PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A
MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

Physical Aspects of Blade Erosion by Wet Steam in Turbines [and Discussion]

A. Smith, J. Caldwell, D. Pearson, D. H. McAllister and D. G. Christie

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XVIII. Physical aspects of blade erosion by wet steam in turbines

By A. Smith
C. A. Parsons and Company Ltd, Newcastle upon Tyne

[Plates 44 to 47]

Blade erosion in wet steam turbines is considered to be preceded by the collection of large water droplets on the blade concave surfaces; this is followed by steam breaking up the resulting water film at the stationary blade trailing edges into fairly coarse, slow-moving droplets, and culminates in their collision with the backs of the following moving blade row.

Experimental information on droplet collection and on the breakup of water film at the trailing edges has been obtained on turbine blade cascades in a wet air tunnel, and suggestions have been made for relating these results to low pressure steam turbines.

The erosion of tool steel and Stellite 6 blade shield materials has been measured in a contra-rotating test rig for calculated impact speeds of 1730 ft./s; the best erosion rates to compare appear to be those in a tertiary zone where the rate of weight loss has fallen from a maximum to a lower constant value. The influence of vacuum on specimen weight loss is also considerable, being second only in severity to that of speed over the ranges considered, and this has been attributed to aerodynamic influences on the number of droplets reaching the specimen surface in addition to a reduction in the true velocity of impact.

The possibility of reducing erosion in turbines by direct water extraction from hollow stationary blades has been demonstrated on an experimental arcuate cascade. Trailing edge slots have been found to be more effective than face slots if the depression in the hollow centre can be maintained below the trailing edge pressure.

1. INTRODUCTION

The widespread adoption of reheat in central power stations has reduced the moisture content of the steam at turbine exhausts, but the erosive effects of the remaining water could still be significant because of the increase in tip speeds of modern large machines. Temperature limitations imposed upon the steam cycle in nuclear plants have also added to the potential erosion problem by increasing the proportion of water in the later stages of the turbine expansion, although, to date, this has been accommodated by the use of 1500 rev/min designs which are also attractive because of the large volumetric flows involved. The result has been a general intensification of wet steam studies with particular emphasis on the mechanism of blade erosion.

2. PHYSICAL PROCESS

Blade erosion is visualized as being preceded by the collection of the larger water droplets on the concave pressure face of the cylinder blades to form a film, which is drawn towards the blade trailing edges by the drag of the steam. Here this film grows, and may even be sucked round on to the suction face in a region of separated flow, before being torn away by the main steam flow. Large drops (50 to 200 μm) are thus formed and, because of their size, are difficult to accelerate; in consequence, they are struck by the backs of the following spindle blades with a velocity approaching the peripheral speed of the blading (figure 1) (1780 ft./s in the case of a 136 in. tip diameter blade rotating at 3000 rev/min.). That such droplets are responsible for erosion is suggested by the position of damage to the convex face of the moving blades in actual machines (see figure 2, plate 44). Large droplets, however, probably constitute only a small proportion of the total water present, the majority being only 0·5 μm or less. This size is suggested by the absorption of the blue end of the light spectrum in the last stages of an experimental l.p. steam turbine at Heaton Works, and is more consistent with supersaturated droplet growth theory.

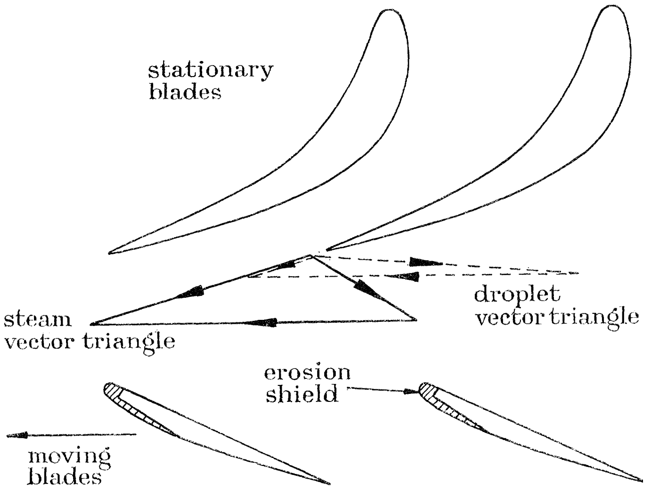

Figure 1. Diagram showing velocity and angle of attack of large droplets stripped from stationary blade trailing edges at low pressure turbine blade tips.

2·1. *Droplet collection*

Damage to stationary blading is relatively insignificant compared with that to the moving blades and would indicate that in the last few stages the centrifugal action of the preceding moving row is effective in removing most of the water to the cylinder wall before it reaches the blade trailing edges. A mathematical analysis of the centrifugal action based on suggestions made by Gardner (1963–64) would support this observation.

A method of assessing the proportion of droplets reaching the surface of an aerofoil was outlined by Taylor (1940) in a survey of aircraft icing problems and this was followed in 1960 by a publication from Martlew (1960) on blade fouling in gas turbines by the products of combustion. Martlew found that the effectiveness of capture of paraffin wax droplets on a typical turbine cascade agreed well with the calculated value based on assumptions of Stokes's law and idealized potential flow around the blading. Collection effectiveness, moreover, was coupled with 'impact number', a nondimensional parameter proposed by Taylor which is equal to

$$\frac{2}{9}\left(\frac{\rho_w}{\rho_s}\right)\left(\frac{d}{2C}\right)^2\left(\frac{CV_m}{\nu}\right),$$

where ρ_w and ρ_s are the density of water and steam respectively, d the droplet diameter, C the blade chord, V_m the vector mean steam velocity, and ν the kinematic viscosity of steam.

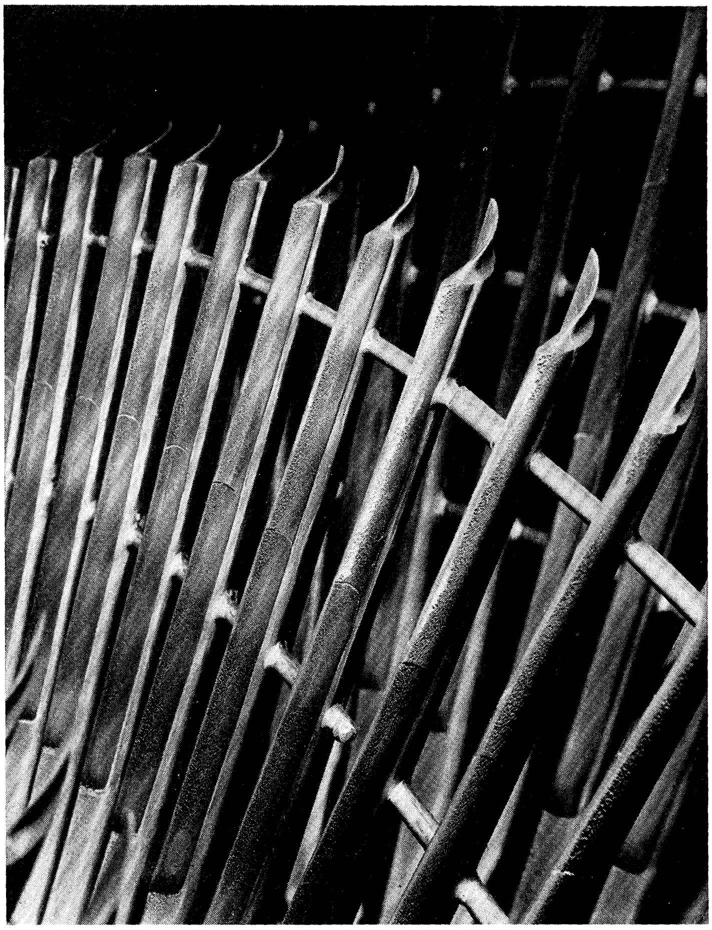

Figure 2. Typical erosion damage to low pressure turbine blades.

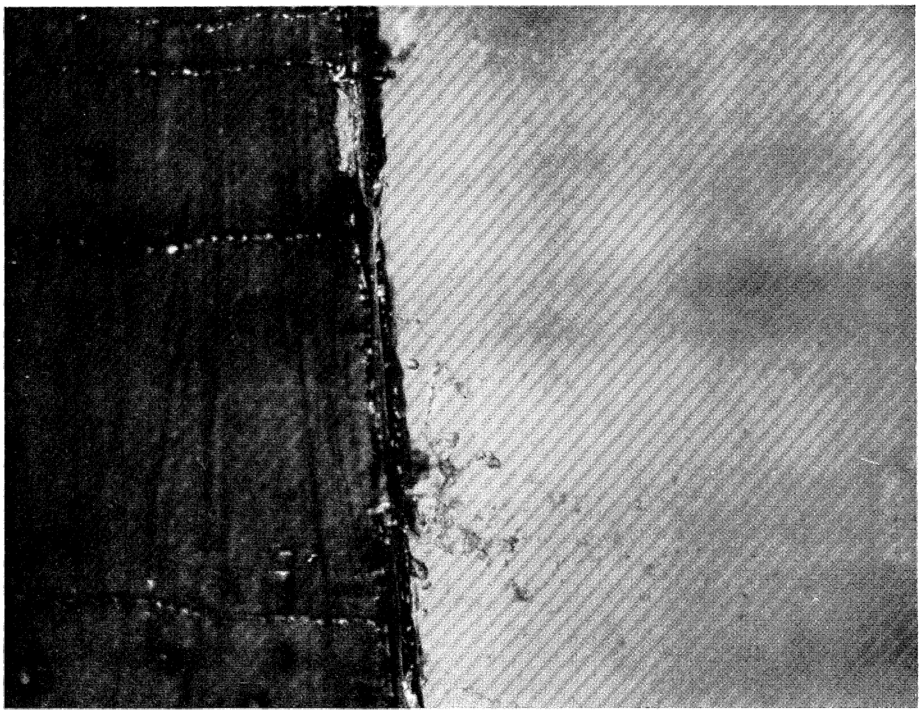

Figure 3. Breakup of water film at blade trailing edges.

