Science and Engineering.¹

By Prof. F. C. LEA.

THE economic and beneficent importance of the work of the engineer is recognised by all, in the provision of safe, reliable, and efficient means of transport and in the wonderful harbours and docks which make possible the interchange of commodities between the nations; in the utilisation of sources of energy for doing the work of the world; in the equipment of factories and workshops with machines that produce abundantly so that the standard of life is raised; in supplying to communities pure water and in the disposal of sewage without danger to health or to the contamination of rivers and streams; in making it possible to plough the great spaces and gather the abundant harvests with little labour; in the provision of implements to combat the enemies of the fruit harvest and in the construction of dams and reservoirs to store the abundant rains for the time of drought so that even the barren places shall be fruitful and rejoice. For these achievements of engineering it is not difficult to obtain recognition, but it is often overlooked that engineering is affecting the intellectual outlook of peoples and by its very successes may introduce social and political problems of great significance.

It is not, however, desired in this address to emphasise the intellectual or political influences of engineering but rather to suggest: (1) the vital importance of scientific research to engineering; (2) that as in the remarkable engineering developments of the last century the scientific method has been the key to progress, even so it must be in the future; and (3) that there are many engineering problems of great interest and importance, not only to engineers but also to the general public, which can only be solved by supplementing experience by direct and indirect attack, using all the aids that mathematical and experimental science can give. It is also desired to suggest that all the arguments for a public interest in scientific research apply with particular force to the subject of engineering.

[To illustrate these three aspects of his subject, Prof. Lea touched upon many branches of engineering and scientific inquiry, ranging from ancient engineering as seen in Mesopotamia, Egypt, and Rome, to the pregnant researches of Carnot, Clausius, Froude, Reynolds, Rayleigh, Maxwell, Hertz, Fleming, Coker, Eddington, Einstein, Michelson, and Morley. "Upon almost every section of this Association", he said, "engineering lays tribute, and in return engineering has given something at least to make possible much of the brilliant work associated with other sections". Only the precision of modern engineering has made possible the manufacture and control of great telescopes and other instruments by which the predictions of Einstein could be tested.

In the main, however, Prof. Lea kept to the important matters of prime movers, structures, aeroplanes and airships, materials and roads, all of which afford abundant testimony to the interdependence of

engineering and abstract science. There were great bridges in ancient times, but such structures as the Forth Bridge, the Sydney Harbour Bridge, the Zambesi Bridge, and the Hudson River Bridge of 3500 ft. span, now in course of construction, were not possible before the birth of modern science and the scientific method. Neither was there a useful steam engine or other great and efficient prime mover before there came into the intellectual life of Europe that wonderful renaissance out of which modern experimental science was born.

Before Savery and Newcomen produced the first successful steam engine, many experiments on the pressure of the atmosphere, the relation between pressure and volume in gases and on the condensation of steam, had been made by Porta, Torricelli, Papin, Boyle and others. Watt's great improvement of the steam engine was surely not an invention in the ordinary sense, but a splendid deduction from the quantitative knowledge of the latent heat of steam obtained from his own experiments and those of Black. In the latter part of the eighteenth century and the beginning of the nineteenth, organised experiments on the flow of fluids were carried out, relative velocities, momentum, and kinetic energy were well understood, and the next step was made by Poncelet in 1832, who enunciated the guiding principles underlying the design of vanes receiving moving fluids, and from that time progress has been so remarkable that to-day water turbines of more than 70,000 h.p., having efficiencies greater than 80 per cent, are being constructed. The brilliant achievements in the development of the steam turbine of Sir Charles Parsons and others following in his steps are to-day well known.

At the beginning of the nineteenth century there were probably 10,000 engines in England, giving a total horse-power of about 200,000. To-day, steam turbines, each capable of developing 200,000 h.p., have been or are being made for stations in various parts of the world. It seems very doubtful if this could have been possible except as a consequence of the work of Poncelet and two centuries of scientific experiment.]

PRIME MOVERS.

Though so much has been done in the development of prime movers, there is perhaps no movement in engineering to-day that is of greater interest, not only to engineers but also to the general community, than the attempts that are being made to increase considerably the efficiency of power production from coal and other fuels. The average overall thermodynamic efficiency of the public stations distributing electrical energy in Great Britain for the year ending March 1928 was about 15 per cent. The best station had an efficiency of 21·3 per cent. Recently a power unit has been supplied from England to Chicago which on test gave an efficiency of 34 per cent—a remarkable figure. Making allowance for boiler losses, efficiencies of from 25 to 35 per cent ought to be possible, therefore, in the future, and if only suitable materials can be developed to meet the onerous conditions of temperature, corrosion, and erosion, higher efficiencies than 35 per cent may be anticipated with steam plant. Still higher thermodynamic efficiencies may be expected, as

¹ From the presidential address to Section G (Engineering) of the British Association, delivered at Johannesburg on Aug. 1.

well as the chemical riches of the coals preserved, if, as a result of research, solid fuel engines or gas turbines can be developed.

