Observation of Events Leading to the Formation of Water Drops which Cause Turbine Blade Erosion

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D. EROSION OF STEAM TURBINE BLADES

XV. Observation of events leading to the formation of water drops which cause turbine blade erosion

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[Plates 33 to 36]

The large blades required in the last low pressure stages of modern turbines of 350 MW and above makes them more susceptible to erosion by wet steam owing to the increase in blade tip velocity.

A specially developed periscope combined with a ciné camera has been used for viewing inside an operating turbine to record the flow of water over the fixed blades and the subsequent formation and stripping of the water drops which then impact on the moving blades causing erosion.

The drops had a maximum diameter of 450 μm and the estimated total mass of the drops impacting on the blades was only a few per cent of the mass flow of water condensed from the steam. This confirms that the condensed steam forms a fog of droplets which are so small that only a very small proportion of them is captured by the turbine surfaces to produce large drops capable of causing erosion.

In addition to the direct practical value of these observations, the data provide background information in support of the high speed photographic studies of the drop-forming processes on a blade cascade in the laboratory.

Experiments in a steam tunnel in which the turbine low pressure steam conditions can be simulated, indicate that drops of 350 to 1600 μm leave the trailing edge of a blade and accelerate to a maximum velocity of 70 ft./s over a distance of about 1 in. in the blade wake. They are then caught in the main steam flow, which has a velocity of up to 1200 ft./s, where they are broken up and rapidly accelerated.

Analysis of the ciné films of observations in a turbine and in the steam tunnel gives the velocities and sizes of the drops causing turbine blade erosion.

1. Introduction

The large reheat steam driven turbo-alternators coming into service in the next few years with individual generating capacities of 350 to 500 MW will have moving blade tip speeds between 1700 and 2000 ft./s in the final low pressure stage. This is significantly higher than in existing machines which have maximum values of 1200 to 1400 ft./s and makes the new turbines more susceptible to moving blade erosion. The steam in the last low pressure stage of the new machines has a moisture content of about 6% at working load, and erosion is caused by relatively slow moving water drops which detach from stationary blade surfaces in the wet steam and are struck by the rotating blades. Figure 1 shows how this erosion occurs, water is deposited from the wet steam on to the fixed nozzle blades and drops of water collect at the outlet edge *F* where they eventually detach. Starting from rest these water drops are accelerated by steam drag to a velocity of only *AD* on reaching the moving blades, instead of *AB* the steam velocity, and they are struck by the leading edge of the back of the moving blade at *E* with a relative velocity of *CD* causing erosion damage to the blade metal.

Although eroded turbine blades have been studied in great detail when machines have been shut down, the actual erosion mechanism within a running turbine has remained the subject of speculation owing to the lack of reliable test data. To follow the processes in operating machines, a special periscope combined with a ciné camera has been developed which can be fitted into any turbine. It can be used at all loads to observe the water flow over the convex side of the last stage of fixed blades or in conjunction with a high powered xenon flashlight source to photograph the drops leaving these blades up to the time just before their impact with the moving blades. These observations enable the sources of the water drops to be accurately located.

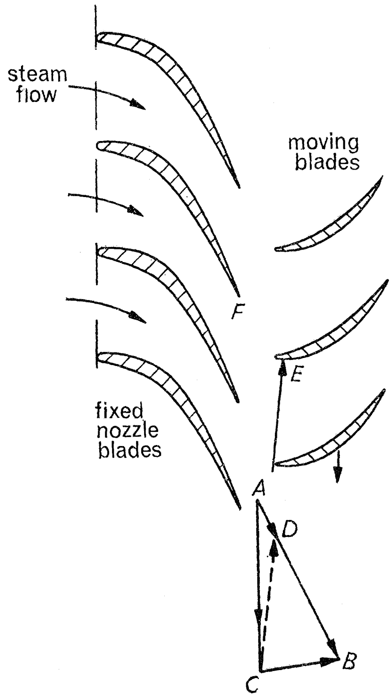

FIGURE 1. Diagram of blade, steam and eroding water drop velocities at the inlet to the moving blade row. Vector notation: *AC* represents the moving blade velocity; *AB* the velocity of steam leaving fixed blades; *CB* the steam velocity relative to moving blade; *AD* the velocity of entrained water drops at entry to moving blades; and *CD* the velocity of drops relative to moving blade at impact point *E* where erosion takes place.

In addition to the direct practical value of these observations, the data provide background information in support of the more detailed study of the drop-forming processes, which is possible in the laboratory under simulated conditions in a steam tunnel.

This facility reproduces the range of temperature, pressure and flow conditions existing in the last stages of the turbine. The flow over a cascade of blades and the drops stripped from them can be studied by direct measurement or by high speed photographic methods. The preliminary work which has been completed has been restricted mainly to observations of the drops and the results can be compared directly with the periscope observations.

2. Observations in the turbine

Experimental arrangement of periscope

Figure 2, plate 33, shows the periscope especially developed for this work which is fitted with a powerful tungsten light on a swivel at the remote end. A tilting mirror, mounted behind a pressure-tight glass window adjacent to the light source, allows the direction of view to be turned at right angles to the main body of the periscope. A lens mounted in the tube brings the image reflected down the tube to a focus at the film plane of a ciné camera at the outer end of the instrument. Alternatively the image may be focused on to a measuring graticule mounted in a microscope eye piece for visual observation as shown in the photograph. The arrangement of the apparatus in the turbine is shown in figure 3. A flexible seal at the outer casing of the turbine allows the periscope to be traversed to scan along a single blade, and by raising or lowering the inner end of the periscope on a support inside the turbine, several adjacent fixed nozzle blades can be examined. By twisting the periscope about its own axis to view at an angle of about 40° to the horizontal it is possible to obtain an almost unobstructed view of the convex sides of the upstream fixed nozzle blades which shed the erosion producing water drops as shown in figure 5.

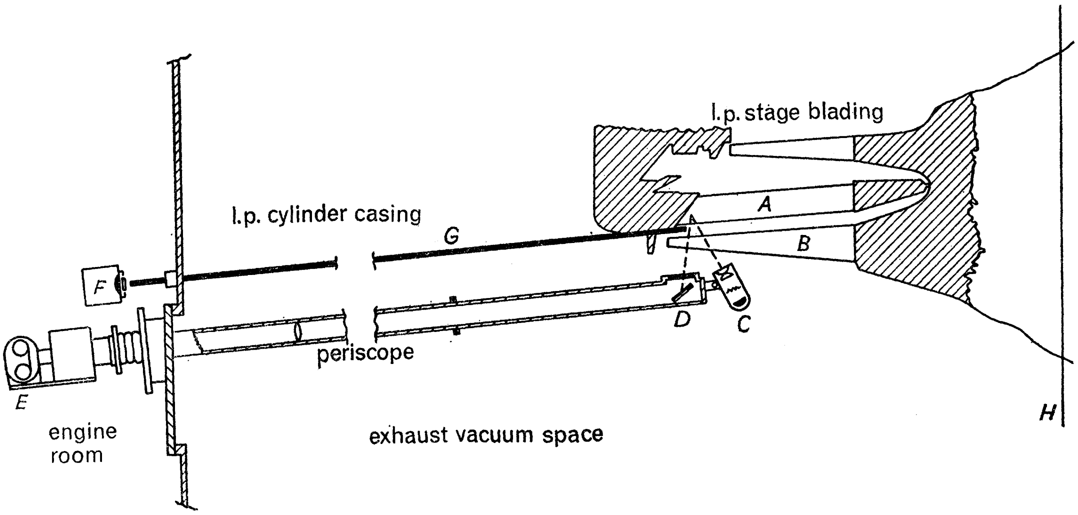

Figure 3. Arrangement of periscope in the turbine. *A*, last low pressure fixed nozzle blades; *B*, rotating blades (tip speed 1440 ft./s); *C*, tungsten light source; *D*, tilting mirror; *E*, ciné camera; *F*, xenon flash light source; *G*, quartz rod light-guide; *H*, centre line of turbine.

To obtain satisfactory photographs of the small water drops in flight with the periscope it was necessary to illuminate them from behind. This was achieved by inserting a source of illumination into the 2 in. axial clearance space between the fixed and moving blades of the last stage, as shown in figures 3 and 4. It consisted of a 20 J xenon flash light source mounted outside the turbine and a quartz rod light-guide 5 ft. in length to transmit the light into the machine. A mirror and lens were used to direct the light behind the water drops. The duration of each light pulse from the xenon flash was about 4 μs and its repetition rate could be synchronized with the framing rate of the camera up to a maximum of 25 flashes per second.

It is of interest to note that the optical conditions for viewing within a running turbine are difficult since the high velocity wet steam flowing through the last low pressure stage resembles a thick fog and scatters the light. To provide a light level of 1 to 2 foot-candles at the film plate it was necessary to use an overrun 200 W quartz-iodine lamp focused on the blade.

