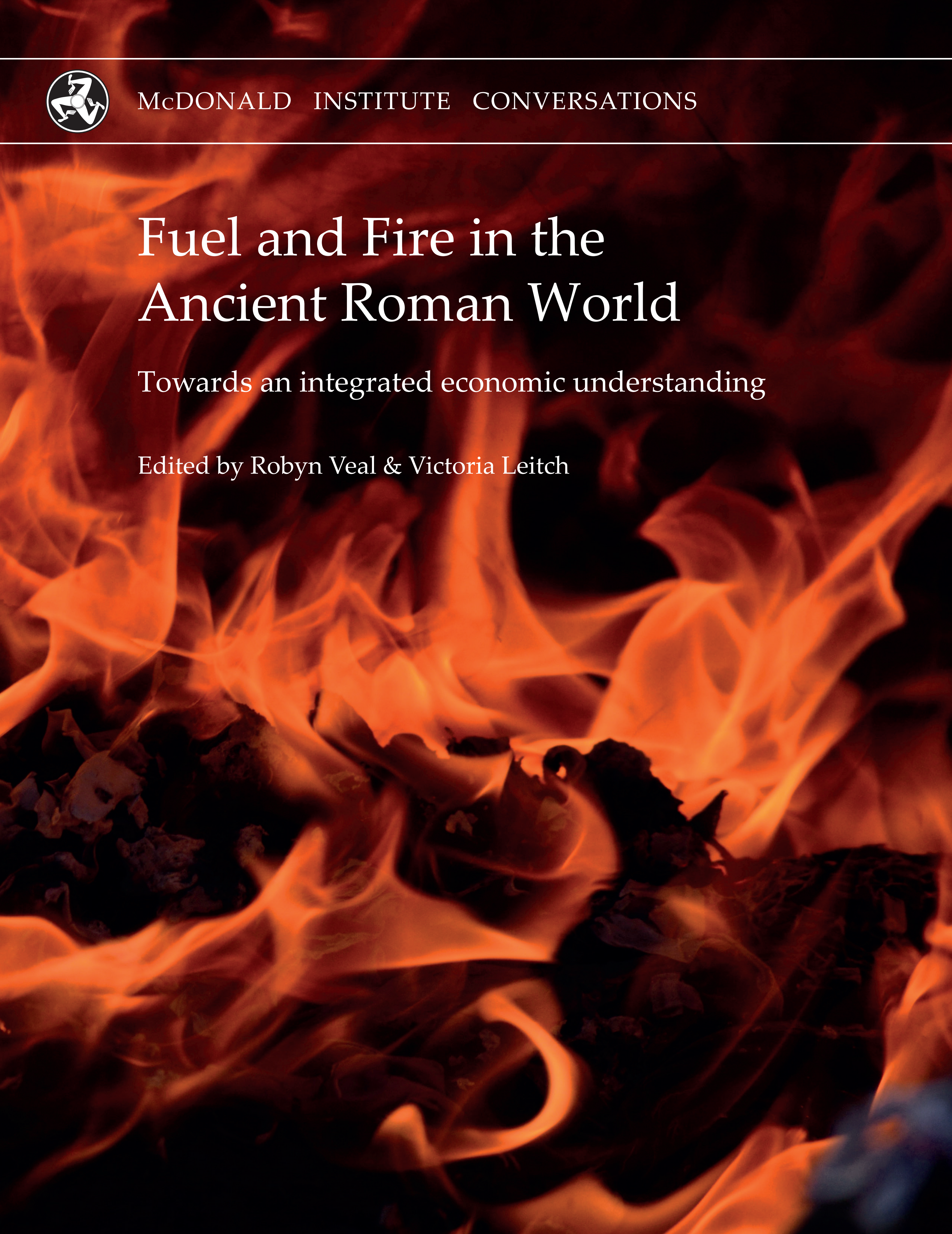

McDONALD INSTITUTE CONVERSATIONS

Fuel and Fire in the Ancient Roman World

Towards an integrated economic understanding

Edited by Robyn Veal & Victoria Leitch

Fuel and Fire in the
Ancient Roman World

McDONALD INSTITUTE CONVERSATIONS

Fuel and Fire in the Ancient Roman World

Towards an integrated economic understanding

Edited by Robyn Veal & Victoria Leitch

with contributions from
Jim Ball, H.E.M. Cool, Sylvie Coubray, David Griffiths,
Mohamed Kenawi, Victoria Leitch, Archer Martin, Ismini Miliaresis,
Heike Möller, Cristina Mondin, Nicolas Monteix, Anna-Katharina Rieger,
Tony Rook, Erica Rowan, Robyn Veal, Véronique Zech-Matterne

This book, and the conference upon which it was based, were funded by: the Oxford Roman Economy Project (OxREP), University of Oxford; a private contribution from Jim Ball (former FAO forestry director, and President, Commonwealth Forestry Association); the British School at Rome; and the Finnish Institute of Rome. The editors would also like to acknowledge the support of the McDonald Institute for Archaeological Research, and the Department of Archaeology (University of Sydney).

Published by:
McDonald Institute for Archaeological Research
University of Cambridge
Downing Street
Cambridge, UK
CB2 3ER
(0)(1223) 339327
eaj31@cam.ac.uk
www.mcdonald.cam.ac.uk

ISBN: 978-1-902937-91-5

Cover design by Dora Kemp and Ben Plumridge.
Typesetting and layout by Ben Plumridge.

Edited for the Institute by James Barrett (*Series Editor*).

Contents

Contributors

Dr Robyn Veal
McDonald Institute for Archaeological Research, University of Cambridge
Downing Street, Cambridge, CB2 3ES
Department of Archaeology, University of Sydney
Camperdown, NSW 2006, Australia
Email: rjv33@cam.ac.uk
Website: www.robynveal.com

Dr Victoria Leitch
School of Archaeology and Ancient History, University of Leicester
University Road, Leicester, LE1 7RH
Email: vl46@le.ac.uk

Jim Ball
Formerly Food and Agriculture Organization, Rome
Email: jbball1@yahoo.co.uk

Dr H.E.M. Cool
Barbican Research Associates
Email: hilary@coolarchaeology.com

Dr Sylvie Coubray
INRAP/MNHN, UMR 7209 Archéozoologie, Archéobotanique: sociétés, pratiques et environnements)
