Heat-Resisting and Non-Corrodible Steels.

Paper read by Mr S A Main, B Sc, F Inst P, (of the Hadfield Research Laboratories, Sheffield), before the Institution, in the Lecture Theatre of the Royal Society of Arts, John Street, Adelphi, W C 2, on 23rd May, 1927 Colonel N Belaiew, C B, M I Met, M Inst Met, M I M E, M I Ae E, in the Chair

Section I —Introduction

THE CHAIRMAN Mr Sidney Arthur Main, B Sc, is a distinguished engineer and scientist He takes a prominent part in the Research Laboratories of Messrs Hadfields, Ltd, Sheffield With Sir Robert Hadfield he was joint author of the paper on " Shock Tests and their Standardisation," read before the Institution of Civil Engineers in 1921, and for this paper that Institution awarded him the " James Watt " Gold Medal

During recent years general interest in Heat-Resisting Steels has grown considerably, and there is a wide field for their application in aeronautical engineering However, little has been published with regard to the more complex non-corrodible and non-scaling steels, and it is a matter of satisfaction that this Institution has been able to secure a paper on the subject by such an eminent collaborator of Sir Robert Hadfield, as the present lecturer

I now have much pleasure in calling upon Mr Main to deliver his paper

In choosing a subject for this paper, in response to the kind invitation of your Secretary, the author thought that he could not do better than give some account of the progrIss which has taken place lately and including the development and practical application of Heat Resisting and Non-corroding Steels

In few branches of engineering is enterprise more necessary, and indeed more evident, than in aeronautical engineering Since all engineering progress is based upon the properties of the available materials, it is of first importance that the engineer should have up-to-date knowledge of the latest developments in this direction, and of the properties—and also the limitations—of the materials provided for his use

Without a knowledge of the latest progress of the metallurgist the engineer may perhaps be entirely ignorant that schemes, which are beyond the capacity

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of existing materials as he knows them, and therefore remain in abeyance, may be brought to fruition On the other hand, any project which demands from a constructional material more than it can reasonably be expected from its known characteristics to endure, naturally must end in failure Engineers too, have probably not fully appreciated in some cases that their appliances are capable of much more efficient performance through the use of improved constructional materials which have become available Here naturally are referred to more specially the products of the metallurgist, and particularly of the ferrous metallurgist, steel being the material par excellence upon which engineering progress is mainly based In the same way we as metallurgists need to keep ourselves in touch with engineering progress as a guide to our further efforts, and it is to be hoped therefore that the discussion to follow the present paper may be reciprocally helpful

Special steels of many different types are already much used in the construction of aeroplanes and airships, particularly for engine parts, and a general survey of the different types of steel, and their uses in this connection, would undoubtedly have formed an interesting paper It was considered however, that such a paper in sufficient detail might prove unwieldy, and that it would be best to confine attention more particularly to the new types of heat and corrosion resisting steels These materials may or may not enable quite new ideas to be worked out in aeronautical engineering, but that they will eventually give considerable assistance in the further developments in this field, is undoubted Use has already, in fact, been made of them in aeronautical work, as will be shown In the present paper the characteristics of these special types of steel are described, and examples given of their successful application in various directions These are many of them concerned in directions other than those of aeronautical engineering They will however, the author trusts, serve to show what are the special qualities of these steels and how they meet practical conditions It may well be left to the ingenuity of you as engineers, who know much better than the author does what are the requirements called for in the materials of which you make use, or in any novel forms of construction which you may be contemplating to decide as to their utility for your own purposes Apart from the construction of aeroplanes and airships themselves, there is also naturally a potential field of use in the plant and machinery used in their manufacture

The present paper is naturally concerned with the products resulting from research carried out by my firm, Messrs Hadfields, Ltd , of Sheffield, and by our French confreres, Messrs Commentry Fourchambault et Decazeville, of Imphy, in whose laboratories were carried out the researches of the well-known metallurgists, Dumas, Guillaume, Chevenard, Muguet, Fayol and Girin If, therefore, it bears at times a somewhat commercial aspect, through the use of trade names under which these products are now known, this cannot be altogether avoided It is hoped, however, this feature will not be found unduly obtrusive

It was further considered that your members would probably be more interested in these alloys from the point of view of their properties and uses, rather than from the scientific and metallurgical aspect Although the metallurgy of such products is profoundly interesting to those engaged in its pursuit, it would, if discussed fully, form the subject of a paper in itself and one which would presumably be of less interest to you as engineers As an introduction some remarks on their general character will, however, not be out of place

Nickel-chromium steels, containing only a few per cent of these elements, are already familiar to aeronautical engineers, in their well established uses as high tenacity steels possessing excellent ductility and toughness Further research among the range of the nickel-chromium alloys of iron of considerably higher percentage disclosed a highly promising field of alloys with many attractive properties, which, if they could be made use of, should prove of the highest value and it is to this class that the steels to be described belong

The range of alloys concerned in the present paper cover from about 10 to 30 per cent of chromium and about 7 to 40 per cent of nickel, with an iron content of from 50 to 70 per cent Actually the most useful alloys are found in two separate ranges, the one containing from say, 18 to 25 per cent of chromium with 7 to 10 per cent of nickel, the iron content amounting to 65 to 70 per cent The second range is higher in nickel, its percentage being in this case from 30 to 40, the chromium amounting to 10 to 15 per cent and iron 50 to 60 per cent In all cases certain additions of other elements such as silicon, tungsten or molybdenum may be added according to requirements

These alloys all possess certain general distinguishing characteristics as compared with ordinary steel Among these are greater resistance to scaling by heat , improved strength at high temperatures and resistance to corrosion They further do not undergo critical thermal changes on heating, and heat treatment has not the same effect on them as in the case of ordinary steel

While, therefore, ordinary steels and many useful alloy steels undergo those changes of structure on heating and cooling which constitute heat treatment, these alloys have a homogeneous microstructure which remains the same under heating however long maintained or under repeated heating and cooling They therefore remain permanent in their physical character—naturally an important point specially in connection with heat resisting steel

The microstructure of " Era " Heat Resisting Steel seen in Fig 1 shows a homogeneous grain structure and is also typical of the alloys in this group The small amount of free carbide, up to 0 2 or 0 3 per cent , present in some cases does not affect their thermal stability

In their mechanical characteristics as exhibited at ordinary temperatures, these alloys are in some ways rather different from what the engineer has by long use become accustomed to know as steel They are, in fact, of the general type known to the metallurgist as " austenitic steels," of which manganese steel, although quite distinct in many ways from those now described, was the original representative

The features of a high modulus of elasticity and high elastic limit common to ordinary steels, are lacking in these austenitic steels Notwithstanding this, however, where such desirable qualities in other directions are obtained as in the case of the wearing qualities of manganese steel, this unorthodox character has not been found a disability Such is indeed proving to be the case with the present alloys It is necessary to mention this because the fact that they may not comply with existing

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specifications based on more ordinary steels, might otherwise, quite wrongly, be allowed to prejudice their uses in applications particularly suited to them

Returning to the special physical qualities found in these high percentage nickel-chromium steels, while it is true as stated that they all partake of a heat and corrosion resisting character, all do not possess these qualities to an equal degree Further, when various practical considerations, such as machinability and adaptability to other manufacturing operations are taken into account as they must be, the development of the types most suited to particular uses becomes a matter of much patient research, the addition of elements other than nickel and chromium, such as tungsten, molybdenum and silicon in small percentages, has further been found beneficial in obtaining the desired qualities to an enhanced degree in certain cases It will be understood therefore that although for convenience of manufacture the types of steel now to be described have been standardised as far as possible, the knowledge obtained from the large amount of research work carried out by our friends and ourselves often enables suitable modifications to be made, so as to deal with cases where difficulties of a special nature are met with

With these introductory remarks the different types of steel will be described in their respective classes, and some idea given as to the progress already made with them in their application to industry

SECTION II —HEAT RESISTING STEEL

Everyone is familiar with the general effects of heat upon ordinary steel and iron The important results are of two different kinds The first concerns what is known as heat scaling which, in the kitchen poker is a matter even of ordinary domestic observation In mechanically-operated furnaces, and in metallic parts which have to be used inside furnace or combustion chambers, heat scaling often affords a problem of economic or technical importance to the engineer In addition, corrosion at high temperatures may occur from vapours and gases other than air

The other important effect of heat is the softening influence which it has upon steel This, of course, operates to advantage in some respects, as it enables us to forge our steel and work it comparatively easily into desired forms Where, however, the engineer requires steel, as he does, to sustain loads or other types of stress at high temperatures, or to resist abrasion, and perform other functions, for which steel is used at ordinary temperatures, this characteristic is disconcerting Ordinary steels, and even what are known as high tenacity alloy steels, lose practically all their rigidity at any temperature above a red heat, and in fact, in many cases cannot be relied upon to support their own weight, much less additional designed stresses

The need therefore for a steel which does not possess either of these disabilities is apparent To such an extent is this the case that engineering progress has undoubtedly been held up in some directions owing to the absence of such a material In particular, the development of the gas turbine has probably been delayed through this particular difficulty more than any other It is this requirement which, in the development of the steel known as " Era " Heat Resisting Steel,

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it has been the aim to meet This steel happily combines excellent non-scaling qualities with remarkable mechanical strength at high temperatures, and its special qualities are demonstrated among the specimens exhibited

" Era " Steel may be considered as non-scaling for practical purposes up to about 1,000° C In a test at this latter temperature extending over three hours the loss sustained by a specimen of ordinary steel amounted to 9 3 ozs per square foot of its surface Under similar conditions a specimen of " Era " Steel lost only 0 023 ozs per square foot, a ratio of 400 to one Although under the much more drastic effects of still higher temperatures " Era " Steel suffers a certain amount of oxidation, it remains markedly superior to ordinary steel

As regards its strength at high temperatures, it is necessary to digress for a moment into the question of suitable methods of mechanical testing, because the methods applicable to steel at ordinary temperatures may be misleading when applied at high temperatures

At ordinary temperatures as is well known, steel in general is more or less elastic, that is, under the tensile test it recovers its original dimensions after stretching up to a point not exceeding its yield point On further stretching, the steel finally breaks under a stress, which, although not independent of the speed at which the test is carried out, is reasonably so within the range of speed of most testing machines Thus two of the important characteristics from which designs may be calculated, are determined more or less definitely

TABLE I

Tensile Qualities of "Era H R" Steel under the Ordinary Tensile Test at Normal and Elevated Temperatures