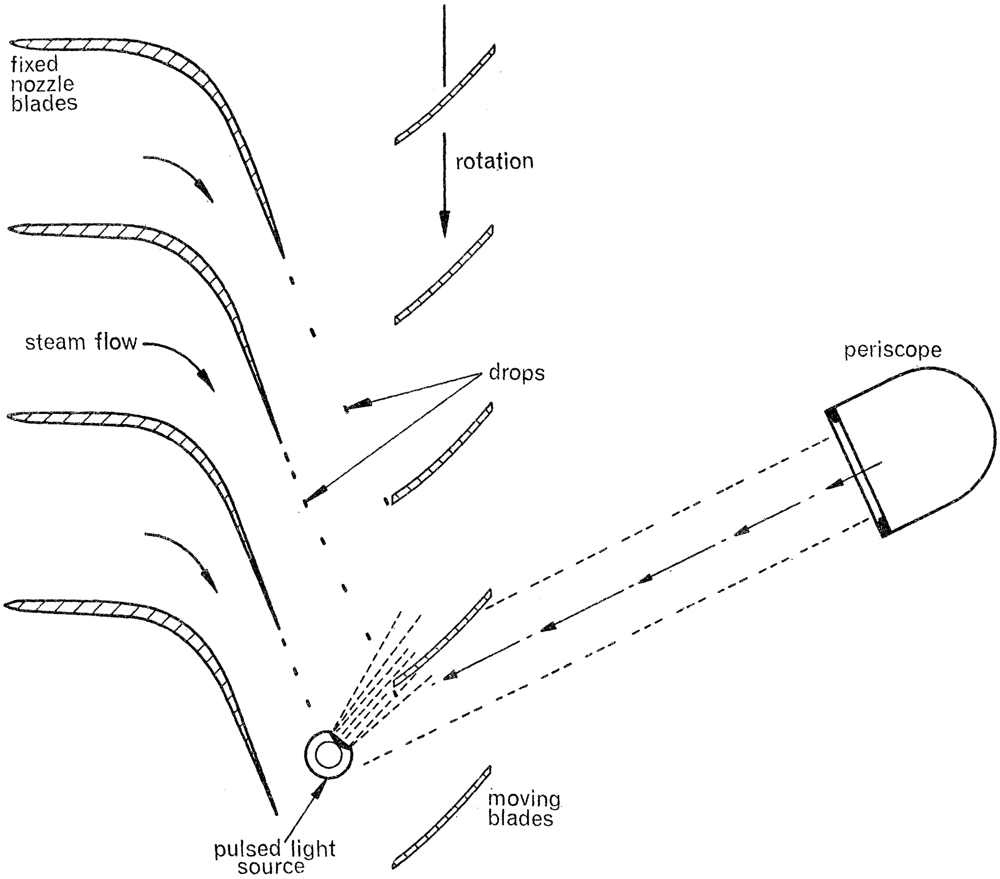

FIGURE 4. Method of observing water drops at the point of impact with moving blades.

Observation of water film and drops on the fixed nozzle blades of a turbine

The observations described in this paper were all made on a 120 MW turbine with a twin flow low pressure cylinder, and are concerned with steady state operation at loads between 40 and 100 % of full load. Other operating conditions were examined and an extract of a film made during start up of this turbine was shown at the Discussion Meeting. The analysis of this and other similar films indicate a number of consistent features which will be described.

Figure 5 is a diagram of the convex downstream faces of the blades in a sector of the last low pressure diaphragm ring of the machine as seen from the periscope position. It shows the positions of the observed sources of water responsible for moving blade erosion within the limits of observation of the periscope as indicated by the broken line. In the full diaphragm there are 104 fixed nozzle blades of radial length 2·25 ft. having a mean radius of 3·8 ft. The erosion producing water sources are representative of conditions between

40 and 100% of full load and referring to the annotation of figure 5 can be summarized as follows:

(1) Water streams at the junction of the nozzle blade convex surface and outer casing wall which flow forward with the steam to escape at the periphery of the next moving blades. This water shown at *A* usually does only minor damage to the moving blade as it can escape via the relatively large axial and radial clearance at the tip of the blade. There is, however, a certain amount of flow instability in this area, and occasional breakaway of the water occurs at *B* which causes some of the water to flow radially inwards to be shed at the nozzle outlet edge. This water can do erosion damage to the moving blades which pass in front of the nozzle at this point with a velocity of 1440 ft./s.

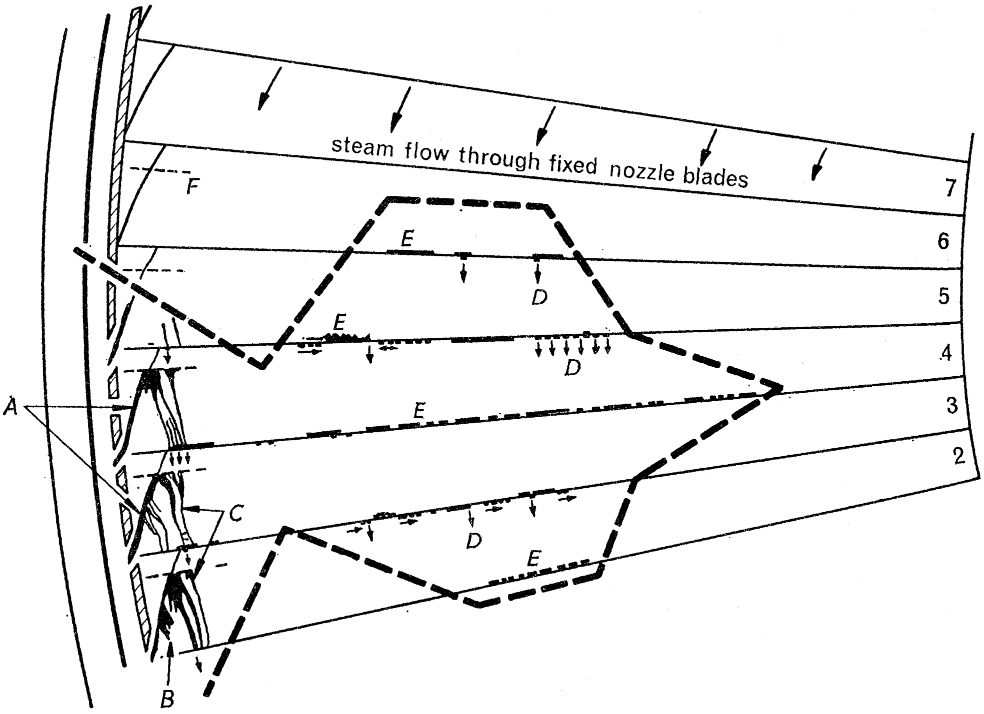

FIGURE 5. Sector of last low pressure diaphragm showing sources of erosion producing water drops on the downstream convex face and outlet edge of fixed nozzle blades 2 to 6. *A*, water streams in corner of nozzle; *B*, flow instability causing breakaway of water *A*; *C*, water concentrated by secondary flow in nozzle; *D*, water drops shedding at preferred positions (vertical arrows); *E*, areas of flow separation containing water; *F*, upstream limit of view due to inclination of periscope; horizontal arrows indicate direction of movement of water drops.

(2) The steam secondary flow in the fixed nozzle blades near the casing concentrates the surface water film from the concave surface of the blade and adjacent nozzle wall, directs it in a steady stream down the convex surface of each blade as shown at *C* where it is shed from the outlet edge of the blade. The arrows show these shedding positions, about 2 in. from the casing, where the water enters the low velocity wake downstream of the blade edge. Water drops up to 1400 μm in diameter have been observed at this point of detachment from the blade. The moving blade is travelling at about 1400 ft./s here, and

figure 6, plate 33 show the type of blade damage in this area using unshielded blades. Figure 7, plate 34, shows the water concentrated by the secondary flow on blade 3 where it first becomes visible at the overlap of blades 4 and 3.

(3) Water collected on the concave surface of the nozzle blades was observed to shed continuously as drops at preferred positions along the blade outlet edge, shown at *D* by vertical arrows.

(4) At other positions on the blade water drops were observed to appear leisurely at the outlet edge of the blade then shed, or sometimes to travel radially to a preferred shedding point before detachment from the blade. These water drops are shown on the edges of the blades in figure 5 without vertical arrows.

(5) Water at positions *E* indicate an area of steam flow separation from the convex surface of the blades just upstream from the outlet edge.

(6) Very little water was seen to be present under steady load conditions on the convex surface of the blades except where noted in (1) and (2) above. Thus deposition of water from the moisture in the steam occurred primarily on the concave surface of the nozzle blades.

