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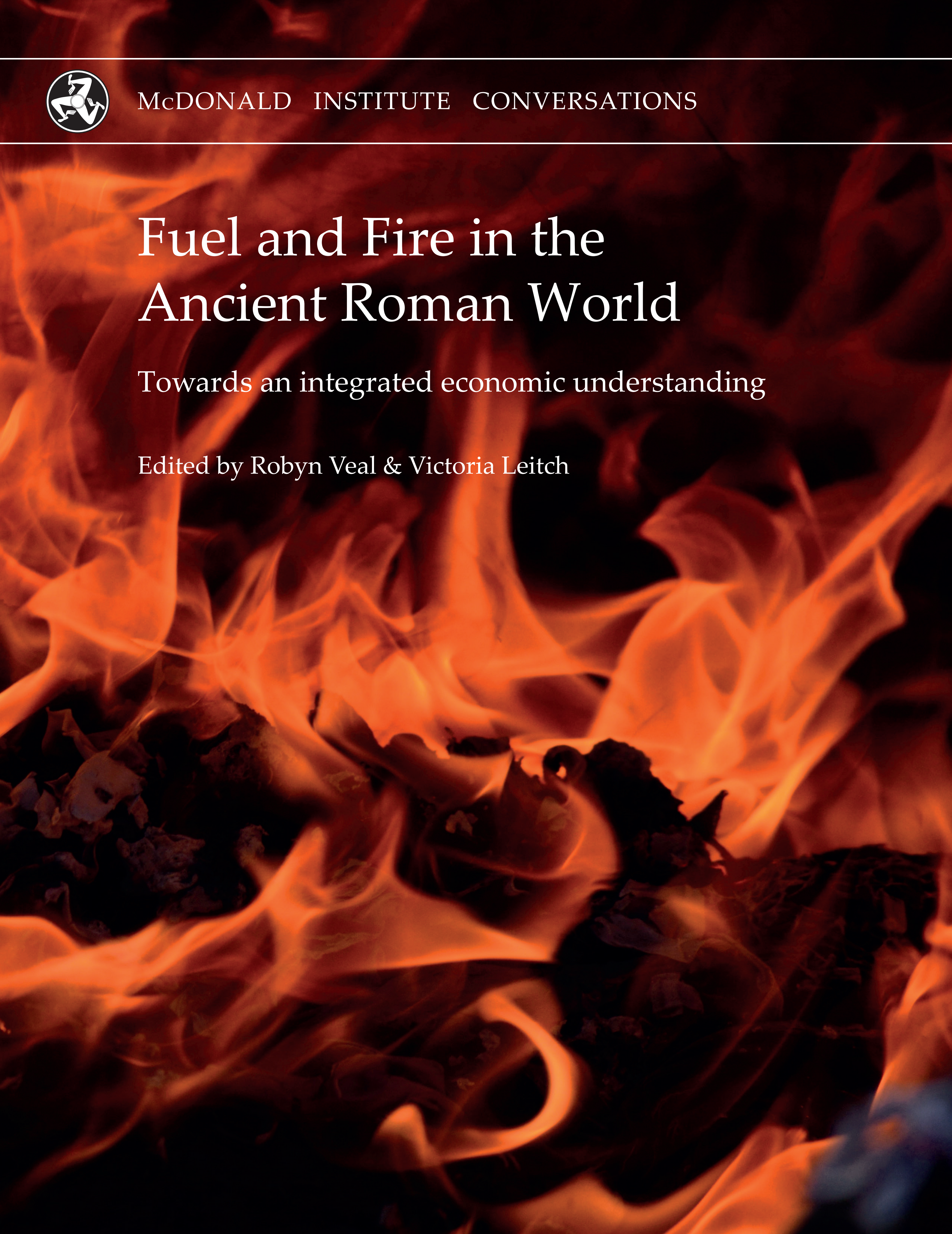

Fuel and Fire in the Ancient Roman World

Towards an integrated economic understanding

Edited by Robyn Veal & Victoria Leitch

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Preface

This book arises from a conference held at the British School at Rome, and the Finnish Institute in Rome, in March 2013, entitled Fuel and Fire in the Ancient Roman World. The conference represented the first real attempt to try to bridge the gap between 'top-down' generalized models about Roman energy consumption (itself, still a relatively new area of research), and research carried out by artefact and environmental specialists. In many ways it exceeded our expectations, although it probably raised more questions than it answered. As fuel is used in many different domestic and industrial contexts, the papers were very heterogeneous; some presenters came from a strong archaeobotanical background, which is a central area for fuel research, while others came from social, technical and economic spheres, opening up the discussion beyond archaeobotany. Some papers presented more 'qualitative' rather than 'quantitative' results but, as a new research area, this was inevitable and qualitative evaluation can provide the framework for approaching quantitative studies. Nevertheless, useful quantitative beginnings are proposed in a number of papers. Although focused on the Roman period, the research often extended beyond this chronological span, to help contextualize the results.