National d'Histoire Naturelle, Paris
Email: sylvie.coubray@inrap.fr

Dr David Griffiths
Independent researcher
Email: david.griffiths1973@gmail.com

Dr Mohamed Kenawi
EAMENA Project, School of Archaeology, University of Oxford
Email: mohamed.kenawi@arch.ox.ac.uk

Dr Archer Martin
Independent researcher
Email: archer.martin@alice.it

Dr. Ismini Miliaresis
University of Virginia, Charlottesville, VA, USA
Email: iam5f@virginia.edu

Dr Heike Möller
German Archaeological Institute, Berlin
Email: heike.moeller@dainst.de

Dr Cristina Mondin
Padua University and Asolo Museum
Email: cristina.mondin@unipd.it

Dr Nicolas Monteix
Département d'histoire, Université de Rouen
1 Rue Thomas Becket, 76130, Mon-Saint-Aignan, France
Email: nicolas.monteix@univ-rouen.fr

Dr Anna-Katharina Rieger
Institute for Ancient Studies, University of Graz, Austria
Email: anna.rieger@uni-graz.at

Tony Rook
Independent researcher
Email: tony.rook@virgin.net

Dr Erica Rowan
Department of Classics, Royal Holloway, University of London, London
Email: Erica.Rowan@rhul.ac.uk

Dr Véronique Zech-Matterne
CNRS/MNHN UMR 7209 AASPE
Centre national de la Recherche Scientifique
UMR 7209 team, Muséum National d'Histoire Naturelle, Paris
Email: veronique.zechmatterne@mnhn.fr

Figures

Tables

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 3

Problems in estimating fuels consumed in buildings: fuel requirements of hypocausted baths

Tony Rook

In the 1950s, in addition to advising on conventional heating of buildings I did original research on the introduction of domestic electrical underfloor heating.[1] My excavation of the Welwyn Roman baths (published in full in Rook 1986), and my work on the study of Roman domestic baths in Britain (Rook 1975, 1976)[2] led to my publishing a paper (Rook 1978) in which I attempted to calculate approximately the fuel consumption of a small suite of Roman baths, based on the remains excavated at Welwyn. This was intended to be a *ballon d'essai.* Was the suggested reconstruction feasible? Were the assumed conditions correct? Were my naive mathematics satisfactory? Unfortunately, I received no feedback.

