lehr. The difference in temperature between the chamber at shelf height and at roof height was about 100°C, but this might have been adjusted by building a bag wall[20] to shelter the floor and to direct the gases toward the top.

A fault common to both lehrs was that the waste gases dulled the surface of the finished glass (Fig. 22). There was a noticeable buildup of ash in the free-standing lehr, and ash also became stuck to some of the glass that was being preheated in this lehr. The ash, which could not be removed, disfigured the surface of the resulting vessels. Both of these problems would have been prevented only by completely shielding the glass from the hot waste gases.

FUEL

The wood was weighed in the workshop, usually in 10-kilogram units, and allocated to each furnace as necessary.

Table 1 shows the total weights of wood burned during both three-week sessions. Seasoned lump wood was predominant, while some green wood was burned during the second firing. The increase in the total weight of wood burned in this firing is partly explained by the greater amount of time spent on glassworking, which demanded higher temperatures and increased the demand for cullet. The other reason for this increase is the use of green wood.

The total for the six weeks of firing was just over 24 tons of wood. This includes periods of heating the furnaces from cold, shutting one furnace down completely for two days, and lowering the temperature of another over almost all of the nights of the first three weeks. Running all of the furnaces at glassworking temperatures for six weeks could have consumed almost 40 tons of wood.

From Table 2, the general trend in both years was for the fuel consumption rate for each furnace to rise during working hours, which is as one would expect.

The figures for the higher temperatures in the pot furnace during the first firing show the increase in fuel needed for such temperatures of between one and a half and twice the hourly fuel uptake.

When a mixture of seasoned woods was burned in the pot furnace during both firings and in the small furnace in the second firing, fuel consumption during the night was between 82% and 84% of that during the day. This reflects the absence of glassworking during the night and a drop in temperatures of 50°C to about 1000°C.

20. This term is used in pottery to denote a wall in a kiln chamber that is used to shelter objects placed in the kiln from direct heat and to alleviate hot spots within the chamber by modifying the direction of the flow of hot gases within the chamber.

TABLE 1

Weights of Fuel Consumed (kg)

	Pot Furnace	Tank Furnace and Lehr	Small Furnace	Free-Standing Lehr	Totals
First Firing (2005)					
Ash wood	332.25	110.50			442.75
Beech wood	589.25	246.00			835.25
Mixed wood	5,362.00	2,628.25			7,990.25
Totals	6,283.50	2,984.75			9,268.25
Second Firing (2006)					
Seasoned wood	6,759.75		4,381.50	1,676.00	12,817.25
Green wood	420.00		160.00	40.00	620.00
50:50 seasoned:green wood	1,220.75		20.00	70.00	1,310.75
Totals	8,400.50		4,561.50	1,786.00	14,748.00

TABLE 2

Average Fuel Consumption Rates per Hour (kg)

	Pot Furnace		Tank Furnace and Lehr		Small Furnace		Free-Standing Lehr	
	Day	*Night*	*Day*	*Night*	*Day*	*Night*	*Day*	*Night*
First Firing (2005) (08.00–17.00 hrs., 17.00–08.00 hrs.)								
Ash wood	13.05	13.45	4.50	4.67				
Beech wood	12.23	15.94	6.37	5.57				
Mixed wood (glassworking temps.)	15.92	13.25	9.89	5.62				
Mixed wood (up to 1100°C)		21.11						
Mixed wood (up to top temp.: 1175°C)		28.75						
Second Firing (2006)								
Seasoned wood (glassworking temps.)	17.83	15.06			14.38	11.81	9.36	
Green wood (glassworking temps.)	36.14	26.14				13.33	14.98	
50:50 seasoned:green wood (glassworking temps.)	26.52	23.48			12.00		13.13	

With the failure of the tank, no glass was worked from the tank furnace, and the figure of 57% reflects a saving in fuel by dropping temperatures overnight to between 680°C and 400°C, before returning to about 1050°C the next day to heat the lehr.

The experiment with burning green wood in the pot furnace emphatically showed the problems associated with burning wood with a high moisture content. The difficulty of maintaining temperatures led the stokers to mix seasoned wood with the green wood, with the result that almost as much seasoned wood was burned per hour as when the seasoned wood was burned on its own.