Tested at	Yield Point (Tons per sq in)	Maximum Stress (Tons per sq in)	Elongation % (on 2-in)	Reduction of Area %
Normal temperature	38	58 5	37 5	52
700° C	—	31	35	57
800° C	—	24 6	32	60
900° C	—	19 0	30 5	64

When such a test is applied at a high temperature, say about 500° C it is found that ordinary steel no longer possesses the same elasticity, and as the temperature increases the yield points loses definiteness until it finally vanishes Further, on carrying the test to completion, fracture besides occurring at a much lower maximum stress than in the cold, is much more easily accomplished if the test is carried out slowly than at a more rapid rate While for example a specimen of 0 25 per cent carbon steel at 800° C is broken in three minutes by applying a load of six tons per square inch, a load of only half a ton per square inch will cause fracture by continuous stretching if allowed to remain for as long as 100 hours Steel of all kinds in fact at high temperatures loses its highly elastic properties and becomes of a viscous character While, therefore, steels of a heat resisting

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character, and " Era " steel in particular as shown by the test data in Table I, show up favourably under the ordinary tensile test at elevated temperatures, the method of discriminating between them must be modified if data of practical value are required

Research on this question has demonstrated that if the load applied to any given steel at any particular high temperature is gradually reduced, a stress is reached at and below which no continuous stretching is produced, however long the load is maintained The expression " continuous stretching " is used advisedly because in some cases, and particularly at the higher temperatures, there is a slight extension—not more than about 0 5 per cent —which, however, is not maintained Under continued loading at the critical stress this slight set becomes permanent and no further stretching occurs This critical stress therefore provides a useful criterion of the merits of a steel for use at high temperatures, and obviously one of use to the engineer as a basis for his designs The determination of this stress, known as the " creep stress limit " or " creep stress " is therefore the method applied in testing the strength of heat resisting materials In the case of " Era " Steel the creep stress thus ascertained at various temperatures is as follows 600°—8 tons per sq inch, 700°—5 tons, and 800°—2½ tons These figures may appear to be rather low by comparison with the figures given by steel at ordinary temperatures, but when it is realised that under similar conditions, *e g* , at 800° C ordinary steel fails to support a load even of half a ton per sq inch without continuous stretching, finally breaking in 107 hours, and that cast iron will break under even a quarter of a ton, it will be appreciated that " Era " Steel represents a very considerable advance

A number of applications in which " Era " Steel is being successfully used, may now be referred to The conditions of service in these various applications naturally vary considerably, and there are often special circumstances which require to be legislated for The best type of steel for one particular application is therefore not always necessarily the best for another Research and experience have, however, indicated the lines upon which the composition and characteristics should be varied to give the best performance in given cases " Era " Steel therefore, really represents a range of steels, and for some purposes which will be indicated, a distinct type known as " Era/ATV " is employed

Fig 2 shows recuperator tube castings which serve to illustrate the possibilities of " Era " Steel in replacing with considerable advantage the ordinary non-metallic refractories, which have hitherto been necessarily employed only because of the absence of suitable metallic materials

The function of these tubes is to effect pre-heating of the air supply to a furnace, the air passing through them, and being heated by the waste gases which pass outside The considerably higher heat conductivity of " Era " Steel as compared with fireclay, therefore very much improves the efficiency of the heat transfer, and also in addition it is, of course, very much less fragile Incidentally, this illustration demonstrates the excellent casting qualities of " Era " Steel, the castings, being of a difficult character and very thin in section, only in fact 1/16th inch in thickness at the edges of the fins, yet the material runs perfectly

Fig 3 illustrates castings provided in considerable quantities for use in furnaces for the roasting of zinc ore The special feature illustrated by this application is the high resistance which "Era" Steel offers to a sulphurous atmosphere, which has a disastrous corrosive effect on many materials which otherwise might be suitable

Figs 4 and 5 show how the material is being applied successfully in our own Works Racks of the type shown in Fig 4 are necessary for supporting and spacing motor car spring leaves in the furnace while they are being heated for hardening The temperature is 950° C, and with racks of cast iron, or mild steel, scaling occurs so rapidly as to choke up completely the spaces between the teeth in a few weeks With similar racks of "Era" Steel a life of at least 18 months has been obtained, after which the racks are still serviceable Cast Sheaths of "Era" Steel for the protection of thermo-couples are also employed in the same furnace and have a similar life This furnace is oil-fired, and owing to the high sulphur content always found in fuel oil the furnace atmosphere is of a very sulphurous character As a consequence, pyrometer protection sheaths of heat resisting alloys of the type containing high percentages of nickel, and more expensive in the first cost, were found unfit for further service after only five months use With the growing use of oil fuel in many directions these successful applications of "Era" Steel are therefore of special interest

Fig 5 shows a continuous type of oil-fired furnace through which these spring leaves are carried in comb-like teeth of "Era" Steel attached to a continuously moving chain This photograph was taken after seven or eight months use and shows that the teeth which are alternately heated to about 950° C and cooled on their return journey under the furnace, have suffered no deterioration

Another application of interest is that for soot blower tubes and fittings These soot blowers remain permanently installed in the boiler and are used periodically for blowing the soot from the tubes The temperature is liable to attain 1000° C or even higher, and here again a highly sulphurous atmosphere is experienced, yet the tubes behave admirably, and the use of "Era" Steel was decided upon after competitive trials These tubes and fittings are castings

A still further application is for what are known as slicing links attached to mechanical stokers It is the function of these slicing links to work in the fuel bed of the boiler furnace The particular boiler installation in which trial was first made of "Era" Steel for this purpose was that of an important Electricity Generating Station in the North of England The furnaces are operated with pre-heated air and temperatures above 1600° C have been observed with an optical pyrometer on the wall of the boiler furnace These temperatures are probably the highest in use in any mechanically-operated boiler furnace in this country The slicing links do not attain quite these high temperatures, because they are protected to some degree by their conduction of heat from the hot clinker bed to the mechanical grate Nevertheless, the tips of the links work at temperatures up to about 1,400° C, not far short of the melting point of the material

Under these very onerous conditions "Era" Steel links are giving an average life of 1,000 hours actual steaming time Links of ordinary steel, even when protected by a special metallic coating only lasted 180 working hours, and were a

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constant source of expense and attention owing to the very frequent replacements, in fact, there was difficulty in obtaining a sufficient supply of links for renewals The abrasive action of the clinker on the links is very pronounced, and the superior hardness of "Era" Steel at high temperatures is therefore of importance in this application Its successful use in this particular installation has since led to its adoption in many other boiler plants of a similar character

In competitive trials by the British Admiralty for certain furnace parts to which it is not permissible to refer in detail except that these are required to remain perfectly rigid at an operating temperature of 850° C , and for which the parts are required both in the form of castings and forgings, "Era" Steel proved the best and has been adopted on a considerable scale

Coming now to applications of heat resisting steel connected with your own work, the components for which the necessity for a material of this type is greatest, are the valves, and more particularly the exhaust valves While in the early days of the internal combustion engine a steel such as 3 per cent nickel steel had sufficient of a heat resisting character for the purpose, with the increasing efficiency of the engine, and specially in aeroplanes, higher and higher temperatures have been imposed upon the exhaust valves , at the present time they are required to work, of course, reliably and successfully, at temperatures even as high as 850° C , that is, well above a red heat, the red colour first appearing in steel at about 520° C

Valves nowadays, therefore, to endure the rapid battering which their duty calls for while at this elevated temperature, and also to resist the scouring action of the exhaust gases which rush past them at enormous velocities, must be made in a material which has heat resisting qualities developed to the highest degree Nickel steel was followed by high speed steel and by "stainless" chromium steel, and these were able to take care for a time of the advances in exhaust temperature In turn however, they also became over-matched by the conditions, and have had to give place to still better types in the silicon-chromium and high percentage nickel-chromium steels nowadays used

In view of the importance of the valves as a factor in the reliability of aeroplane engines, and the diversity of the conditions to which they are now subjected, much attention has been given by manufacturers to the question of the most suitable material The subject has been pursued by exhaustive comparative trials by a prominent firm of aeroplane engine builders, in collaboration with the Air Ministry, and as the result, having regard to the several special features required in valves, the material known as "Era/ATV," a type of heat resisting steel specially developed for such purposes, came out best, its strength, toughness and non-scaling properties giving it excellent recommendations for the purpose Valves of "Era/ATV" Steel are as a consequence now being used in considerable quantities , (Fig 6) for racing motor cars and cycles also which impose a very high and critical duty upon the valves, this material has proved of value

In the absence of an entirely satisfactory material for valves, efforts had been made to ameliorate the conditions under which they have to work under modern conditions, *i e* , by the use of a water jacket to reduce the operating temperature Alternatively, an ingenious method was devised by which the valve stem was filled

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with a fluid which, by its circulation, assisted the conduction of heat between the head, which is most exposed to the high temperature, and the stem, which is relatively cool It is satisfactory however, to find that valves of " Era/ATV " Steel are fully able to endure the operating conditions quite successfully without such expedients

It has been a fairly common experience to find valve breakages, *i e* , of valves in some kinds of steel, occurring immediately after the engine has been re-started after a period of rest An explanation which has been suggested is that the cessation of the hot exhaust gases, followed by the sudden cold draught of air when the petrol supply is cut off, causes a rapid cooling of the valve, such that if the steel is of an air-hardening character it becomes air-hardened and so embrittled Thus, on the action of the engine being resumed, it is with exhaust valves which are in a hard and brittle condition, and so, very soon broken If such is the true explanation, then it may be supposed that " Era/ATV," not being affected by heat treatment, would not be liable to this particular trouble, and in fact, it has not so far been experienced

To demonstrate the non-susceptibility of " Era/ATV " to such hardening and embrittling effect, the following test was carried out A valve of " Era/ATV " steel was heated to 900° C for a period of half-an-hour, suddenly withdrawn from the furnace and submitted to the air blast from a $\frac{3}{4}$-in nozzle inside a tube, the air passing from the end of the stem towards the head When cold the stem of the valve was gripped in a vice and the head struck sideways with a hand hammer, under which treatment it bent 50 degrees without fracture, as shown in Fig 7 Its Brinell hardness after the test was 190 Thus there had been no material alteration in the physical characteristics of the steel brought about by such treatment That the method of testing employed is effective in causing air hardening, of the kind suggested as an explanation of the trouble mentioned, in a material capable of it, is demonstrated by the result obtained with the valve of high speed steel shown on the right of Fig 7 This was similarly handled, and acquired a hardness of 555 Brinell breaking off in quite a brittle manner when hammered Before the test with a hardness of 260 Brinell, a similar valve of high speed steel could be bent 25 degrees before fracture

