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The Mastery and Uses of Fire in Antiquity

J.E. REHDER

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To Nonnie, wife and best friend

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It was on the gentle but persistent encouragement of Professor Emeritus Ursula M. Franklin that the writing of this book was started. I have taken advantage of her practised teacher's eye to try to keep the writing style reasonably simple and interesting, while being informative. The subject matter has many facets, and it is all too easy to drift into a byway that can confuse the issue. Her continued interest and support in both the subject matter and its transmission have been invaluable. Dr Martha Goodway of the Smithsonian Institution and Professor Bruce Trigger of McGill University read an early draft and made useful comments. The support of Professor Alex MacLean and the late Professor Alan Miller of the Department of Metallurgy and Materials Science in the University of Toronto is appreciated, especially in making available space and the services of a technician for the construction and operation of a bloomery furnace to make several blooms of iron. In particular I appreciate the excellent work done by my editor, Maureen Garvie, in smoothing out the wrinkles and style changes in the manuscript, occasioned by its having been written over a period of several years, and the ease of working with coordinating editor Joan McGilvray.

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Foreword

It is a great privilege for me to write this foreword to the book by my friend and colleague J.E. Rehder. The book is an important and quite unique work, and I would like to illustrate its great potential and at the same time give the reader an indication of the philosophy behind the work.

As a contribution to the reconstruction of the past, Rehder's book is essentially a companion, a knowledgeable friend to have by one's side while studying ancient objects and thinking about the accomplishments of those who made them.

This companion, like its author, is both a scholar and a practitioner, steeped in the complexities of the field but waiting to be asked, trying not to overwhelm the inquirer with unessential details – yet at the same time also not permitting illusions of quick comprehension or an easy glossing of the intricacies of technical processes.

Like any real teacher and friend, the book makes it easy to come back to a particular question as more and deeper knowledge is needed. The appendices serve this process by providing additional information without intimidating the initial enquirer, and it is here that the basic philosophy of Rehder's approach to the study of ancient materials and processes becomes apparent. Two central considerations inform this approach – evident not only in this book but also in his many scientific papers in this field. The first relates to artifacts as primary historical evidence, and the second focuses on the requirements for scientific and technical rigour when interpreting ancient processes and products.

First, the "reading" of ancient artifacts, based on their microstructures and compositions, provides essential sources of historical evidence. There is, however, an important proviso here: those "reading" and interpreting technical evidence must know the "grammar" of technology, i.e., the relevant laws of physics and chemistry. And in this proviso we find the second strand of Rehder's approach – to give to the archaeologist and historian technically and scientifically correct and consistent guidance.

Today's engineers may express the processing variables in terms of symbols and equations, while the ancient artisans transmitted the knowledge of their hands and minds in the language of their craft and culture; yet the underlying reality is the same. It is on the bases of these premises that Rehder gives those who do not have an adequate pertinent scientific or technical background the tools to assess the basic technical processes of antiquity.

The book begins with an outline of the natures of temperature and of heat, acknowledging that the combustion of biomass was essentially the sole source of manageable heat in antiquity. The reader is then quickly introduced to the modes of heat conduction and loss, and to the realization that if materials are subjected to higher than ambient temperature, problems of containment arise – and furnaces and their precursors appear.

At the same time it is made clear that the combustion of biomass does not only result in the production of heat but the chemistry of burning changes the composition of the products of combustion, often resulting in complex composition and temperature profiles in the furnace. These in turn must be taken into account in the design of furnaces and the tasks to which they are to be put.

Rehder looks at charcoal, the synthetic fuel used particularly for metallurgy throughout antiquity and into the early twentieth century A.D. In a series of quite unique compilations on the making of charcoal, he provides information on its technology in a concise and accessible form not available anywhere else, and the appendices guide the more technically sophisticated to some of the roots of the issue addressed.

Having laid this thorough foundation, Rehder turns his attention first to the furnace designs appropriate to charcoal fuel and then the tasks to which such furnaces are put. Here we find ourselves in the heartland of the development of the smelting and uses of metals, the important role of slags, illuminating details on the metallurgy of copper, and the complexity of the production and manipulation of iron.