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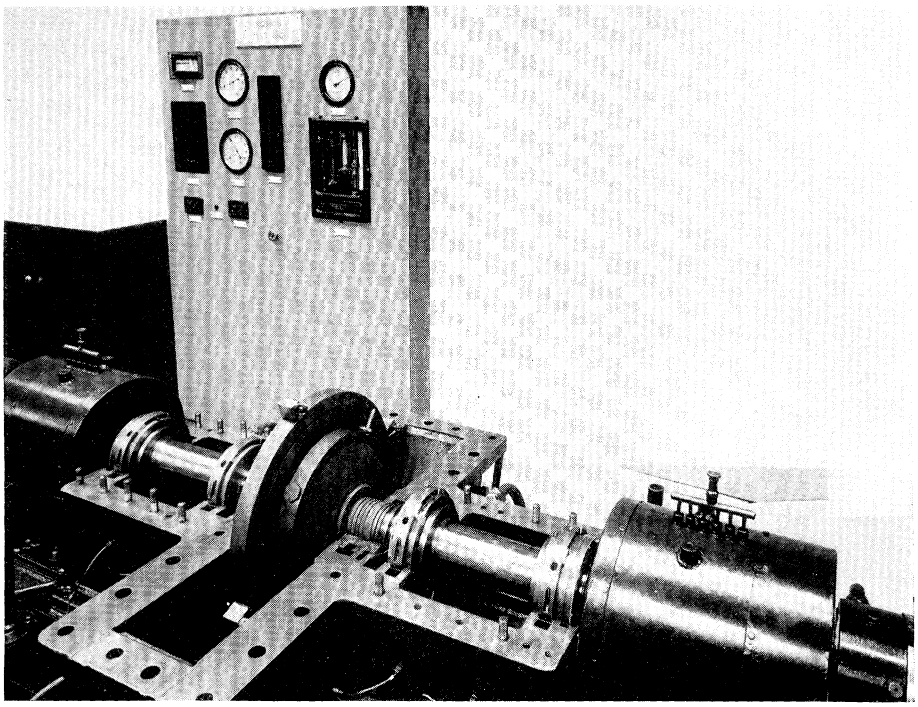


FIGURE 4. Contrarotating erosion test rig.

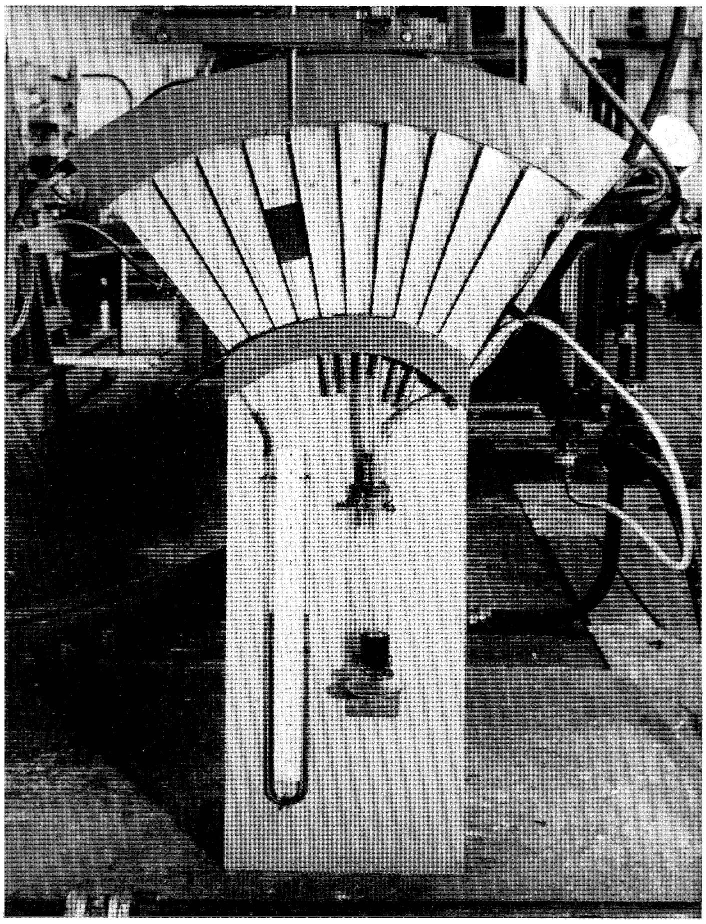
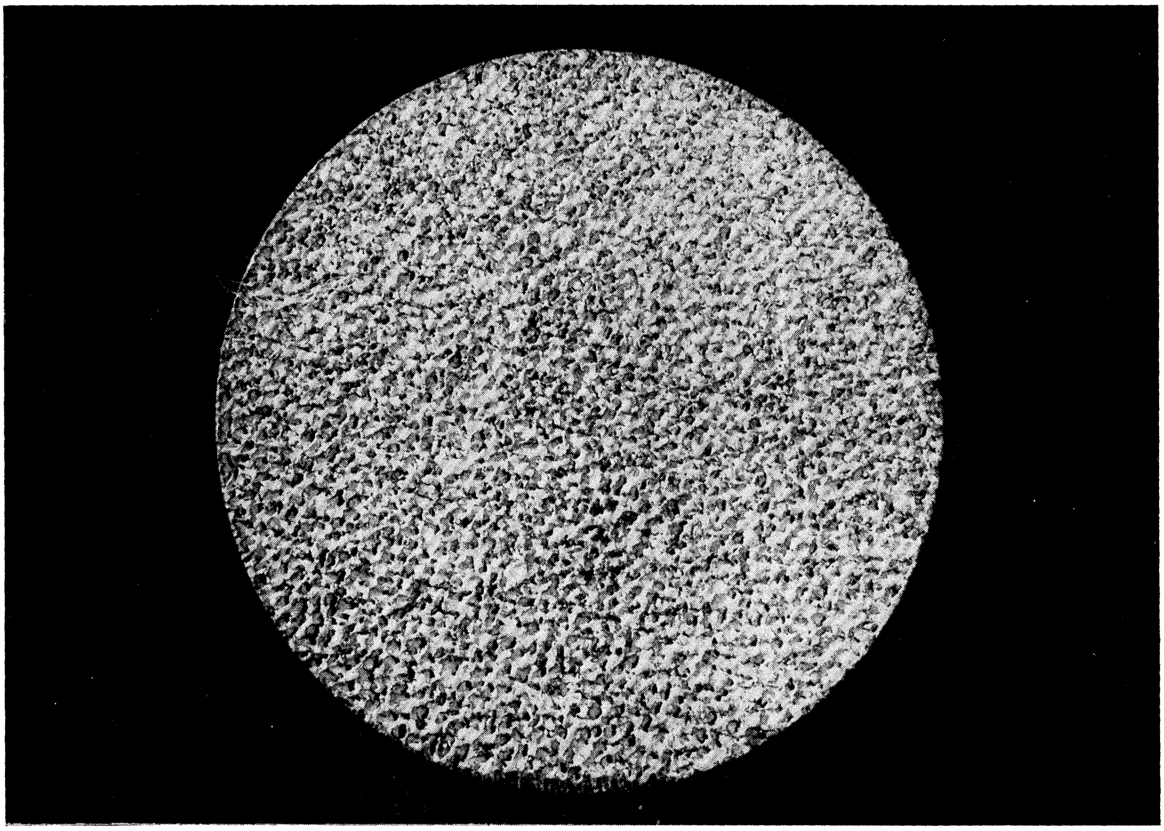


FIGURE 10. Arcuate hollow bladed cascade on wet air tunnel.



