Conclusion

If supported by further work, the results obtained thus far from radiocarbon dating constitute perhaps the most important event in Pleistocene research since the recognition of multiple glaciation and the establishment of a pollen stratigraphy. The examples[4] mentioned above are samples of the kind of result radiocarbon dating can accomplish. Radiocarbon can supply the dates of glacial advances and of climatic changes recorded by pollen frequencies ; it can establish intercontinental correlations ; it can date a sequence of strand-lines or a volcanic eruption ; and, of perhaps greatest human interest, it can provide a firm chronology of ancient man. The universal importance of radiocarbon dating lies in the two facts that such dating is *absolute* and *world-wide*.

The Geochronometric Laboratory, now being set up at Yale University with funds provided by the Rockefeller Foundation, expects soon to begin a systematic programme of dating by means of the method pioneered by Libby and Arnold.

[1] For example, Arnold, J. R., and Libby, W. F., *Science*, **110**, 678 (1949); **113**, 111 (1951), and references given there.

[2] Wilson, L. R., *Torrey Bot. Club. Bull.*, **63**, 317 (1936), and references cited there.

[3] Oral communication from the Abbé Breuil.

[4] These examples and many others are discussed more fully in Flint, R. F., and Deevey, jun., E. S., *Amer. J. Sci.*, **249**, 257 (1951).

CREEP-RESISTING ALLOYS FOR GAS TURBINES

ON February 22 and 23, a symposium on "High-Temperature Steels and Alloys for Gas Turbines" was held under the auspices of the Iron and Steel Institute in the rooms of the Institution of Civil Engineers in London. On the evening of February 21, Sir Frank Whittle had given the fifth Hatfield Memorial Lecture on the development of the aircraft jet engine, and the symposium provided an opportunity of reviewing the metallurgical progress to which his invention gave rise, and discussing the problems of the gas turbine at its present stage of development.

Sir Andrew McCance, past-president of the Iron and Steel Institute, in a brief introductory speech, emphasized that materials capable of withstanding stress at the highest possible temperature are essential for the improvements in the efficiency of the use of fuel that are vitally important for our economy. Mr. D. A. Oliver then occupied the chair. The opening paper of the symposium, by Dr. N. P. Allen, described the early history of the creep-resisting alloys, and gave an account of the efforts that were made between 1939 and 1945 in Great Britain, Germany and the United States of America to produce the alloys of which the jet engines were ultimately made. The subsequent papers, of which there were thirty-six, were devoted to British activities during and after the War, and are an invaluable source of information on all aspects of the subject. The meetings were well attended. The presence of a large group of foreign experts testified to the regard in which British work on gas turbines is held. It was pleasant to hear from the Swiss turbine builders of the reliance that they place upon materials supplied from Great Britain, and the forthright and informative contributions of the American speakers were very welcome.

There are now four principal classes of creep-resisting alloy. The austenitic nickel–chromium steels hold pride of place. They are separating into three types. When large forgings are required, and strength must give place to ease of production, a steel with about 18 per cent of chromium, 8 per cent of nickel, 1 per cent of niobium and 0·1 per cent of carbon is favoured. Much attention has been given to the properties of finished components, as distinct from the properties of experimental test bars, and the papers by Mr. H. W. Kirkby and Dr. C. Sykes gave unique and important information. The niobium for this steel is expensive, and becomes increasingly difficult to obtain. 'Austerity steels', in which the niobium is presumably replaced by a more abundant element having a similar effect, are being studied ; but their compositions are not yet announced. For large castings, a steel with 25 per cent of chromium and 12 per cent of nickel tends to be preferred, as it solidifies with a partially ferritic structure and is more plastic just below the melting point than a fully austenitic steel. It is consequently easier to cast and weld. This steel contains carefully adjusted proportions of carbon, silicon and tungsten. Their importance was described in an interesting paper by Mr. J. I. Morley, which showed how, if the ferritic structure is too stable, the steel has low creep resistance and tends to form the brittle sigma constituent on cooling ; whereas if the ferritic structure is not allowed to form, the steel has high creep strength but may contain brittle carbide networks. An intermediate condition is generally best, and may be varied slightly in one direction or the other according to the relative importance of creep resistance and toughness in the casting.

