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by

NORMAN F. H. BRIGHT

MINERAL DRESSING AND PROCESS METALLURGY DIVISION

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NEW AGE NEEDS NEW METALS

During the twentieth century, the science and the technology of metallurgical processes have been extended into many highly specialized fields. One of the most significant of these extensions has been a continuing search for materials capable of withstanding higher and higher temperatures.

Within the past decade particularly, this search has been sharply intensified, and high-temperature materials have assumed an importance greater than ever before. Great advances have been made in the development of high-speed aircraft and aero-engines, missiles and satellites, atomic reactors and power plants. In order to keep pace with these advances, industry has been required to extend its range of high-temperature processes and products. These developments have had the result that the operational temperatures in industry have, in many cases, moved from the 1000°C-1800°C range, to figures in the 2000°C to 4000°C range, and, in special cases, even

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(1) Head, Physical and Crystal Chemistry Section, Mineral Dressing and Process Metallurgy Division, Mines Branch, Department of Mines and Technical Surveys, Ottawa, Canada.

higher still. In these latter ranges, there has been little or no previous scientific or industrial experience.

Some industries are now having to solve the problems associated with continuous operation at these elevated temperatures; as a result, modern metallurgical science and technology are faced with overwhelming requirements for new basic data at high temperatures, such as thermal and electrical conductivity measurements, vapour pressure and melting-point data, new materials, new standards, new techniques and instruments for temperature measurement and control.

In many cases, this need is so crucial that further advances are being handicapped by a lack of the above-mentioned basic scientific data. There is a reasonable, but by no means complete, background of scientific theory and data for the temperature range 1000 to 1800°C; in the range 2000°C to 3000°C, there is a serious lack of information; at still high temperatures, virtually nothing is known with any degree of reliability.

The information presently available for the lower temperatures is often of little value above 2000°C because it may not be safe to predict the behaviour and properties of materials at elevated temperatures by extrapolation from knowledge at lower temperatures. Indeed, in the regions of the highest industrially obtainable temperatures - above 4000°C, - the general lack of scientific information is accentuated by a lack of adequate temperature scales, adequate measurement devices, and even of comprehensive theoretical concepts. Thus, to measure, describe, and explain the behaviour of materials at the higher temperatures, and then to adapt them for the use of mankind, new concepts, techniques and instrumentation must be developed which, in themselves, may constitute almost a new branch of physical science.

Before one can extend the present horizons of knowledge of high-temperature phenomena and technology, one must give consideration to the problem of available container materials in which to hold and isolate the system under study.

When one is faced with the problem of selecting a material suitable for a given application at high temperatures, one needs all the knowledge currently available to chemists, ceramists, and metallurgists as well as a vivid imagination of one's own. Then, of course, come the simple and very practical considerations of price and availability of the materials.

MANY REQUIREMENTS

The ability to withstand the high temperatures without melting is not the only requirement. For example, thoria is the highest-melting refractory oxide, but it is fairly scarce and not easily fashioned into suitable forms; further, it has the disadvantages of poor thermal shock, very high density, and is radioactive. Nevertheless, the ability to withstand high temperatures is the prime requirement and the materials which meet this requirment will be discussed later.

High-temperature studies may be considered from three aspects, viz.,

a) the generation of the high temperatures;

b) the equipment needed to contain the reactants and products involved in the high-temperature process; and

c) the measurement of the high temperatures.

Let us consider each aspect in turn.

Insofar as the generation of a high temperature is concerned, one must distinguish between methods which are presently of purely academic interest, and those which are capable of industrial application, either in actual fact at the moment or as a possibility in the near future.

ATOMIC FUSION

Within the last year or so, mention has been made of work, principally in the United Kingdom, in which temperatures of the order of hundreds of millions of degrees may have been generated for brief moments. One refers to the thermonuclear reactions, in which these extreme temperatures are produced as a result of fusion reactions between light atomic nuclei to yield new atomic species with the simultaneous evolution of tremendous quantities of energy. Such a process requires extremely expensive and highly specialized equipment and, at the moment, is of more academic than immediate technological interest. The time may, however, be not too far distant when ways will have been devised to control and harness these tremendous evolutions of energy to produce useful power, in the way that nuclear fission reactions have already been utilized.