At the temperature of from 400° F. (205° C.) to 600° F. (315° C.) at which boilers and super-heaters have until recently worked, mild steels have been found suitable. To realise higher efficiencies than at present, much higher temperatures will be required, and at contemplated temperatures of 1000° F. (538° C.) and upwards carbon steels creep at low stresses. Below a certain stress, at a particular temperature, which I have ventured to call 'the limiting creep stress', the creep ceases or becomes so small that it cannot be observed in, say, a number of days. This 'limiting creep stress' is evidently the important factor in the problem of high working temperatures. Experiments indicate that, with alloy steels, limiting creep stresses much higher than those obtained from carbon steels may be expected, and that alloys of iron, nickel, chromium, and with or without other alloyed elements, containing so much as 60 per cent of nickel and chromium, have considerable strength at high temperatures and also resist corrosion and erosion. There is still, however, a very large amount of research to be done in which the laboratory and the workshop must co-operate; as new workshop technique is required before these alloys can be used for specific purposes.

STRUCTURES.

The indebtedness of structural engineering to mathematics and to experimental science has already been suggested, but these powerful aids to progress had to be supplemented by the development of new materials and by a direct experimental attack before the remarkable achievements of recent times were possible.

In this respect it is well to go back occasionally to William Fairbairn, president of Section G of the British Association in 1862. He carried out his classical experiments during the forties of last century to determine stable forms of compression elements for structures, and upon his experiments practice followed rather slavishly for more than forty years. The failure during erection of the cantilever of the Quebec Bridge dramatically forced attention upon the problem of the stability of compression elements. Again a series of experiments filled the gap in knowledge and led to success.

Further work on a large scale, the cost of which can probably only be undertaken by public authorities, is desirable. During the last twelve years attempts have been made, with considerable success, to design all-metal aeroplanes and rigid airships, the compression elements and beams of which must of necessity be as light as possible. With a fair degree of precision the external forces can be determined by experiments upon models. The structure of an aeroplane has a certain degree of 'statical indeterminateness', but the forces and the bending moments in the elements can be approximately obtained, and what might be called the primary stresses can be found with the same degree of approximation.

Three serious difficulties, however, immediately faced the designers: (1) materials of a suitable character and in a suitable form for constructing the very light but strong elements; (2) the lack of technical skill and suitable machinery for building up the elements; (3) the lack of knowledge and the almost insuperable difficulty of determining by analytical methods the secondary, and what might be called stresses of even higher orders of indeterminateness. The only way was a courageous combination of experiment and mathematical investigation. One without the other was useless, but by a combination of the two rapid progress was made, and to-day all-metal aeroplanes are being constructed of steel or of duralumin which are as light, more durable, and stronger than the aeroplanes made of the best spruce.

There is still, however, a great deal to be done in connexion with structures, and the only hope of a satisfactory solution of many problems is not simply by accumulating experience, but by combining experience, experiment, and mathematical analysis in an endeavour to reduce the whole to definitely co-ordinated knowledge. Nearly thirty years ago I was privileged to assist with some experimental inquiries on the deflection of bridges produced by rapidly moving loads. They were incomplete, but they definitely indicated that the assumptions often made by engineers as to the effect of rapidly moving loads were not justified. In view of the publication in the early part of this year of the report of the Bridge Stress Committee, published by the Department of Scientific and Industrial Research, of which perhaps it is only necessary to say that it is worthy of its distinguished chairman, Sir Alfred Ewing, and his colleagues, it is fitting to refer particularly to this subject of impact on bridges.

So early as 1849, in the Report of the Royal Commission on the use of wrought iron in railway bridges, the subject was discussed, and Sir George Stokes gave a mathematical solution for a load moving over a girder, but this solution was of little value in practice. For eighty years the effect of travelling loads has been treated in an empirical, illogical manner and a number of impact formulæ, which the Bridge Stress Committee Report shows have no valid foundation, have been used rather blindly by engineers. The report shows very clearly that what is important is not the fact that the load is applied suddenly to the structure, but the possibility of synchronism or otherwise of the structure with the periodicity of unbalanced forces due to the engine or to other causes. Experimental data of the vibrations produced in the structure by the various types of moving loads have been carefully obtained and methods of analyses developed which have made it possible to determine with some degree of precision the true impact factors to be applied.

