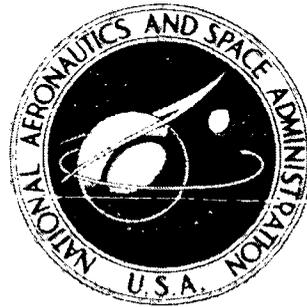


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**A HIGH-SPEED PHOTOGRAPHIC SYSTEM
FOR FLOW VISUALIZATION
IN A STEAM TURBINE**

by Gerald J. Barna

Lewis Research Center

Cleveland, Ohio 44135

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16. Abstract A photographic system was designed to visualize the moisture flow in a steam turbine. Good performance of the system was verified using "dry" turbine mockups in which an aerosol spray simulated, in a rough way, the moisture flow in the turbine. Borescopes and fiber-optic light tubes were selected as the general instrumentation approach. High-speed motion-picture photographs of the liquid flow over the stator-blade surfaces were taken using stroboscopic lighting. Good visualization of the liquid flow was obtained. "Still" photographs of drops in flight were made using short-duration flash sources. Drops with diameters as small as 30 μm (0.0012 in.) could be resolved. In addition, motion pictures of a spray of water simulating the spray off the rotor blades and shrouds were taken at normal framing rates. Specially constructed light tubes containing small tungsten-halogen lamps were used. Sixteen-millimeter photography was used in all cases. Two potential problems resulting from the two-phase turbine flow (attenuation and scattering of light by the fog present and liquid accumulation on the borescope mirrors) were taken into account in the photographic system design but not evaluated experimentally.			
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A HIGH-SPEED PHOTOGRAPHIC SYSTEM FOR FLOW

VISUALIZATION IN A STEAM TURBINE

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SUMMARY

Condensate in vapor turbines that operate in the "wet" region of the Mollier diagram reduces turbine efficiency and can cause erosion damage to rotor blades and shrouds. Visualization of the condensate flow could lead to a better understanding of the flow phenomena and better methods of controlling the damaging liquid. For this purpose a photographic system was designed to visualize the moisture flow in a steam turbine. Good performance of the system was verified using "dry" turbine mockups in which an aerosol spray simulated, in a rough way, the moisture flow in the turbine.

Borescopes and fiber-optic light tubes were selected as the general instrumentation approach. High-speed motion-picture photographs of the liquid flow over the stator-blade surfaces were taken using stroboscopic lighting. Good visualization of the liquid flow was obtained. Still photographs of drops in flight were made using short-duration flash sources. Drops with diameters as small as 30 micrometers (0.0012 in.) could be resolved. In addition, motion pictures of a spray of water simulating the spray off the rotor blades and shrouds were taken at normal framing rates. Specially constructed light tubes containing small tungsten-halogen lamps were used. Sixteen-millimeter photography was used in all cases. The effects of painting blade surfaces on the visualization of the flow were investigated.

Two potential problems resulting from the two-phase turbine flow (attenuation and scattering of light by the fog present and liquid accumulation on the borescope mirrors) were taken into account in the photographic system design, but the problems were not evaluated experimentally.

INTRODUCTION

In wet-vapor turbines such as those used in advanced space power systems (ref. 1) and central station steam powerplants, the condensate that forms and collects on blade

and casing surfaces reduces turbine efficiency and can cause serious damage to turbine rotor blades and shrouds. In order to bring about a better understanding of the nature and control of the condensate flow in wet-vapor turbines, the NASA has undertaken a program to analyze and photograph the flow in a steam turbine. As part of this program a high-speed photographic system was designed for the purpose of visualizing the condensate flow in a test turbine. This report describes the design of the photographic system and the verification of its performance using "dry" turbine mockups.

Results of photographic studies of the condensate flow in steam turbines are reported in references 2 to 4. In these studies photographs primarily of the condensate flow on the suction surface of the turbine stator blades and of drops in flight from the stator to the rotor blade rows were taken. In the present NASA program a more comprehensive study of the condensate flow was desired, including the flow on the stator-blade pressure surface, suction surface, and, at the trailing edge, drops in flight from the stator to rotor blade rows and the spray of condensate spun off the rotor blades and shrouds. The effects of stator trailing edge and casing slot condensate removal on the condensate flow were also to be photographed.

Because of the comprehensive nature of the intended photography and the variety of flow phenomena to be observed, considerable flexibility was required in the photographic system. The general approach selected used fiber-optic light tubes to transmit light into the turbine and rigid, lens-type borescopes to transfer the image out to the cameras, which were mounted outside the turbine. For the most part, high-intensity, short-duration, single-flash, double-flash, and stroboscopic lighting was used. Sixteen-millimeter still and motion picture photography (up to 6000 frames/sec) was used. Lighting-to-subject and borescope-to-subject distances were approximately 2.5 to 10 centimeters (1 to 4 in.).

The performance of the photographic system was demonstrated using "dry" simple mockups of the steam turbine. Condensate flow was simulated by using an aerosol spray of water drops. Two potential problems resulting from the two-phase flow environment in the steam turbine, namely, the attenuation and scattering of light by the fog present and the collection of liquid on the borescope optical surfaces, were taken into account in the photographic system design but not evaluated experimentally.