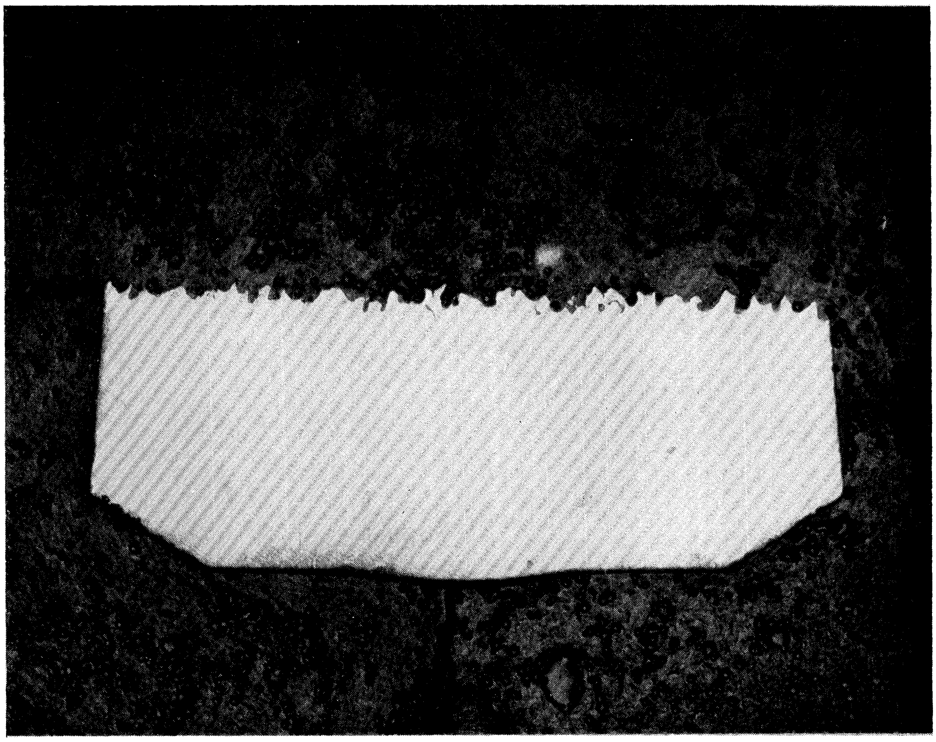


Figure 8. Tool steel specimen eroded for 100 h at a pressure of 2 in.Hg (abs.). Eroded face and microsection.

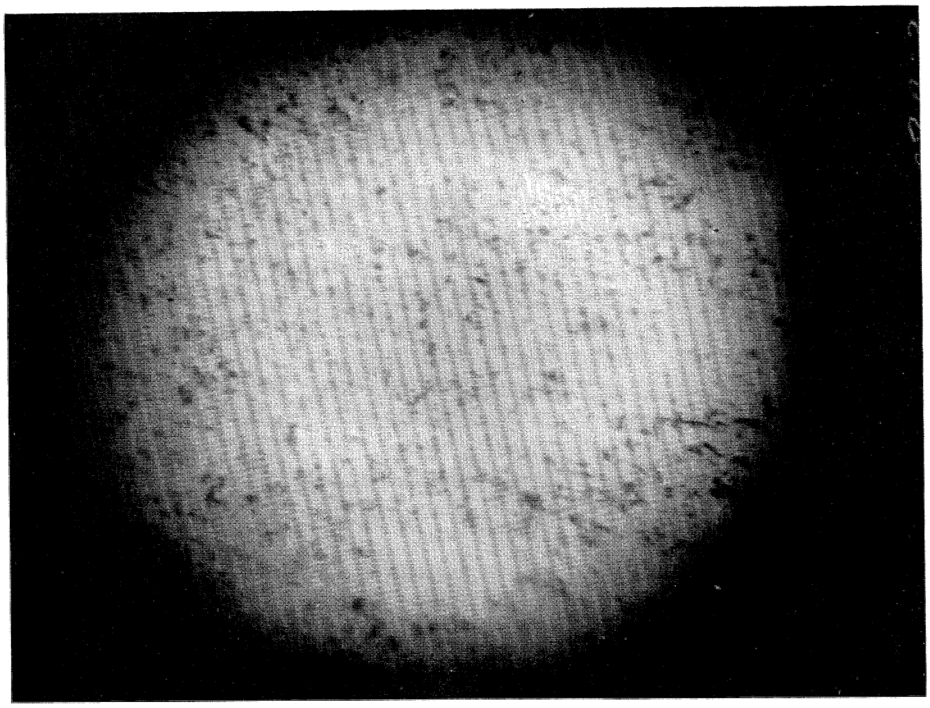


FIGURE 9. Droplet spectrum at pressure of 2 in.Hg (abs.).

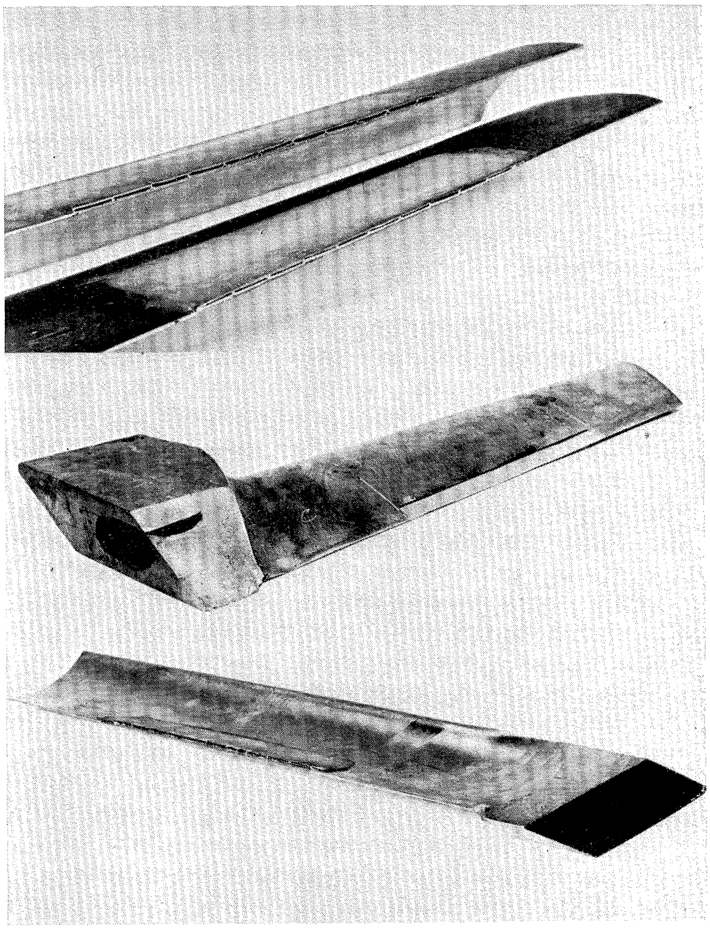


FIGURE 11. Drainage slots in hollow low pressure cylinder blading.

The collection of droplets by blading in a turbine differs from a stationary cascade because individual droplet sizes are accelerated to unique velocities across the axial gap between the blade rows and this, coupled with the relative blade motion, varies both incidence and velocity on to the following blades. The 'impact number', found experimentally from cascades, has nevertheless been used as a method of estimating the effectiveness of droplet collection in turbines.

Experiments on an l.p. cylinder blade cascade supplied from an open jet air tunnel with water spray injection have shown that the collection efficiency of droplets on the concave blade surfaces approaches 100% if their Sauter mean diameter (S.m.d.) lies above 60 μm for the Mach and Reynolds number ranges of 0·15 to 0·5 and $(2{\cdot}5 \text{ to } 8{\cdot}3) \times 10^5$†, respectively. Thus for efficient collection of the droplets with this particular blading an 'impact number' of 3·5 or above would be required which would correspond to a droplet size of 30 μm at the inlet to a 500 MW last stage turbine diaphragm.

2·2. *Breakup of water film*

The stripping of the surface water film by the steam flow near the blade trailing edges has been studied in a two-dimensional cascade in a wet air tunnel. High speed photographs of breakup of the water film (figure 3, plate 44) suggest that final droplet sizes are given by Weber numbers $\mathrm{We} = \rho_s V_2^2 d/\sigma$ (V_2 being the outlet steam velocity and σ the surface tension) of from 10 to 30 at a distance of 10% of a blade chord downstream. This corresponds to droplets of diameter 70 to 200 μm from the last stage diaphragm in a turbine, or 55 to 170 μm droplets from the preceding moving row.

Although much of the water on the moving blades is centrifuged to the outer periphery, some will be re-atomized at the trailing edge before reaching the sanctuary of the boundary layer on the cylinder wall and, from 'impact number' considerations, will be re-collected by the following row. This, as well as the higher peripheral speed, explains why erosion damage is normally confined to the blade tips.

2·3 *Collision*

Collision between the droplet and the moving blade constitutes the last stage of the erosion process, but the influence on true impact speed of water breakup time from the preceding stationary row, coupled with a cushioning effect of the pressure field between the droplet and the blade, makes this a most difficult problem to analyse.

The last few moving blade rows of an l.p. turbine are generally protected towards their outer periphery by erosion shields brazed along the leading edges, and to aid the selection of shield materials suitable for tip speeds of up to 2000 ft./s, a contrarotating erosion rig (figure 4, plate 45) was built. Coaxial, contrarotating shafts are driven electrically, one shaft carrying four button-shaped specimens at the periphery of a disk and the other, two sprayers, both enclosed in a sealed chamber (figure 5).

The erosion rates of similar materials at comparable speeds are very much higher in this rig than in turbines and could be the result of variation in one or more of the following factors: (*a*) weight of impacting water, (*b*) droplet size, (*c*) true velocity of impact, but this

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† Reynolds number based on chord and efflux velocity.

has not prevented comparison of the weight loss at a selected water injection rate of wide selection of materials at design speed and vacuum.

Materials are eroded only when the impacting droplets reach some threshold velocit where repeated local surface stressing becomes excessive (Gardner 1932). The subsequen erosion accelerates rapidly with further increase in speed following a power law with the value of the exponent probably lying closer to two than three. The fact that the present tip speeds of l.p. turbines exceed the threshold velocity of all known materials is, of course, the reason for the present research effort.