Observations at the reconstructed *mansio* baths at Xanten (Rook 1993) strongly suggested that the conditions assumed in my 1978 paper, which were based on published figures for present-day so-called 'Turkish' baths in England, were incorrect. In particular that a maximum temperature of 40 °C could be assumed for the *caldarium*. Since this article was published, more modern studies, particularly of comfort physics, have made a more sophisticated approach possible.[3] So this present paper attempts to show in relatively simple terms how heat loss calculations from buildings are performed now, and also questions some of the basic assumptions I made in the 1978 article and suggests approaches to correcting some of them.

Simplified calculation of heat loss from buildings

When calculating the heat input required for a building, it is usual to take a total over a long period, such as a year, taking average conditions over the period. The procedure is as follows:

1. Decide on inside temperature
2. Decide on outside temperatures (based on published meteorological tables)
3. Calculate areas of walls, doors, windows and ceiling
4. Determine U-values[4] of these (from published tables)
5. Calculate heat loss = area × U-value × ($\theta_{\iota} - \theta_{o}$) through:
    a. walls
    b. doors
    c. windows
    d. ceiling
6. Determine ground-loss U-value from floor dimensions and published tables
7. Calculate ground loss
    Loss = U-value × ($\theta_{\iota} - \theta_{o}$)
8. Add these to give total conductive heat loss
9. Calculate volume of room
10. Determine the air changes (depends on type of room)
11. Calculate ventilation loss:
    Loss = volume of room × air changes per second × ($\theta_{\iota} - \theta_{o}$) × 0.33
12. Add together the results of steps 4, 6 and 10.

A real situation can be more complicated, e.g. by having a range of temperature differences across walls (into other rooms).

Openings

Some of the factors involved in calculating heat losses in ordinary buildings, especially heat loss through openings, pose special problems. The example of windows in Roman baths (in this case, the main baths at Ostia) is discussed in detail by Miliaresis in this volume. Whereas an opening that is *efficiently* closed by a door, shutter or by glass (or double glazing) can be treated as a conductivity issue mathematically; problems with U-values; openings without doors, shutters or glazing, (involving ventilation, either by convection or by wind), cannot accurately be known.

Heat requirements of a simplified *caldarium*

The case of a hypothetical *caldarium,* where all the walls are lined with all the *tubuli* functioning as chimneys, is illustrated here. No heat is lost through the walls *from the room*. It is lost only through the ceiling, i.e. through heating the roof space. The roof space loses heat through the (usually) tiled roof. The fuel required *to heat the room* can easily be calculated. A difficulty exists, however, with any attempt to estimate the amount of heat lost in the gases leaving the hypocaust.

It is noteworthy that, like most Roman furnaces, those of hypocausts were without grates; the fire burned on the ground. Most of the air entering the system flowed *over* the fire, and there was no inlet air control or outlet damper (as far as we know).

Although radiation must have been important close to the furnace, the transfer of heat further from the fire was mainly achieved by gas flow, which was powered by convection. With a conventional chimney this depends upon its area of cross section, its height and the temperature difference between its bottom and its outlet at the top. In the wall cavities provided by *tubuli* or *tegulae mammatae*, flow was not greatly restricted, and it is probably convenient to think of the furnace as a bonfire. Actual heat transfer was affected by two factors: gases lost heat as they travelled away from the furnace and they were also actually leaving the system. This probably defies theoretical analysis.

There are two additional ways in which heat is lost by the furnace gases: through the walls from the gases in the *tubuli* and as sensible heat in the gases leaving the system to the outside. In my 1978 article an attempt was made to estimate these and hence to calculate the fuel consumption.

