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Description of the Damage in Steam Turbine Blading due to Erosion by Water Droplets

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XVII. Description of the damage in steam turbine blading due to erosion by water droplets

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[Plates 41 to 43]

Efficient expansion of steam in turbines cools the vapour to the point where it becomes wet. As turbines become larger the higher blading speeds employed lead to erosion damage of the blading as a result of impact with accumulated water in the form of drops.

The distribution of this damage in the turbine is discussed. The processes of drop formation, release and subsequent motion before impact with the moving blades are described and the application of this knowledge to practical design is illustrated by particular examples.

Before we consider some aspects of the damage due to the impact of water drops on the blading in steam turbines it will be helpful to recall some pertinent design features.

The steam normally enters the turbine as superheated vapour at considerable pressure, but before reaching the condenser it yields up large quantities of energy in doing work on the shaft. In the process the steam becomes a wet, cool vapour of very low pressure and density, with water present to the extent of some 5 to 15% by weight.

The large volume of the vapour to be handled by the low pressure stages of the turbine requires blade annuli of large diameter, even though the axial velocity at exit may be high (700 ft./s). In current designs for high power the blades move at tip speeds which reach 1800 ft./s and as the steam is wet some impact effect between moving blades and water particles is only to be expected. As these turbines operate continuously, relatively minor deformation at each impact on the blade surfaces can very soon lead to more damage than is tolerable.

The time which elapses between the first formation of moisture droplets and the exit of the steam to the condenser may be less than 0·01 s, but the vapour has to follow a rapid and devious course through alternations of fixed and rotating blade rows, in the course of which it is subjected to high accelerations as a result of repeated changes of direction. The accelerations have a separating effect on the two phases of the vapour, the dry steam and the moisture particles or fog, as a result of which a small fraction of the latter wets the surfaces of the fixed and moving blading.

The wetness on the moving blades is centrifuged by the rotation and thrown to the outer wall of the casing annulus, where some of it may be absorbed into water films already moving there, while some may be bounced back. Water particles which have wetted the fixed nozzles and other stationary surfaces move slowly under forces due to gravity and steam drag to points of concentration, such as the trailing edge of these blades. Accumulations of water in the form of films or large drops may adhere to the nozzle or other fixed surfaces for a brief time, but are ultimately moved on downstream by steam drag to drift into collision with the fast-moving running blades.

The impact smashes the drops and the velocity imparted drives the water outwards to

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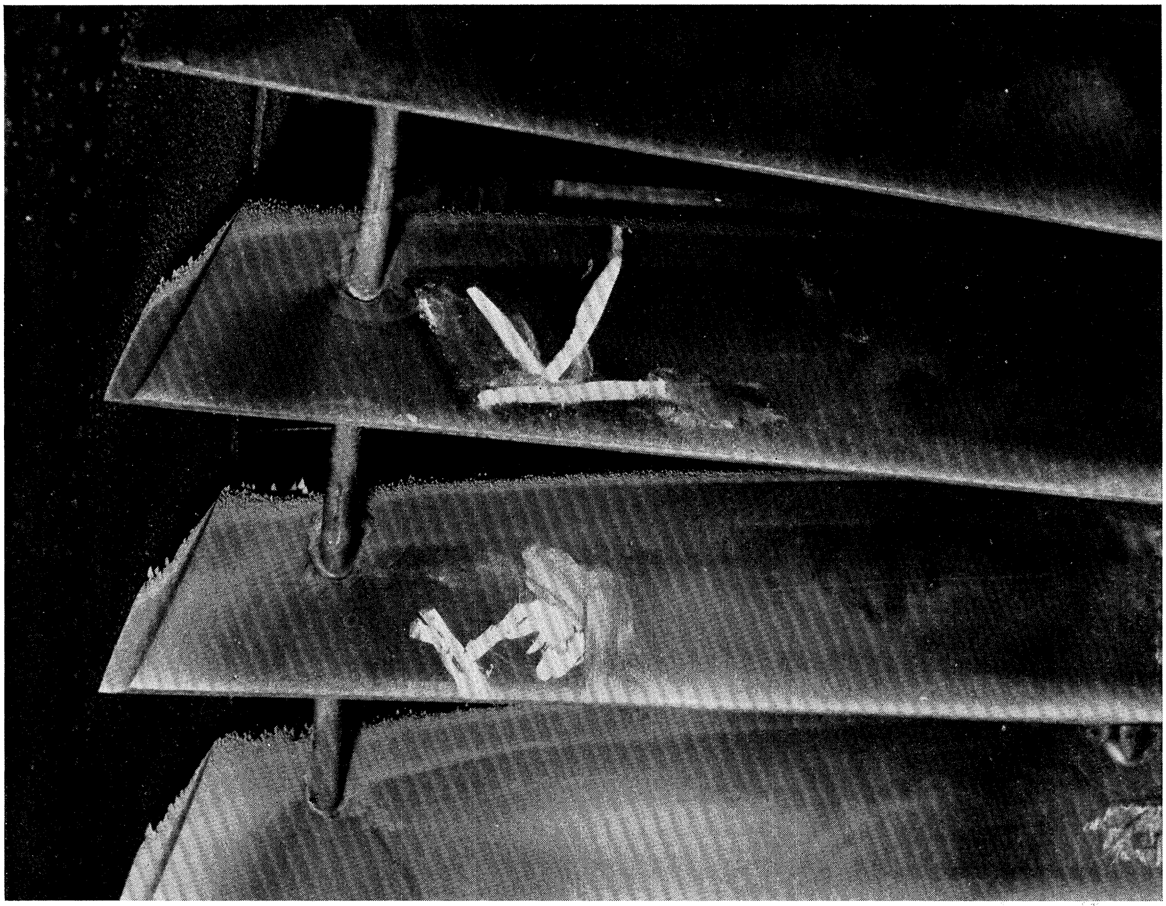

FIGURE 1. Erosion attack on unshielded stainless iron blade (0·1 % C, 12 % Cr).