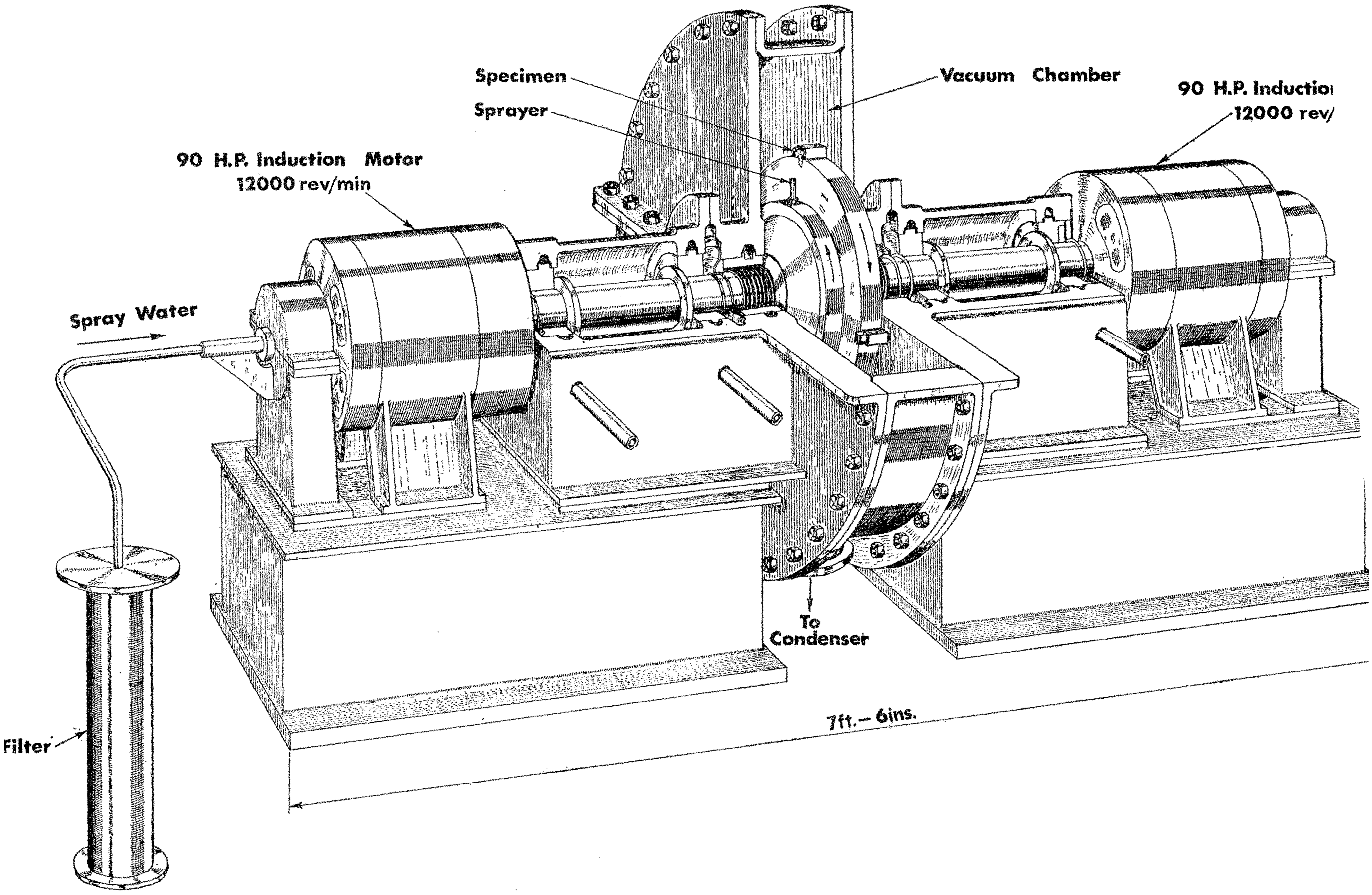

Figure 5. Contrarotating erosion rig section.

When subjected to droplet impact at speeds in excess of the critical value, most materials exhibit a small initial rate of weight loss,† followed by a fairly rapid rise to a maximum value, after which it ultimately falls to a constant value (figure 6). The maximum erosion rate appears to be unrelated to the final constant value in the tertiary zone and this, coupled with the requirement that steam turbines should operate for considerable periods without overhaul, would suggest that erosion rate comparisons be made in the final zone.

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† Erosion rate is defined by $\mathrm{d}M/\mathrm{d}W$, where M is the mass of specimen and W the calculated weight of impacting water on the assumptions of uniform spray density and that droplet collection by the specimen is unaffected by aerodynamic forces.

Certain die steels and vacuum melted tool steels have shown marginally superior erosion resistance to both standard tool steels and stellites, but lack of ductility may limit their use for turbine erosion shields because of the possibility of crack propagation into the base material of the blade. Ausforming and other treatments are also being attempted to increase the ductility of selected steels without sacrificing their erosion resistance.

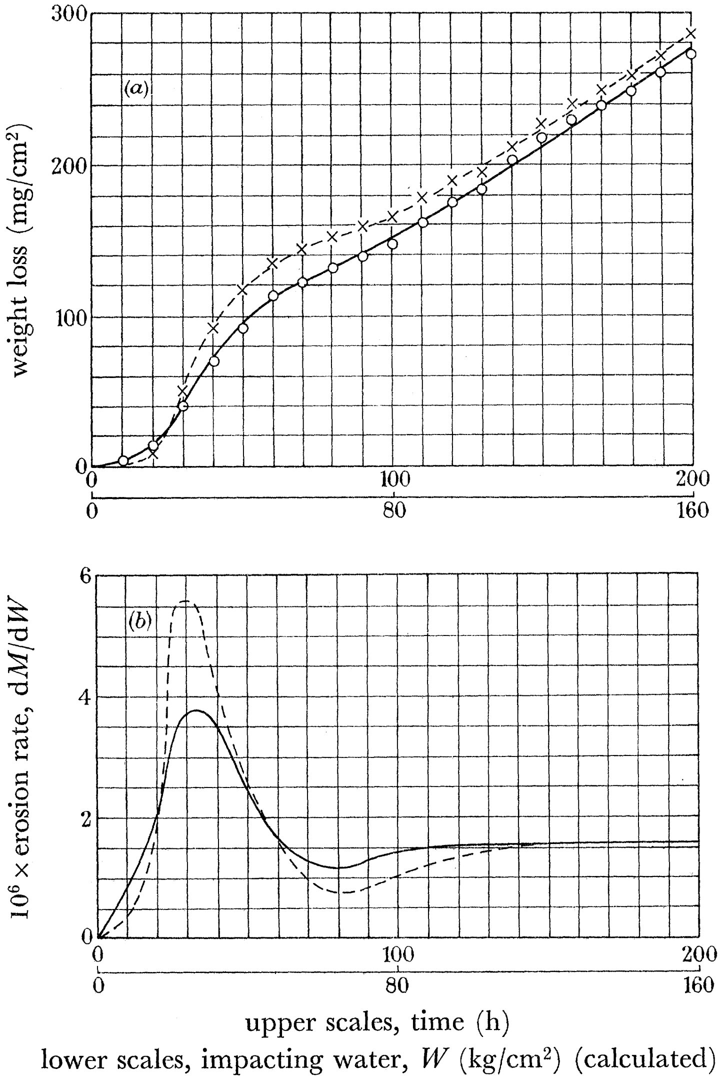

FIGURE 6. Weight loss and erosion rates of spec. 24 tool steel and Stellite 6 at 1730 ft./s. - - -, Stellite 6: 66 % cobalt, 26 % chromium, 5 % tungsten, 1 % carbon; hardness 408 V.p.n. ——, Tool steel (spec. 24): 18 % tungsten; 6 % chromium; 0·7 % carbon; hardness 612 V.p.n. Droplet size, 110 μm (S.m.d.); absolute pressure 1·5 in.Hg; impact normal.

Variation in vacuum has been found to have a pronounced influence on the weight loss of specimens, second only to that of the shaft speed. The weight loss over 100 h at a calculated impact speed of 1730 ft./s for tool steel specimens hardened to 596 and 813 V.p.n., respectively, is shown in figure 7 (*a*) for four different vacua. The corresponding erosion rates (figure 7 (*b*)) indicate that the test period was too short at the higher absolute pressures for the specimens to reach the tertiary erosion zone.

Microphotographs (figure 8, plate 46) of the specimens show that the mean depth of the craters measured in three places of each specimen decreases almost linearly with increase in pressure over the range of 2 to 5 in.Hg absolute, and is independent of the hardness of the specimens. The mean pitch of the craters, however, did not differ significantly with either pressure or hardness. Photographic evidence (figure 9, plate 47) has subsequently shown that the S.m.d. of the droplets is almost constant (90 to 110 μm) over the full pressure range and the sizes are of the same order as the crater widths, half pitch. This suggests that further droplet breakup does not occur immediately before impact and the observed reduction in erosion damage with increase in pressure is caused by aerodynamic influences on droplet collection and impact velocity.