Inside temperature

The calculation of heat loss (and therefore requirement) of a building relies on the assumption of the temperature inside it. In living/working spaces this is comparatively simple. In the cases of the warm and hot rooms of baths, however, *we do not know what conditions were desired.* Clues are provided, however, by the study of thermal comfort.

The temperature a person perceives depends mainly upon:

- Clothing (in a study of baths we may assume that the person is naked)
- The air temperature
- The air velocity
- Humidity (how much water vapour there is in the air)
- Personal metabolism (heat generated by the body)
- Radiation (infrared) in the environment

The thermal conditions in a room are usually measured by fairly simple instruments:

- T – Air temperature measured by an ordinary mercury-in-glass thermometer
- W – The 'wet-bulb' temperature, given by a thermometer with its bulb wrapped in a wick and therefore cooled by evaporation. This takes into account both humidity and air velocity
- B – The 'black bulb' temperature, read from a thermometer with the bulb inside a hollow, matt-black, copper sphere. This takes into account infrared radiation. It was not considered when I did my earlier work

For an average person who is naked and not taking exercise, and when infrared is negligible, a simplified formula is:

$0.7W + 0.3T$[5]

The introduction of cavity walls (e.g. employing *tegulae mammatae* or *tubuli*) led to a considerable increase in the radiant heat in rooms. In fact, it probably resulted in the introduction of unglazed, single-glazed and double-glazed windows in some bath rooms, and in 'sunbathing lounges' or *cella solaris*, which can be seen (or postulated) in late public baths (Rook 1975, 2005, 2013). The ramifications of these architectural developments are further discussed by Miliaresis in this volume.

Where infrared radiation is significant, a composite 'wet-bulb globe temperature (WBGT)'[6] can be calculated using the formula

$WBGT = O.7W + 0.2B + 0.1T$

The US military uses this to produce temperature categories for each of which the quantity of physical work and type of clothing are recommended.

(A more sophisticated '*thermal limit algorithm index*', concerned principally with working conditions, has also now been developed. It uses published experimental studies of human heat transfer and established heat and moisture transfer equations for clothed people doing physical work. Work areas are measured and categorized based on a metabolic heat balance equation, using dry-bulb, wet-bulb and air movement readings to measure air-cooling power. Instruments are made that measure this directly.)

The structure of a hypocausted building

The basic idea of a hypocaust, at least at ground level, is so well known as to require no description. Problems arise when a reconstruction is contemplated, because usually insufficient amounts of the structure survive at higher levels. For example:

- How tall was the building? How were the ceiling and roof constructed?
- How large were the windows?
- Were the windows glazed? Double-glazed?
- Were hollow vaults used as flues?
- What sort of chimneys were there?
- What was the ventilation rate?

As with most fires, a hypocaust obtained air by convection and would work only if there were chimneys of some sort connecting the space under the floor to the outside at a higher level. The evolution of these is dealt with in my 1978 paper. Little evidence survives, or has been published or perhaps sought, for what happened at the top of walls that were lined with *tubuli*. I postulated that they all connected to a continuous 'collecting channel' which took the exhaust gases to outlets at the corners of the rooms. A collecting channel of this sort can be seen under a window in the Hadrianic Baths and leading to the chimneys of the 'annex' to the Hunting Baths at Lepcis Magna.[7] In discussions regarding the NOVA reconstruction (Yegül & Couch 2005) this idea was at first fiercely resisted, but an unspecified compromise was tacitly adopted, where only *some* of the *tubuli* were assumed to have been connected to the collecting channel. The reason for this compromise is not clear, and the actual construction was not made public, despite a documentary being filmed.

The fuel consumption of a hypocaust

A clear error in my 1978 paper, which was not pointed out by anybody, lies in the assumption that for calculations, one can make use of the concept of an *average* temperature of the gases in a hypocaust. The actual conditions are complex. The temperature decreases as the gases flow away from the furnace, since they are losing heat, mainly to the rooms. In addition, their mass and rate of flow are decreasing as more and more are lost up the flues as the distance from the furnace increases. The effect of this is indicated by the inside surface temperatures that I measured at Xanten. The physics of it probably cannot be theoretically predicted, and experimental reconstruction would be a useful exercise.