Study of the drops immediately before impact with the moving blades

Using the xenon flashlight source, synchronized with the shutter on the ciné camera, water drops were photographed just before impact with the moving blades in the region of maximum damage about 2 in. from the blade tip. Figure 8, plate 34, is typical of the many hundreds of photographs taken on the turbine between 100 and 40% load. It shows the small water drops in flight which will impact with the moving blade in the top left-hand corner of the picture 20 μs or so later. Although drops up to 1400 μm diameter were seen to leave the fixed nozzle blades, the largest drop recorded in the vicinity of the moving blades was 450 μm diameter indicating that the larger ones break up during flight.

By analysing these photographs, taken at different turbine loads and flash repetition rates, the size of the drops and the number passing through the field of view per second was determined in order to estimate the mass flow of water responsible for the erosion at each load condition.

Table 1 gives the total number of drops impacting per second with a moving blade within the field of view in each of four size ranges at 100, 60 and 40% of full load.

TABLE 1

size range of drop diameters (μm)	total no. of droplets per second in each size range at given load		
	load 100%	load 60%	load 40%
50 to 150	384	1160	1283
150 to 250	322	414	744
250 to 350	16	54	125
350 to 450	0	4	10

It can be seen that the number of large water drops increases significantly as the load on the machines is reduced.

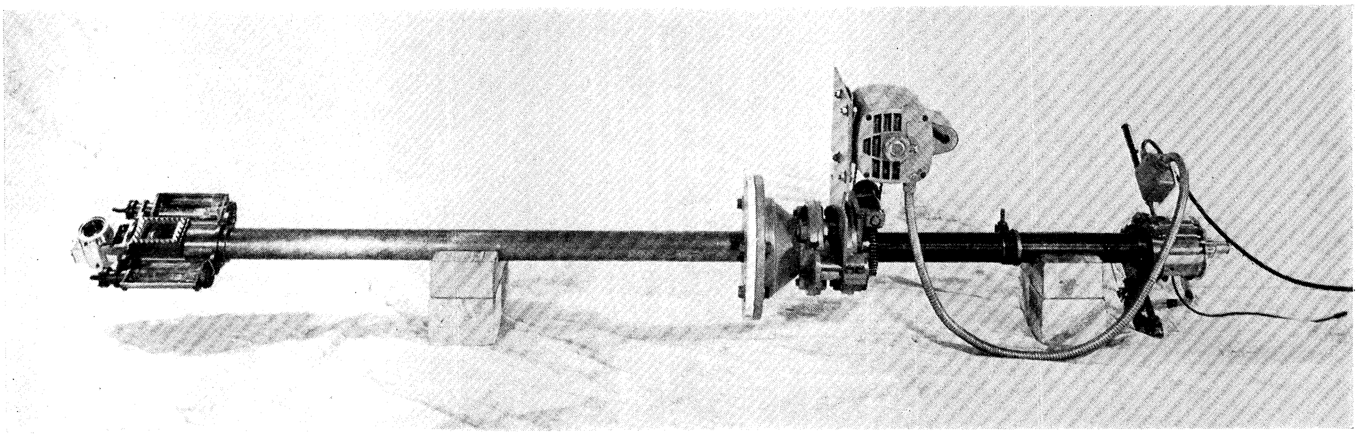

Figure 2. Periscope used in the low pressure cylinder.

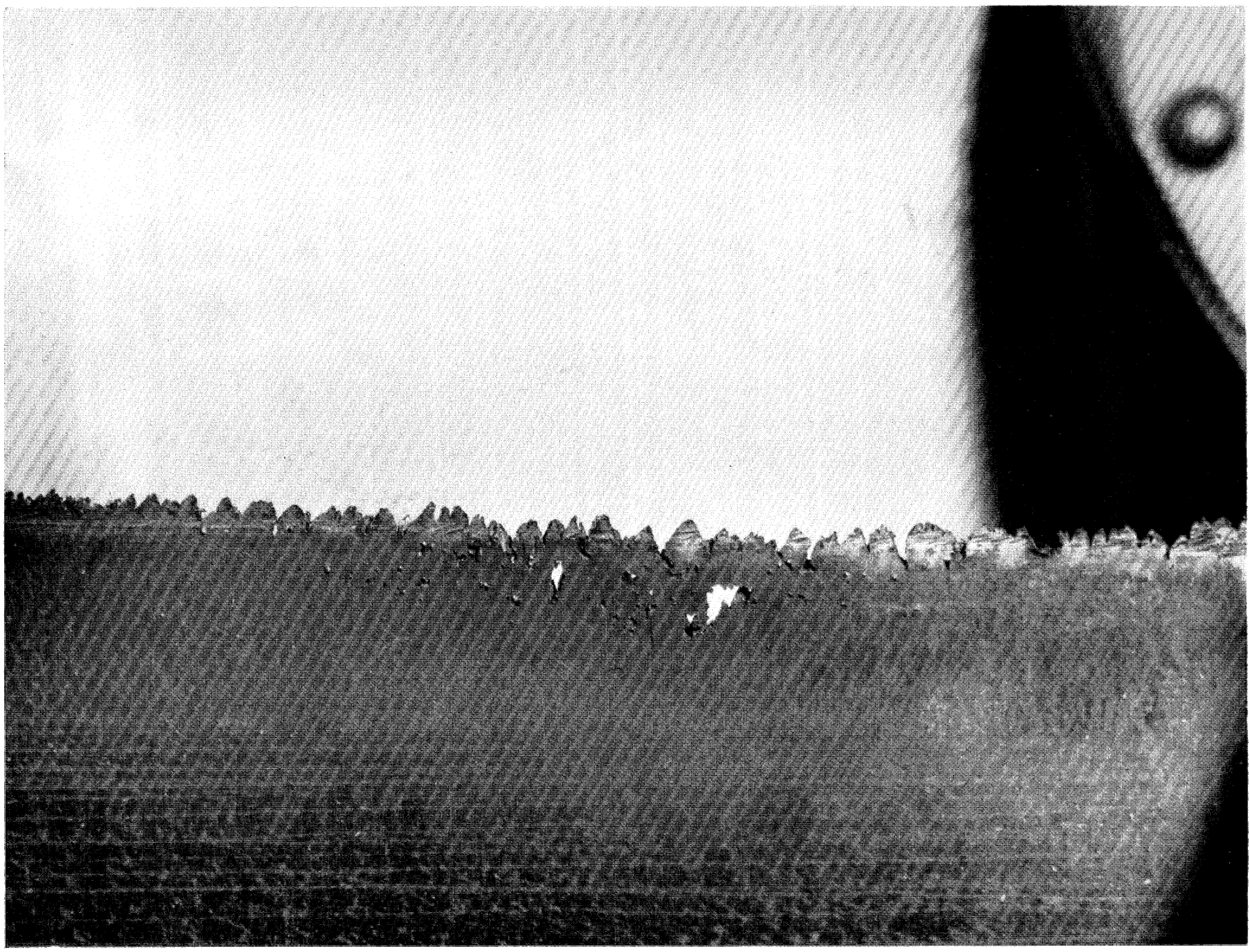

Figure 6. Working face of moving blade showing perforation damage caused by water *C* on figure 5 after 8200 h in service.

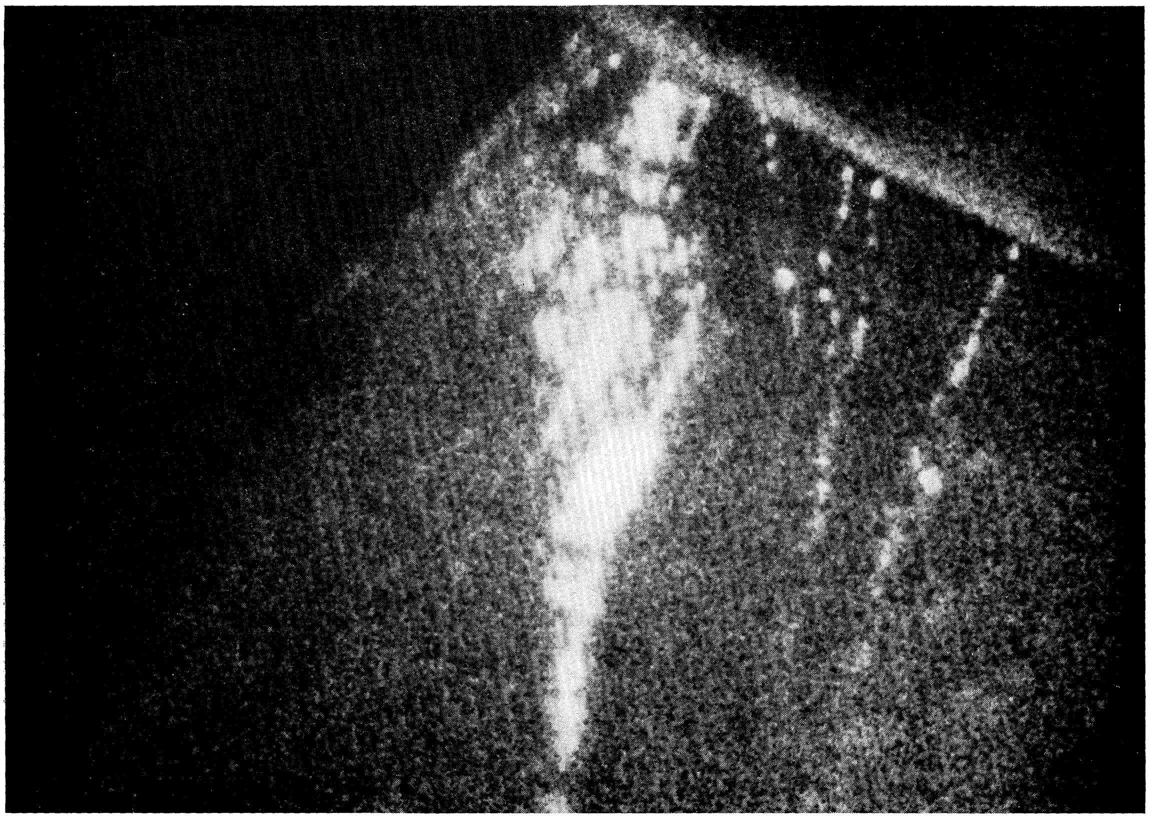

FIGURE 7. Water concentrated by the secondary flow on the convex surface of nozzle blade 3 in figure 5. The outlet edge of nozzle blade 4 can be seen at top right of photograph.