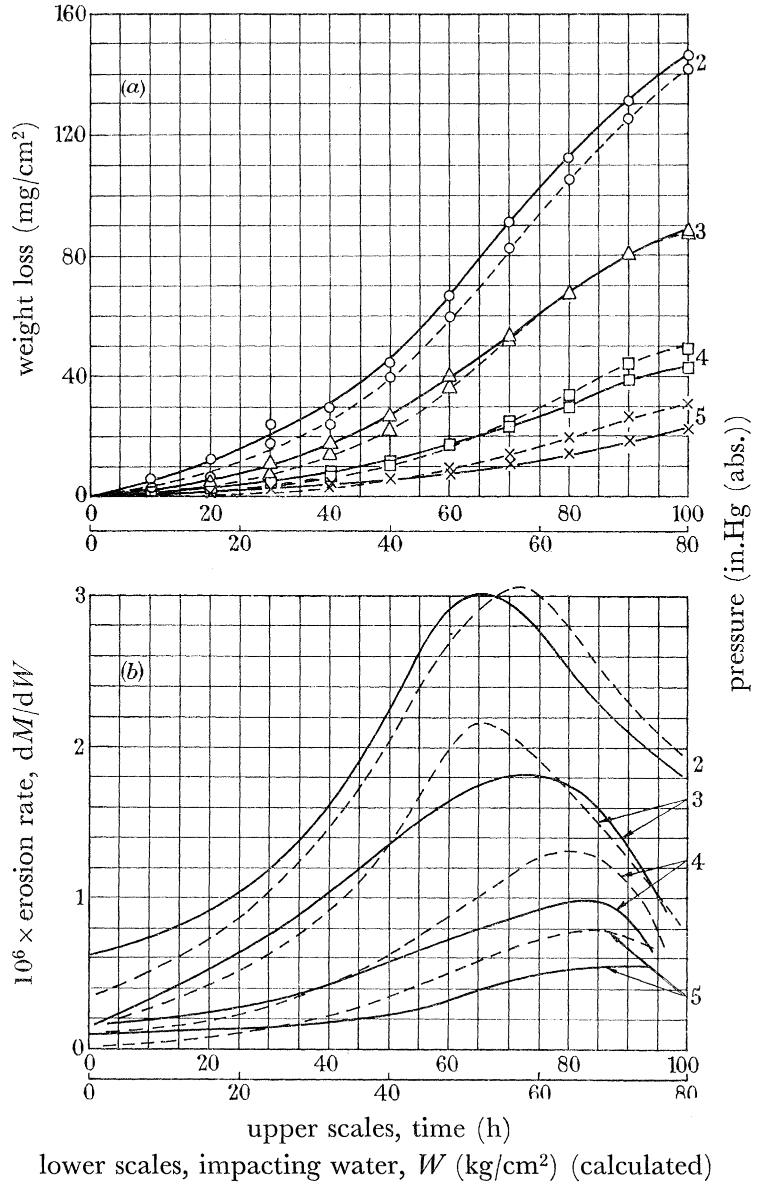

FIGURE 7. Effect of vacuum on weight loss and erosion rate. (Contrarotating erosion rig.) Theoretical impact speed, 1730 ft./s (normal to specimen face); droplet size 110 μm (S.m.d.); material, tool steel spec. 24. ——, Hardness 596 V.p.n.; - - -, 813 V.p.n.

It is worthy of note that at higher absolute pressures the weight loss of the softer specimens is less that than of the harder specimens and earlier theories that the erosion resistance of any one material increases with hardness (Gardner 1932) may now have to be qualified by stipulating the absolute pressure.

Unexplained variations in the shield erosion rates of similar turbines in service have, on occasions, been attributed to differences in the feed water treatment. Comparison of the erosion rates of similar materials when the oxygen content of the spray feed of the rig varied from 0·01 to 8 ml./l., however, showed chemical attack to be relatively insignificant.

3. Water drainage

Direct drainage of water from the trailing edges of turbine cylinder blades offers a positive solution to the erosion problem and an arcuate cascade has been built from spare hollow blades from a model diaphragm for an experimental turbine to determine the best slot arrangement for water drainage (figure 10, plate 45). A slot along the trailing edge has proved superior to both convex and concave face slots (figure 11, plate 47) when the blade is unstalled, and almost complete drainage seems possible so long as the depression in the hollow of the blade can be kept below the static pressure at the trailing edge. The necessary depression is approximately 10 % of the outlet dynamic head for this particular blading, the steam bleed amounting to less than one-third of 1 % of the gross flow.

Positive incidence of the steam on to the blading at low Reynolds numbers can induce boundary layer separation on the convex surface in regions of adverse pressure gradient. To simulate this condition, a boundary layer trip was fitted on the convex surface of the cascade approximately half an inch from the trailing edge. Water deposited on the concave surface was shown by the die injection techniques to be drawn round the trailing edge to fill the separation region. Suction on suitably placed convex face slots could, under these circumstances, effectively remove the local water film and possibly prevent separation, but in the final analysis trailing edge slots remain the most effective method of water removal.

The author thanks C. A. Parsons and Co. Ltd for permission to publish this paper, and acknowledges the valuable assistance of his colleagues in its preparation.

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XIX. Discussion

J. Caldwell

The way in which we look at the work to be done in this field of mechanics depends on the experimental approach and the practical application of the knowledge gained which each of us has in view.

In studies of individual drop impacts the measure of the severity of the effect is taken to be illustrated by the peak value of the surface pressure generated, $P = \rho CV$, and possibly by its duration. In multiple random impact, wear or removal of material near the surface for a given number of impacts is taken as a measure of the damage and it has been found by numerous investigators that the wear rate depends on V^n where V is the impact velocity and the index n lies, most commonly, somewhere between 2 and 3 for wear after the initial incubation period has elapsed. Wear would appear to depend not only on the peak stress achieved, but also on the rate at which it is applied. Some work towards correlating the results of the two approaches is needed.

It is rather easier to reconcile the conclusions from the two experimental methods with regard to the effect of drop size. The multiple impact test suggests wear increasing as d^m where d is the drop diameter and m is of the order of 3. The results of experiments with single drops indicate no increase of peak pressure with size of drop, but a longer continuation of the pressure. As the area affected would appear to increase with frontal area of the drop, the dependence of the rate of wear on d^3 would seem not unreasonable.

Our attitudes towards suitable forms of protection against damage naturally vary with the severity of the operating conditions, and with the readiness with which a given type of protection can be applied without affecting the main duty of the machine parts requiring shielding. Two examples from the interesting rain erosion paper by Busch, Hoff & Langbein invite comparison with knowledge already existing in the more difficult field of steam turbine blade erosion.

These authors indicated that nickel plating was effective under the conditions of their tests. Figure 3, plate 41, of my paper (facing p. 204) indicates that for light tangential impact chromium plating is helpful in suppressing turbine blade wear. However, it has been known for a long time that light protective coatings of hard materials of this type or even nitriding of the steel to a depth of 0·010 in. offer no worthwhile protection for impact at right angles to the metal surface. On the other hand, chromium plating of rotors is used successfully by one builder of small turbines.

In the paper by Busch *et al.* it was stated that a low Young's modulus makes rubber more erosion resistant. This result would appear not unexpected for the cup type of container in which these tests were done, since the shock absorbing capacity of the rubber would appear to be fully developed. It would be wrong, however, to conclude that a rubber shield of only moderate thickness applied to metal would be effective against severe erosion attack. Tests using rubber were made many years ago in trials of shields for steam turbine blades and were not successful. The rubber spreads under the impact of the water drops and fails primarily by fatigue of the material bonding it to the metal underneath. It would be expected, therefore, that a low Young's modulus, by encouraging spread, would lead to earlier failure, but the authors may have special means of bonding rubber to metal to get over precisely this difficulty.

A. Smith

Three zones of weight loss in the erosion process have been mentioned in the paper by Baker, Joliffe & Pearson, a primary zone where the erosion rate is small, a secondary zone where the rate rises to some maximum value, and a tertiary zone where the rate falls asymptotically to a lower constant value. Since steam turbines are expected to operate for long periods without overhaul, would it not be more realistic to compare the erosion rates of materials in the tertiary zone rather than the maximum rates?

Absolute pressure has been found to have a considerable influence on the weight loss of specimens tested in a contrarotating test rig at theoretical impact speeds of 1730 ft./s and under constant spray injection rates (see my figure 7 (*a*) above). Mean droplet sizes were of the order of 90 to 110 μm over the test pressure range of 2 to 5 in.Hg absolute.

The reason for the variation in weight loss with pressure is considered to be caused by aerodynamic effects influencing the number of droplets colliding with specimens as well as their true velocity of impact, and it would be of interest to know whether the authors have used a droplet collection factor in assessing the weight of impacting water.

Precautions were taken to ensure comparable results from the tests by machining all specimens from the same bar, after which they were given simultaneous solution treatment and were only separated for the actual hardening process. Finally, both hard and soft specimens were tested together at any one pressure and it was therefore considered significant that the weight loss of the harder specimens was lower than the softer specimens at low pressure, whereas at higher pressures the softer specimens appeared superior.