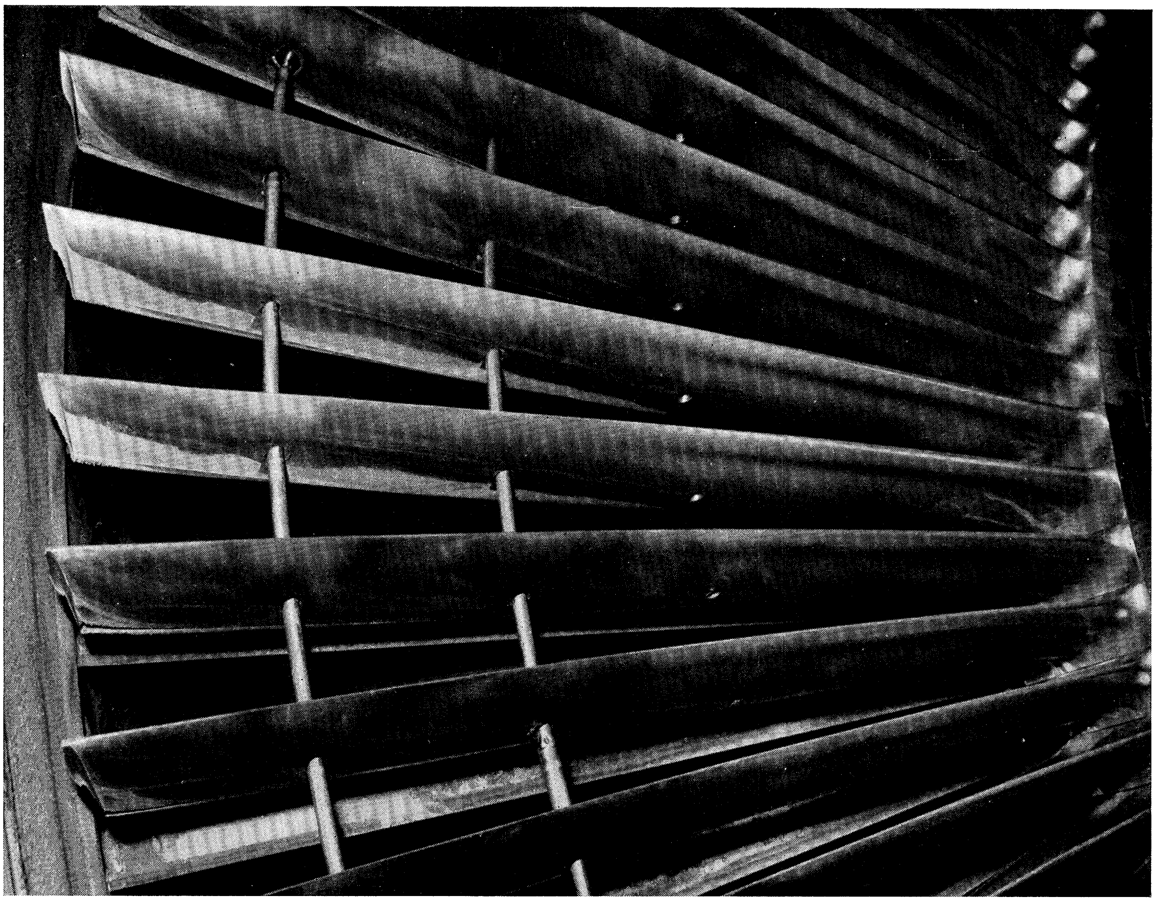

FIGURE 3. Tangential erosion of stainless iron blades behind the cobalt alloy shields. The middle blades are of stainless iron, those on either hand of manganese nickel steel (0·8 % Mn, 0·9 % Ni) hard chromium plated to a thickness of 0·001 in.

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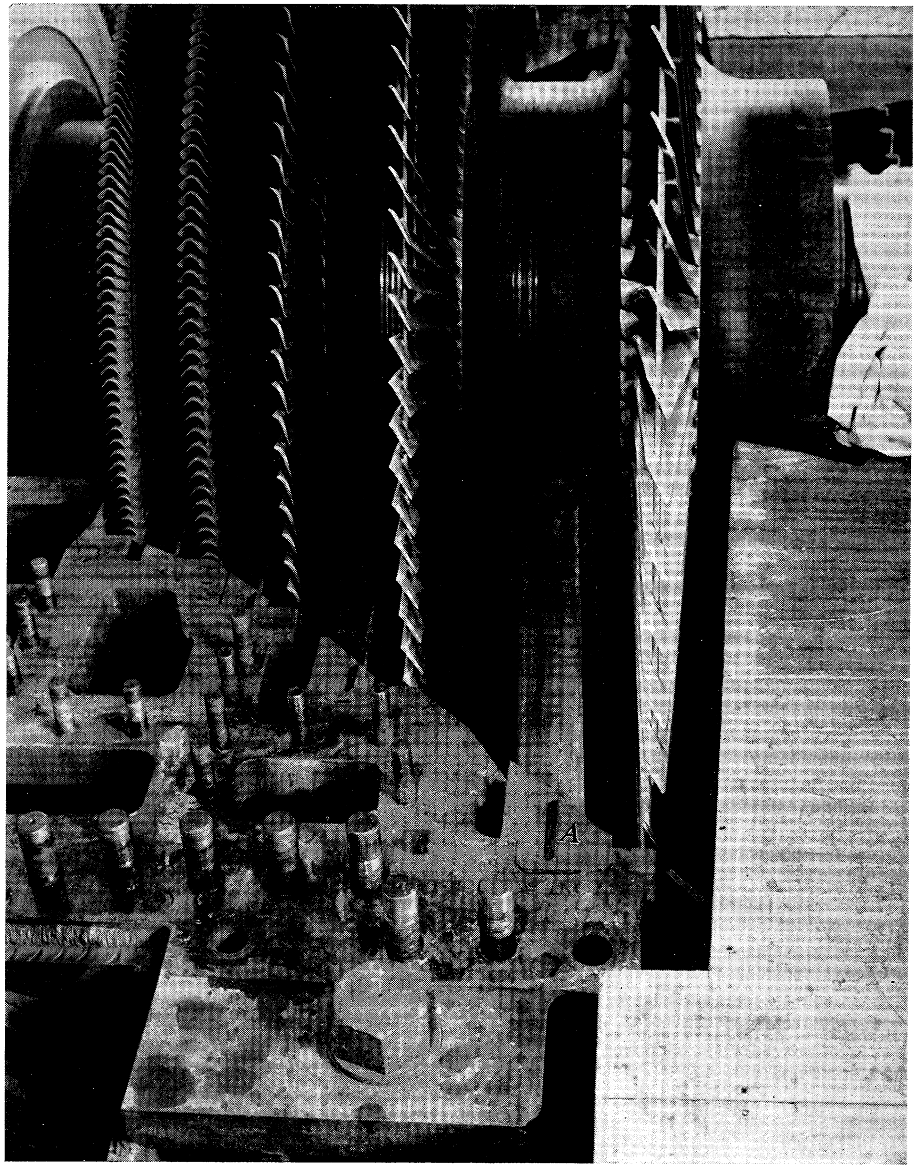