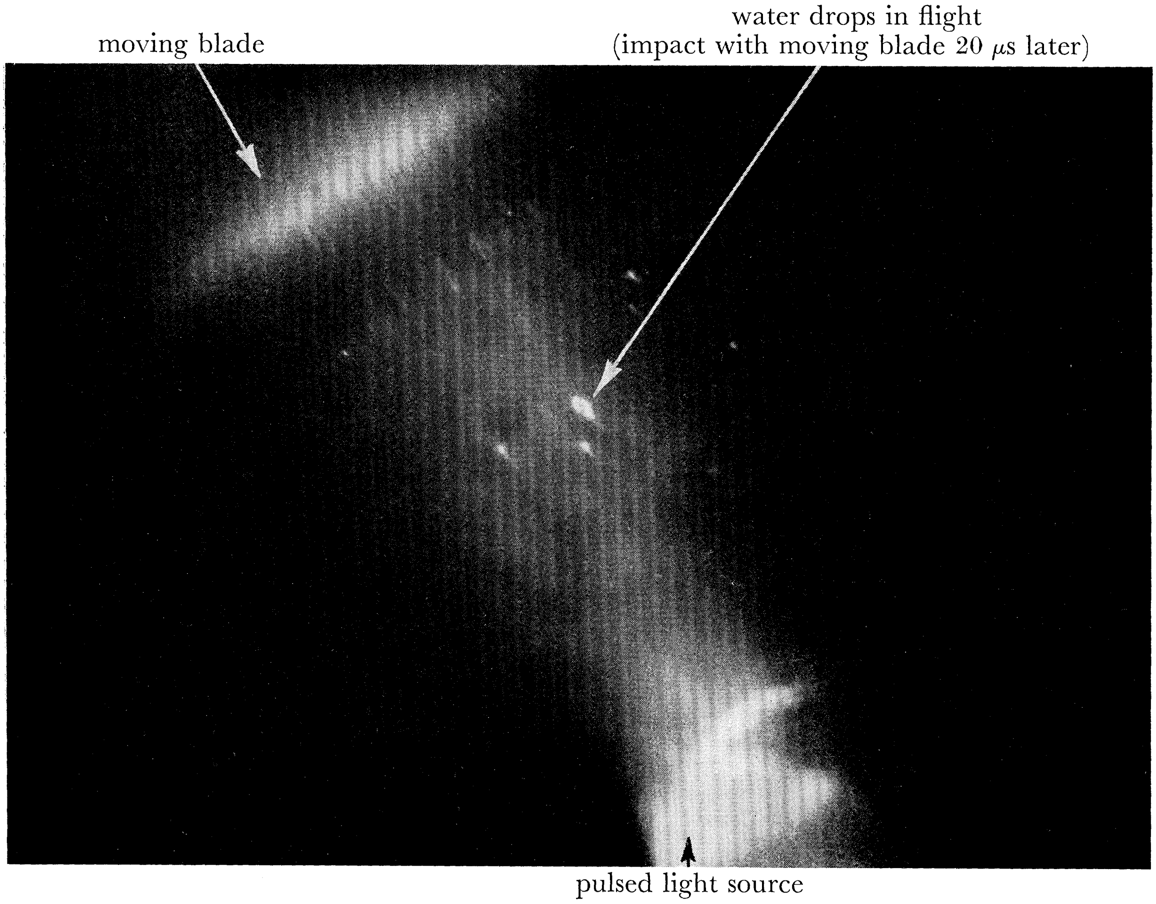

FIGURE 8. Water drops just before impact with the moving blade. Both the blade and the water drops are moving towards the light. The blade velocity is about 10 times that of the drops (exposure time, 4 μs).

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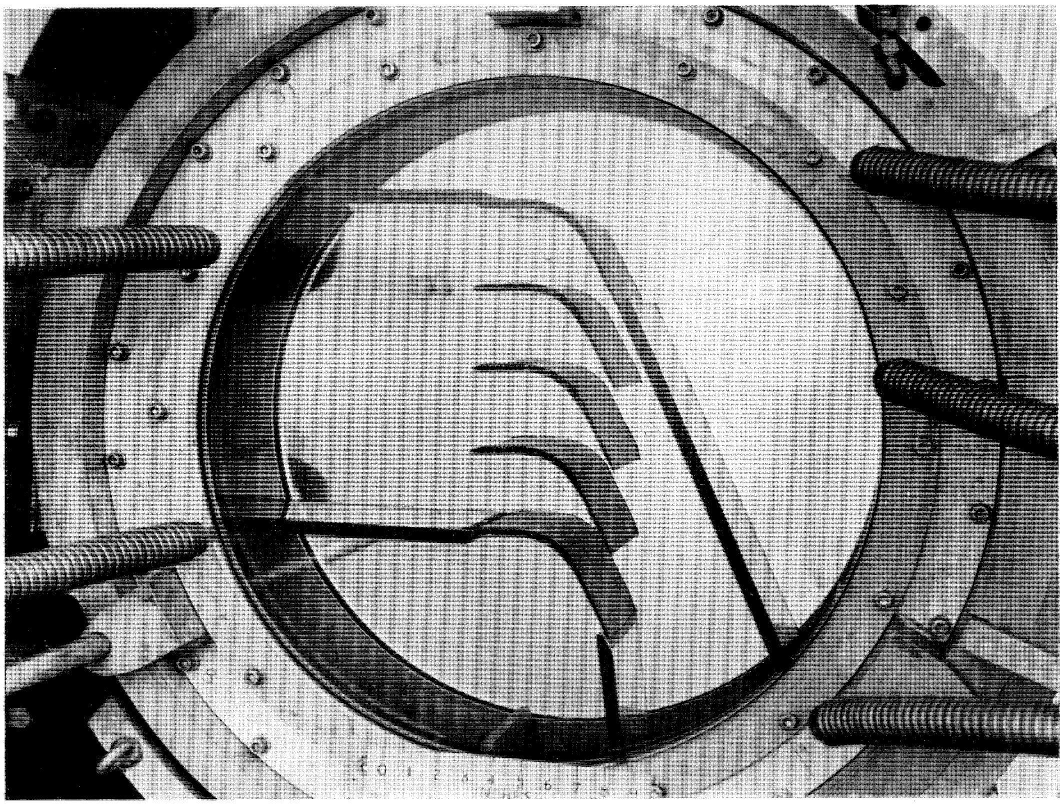


FIGURE 10. Test section of steam tunnel with cascade of blades in position.