D. Pearson (Central Electricity Generating Board)

Mr Smith suggests that the erosion resistance of materials should be assessed in terms of the final rate of erosion rather than the maximum rate. His proposal would be justified if the eroding material was sufficiently thick for the final rate of erosion to be obtained, and continue so long that the time taken by the earlier stages of erosion was relatively small. For drops of 500 μm diameter a thickness of about $\frac{1}{4}$ in. of metal is required for the final rate of erosion to be achieved, this thickness being proportional to the drop diameter. For existing turbines the erosion shield thickness appears to be too thin relative to the drop size for the final rate of erosion to be obtained, so the maximum rate of erosion is a better guide to the suitability of materials for erosion shields. Improvements to turbine aerodynamics should eventually permit the use of Mr Smith's method of assessment.

The effect of steam pressure on erosion has not been specifically investigated, and results at the pressures quoted in the contribution could not be easily obtained with the C.E.G.B. rig. Four specimens have been tested at both the lowest and highest test pressures ($23\frac{1}{2}$ and 36 mmHg) employed during the experiments, there being no statistical difference between the results obtained at the two pressures. The quoted results for the effect of pressure may well be due to the particular design features of the Parsons rig (Kent, R. P., *Parsons J.* **10**, 290–291). The drop collection efficiency for the C.E.G.B. rig was calculated to be so close to unity that no correction was made to the results.

Mr Smith's results for the interaction of pressure and hardness are surprising, but unfortunately he gives no information on the consistency of the erosion behaviour of nominally identical specimens. Without this, it is impossible to decide whether or not the differences between the hard and soft specimens is significant. Assuming that each line represents results for one specimen, from our own experience the effect of pressure on the differences between the hard and soft specimens could be explained by random scatter in the specimen properties.

D. H. McAllister (C. A. Parsons and Co. Ltd.)

Three most important factors in turbine blade erosion are (1) impact velocity, (2) water quantity, (3) droplet size.

Tests on an atmospheric wet air cascade tunnel have shown that the final size distribution of water droplets torn off a stationary blade is largely independent of the type of water formation on the blade; i.e. whether the water is torn off the trailing edge, or from a boundary layer separation point on the convex side, by the time the droplets strike the following moving blade their final size distribution will have been dictated only by the impact of the steam at blade outlet velocity. (This effect has been stated to be proportional to velocity head, ρV^2.)

The velocity head and hence also the impact velocity on the blade are dictated by turbine design conditions. Thus the only factor that is open to improvement is the water quantity leaving the fixed blades.

Concentration of water at various areas on the fixed blades, i.e. by secondary flow near the cylinder wall, or in the wake of a lacing wire, would therefore be expected to cause proportionally greater erosion at the corresponding area on the moving blades. Anything that could be done to eliminate such concentration would therefore be very valuable.

Efforts are now being directed towards removing the water from the fixed blades, and the most promising development appears to be a slot in the trailing edge of the blade through which water can be drawn off into the cavity of the hollow blade and thence removed from the turbine. Tests on the cascade tunnel have shown that a very high proportion of the water arriving on the fixed blade can be removed in this manner.

J. Caldwell

I am in general agreement with the observations made by Mr McAllister. It would be interesting to see whether any benefit results from the most recent attempts to remove the water from the blade by sucking at slots on the trailing edge. This approach is not new, however, and attempts in the past have been somewhat disappointing, although with the greatly increased knowledge provided by the visual observation carried out in cascade tunnels and in running turbines one would hope that more success would be achieved. One very real source of difficulty in attaining such success is the fact that the differential head available between the pressure at the trailing edge of the blade and the condenser pressure is quite low and is of the same order as the gravitational heads to be overcome.

D. G. Christie

Preliminary tests on the steam tunnel at C.E.R.L. confirm Mr McAllister's observations that once the drops are stripped from the trailing edge of a blade and have travelled more than about 1 in. downstream, their size is largely independent of the location at which they are formed. This appears to be principally due to the fact that under the actual steam flow conditions in the last l.p. stage, there is a maximum size of drop which is stable. Observations in the turbine with the periscope indicate that no drops larger than 450 μm impact on the rotor blades, although larger drops are seen leaving the fixed blades and in the steam tunnel investigations these were found to be up to 1500 μm.

Sucking the water from the blades is obviously very desirable if it can be achieved. The main problem is that in the last stage of the turbine the available pressure differential to remove the water is very small. In addition, both the slot in the blade and the extraction channel may have to be large enough to take a flow of steam and water, this would be particularly important if the steam 'flashes' under the lower pressure in the extraction channel.

A possible alternative method of reducing erosion would be to strip the drops from the fixed blades by blowing higher pressure steam out through the slots. In the higher density flow the maximum stable size of the drops would be less than in the main flow and it should also be possible to accelerate the drops to higher velocity before they reach the rotor blades. Both effects would tend to reduce erosion.

If the flow of water drops over the blades can be localized, then whatever system is used to control the eroding drops it will only be necessary to fit it over a small portion of the blade.

FIGURE 2. Typical erosion damage to low pressure turbine blades.

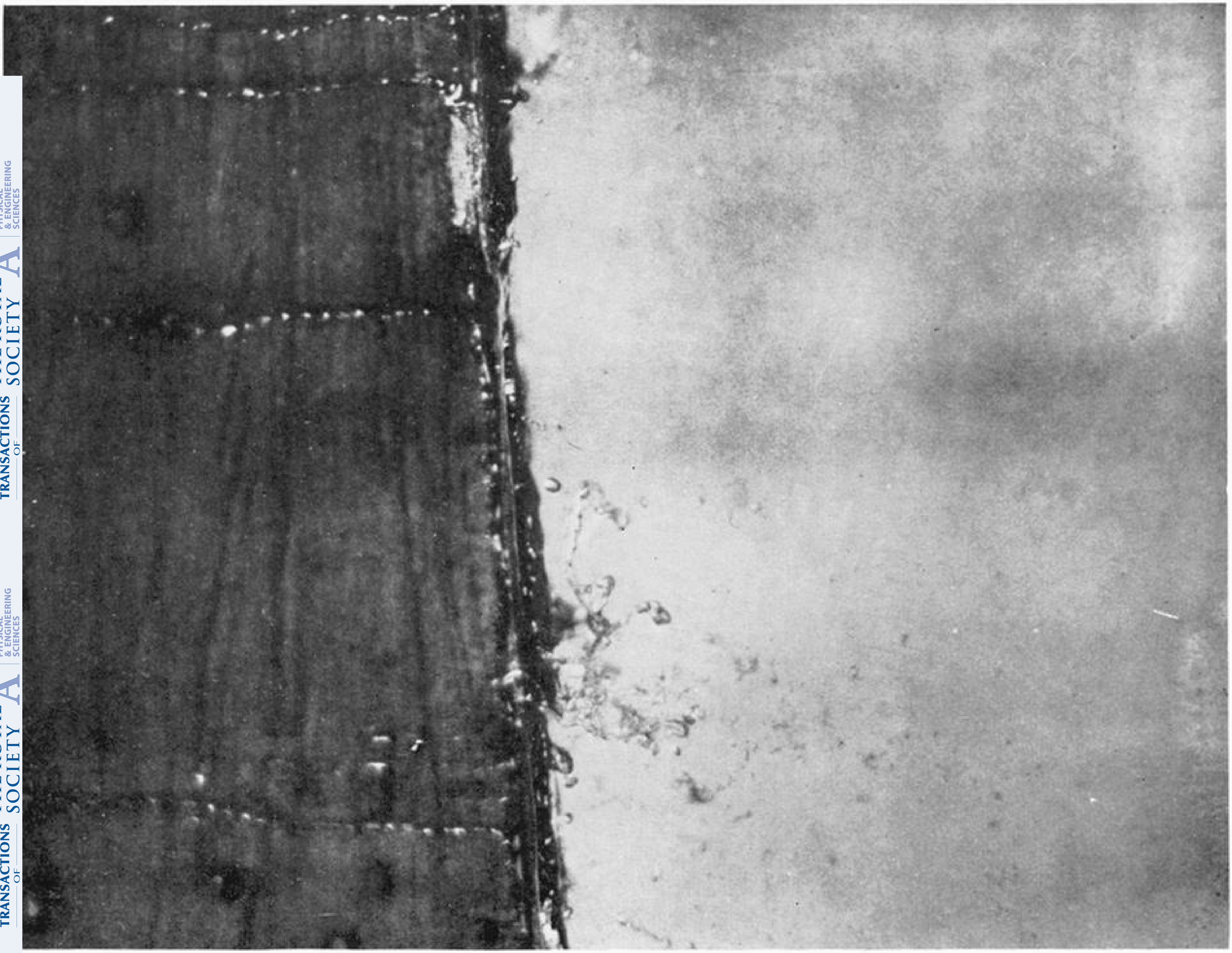
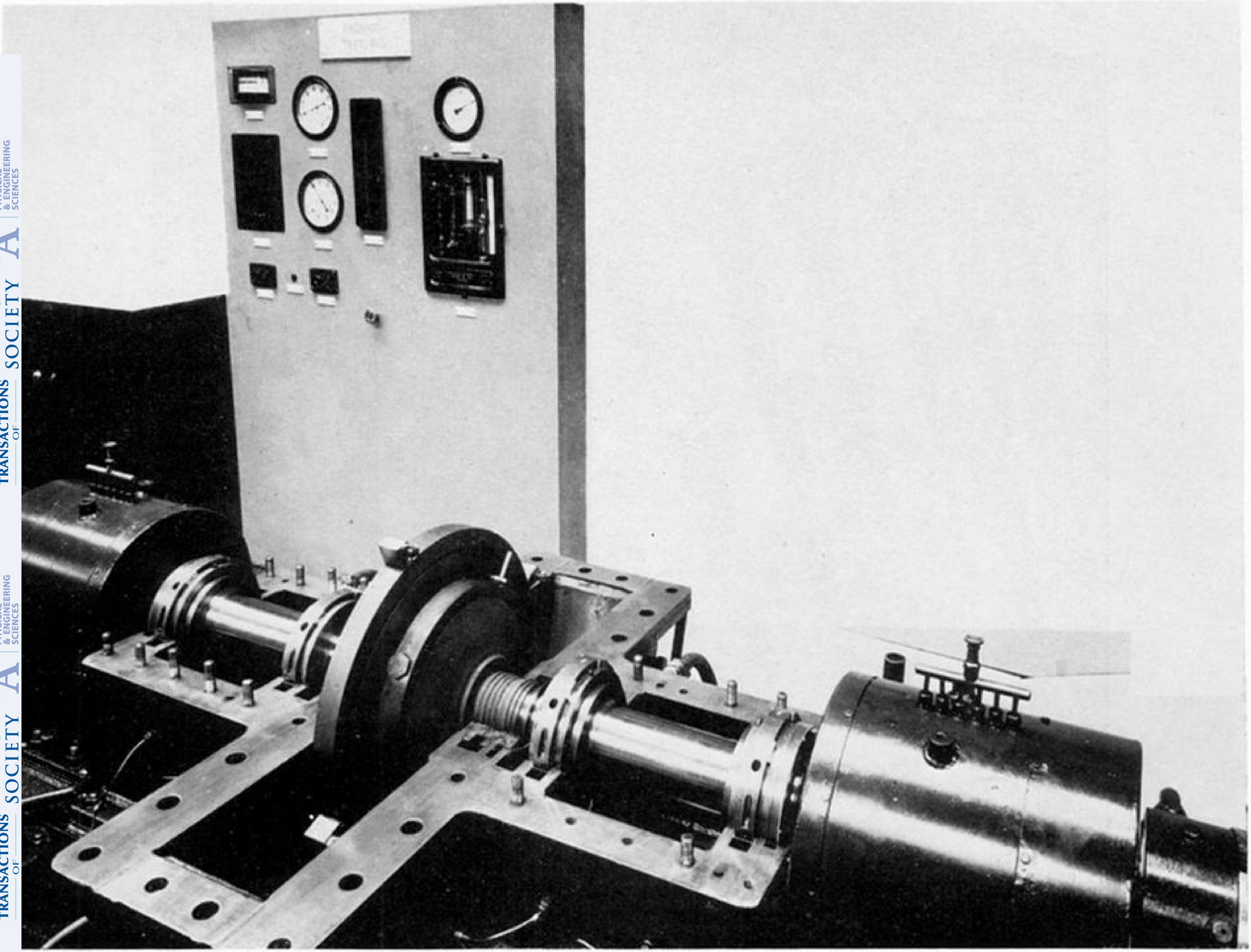