We gratefully acknowledge the support and assistance of the British School at Rome and the *Institutum Romanum Finlandiae* (Finnish Institute of Rome). In particular we thank Professor Katariina Mustakallio, then director of the *IRF*, for generously hosting the conference lunch on the final day. The financial support of the Oxford Roman Economy Project, through Professor Andrew Wilson, and a significant private donation from Mr Jim Ball, former Commonwealth Forests Chairman (administered through the BSR Rickman Fund) allowed speakers' travel, accommodation and subsistence costs to be covered, as well as a contribution towards publication costs. Professor Wilson and Mr Ball both provided much appreciated moral support and intellectual input, acting as our major discussants. The McDonald Institute for Archaeological Research, through its Conversations series, also helped fund publication. Professor Graeme Barker (McDonald Institute director to September 2014), Professor Cyprian Broodbank (current director), Dr James Barrett (current deputy director) and Dr Simon Stoddart (former acting deputy director) all provided advice and guidance over time. This was much appreciated. Dora Kemp provided initial advice on manuscript preparation, and after her untimely death, Ben Plumridge took over the practical side of production. Maria Rosaria Vairo, then a Masters student of the University of Lecce, and Dana Challinor, a doctoral student at the University of Oxford, provided significant voluntary support during the conference and we thank them both profusely. Robyn Veal would also like to acknowledge the long-term financial and intellectual support of the Department of Archaeology, University of Sydney, through much of her early work on fuel. This led to the opportunity of a fellowship at the BSR, and the idea for this conference. The feedback from reviewers has greatly improved the book.

Robyn Veal & Victoria Leitch

Chapter 2

Glass and fuel

H.E.M. Cool

Glass can be viewed as coming of age early in the Roman period. For centuries, it had been used as a luxury material to make things such as small perfume containers and items of jewelry. In the Roman period, technological developments meant it became a much more versatile material used for a wider range of functions. As a result, it moved from being a small player in the high temperature industries to being a major one. To understand what the demand on fuel supplies would have been, it is necessary to consider both the chemistry of the glass itself, and the technology being used for production. This paper seeks to summarize what is currently known about this. Although questions relating to where and how glass was made in the Roman period have been research topics that have attracted considerable attention over the past few decades, there are still some very large gaps in our knowledge. One of these is how the industry was fuelled, as there is little hard archaeological evidence about what the fuel or fuels might have been. Courtesy of some interesting experimental work that will be outlined, it is possible to start trying to estimate what the fuel demands may have been.

The development of the glass industries

The glass industries of the Imperial period were born during the late Hellenistic centuries. Prior to that glass vessels had been made by either the core forming techniques, which were suitable for making small perfume containers, or by using lapidary techniques to grind and polish the desired shape from solid blocks or hollow blanks (see, for example, Grose 1989 and Stern & Schlick-Nolte 1994 for useful summaries). None of these techniques leant themselves to mass production, and glass remained a material only suitable for the luxury end of the market as far as vessel use was concerned.

The change came in the mid second century BC when it was discovered that discs of hot glass could be sagged over formers to produce conical or hemispherical bowls (Grose 1989, 193–4). These are generally referred to as Syro-Palestinian bowls because of the large numbers that have been found in that area, but their distribution spreads across the eastern Mediterranean and into Italy, and there is evidence for manufacture in Rhodes (Triantafyllidas 2003, 136–7). As has been noted in a consideration of those from Israel, these mark the beginning of the perception that glass vessels could be an alternative to pottery (Jackson-Tal 2004, 28), and thus opened the way to their large-scale use. The industries using sagging and manipulating methods of making bowls expanded and grew in the late Republican and early Imperial periods. Their ultimate form was the ribbed bowl (Isings 1957, 17–21 Form 3), known in the Anglophone literature as a pillar-moulded bowl. These are ubiquitous on first century AD sites across the empire, bearing witness to how large the industry must have been.