Thus a problem of real difficulty, in connexion with which doubt and uncertainty has probably led to expenditure far greater than the necessities of the case demand, comes within the possibilities of solution. The carefully conducted work of the

Committee spread over a few years has given more precise guidance for future designers than a hundred years of practice.

AEROPLANES AND AIRSHIPS.

The development of the forms of aeroplanes and rigid airships and the determination of the forces acting upon them—lift and drag—and the distribution of these forces, is another illustration of the splendid use that can be made of the combination of experiment and mathematical analysis. Following the fundamental principles of Newtonian mechanics, dynamical laws of similarity have been developed which, in combination with the wind chambers and the precise measuring devices used for the determination of forces and moments acting upon models, have made it possible to anticipate certain of the forces acting upon machines. Other forces could only be estimated from meteorological data obtained from an examination of the velocity and upward and downward currents of air which a ship or aeroplane may suddenly encounter.

Much could be said of the many other contributions of 'pure science' to the successful development of the aeroplane. Many of the details and instrumental equipment owe much to science, but success could not have been achieved if these gifts had not been supplemented by the application of the experimental method, in which precise measurement has played an important part, to the solution of the specific engineering problems associated with the engine and the structure.

MATERIALS.

Allied to the subject of structures is that of the strength of materials and their behaviour under various types of stress. For nearly seventy years experiments have been carried out to determine the effect of repeated stresses on metals, but the development of high-speed machinery during the last twenty years has focused attention upon this important subject, and it is now realised how imperfect is our knowledge.

A vast amount of experimental data has been accumulated, and it has been clearly shown that the safe range of stress to which a piece of material can be subjected for, let us say, an indefinite number of times, depends in some way, not yet clearly defined, upon other and more easily determined physical properties. But it is not yet always possible to foretell that some element of a locomotive or of an aeroplane engine, or structure, or other machine will not fail under the conditions it has to meet in practice. Small discontinuities in the structure of wheel tyres, a surface defect in an axle, a wheel gripping very tightly on an axle at one section, surface cracks which cannot even be seen by the microscope on a wire used for a rope, or in the disc of a steam turbine rotor; the surface condition of a quenched and tempered spring used for a locomotive, an aeroplane engine, or a motor-car, may lead to failure under the repeated stresses due to the normal forces acting upon the element, or due to repeated blows, such as, for example, a locomotive experiences whenever it passes over a

rail joint, or a motor-car along a road. Cam-shafts for the stamping mills used in the gold mines frequently fail, and engineers and metallurgists are often at a loss to give a reasonable explanation. The whole problem is bound up, not only with the physical properties which statical experiments are capable of testing, but apparently in some unknown way with the nature of the crystal structure of a metal.

ROADS.

Before concluding, I should like to refer to another subject of interest. The rapid developments of road traffic during the last quarter of a century has made the road problem one of considerable importance. From the point of view of the user and the community, the general policy of road construction, the capital expenditure involved, and the cost of upkeep are of primary concern. These are dependent upon the materials available and the use made of them. Incidental to the problem is that of vibrations produced in structures adjoining the road and the probable damage accruing from them, but of this there is only time to say that experiment is necessary to determine the importance of these vibrations on the materials of structures.

Reference has already been made to the lack of knowledge of the effect of blows and stresses due to vibrations in causing failure in metals, and the lack of precise knowledge which will make it possible to choose with assurance the particular material to meet certain circumstances. The problem of road surfaces is in a large measure one not only of the suitability of materials to resist impacts but also of the prevention of impacts.

Many experiments of actual road surfaces are being carried out in all parts of the civilised world, but considering its economic importance, the cost of upkeep of roads and the inconvenience of repeated repairs, it would appear that it would be well worth while, even though there may be doubt as to whether any definite and final conclusions can be reached in the laboratory, to let carefully but boldly conceived laboratory experiments direct the large-scale experiments much more than at present. If the history of other engineering developments is to repeat itself, only by such a procedure is the solution likely to be found.