Although the short time spans of ash and beech usage make it unrealistic to deduce trends for day and night use, average usages for day and night combined suggest that, although ash and beech can be more economical as a fuel, a mix of seasoned timber is perfectly acceptable in practice.

The consumption of seasoned wood by the tank furnace and its attached lehr is very close to that of the free-standing lehr. The temperature records for the attached lehr suggest that the vessels were held at about 450°C, about 100°C below the annealing range of about 540°–550°C, while the records for the free-standing lehr show temperatures of about 520°C. This means that more fuel would have been needed to heat the attached lehr to a similar temperature. If the tank furnace had been able to hold molten glass, however, it would have made more efficient use of the fuel. At these temperatures, the attached lehr did appear to be reaching its maximum, while the free-standing lehr could have been taken to much higher temperatures.

Ash and Charcoal

Ash and charcoal were usually emptied from the fire chambers in the morning, before glassworking, and in the evening, after glassworking, with small loads removed whenever necessary. Each morning, during the second firing, one bucket was taken from one of the furnaces to light the lehr. During the second firing, on average, between five and 10 buckets were taken from the pot furnace each day, and between four and eight from the small furnace. This did not always completely empty the fire chambers, especially that of the pot furnace. Because it was larger, it proved more difficult to reach with a rake into the sides, against which a compacted layer of ash had built up.

Removing the ash and charcoal caused the temperature of the furnace to drop because a source of heat was being removed to the ash pits, where the charcoal continued to combust, but this was offset by not removing all of the logs from the fire chamber in order to keep a small fire going, and working around them. The temperature recovered very quickly upon restoking.

Each night, the free-standing lehr was allowed to cool slowly, with the embers aiding in this process, before the glass was removed. Each morning, one bucketful of cold ash was removed from the lehr, and the fire was relighted using some hot ash from one of the furnaces.

TEMPERATURE

Thermocouples were set in the walls of each furnace and lehr to measure the hot-face temperatures. Each thermocouple had a small ceramic protector, which extended about two and a half centimeters into the interior. The thermocouples were wired into switch boxes connected to portable temperature indicators. The corresponding cold faces on the outside of the walls were also measured.

Most of the heat loss from a furnace is through the exiting of waste gases and radiation. This is particularly the case with these furnaces, which have large exit holes and no form of heat recovery. It has been calculated, using figures for the melting chamber of the pot furnace at 1020°C,

TABLE 3

Average Temperatures and Standard Deviations (SD)
at Related Hot- and Cold-Face Points on the Furnace Walls

	Hot-Face			*Cold-Face*		
	Average (°C)	*SD (°C)*	*2SDs (°C)*	*Average (°C)*	*SD (°C)*	*2SDs (°C)*
Pot furnace (PF) (days 6–14 inclusive)	993.05	50.67	101.35	168.61	16.70	33.40
PF daub and tiles (days 6–14 inclusive)	1099.59	45.54	91.08	113.01	9.04	18.08
Tank furnace (daytime only)	1004.09	27.80	55.60	141.41	26.31	52.61
Small furnace (days 5–12 inclusive)	1016.32	52.86	105.72	169.66	14.41	28.82
Modern HTI bricks (Th. 15 cm)	1009.70	0.00	0.00	169.30	0.00	0.00

that 80% of heat exits as hot gas, 18% is lost through the walls, and 2% is lost as radiation through the various exit holes.[21]

Very little could be done to reduce the 82% heat loss, particularly during glassworking, because the exit holes must be open. They can be trimmed to optimize the intake of air and the exiting of waste gas, but the reduction of heat loss will be very small. Of course, some of this heat will be used for reheating glass objects as they are made, but only during the working periods, so it would make sense to work for as long as possible, utilizing all of the available daylight.

One possible efficient reuse of heat would be for heating a lehr.

The temperature measurements highlighted several points concerning heat distribution and heat loss through the furnace walls:

Hot- and Cold-Face Temperatures

The difficulty in maintaining a constant temperature using wood is reflected in the large values for the standard deviation[22] of the hot-face temperatures (about 50°C), as shown in Table 3. The standard deviation (SD) figures for the hot face of the tank furnace are low because the nighttime temperature readings (taken as the furnace was on its cooling cycle) have been ignored. The low cold-face average and large SD reflect the time taken for heat to penetrate the furnace wall as the tank furnace increased in temperature for the day's work.