FIGURE 4

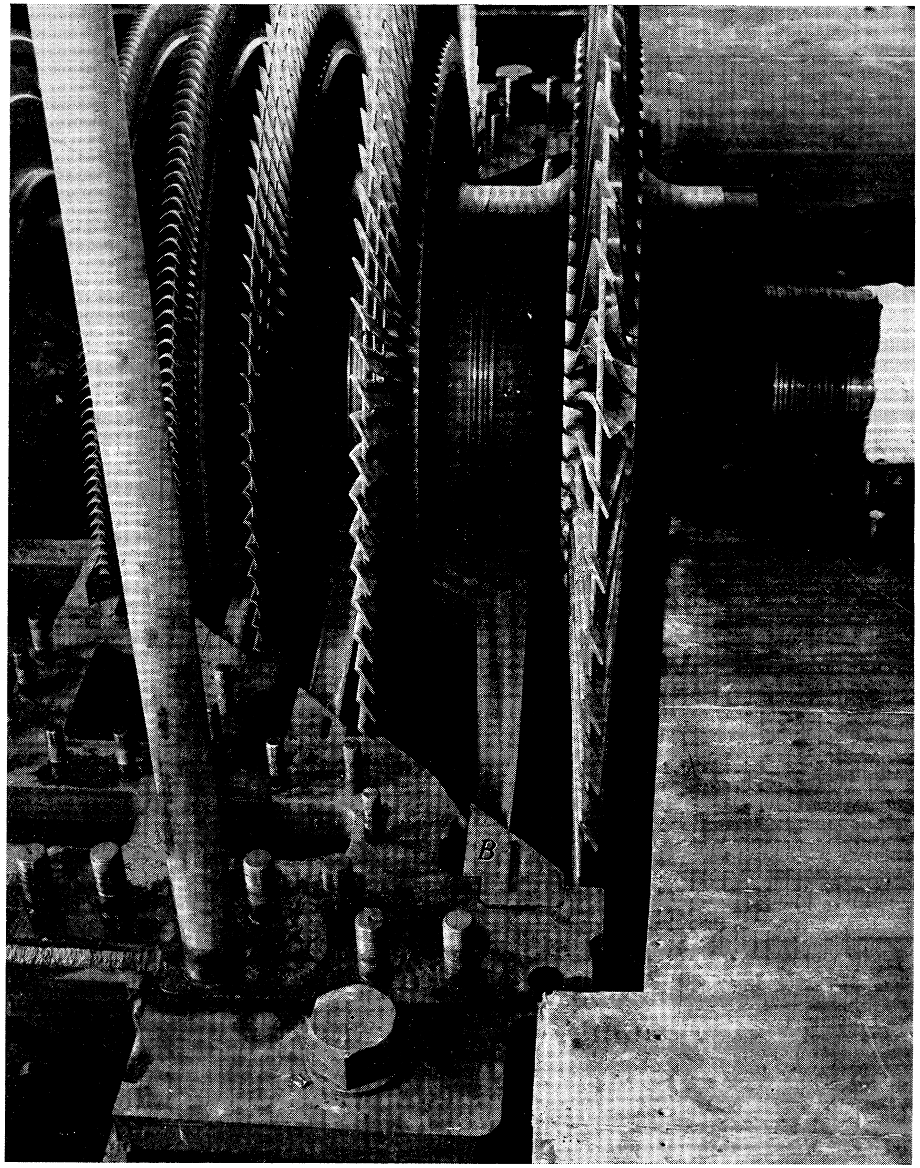

FIGURE 5

FIGURES 4, 5. Low pressure steam turbine with upper half casing removed showing at *A* older design of diaphragm with wide nozzles set closely to the running blades (36 in. long) and at *B* a revised design of diaphragm with nozzles of minimum wetted area set back from the running blades.

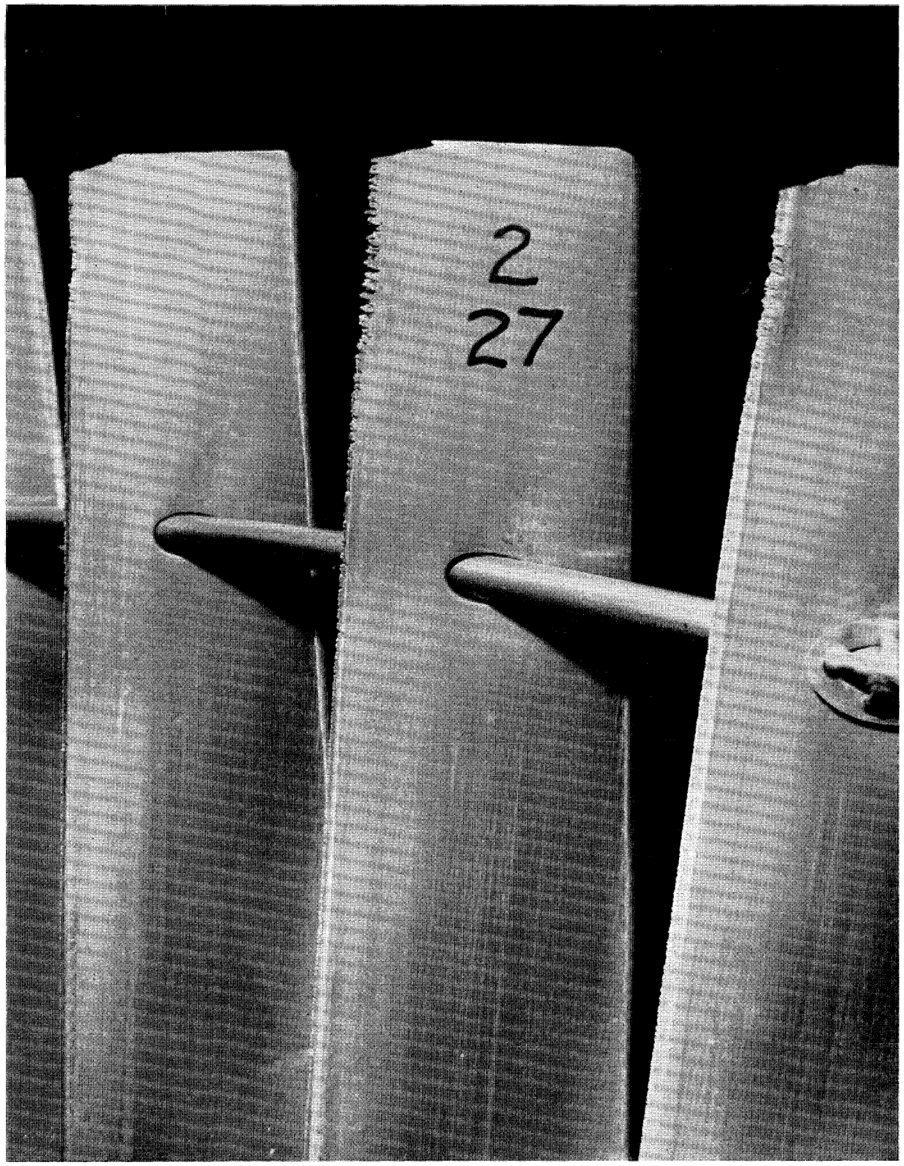

FIGURE 6. The erosion damage on the 36 in. blading run in connexion with the wide closely set diaphragm of figure 4 opposite.