The more important technological breakthrough in the use of glass came with the discovery of how to blow vessels. Using this technique a much wider range of vessel types, both open and closed, could be produced quickly and in large numbers. The discovery of glass-blowing is generally placed in the middle of the first century BC. The earliest glass-blowing waste that has been discovered comes from Jerusalem, where it was found sealed by a road built by King Herod in 37–4 BC (Israeli 1991). This was not the form of blowing where a gather of molten glass is taken from the furnace and inflated on a blowing iron. Rather, it was the inflation of one end of a pre-formed tube to provide a reservoir for a small unguent bottle. It is probable that experimentation was ongoing during the second half of the first century BC to develop the hot gathering method. Blown glass vessel fragments are rare in the first century BC but start to appear more regularly during the Augustan period (Grose 1977). It is then found in ever increasing volumes during the Tibero-Claudian period when it use overtakes that of the sagging industries. Roman Britain is a good example of this. Glass vessels of any sort were extremely rare prior to the Claudian invasion of AD 43. Thereafter glass vessels flooded into the new province and by far the majority were blown. At the fortress and *colonia* at Colchester a snapshot of the vessel use between AD 43 and AD 60/1 has been captured because it was burnt to the ground during the Boudican rising. The extensive city centre excavations revealed a ratio of almost three to one for blown to cast fragments (Cool & Price 1995, 11, Table 1.4).

With blowing, the functions that glass vessels served increased. Glass could be used for both fine tablewares and, possibly more importantly, for utilitarian containers. Columella, writing his treatise on agriculture in the mid-first century AD, urges the bailiff's wife to be sure she has suitable glass storage vessels as well as pottery ones for preservation (*De Re Rustica* XII, iv.4). The impact of glass vessels as a storage medium by the final third of the first century AD is vividly shown by the numbers recovered from the eruption levels at Pompeii. Scatozza Höricht (2012, 36 Tav. B) has usefully tabulated the types present within the 2000 vessels available for study. From this it can be seen that over 50 per cent are unguent bottles and small flasks for the storage of perfumes, bath oil and the like. A further 15 per cent belong to the utilitarian range of storage bottles and jars (Isings 1957, 63–9 Forms 50–1, 81 Form 62). These are the types that the bailiff's wife would have needed. Many of the container forms would have been reusable, but some were literally disposable packaging, as the contents could only have been accessed by breaking the vessel. The elegant blown birds that are such a feature of the northern Italian glass industry of the early to mid-first century AD, for example, needed to have their beaks or tails snapped off before the contents could be extracted (Isings 1957, 24 Form 11 – see, for example, Harden et al. 1987, 95 no. 37).

This increased demand caused a change to the nature and distribution of the glass-working industries. Whereas the sagging industries were most probably based in the eastern Mediterranean and latterly Italy, blowing industries spread relatively rapidly across the whole empire in the early to mid-first century AD. Even in Britain, a newly absorbed province, there is evidence of this. In the decade following the Boudican rising of AD 60/1, which had also destroyed the new foundation at London, a glass-blowing workshop was active in the harbour area once it had been rebuilt (Brigham 1997, 27).

It is possible to trace the spread of the blowing technique because the waste glass that comes from the ends of the blowing irons (moiles) is very distinctive (see, for example, Amrein 2001, 21–33; Price & Worrell 2006, 132–3, colour plates 2–7). Since the fragments became widely recognized for what they were in the 1980s, there has been an ever increasing number of sites where it is known glass-blowing must have been carried out. In the latest publication of excavations in London where such debris has been found, it was noted that, to date, 21 different sites had produced it from contexts ranging from the first to late fourth century (Wardle 2013, 53). Comparable material is not uncommon throughout the rest of the province. On the continent the situation is similar. Over a decade ago it was possible to produce a map of Gaul with over 50 sites with evidence of glass-working (Foy & Nenna 2001, 43), and the number has increased since then. The pattern appears to have been for a widespread and dispersed industry serving local communities with their everyday needs. It can often be noted that where there is *in situ* evidence of glass-blowing which includes the furnaces, it is often located in zones where there were other high-temperature industries such as the manufacture of pottery (Price & Cool 1991, 27; Keily & Shepherd 2005, 154), and so it might be surmised that both industries were calling upon the same fuel supplies.

So far attention has been focused on vessel production, but glass also had an important role in building. Windows must have been regularly glazed given the frequency of window fragments in glass assemblages of all types of sites. The window glass of the first to third centuries AD (known as matt/glossy) was made by manipulation and sagging like the earlier bowl tradition. It was not until the fourth century that blown window glass came to be more commonly used (see Allen 2002 for discussion). Matt/glossy glass was translucent rather than transparent, but the important thing was that it could allow light into a structure whilst also keeping heat in. For this reason it was a vital element of bath-houses, but it was also a key part in the development of other new forms of architecture from the first century AD onwards (Ward-Perkins 1981, 187 fn 3, 151).