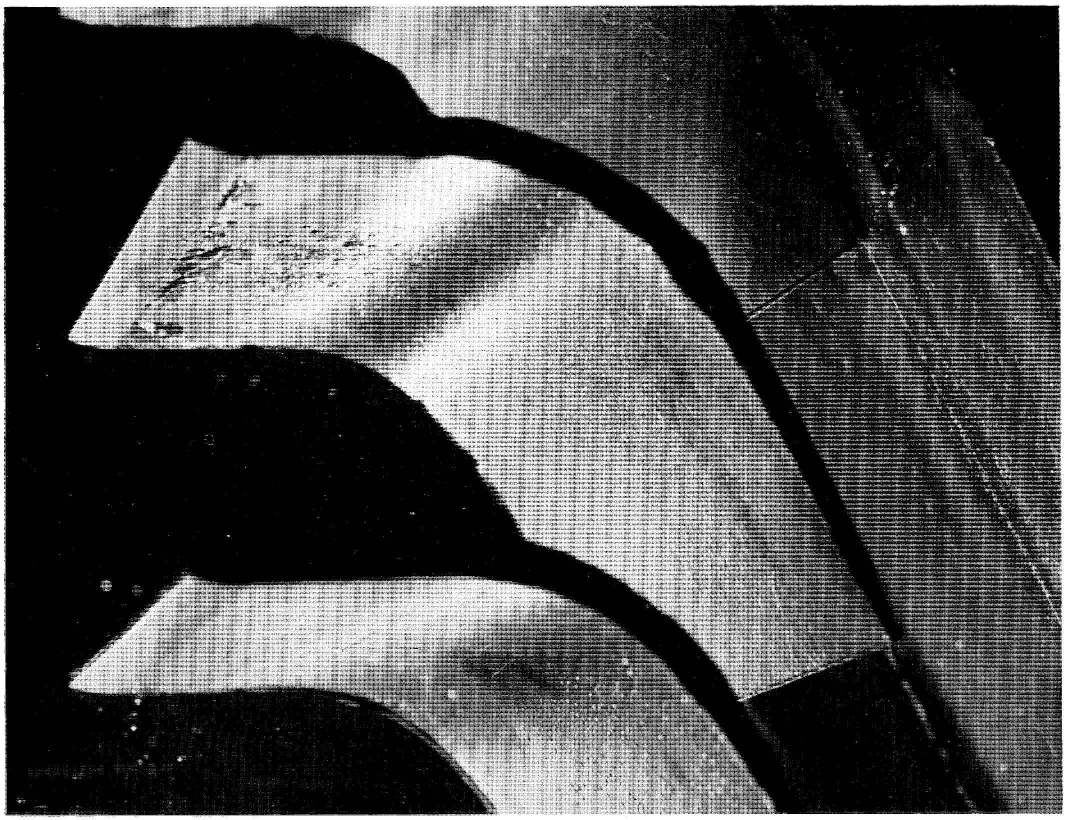


FIGURE 12. Quiescent water puddles in the region of flow separation
on the concave surface of a stalled blade.

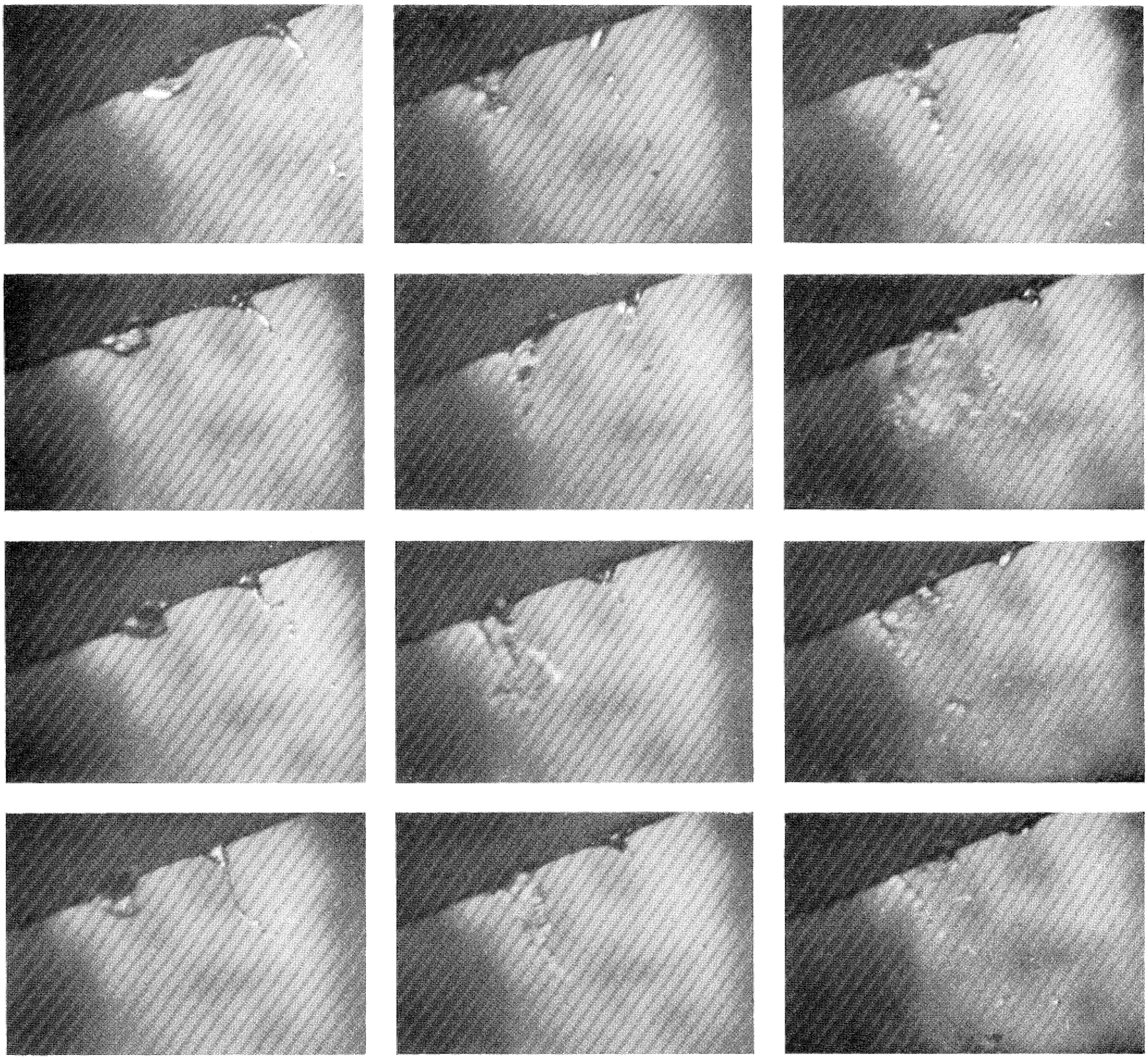


FIGURE 11. Section of ciné film showing water drops stripping from the trailing edge of the centre blade in figure 10. Steam conditions 0·66 Lb./in.^{2} (abs.) and 1020 ft./s. (Read downwards, from left to right.)

The total number of water drops at each load, together with the mass flow of water as drops over 50 μm in diameter is given in table 2. This water is responsible for eroding a radial length of about 1·5 in. of the moving blade edge in the region of maximum damage where the erosion is about three times as great as in adjacent areas.

TABLE 2

turbine load (%)	total no. of droplets impacting per second	mass flow of water (lb.) as droplets over 50 μm in diameter striking each moving blade per hour
100	722	0·032
60	1632	0·059
40	2162	0·107

If we assume that erosion damage is proportional to the mass flow of water drops striking the blade then the average mass flow per unit length of blade will be about one-third of the value obtained directly from the observations. Hence an estimate of the amount of water shed from one 27 in. fixed nozzle blade at full load is given by

$$\tfrac{1}{3}\times 0{\cdot}032\times\frac{27}{1{\cdot}5}\times\frac{110}{104}=0{\cdot}20\ \text{lb./h},$$

where the last factor is the ratio of the number of moving blades in the last stage to the number of fixed nozzle blades.

Thus at full load when the theoretical wetness content of the steam at the entry to the last low pressure stage is estimated as 6·8 %, corresponding to 31 550 lb./h, only 41·6 lb./h or 0·13 % of the theoretical moisture content participates in the erosion process. Water drops or less than 50 μm in diameter are not considered to contribute significantly to erosion.

Table 2 shows also that the water striking the moving blade at 40 % load is about three times the quantity at full load, which is consistent with the increased moving blade damage observed in similar machines run for long periods at part load. The additional water can be attributed to a higher rate of deposition of the water drops present in the steam which is consistent with the idea that these drops grow to a larger size under low load conditions.

3. LABORATORY INVESTIGATION IN A STEAM TUNNEL

Description of the steam tunnel

Since the drops causing erosion are produced by the fixed nozzle blades, their formation can be studied in detail in the laboratory with a simple cascade of blades through which steam can be passed under conditions which simulate those in the turbine. A steam tunnel has been constructed to produce the required flow through a test section which has a maximum height of 12 in. and a width of 6 in. between the two vertical viewing windows which form its sides. A sketch of the complete equipment is shown in figure 9 and the test section with a set of blades installed is illustrated in figure 10, plate 35. Both the angle of the exit duct, seen at the lower right in the photograph, and the height of the steam passage through the test section can be varied to suit the cascade under test. The currently available maximum steam flow is 4500 lb./h at pressures down to about $\frac{1}{2}$ Lb./in.^{2} (g) and the test rig has been operated with the exit velocity from a cascade up to about 1200 ft./s.