A type of valve steel which has come to the fore within recent years is the Silicon-Chromium Steel now supplied by several manufacturers and known under various trade names While a derivative from chromium steel of the type familiarly known as stainless, it is somewhat modified in composition and contains, in addition, to chromium about 8 to 9 per cent , silicon to the extent of 3 to $3\frac{1}{2}$ per cent , and in some cases a little vanadium Its non-scaling properties are excellent, being appreciably superior to those of the plain chromium steel Since it is also less expensive than the nickel-chromium types of alloy, and capable, when properly handled, of giving quite good results, it has found favour specially for valves of some motor car engines Use has also been made of it for the valves of certain aeroplane engines The engines in these cases however, are such as, either by water cooling or otherwise, do not call for the highest duty from the valves Under the more searching conditions which obtain in air cooled engines of the boosted

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type, the silicon-chromium type of steel breaks down, and has to give place to the high nickel-chromium type of steel, of which " Era/ATV " is the best representative

The reason is apparent when the tensile qualities of the two types are compared, " Era/ATV " having at 900° C a tenacity of 16 tons per square inch, while that of the silicon-chromium steel is only five tons The operating temperature reached by the valves in such service closely approaches this temperature, namely, about 850° C

A useful characteristic of this silicon-chromium steel which should be mentioned in its favour, but not altogether an essential one, is that it is capable of being hardened by a quenching and tempering treatment, so enabling the tappet end of the valve to resist wear

Apart however, from its failure to achieve the highest performance, this steel has certain important disabilities The first is that it is essentially notch-brittle, *i e*, very readily broken at a sharp corner It is true that by suitable methods of heat treatment the toughness may be considerably improved, but even then the Izod impact value is only 10 to 12 ft lbs, as compared with 30 to 45 ft lbs for " Era/ATV " Thus it is of the highest importance with steel of this type to insist that sharp corners, as at the tappet groove at the end of a valve stem, should be rounded off, otherwise fracture may easily occur in service Further than this, it is essential to see that all machining marks are carefully polished out, as even these may, and have in our experience, resulted in fracture by acting as notches This is specially the case in the region at the junction of the head and stem

The further characteristic of this steel referred to is its tendency to acquire a highly crystalline platey structure, specially noticeable in the fracture as seen among the exhibits When these large crystals appear the naturally brittle character of the steel is enhanced, and to such an extent is this the case that valves merely by dropping from the bench to the floor may break in two My firm have made a special study of this characteristic and of the conditions under which such platey structure is formed, and it has been clearly shown to result from the forging being finished at a temperature in the neighbourhood of 800° C followed by annealing at about 850° C Now a finishing forging temperature of 800° C comes well within the common practice of forging steel in general Consequently, silicon-chromium steel, if forged without special precautions, will result in valves of which a considerable proportion, if subsequently heated in the neighbourhood of 850° C, will show this undesirably large crystalline structure All forging should therefore, be carried out at a sufficiently high temperature, preferably about 1000° C, while ensuring that the temperature never falls below 900° C while the material is being worked Annealing subsequent to the forging operation should further be studiously avoided, the correct treatment being to quench the valves in water from about 1000° C and reheat to 800° C, followed again by a quenching which results in a hardness of about 280 Brinell and puts the material into a satisfactory condition as regards toughness, that is, an impact value in the Izod test of 10 to 12 ft lbs as mentioned above

The development of a platey structure in this steel seems to be closely allied to the crystallisation of mild steel and iron, and of other metals, by cold working

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and subsequent annealing, the development of which method has enabled single crystals of large size to be made In a heat resisting material of the character of silicon-chromium steel, forging at a temperature as low as 800° C in fact constitutes what is the equivalent in an ordinary steel, of cold working The necessary temperature for the development of the crystallisation subsequent to such " cold " working, is naturally also different from that necessary in the case of ordinary steel and iron, that is, higher The awkward thing is that these critical temperatures, both for forging and annealing, for silicon-chromium steel are such as come within the range of ordinary metallurgical operations, and therefore they must be avoided by the procedure above mentioned

From these observations as to the character of silicon-chromium steel it is obvious that its use should not be adopted where the necessary facilities for the proper control of its metallurgical handling are not available, or the necessary supervision exercised, otherwise the steel may be unfairly condemned The complete production of the valve forgings is in fact best placed in the hands of a competent firm of steel manufacturers, and with correct handling this steel is capable of making excellent valves suitable for all but the highest performances

The development of the Diesel engine has resulted in a similar demand for an improved valve material, and here also trials have shown " Era/ATV " Steel to fully meet all requirements, even of the most advanced practice (Fig 8) Its more extended use for these valves seems justified, particularly as in the trials referred to the valves operated quite successfully without the necessity for water-cooling—always an undesirable feature

A further successful application of " Era/ATV " Steel which will be familiar to you is that for the exhaust turbine rotors illustrated in Fig 9 The performance demanded of such rotors is really extraordinary, spinning as they do at an enormous speed, at which the centrifugal stresses, apart from the actual transmitted stresses, constitute no light duty upon the steel Yet these rotors are required to perform their functions at a temperature of something like 850° C , while at the same time being subjected to the erosive and corrosive action of the hot exhaust gases It is apparent therefore, that only a steel of the highest possible merit as a heat resisting steel can successfully be employed for such a purpose

Much information regarding the construction and use of these turbo compressors was contained in a paper on the subject read in 1922 before the Institution of Mechanical Engineers, by Professor Rateau He goes very fully into the principles underlying the action of these applicances, the object of which is by supercharging the motor at high altitudes, to restore it to the same running conditions as at ground level He further states that taking into consideration only those appliances that have been actually tested, and give double the induction pressure (and there would be no difficulty, if required, in making these appliances capable of compressing the air to a much greater ratio), the formulæ which he has established show that, for equal weight of aeroplane, there is an increase of about 4,000 m in the height of ceiling Referring to the results obtained at that time, it is mentioned that on a Breguet aeroplane having its ceiling at about 6,000 m , Lieut J Weiss, after a turbo-compressor had been fitted, flew, in July 1919, with his

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mechanic, to a height of over 9,000 m and he was still far from the new ceiling This at the time was a record for height with a passenger

With regard to speed, there is a loss at ground level, because it is necessary to change the airscrew and to substitute for it one of larger diameter in order to be able to maintain the speed of the motor at high altitudes within the permissible range of speed But above 2,000 m the turbo-compressor rapidly makes up for this The Breguet aeroplanes in question, fitted with 300 h p motors, without turbo-compressors, have a normal speed at ground level of 180 km per hour , near the ceiling this speed falls to 145 km per hour With the addition of the turbo-compressor a speed is obtained, at the former ceiling height of 6,000 m , which from many measurements has been found to be from 215 to 220 km per hour At this speed many flights have been made with these aeroplanes from Paris to Lyons, to Tours, to Nancy, to Metz, etc

The constructional details of the experimental turbo-compressors are described and reference is made to the very high speeds of revolution up to 33,000 per minute necessary to obtain the same pressure as at ground-level, the rotors actually running at a normal speed of 30,000 revolutions per minute Professor Rateau further points out that the construction of such compressors of very compact form, very light although absorbing about 50 h p , running at an enormous speed, having gases at 800° C on the one side, and extremely cold air (as low as —50° C) on the other side, and was not an easy matter

Experimental work with a view to obtaining a satisfactory material for the rotors was carried out as long ago as the year 1913 by our confrères, La Societé Anonyme de Commentry Fourchambault et Decazeville of the famous Imphy Works At that time the solution was sought for in the use of high speed steel This material however, proved to be too easily oxidised, and unsuitable also owing to its loss of strength at temperatures much exceeding 500° to 600° C The exceptional difficulties encountered in forging a series of alloys containing high percentages of nickel and chromium under preparation at that time for M Guillaume led to their merits being considered for the particular purpose of these rotors It was argued, and with some reason, that a material which was so difficult to deform under the hammer at a red heat should have the best recommendation for purposes of this kind where stresses have to be sustained at a high working temperature Such proved to be the case, and the type of steel finally evolved and known as " Era/ATV " Steel is now being used for these exhaust turbine rotors with entire satisfaction Its use was not adopted without thorough tests of a practical nature, and such rotors in " Era/ATV " Steel have run continuously for long periods at a temperature of from 800 to 900° C at a speed of 30,000 revolutions per minute The only effect upon the steel was a slight surface colouration in the nature of a temper colour, the edges of the vanes remaining sharp, and the efficiency of the steel in transmitting its drive quite unimpaired

In the earlier forms of these rotors, the turbine disc and spindle were of different materials owing to the very different conditions under which they operate At the time when high speed steel was utilised, though not altogether successfully, for the disc, it was found necessary to employ nickel steel for the spindle, which at the compressor end was subject to very low temperatures

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In the rotors of "Era/ATV" Steel as shown in the illustration, the disc and spindle are made in one piece Thus the steel is called upon to perform its functions while being submitted at one and the same time to such extremes of temperature as, on the one hand, 850° C at the turbine disc, and on the other minus 50° C at the end of the spindle That it is able to do so quite successfully, it will be agreed is a remarkable example of the possibilities brought about by modern alloy steels

A point which should be mentioned is that the heat resisting steels described have distinct merits as non-corrodible steels, that is, at ordinary temperatures In periods of disuse of plant, parts made from these steels do not therefore deteriorate or rust up as does ordinary steel, consequently less attention is necessary in re-starting

The use of castings rather than forgings is recommended wherever possible on the score of cost Just as the loss of strength of ordinary iron and steel at temperatures above a red heat enables them to be forged with facility, so the very objective of obtaining a steel as strong and rigid as possible at high temperatures necessarily entails difficulty in hot working of all kinds The lower conductivity for heat also, resulting from alloying steel, involves more cautious heating to ensure uniformity in temperature and the avoidance of expansion strains and consequent cracks

The production of a heat resisting steel such as "Era/HR" or "Era/ATV" in the form of forgings necessarily therefore, further increases the disparity in cost as compared with ordinary steel, above that which exists in the form of castings Nevertheless, the difficulties of forging and rolling have been successfully overcome by experience, and "Era/HR" and "Era/ATV" Steels are being produced in the form of bars and sections or sheets, also forgings and stampings, if of not too complicated a character, as shown by some of the examples just described They can also be cold drawn into wire By the use of efficient methods of production as the result of experience it is found possible to keep the cost even of the worked material down to an economic level which justifies its use for many applications where castings are unsuitable