Some indication of the scale of the problem can be seen by attempting a description of the combustion process. If wood is the fuel, 1 kg of it requires 6.4 kg of air for complete combustion, and yields about 1.83 kg of $C0_2$, 0.52 kg of H_20 (as a superheated steam) and 5.05 kg of N_2 and about 20 MJ of heat. Damp wood would use some of this heat to evaporate the water, and yield a corresponding quantity of steam. Air-dried wood can contain up to 25 per cent moisture.

Complete combustion of the fuel requires at least 100 per cent excess air: it seems likely that a much larger quantity of air flowed over the fire, and the stoker adjusted the geometry of the fire to ensure that the gases going under the floor were at the optimum temperature: an empirical result. Thus, we cannot know the temperature or mass of the gases entering the hypocaust from the furnace.

Whatever these were, the gases left the 'chimneys' (whatever their form) and took heat with them. 'How much?' is an important question for which we can only estimate possible limits. It is possible to assume an average temperature in this case. In a suite of baths the furnace would have heated at least two rooms, which would make the problem more difficult. It is useful, however, to approximately calculate, for example, the heat lost in the gases leaving the chimneys of a hypothetical hypocaust burning 1 kg of wood per hour.

Thus, for a furnace using five times the theoretical (stoichiometric) quantity of air, with the flue gases leaving the chimneys with an average temperature 100 °C above outside temperature, the heat loss would be 19.4 per cent.[8] Carbon dioxide would be 4 per cent of the gases, assuming that the water vapour/steam has condensed.

Measurements were made in the NOVA baths that were constructed at Sardis.[9] The results, although subject to a number of caveats, were salutary and surprising. It was calculated that only 8 per cent of the (theoretical) heat produced by the combustion of the wood was used![10]

Conclusions

To date, we have been able to model various aspects of heating a Roman bath building. The film documentary of the NOVA project that reconstructed a Roman bath at Sardis, and the subsequent work of the coordinators, suggested quite a large loss of heat in the building (only 8 per cent efficiency). Much could be learnt by repeating the exercise of reconstruction, which also allowed for measurement of gas temperatures as they pass through the system. This would be costly, but it would provide us with a more detailed understanding, at least of one building. However, studying bathing suites in Britain (Rook 1975, 1992) seems to confirm that which is intuitive: every bathing suite was unique, apart from some modularity of plan which is imposed by the dimensions of bipedales used in flooring. There does not appear otherwise to be any standardization of plans and many domestic baths were 'do-it-yourself' jobs. Large public baths and their complexity are another thing entirely. Any experimental reconstruction, besides detailed instrumentation, would also need the ability to vary the operation of the flues. At Xanten and at Sardis, I was unable to find a satisfactory configuration of flues, and so in some ways a reconstruction would be hampered until (or unless) archaeology can provide us with more details. Questions also arise as to whether bath furnaces would have been kept burning overnight (probably they would have in most cities), but this too would have varied by demand, climate and fuel availability. Generally speaking, a lot of fuel is required to get a bathhouse up to temperature (from cold), and less fuel is required (per hour) to keep it running. From the point of view of fuel consumption, it would be possible to run a reconstructed bathhouse and observe the fuel used – and to use this data to create a rough model to estimate an annual/per capita basis of fuel consumption for bathing for a small town, and eventually for larger cities.