PHOTOGRAPHIC SYSTEM DESIGN AND EQUIPMENT SELECTION

Design Considerations

Test turbine. - A simplified longitudinal section of the four-stage test turbine is shown in figure 1. The first three stages are designated "slave stages" because their

function is to provide steam at the proper conditions to the fourth stage, designated the "test stage." All the photographic testing is done on the fourth turbine stage.

The test turbine flowpath has a constant mean diameter of 64.3 centimeters (25.3 in.). The pitch of the fourth stage stator blade row is approximately 4.06 centimeters (1.6 in.) at the three-quarter blade height position, and the stator blade height is approximately 5.69 centimeters (2.24 in.) at the trailing edge. A 2.5-centimeter (1-in.) axial spacing between the fourth-stage stator and fourth-stage rotor blade rows was used to provide space for optical instrumentation. Condensate removal slots are located in the casing at the trailing edge of the third and fourth stage rotor blades and in the trailing edge of the fourth stage stator blades.

To get the flow path from outside the turbine, a heavy casing and the stator blade ring must be penetrated. The thickness of metal, more than 15 centimeters (6 in.), and the high-pressure annulus between the blade ring and casing impose constraints on the photographic system design. Borescopes and fiber-optic light tubes lend themselves well to these constraints and were selected as the general instrumentation approach. O-ring seals were used at the outside of the turbine casing and on the outside of the blade ring at the high-pressure annulus to prevent leakage of steam through the penetrations used for the borescopes and light tubes.

Flow interference constraints. - An important consideration in the photographic system design was avoiding disturbing the flow being photographed. Cascade tests performed in air using blading similar to that of the test turbine indicated that reasonably small-diameter instrumentation could be placed in certain locations in the stator-rotor axial space without seriously disturbing the flow either on the surface or in the wake of the blade being photographed. These tests showed further that a large cutout in an adjacent stator blade could be tolerated without seriously affecting the flow on the blade being photographed. A diameter of 0.953 centimeter (0.375 in.) was selected for instrumentation that would be inserted in the turbine flow path as a compromise between optics and light transmission, which favor large diameters, and avoiding flow disturbances, which favor small diameters. With a 0.953-centimeter (0.375-in.) diameter the cascade tests indicated that instrumentation in the stator-rotor axial space should be at least three-quarters of a blade pitch circumferentially away from the blade being photographed to avoid significant flow disturbance. This criterion, along with the acceptability of a large cutout in the adjacent blade was used as a guideline in the photographic system design.

Photographic and condensate removal testing is desired over a wide range of turbine operating conditions with turbine exit pressures from approximately 6.89×10^3 to 6.89×10^4 newtons per square meter (1 to 10 psia). Most of the condensate present in the turbine is in the form of submicrometer diameter drops. This fog of small diameter drops scatters and attenuates the light. At the low pressure end of the desired test

range, rough calculations indicate small light attenuation from the fog. However, at the high pressure end calculations indicate substantial light attenuation. The results of these calculations are qualitatively consistent with the observations of references 2 and 3. To minimize the effects of the fog on light attenuation and scattering, the lighting to subject and borescope to subject distances were kept as small as possible without disturbing the flow.

While most of the condensate is in the form of submicrometer-diameter drops, a small fraction is collected by blade and casing surfaces. This liquid may run over the borescope mirrors and obscure the view. To keep the borescope mirror surfaces free from liquid there is at each borescope location in the turbine a small tube which directs a jet of "screening" gas over the borescope mirror.

Drop Photography

The fraction of the condensate that collects on stator blade and casing surfaces flows to the blade trailing edge where it is torn off in large drops by the high-speed vapor flow. These large drops undergo a secondary atomization and are rapidly accelerated in the blade wake as they travel farther downstream of the trailing edge. For the range of turbine operating conditions given previously, drop diameters after secondary atomization of less than 25 micrometers (0.001 in.) to more than 150 micrometers (0.006 in.) are predicted by an analytical model of the process (ref. 5). At 1 centimeter (0.4 in.) downstream of the trailing edge, the velocity of a 25-micrometer (0.001-in.) drop could exceed 61 meters per second (200 ft/sec). The objective of the drop photography is to measure drop sizes and if possible drop velocities at several locations downstream of the blade trailing edge.

Illumination system. - An Edgerton, Germehausen, and Grier Model 2307 double-flash light source was selected as a promising source of illumination for the drop photography. The light source flashes when a spark is generated across tungsten electrodes mounted in a quartz or Pyrex tube and separated by an air gap. The light source can be operated with a single flash or a double flash separated by a variable time interval from 5 to 100 microseconds between the two flashes. The flash duration and light output of each flash when operated as a double-flash source are approximately 0.15 microsecond and 0.003 candlepower second (cp-sec), respectively. The EG&G 2307 can be operated as a single-flash light source either by setting the time delay to zero or by disconnecting half the discharge circuitry. If the time delay is set to zero, the flash duration and light output are approximately 0.4 microsecond and 0.006 cp-sec respectively. If half the discharge circuitry is disconnected the single-flash duration and light output are about the same as for each flash when operated as a double-flash light source.