FIGURE 3. Breakup of water film at blade trailing edges.



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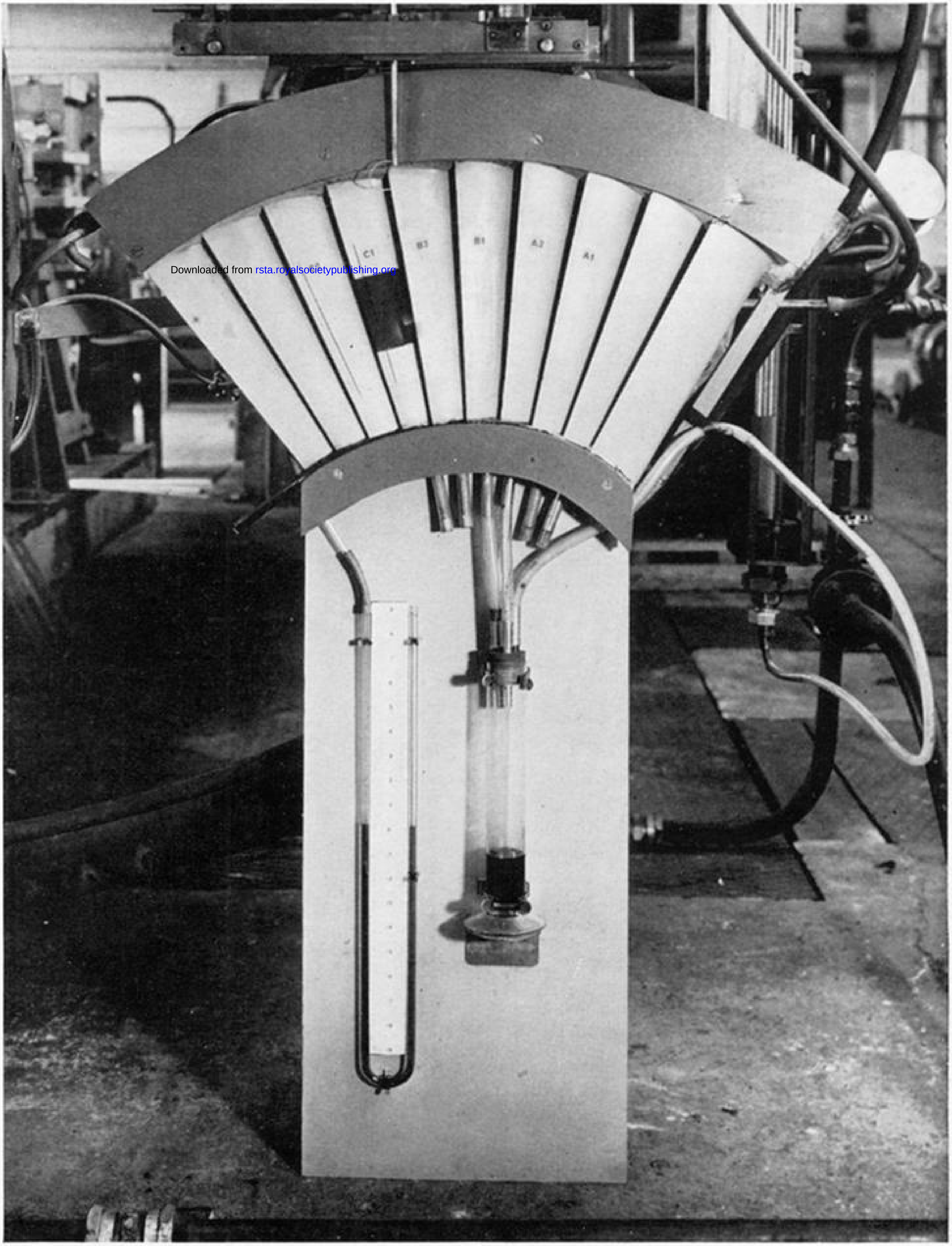

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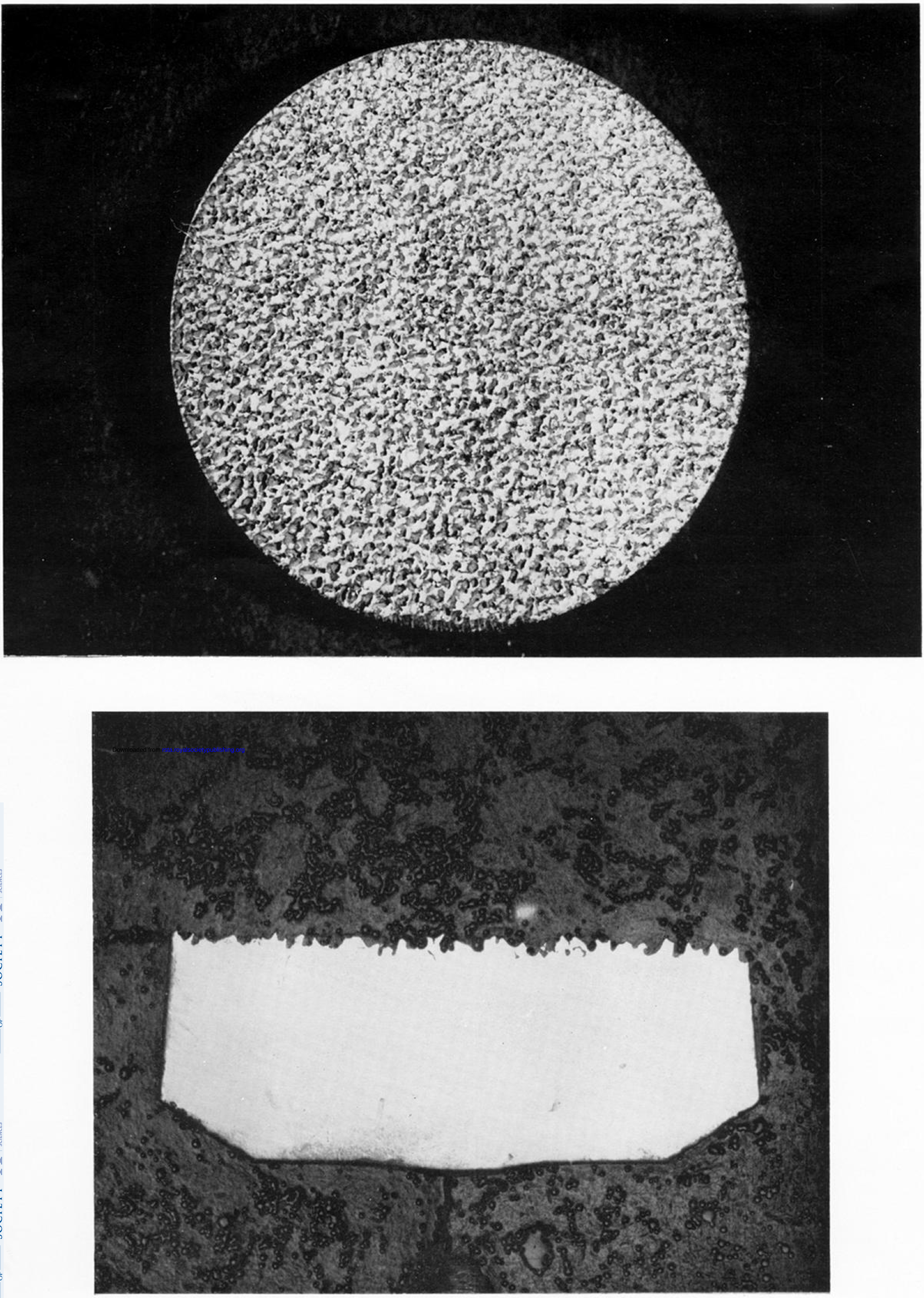