Whilst these would have been the two main uses of glass by volume used, the material also continued to be used for jewelry and had other uses in building such as in tesserae for wall and floor mosaics and blocks for *opus sectile*. As can be seen the Roman world was thus quite a voracious user of glass, and the implications of this for fuel use can now be addressed.

Glass chemistry, manufacture and melting temperatures

To understand the amount of fuel used, it is necessary to consider the ranges of temperatures that would regularly have to be reached and sustained to make and work glass. The viscosity of glass at particular temperatures varies according to the chemical composition, and so attention has to be given to this. Fortunately for this period that recipe is stable and uniform across the empire.

Technically Roman glass is a soda-lime-silicate. The silica may be thought of as forming the body of the glass and typically contributes about 70 per cent to the recipe. Silica has a very high melting temperature at just under 2000 °C, so a flux was needed to bring the temperature down to a level ancient technology could attain. For Roman glass, and from this point on the term is being used to include the Hellenistic material, that flux was an inorganic soda and averagely contributes *c*. 20 per cent to the recipe. Lime was also needed to stabilize the end product and added a further six per cent or so to the mix. The remainder of the ingredients are the minor elements, both the naturally occurring ones, such as iron which influences the blue/green colour of natural glass, and ones deliberately added either to colour or decolourize it. Beach sand would normally have included sufficient shell fragments to provide the lime, so for many glass-makers it might have been thought of as a two ingredient recipe. This is naturally a very simplified and brief outline suitable for the purpose of this paper. Further details may be found in Henderson (2000).

When studying glass it is normal to make a distinction between glass-making and glass-working. The former activity takes place in primary installations making glass from the raw ingredients. The latter describes the activity of the glass-blowers, window-makers, bead-makers, etc. Their raw material may often have been chunks of raw glass made in the primary installations but then as now, broken glass was collected for re-use. Collectors of cullet for re-use must have been common in the AD 70s and 80s in Rome, for example, as Martial used the profession as an insult in a poem (*Epigrams* I.41). The recycling of glass in this way must always be kept in mind when assessing how much glass people were using. Pottery *can* be reused when broken, as the make-up levels in buildings, or to make items such as counters, etc., but that may have been an exception. In the case of glass items, recycling was their *normal* fate. This means that in any archaeological assemblage, the number of glass vessels will always appear tiny compared to the amount of pottery ones. This need not imply that glass vessel use was necessarily small when both categories of finds were in active use. There is certainly evidence in Roman Britain that by the later second century, people across all site types and social levels were preferring to drink out of glass, with the consequence that the volume of pottery cups in use fell (Cool 2006, 149).

Our state of knowledge of the primary installations of the Roman world is minimal. There is a model that suggests much may have been made in the Middle East (Freestone et al. 2002), but physical evidence is, on the whole, lacking. Tank furnaces for primary glass production have been found in the region but these appear to date to the Byzantine era (Gorin-Rosen 2000, 52–6). Traces of primary glass-making installations that may be of Roman date have also been found in the Wadi el-Natrun in Egypt (Nenna et al. 2000, 99–103; Nenna et al. 2005), which is an area that supplied the type of inorganic soda (natron) used in Roman glass-making. Very occasionally semi-reacted batch material has been recovered elsewhere suggesting the manufacture of raw glass, as at York. There the activity is thought to belong to the late second to early third century AD, based on the typology of the glass-melting pots it was associated with (Cool et al. 1999). Elsewhere a case has been made for local production of raw glass in the fourth century glass houses in the Hambach Forest in Germany, based on lead isotope data and other chemical correlations with the local sands (Wedepohl et al. 2003).

Amongst glass scholars the question of whether there was a centralized or dispersed production tends to be a matter of individual belief in the balance of likely probabilities. This is naturally of interest to them, but here the relevance is that it makes it difficult to access fuel requirements in any detail. Some general points, however, can be noted. There are two stages in making raw glass. The sand and soda are mixed together and heated at a relatively low temperature, certainly not exceeding 850 °C. The aim of this is to produce a substance known as frit. The heating causes the two ingredients to react with each other and drives off gasses and impurities. It is a solid-state process. The resulting solid can then be melted to make the glass. This can be done sequentially in the same furnace.