Both "Era/HR" and "Era/ATV" Steels are, with suitable adaptation of the cutting angles of the tools and cutting speeds and feeds, quite readily machinable Grinding, turning, drilling, milling, and screw-cutting operations are in fact being regularly carried out in everyday practice A curious point arises in connection with grinding from the fact that no sparking occurs Thus the ordinary indicating as to the weight of "cut," in the volume of the shower of sparks is missing, but once the machinist realises this, and relies on other indications, there is no danger of spoiling even delicate work

SECTION III —NON-CORRODIBLE STEEL

The problem of corrosion may be better described as a whole series of problems, because taking industry at large, the number of corrosive agencies met with, and the different conditions under which they operate are of great variety Every branch of engineering experiences corrosion in some form or other as a technical

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difficulty, though no doubt the chemical engineering trades stand foremost in this respect

Sir Robert Hadfield has at different times pointed out the great economic loss to the World from wastage due to corrosion It is not claimed that present advances in the production of non-corrodible steels will wholly do away with such loss For general application for structural purposes, which absorb the main quantities of the World's steel production, the cost of the new special steels is undoubtedly prohibitive, and likely to remain so for some time to come Still there is no doubt that for a great many purposes their advantages have only to become more generally known to lead to their solving many of the problems of industry where corrosion is the chief factor

The final goal of a universally resistant steel at an economic price is not yet reached The production of non-corrodible steel must in fact be regarded as a process of evolution which can be traced in stages and in which rapid advances have been made within recent years Among the exhibits will be found a series of specimens which attempts to portray, necessarily in an incomplete way, this evolution

From the earliest times the corrosion of iron and steel has been met by the use of a protective coating, either in the form of pain or various pigments , later, different forms of metallic coatings such as galvanising have been employed with some success Such methods, however, could never be entirely satisfactory, and can only at the best be regarded as palliatives, while painting also involves a considerable recurring expenditure in upkeep

In the case of structures such as bridges where human safety is concerned, the special care and attention which is given in periodical painting and inspection is undoubtedly effective in a large measure, but there are often places difficult of access, which the engineer must take more or less upon trust, and at which corrosion of a dangerous character may go on unobserved It is obvious in fact, that the problem can only be adequately met by the use of steel which is in itself non-corrodible, and does not rely upon any special surface protection

The first important step in this direction was the introduction of chromium steel, containing about 12 or 13 per cent of this element, also with comparatively low carbon up to about 0 30 per cent and which has become familiarly known under the name of stainless steel

The use of chromium steel in this direction is not the result of the efforts of any one individual, but rather of developments dating back many years, and in which many investigators have taken part

The history of chromium steel, and of the subsequent development from it of the modern non-corrodible steel of the high percentage nickel-chromium types, it is in fact, particularly interesting and some account of it is given in the article by Sir Robert Hadfield published in Pitman's " Engineering Educator "

The application of chromium steel as a non-corrodible steel first took definite form following the well-known experimental work by Mr Harry Brearley, from 1912 to 1914, on high chromium steel arising in connection with a search for an improved material for rifle barrels and liners for gun tubes It is understood that although the experiments to discover a steel highly resistant to gaseous erosion did not lead to any immediate practical results, and that the work was not originally inspired by any intention or hope of discovering stainless steel, observations made at the time of the experimental work referred to led to the discovery by Mr Brearley that by hardening, tempering, and polishing, steel of such character could be made into stainless cutlery This was followed by numerous developments in the application of chromium steel by many others in this country, the United States, France, Germany, and elsewhere

Chromium steel in fact possesses excellent advantages for many purposes where the effect of corrosion are experienced, that is, apart from domestic uses It is not so generally resistant to various forms of corrosion as the more recent types of steel to be referred to later, and compares unfavourably in some other ways At the same time against the more ordinary types of corrosion, and when suitably heat treated, it is able to render an excellent account of itself besides possessing special recommendations as a high tenacity steel

For some engineering purposes, therefore, chromium steel can be recommended Figs 10 and 11 illustrate two such applications The first represents bolts for marine lock gates, a more or less experimental application which has, however, demonstrated the utility of chromium steel for such a purpose Fig 11, on the other hand, illustrates submarine hydrophone diaphragms which have been supplied in considerable numbers Chromium steel resists the corrosive action of the sea in a very satisfactory manner, and further possesses excellent acoustic qualities Its advantages have not been overlooked for the construction of aeroplanes and airships The demands for an all-metal construction called for high tenacity steel in the form of strip which could be shaped into spars and their necessary fittings The technical difficulties to be surmounted in the production of such strip, which had to be only some 0 012 to 0 030 inch in thickness in sufficient length, and with the necessary freedom from imperfections, were after much experimental work eventually overcome With a heat treated nickel-chromium steel containing about 3 per cent of nickel and $\frac{1}{2}$ to 1 per cent of chromium, it was found possible to produce such strip which lent itself to being shaped into the various complicated forms taken by the various spars, also when suitably heat treated to a high tenacity condition it is able to withstand a proof tensile stress of about 70 tons per square inch without any appreciable yield, while giving satisfactory evidence of toughness in a bend test, that is, the ability to withstand a bend of 180° round a radius of three times the thickness of the strip without fracture Thus an excellent constructional material is provided giving the necessary strength associated with lightness

Such material, however, suffered from the disadvantage of having to be protected from corrosion which necessitated a by no means negligible addition in weight caused by the necessary protective coating In these circumstances, further experiments were carried out with chromium steel to see whether with such material similar mechanical strength and toughness could be obtained with the added advantage of non-corrodibility After much experimenting, specially with regard to attaining the high degree of surface perfection in this material essential to its non-corroding qualities the manufacture of strip in chromium steel has now been established on a practical basis, such material, in its suitably heat treated condition, having similar characteristics as regards mechanical strength and toughness to the nickel-chromium steel referred to.

The permissible tolerances allowed in manufacture for straightness, width and thickness, are necessarily very narrow, but notwithstanding this, many tons of strip have been successfully produced up to 6½ inches in width and down to 0·012 inch in thickness, complying in all respects with the specifications laid down.

A typical tensile test on strip of 20 S.W.G. (0·036 inch) thickness, air hardened and tempered shows the following figures : Proof stress (not more than 1 per cent: permanent extension) 71·0 tons, Maximum stress 90·3 tons per square inch, with an elongation of 6·5 per cent. on 4 inches. In the bend test a strip cut transversely bent 180 degrees over a radius equal to three times the thickness without any sign of cracking. Practical exposure tests on actual spars constructed from this strip have shown that its non-corroding qualities are satisfactory.

In view of the limitations which a narrow strip imposes upon the aeroplane builder in the construction of the spars, efforts have been made to overcome the difficulties of producing still wider strip, and it will be of interest to know that experiments recently carried out by my firm show that it is commercially possible to produce hardened and tempered strip as wide as 8 inches, and of a thickness down to 0·018 inch, fully complying with specification. The availability of this material should be of great assistance to those who look to the future development of the aeroplane along the direction of the all-metal construction, and also for the construction of airships.

To return to the general question of non-corrodible steel, chromium steel was however, only a partial solution of the corrosion problem. While resistant to certain forms of corrosion, it is liable to be badly attacked by others. Further, to enable it to display its qualities to the fullest extent, heat treatment and the preparation of a smooth surface are necessary, special care being required in both respects, otherwise failure may occur.

With such progress to build upon, however, further research has led into a fruitful field among the nickel-chromium steels which have the desired qualities to a much enhanced degree.

One of the earliest investigators with regard to nickel-chromium alloys was the French firm known as La Société Anonyme La Neo-Metallurgie, who, in 1903, pointed out that alloys of iron, nickel, and chromium presented great resistance to corrosion. The exact words used by this Company, describing in their patent the qualities of their materials, are as follows : "In these conditions of purity, the elements, nickel and chromium, modify very advantageously the properties of the products, steels and irons, in which they are incorporated. In tractive tests, great increase in the resistance of these substances to rupture is found. Their limit of elasticity is also largely increased without their extension experiencing a reduction of any importance. But the most important modification to which these elements, nickel and chromium, give rise consists in the important property (which forms the subject of the researches of metallurgists at the present time), which they communicate to the said products, steels and irons, are presenting great resistance to corrosion."

Since that date research has continued in progress and a more complete and detailed knowledge of the character of the iron alloys containing a high percentage of nickel and chromium has been obtained In this progress my firm has taken an active part, and the new type of non-corrodible steel known as " Era/CR " Steel represents the result of several years of experiment and research

As previously indicated, its chief advantages over chromium steel are not only in the more complete resistance which it offers to the ordinary forms of corrosion due to air and water, but also in the great range of corrosive agencies to which it is resistant A still further advantage is that while, as previously mentioned, chromium steel, to display its highest resistance to corrosion, must be heat treated, and carefully prepared as regards surface, " Era/CR " is, so to speak, intrinsically non-corrodible, and will display its qualities without special heat treatment and without specially careful machining

The number of different chemical agents and other corrosive media to which this special steel is completely resistant, and as definitely ascertained down to the present, is very large, and increases daily as further knowledge is obtained from the researches continuously going on The tests carried out naturally concern not only the nature of the chemical agents, but also the conditions of exposure, since a medium which is not corrosive at a particular temperature and degree of concentration, often becomes so under different conditions of concentration and temperature

An important characteristic of " Era/CR " Steel, shown in Fig 12 and one which distinguishes it from various non-ferrous metals and alloys, is that of complete resistance to nitric acid in all concentrations and temperatures It is also unaffected by solutions such as those of ammonium nitrate, copper sulphate, mercuric chloride, picric acid or sulphurous acid, which are known to attack certain widely used alloys of the non-ferrous class

As has already been stated, however, " Era/CR " is not a universally resistant material, and it is necessary to point out that there are certain corrosive liquors against which full resistance is not claimed Among these are hydrochloric acid and sulphuric acid In such cases, however, when compared with what happens to ordinary steel, the attack on " Era/CR " is very small, and with regard to sulphuric acid, at concentrations below 9 per cent it is not attacked at ordinary temperatures

" Era/CR " Steel can be worked up into various forms including bars, rods, plates, sheets, drop stampings, strip and wire Sheets are now being produced satisfactorily in large dimensions, as shown by Fig 13