The figures for the pot furnace and the small furnace are very similar, taking into account the slightly higher average temperatures for the small furnace, and they reflect the similar insulation properties of the two types of daub. The figures for the thicker daub and the tile wall show the

21. Colin Brain of SE Validation Ltd., e-mail communication to authors, 2005.

22. Standard deviation (SD) is a measure of the spread of values in a data set. At least 75 percent of the values in any population are within two standard deviations of the mean. For a detailed definition and method of calculation, see en.wikipedia.org/wiki/standard_deviation.

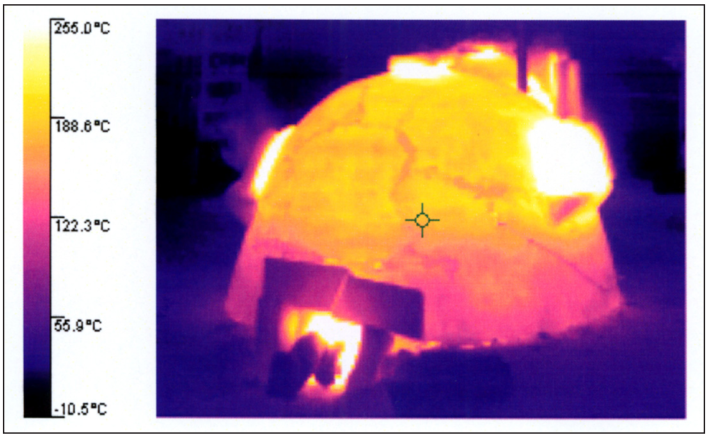


FIG. 23. *Pot furnace.*

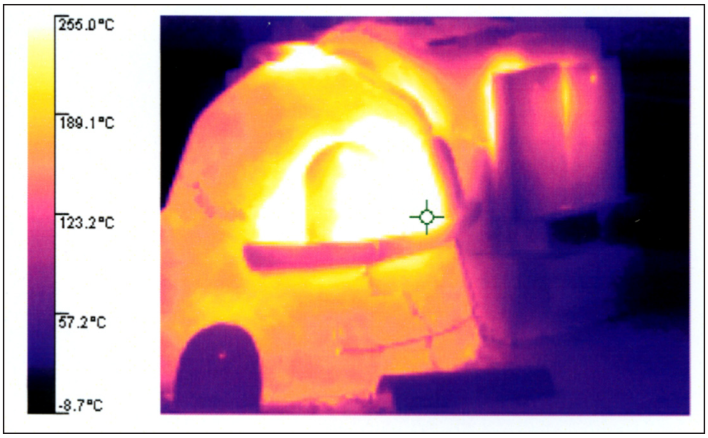


FIG. 24. *Tank furnace.*

increased insulation effect of tile (Th. 34 cm) added to the daub (Th. 13 cm) at that point on the wall of the pot furnace, which helps to account for the extra 100°C or so of heat within the fire chamber. The lower SD figures also show the usefulness of the tiles as a heat sink, helping to decrease the variation in temperatures in the pot furnace.