In the absence of any solid archaeological evidence for the Roman period, it is useful to look at the case of one of the primary glass installations that has been excavated in Israel. There at Bet Eli'ezer, near the modern Hedera, a single-period installation of 17 tank furnaces was recovered in 1992 during rescue excavation. Here I draw on the English summary of Gorin-Rosen (2000, 52–4) and the French account in the catalogue to the exhibition *Tout feu tout sable* (Foy & Nenna 2001, 37–8). The former does not date the installation explicitly but notes it is close to a Byzantine settlement; the latter dates the activity to within the sixth to seventh centuries AD.

The individual furnaces were laid out in a neat row side by side. Each consisted of two firing chambers with a rectangular furnace behind them measuring 2 × 4 m. The excavated evidence, combined with ethnographic observations of raw glass production in India, suggested that here both the fritting and the melting was done in a single operation. The ingredients would have been loaded into the tank, which would have been heated via the firing chambers so that the solid state reaction could take place. The temperature would then have been raised to *c*. 1100 °C. It was suggested this would take between 10 and 15 days. Each furnace would have produced between eight and nine tonnes of glass. When cold the furnace would have been dismantled and the block reduced to chunks of glass. These would then have been transported for sale to secondary workshops. The furnaces were only used once.

It was suggested that this was a seasonal activity with work starting in the spring to prepare the ground for the furnace, as later in the year it would become too hard to dig. The summer would be spent drying the wood for fuel, making the mud bricks with which to build the furnace(s) and then building it/them. Firing was likely to have been a late summer activity to make best use of the prevailing winds, given that the furnaces would have needed continuous air circulation over the fortnight they would have been fired. Interestingly it was suggested that production ceased at the site because the glass-workers might have run out of sufficient fuel in the area. That the production of raw glass is a very fuel-hungry process can be noted from the experience in the late sixteenth- to early seventeenth-century English glass industry (Charleston 1984, 73–5). At that time there was a major increase in the demand for glass, especially for windows. The State became increasingly alarmed about the inroads in the timber stock that was being made to, literally, fuel this (the State being always anxious about maintaining sufficient stocks of good-quality timber for ship-building and the defence of the realm). In this case the concern lead to the move to coal-fired furnaces, which was presumably not option for many Roman glass-makers. It does, though, provide a vivid illustration of the impact the rise in glass use would have had from the first century AD onwards, as more and more people wanted glass vessels in their kitchens and dining rooms, and glass in their windows.

Much more is known about secondary workshops as many more have been found. Well-published examples include those from Avenches (Amrein 2001) and Kaiseraugst (Fischer 2009), and these give a good idea of the sort of installations to be expected. The furnaces tend to be small and circular with internal diameters generally ranging from 0.5 to 1 m (Amrein 2001, figs. 91–4). There has been some debate about how such small installations could successfully reach the temperatures needed, but early experimental work showed that if they were provided with a chimney to ensure good air circulation, this is not an issue (Shepherd 1996). Later work has shown the need for chimney can be done away with if the stoke holes are large enough (Taylor & Hill 2008, 250). It seems likely that the glass was often melted and gathered from a suspended tank inside the furnace as tank fragments often occur in deposits of glass-working waste (Keily & Shepherd 2005, 148–51). Being above-ground features, the size of the suspended tanks is difficult to evaluate, but clearly they cannot have filled the interior of the furnaces as otherwise there would not have been sufficient air circulation to maintain the high temperatures. Some authors maintain that the use of crucibles rather than suspended tanks is a fourth-century and later development (Foy & Nenna 2001, 64). The examples of crucibles from widely geographically scattered sites such as York in England, Kaiseraugst in Switzerland and Ptuj in Slovenia suggest they were in use earlier than the fourth century (for references see above and also Lazar 2003). The volumes of glass it would be possible to melt in the glass melting pots found in the Hambach Forest and at York were calculated at 6 l and 0.0125 cubic metres respectively, equivalent to about 15 to 20 kg of glass.

Interestingly on glass-working sites it is extremely rare to find charcoal or the remains of any other fuel. This is an additional difficulty when attempting to assess fuel use by the glass industries. Some of these installations were excavated prior to systematic environmental sampling, so if the evidence had been there it would not have been found. In other cases there is always the possibility that it was recovered but not reported on. Elsewhere it was looked for and not found. A good example of that occurred shortly before the conference from which this book proceeds. An *in situ* glass furnace was excavated in Winchester by Borders Archaeology with the full panoply of environmental sampling and careful excavation. Being at the time 'fuel-aware', I specifically enquired about any fuel remains and was told that none had been recovered. The reason for the absence will be returned to in the following section.