The difficulties in the production of cold drawn tubes have also been successfully overcome, and examples are shown among the exhibits, together with specimens representing the various other forms in which this material is manufactured

In its ordinary forged or rolled condition with a Brinell hardness of 230, its tensile characteristics are Yield Point 27 , Maximum Stress 52 tons per sq inch , elongation on 2-inch 45 per cent , with Reduction of Area, 55 per cent For the purpose of cold pressing it is necessary to use sheets which have been specially softened by heating them to 1200° C and cooling quickly, in this condition

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it is supplied with a Brinell hardness of 150, the corresponding tensile figures being Yield Point 15, Maximum Stress 41 tons per sq inch, elongation on 2-inch 75 per cent, Reduction of Area 70 per cent

Fig 14 shows how excellently "Era/CR" Steel lends itself to operations of cold pressing, and it is specially interesting when it is remembered that such articles as there shown, including the goblet which is no less than 8-inches in depth, have been pressed from a material having a tenacity of over 40 tons per sq inch Re-annealing is usually necessary between successive pressing or drawing operations, and this is simply accomplished by heating the material to 950° C and cooling in air

"Era/CR" Steel lends itself well to machining operations which can be performed at the rate of 60 feet per minute, using tools with a rake and angle similar to those employed for nickel and nickel-chromium steels, and using ordinary cutting compounds as a lumbricant The tool, however, should be in the hardest possible condition, fine feeds are necessary, and care must be taken to keep the tool well up to the work

Rivetting, brazing and hard and soft soldering present no special difficulties, and welding can be carried out either by the electric or oxy-acetylene processes A firm of welding experts in fact, is prepared to undertake the welding of "Era/C R" Steel on the same terms and with the same certainty as for ordinary steels, ensuring for sheets a tensile strength in the actual weld of 75 per cent Fig 15 shows examples of welded vessels in this special steel It should in fact, prove an admirable material for the construction of exhaust manifolds, being easily worked up into the desired shapes and with welded joints The working conditions of these manifolds further require a material of a distinctly heat resisting and non-scaling character "Era/CR" Steel although not of the type most suitable for the highest temperatures possesses these in an ample degree for this purpose where the temperature, although high enough to be troublesome, does not attain the high figures experienced in some of the applications of "Era/HR" Steel referred to above

A recent application of "Era/CR" Steel, and one which will be of general interest, is its use for the reinforcements employed in the restoration of St Paul's Cathedral The Committee responsible for this important work naturally desired that the work which they are now doing should be as permanent as possible, a result which, in the case of the tie rods if made from ordinary steel or wrought iron could not be guaranteed, that is, though doubtless such ties might last many years before their eventual destruction through corrosion, the Committee did not wish to put any such limitation upon their endeavours, specially in view of the metallurgical progress which had indicated that corrosion need not now be altogether regarded as a necessary evil which must be countenanced Protective coatings were possible, but not such as to ensure the degree of permanency desired, nor of course, would it be practicable to renew them from time to time in such a case

The Committee, with the help of the National Physical Laboratory, carried out exhaustive corrosion tests of a suitable character on various types of non-corrodible steel, and as the result, and having regard to the fact that these tie bars must be capable of sustaining considerable stresses, thus calling for a material of high tenacity, "Era/CR" Steel was finally adopted The material required, in

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the form of tie bars 3 inches and 4 inches in diameter, with their couplers and wall-plates, which are castings, also nuts, as illustrated in Fig 16, amounts to a total weight of 20 tons, thus involving the use of this special steel which has a tenacity of 45 to 50 tons per square inch, upon a considerable scale These reinforcements are to replace those originally used by Sir Christopher Wren, F R S , and made from wrought iron

Finally, a brief reference should be made to a more specialised but equally important type of non-corrodible steel known as "Hecla/ATV" Considerable advances have taken place in steam practice, specially in the direction of higher temperatures and pressures so as to achieve the highest possible thermo-dynamic efficiency There has thus been difficulty in obtaining a material, specially in the case of steam turbine blading and steam fittings generally, which is able to withstand the erosive and corrosive effects of the steam, while also retaining sufficient mechanical strength at these higher temperatures of 750° F and even above Special trouble has always been experienced from corrosion, particularly of contaminated steam, and while non-corroding materials, mostly of the non-ferrous type, have been used with some success, these have not the necessary mechanical strength at the elevated temperatures in steam practice To arrive at a completely satisfactory material has been the aim of researches carried out over several years by our French confreres, La Societe Anonyme de Commentry Fourchambault et Decazeville, and ourselves As the result, this steel known as "Hecla/ATV," has been produced, and has been found to serve these purposes admirably, while also lending itself to the various manufacturing processes employed by the turbine builder (Fig 17)

In total to the present time upwards of 30 turbines with individual capacities up to 50,000 K V A in this country and on the Continent have been fitted with blading of "Hecla/ATV" Steel, while it has also found considerable employment for various steam fittings Practical use in this way, some of the turbines having been at work for over six years, has shown this material to have just the qualities necessary, the maintenance of its hardness at the working temperature successfully resists the erosive action of the steam, while corrosion even of salt contaminated steam,—a particular source of trouble in marine turbines and those situated near the coast—has no effect Thus the profile of the blading is accurately maintained and with it the efficiency and low steam consumption of the turbine, a result which, when capitalised, far outweighs the initial extra cost of this special material

SECTION IV —CONCLUSION

The description of these new types of heat and corrosion resisting steels will, it is hoped, as mentioned at the outset, have given you some idea of their character and the further possibilities of their use in your own particular field of aeronautical engineering It often happens that applications for which these new steels seem likely to be useful involve some special point not common to others, and the fact that a particular difficulty experienced in practice may not appear to fall into one or other of the broad categories into which, for convenience, the materials in this paper have been divided, need not necessarily be a deterrent in attempting to provide a remedy

It may be helpful to remember that each of the types of steel described partakes to some degree of the character of the others, although not to the optimum extent The general characteristics therefore of the type chosen to meet the main problem, say the effects of heat, may be adequate to deal with the lesser difficulties say of corrosion, or *vice versa* Alternatively in cases of special difficulty it has sometimes been found possible, by special study of the operating conditions, to deal with them successfully by the use of a material of somewhat modified composition or mode of preparation

Reference has been made to the higher cost of these new alloys as compared with the more ordinary materials, and it is recognised that this is a factor which must be fully taken into account Our experience with them so far has however, shown that there are many purposes which they are able to serve in which their higher cost is amply justified This sometimes results from their enabling an important technical advance to be achieved, or perhaps greater reliability of performance which is not otherwise possible Alternatively these new alloys may, by a reduction of wastage or replacements, save many times their extra originally cost, while in still other cases, a gain in efficiency by an effected saving in fuel consumption, leads to the same result

Aeronautical engineers have, however, by the already considerable use which is made of special steels and other alloys in their constructions, shown their appreciation to the value of materials with special characteristics, so that there is no need to emphasise this particular point At the same time, it is realised that to produce these alloys in the forms required at as low a cost as possible will facilitate their introduction and more extended use Every effort, therefore, is being made towards that end

DISCUSSION

Dr ROSENHAIN (of the National Physical Laboratory) I do not think I am the most suitable person to open the discussion on the paper we have heard to-night, as it is intended chiefly for aeronautical engineers My part is the metallurgical side, so my remarks will be made from that aspect

I think everyone who knows what has been happening in the world of metallurgy must appreciate the great advances which have been made in recent years in these special materials for resisting high temperatures and corrosion Mr Main and his firm have played an important part in that work, and I think the thanks of all of us are due for that part The importance of materials to resist high temperatures can scarcely be exaggerated There has been waged for many years one of those interesting bloodless battles that eventually lead to the advancement of technology It has been essentially a battle between the steam turbine and the internal combustion engine for supremacy with regard to the economical production of power The battle has been waged by an ever increasing tendency to use higher pressures and temperatures

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The aeronautical engineer at present appears to be interested only in the internal combustion engine , whether he will ever become interested in the steam turbine is doubtful However, whether he is or not, he has profited by the result of the battle, because it drives engineers to use certain materials which the metallurgist is forced to provide Some of us think that even these do not constitute the limit, and that we may have to provide materials which do not merely give a creep stress of two tons per square inch at 800° C , but that ensure strength at temperatures very much higher even than that I remember many years ago I was a student of engineering listening to the words of wisdom of a very intelligent professor, who said " Some of you will live to see engines working with red hot steam " I am sure we should see that if we looked at them in the dark, and we may live to see them working on white hot steam

I think that a valuable forward step in the direction of finding materials able to stand high temperatures and other special conditions has been shown very clearly by the lecturer this evening We have heard in this paper, and we also see by the specimens here, that some remarkable results have been obtained The exhaust turbine rotor in particular is a very fine achievement These, however, are not yet the last word, and that last word will never be spoken , our successors will find out more and more things to carry progress forward

There is one rather minor point Mr Main calls these materials steels That is very natural for a steel-maker, but I do not think they are steels , they are alloys of iron A material that contains only between 50 and 60 per cent of iron is not a steel and has not any of its characteristics It does not harden or do many of the other things that steels do , I think, therefore, that to call it steel is rather misleading

There is another point that is perhaps worthy of mention We are accustomed to think of steel as a cheap metal When we have an alloy containing only 50 or 60 per cent of iron, it is very natural that that material cannot be as cheap as if it contained 90 per cent of iron (It is worth remembering, that they are called steels)

Mr Main said that these steels have not the high elastic modulus of ordinary steel I should like to have figures on that point, as I think they would greatly interest areonautical engineers, particularly with regard to tubes, where it is the elastic modulus which matters more than anything else

Regarding the behaviour of metals under high temperature, the lecturer touched on a difficult point Work at the National Physical Laboratory and elsewhere has shown that at high temperatures it is not at all easy to determine the stress at which a material will ultimately fail If the test piece undergoes any measurable extension during a reasonable length of test, then it is probable, but not quite certain, that it will finally break, but the difficulty is to know when the limit has been reached, unless the test is prolonged over many months Much work has been done on this subject, and also to try and arrive at some method, quicker than continuance of the tests for several thousand hours, for determining what the limiting creep stress really is The whole question is full of interest, and is the subject of a series of researches being carried out by a Research Committee of the

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Department of Scientific and Industrial Research, of which I have the honour to be a member