When the greatest creep resistance is necessary, the austenitic nickel–chromium steels are strengthened by additions of cobalt, molybdenum, niobium or titanium. The alloys made in this way can be hardened by precipitation, and complex heat-treatments are an essential part of their manufacture. They are also capable of improvement by suitable mechanical working. A detailed account of the 'warm working' process as applied to a typical steel of this class was given by Mr. G. T. Harris and Mr. W. H. Bailey, who showed how the amount of mechanical work and the temperature at which it is applied can be controlled so as to produce a material having both a high proof stress at the low temperature existing at the centre of a turbine disk, and a good resistance to creep at the high temperature existing at the rim. The iron in this class of alloy can be replaced by cobalt, with progressive improvement of the creep resistance. Mr. G. T. Harris and Mr. H. C. Child described how by systematic exploration an optimum alloy may be developed ; but this alloy contains 45 per cent of cobalt, and the use of so much cobalt may be difficult to justify.

At present, when creep resistance greater than can be produced in austenitic steel is required, nickel–chromium alloys, precipitation-hardened with titanium and aluminium, are used. The work leading to their development was described for the first time in a paper by Dr. L. B. Pfeil, Dr. N. P. Allen and Mr. C. G. Conway. These alloys are well established in Great Britain, and their strength and freedom from exceptionally scarce elements suggest that they will maintain their place. They have been tested for periods up to ten thousand hours : whether they will maintain their superiority for longer periods, up to a hundred thousand hours, is still open to question, and designers wish to be assured on this point. A hundred thousand hours have not yet passed since the alloys were first conceived, and they have since undergone many minor changes. The turbine designer is faced with the choice between materials that have been completely tested, and are therefore at least ten years old, and materials that are more recent, probably better, but less completely known. His desire for more information and for means of predicting the behaviour of alloys in the distant future is understandable; but there is no reliable way of making forecasts. Since there must be some limit to the amount of creep testing that can be done, it is very important to decide how much of the available effort should be devoted to the detailed testing of existing alloys, and how much to making the improvements that are surely possible.

Ferritic steels are used when the service temperature is not so high as to demand austenitic steels. Two types, containing respectively 0·5 per cent of molybdenum and 0·25 per cent of vanadium, and 3 per cent of chromium, 0·6 per cent of molybdenum, 0·8 per cent of vanadium and 0·6 per cent of tungsten, have received special attention, and have excellent creep resistance at temperatures below 600° C. Extensive tests on the latter steel were reported by Mr. H. H. Burton, Mr. J. E. Russell and Mr. D. V. Walker. A very recent development is the introduction of creep-resistant ferritic steels containing 10–13 per cent of chromium. These steels are resistant to oxidation, and therefore can be used at temperatures above 600° C., at which other ferritic steels fail. They compare very favourably in creep resistance at 600° C. and 650° C. with the first of the three above-mentioned classes of austenitic steel and, since they are more economical in alloying elements, may well replace them in some directions. It is curious that no highly creep-resistant steel has yet been developed with a chromium content between 3 and 10 per cent, although steels with 5 per cent of chromium are quite resistant to oxidation and would be very economical to use if the necessary high-temperature strength could be developed. An interesting paper by Mr. E. W. Colbeck and Dr. J. R. Rait suggested that the carbides found in steels of intermediate chromium content are not of a type favourable to creep resistance, but this may not be an insuperable obstacle.

The fourth type of creep-resisting material now in use comprises the range of cobalt-base precision-casting alloys. These alloys, which usually contain about 30 per cent of chromium and a moderate percentage of either tungsten or molybdenum, did not figure in the symposium as much as might have been expected. They are very costly, and although the results obtained in laboratory tests can be excellent, the alloys are not widely used for highly stressed components because of the difficulty of being certain of the reliability of castings. In Great Britain precision casting has been used principally as a method of making lightly stressed components, such as stator blades, in oxidation-resistant but relatively economical alloys.