Having established the quantities of glass that might have been heated at any one time, it is now appropriate to look systematically at the temperatures that would need to have been achieved and maintained. Table 2.1 summarizes the temperatures required to carry out certain actions with a soda-lime-silicate glass made to the recipe outlined above. It is based on Marianne Stern's extremely useful experimental work conducted when she was working at the Toledo Museum in the United States (Stern & Schlick-Nolte 1994, 21–4).

Table 2.1. *Key temperatures in the working of soda-lime-silicate glass (after Stern & Schlick-Nolte 1994, 21–4).*

Activity	°C	Activity
Working range	700–1100	Simple beads
Chunk gathering	505–590	
Sagging	625–830	
Fuse to other glass	735–800	Making millefiori blanks
Flatten to disc	830–875	Counters
Draw cane	930–965	Beads; canes for millefiori bowls.
Blowing	970–1020	Blown vessels
Hot gathering	1000–1150	Blanks for monochrome sagged bowls; blown vessels
Annealing point	529	
Melting point	1050–1150	Glass manufacture

The glass will start to melt at 1050 °C but temperatures in excess of that are needed to melt a pot or tank full of glass. The annealing temperature should also be noted. After a glass vessel has been made, it has to cool down slowly in a controlled environment (annealing). It is possible that waste heat from the furnace could have been used if annealing ovens were built on top of the furnace or at the back, but the need to anneal may have been an additional call on the fuel supplies.

As can be seen at the top of Table 2.1, the working range is *c*. 700–1100 °C. Within this range different things can be done at different temperatures. The chunk gathering entry (505–590 °C) is the point at which glass can be picked up and softened directly on a very hot iron. Temperatures in the 600s may thus have been sufficient to produce some monochrome beads. Glass will fuse to other pieces of glass at a minimum temperature of 735 °C, so polychrome decorated beads would have had to be produced at that temperature or higher. Some bead forms in the Roman world were made by drawing out a cane or rod and then chopping it into segments and that would need a higher temperature (930–965 °C). Canes were also an important component of the vessels made by the late Hellenistic and early Imperial industries that used the sagging techniques (Grose 1989, 189–92, 195–7, 247–54, 256–62). Thus the canes would have had first to be made at this temperature and then heated again later as part of the vessel manufacturing process.

From time to time during the Roman period, plano-convex glass counters were popular. Heating chunks of glass to the mid-800s °C and putting them on a surface should have been sufficient to make these as at that temperature the glass will naturally seek a rounded shape and flatten.

At this point it is important to start considering not just the temperatures that need to be reached, but also the length of time it is necessary to work at those temperatures. Here the contribution that the work of Mark Taylor and David Hill has made to our understanding of various processes can be drawn upon. Taylor & Hill are commercial glass-workers who became interested in Roman glass, and in the late 1990s and earlier part of the next decade they concentrated on recreating and selling 'Roman' vessels. Experimental work can never prove that an ancient item was made in a particular way; it can only say it could have been. Whilst acknowledging that, it is appropriate to say that I have handled tens of thousands of pieces of Roman glass during my professional life and there have been times when I could not tell the difference between those pieces and their recreations. This has not been the case in the work of some other workers who have attempted to reconstruct working practices. Taylor & Hill's results are very convincing, and it is reasonable to think we can usefully work with them, as is done below (Taylor & Hill 2003a, 2003b).

For millefiori slumped bowls the individual cold cane segments are packed closely together and heated in a kiln to 575 °C before being transferred into the glory hole of the furnace to be manipulated and fused to a disc. As noted that will require the disc to reach a temperature of 735 °C and the slumping can be carried out in the 625–830 °C range. The manipulation needs repeated reheating in the furnace mouth. The plain ribbed bowls need the furnace to be running at the hot gather temperature as the original blank is made from poured glass. Reheating is regularly needed as the ribs are formed. Taylor & Hill note that it takes between 15 and 20 minutes to create a monochrome ribbed bowl, and almost twice as long to create a millefiori one because of the preliminary fusing of the canes.

Blown glass requires hot gathering so the furnace must be kept at temperatures of over 1050 °C even though it is best blown a lower temperature. Some blown vessels such as the simple unguent bottles must have been very quick to make. The square bottles that are so common during the later first to third centuries, were mould blown and so are more complex, with the larger ones possibly needing two gathers. Taylor (1997) estimates from his experience that an output of five bottles an hour should have been achievable.