Notes

1 Unpublished; commercial work for G. Wimpey, Central Laboratories.
2 See also Rook (1975).
3 See, for example, Parsons (2002).
4 U-values measure how effective a material is as an insulator. Thermal performance is measured in terms of heat loss, and is commonly expressed in the construction industry as a U-value (or R-value).
5 This formula can also be employed in weather forecasting.
6 The wet-bulb globe temperature (WBGT) is a type of apparent temperature used to estimate the effect of temperature, humidity, wind speed (wind chill) and visible and infrared radiation (usually sunlight) on humans.
7 Personal observation. See also Rook (2013), fig. 68.
8 Assuming that CO_2 is measured *after* water vapour has been condensed, as in Orsat's apparatus. (The Orsat apparatus consists essentially of a calibrated water-jacketed gas burette connected by glass capillary tubing to two or three absorption pipettes containing chemical solutions that absorb the gases.)
9 The full transcript of the film recording the building of the baths may be read at: https://www.pbs.org/wgbh/nova/transcripts/27rbroman.html.
10 Yegül & Couch (2003) use a Sankey diagram in their figure 4 to demonstrate this (Sankey diagrams are a type of flow diagram in which the width of the arrows is proportional to the flow rate, after a method first documented by Irish engineer Captain Matthew H.R. Sankey, 1853–1925). I am doubtful about the result this diagram represents. Since the temperatures of the exit gases are below 100 °C, some of the heat used to evaporate the water would have been given up in the hypocaust as it condensed, and they omit this consideration in the figure.

References

Lucore, S.K., 2009. Archimedes, the North Baths at Morgantina, and Early Developments in Vaulted Construction, in *The Nature and Function of Water, Baths, Bathing and Hygiene from Antiquity through the Renaissance*, eds. C. Kosso & A. Scott. Brill Online, 43–60. https://doi.org/10.1163/ej.9789004173576.i-538.12

Parsons, K.C., 2002. *Human Thermal Environments (2nd Edition).* London: Taylor and Francis.

Rook, A.G., 1975. *Aspects of the Design and Operation of Roman Hypocaust Baths in Roman Britain.* Princes Risborough: Shire Archaeology.

Rook, A.G., 1975. *Aspects of the Design and Operation of Hypocausted Baths in Rural Britain.* M. Phil thesis, unpublished. London: University of London.

Rook, A.G., 1978. The Development and Operation of Roman Hypocausted Baths. *Journal of Archaeological Science* 5, 269–82.

Rook, A.G., 1986. The Roman Villa Site at Dicket Mead. *Hertfordshire Archaeology* 9, 79–175.

Rook, A.G.,1993. How to Fire a Roman Bath. *Current Archaeology* 135, 114–17.

Rook, A.G., 2002. *The Story of Welwyn Roman Baths (Hertfordshire Histories).* London: Able Publishing.

Rook, A.G., 2005. *I've Come About the Drains. An Adventure in Architecture.* Welwyn: Able Publishing.

Rook, A.G., 2013. *Roman Building Techniques.* Stroud: Amberley Publishing.

Yegül, F.K. & T. Couch, 2003. Building a Roman Bath for the Cameras. *Journal of Roman Archaeology* 16, 153–77.

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.

Editors:

Robyn Veal is a researcher at the McDonald Institute for Archaeological Research, and a Quondam fellow at Hughes Hall, University of Cambridge. At the time of writing she was an honorary research fellow at the University of Sydney, and spent time as a Ralegh Radford fellow at the British School at Rome. She works with a number of international excavation teams as an environmental archaeology advisor and charcoal specialist.

Victoria Leitch has a D.Phil from the University of Oxford on the production and trade of Roman North African cooking wares. She currently works as the Publications Manager for the Society for Libyan Studies.

Published by the McDonald Institute for Archaeological Research,
University of Cambridge, Downing Street, Cambridge, CB2 3ER, UK.

The McDonald Institute for Archaeological Research exists to further research by Cambridge archaeologists and their collaborators into all aspects of the human past, across time and space. It supports archaeological fieldwork, archaeological science, material culture studies, and archaeological theory in an interdisciplinary framework. The Institute is committed to supporting new perspectives and ground-breaking research in archaeology and publishes peer-reviewed books of the highest quality across a range of subjects in the form of fieldwork monographs and thematic edited volumes.

Cover design by Dora Kemp and Ben Plumridge.

ISBN: 978-1-902937-91-5

ISBN 978-1-902937-91-5

9 781902 937915

UNIVERSITY OF CAMBRIDGE

B S R
BRITISH SCHOOL AT ROME