The fact that the light atomic nuclei used in these fusion reactions, namely, the various isotopes of hydrogen, are present in the vast quantities of water in the world, makes the source of supply almost limitless. It is this factor, rather than the extreme temperatures produced, that makes the successful harnessing of the energy of atomic fusion a much-coveted prize. The problem of handling the extreme temperatures involved is less difficult than might be imagined, since it is an entirely gas-phase phenomenon, and the hot gases are surrounded by zones of much cooler gas, so that they do not come into immediate contact with the container or any other solid matter. The conversion of the high temperatures into useful power, however, will inevitably present serious problems to the scientist when he comes to tackle this job.

SOLAR FURNACES

Another means of generating high temperatures that has come into prominence in recent years is the solar furnace. In this device, the energy coming from the sun is collected by suitable optical means, and the radiation falling on a comparatively large area is focussed on to a small area, thereby providing a large energy input at that location. The solar furnace is no new device; every school boy has used a magnifying glass to burn paper, and often himself, too. Archimedes is supposed to have used a type of solar furnace to burn the Roman galleons besieging Syracuse by focussing the sunlight with mirrors arranged in a large hexagonal group. The experiment was repeated by Buffon in 1774, when he was able to kindle wood at sixty metres distance using 140 flat mirrors, and, in the same year, Lavoisier used a two-lens system for concentrating the sun's rays in order to show that diamond was a form of carbon. He had already developed a tracking system to follow the motion of the sun and was able to adjust the environment of his specimen by having a glass envelope surrounding it. He attained temperatures in excess of 1500°C.

It has only been within the last thirty years and, more particularly, since the end of the Second World War, that any real advance in the use of this technique has been made. It is now common practice to use searchlight mirrors, or similar devices, as the collecting instruments. Although the total amount of solar radiant energy striking the earth is enormous, the amount falling on any reasonable-sized collector is quite limited. For example, in a location of unbroken semi-tropical sunlight, the average solar energy received is 1442 B.T.U. (or 0.420 kw-hr.) per sq. ft. per day. The average heat content of bituminous coal is about 13,100 B.T.U. per lb. Thus, all the solar energy striking an area of 100 sq. ft. per day could be equalled by burning 11 lb. of coal. Obviously, a collector for a production-type furnace would need to be immense. Size, nevertheless, has not entirely discouraged the construction of large-capacity solar furnaces. In the Pyrenees, on the Franco-Spanish border, a furnace with a collector 177 ft. long by 131 ft. high has been built; this is a

60 kw. unit and can melt 500 lb. of steel per day. The largest furnace in America has a concentrator 28 ft. square, producing a focal spot four inches in diameter. This device was built by the U.S. Quartermaster Corps for testing the effect of thermal radiation on various materials.

COMPLEX MECHANISM

Temperatures of up to 5000 °C can be attained at a localized area on the receiver; it is customary to use the unheated portion of the charge in the receiver as the container for the hot or molten material. The technique thus has the advantage that, in this way, contamination by the extraneous material of a container can be avoided; also, heating in a vacuum or in a controlled atmosphere is readily performed. The disadvantages are obvious in the limited availability of the necessary sunlight, the large collectors required, and the complex mechanism necessary to cause the reflector to follow the motion of sun.

The natural consequence of these disadvantages was the development of the carbon-arc image furnace, in which the radiation from an intense carbon arc is used as an artificial "sun". By a suitable choice of sizes and focal lengths of the reflecting parabolic mirrors, intense local heating has been achieved over areas of up to 3.5 cm. diameter. Artificial solar furnaces to give larger hot zones have been designed, but always at a sacrifice of the ultimate temperatures attainable. As will be seen, the solar furnace, either natural or artificial, is still more of a specialized laboratory tool than a manufacturing process.

The outstanding development in recent years in the production of high temperatures by chemical means has been the production of the various types of propellants for rockets, satellites, and missiles. Some chemical reactions can produce very high temperatures; for example, the hydrogen/fluorine reaction is extremely exothermic and the flame produced has been shown to be capable of cutting through thick concrete very readily. In rocket propellants, however, a fuel and a source of oxygen supply are usually combined in such a way that the reaction occurring during their combustion, develops temperatures in the 3000-4000°C range. In the high-performance fuels in use today, the elements used are almost exclusively those of very low atomic weight - hydrogen, lithium, beryllium, boron, etc., - in suitable combination. With a low molecular weight fuel, the energy output per unit weight of fuel is high, provided that, as is usually the case, the heats of reaction per atom are comparable with the values obtained for heavier elements.