The reader will find these chapters powerful and totally convincing and will realize that it is the author's thorough understanding of fur-

nace and high temperature reactions – in terms of chemistry, physics, and spacial arrangements – that brings about this seamless understanding. The cobwebs of antiquarian jargon and all hints of magical knowledge or long-forgotten processes known to the ancients vanish in the light of the clear, consistent rationale offered here. The book's final chapters of fuel consumption and deforestation in antiquity round out the work in the same spirit of unbending integrity, so that by taking into account the growth rates of forest, some conclusions on causes of deforestation in antiquity are arrived at that are quite different from those in the current literature.

Ursula M. Franklin

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Preface

The text which follows considers the subject of pyrotechnology from the perspective of the unchanging rules of physics and chemistry, and my fifty years of experience in industrial pyrotechnology in operations, research, and consulting, with publication of more than one hundred papers on the subject. The book is an expansion of a series of papers on ancient pyrotechnology that I have been publishing occasionally in archaeological journals since 1986, as a senior research associate in the Department of Metallurgy and Materials Science in the University of Toronto. It also uses data from my industrial research and development papers published some time ago and contains some of my unpublished experimental work on replicated ancient furnaces.

The approach I have taken is from a furnace operator's point of view, so that the writing style is that of the natural sciences rather than that of the social sciences. This can create problems in understanding across cultures because of differences both in accustomed jargon and in habits of style, but these are perennial difficulties, and a conscious effort has been made to avoid jargon or to explain it when unavoidable. While development of furnace practices through time is necessarily involved, this book is not intended as a history of pyrotechnology.

Many of my examples of ancient pyrotechnology are taken from the archaeological literatures of the east end of the Mediterranean basin where the evidence is over the longest term, in most abundance, and most easily available. Furnaces operate on the same physical and chemical bases everywhere, and I refer to, for example, South America or Africa only for interesting or unusual practices.

Two existing books may seem to be on the same subject as this one, but in fact are not. One is *The Beginning of the Use of Metals and Alloys*, edited by R. Maddin (M.I.T. Press, 1988), a collection of thirty papers from a conference in Zhengzhuo, China, in 1986. Their contents deal almost entirely with evidences of early metallurgy, and only two papers describe iron smelting furnaces, each with insufficient technical detail to permit analysis of their operation. The second is the excellent book by P.T. Craddock, *Early Metal Mining and Production* (1995), which discusses the mining of ores and the production of a wide range of metals in useful historical detail. However, only about one-third of that book concerns matters in which there is some overlap with the material here, and its author has an understandable tendency to take the accustomed archaeological consensual approach, which is not always reliable on testable matters of natural science. Moreover, like the Maddin book it discusses only the branch of pyrotechnology that deals with the smelting of metals, while the present one includes other important products of ancient pyrotechnology such as ceramics, lime, and glass. Pottery, lime, and the two metals copper and iron were made in increasingly large quantities throughout antiquity, in time effectively on an industrial scale.

The organization of this book, in addition to reflecting the nature or kind of fuel used, also is divided according to the products made. These were fired clay, lime from limestone, metals from the reduction of ores, and to a lesser extent, glass from sand. This list is short and simple, but it subdivides into many kinds of products used in quantities that increased throughout antiquity. The complexity of their production technologies increased exponentially from clay to lime to metals, and the ability finally to smelt metals from their ores took millennia to become a reasonably reliable practice. This increase in technical complexity accounts for the considerable amount of space given here to the smelting and uses of copper (for making bronze) and of iron.

These were the two metals in major use in antiquity, iron having a wider range of useful mechanical properties than copper and its alloys. Moreover, the ores of iron are much more widely distributed geographically and on the average are richer than are those of copper. However, the metallurgy of iron is even more complex than those of copper and bronze, and the ability to smelt iron that could be hot-forged to a bar or sheet of strength and ductility superior to those of bronze required successive considerable advances in furnace technology through nearly two millennia. For these reasons, chapter 12, on the smelting and properties of iron, is the longest in the book.