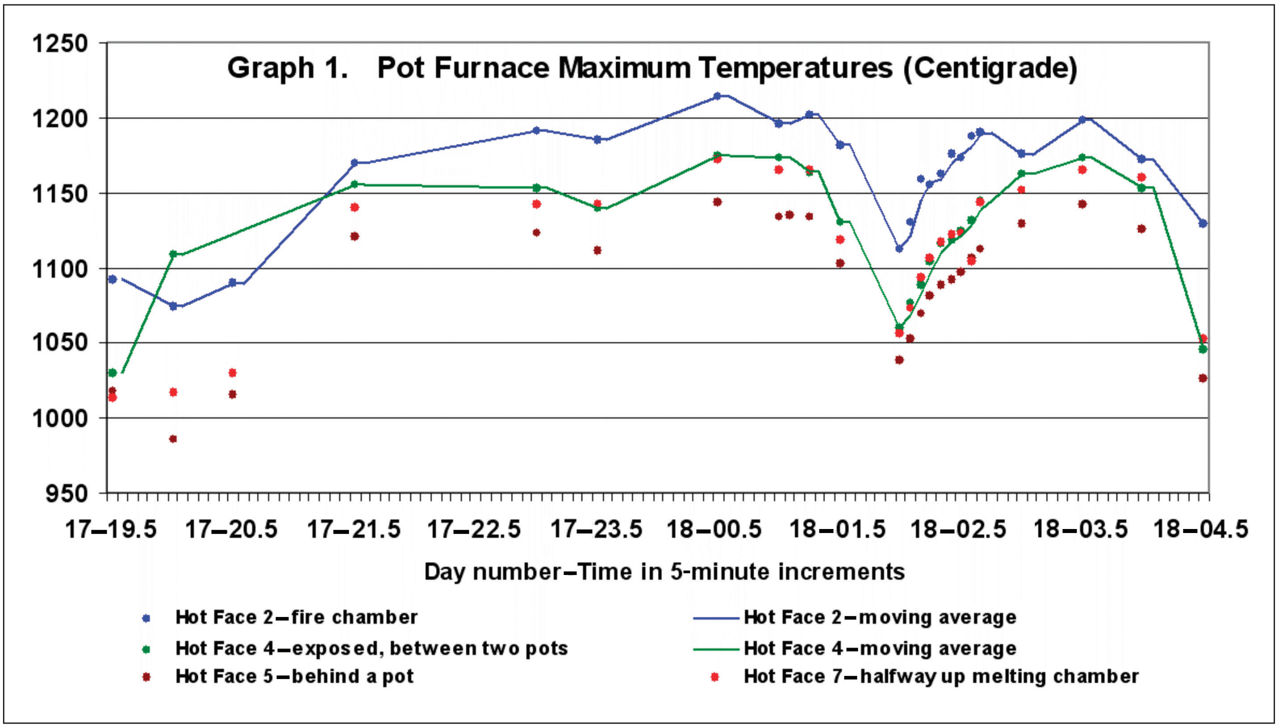
The daub compares well as an insulator with figures for modern high-temperature insulation (HTI) bricks.[23]

Temperature Distribution

There was a clear difference between the hot-face temperatures of the pot furnace's fire and melting chambers, usually about 100°C, primarily because of the thick tile wall. Temperatures in the melting chamber tended to be higher toward its top, where the waste gases exited through the top hole. The lowest temperatures were recorded by probe 5, which was sheltered from the direct heat, behind a pot (see Graph 1). The other two furnaces showed a more even distribution of hot-face temperatures, with a tendency for the temperatures to be 10°–20°C lower above the tank and pot than below them.

The thermal images (Figs. 23 and 24) show the temperature distribution on the outer wall (cold face) of the pot and tank furnaces, and

23. 1400-grade alumino-silicate bricks. The set of single readings (hence no SD figures) was made using a modern furnace sheltered from air movement in an enclosed workshop, whereas the temperature readings for the wood-fired furnace were taken in less sheltered conditions (which could affect the cold-face temperatures).



they highlight the influence of the thick tile wall of the pot furnace. They also show the areas of greatest heat loss: the gathering and top holes.

Top Temperature

Graph 1 shows the temperatures recorded in the pot furnace over a nine-hour period. The top temperatures reached in the fire and melting chambers were 1214°C and 1175°C respectively. To achieve these temperatures, the amount of wood burned per hour doubled (see Table 2), and the dip at 18–02.0 is the result of emptying charcoal from the fire chamber.

Heat Loss on Ash Removal

Graph 1 also shows the rapid cooling when raking out, as well as the rapid rise in heat (103°C in 60 minutes) on restoking, from 1060°C to 1163°C (Hot Face 7 readings).

At temperatures near 1000°C, even more rapid increases (up to 100°C in 20 minutes) were recorded. These measurements illustrate the ability of the furnace to respond quickly to rapid stoking after the fire chamber has been cleared.

Lehrs

The thermal images (Figs. 25 and 26) show the distribution of temperature within the attached lehr. The hot spot and the finished vessels are visible in Figure 25, while the insulation properties of the daub are illustrated in Figure 26. The cooler areas in the foreground of Figure 25 are the result of the necessarily open door.