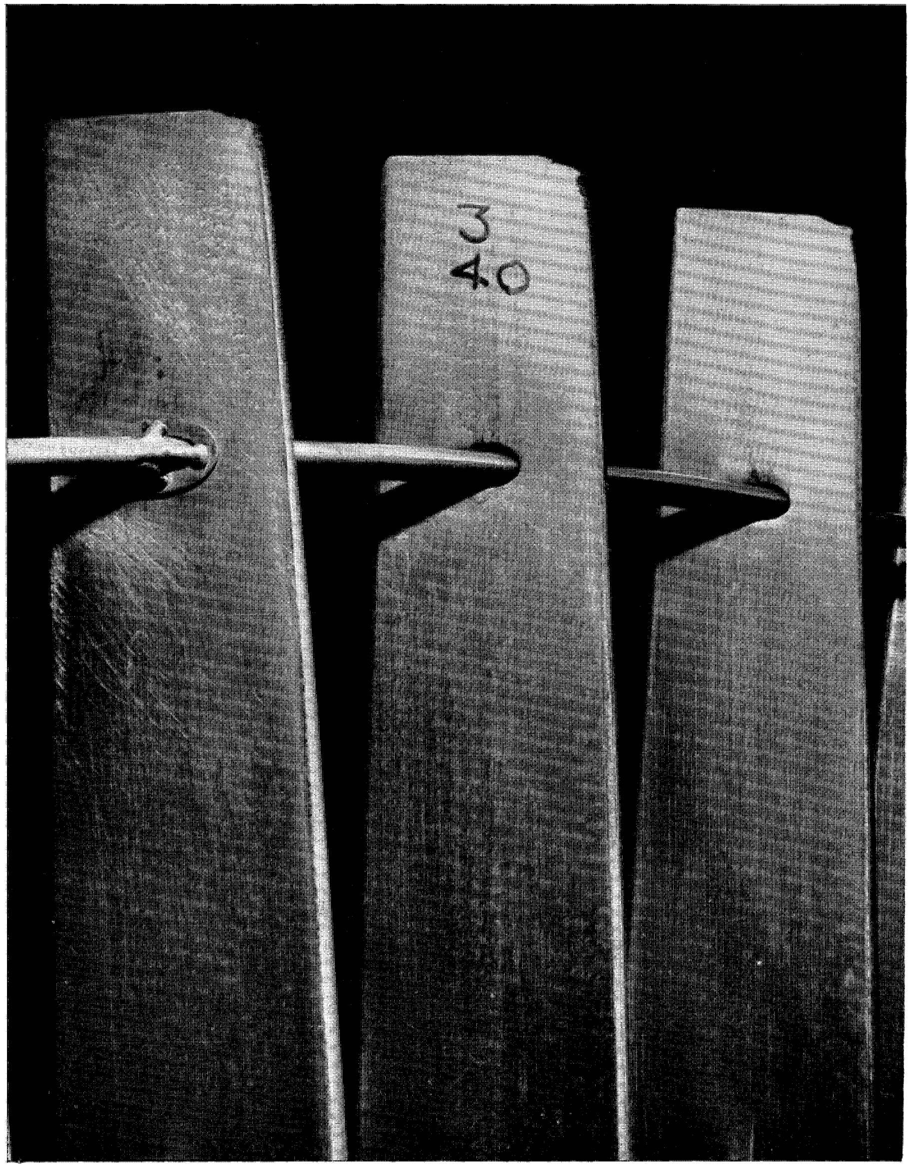

FIGURE 7. The greatly reduced damage resulting from the use of the narrow diaphragm set farther back from the running blades as in figure 5.

adjacent stationary surfaces. The process of collection and tearing-off followed by impact with running blades repeats itself until the water finds its way through the blading or possibly through some drain opening to its ultimate destination in the condenser.

The exhaust blading of a steam turbine is therefore subjected to a severe ordeal by liquid impact, and very commonly considerable damage ensues. There is also a braking effect due to the impact, but our interest here is concentrated on the damage to the blade surface and form.

The severity of the conditions of operation of the blading will be realized when we compare them with those for an aeroplane wing.

(*a*) The speed of impact is of the order of 1000 mi./h.

(*b*) The shower of water droplets continues during the whole period of operation at full load, which may extend up to 100000 or 200000 h during the operating life of the turbine.

(*c*) The stationary surfaces ahead of a particular rotating blade row act as collectors and concentrate the smaller particles of moisture into large drops, which are then dispensed to the running blades. This concentration, together with that due to the centrifuging action by running blades, brings much of the moisture to the outer radii, where the impact is most severe since the blade surfaces are moving at the highest speeds.

The turbine blades, being of steel, are of course much better able to sustain continuous bombardment than an aeroplane wing—subjected only to occasional rain showers. But the rate of attack on unprotected steel is nevertheless high, as shown in the photograph (figure 1, plate 41). This shows the extent of attack on a blade of stainless iron (12% Cr, 0·1% C), moving with a tip velocity of 1253 ft./s in steam of average wetness 12·6%. For experimental purposes the blade was exposed to normal operating conditions but without any form of protection on the leading edge of the blade.

The general character of the damage to turbine blades by impact with water droplets is well known, and the reason for the very concentrated attack on the leading edge of the blading is easily demonstrated in figure 2. When a water drop is pulled away by steam drag from the fixed surface its initial velocity is zero, and it acquires only a fraction of the nozzle steam velocity before it collides with one of the blades in the fast moving row. As shown by the velocity triangle, it enters the blade passage with a very flat relative angle and its area of impact on the blade is therefore limited as shown in the diagram. When the blade surface is struck in a normal direction the damage can be severe. Damage of a less severe character, apparently caused by nearly tangential impact, can occur simultaneously but farther back along the surface of the blade (figure 3, plate 41). It appears likely that this is caused by smaller drops coming in at nearly full steam velocity or the damage may be due to fragmented drops from the initial impact near the leading edge. Stainless iron appears particularly prone to this form of erosion attack.

The impact of water on the blades continues without intermission so long as the turbine continues to operate—as it normally does—at or near full load. However, it is a well known fact that the rate of wear in the turbine is not linear with time, but proceeds at a diminishing rate. It appears that initial roughening of the surface due to erosion damage diminishes the deceleration of the liquid drops in subsequent impacts, with reduction of the associated stresses in the material. Retention of water by the roughened surface may help in diminishing the stress applied to the metal.

From the description given it will be clear that there is a great variation in the size of drops just before impact. This size probably ranges from 0·01 to 1500 μm. This presents a difficulty for the reproduction in the laboratory of the exact erosion conditions in the turbine in order to test the resistance to erosion of various metals.

Only minor damage appears to occur on stationary surfaces from the impact of flying droplets. This is probably because water thrown from the bladed wheels nearly always strikes a stationary surface in a direction which is close to being tangential to the surface.