Other notes on organization: The first three appendices are technical in nature, intended for serious students of furnace technology, and can

be ignored by others. Also, illustration is limited to line drawings and necessary graphs. While a valid criticism might be made that there are not enough illustrations of ancient furnaces and their associated equipment, there is a basic reason for this lack. The book covers a very long time span – about 10,000 years – during which the technology of the uses of fire was slowly developed through simple trial and error. Thousands of different furnace shapes and kinds were tried, by definition mostly unsuccessful, and remnants of these attempts fill the extensive published archaeological record. There is then the question of selection, since this book is not intended as a history of furnace architecture. Reconstructions have been made, but they necessarily involve speculation and it is one of the purposes of this book to decrease the extent of such guesswork by supplying the technology of furnace mechanisms. Thus only a moderate number of functional graphs and a few sketches have been included.

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Introduction

The material fabrics of nearly all settled civilizations have by and large consisted of things that exist only because of pyrotechnology – the generation, control, and application of heat, which at sufficient temperature can alter the properties and compositions of all materials. When the materials are of the earth itself, since antiquity the resulting products have formed a large part of the material bases of human well-being. The list of such products is today extensive, as a little thought will suggest: steel beams, reinforced concrete floors, brick walls, glass windows, metal and plastic pipes for water, gas, and sewage, copper wires for electricity and communication, kitchen ware – as well as trains, automobiles, airplanes, and so on.

Such accomplishments are the result of some ten thousand years of development of the intentional use of fire for other than warmth and food. The early archaeological evidence is slim and scattered, but it noticeably increases towards the end of the most recent ice age. The firing of clay into pottery was apparently the first major product of pyrotechnology, but early evidence of another considerable application was the extensive use of lime plaster at Cayonu Tepesi in 6500 B.C., where a house floor was found to be made of 4.5 cubic metres of lime plaster. The decomposition of limestone into quicklime requires heat at close to 1,000°C; however, reduction of iron ore to iron metal not only requires heat but involves complex and invisible chemical changes at different temperatures, and this took another five thousand years to master.

By the close of antiquity, defined here as the collapse of the Roman hegemony before the middle of the first millennium A.D., a plateau of

development of the uses of fire had been reached. This was exemplified by the following quotation from Pliny the Elder in his *Natural History* of 77 A.D.: "Fire takes sand and melts it into glass. Minerals are smelted to produce copper. Fire produces iron and tempers it, purifies gold, and burns limestone to make mortar that binds blocks together in buildings." Pliny overlooked, probably from its familiarity, the firing of clay into pottery, which probably was the earliest widely used product of high temperature heat.

When our modern extensive abilities in the uses of heat are considered, arguably the growth of skill in such an important and complex technology could be considered as the longest continuous intellectual endeavour undertaken by humankind. Indeed there is justification for considering that the extent and the complexity of uses of heat is a measure of the level or quality of a civilization. This position has been noted by Mumford (1946), White (1962), and Nef (1967). Caasen and Girifalco (1986) have created a chart showing that a linear relationship exists between per capita consumption of heat energy and personal income for twenty-eight countries around the world, from a Pacific island to the United States.

The practice of pyrotechnology evidently was basic to the civilizations of antiquity, and so is of proportionate importance to archaeology and to anthropology. However, as far as I know, the subject matter and its importance receive only minor attention in the teaching of archaeology, and there also seems to be no publication that discusses in useful detail how pyrotechnology was practised in antiquity, using the limited knowledge and sources of heat then available. Such information is essential to both the tracing of its development through its artifacts and to the understanding and replication of ancient practices, and it is the objective of this book to supply it on the basis of modern knowledge of the subject.

Curiously, the word "pyrotechnology" is in few dictionaries, though its entomology is obvious. Apparently its earliest appearance was in Italian as the title of the famous work of Biringuccio published in 1540, *Pirotechnia,* which described in useful technical detail the contemporary uses of heat to alter materials. In modern times the late Theodore A. Wertime used the word in this sense in his many well-known publications on ancient pyrotechnology, as have others, and it is now common in archaeology and anthropology.

The history of the development of pyrotechnology following the end of the last ice age was outlined in a collection of papers edited by Theodore and Steven Wertime (1982). Yet almost without exception, this and other modern studies of ancient pyrotechnology have dealt with the artifacts that are the products of furnaces and, to a much lesser