With regard to the welding of some of these steels, that is of particular importance in regard to strip for certain types of aircraft construction I remember a firm who during the war made all the nickel-chromium strips for the production of spars by means of a machine in which the strip was turned over into a suitable section and then welded It could not be done, because the steel was of an "air-hardening" type, and the result was a series of cracks If these particular steels do not harden I take it that this kind of crack would not occur, and welding could be done in strips If that is so it might facilitate a type of construction which would be of great advantage

Coming to the non-corrodible side, there, of course, we have to deal with a question which from the aeronautical point of view is a very open one By using *high tensile nickel-chromium steel of the type described by the lecturer*, certain advantages and disadvantages are obtained The density of the steel is a disadvantage, and in order to keep down the weight of a structure we have to use steel of a very thin section, and this is a serious disadvantage All kinds of difficulties arise, local buckling stresses become a serious matter, and the risk of local damage is very great Therefore I suggest that even these steels are not completely victorious over light alloys, and I do not think they will be in the end

With reference to the reinforcement of St Paul's, I saw something of the tests on a variety of steels The way in which several of these corrosion-resisting materials withstood severe tests was astonishing Whether or not it is really necessary to use such material when it is going to be buried in concrete, is another question

I thank you for giving me this opportunity to express my interest in Mr Main's lecture, and my very cordial appreciation of the work that he and his firm have done in this matter

Mr W O MANNING I do not think that the extent to which the progress of engineering depends on the work of the metallurgist is perhaps generally appreciated If we take all the more recent developments of all kinds, we see that those things have only become possible because the materials have been available for the engineers To take a specific example suppose that to-day the only materials we had were cast-iron, copper, and a few of the non-ferrous metals, I doubt if we could produce a better battle-ship than Nelson's "Victory" As a matter of fact, I believe I was very nearly the first to use stainless steel in aircraft construction, and as I am particularly interested in seaplanes, it was a very important item I started by using some strips of plate on one side of the hull to prevent damage by water These materials were known as stainless irons After 18 months' use the amount of corrosion was negligible After that I started using the stainless steel fittings, and it is beyond doubt that there is an immense field for stainless steel in that kind of work

I am very glad that Mr Main has referred to the question of manifolds, because these have been a serious difficulty for many years I shall be glad to

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know whether any manifolds made in that way have been tried, and what the result was—whether the weld was as non-corrosive as the material itself

The question of exhaust turbines is interesting If the difficulties in that direction can be got over, I think the exhaust turbine will be used very extensively in the future in supercharging engines The progress in that respect is of special interest to aeronautical engineers

Will the lecturer please let us know to what extent these steels can be soldered and brazed ? Has brazing any effect on the existence of corrosion ?

Referring to some of the points raised by Dr Rosenhain, may I suggest to metallurgists that in considering the manufacture of alloy steels they should endeavour to reduce the specific gravity

Dr ROSENHAIN The only alloying element of low density which can be used in steel with any great success is silicon, and one cannot use much of that without making the steel brittle The real difficulty about alloys of intermediate density is that metals of widely different densities produce alloys which, except near either end of the series, are useless for structural purposes because they are weak and brittle Alloys which contain two such metals in anything like equal proportions are useless mechanically Consequently, while we have alloys consisting mainly of aluminium, strengthened by the addition of small amounts of heavier metals, and alloys of iron containing small amounts of lighter elements, useful alloys of intermediate density cannot be produced I am afraid that the chance of producing a useful iron alloy of low density is very remote Some of our metallurgists have, of course, succeeded in doing it, but then it is a mixture of iron with air !

Mr C G CARLISLE I should like to express my thanks to Mr Main for his interesting lecture

I had no idea that these steels would be referred to to-night , what few remarks I had thought of making were in connection with the usual aircraft steels as indicated in the announcement, but perhaps Dr Rosenhain's remark about the last word in heat-resisting gives me a slight lead in saying that I may be able to supply the " next word " with regard to the base from which these steels are made

Mr Main has not referred at all to the base of iron from which these steels start, and it seems to me an important point that that base should be as pure as possible Recent work I have done on steels leads me to believe that steel or iron made from an entirely different source from that we are familiar with, namely, from, say, a highly refractory ore containing Titanium Oxide, would give us a better base to work on, and yield results much superior to the present steels

To me as a steel-maker it is not at all impressive to make these various additions of Nickel, Chromium, etc What is worth accomplishment is to obtain greater purity of product, rather than the juggling with a number of elements I can get my bread and butter more or less in making stainless steel of the common and garden variety Many users of stainless steel, particularly the cutlery manufacturers, have not minded the price at all, and have gone on improving and cheapening their product, and now they can produce an alloy article in many cases cheaper

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than ordinary steel. I feel that if the engineer would stop thinking about the commercial side every time, and would get ahead in encouraging the metallurgist in making these steels, it would be a considerable help, and the metallurgist could then cheapen his product, due to the fact of greater quantity being required.

M. DE SAINT AUBIN: I should be very interested if the lecturer can give us any information as to the result of experiments in connection with condenser tubes.

Mr. J. R. HANDFORTH: The use of "Era" Steel has been spoken of with regard to its success for exhaust valves of aero engines. I believe it has also been tried for sparking plugs, and in a discussion regarding its value for that purpose it was mentioned that after being in use for a fair time the material became "rotten."

It has also been suggested from Sheffield that there is a possibility of a change in this material when used for exhaust valves for engines.

I should like to ask the lecturer whether he has, through his firm, any information on that particular point. Does this material change in physical properties after long use—say of a thousand hours?

MR. MAIN'S REPLY TO THE DISCUSSION.

It is very gratifying to have such an excellent discussion as you have given to the paper.

Dr. Rosenhain made some remarks about the future for Heat and Corrosion Resisting Steels, which appear to be in complete accord with our own views. I believe these steels have an important future in engineering, and with the tendency towards still higher operating temperatures and pressures their use must become more and more imperative. The knowledge that these steels exist will no doubt stimulate engineers who may have been holding back for want of them.

The question was raised as to whether or not these materials may rightly be called steels. Dr. Rosenhain is, of course, fully aware of the many discussions which have taken place in the metallurgical world regarding the proper use of the word "steel." I do not know that there is any special reason for calling these present products "steels" except as a matter of convenience, and that some distinctive term seems necessary for alloys which have a preponderant ferrous base, as compared with more distinctly non-ferrous materials. As the result of the many discussions which have taken place no generally agreed definition of the term "steel" seems to have been arrived at, and although the present materials contain comparatively high percentages of alloying elements, it is difficult to know at what limit to draw the line, in separating what may be called steels from alloys to which some other description should be applied.

With regard to the elastic modulus of these steels, in the case of "Era C.R." Steel we have had occasion to specially determine the point. While with ordinary steel and most alloy steels the figure, as is well known, varies very little from 30

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million pounds per square inch, in the case of "Era C R" Steel the modulus was found to be 27 million pounds per square inch

I can agree with all Dr Rosenhain has said about the difficulties with regard to the determination of creep stress As he says, it is a matter of very careful and patient research to be able to say what the creep stress limit is for any steel at any particularly high temperature It is only as the result of such long continued tests that we are able to say, for example, that for practical purposes the creep stress limit for "Era" Steel at 800° C is $2\frac{1}{2}$ tons per square inch A similar position obtains with regard to the determination of the fatigue stress limits of steels, and much work in that direction has been and is still being done by prominent investigators, both here and in America Down to the present no easy way of determining fatigue limits has been arrived at, just as there is no short method of determining the creep stress Perhaps rapid and reliable methods may be found eventually, and I should personally be one of the first to welcome them in either of these two cases

As regards the question of welding, the steels referred to in the paper do weld in a very satisfactory way, though if put in the hands of the ordinary welder, without previous experience of these particular products, he will probably not turn out very satisfactory welds In the hands of expert welders, by accommodating themselves to the special nature of these materials, simple methods have been established by which the actual welding is carried out by girls who do the work quite satisfactorily

Dr Rosenhain put in a word regarding the rival merits of the light alloys—in the development of which for aeronautical purposes he has taken such a prominent part—in comparison with high tensile steels It is not, of course, for me to say what the final result of this rivalry may be It is our business to bring the material with which we are specially concerned, namely steel, to its highest point of development, and I think the paper shows that some quite goods results have been achieved

Mr Manning's remarks too were specially interesting With regard to manifolds, so far as we are concerned the matter is in the experimental stage Manifolds have been made up in "Era C R" Steel but are not yet actually put to practical test, though we feel very confident of their success for the reasons mentioned in the paper

His question with regard to the specific gravity of these steels has already been admirably dealt with by Dr Rosenhain, and I would only add that the necessity for as low a specific gravity as possible is one of the things which we bear in mind However, in face of other considerations, for example the beneficial results obtained in some cases by the addition of the heavy metal tungsten, there is not much one can do

With regard to brazing and soldering, each of the steels mentioned submits to these processes very well with a suitable technique , so far as the corrosion of joints is concerned, an autogenous weld gives the best results, as in that case the junction of dissimilar metals favourable to electrolytic action is to a large extent avoided However, while pointing out that the same degree of freedom from corrosion is not to be expected from brazed and soldered joints as compared with welds, I do not wish to convey the impression that serious corrosion is to be expected ,

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it is characteristic of these special steels that electrolytic action between them and other metals is nothing like so pronounced as, for example, is the case with non-rusting chromium steel

I was very pleased to hear Mr Carlisle's remarks, and was particularly struck by his reference to "stainless steel of the common or garden kind" Coming as it did apparently straight from his heart the expression seems to me to have a good deal of meaning, because does it not show what progress is being made, when stainless steel, the practical application of which is after all, not so very old, can be talked of to-day as a common or garden product As regards the iron base used, these steels lend themselves to most of the steel making processes It is however, fully realised that, as in the case of other steels, the character of the iron base as regards purity is of importance, and it is idle to expect to obtain the best results without using the best materials

Replying to M St Aubin with regard to condenser tubes, I should like to say that the matter is under our consideration, and we have experimental work going on in that direction at the present time Naturally it takes some time to initiate and carry through to completion practical trials of such a nature, and I am unable to report any results at the moment We appreciate however, that such an application if successful, would be a very important one for non-corrodible steel

Mr Handforth raised the question as to the possibility of a change occurring in "Era" Steel in the course of time under exposure at high temperatures, in our experience of its use, that is to say mainly at temperatures up to about 1000° C, we have not observed any such change What may happen beyond this temperature, above which in general we do not advocate its use, I am not prepared to say, although I should not anticipate any change The question of the use of "Era" Steel in sparking plugs has been taken up, and "Era" Steel is now being used with advantage in quite considerable quantities for the purpose One of the difficulties has been that the manufacturing costs of these articles are specially low, and the introduction of a comparatively expensive material therefore not altogether welcomed However, its adoption evidently shows that this is a case where the advantages gained fully justify its use Even in this case where the temperature of the material at the actual sparking point naturally reaches the region of the melting point of the material, we have not heard of any deterioration in course of use