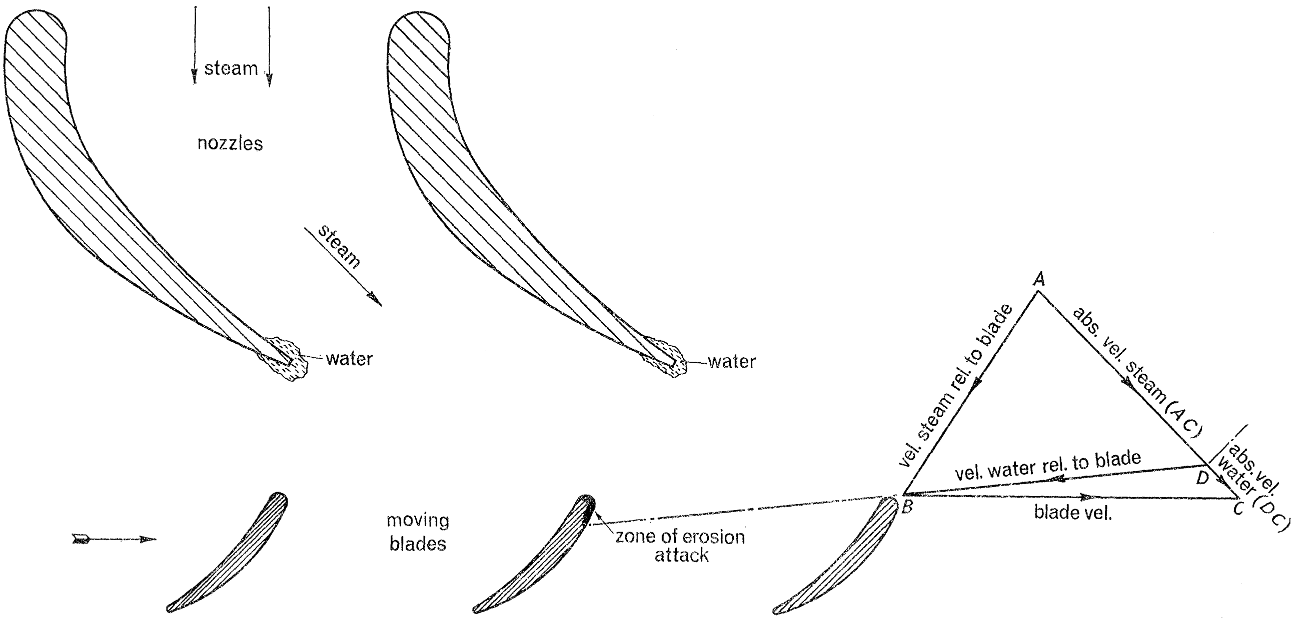

FIGURE 2. Vector diagram illustrating the relative velocities of steam and drops of water to the inlet edge of the moving blades in a turbine stage using wet steam.

Engineering interest naturally centres on those aerodynamically important surfaces which show the main damage, i.e. the outer one-third to one-sixth of the length of the moving blades and on the history and size of the drops of water which cause the damage there.

It has been apparent for some time that the accumulation of drops or flags of water on the trailing edge of the stationary nozzles or at corners on the casing bore has been the source of the larger drops which collide with the running blades. The presence of this water has been shown in films such as that shown by Mr Broom. An earlier film made in 1962 was shown by J. Caldwell during discussion at the 6th World Power Conference, Melbourne, 1962. We still do not know precisely the form in which this water reaches the leading edge of the blading. The subject is under active research and much has been written on the theory of the motion of large drops in a gaseous stream after leaving a position of rest, their acceleration and disruption into smaller drops, but only a limited amount of observation appears to have been completed as yet to compare theoretical predictions with the flight of actual drops in the turbine. It has to be remembered that the bulk of the wetness is present in the form of a fog and this greatly hinders observation.

Much evidently remains to be done. Clarification of the dynamics of water movement in the turbine will doubtless bring with it explanations for the fact that the degree of erosion attack in a new design is not always predictable and that the pattern does not always repeat exactly in turbines of the same design and manufacture running side by side under nominally similar conditions.

Although exact prediction is not yet possible, it does appear that a drop leaving the trailing edge of a stationary nozzle can be influenced favourably by giving it a longer path to traverse before impact with the running blade occurs. This will allow the drop to be accelerated more nearly to the steam speed and also cause a large drop to disintegrate into smaller drops, which in turn are more readily accelerated and cause less damage when they collide with the blade. It is also no more than commonsense to reduce the surface of the stationary nozzles as far as is possible without causing loss of aerodynamic efficiency. It is to be expected that with a lesser surface there will be a reduction in the wetness collected and shed as drops from the discharge edges of the stationary nozzles.

Figures 4 and 5, plate 42, show two arrangements of the stationary diaphragm, or ring of nozzles, associated with a wheel carrying blades 36 in. long with a tip diameter of 136 in., operating at 3000 rev/min. The axial spacing has been increased from 0·9 to 4·3 in. and the nozzle vanes reduced in number and chord width. As the two arrangements constitute the last stages of the opposing halves of a double-flow low pressure turbine (back pressure 1 in.Hg) the exposure to wet steam conditions is identical for practical purposes. The diaphragm with the original area and close axial spacing shows severe notching at the tip and an erosion marking of the blading extending inwards for some 18 in. from the tip (figure 6, plate 43), while the reduced area diaphragm with wider spacing of 4·3 in. between diaphragm and running blades shows much less notching and a reduced eroded length of 8 in. (figure 7, plate 43).

The illustrations shown refer to a design in which the blade annulus is relatively lightly loaded and operates over much of the year at a back pressure of only 0·75 in.Hg. The kinetic head sweeping accumulations of water from the exit of the fixed nozzles is only of the order of 10 in.H_2O, corresponding to a speed of about 140 mi./h in atmospheric air at ground level.

More highly loaded designs have greater kinetic losses at exit from the turbine, which affect adversely the economy of operation. They offer, however, in addition to the advantage of reduced first cost due to lesser size, a possible reduction of erosion attack, because the increased kinetic head at the nozzle exit reduces the size of the drops reaching the running blades. Theory also indicates the possibility of delayed condensation (supersaturation) and less deposition of water if the expansion through the stage is rapid.

The turbine designer is naturally interested in deformation and damage to his blading caused by the impact of water drops. He knows from experience that blading steels in the moderately hard condition best suited to withstand the high mean stress due to centrifugal forces and the possible excitation of vibration are not in the best state for withstanding erosion attack. It is therefore the practice to harden blades by various means along the outer length of the leading edge or over the whole tip area. Alternatively, hardened shields may be attached on the leading edges by welding or the use of silver solder.

Having had recourse to such means, which are very effective, the designer's interest is in how hardened leading edges behave under long sustained bombardment by many drops striking randomly at speeds not above 2500 ft./s. It is interesting but not immediately

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useful to be told in great detail what happens under a single impact. There is no assurance, for instance, that if a material shows a better ability than another to stand up to a single impact this ability will be maintained under multiple, random impact. There is a need, therefore, for the dual approach which already exists, i.e. the study of the effects of single impact on the one hand and the erosion wear or attrition resulting from long bombardment at speeds encountered in practice. Neither approach is more scientific than the other, nor is it useful to think of 'laws' of impact damage in the one case as necessarily excluding different laws in the other.