Because of the rather low light output provided by the EG&G Model 2307, it was felt that transmitting the light through a fiber-optic light tube would not provide sufficient illumination. Therefore, a specially constructed light tube was made with the tungsten electrodes mounted inside a sealed, stainless-steel tube that could be placed inside the turbine to directly illuminate the blade wake. The light tube is shown in figure 2. The light tube has a 0.953-centimeter (0.375-in.) diameter and is approximately 27.7 centimeter (10.9 in.) long. A lens is located in the tip section to reduce the divergence of the light from the spark flash.

Although the EG&G 2307 light tube is a convenient way of obtaining both single- and double-flash photographs, its low light output is a serious handicap. A fiber-optic light tube was constructed that could be used with a variety of other light sources for single- or double-flash photography. The fiber-optic light tube is shown in figure 3. It consists of a rigid stainless-steel clad section 0.953 centimeter (0.375 in.) in diameter, a tip section containing a mirror, a flexible section with polyvinylchloride (PVC) sheathing, and a rectangular light-coupling section sheathed with a rigid plastic covering. The overall length of the light tube is 91 centimeters (3 ft). The ends of the glass fibers are potted in high temperature epoxy, ground flat, and polished. The fibers are not aligned as would be required for image transmission.

One light source selected for use with the fiber-optic light tube is the EG&G Model 501 high-speed strobe. When using an FX-11-0.125 xenon flash tube with a capacitance setting of 0.01 microfarad, the light output is 0.4 cp-sec, more than 60 times that of the EG&G 2307. However, the flash duration is longer, 0.9 microsecond, so that small drops traveling at high velocities will not be "stopped" by the flash. No double flash, and hence direct drop velocity measurement, can be obtained.

If high light output and shorter flash duration are required the EG&G Model 549 Microflash can be used with the fiber-optic light tube. The EG&G 549 is an air gap spark source with the spark "guided" along the outside of a quartz capillary tube containing a trigger electrode. The flash duration and light output are 0.4 microsecond and 3.6 candlepower-seconds, respectively, when the flashtube is viewed from the side (ref. 6). An operational disadvantage of the EG&G 549 is the long recharging time of approximately 5 seconds required between successive flashes.

Other short flash duration light sources can be used with the fiber-optic light tube. In addition pulsed laser light sources could also be used if ultrashort, high-intensity single or double flashes are required.

Although predicted by analytical modeling of the drop forming and acceleration processes, some uncertainty exists concerning the drop diameters and velocities that will occur. The flexibility in selecting the light source afforded by the fiber-optic light tube can be used to great advantage in obtaining good results in the actual test turbine.

Photographic system. - The custom-made borescope used for the drop photography

is shown in figure 4. It is made of rigid, stainless-steel tubing with a 0.953-centimeter (0.375-in.) diameter portion over the length that is inserted into the turbine flow path and a 1.9-centimeter (0.750-in.) diameter elsewhere. It is approximately 31.1 centimeters (12.25 in.) long. The tip section contains a mirror. A camera adapter with standard C-mount threading is used to attach the borescope to a camera or an eyepiece for visual observation. A thumbscrew locks the position of the borescope barrel relative to the C-mount adapter after proper focus is achieved by sliding the borescope barrel relative to the C-mount adapter. The borescope lenses are coated to improve the light transmission through the borescope. The borescope has a magnification of 1.5 at an object to borescope centerline distance of 2.54 centimeters (1 in.).

Sixteen-millimeter motion picture cameras were used for the drop photography; however, the photography discussed is essentially still photography using high-speed single- or double-flash light sources.

Equipment installation. - A planview of the configuration of the photographic hardware in the turbine is shown in figure 5. The borescope is located in a cutout portion of the adjacent blade near the blade trailing edge. There are three positions for the light tube to photograph drops in the blade wake at approximately 0.1, 0.5, and 1.0 centimeter (0.04, 0.2, and 0.4 in.) downstream of the trailing edge. A retractable transparent target is used for focusing of the borescope and camera. It is air actuated and retracts by a spring built into the actuator mechanism. Backlighting was selected to minimize the amount of light required for proper film exposure.

Stator-Blade Surface Photography

It has been stated that a small percent of the condensate in the turbine collects on the stator-blade and casing surfaces. The portion of the condensate that reaches the stator-blade surfaces is swept toward the blade trailing edge under the influence of the high-velocity vapor flow. Considerable uncertainty exists about the nature of this flow: whether it will occur as a thin sheet of liquid, as liquid streams or drops, or some combination of these forms. Considerable uncertainty also exists concerning the velocity and course of the flow as it traverses the stator-blade row.

The objective of the stator-blade surface photography is to qualitatively examine the nature of the condensate flow and the influence of condensate removal devices on the flow through motion picture photography and visual observations. For convenience and since in wet vapor turbines erosion damage to rotor blades is more likely to occur from liquid torn from the outer regions of the stator blades, visual observations and photography were confined to the outer half of the stator blades.