A number of papers dealt with the problems of fabricating creep-resisting alloys, and it is clear that as much work has been required in solving these problems as in developing strength at high temperatures. We are, indeed, in the process of building up a workshop technique for creep-resisting alloys comparable with that which has been developed for the common engineering steels during the past hundred years. The gas turbine being built up of a series of rings, centrifugal castings have played a large part in its construction, and a rivalry between the centrifugal processes making use of metal moulds and those making use of sand moulds became apparent, the arguments being generally in favour of the use of the metal mould when applicable. Precision-casting processes are used for a variety of smaller shapes. The processes are interesting as being a revival of the ancient lost-wax process. They differ from the ancient process in being adapted, by an elaborate procedure, to the production of a large number of accurate replicas of the pattern, and in the use as mould materials of special refractories that can withstand the chemical attack of molten alloys at very high temperatures.

In the construction of large gas turbines for marine engines and electric generators, the arc welding of austenitic steel forgings and castings has proved difficult, and many references were made to the danger of cracks in welds. The cracks can be avoided by the use of suitable techniques and by the control of the silicon content of the weld metal. There is uncertainty about the mechanical properties of arc welds at high temperatures, though such information as exists is reassuring. The construction of flame tubes, jet pipes and ducts of many kinds in both austenitic steel and nickel–chromium alloy sheet has been accomplished by resistance welding with great success. As described by Mr. H. E. Lardge in a very informative paper, the distortion due to the high thermal expansion and low thermal conductivity of the alloys was overcome by welding with the smallest input of heat, and using effective means of cooling. The machining of creep-resisting alloys at first presented great difficulties, which were overcome by the skill and resource of the men in the machine shops, to whom the gas turbine owes a great deal.

The modern gas turbine has an inlet gas temperature of 650–800° C. or perhaps 850° C. Its thermal efficiency is rather low, and could be improved if the gas temperature were raised. Naval representatives at the meeting emphasized that higher efficiencies must be developed before gas turbines can be widely adopted in ships. The materials necessary to make higher working-temperatures possible are not yet in sight. Cobalt–chromium–tantalum alloys having promising strength at 900° C. were described by Mr. J. C. Chaston and Mr. F. C. Child: their use seems to be impossible under present economic conditions; but it must be remembered that several of the alloys that are now in use would have been considered fantastically expensive twenty years ago. Chromium-base alloys have been studied by Mr. E. A. G. Liddiard and Dr. A. H. Sully. They are too brittle, and no way of making chromium sufficiently tough has yet been found. Excessive brittleness also prevents the use of refractory oxides such as sintered alumina. It seems to be generally agreed that a certain amount of plasticity is essential in any practical material, as a protection against thermal shock, which can be very severe, and against excessive stress concentrations at changes of section. 'Ceramels', which are mixtures, made by the methods of ceramics, of refractory oxides or carbides embedded in a metallic base, were considered by some authorities to offer the most promising combination of properties. One speaker described engine tests on turbine rotor blades made of a ceramel consisting essentially of titanium carbide bonded with nickel or cobalt, in which the creep resistance of the material had proved to be adequate; but failure had resulted from insufficient resistance to the stress concentrations in the blade root. Confidence in this type of material has not yet been established, and its future seems to depend on the achievement of sufficient plasticity without loss of creep resistance.

The alternative way of achieving high inlet gas temperature is to cool the critical metal parts. The problem then is to secure the greatest effective cooling with the least loss of heat and energy in the cooling agent. There is little doubt that the most effective device is to interpose a stable blanket of cool gas between the hot gases and the surface to be cooled. Mr. P. Grootenhuis and Mr. N. P. W. Moore described how this can be done by leading a small quantity of liquid continuously to the surface through fine pores provided in the component. This is known as 'sweat cooling'. It can be readily applied to lightly stressed components, but not so easily to severely stressed components. It is possible that in view of the need for conserving scarce metals, and the improbability of a large and swift improvement of the available alloys, the correct policy for the next few years will be to stabilize the main types of creep-resisting alloy and concentrate upon the efficient use of cooling.