Another means whereby high temperatures are produced as a result of chemical reaction is, of course, that associated with the flames produced during explosions. The internal combustion engine depends for its efficiency on the rapid production of a high temperature, and consequent high pressure, as a result of gaseous flame reactions. A further chemical high-temperature application is the use of oxidizable metal/metal oxide systems in thermite-type compositions. Not only are such systems of beneficial use in welding, delay-action detonator compositions etc., but, at the other end of the scale, such systems formed the basis of many of the incendiary bombs used in the Second World War.

HIGH TEMPERATURES PRODUCED BY ELECTRICAL MEANS

The electrical means of producing high temperatures are, perhaps, much more widely known, and advances in the technology of their use possibly less spectacular than in the case of the more modern, unconventional methods.

Under this heading one includes direct resistance heating, high-frequency induction heating of electrically conducting bodies, ultra-high frequency dielectric heating of electrically insulating materials, and the various types of arc-fusion techniques.

The highest temperature conveniently attainable using resistance heating is about 1500-1600°C using noble metal windings in air, or about 3300°C using graphite resistors in a protective atmosphere. The limit so far obtained on an experimental basis with resistance heating, involved the use of tantalum/hafnium carbide elements, and was about 3800°C.

The induction furnace is in wide use for a variety of metallurgical processes such as the vacuum melting of reactive metals, zone refining, welding, and so on. The limiting temperature obtainable is again about 3500°C, using graphite equipment and a suitable protective atmosphere.

ARC-MELTING

Arc-melting has been extensively used in a variety of metallurgical and high-temperature electrochemical processes, such as the manufacture of ferro-alloys, calcium carbide and phosphorus. Arc furnaces can be of very large dimensions. The carbon electrodes used in submerged-arc furnaces range up to 45 in. in diameter, while the graphite electrodes employed in open-arc furnaces commonly range up to 24 in. in diameter. Currents of 30,000-50,000 amperes are common, and a single charge of steel may weigh as much as 200 tons.

The temperatures in the arc itself are very high----up to 50,000°C: indeed, momentary temperatures as high as one million degrees Centigrade have been claimed in the U.S.S.R. for a very high-intensity arc discharge. The satisfactory use of the arc furnace depends on the operator being able to employ the high temperatures within the arc to heat the required portion of the operating charge. The proper use of such arc furnaces can achieve the melting of even the most refractory of known materials; for example, fused thoria is commercially available, which has been produced by these means at a temperature well in excess of 3000°C.

The development of the carbon arc has enabled emission spectrography to be developed as a powerful analytical tool, since the elements to be estimated can be quantitatively vapourized into either an arc or a spark, and the spectra developed can be examined to give a means of analysis well beyond the capabilities of conventional wet chemical methods.

EQUIPMENT FOR HANDLING HIGH TEMPERATURES

The problems associated with the handling of high temperatures are, of course, intimately bound up with those of producing these same temperatures. It would obviously be no use from a technological standpoint to have equipment in which high temperatures could be produced if that equipment were not able to withstand those temperatures in the critical area where the charge is located.

The vision of inter-planetary travel, which is now being placed before us, will only come to reality when all the problems associated with the high-performance propellants and the means to contain and control them have been solved.

In practically all high-temperature studies, it is desired to avoid any interaction between the charge to be heated and its environment. This is necessary in order to ensure that the changes in the material under investigation occur only by reason of the high temperatures to which it is subjected and are not the result of extraneous interactions.

The materials presently available for use as components in high-temperature equipment, either as heating elements, containers, refractories, or measuring devices, include the following:

a) the high-melting point metals such as tungsten, rhenium, tantalum, molybdenum, niobium, hafnium, and the noble metals;

b) refractory alloys, generally involving these same metals;

c) refractory oxides, carbides, nitrides, sulphides, borides, and silicides;

d) carbon and graphite;

e) combinations of these materials, such as cermets, in which a composite body involving a refractory metal and a refractory, non-metallic, ceramic material are intimately bonded together to give a product having, in large measure, the favorable properties of both of its components.