Illumination system. - Figure 6 shows the fiber-optic light tubes used for the blade surface photography. The light tubes have a rigid section clad with stainless-steel

tubing, a flexible section sheathed with PVC, and a quadrifurcated section with rigid rectangular plastic ends to efficiently gather light from the light source. One light tube shown in figure 6 has a mirrored tip to direct the light 90° to the light tube axis. The other light tube shown in figure 6 has no mirror so that a cone of light shines outward with the cone centerline parallel to the light tube axis. The rigid stainless-steel clad section of the light tubes, which are inserted in the turbine, are 1.427 centimeters (0.562 in.) in diameter. These light tubes are never inserted directly in the turbine flow path, so their diameter can exceed 0.953 centimeter (0.375 in.) without disturbing the flow being photographed. The overall length of the light tubes is approximately 91 centimeters (3 ft). In all other respects the fiber-optic light tubes are similar to the one used for the drop photography.

The light source selected for the blade surface photography is the EG&G Model 501 high-speed strobe. The EG&G Model 501 consists of a power supply, modulator, and timer unit housed in a cabinet plus lampholders and cables. The short-duration flash of the strobe stops the motion of the flow and gives the same illumination with a camera operating at different framing rates. Up to 6000 flashes per second are possible with the EG&G Model 501.

A variety of xenon flashtubes are available for use with the EG&G Model 501. Two flashtubes selected for this application are the FX-11-0.125 and FX-1-0.25 shown in figure 7. Both flashtubes are 0.61 centimeter (0.25 in.) in diameter and approximately 9.53 centimeters (3.75 in.) long. The FX-11-0.125 has a 3.1-millimeter (0.125-in.) gap in a 4-millimeter (0.157-in.) inside-diameter quartz tube. The FX-12-0.25 has a 0.635-centimeter (0.25-in.) gap in a 1.6-millimeter (0.063-in.) inside-diameter quartz tube. The FX-11-0.125 and FX-12-0.25 flashtubes are filled with xenon to a pressure of 2 atmospheres and 1 atmosphere, respectively.

The EG&G Model 501 has three capacitance settings, 0.01, 0.02, and 0.04 microfarad, for varying the flashtube light output. The flash duration and light output for the FX-11-0.125 and FX-12-0.25 flashtubes are shown in table I for the three capacitance settings (data from private communication with EG&G). With a capacitance setting of 0.01 microfarad on the FX-11-0.125 and FX-12-0.25 flashtubes, it is recommended that operation is limited to bursts of 500 and 100 flashes, respectively, to prevent overheating of the electrodes and quartz capillary walls and insure long flashtube life (ref. 7). Additional information on electronic flash and stroboscopic lighting and equipment may be found in reference 8.

To use these small flashtubes, a coupling transformer unit is required. It has a 5 to 1 voltage stepdown ratio with the lamp on the low voltage side. The 2000 volts produced on the flashtube is insufficient for starting so an 8000-volt starting pulse is obtained with a trigger electrode or starting coil. The transformer unit with a Lucite adapter to hold the fiber-optic light tube ends is shown in figure 8. Since the flashlamps

get very hot, a stream of cooling air can be passed between the flashlamp and the fiber-optic light tube ends to help keep the fiber-optic ends from getting too hot.

A cross-sectional sketch showing the arrangement of the light tube ends around the flashlamp is shown in figure 9. The flashtube and light tube ends are separated by a space of approximately 0.16 centimeter (0.0625 in.). Because there is an 8000-volt potential on the trigger electrode, the cladding on the light tube ends and the light tube holder were made of nonmetallic materials.

Photographic system. - Figure 10 shows the borescope used for the stator-blade surface photography. It has a fixed mirror and two camera adapters; one with a Fastax bayonet and the other with standard C-mount threading. The magnification of the borescope is 0.2 at an object to borescope centerline distance of 2.5 centimeters (1 in.). The borescope field of view is approximately 53° . Its length is approximately 32.8 centimeters (12.9 in.). In other respects the borescope is similar to the 1.5 power borescope used for the drop photography.

The camera selected for the blade-surface photography is a 16-millimeter Fastax WF3 camera. A reluctance pickup on the Fastax camera is used to synchronize the flashing of the EG&G 501 to the camera shuttering. With a goose attachment high-speed photography (up to 8000 flashes/sec) can be obtained. Since, as mentioned previously, the EG&G Model 501 high-speed strobe can only be flashed up to a rate of 6000 flashes per second, this will be the upper limit on the framing rate. Rough estimates indicate that framing rates on the order of 2000 to 4000 flashes per second might be required. However, if lower framing rates are desirable, the EG&G 501 can be synchronized to a suitable framing camera for photography in the range of 18 to 500 flashes per second.

Equipment installation. - As an aid in developing the photographic system design and verifying its performance, a full-scale model of a portion of the fourth stage of the test turbine was made. The model duplicated the distances and orientation of the penetrations used for the photographic instrumentation. Actual fourth-stage stator and rotor blades were used in the model. Figure 11 shows the model with a borescope and fiber-optic light tube inserted in the penetrations used for stator-blade trailing edge photography.

To illustrate the orientation of the instrumentation and the views for the stator-blade surface photography, photographs were taken showing the instrumentation inserted in the model. Figures 12 to 14 show the orientation of the instrumentation for the pressure surface, suction surface, and trailing-edge views.