The ideal solution to the problem of erosion in turbine blading lies in the complete extraction of water from the steam at a rate which keeps pace with the rate of water formation as the steam expands. To see this is easy: to achieve it very difficult indeed. The whole process of expansion in the wet field may occupy only 0·01 s, and much of the water may be as far as 20 in. from either the inner or outer wall of the blading annulus. It is also water which has just condensed from steam, and a slight lowering of its pressure will make it revert to steam. It is not, therefore, easily collected to be taken to where it can do no harm, although attempts to do this have been made and are still being made by employing hollow, fixed nozzles in an attempt to suck or blow off accumulations of moisture from the trailing edge. Blowing off the water will reduce the size of the drops reaching the running blades, but will not reduce the total amount of water. It will do no more, therefore, than can be done by using diaphragms of reduced area, set farther back from the running blades. Water extraction belts at the casing wall are effective, provided a good flow of steam is drawn off through the same opening for regenerative heating of the condensate as it returns as feed-water to the boiler.

The main obstacle to progress has been, until recently, lack of visual evidence of the processes involved. The present series of observations in turbines, assisted by studies of drop impact effects, will provide valuable clarification, but, as has been shown above by the example of the modified diaphragm, the turbine engineer will almost certainly still find plenty of scope for his ingenuity in designing his way out of what is a difficult problem.

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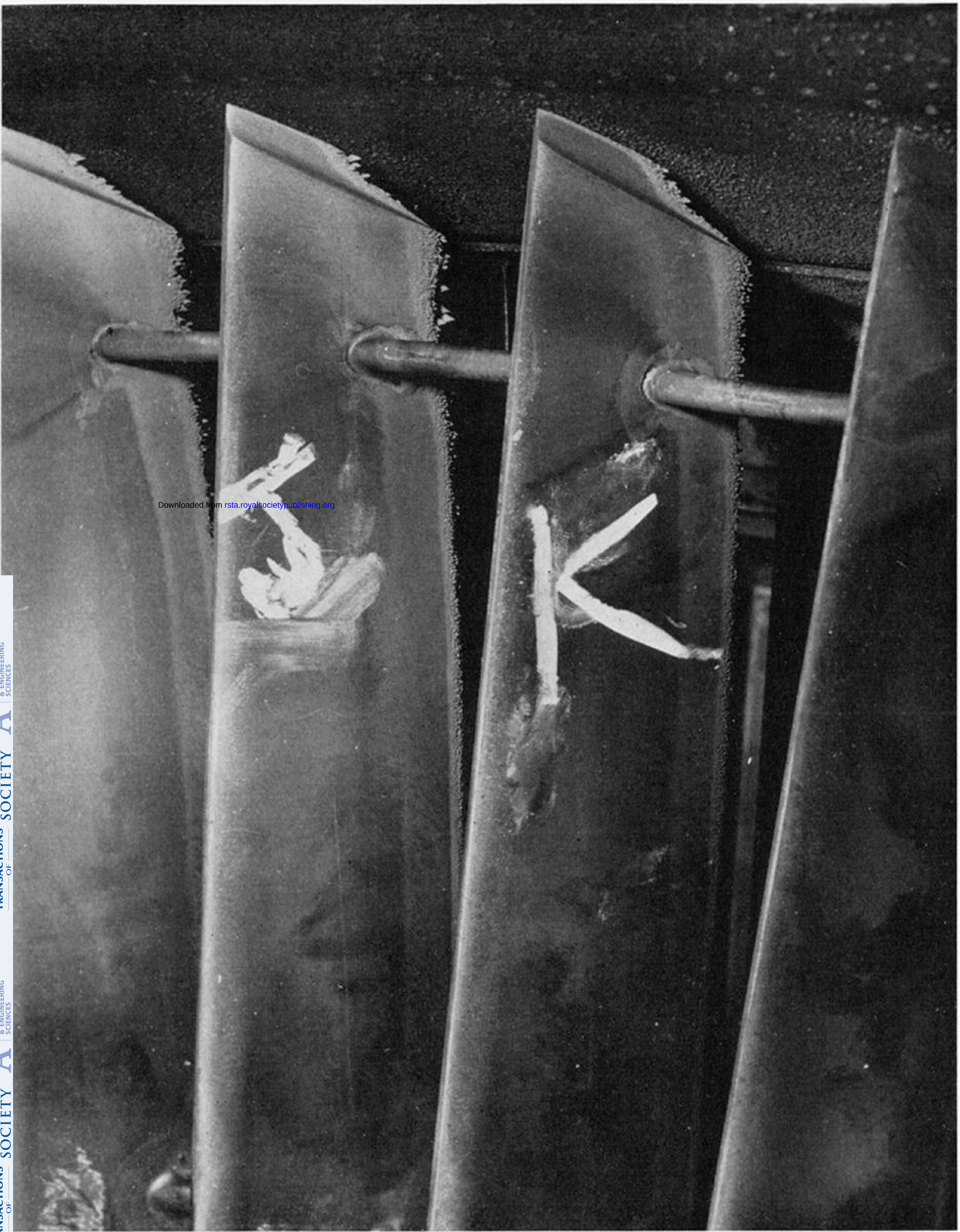