The second problem of the gas turbine is to increase the useful life of the engine from the thousand or so hours demanded of the aircraft engine to the ten thousand or hundred thousand hours required for most industrial applications, while at the same time adopting a cheap fuel, such as heavy fuel oil or pulverized coal. The need for more data on the behaviour of the new alloys over extended periods of time was repeatedly stressed. The difficulty of providing this information while the alloys themselves are being modified continuously has already been mentioned, and furnishes an additional argument for standardizing the alloys as soon as it becomes possible to do so. It was mentioned, however, that the performance of the gas turbine will be seriously diminished if unnecessarily long service lives are insisted upon. The use of cheap fuel introduces the danger of corrosion of the engine by the mineral constituents of the fuel, particularly by the fusible vanadium salts that are present in many fuel oils. Metallurgists could hold out no hope of finding a serviceable alloy that would resist contact with partially molten fuel ash, and looked to the oil technologists to remove, or render harmless, the objectionable constituents of the oil; but the oil technologists could suggest no method cheaper than distillation. It is to be hoped that the last word has not yet been said on this subject. Gas turbines have run successfully for short periods on vanadium-containing fuel oils without serious effects. Much can be done to minimize the danger of corrosion, and it may be that the importance of the problem is exaggerated; but it undoubtedly gives rise to much anxiety.

The immediate future appears to demand the detailed improvement of the existing types of alloy, as a result of which a gradual rise of the strength and reliability of components of all kinds will no doubt take place. The shortage of many essential metals overshadows the situation, and it will be necessary to ensure that the strongest alloys are not used where weaker ones would do, and that no excessive amounts of scarce elements are employed even to meet the most onerous conditions. A prolonged struggle between the more advanced ferritic alloys and the less developed austenitic alloys for use at temperatures between 550° C. and 650° C. is to be expected, with the austenitic alloys gradually yielding place. In view of the complexity of the alloys, all this work will call for a vast amount of metallurgical experiment and mechanical testing. How much improvement is to be expected? The opinion was expressed that the possibilities of the austenitic solid solution alloys based on iron, nickel, chromium and cobalt are approaching exhaustion; and although a somewhat similar opinion was expressed in 1924, it now seems rather unlikely that the temperatures to which these alloys will maintain their strength can be much increased. Improvements of the reliability with which the best properties can be secured are more probable. Some major discovery seems to be required before the service temperatures of gas turbine materials can be greatly increased: it will no doubt be made, but how and where cannot yet be foreseen.

N. P. ALLEN

OBITUARIES

Prof. V. F. K. Bjerknes, For.Mem.R.S.

PROF. VILHELM F. K. BJERKNES, foreign member of the Royal Society, honorary member and Symons Medallist of the Royal Meteorological Society, who died at Oslo on April 9, 1951, was the doyen of meteorologists. V. Bjerknes, as he was generally known, was born on March 14, 1862, the son of C. A. Bjerknes, professor of mathematics at Christiania, himself a pioneer in the investigation, theoretical and experimental, of fluid motion. V. Bjerknes, during his education at Christiania, assisted in his father's investigations and afterwards worked in Germany under Hertz. He became specially interested in the (apparent) action at a distance of solids moving in a circulating fluid and the analogies with electrodynamics. After his appointment in 1893 as professor of mechanics and mathematical physics at Stockholm, he prepared his first important work, lectures on "Hydrodynamische Fernkräfte", issued in two volumes during 1900–2. He was later to indicate in a lecture at the Royal Institution in May 1924 the analogy between the forces on a rotating cylinder moving through a fluid and the forces on an aeroplane due to the circulation induced by the asymmetry of the wing. The forces, lifting the cylinder, at quite moderate speeds are substantial and can be exactly controlled by adjusting the speed of rotation.

In 1898 Bjerknes introduced into dynamical meteorology the concept of 'solenoids', the tubes formed by the intersection of a system of isobaric surfaces at unit intervals with a system of isosteric (equal specific volume) surfaces also at unit intervals. He showed that if C is the circulation around any closed circuit, $dC/dt = N$, the number of solenoids intersecting the circuit. He deduced that, for a fluid in equilibrium, N must be zero, and that if N is not zero, the induced circulation is in the direction which will bring the isobaric and isosteric surfaces into coincidence (or parallelism). Bjerknes thought at first that this would have very wide meteorological uses and he applied it to the sea breeze and the Indian monsoon. But he soon realized that the effect of the rotation of the earth, though small in the initial development of motion from rest, became of