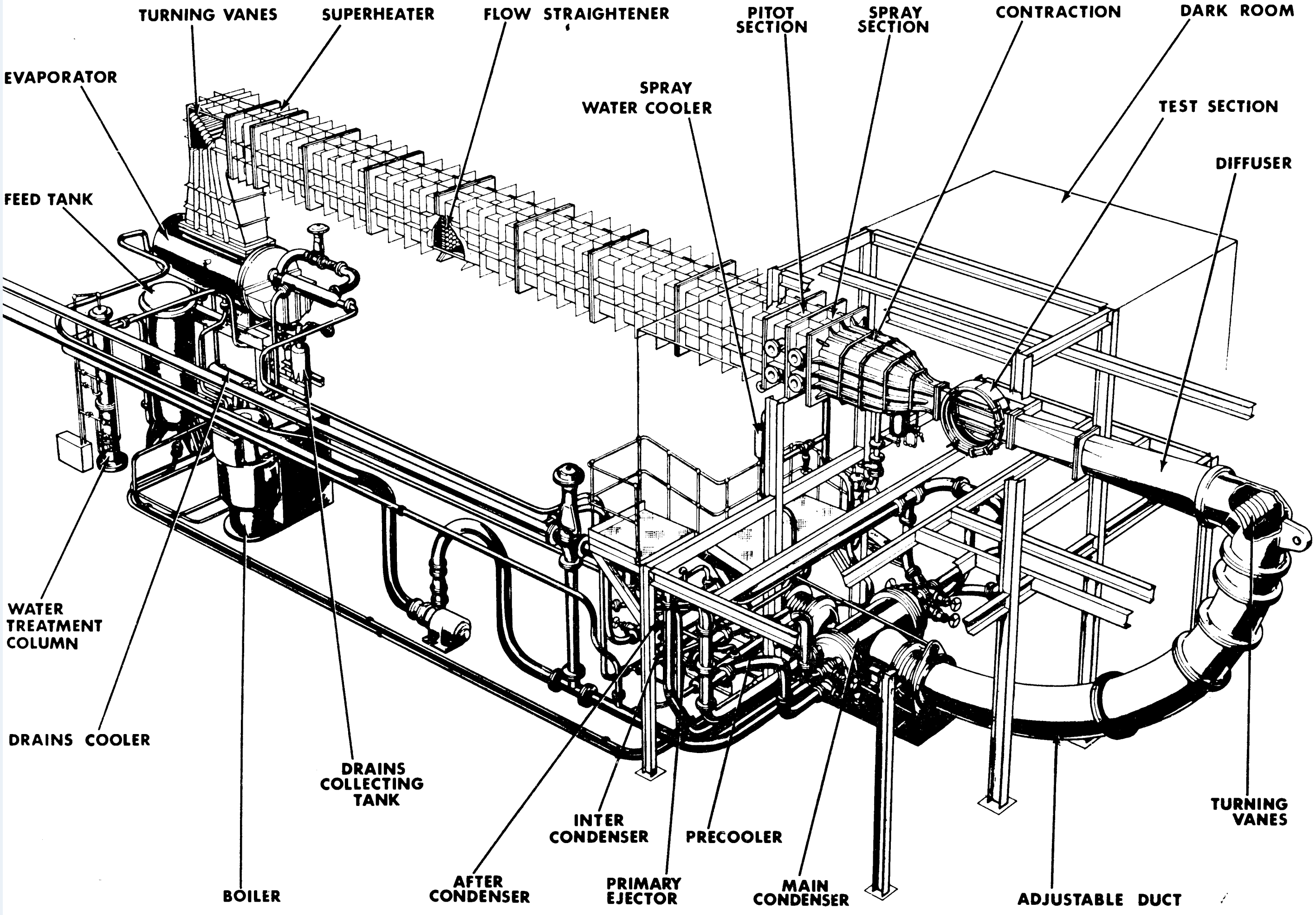


FIGURE 9. Diagram of cascade steam tunnel.

Briefly the operation of the rig is as follows: the low pressure steam is produced by heating the water in an evaporator with a submerged bundle of tubes inside which steam supplied from the boiler at 100 Lb./in.^{2} is condensed. The condensate is returned to the boiler via the feed tank and the low pressure steam passes along a 2 ft. 9 in. square horizontal flow stabilizing duct 40 ft. long to enter the test section through a contraction with an inlet to outlet area ratio of 16:1. After leaving the test section the steam is decelerated through a diffuser and passed to the condenser from which the condensate is returned to the evaporator. For any specific test arrangement the mass flow and the pressure in the test section depend only on the pressures in the evaporator and condenser. Since both these vessels contain saturated steam their pressures can be controlled more conveniently with automatic temperature controllers.

The steam is made wet by injecting water through a set of steam atomized water spray nozzles in the duct about 20 ft. upstream of the contraction. These nozzles produce a particularly fine spray and most of the drops reaching the test section are in the range of 10 to 50 μm diameter. However, this does not truly correspond to the fog of droplets produced by expansion of the steam in the turbine which are believed to be about 1 μm diameter or less. Although the mechanism of deposition of the drops on the cascade will not therefore be the same as in the turbine, the formation of the large drops on the downstream edges of the blades, which is being studied, will be unchanged.

However, a method of producing a more representative fog of drops in the steam is being sought in order to investigate the deposition process which is an important stage in the events leading to blade erosion.

Observations on a cascade

The observations to be described were obtained with a cascade of blades corresponding to the tip sections in the last stage of fixed nozzle blades in the turbine used for the periscope study. Their arrangement is illustrated in figure 10, plate 35. The steam conditions at the outlet from the cascade covered a range of pressures from 0·6 to 1·7 Lb./in.^{2} (abs.) and velocities from 800 to 1200 ft./s. The water drops leaving the trailing edge of the centre blade of the cascade were recorded with a Fastax camera running at approximately 4000 frames/s.

A typical sequence of frames printed from one of the ciné films is reproduced in figure 11, plate 36, and shows the drops formed downstream of the blade from the same viewpoint as figure 10, plate 35. An analysis of a number of films showed that a wide range of sizes were produced at any one steam condition but the average size decreased with both increasing pressure and velocity. The range was 700 to 1600 μm diameter for the lowest velocity and pressure and 350 to 700 μm diameter for the highest.

The corresponding average drop velocities $\frac{3}{4}$ in. downstream from the blade were only 25 and 60 ft./s respectively. Beyond this distance and within the region up to about $1\frac{1}{2}$ in. from the blade the drops were seen to accelerate and break up owing, it is assumed, to their leaving the low speed wake of the blade and entering the main stream. This is consistent with the periscope observations that drops up to 1400 μm diameter were seen leaving the fixed blades but no drops larger than 450 μm diameter were seen approaching the rotating blades. The secondary breakup mechanism is to be studied in more detail with a higher speed camera.

Figure 12, plate 32, is a photograph of the leading edge of the concave side of a blade in the cascade. The long photographic exposure time of 1 s indicates that the water puddles were almost stationary implying a separation of the steam flow over this region of the blade. Whether this unsatisfactory condition exists in the turbine can only be checked with new equipment since this part of the blade is beyond the field of view of the present periscope.

Considerable caution must be exercised in drawing general conclusions from the laboratory observations since they strictly apply only to one particular cascade. However, the favourable comparison with the periscope observations on an identical blade arrangement in a turbine give confidence in the method of simulating these turbine conditions in the laboratory.

4. Conclusions

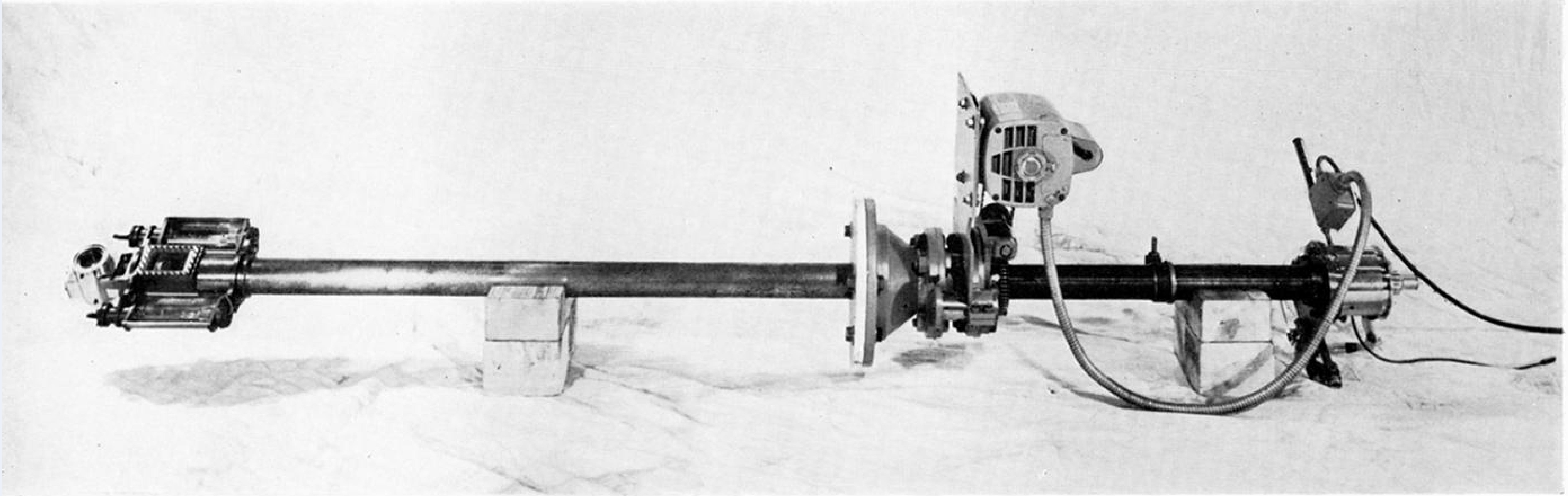
Erosion damage to the moving blades in the 120 MW turbine investigated with the periscope is caused by water shed into the low velocity wake at the outlet edge of the fixed nozzle blades. The source of the water is the deposition of drops from the steam principally on to the concave surface of the fixed blades.