There is another aspect of the subject which is perhaps related more to economics than to engineering, but it nevertheless demands a definite scientific approach, rather than a policy of drift. I refer to what has almost become a contest between road and railway development. At home there seems no doubt that thousands of tons of heavy materials are carried upon roads, with some element of convenience, it is true, that should be carried on rails, at much greater gross cost to the community than if sent by rail. The calorific value of the fuel consumed per ton mile and consumption of other materials is greater for road than for rail transport, and the actual damage done to road surfaces and vehicles is much greater for the heavily loaded road vehicles than for rail vehicles. True it is that flexibility, direct delivery, and many other

advantages are claimed for road traffic which may far outweigh the disadvantages just referred to, but a failure to visualise the problem of internal transport as a whole may lay unnecessary burdens upon the community. In the opening out of new country that may be the problem in South Africa. I venture to suggest that a courageous but, so far as is humanly possible, a 'scientific' policy of development by road and rail should be followed.

SCIENCE IN ENGINEERING.

The argument of this address can be summarised into a few sentences. New epoch-making developments in engineering depend upon the discovery of new facts of science and upon materials and technical processes. The only hope of solving many of the problems which face the engineer to-day is by carefully organised experiment. Engineering is of such vital importance to modern life that not only manufacturers but also large users, public authorities, and governments must be interested and provide funds for research.

In Great Britain a good deal of engineering research is being done by large firms, by research associations connected with certain industries, by the universities and by the technical colleges, the National Physical and the Building Research Laboratories, which are under the direction of the Department of Scientific and Industrial Research. This Department also assists research associations by grants, and the universities by the provision of research scholarships and research assistants, but at present it seems that sufficient research is not being done, and that not nearly enough research workers are being trained to meet the needs. How can the demands of the case be met?

It would appear that we must look largely to the universities to train research workers. Training in strict habits of observation and in the investigation of problems theoretically and by experiment should form part of the work of all engineering students. Much of the theoretical knowledge that a young engineer requires to learn is now to be

found in excellent text-books and in current periodicals, and these he should be taught to read critically and with understanding, but he should also be taught to face all his problems in the spirit of an investigator. Certain selected students should be encouraged to remain at the universities after graduation or to return after some experience of actual works to engage specifically in research.

Engineering needs such men, some to give their whole time to research while others carry the spirit of research into the ordinary problems of industry and engineering. Employers, public authorities, and governments must utilise this research ability, and more men should find their way into industry from the research institutions. The universities, however, cannot do this most important work of training research workers unless they are adequately equipped and staffed to give members of the staff the necessary time for research and to devote themselves to the training of students in research. To this end sufficient funds must be provided from private and public sources.

The engineer is faced with many unsolved problems. Nevertheless, he must find immediate, if only approximate and tentative, solutions to many of them, and in the solution he often has to deal with many types of men. If experimental science and mathematics cannot give him an exact solution he must still carry on, and in this way much has been achieved. It is for this reason that the engineer has to learn much by actual experience in the workshop, in the field, and frequently he becomes impatient of science and lays too great emphasis upon experience. Manufacturers wish to see returns upon their capital and remuneration for their energy, but as an effective guarantee of future progress and in the solution of many problems in design, in processes, in materials, as well as in the discovery of new methods, it is necessary, as Francis Bacon would to-day remind us, "to apply natural philosophy to particular problems, and particular problems must be carried back to natural philosophy".

News and Views.

ON Sept. 14 most hearty congratulations will be extended by a large circle of men of science in Great Britain and elsewhere to Prof. Ivan Petrovitch Pavlov, the distinguished Russian physiologist, on the occasion of his eightieth birthday. He was born—son of the village priest—in the district of Rjāsan, Russia, on Sept. 14, 1849. Pavlov, after graduating at the University of St. Petersburg, engaged in medical studies, showing, very early, marked aptitude for experimental research, combined with adaptability in matters requiring manipulative skill. This natural bent was encouraged by two years' guidance in Germany in the laboratories of Ludwig and Heidenhain. Returning to the Russian capital, Pavlov filled various important academical posts where his scientific activities and his acumen had ample play. Thus began that broad scheme of work, foreknowledge, and intensive application to novel

modes of procedure which led ultimately to the opening of new chapters in physiological history. Little effort was required to attract to his laboratories pupils and associates who shared his patient enthusiasm.

PAVLOV's earliest researches (dating from 1878) related to the physiology of the circulation, and the dog formed a convenient subject for observation. In these experiments he trained a dog to allow the insertion of a cannula in a small superficial artery on the inner side of the knee-joint and to remain quiet while the blood pressure was noted. Prof. E. H. Starling has recorded the extreme care and solicitude evinced throughout by Pavlov for the animals which were essential for his varied purposes. He would take them home from the laboratory and "in his small flat they would be looked after by his wife, with the