Graph 2 shows the massive drop in temperature as the gases travel from the tank furnace to the attached lehr. Raising the height of the lehr, so that the hot gases enter at just under floor level, may help to correct this problem by heating the base first, improving the draft on the furnace, and allowing the gases to spread out and so avoid hot spots. The temperature drop at night was regulated by allowing the furnace to cool and by closing the heating duct.

As shown in Graph 3, for the free-standing lehr, the stoker was usually able to keep the

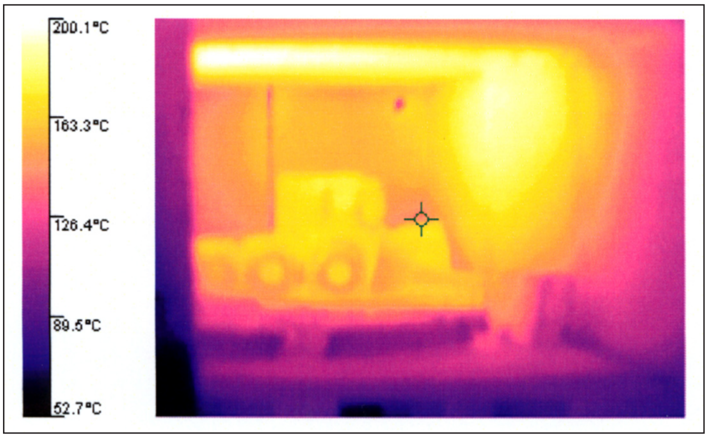


FIG. 25. *Attached lehr.*

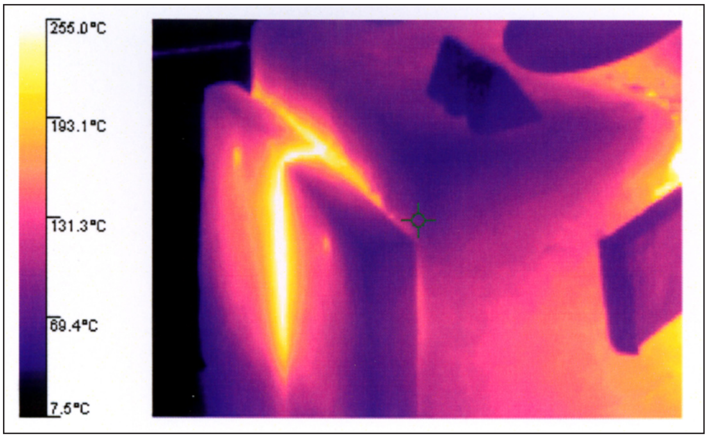
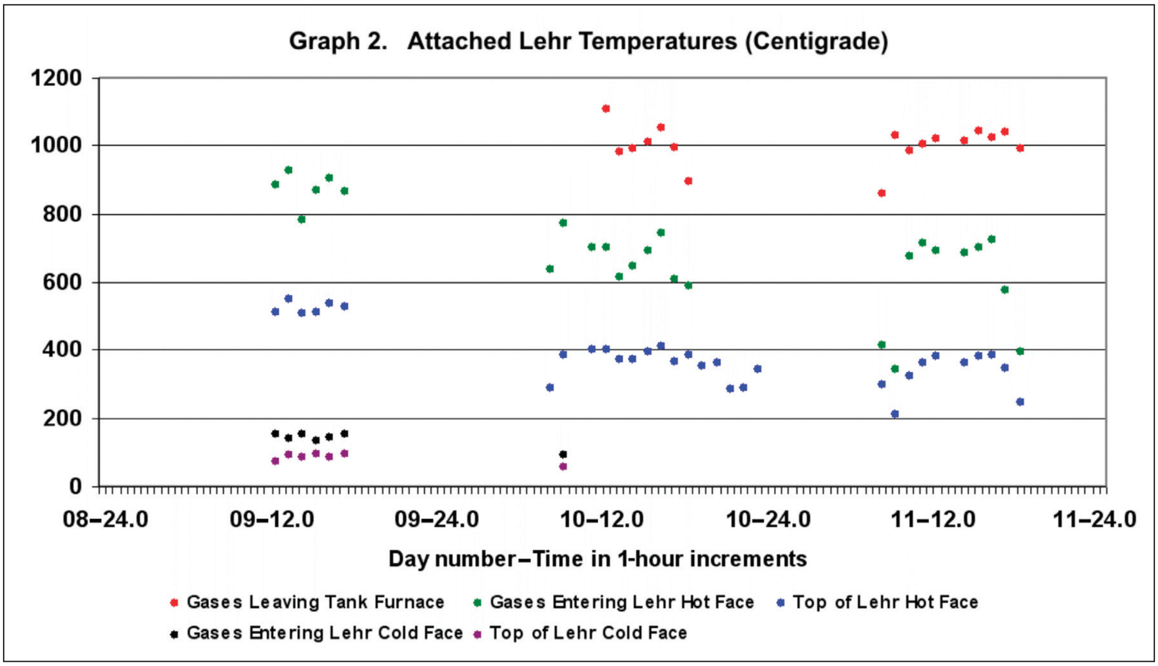