The secondary flow conditions at the outer ends of the fixed blades next to the casing concentrate water near the outer ends which causes the most severe damage to the moving blades. The maximum diameter of water drops impacting with the blade was found to be 450 μm. The quantity of water causing the erosion damage was estimated as 0·13 % of the moisture theoretically present in the steam at the inlet to the low pressure stage under full load. When the turbine load was reduced to 40 % it was observed that three times the quantity of water drops impacted with the moving blade compared with full load. This agrees with the extra damage found to be sustained by blading in this type of machine run at partial loads.

Photographic records of water drops stripped from a cascade of blades of similar form to those observed in the 120 MW turbine indicate that, under simulated conditions in a laboratory steam tunnel, the eroding drops are produced in two stages. They are first shed into the low velocity blade wake with a range of diameters from 350 to 1600 μm and reach a velocity between 20 and 60 ft./s after travelling about $\frac{3}{4}$ in. Within the next $\frac{3}{4}$ in. of travel they escape from the wake into the high velocity main stream where they are rapidly accelerated and broken up.

The drop sizes measured in the steam tunnel agree with those measured under similar conditions in the turbine. This provides a degree of confidence that methods developed in the steam tunnel to reduce erosion will be applicable to the turbine.

The authors wish to acknowledge the experimental work carried out in the S.E. Region by Mr P. Sculpher and at the Central Electricity Research Laboratories by Mr A. N. MacDonald.



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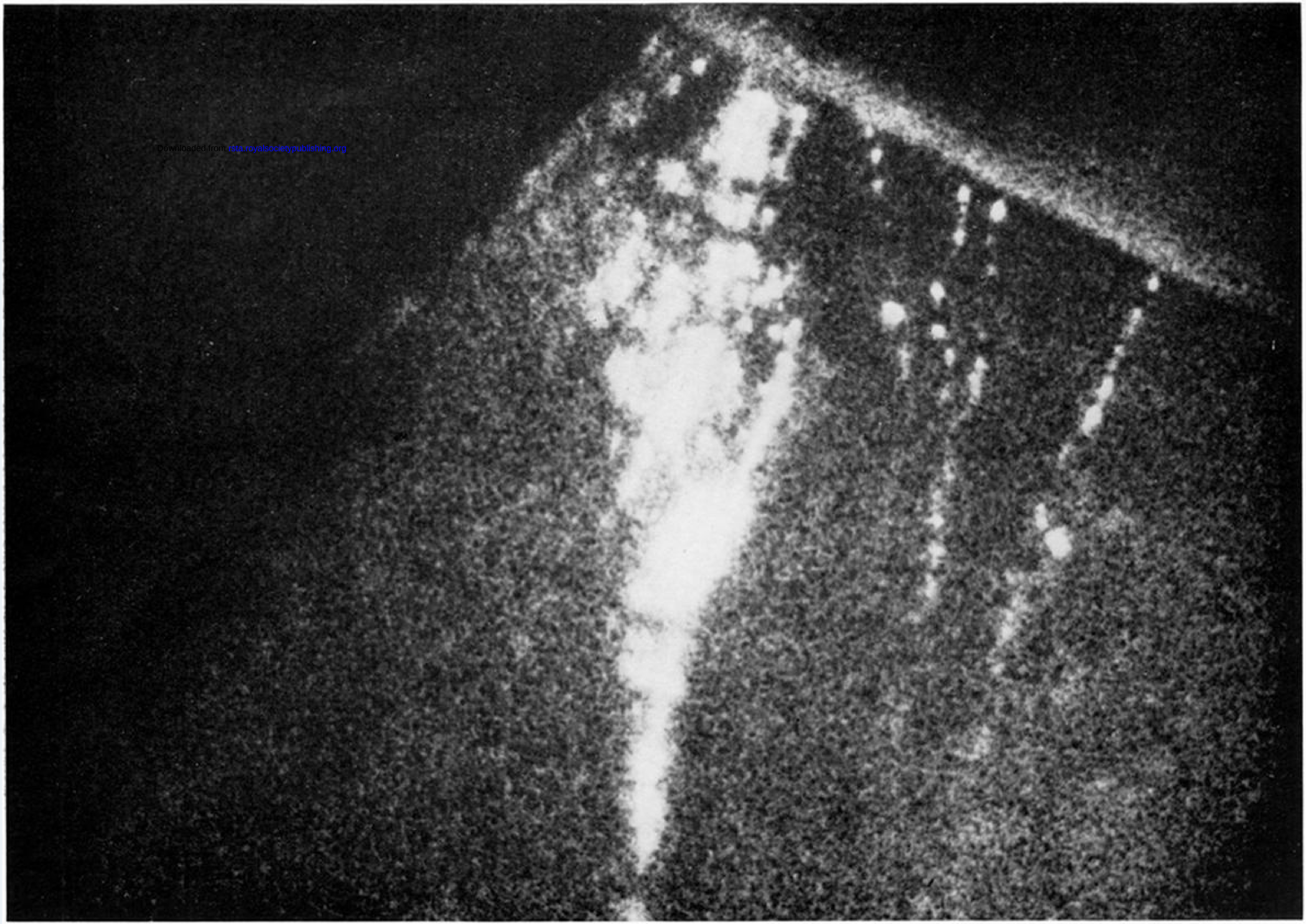

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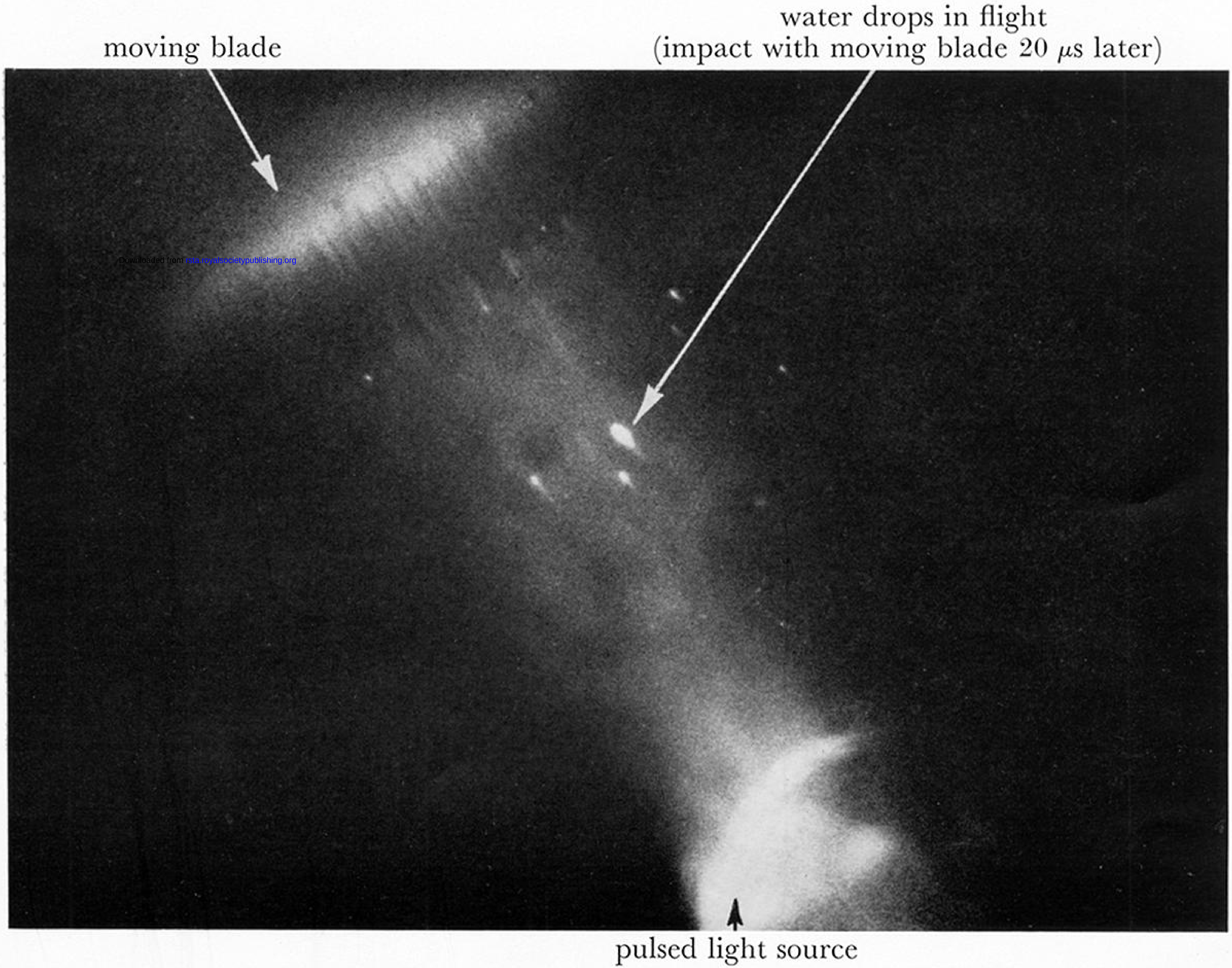