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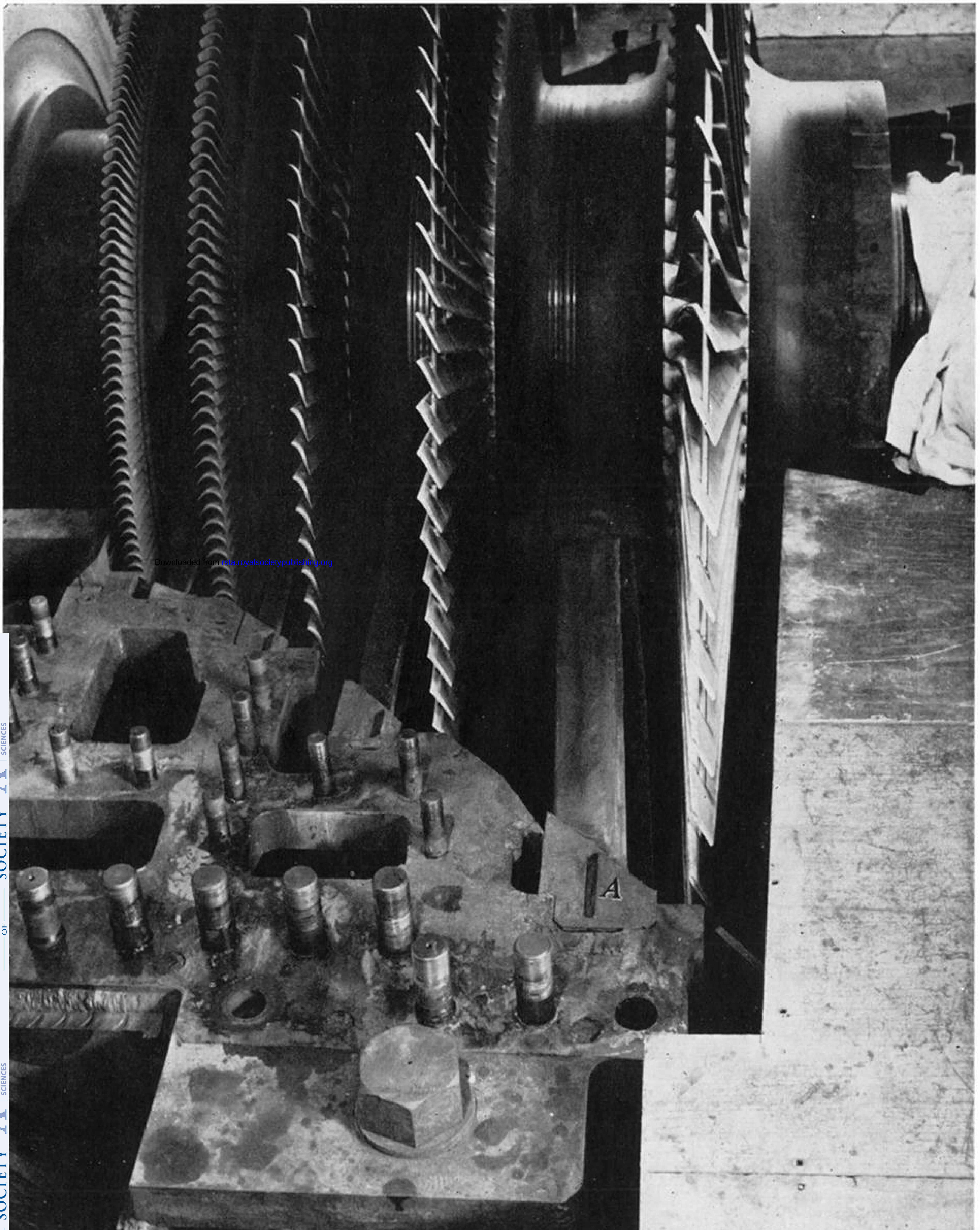