In figure 12 the borescope and a mirrored fiber-optic light tube are shown to be inserted through nearly radial penetrations through the turbine casing and blade ring. The borescope and light tube are actually located in a cutout in the stator blade adjacent to the one being photographed. By rotating the borescope and light tube, most of the outer half of the stator-blade pressure surface and portions of the blade wake can be photographed. By moving the instrumentation radially outward, portions of the casing can

also be photographed. The stator blade was painted white with a black grid for reasons that will be discussed later. When oriented to view the area of the blade extending from the trailing edge to approximately 1.9 centimeters (0.75 in.) upstream of the trailing edge, the light tube centerline to blade and borescope centerline to blade distances are approximately 2.3 centimeters (0.9 in.) and 2.5 centimeters (1.0 in.), respectively.

Figure 13 shows the instrumentation inserted for the suction-surface view. An un-mirrored light tube is inserted in a "skewed" penetration in the turbine casing and blade ring. The borescope is situated in the axial space between the stator and rotor blade rows. The borescope centerline to blade and light tube face to blade distances are approximately 3.3 centimeters (1.3 in.) and 3.8 centimeters (1.5 in.), respectively.

Figure 14 shows the instrumentation inserted for the trailing-edge view. The light tube is located in a skewed penetration for this view, also. The borescope is in a cutout in the adjacent blade. Bore-scope centerline to trailing edge and light tube face to trailing edge distances are approximately 3.3 and 3.8 centimeters (1.3 and 1.5 in.), respectively.

Rotor Spray Photography

The liquid in the turbine that is collected on the rotor blades is quickly spun to the blade tip shroud by centrifugal force and is thrown off at high velocity. Because of the high peripheral speed of the rotating blades, the drops are well atomized but still large compared with the fog drops. The purpose of the rotor spray photography is to qualitatively photograph the course of the spray with and without suction applied at the casing slot at the trailing edge of the rotor blade row.

Illumination system. - It was intended that the mirrored fiber-optic light tubes with the EG&G Model 501 strobe would be used for lighting in this view. However, the lighting distances are somewhat larger than for the stator blade surface photography, and the lighting using this method was found to be marginal. Therefore, as an alternate lighting approach, special light tubes containing small, high-intensity, tungsten-halogen lamps to directly illuminate the view were fabricated.

Figure 15 shows one light tube along with the $8\frac{1}{2}$ -volt, 62-watt tungsten-halogen lamp it contains. The light tube diameter is 1.426 centimeters (0.562 in.), the same as that of the fiber-optic light tubes. This light tube could be used for the stator blade photography if more intense lighting is required and low framing rates are acceptable. The lamp is exposed to the steam flow, but the electrical leads are sealed from the steam by high-temperature epoxy. A second light tube with a 1.9-centimeter (0.75-in.) diameter was also fabricated. This light tube contains a 120-volt, 250-watt tungsten-halogen lamp.

Photographic system. - The same borescope was used as for the stator blade surface photography. A standard 16-millimeter C-mount motion picture camera is used for this view.

Equipment installation. - Figure 16 shows the instrumentation inserted for the rotor view. A mirrored fiber-optic light tube is shown. The lighting to subject and borescope centerline to subject distances are approximately 4.8 and 6.9 centimeters (1.9 and 2.7 in.) when the light tube is directed axially forward. The view of the rotor can be changed by rotating the light tube and borescope with the resultant longer lighting and viewing distances. A penetration is shown in figure 16 without instrumentation. This penetration is for the larger diameter light tube. The lighting distance for the light tube is approximately 10.2 centimeters (4.0 in.). Both light tubes can be used at the same time if required. The rotor blade shown in the figure was painted black for better visualization of the spray.

VERIFICATION OF ILLUMINATION AND PHOTOGRAPHIC SYSTEM PERFORMANCE

The prime purpose of the verification of performance testing was to demonstrate that the photographic system could provide adequate lighting and good visualization of the moisture flow in the turbine. A second purpose was to check the performance of the borescopes in those areas deemed critical to successful operation of the photographic system. Dry mockups in the turbine model were used with aerosol sprayed water simulating the moisture flow in a rough way. No attempt was made to try to duplicate the drop diameter distribution, velocities, or amount of liquid anticipated in the actual turbine.

Drop Photography

Borescope checkout tests. - A brief checkout of the custom made drop photography borescope was made to determine its magnification and depth of field at the nominal distance of 2.5 centimeters (1 in.) from borescope centerline to wake centerline. The magnification was determined by photographing a resolution chart at the 2.5-centimeter (1.0-in.) distance using Kodak Plus-X film and measuring the distance between grid lines on the exposed film compared with measurements made directly on the resolution chart. The magnification was found to be approximately 1.5.

At this magnification the borescope depth of field is rather small so this was also measured. This was done by focusing on a resolution chart 2.5 centimeters (1.0 in.) away and then moving the resolution chart in small increments 0.051 centimeter

(0.020 in.) closer and farther than the 2.5-centimeter (1.0-in.) nominal distance. Photographs of the resolution charts were taken through the borescope at each position using Plus-X film. The depth of field was defined as the difference between the closest and farthest distance where 40 line pairs per millimeter or more could be resolved on the film. The depth of field was found to be approximately 0.30 centimeter (0.12 in.).