The most refractory materials at present known are the carbides, borides and silicides of the metals such as tungsten, tantalum, molybdenum, and hafnium.

Actual failure in use is, of course, the criterion that eliminates a particular material from consideration for a high-temperature application. The usual types of failure observed are melting, sublimation, decomposition, oxidation, nitridation, compound formation, loss of mechanical properties such as strength, creep resistance, and thermal shock resistance. No single material at present known to man possesses all these qualities to the desired degree at high temperatures. It is always a matter of choosing the material which is least unsuitable for the job in hand. Efforts have been made to produce materials combining the good oxidation resistance of the ceramic oxides with the favourable mechanical strength and thermal shock resistance properties of the high melting-point metals; these efforts have resulted in the manufacture of cermets, as mentioned above, and in various refractory-coating and vapor-plating techniques.

MEASUREMENT OF HIGH TEMPERATURES

The problems associated with the measurement of high temperatures have necessitated the development of a variety of techniques. The use of thermocouples is, of course, well known. Base metal thermocouples are usable, under favourable conditions, to temperatures not far in excess of 1000 °C. Noble metal couples, such as platinum/platinum:rhodium alloys, are usable in neutral or oxidizing conditions up to temperatures of the order of 1600 °C for long periods, and slightly higher for short periods. However, if temperatures above 2000 °C are to be measured, it is more usual to employ entirely different techniques.

Foremost among these is the use of the optical pyrometer, in which the colour of the hot body is matched, after suitable filtering to extend the range of measurement if necessary, against that of a hot wire. The instrument must have been previously calibrated since it does not measure temperature absolutely. The upper limit of measurement with commercially available optical pyrometers of this type is about 2850 °C.

The measurement of temperatures in still higher ranges necessitates the use of a spectrographic technique wherein the quality of the radiation emitted by the hot body is used as a measure of its temperature. This technique depends upon the fact that, as a body is heated to progressively high temperatures, the region of the spectrum of the emitted radiation which carries the greatest proportion of the radiant energy, moves progressively towards the high-energy or short-wavelength end of the spectrum.

The correlation of the various types of temperature measurement techniques involves complex theoretical considerations which need not be discussed in detail here. Suffice it to say that it is possible, by the use of appropriate theory, to correlate temperatures which have been measured by various means, and which depend on many different physical phenomena. These include thermometric measurements, thermo-electric and optical pyrometric observations, colour temperatures, black-body and total radiation temperatures. The ranges of the various techniques overlap and it is often possible to measure a given high temperature by more than one technique; the numerical values obtained may vary, but appropriate theory permits us to reconcile these apparently diverse results to give a true temperature.

WHAT ARE THE PRIZES?

Thus far we have been almost exclusively concerned with the problems that face the worker in the high-temperature field; what now of the prizes he may expect to win? To the researcher, the solution of the problem is often its own reward, but to the far greater number of people who are technologists of one type or another, the prizes resulting from high-temperature work need to be somewhat more concrete -- and, indeed, they are, in terms of industrial advancement.

Many of the amenities of present-day existence owe much to the development and use of high-temperature techniques in recent decades. A few examples of such applications are:-

a) the sintering of tungsten prior to drawing in the manufacture of filaments for electric light bulbs, radio tubes, etc.;

b) the manufacture of synthetic sapphires for use as jewel bearings;

c) the manufacture of abrasives in the electric arc furnace, and, indeed, electric furnace operations generally;

d) the melting of titanium and other metals in arc furnaces, and the preparation of these metals in a form having satisfactory mechanical properties;

e) thermite reactions;

f) gas and arc welding;

g) in the scientific rather than the technological field, the techniques of spectrography achieved by the use of arc and spark sources;

h) the jet engine with its special alloys and other refractory components enabling the turbines to operate at temperatures in the region of 2000°F (1100°C) or even higher; and

j) nuclear reactors incorporating ceramic fuel elements.

All these, and many more, have arisen from the study and application of high-temperature phenomena.

It seems likely that high-temperature phenomena will always find their applications in high-cost, specialized processes and products; nevertheless, they will still play a very important role in the field of technology. It is reasonable to assume that this field of human endeavour will, in the years that lie ahead, yield many more rich dividends in the way of technological advances, and present to the scientific worker, not only his fair share of problems, but also, an equitable proportion of its prizes.

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