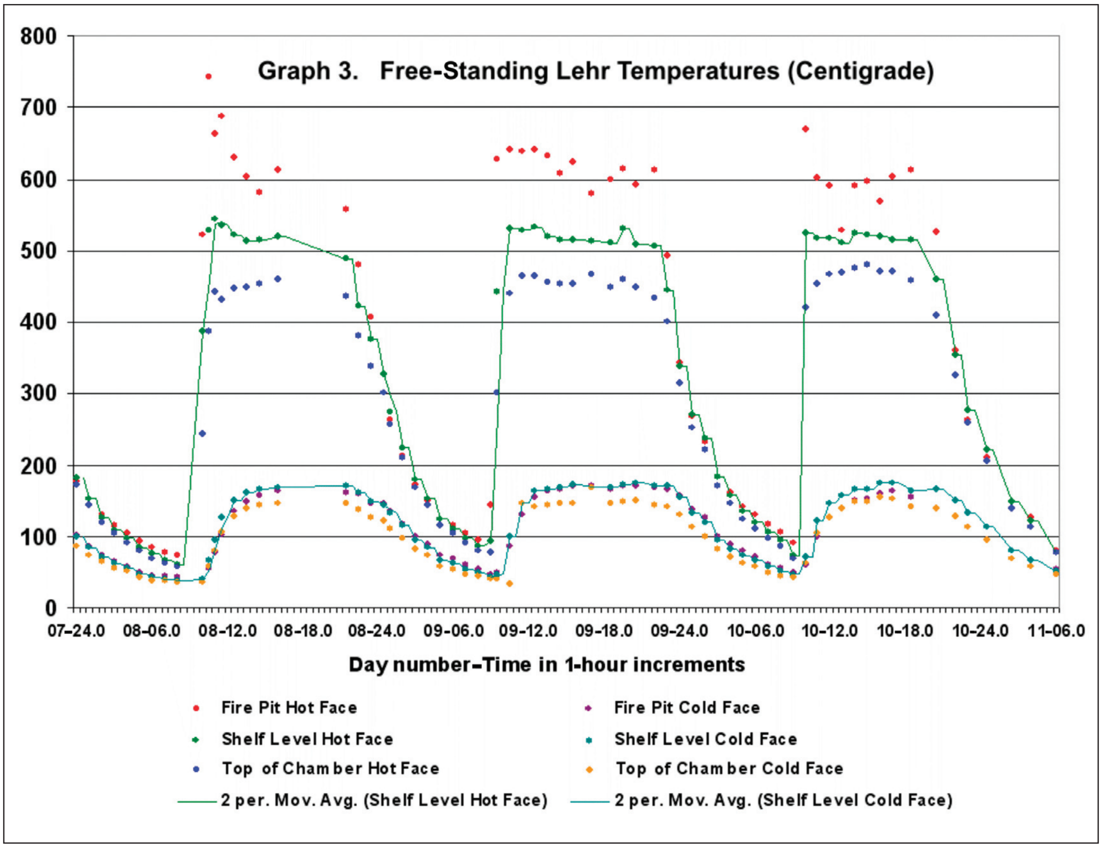


FIG. 26. *Attached lehr.*





temperature at shelf level about 10°C either side of 520°C, which annealed the vessels satisfactorily. The hot-face temperature differences were not significant, but the difference in temperature between the shelf and the top of the chamber would affect annealing if vessels were on a higher shelf, and this would need to be addressed, perhaps by using bag walls.[24]

The speed of the rise in temperature for the free-standing lehr shows that the system of daily firings for this type of lehr is perfectly possible, but the cost in wood (in this case, 100 kgs/day) would make it worthwhile to explore other ways of heating.