I will conclude by thanking the speakers for their very kind remarks generally on the paper

The CHAIRMAN Our lecturer has mentioned that in few branches of engineering is enterprise more evident that in aeronautical engineering It has been said, I think by Mr Blake, that *in aviation the bold conception is the nearest to commonsense*, and the recently accomplished flights of Colonel Lindbergh and also of Flight-Lieuts Carr and Gillman, bear testimony to it I would like, however, to add that of all forms of enterprise that which is the most rare is the gift of suddenly perceiving that which was hidden from other men It is this gift that we honour in pioneers in invention such as Sir Robert Hadfield, to whom we owe *manganese steel*, a discovery which in the words of the eminent French metallurgist, the late

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M Floris Osmond, *ranks in the history of the metallurgy of iron as equal in importance to that of quenching of carbon steel*

As our lecturer said, manganese steel was the original representative of the so-called " austenitic " steels, and with that steel commences the history of modern alloy-steel development A further step is marked by the introduction of heat-resisting steels, their most important feature being the permanence of their physical character under a wide range of temperatures The constructor and the engineer must be made, however, to realise (and our lecturer as well as Dr Rosenhain emphasised this point) that here they are dealing with a material of a new and peculiar kind, extremely valuable, indeed in most respects unique, but different from what has usually been called *steel*

It was interesting to hear about the co-operation established between the lecturer's firm and the French works of Commentry-Four-chambault as regards the introduction of many new alloys, for rotors, etc It is a special pleasure to me to mention in that respect the name of their eminent expert, M Chevenard, whose name is widely known amongst metallurgists

I think all concerned in the preservation and restoration of the beautiful work of Sir Christopher Wren were interested to learn that one of the most recent applications of " Era" Steel is its use for the reinforcements of St Paul's Cathedral

We all feel very much indebted to the lecturer for the interesting and charming way in which he introduced us into the mysteries of heat-resisting steels, and it is now my pleasant duty to ask you to accord to Mr Main a hearty vote of thanks for his valuable paper

Mr DUDLEY WRIGHT I have great pleasure in proposing a hearty vote of thanks to Colonel Belaiew for so kindly and ably presiding at this meeting

The votes of thanks were carried with acclamation, and after the lecturer and Chairman had responded, specimens of steel from the Hadfield Research Laboratories were examined with much interest

NOTE —Accompanying this Paper is a Temperature Colour Chart prepared by Sir Robert Hadfield, Bt , F R S

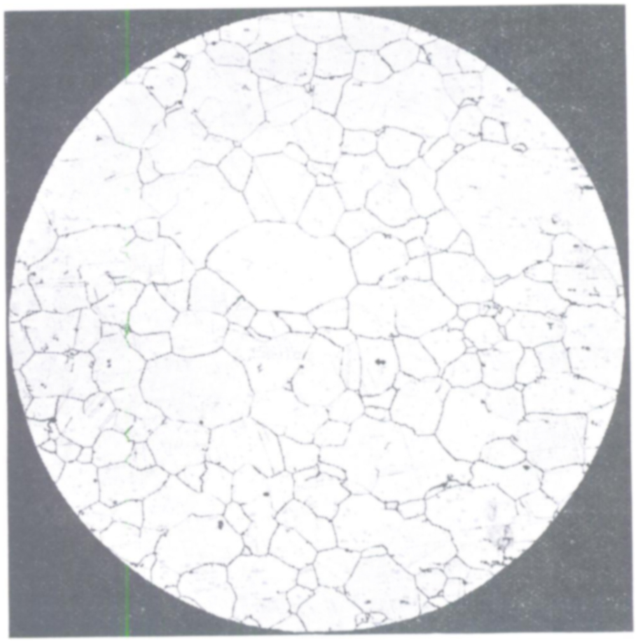

FIG 1

MICROSCTRUCTURE OF " ERA " HEAT RESISTING STEEL

(*Magnification*, 50 *diameters*)

Equiaxed austenitic grain structure showing typical twinning of grains A small amount of free carbide is present in the form of tiny globules

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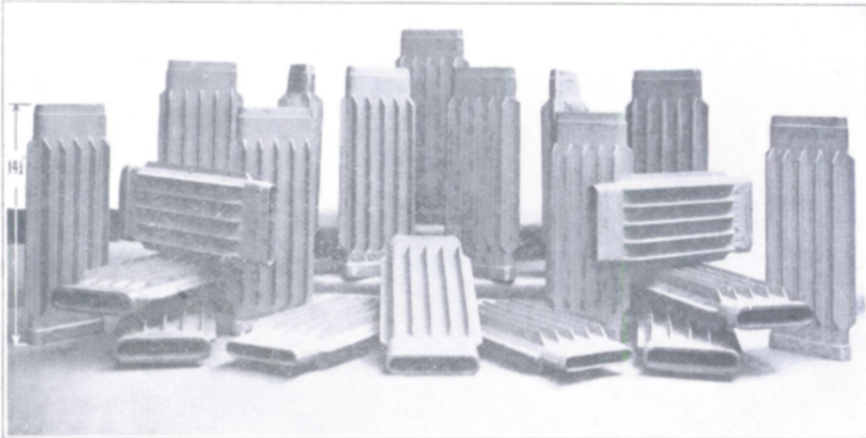

Fig 2
Recuperator Tube Castings of "Era" Heat Resisting Steel

Fig 3
Hearth Bricks and Rabble Teeth for Zinc Roasting Furnaces

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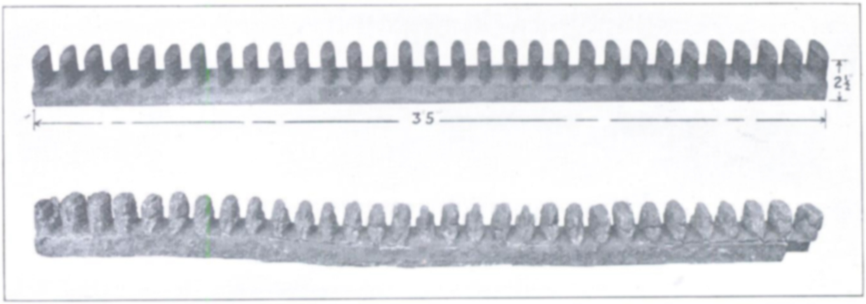

FIG 4
Showing a rack of mild steel after twelve weeks service at 950° C The upper illustration shows a similar rack of " Era " Steel after the same service

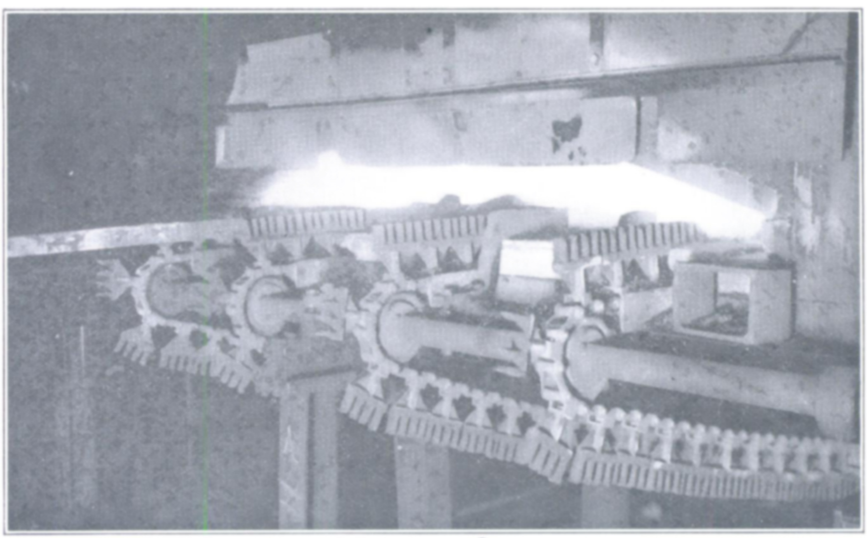

FIG 5
CONTINUOUS CONVEYOR OF " ERA " HEAT RESISTING STEEL
This has been in service in a continuous heat treatment furnace at a constant minimum temperature of 950° C

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Fig 6

Aeroplane Engine Valves of "Era/ATV" Steel

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FIG 7

" ERA/ATV "

Brinell hardness, 196

Angle of Bend 50° (without fracture)

Brinell hardness Before treatment, 196
After treatment, 196

HIGH SPEED STEEL

Brinell hardness, 550

Angle of Bend, Nil

Brinell hardness Before treatment, 260
After treatment, 550

Bending test on Valve of " Era/ATV " steel after sudden cooling from 900° C, showing absence of air hardening and embrittling effect

The Valve of High Speed Steel similarly treated is shown for comparison, and demonstrates the effect of such treatment on steel of air hardening type

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FIG 8
VALVES OF " ERA/ATV " STEEL FOR DIESEL ENGINES

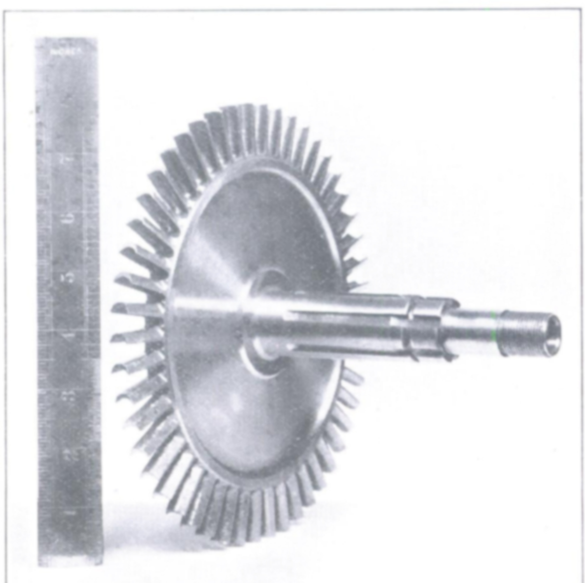

FIG 9
ROTOR FOR EXHAUST GAS TURBINE

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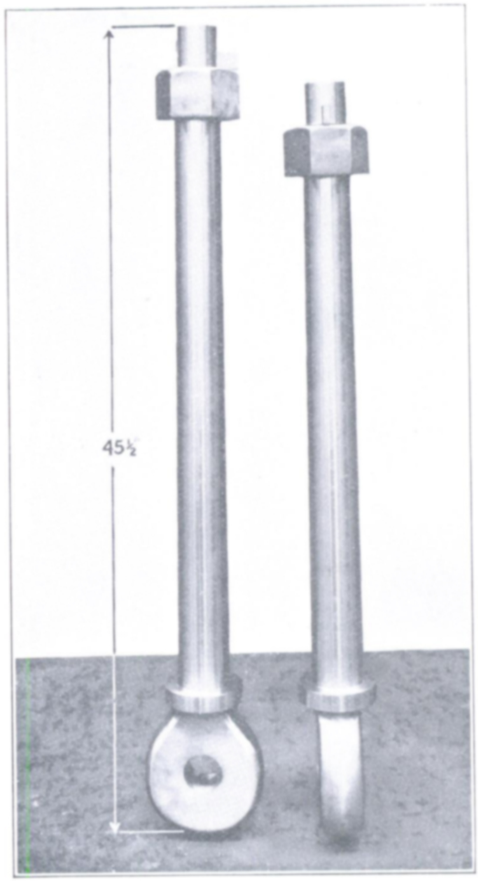