Putting the numbers together

It is possible to make some estimates of fuel consumption courtesy of an experimental Roman glass furnace project that Taylor & Hill ran in 2005 and 2006 (Taylor & Hill 2008). Two glass furnaces of the type found in the secondary workshops already discussed were reconstructed. One used the suspended tank system, and one used a melting pot. The former failed at an early stage and so the figures presented here are based on the pot furnace, which was successful. The glass-melting pots used were based on the Hambach Forest vessels discussed above. There were two three-week seasons; in the first seasoned wood was used and in the second they had a mixture of seasoned and green wood. Species used included beech, ash, walnut, chestnut and yew. Once up and running the furnaces were stoked day and night, with the night-time temperature being allowed to drop a little below the gathering minimum temperature of 1050 °C. Fuel was weighed and thermocouples used to record temperature. The full article the following summary is based on records a wealth of quantified detail which people concerned with other high-temperature industries and fuel use will no doubt find of great value.

One fact that the work showed was just how long the very high temperatures needed for hot glass gathering had to be maintained even before blowing commenced. Following two days of low temperature drying out, the furnaces were gradually taken up to the working temperature of 1050 °C over two days. The empty glass-melting pots were kept in the furnace running at full temperature for two more days to season them and check for any defects or cracks that might emerge, before being charged with cullet. It was found that the melting of the glass then needed a night/day/night cycle before it was ready to blow – this allows the waste gasses to escape and so ensures that the glass is not full of bubbles. First- to third-century Roman glass is normally of very good quality and often virtually bubble free, so the Roman glass-blowers must have followed this practice.

With regard to the type of timber used, it was found that controlling the temperature was very difficult with green wood, and so seasoned wood must have been preferred. Cordwood up to *c.* 1.2 m long and 0.15 m in diameter worked very well with the types of stoke holes that have been found on glass furnaces of this type. This size allowed sufficient air to circulate around it as it combusted. It was also found to be easier to adjust the temperature if logs, rather than lump wood, were used.

The project also provided the answer to why it is so difficult to find evidence of fuel at glass-working sites. Spent fuel was removed morning and evening from the furnace, and dumped in an ash pit. Once there it continued to combust at about 600 °C. All that was left in the ash pit at the end of the project was a few buckets-full of ash. During the project some 49 tonnes of timber were consumed, so only to have a few buckets of ash left at the end of the process suggests that it will be normal not to find fuel remains at Roman glass-working sites.

Table 2.2. *Fuel consumption recorded by the Roman Glassmakers furnace project (data taken from Taylor & Hill 2008, Tables 1 and 2).*

	Total weight consumed (kg)	Day – average fuel consumption per hour (kg)	Night – average fuel consumption per hour (kg)
First firing (2005)			
Ash wood	332.25	13.05	13.45
Beech wood	589.25	12.23	15.94
Mixed wood	5362.00	15.92	13.25
Total	6283.50	-	-
Second firing (2006)			
Seasoned wood	6759.75	17.83	15.06
Green wood	420.00	36.14	26.14
50:50 seasoned/green	1220.75	26.52	23.84
Total	8400.50	-	-

Table 2.2 shows the consumption of fuel used in the pot furnace running at glass gathering temperatures. If we take an average of the day and night fuel consumption of seasoned wood we can work with 15 kg of seasoned fuel per hour; that means that once the furnace gets to 1050 °C, 720 kg fuel would be needed to season the glass-melting pots and then a further 540 kg would be needed for the 36-hour melting process.

If we use the same rate of fuel use we can start to estimate how much timber would be involved in making particular types of vessels. Earlier in the paper estimates of how long it would take to make pillar moulded bowls and prismatic bottles were given. These are amongst some of the commonest Roman glass vessels found. They must have been made in huge quantities given the number that would never have entered the archaeological record because of recycling. Let us assume that a working day is eight hours. Working glass is physically taxing and so that would be a long day. Let us further say that in that day a glass-worker could produce 42 ribbed bowls (8 × 4 per hour) or 50 square bottles (8 × 5 per hour). Furthermore let us assume each of these uses 0.25 kg of glass. Both types vary in size but both can include substantial vessels. So in a charged pot of 20 kg of glass there would be enough material for 80 vessels. Making the bowls would require the furnace running for 32 hours, and making the bottles would require it to run for 30 hours. Both of these assume only one glass-worker and assistant at the furnace. This seems reasonable because many furnaces are quite small and, given the reheating frequently needed at the mouth of the furnace, two teams might have been in each other's way.