Drop photographs using 2307 light tube. - Backlighted photographs of a spray of drops were made using the EG&G Model 2307 light tube as the light source. No attempt was made to carefully orient the spray in the proper direction shown in figure 5. The EG&G 2307 was operated in the single-flash mode by setting the time delay between flashes to zero. The borescope and light tube were set up with borescope to spray centerline and light tube to spray centerline distances of approximately 2.21 centimeters (0.87 in.) and 4.45 centimeters (1.75 in.), respectively. Figure 17 shows the results obtained on a typical frame of film. The drops in the figure range in size from roughly 30 to 70 micrometers. The field of view is light limited and is approximately 0.23 centimeter (0.09 in.) in diameter. Because of the low light output of the 2307 light tube Kodak Tri-X film was required for proper film exposure. The light output of the 2307 light tube varied considerably from flash to flash so that, while the frame shown is typical, other frames were somewhat brighter or darker than that shown. Because of the small depth of field of the borescope, accurate focusing is of great importance in obtaining photographs of the drops in the blade wake.

To get a feeling for double-flash photography that would enable drop velocity measurement, some photographs were taken using a Polaroid camera (without the borescope) and the EG&G Model 2307 operating in the double-flash mode. Lenses were used on the camera to get approximately the same magnification. The resulting photographs were extremely difficult to interpret with any confidence. Many drops were recorded in a single frame and since these were not "tagged" in any way, considerable uncertainty existed concerning which drops appeared once and which appeared twice in the frame. Depending on the number of drops and size distribution in the turbine, this could be a serious handicap there, too. Furthermore, the intensity of each flash is roughly half that used to obtain the results shown in figure 17. This decrease in the already limited light output, along with the possible difficulty in interpretation, raised serious doubts about the value of the double-flash photography using the 2307 light tube to obtain drop velocities.

Drop photographs using fiber-optic light tube. - Photographs were taken of a spray of drops using the fiber-optic light tube shown in figure 3. The EG&G Model 501 high speed strobe was used as the light source. An FX-11-0.125 xenon flashtube was used. The borescope to spray centerline and light tube to spray centerline distances were approximately 2.5 and 4.2 centimeters (1.0 and 1.65 in.), respectively. Orientation of the spray direction relative to that of the wake was again not considered significant. Figure 18 shows the results obtained on a typical frame of film. The drops shown range

in size from approximately 30 to roughly 60 micrometers in diameter. The field of view is again light limited and is approximately 0.36 centimeter (0.14 in.) in diameter. The area of the wake photographs using the fiber-optic light tube is therefore almost $2\frac{1}{2}$ times that using the EG&G Model 2307 light tube. This means that fewer frames are required to photograph the same number of drops. Kodak Plus-X film, a finer grained, slower film than Tri-X was used. The lowest light output setting on the EG&G Model 501 was used to obtain these photographs, which indicates that considerable light margin is available using this approach to the drop photography. In fact, the central portion of the photograph is actually somewhat overexposed, washing out meaningful data.

There is considerable variation in exposure across the field illuminated. This was also true for the photographs obtained using the EG&G Model 2307 light tube. Because of the light margin available with the fiber-optic light tube approach, an attempt was made to reduce the variation in light intensity across the field by placing a diffusing screen of translucent film around the light tube. This worked well, but, of course, at some loss in the level of illumination. Since the fog in the turbine may have a similar diffusing effect, no further effort was expended in this area. It should be noted that careful handling of the film was required to avoid introduction of dust and dirt on the film which could be misinterpreted as drops.

Stator-Blade Surface Photography

Borescope checkout tests. - Because the performance characteristics of the borescope were of crucial importance to obtaining good results in the stator-blade surface photography, tests were made to check critical aspects of the borescope performance. The amount of illumination reaching the film was especially critical. Specifications for the transmission and f-number of the custom made borescope had been made based on rough preliminary photographic tests and calculations. The method of measurement and results of the checkout tests for transmission and f-number are discussed in the following paragraphs.

For the transmission measurement, a stabilized tungsten strip lamp filament was imaged onto the first surface of the objective lens of the borescope. The light was transmitted through the borescope to an optical pyrometer placed 0.61 meter (2 ft) from the borescope eyepiece. The pyrometer was focused on the image of the lamp filament that appeared at the eyepiece. The temperature T_1 (in K) at the near surface of the eyepiece was measured at a 0.65-micrometer wavelength. The borescope was removed and the temperature T_2 at the filament image (former plane of the objective) was measured. The overall optical transmission τ was calculated from

$$\log \tau = -9.61 \times 10^{-3} \frac{T_2 - T_1}{T_2 T_1}$$

The overall optical transmission was approximately 0.45.

The f-number was determined using a point source 2.5 centimeters (1.0 in.) from a folding mirror and measuring the spot diameter on a ground glass as a function of ground glass position. The f-number was then calculated to be approximately 7.5.