Methods for estimating the temperature would have been needed for Roman lehrs. In the absence of observable color from heat radiation, which will give a rough indication of furnace temperature, one method would be to suspend thin glass rods horizontally and to check regularly for any sagging that may occur. It would be important to put these rods near known hot spots. This method would merit testing.

WEATHERING

Between the two firings, the tank furnace was dissected with a saw and left exposed to the elements (Fig. 14). Rain, followed by the drying action of the wind and sun, accounted for most of the weathering of the unfired daub, and for its redeposition at the base of the walls. This layer, which lost some of its thickness (about 3 cm) through the autumn and winter, protected the inner, fired layers. The large lumps of wall removed from the furnace and left on the ground did not have this protection, and so they were attacked by frost, breaking them into small flakes.

24. See note 20.

The highly fired and glazed areas of the daub did not suffer from their brief exposure to the elements, and these are the parts that would be most likely to survive in the archeological record.

CONCLUSION

The aim of this experiment was to gain insights into how Roman furnaces may have worked, and we have discovered some of the finer points of firing them. The simple furnaces we designed were easy and quick to construct, and the materials we used were reliable and able to withstand significant thermal shock. We were also able to reuse a fire chamber, something that could be difficult to detect in the archeological record.

Roman-style furnaces are easy to fire, and the stokehole and fire chamber work very well, but they require continual attention to maintain working temperatures. In particular, the smaller furnaces, with their lower mass and fire chamber capacity, lose heat faster and require greater attention. Wood-fired furnaces are silent, compared with the constant rushing sound of modern gas-fired furnaces, and stoking them at night is not an unpleasant job.

We based the superstructures on the evidence we had, but how well do they represent Roman furnace superstructures? Glassworking furnaces tend to plan themselves. The structures need to be strong, easy to build, and able to withstand heat. There must also be an arrangement for fuel —the stokehole and the fire chamber, receptacles for molten glass, points of access to the glass, supports for collars and doors, and exit points for waste gases. These requirements will strongly influence the basic design of each furnace.

Our furnaces were suitable for general glassblowing, but during the experiment it soon became apparent that different products, requiring specific techniques and processes, would call for specialized furnaces,[25] some larger and some smaller, and diversity of furnace design is seen in the archeological record. Undoubtedly, there were more complex furnaces in the Roman world, and the larger they were, the more wood they would have burned, but they would have been just as simple to operate.

The most difficult problem in constructing these furnaces is the design of the interior. It is important not to restrict the passage of waste gases. Our design may have restricted the airflow in the tank furnace and, to a lesser extent, in the small furnace. One serious problem is the relative lack of evidence for pots used for holding molten glass before the fourth century A.D., and any tank system has to avoid cracking due to shrinkage. A shelf resting on brackets makes an excellent support, and it is one way of overcoming the problem. It allows a natural adjustment for shrinkage, and it would be possible to mold a thick-walled clay "tank" on the shelf instead of using a pot.

Over six weeks, we used a large quantity of wood, so any savings that can be made are important. Furnaces can be allowed to run at lower temperatures during the night, and it is possible to design a lehr to reuse waste heat. We did not test our furnaces to destruction, but the indications were that they would last for seven or eight months, if not longer, with repairs made as necessary, although doors and collars would need to be replaced often.

The free-standing lehr was more successful than its predecessor, although it increased wood consumption. The attached lehr has shown that it was possible to use waste heat, although the design needs to be improved. The Romans would have experienced, as we did, dulled surfaces on the cooled glass vessels, but they would have found ways to isolate the glass from the hot gases. They must also have had methods of controlling lehr temperatures.

There is a lot of scope in Roman furnace reconstruction, particularly in investigating design and control of tank furnaces and lehrs, and in relating furnace design to different products and working practices.

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25. This idea was also offered by John Shepherd of University College London in a verbal communication to the authors in 2005.