If these assumptions are accepted, there would be a timber consumption of 480 kg for the manufacture of the bowls and 450 kg for the bottles. To both of these figures 1260 kg must be added for seasoning the pot and then melting the glass. So it would need between 21 and 22 kg of fuel to make each vessel. Cast window panes would have needed the same amount as producing them is comparable in time to producing ribbed bowls and they need to be hot gathered (Allen 2012, 105). To this would have to be added the amount of fuel needed to bring the furnace up to running temperature, and that to run the annealing ovens. There is also the amount of fuel needed to make the glass in the first place, but in the absence of knowledge about the size of the installations that is difficult to do. The Bet Eli'ezer furnaces were much larger than the secondary glass-working furnace the experimental figures relate to, and so presumably would have needed a higher input of timber per hour.

There can be no doubt that the glass industries were fuel hungry, but equally there can be no doubt that glass was in everyday use by large numbers of people throughout the empire. So by implication the glass vessels and windows were not luxury goods. Does this give us any insight into how fuel was valued? The Edict on Maximum Prices issued by Diocletian in AD 301 is not without its problems (see, for example, Rathbone 2009, 317–21), but prices for both loads of timber and finished glass artefacts are given. Using these and the fuel estimates proposed above, it is possible to start exploring what the relative cost of the fuel would have been compared to the finished goods. The artefacts we can estimate the fuel needs of (ribbed bowls, bottles and window panes) are all earlier than the Price Edict, but in the absence of any other indication of the cost of fuel and vessels, this one will have to serve.

The Edict sets the rate of the cost of a wagon load of wood at 150 denarii (Graser 1940, 360 XIV.8). The load is set at 1200 lb, so following the equivalent offered by Rathbone (2009, 301) that would represent 3715 kg. The fuel costs for the bowls, bottles and window panes per unit, as calculated above, would be slightly under 1 denarius (excluding the fuel cost for the primary glass manufacture, etc.). The part of the Edict that relates to glass divides it into vessels and window glass, giving four different prices for vessels varying from 13 to 30 denarii per pound for vessels and 6 to 8 denarii per pound for window glass (Barag 2005, 184). We do not know quite what the different categories of vessels represent or how many you would have got to the pound. Taking all the figures together, they do suggest that the fuel cost for window glass might have represented a higher proportion of the total cost than it would have done for vessels. For the latter it does seem to be quite low. For this fuel-hungry industry, these figures suggest fuel costs would not appear to have been a problem, at least in the later third century and presumably before.

In the absence of hard evidence, this paper has made many assumptions ranging from the working speed of the Roman glass-worker to the reliability of Diocletian's price edict. Some may be reliable, some may not be. The aim has been to bring the glass industries into the equation when considering fuel use in the Roman Empire. To finish it is useful to pose a final question that it may be useful to consider more widely. Were the fuel resources running out in the later Roman period? Were they being consumed faster than they could grow? The question arises because early in the fourth century there is a major change in Roman glass. It goes from being good quality, bubble-free glass in primarily blue/green and colourless shades, to being pale green and full of small bubbles. The reason for this is unknown. It could be aesthetic, for the new glass is attractive and the bubbles catch the light. Equally though, is this a reflection of stress in the fuel supplies? We have seen the length of time a batch has to be heated to drive off the gasses that cause the bubbles. Perhaps if fuel was becoming scarcer and more expensive, this stage could no longer be afforded. It would be most interesting to explore whether other categories of evidence suggest that there might have been problems with fuel supplies at this time, but that is a task for other authors.

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Afterword

This paper was written in 2014 and glass scholarship has naturally moved on. An important project was published at about the same time this was written, which would have been referenced had it been available (Degryse 2014). This addresses the theme of where Roman glass might have been made and naturally has important implications for where fuel supplies might have been needed. A more recent note (Taylor 2018) revisits the experimental work used here and indicates that the fuel consumption figures originally reported on have been confirmed in other experimental glass furnaces.

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Fuel and Fire in the Ancient Roman World

The study of fuel economics in the Roman, or indeed in any ancient world, is at a pivotal point. New research in archaeological science, the ancient economy, the ancient environment, and especially, the increasing collection of bio-archaeological datasets, are together providing a greatly enriched resource for scholars. This volume makes a first attempt to bridge the gap between 'top-down' generalized models about Roman energy consumption with the 'case study' detail of archaeological data in the Mediterranean. The papers here are the work of scholars from a variety of disciplines: from archaeobotanists and historians to archaeologists specialising in social, technical and economic fields. A more nuanced view of the organization of the social and industrial structures that underpinned the fuel economy arises. Although focused on the Roman period, some papers extend beyond this era, providing contextual relevance from the proto-historic period onwards. Much exciting interdisciplinary work is ahead of us, if we are to situate fuel economics more clearly and prominently within our understanding of Roman economics, and indeed the ancient Mediterranean economy.

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