Stator-blade surface photographs. - Motion picture photographs of liquid flowing on stator-blade surfaces were taken using the turbine model. Aerosol-sprayed water was used to simulate, in a rough way, the moisture flow in the test stream turbine. The EG&G Model 501 high-speed strobe was used at its lowest light output setting. Kodak Tri-X film was used. Motion pictures using a Fastax camera were taken with framing rates in the range of 2000 to 4000 frames per second.

Figures 19 to 21 show single frames taken from the movies of the flow on the pressure surface, suction surface, and at the blade trailing edge, respectively. The framing rate was 4000 frames per second. The grid lines seen on the blade are approximately 1.27 centimeters (0.5 in.) apart.

In figure 19, the pressure surface view, accumulations of liquid can be seen near the trailing edge along with streams of liquid feeding these accumulations. Puddles of water can be seen on the blade. The movement of the liquid in the motion pictures could be seen very clearly. The information about the flow that can be obtained is more evident from viewing the motion pictures than is apparent in the single frame shown.

The liquid flow on the suction surface turned out to be primarily in the form of a sheet of liquid traveling across the blade as shown in figure 20. A large accumulation of liquid can be seen at the blade trailing edge near the blade root. As in the case of the pressure surface, the visualization of the liquid flow in the motion pictures was very good.

In figure 21 three of the four slots in the blade trailing edge are illuminated. Two large accumulations of liquid are shown. The stripping of liquid off the trailing edge and breakup into small drops were clearly shown in the motion pictures. Highlights of some of these drops can be seen in the figure.

The stator blade used in figures 19 to 21 was painted with a flat white paint to reduce the amount of light required for proper film exposure. Photographs were also taken using an unpainted blade. Figure 22 shows the liquid flow on the pressure surface of an unpainted blade. The EG&G Model 501 high speed strobe was used at its lowest light output setting as was done in obtaining the pressure surface view shown in figure 19. Kodak Tri-X film was used in both cases also.

Comparing the results from figures 19 and 22, a larger area was illuminated sufficiently using the painted blade - as was expected. However, much greater contrast was

obtained using the unpainted blade. This greater contrast was very beneficial to the visualization of the liquid flow in the motion pictures taken. This improved contrast could be additionally important if the fog in the turbine results in an overall reduction of scene contrast. The grid used on the painted blade was very useful for viewer orientation and for focusing, however, the machining marks on the bare metal blade could also be used for focusing. With a painted blade there is a potential difficulty resulting from the paint not adhering well or degrading substantially due to the high velocity steam environment. The advantages and disadvantages of a painted blade surface will have to be resolved by tests performed in the actual turbine.

Both FX-11-0.125 and FX-12-0.25 xenon flashtubes were used in trial photographs. Greater divergence of the light from the light tubes resulted from the use of the FX-11-0.125 flashtube. Since the area illuminated was the factor limiting the field photographed, the FX-11-0.125 flashtube was selected for the stator-blade surface photography. The FX-11-0.125 flashtube was used to obtain figures 19 to 22.

Rotor Spray Photography

As mentioned previously initial photographic testing indicated marginal lighting using the fiber-optic approach for the rotor spray photography. Motion pictures of a water spray using the tungsten-halogen light tubes, on the other hand, indicated that considerable light margin was available. Motion picture photographs were taken using a standard C-mount camera operating at several framing rates. The view was set up outside the turbine model using an unshrouded rotor blade. The distances, angle of viewing, and the like were duplicated in the setup. The model was not used because the light tube gets rather hot when operating and could have damaged the painted surfaces on the wooded portions of the model.

Figure 23 shows a frame taken from one motion picture run. The 1.427-centimeter (0.562-in.) diameter light tube was used. Framing rate was 12 frames per second. Plus-X film was used. The spray is clearly defined. Liquid accumulations on the blade at the trailing edge can be seen. The spray could be seen quite well in the motion pictures.

The rotor blade used in the model and the one used to obtain figure 23 was painted with a flat black paint as a result of a brief investigation made of the effects of different backgrounds on the visualization of the spray. Black and white backgrounds were used as well as the unpainted blade surface. The black background enhanced the visualization of the spray and eliminated reflections present with an unpainted blade. Therefore, the rotor blade and shroud were painted black. A white strip on the outer edge of the blade shroud helps define the outer shroud diameter (see fig. 16).

CONCLUDING REMARKS

Because "dry" mockups were used, two potential problems associated with the two-phase turbine flow were not experimentally evaluated, namely, (1) attenuation and scattering of light by the fog present and (2) liquid accumulating on the borescope mirrors and obscuring the view. However, these factors were taken into account in the photographic system design. The potential difficulty of the degradation of painted surfaces because of the steam flow environment was likewise not evaluated experimentally but must be resolved by testing in the actual turbine.