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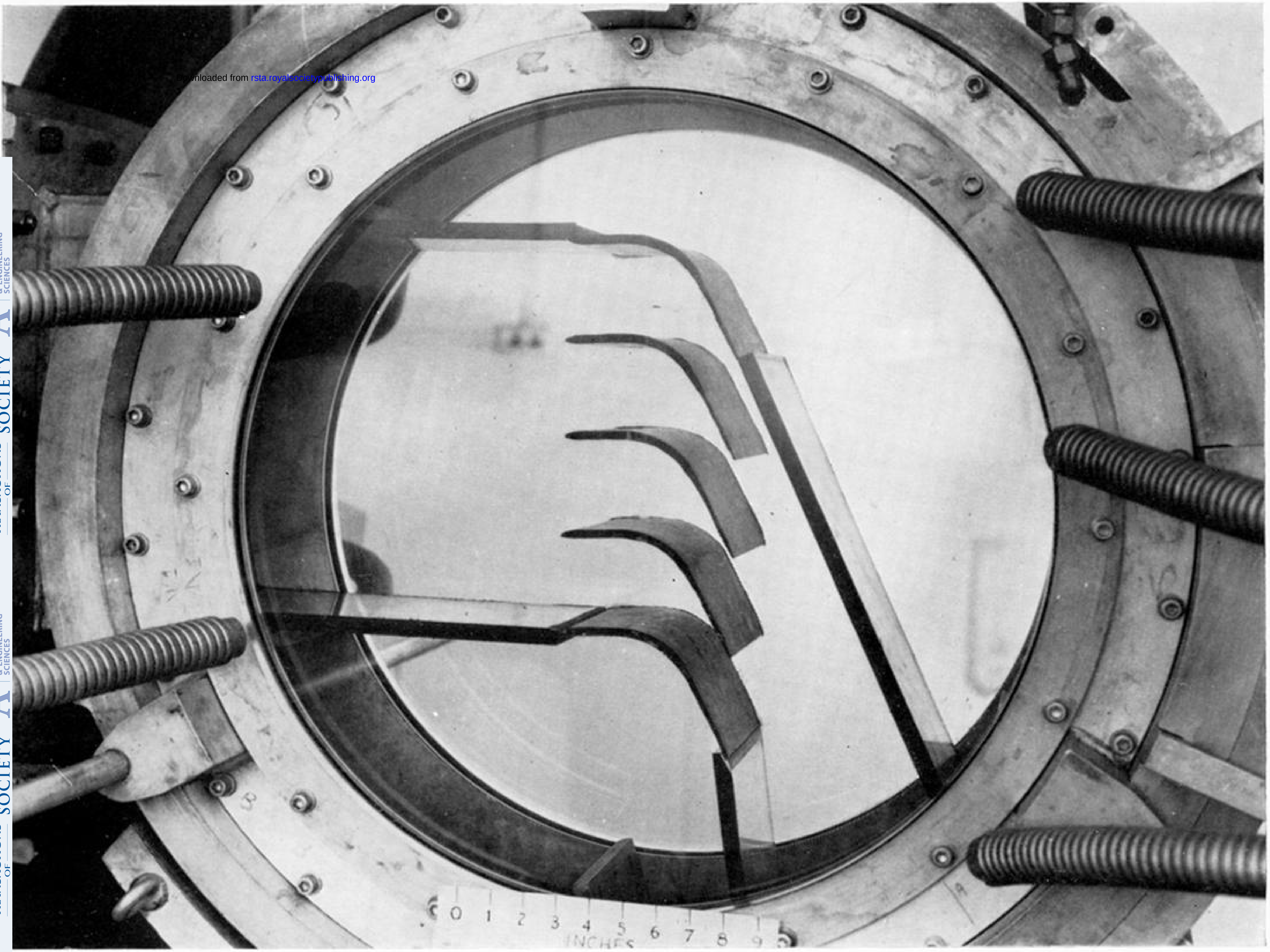
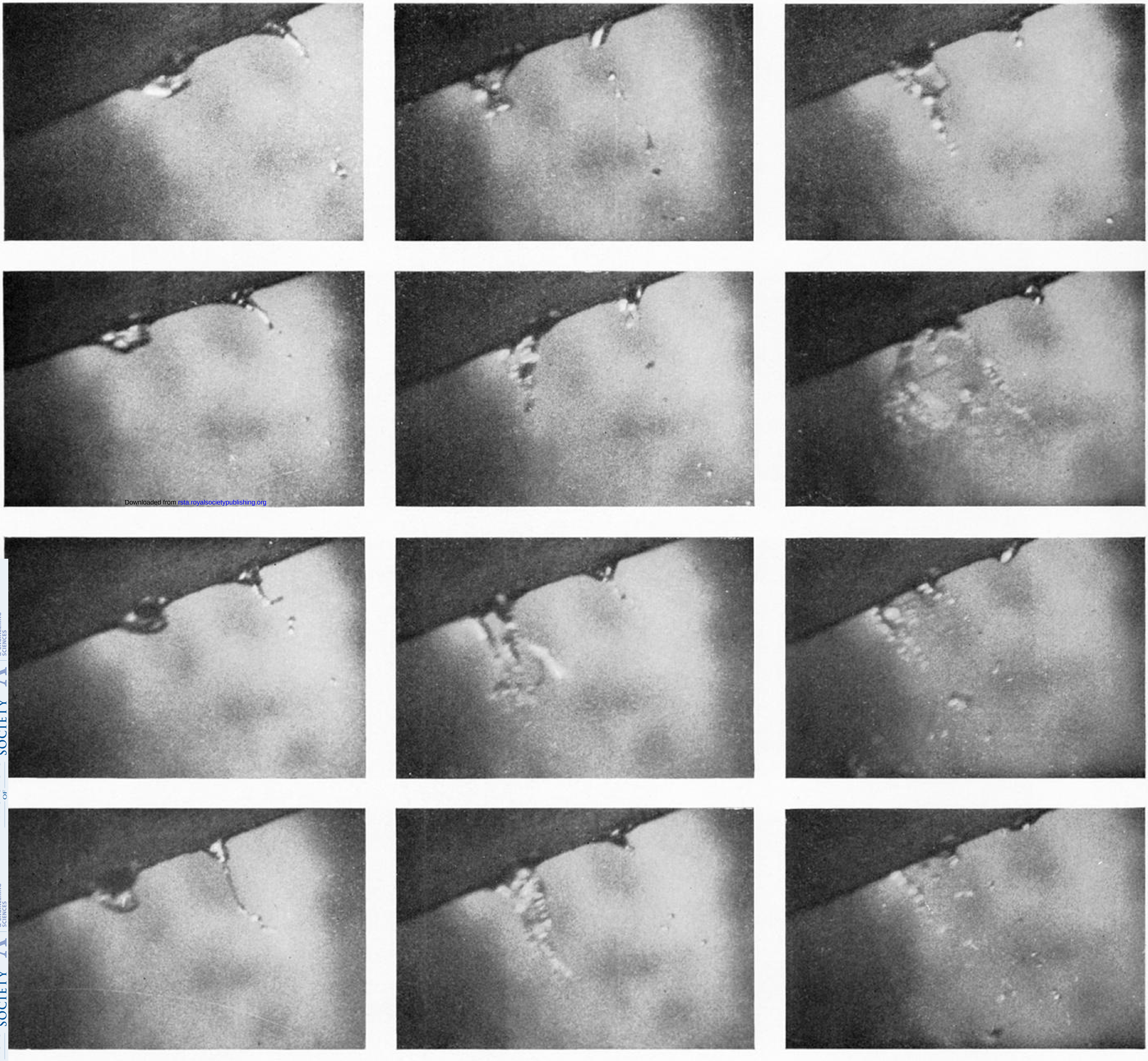


FIGURE 10. Test section of steam tunnel with cascade of blades in position.

FIGURE 12. Quiescent water puddles in the region of flow separation on the concave surface of a stalled blade.



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