FIG 10

BOLTS FOR HARBOUR LOCK GATES

Complete with Nuts and Cotters

Made from Non-Rusting Chromium Steel

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Fig. 11

Submarine Hydrophone Diaphragm of Non-Rusting Steel

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FIG 12

UNTESTED (1)	(2) & (3) after immersion to depth of 9 inches in Nitric acid (1 20 Sp Gr) at room temperature for 24 hours	
ORDINARY CARBON STEEL (Original size)	(2) ORDINARY CARBON STEEL, 45% loss in weight by Corrosion	NON-CORRODIBLE STEEL "Fra C R" No loss

RESISTANCE OF "FRA/C R" STEEL TO CORROSION BY NITRIC ACID

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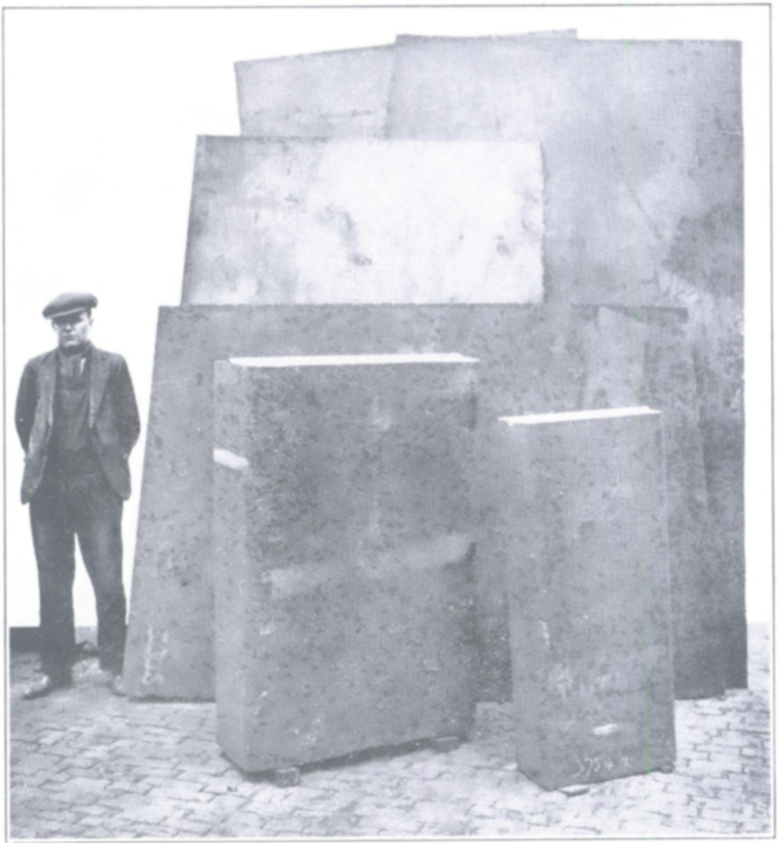

FIG 13

"ERA" NON-CORRODIBLE STEEL

The Four sheets in this photograph were rolled from ingots as shown, into two plates, about 20 feet in length by 5 feet in width by $\frac{1}{4}$ inch in thickness

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Fig 14

Hollow-ware of "Era" Non-Corrodible Steel Formed by Cold Pressing

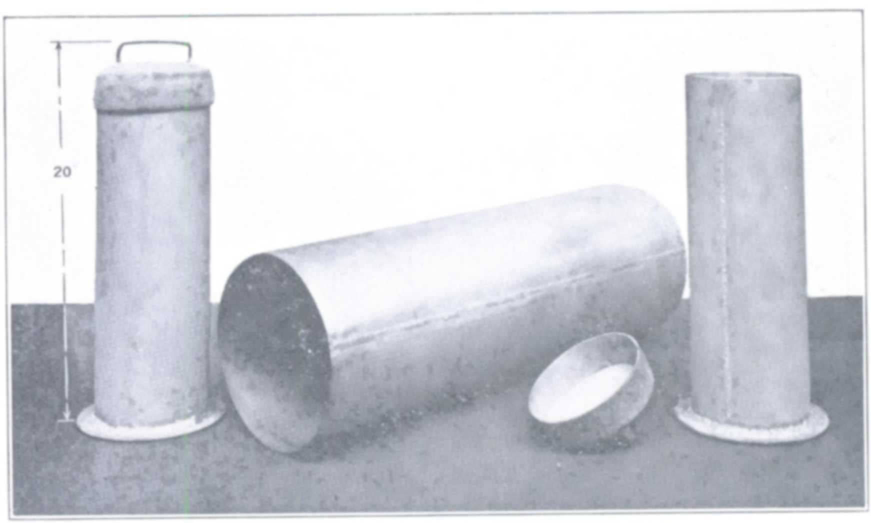

Fig 15

"Era" Non-Corrodible Steel Welded Containers for Corrosion Resisting Purposes

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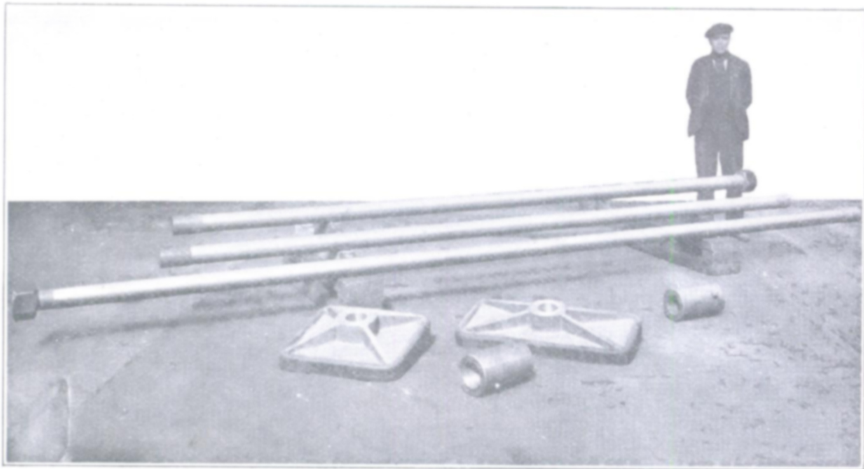

Fig 16

Reinforcements for the Restoration of Saint Paul's Cathedral

The Photograph shows a Complete Unit comprising

1 Tie Bar 4 inches diameter by 18 ft 7 inches in length
1 Tie Bar 4 inches diameter by 14 ft 6 inches in length
1 Tie Bar 4 inches diameter by 13 ft 6 inches in length
2 Nuts, 2 Screwed Couplings, and 4 Pins
2 Wall Plates

The whole of the above are made of "Era" High Tensile Non-Corrodible Steel

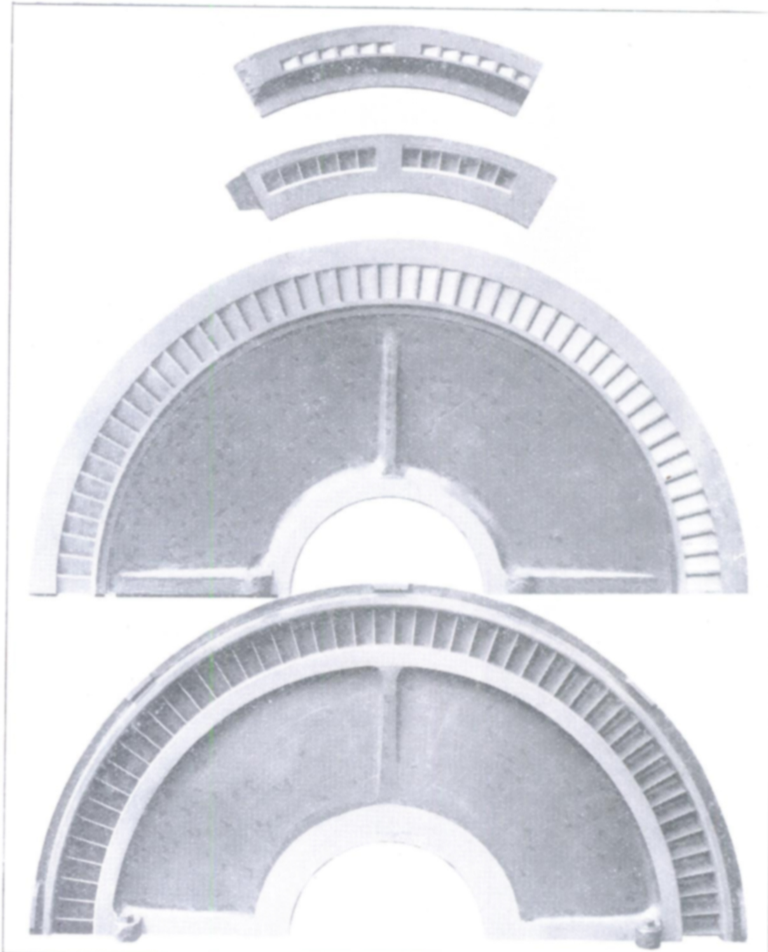

FIG 17

NOZZLE PLATES AND DIAPHRAGMS FOR 67,000 H P TURBINE (Speed 7,000 r p m) Made of " Hecla A T V " Steel

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