FIGURE 8. Tool steel specimen eroded for 100 h at a pressure of 2 in.Hg (abs.). Eroded face and microsection.

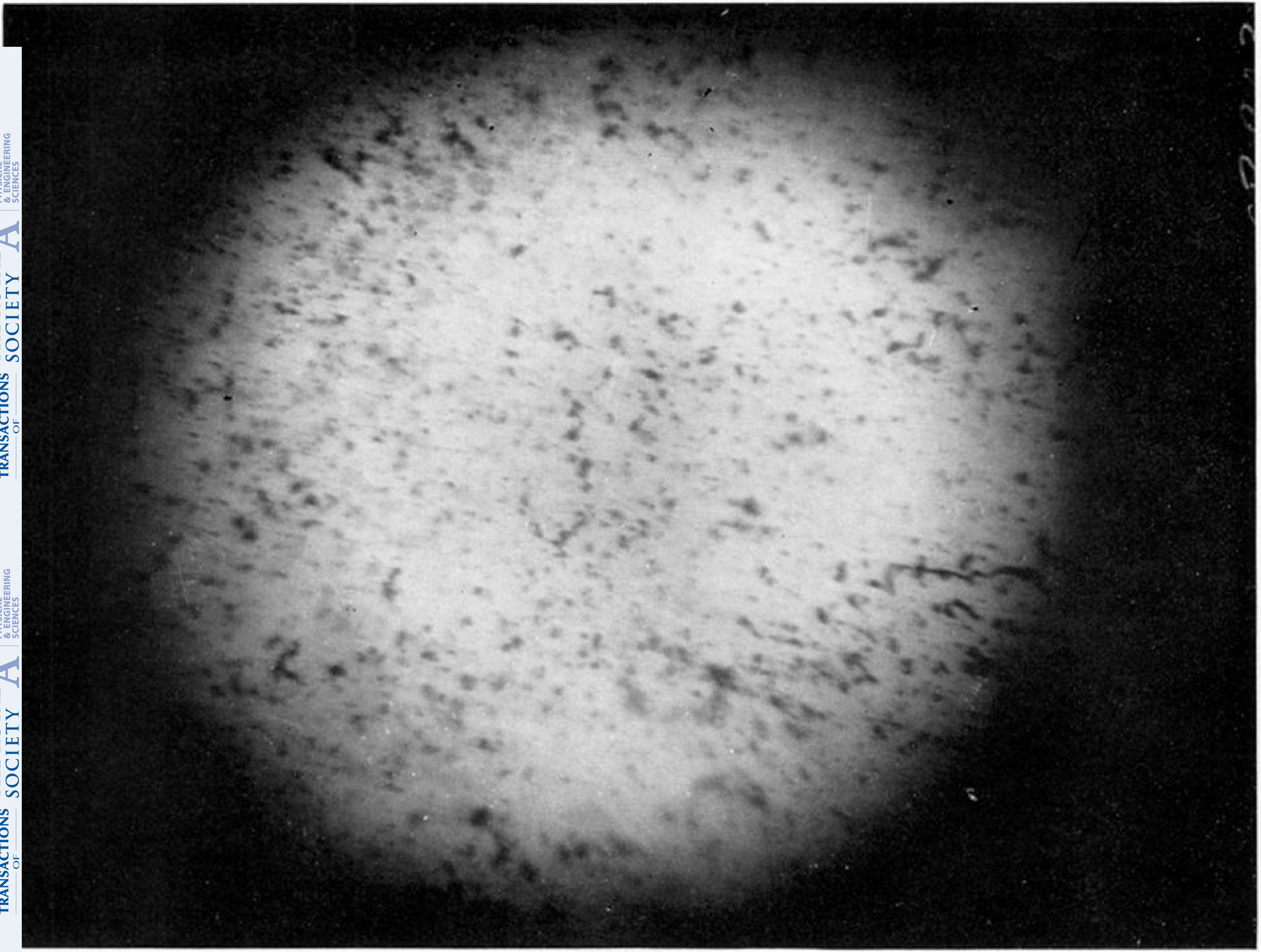

FIGURE 9. Droplet spectrum at pressure of 2 in.Hg (abs.).

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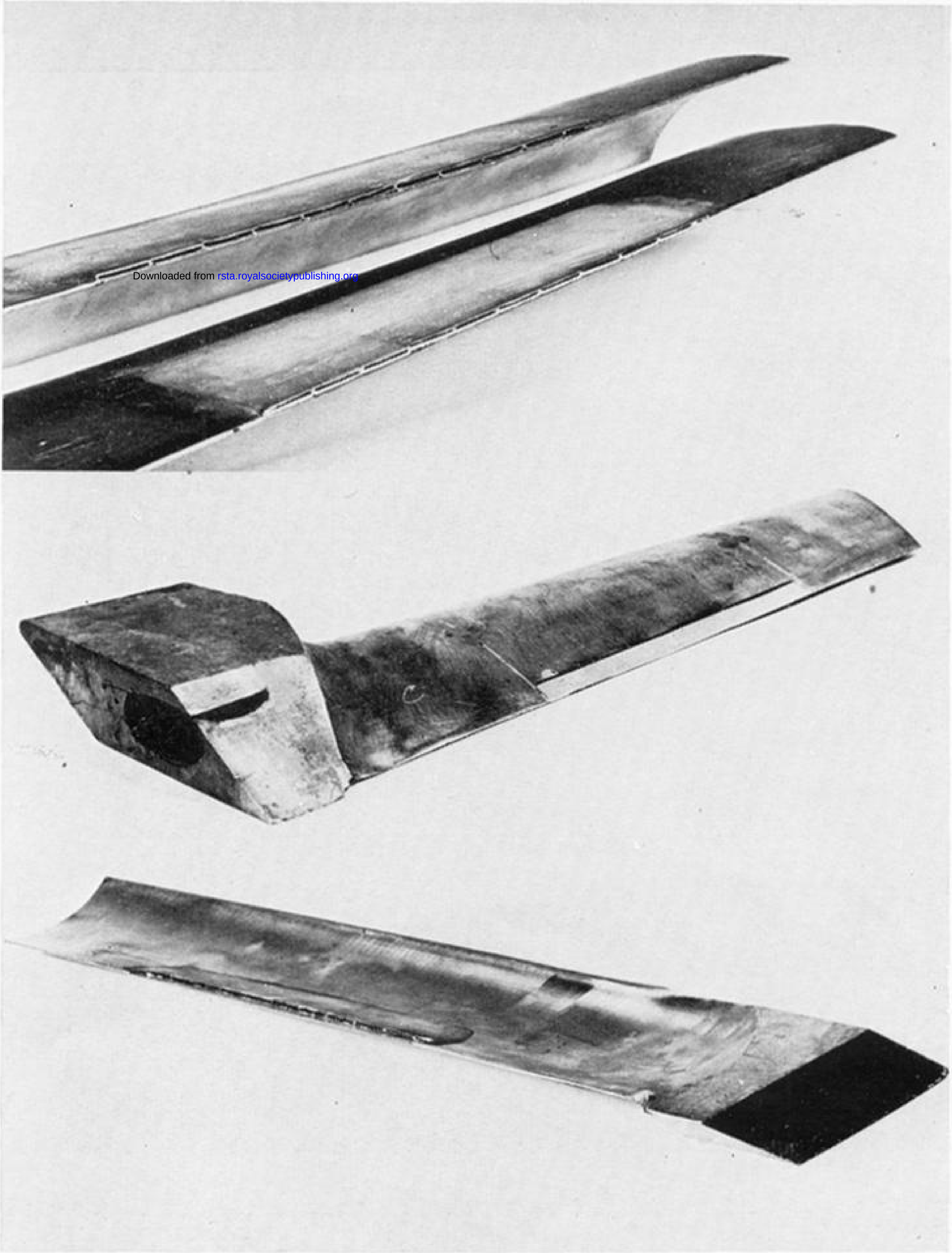

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