Figure 4

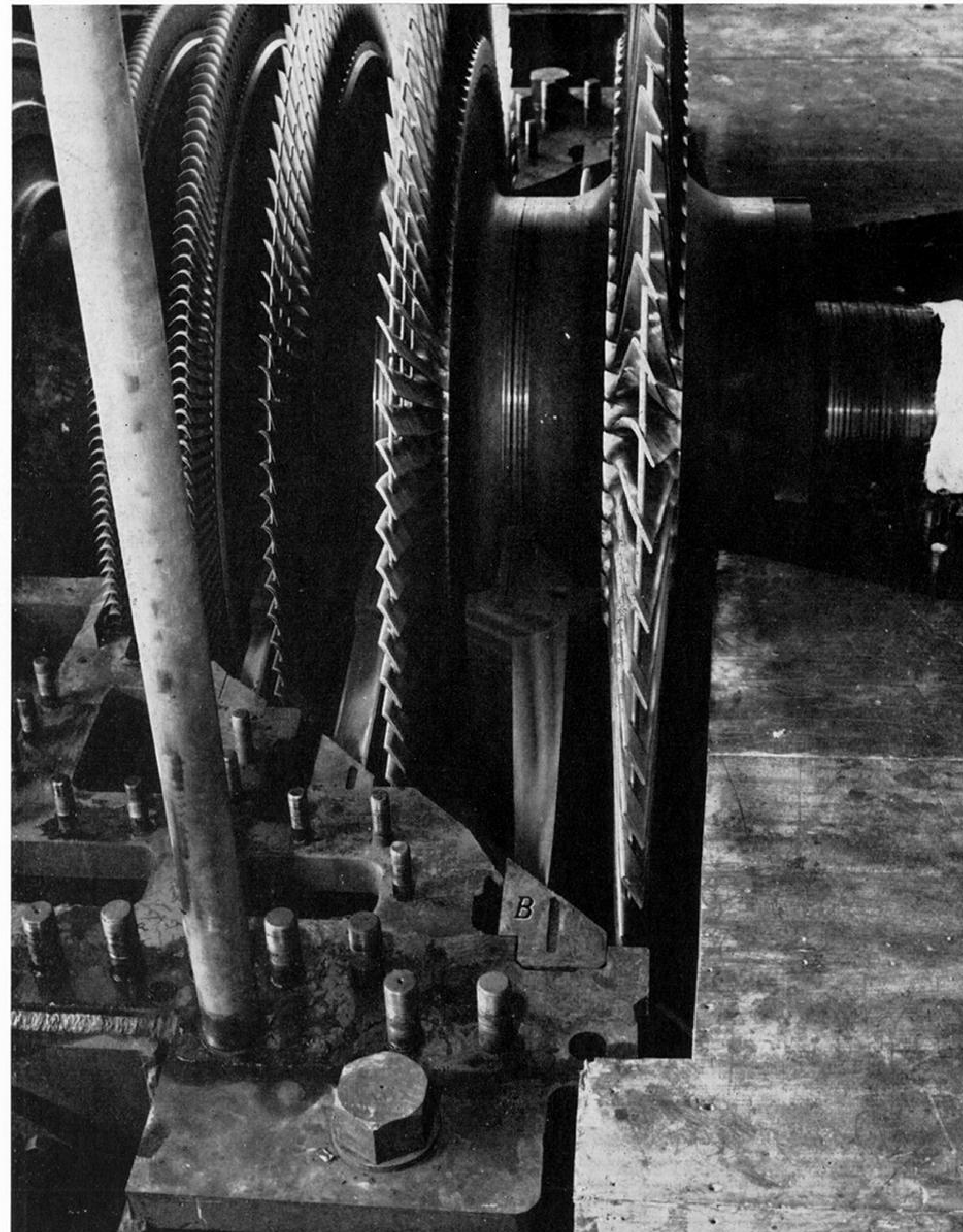

Figure 5

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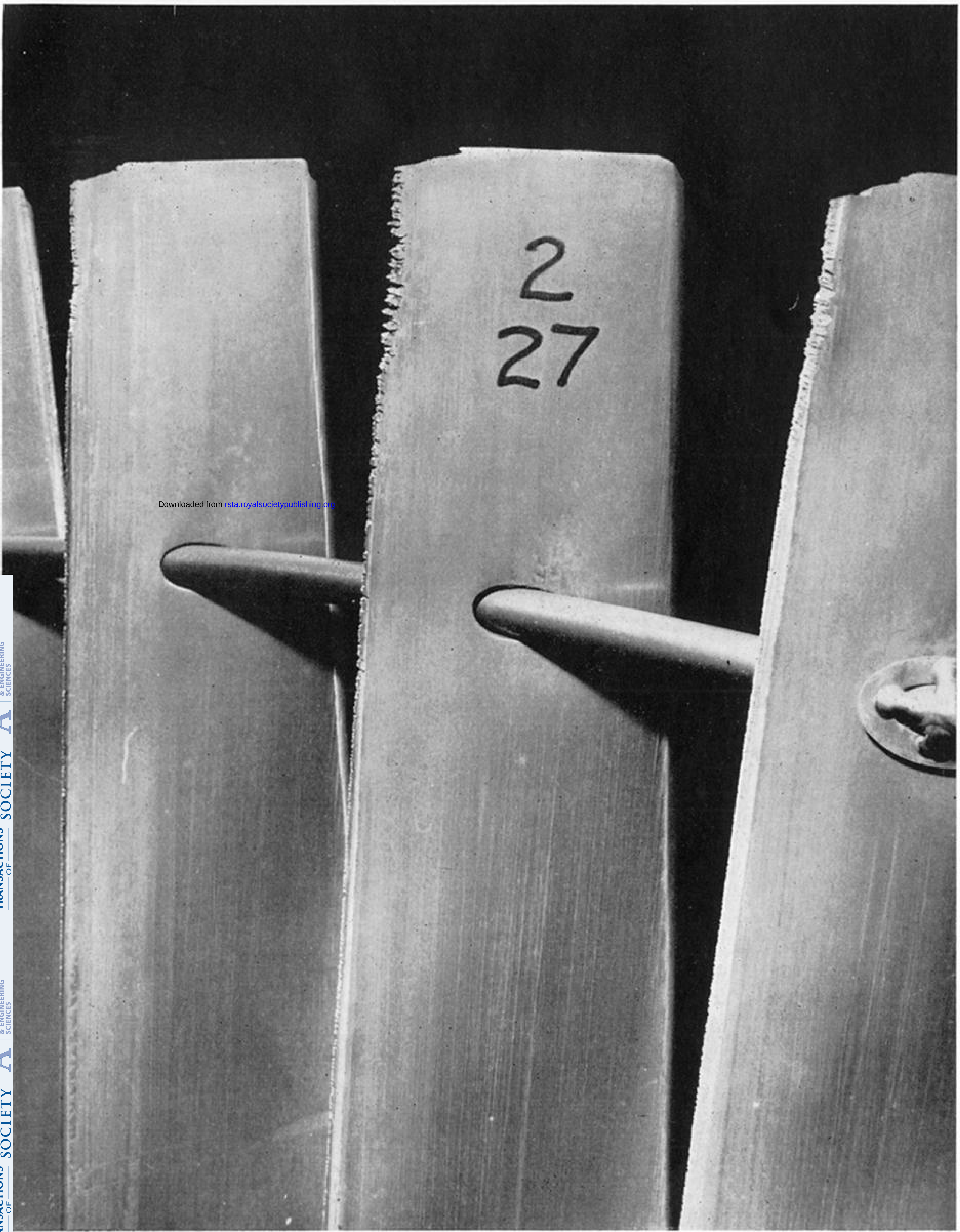

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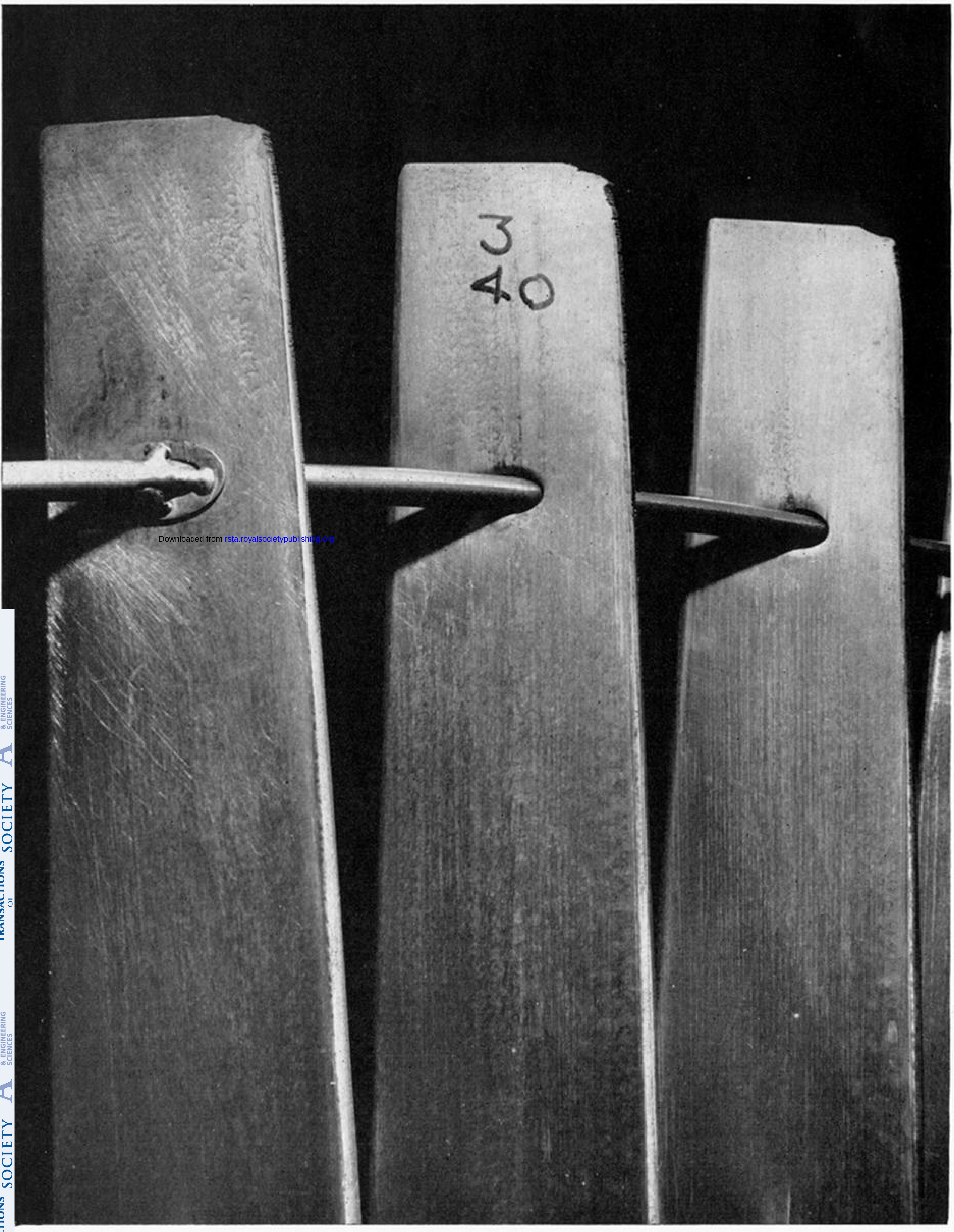

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