SUMMARY OF RESULTS

A high-speed photographic system was designed to photograph the moisture flow in a steam turbine. Good performance of the photographic system was verified using "dry" turbine mockups with aerosol-sprayed water simulating the moisture flow. The following results were obtained:

1. Using backlighting and single-flash still photography with a flash duration of less than 1 microsecond, drops as small as approximately 30 micrometers (0.0012 in.) could be resolved. Double-flash photographs taken in an attempt to measure drop velocities were difficult to interpret.
2. Using fiber-optic light tubes, borescopes, and a high-speed stroboscopic light source resulted in sufficient light and good visualization of the flow of liquid on stator-blade surfaces. A reduction in the lighting requirement was obtained by painting the stator blades with a flat white paint. However, greater contrast was obtained with a bare metal blade.
3. Good visualization of a spray of liquid was obtained using light tubes containing small tungsten-halogen lamps. Improved visualization of the spray resulted from painting the rotor blades with a flat black paint.
4. Painting of grids and other identifying markings was useful for viewer orientation and for focusing purposes.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, January 30, 1973,
770-18.

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TABLE I. - FLASHLAMP CHARACTERISTICS

Flash lamp	Capacitance, μF	Light output, cp-sec	Pulse width ^a , μsec
FX-11-0.125	0.01	0.39	0.9
	.02	.97	1.4
	.04	1.67	2.2
FX-12-0.25	0.01	0.38	1.2
	.02	.90	1.4
	.04	1.57	2.2

^aAt one-third peak amplitude.

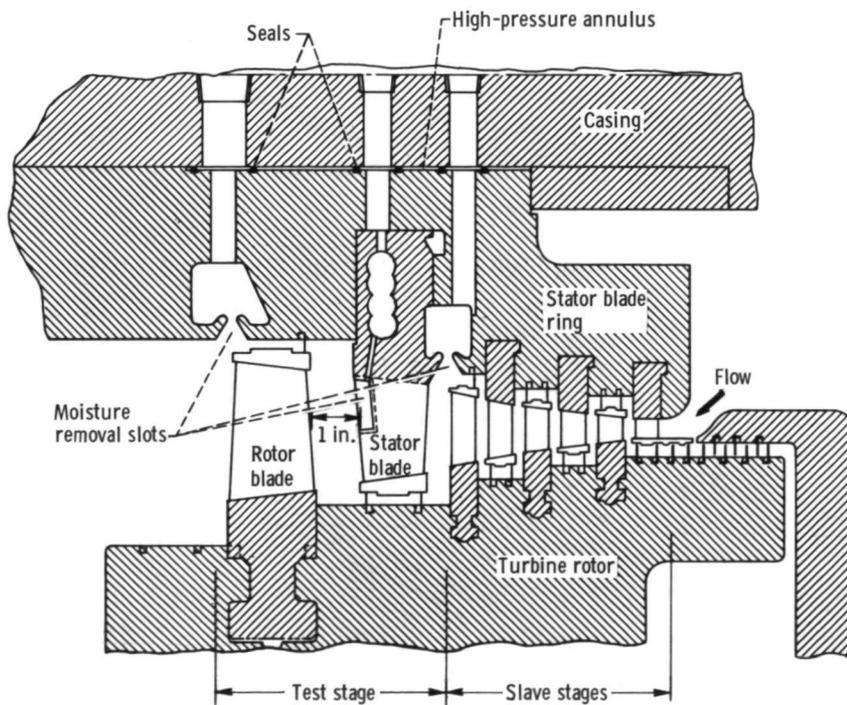


Figure 1. - Test turbine longitudinal section.

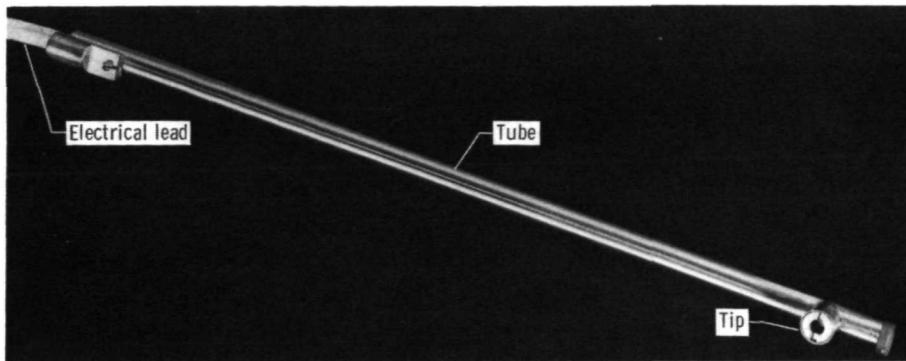
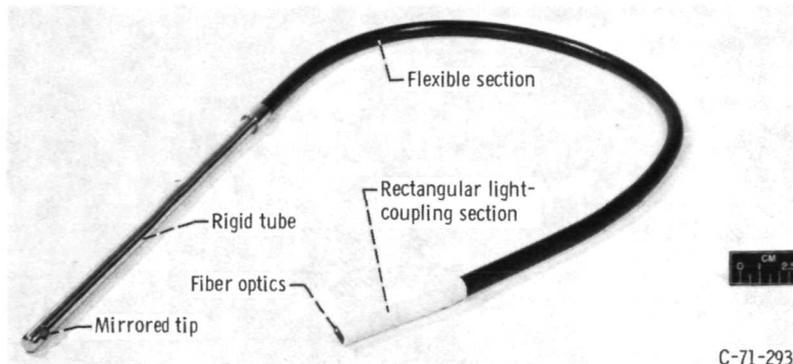
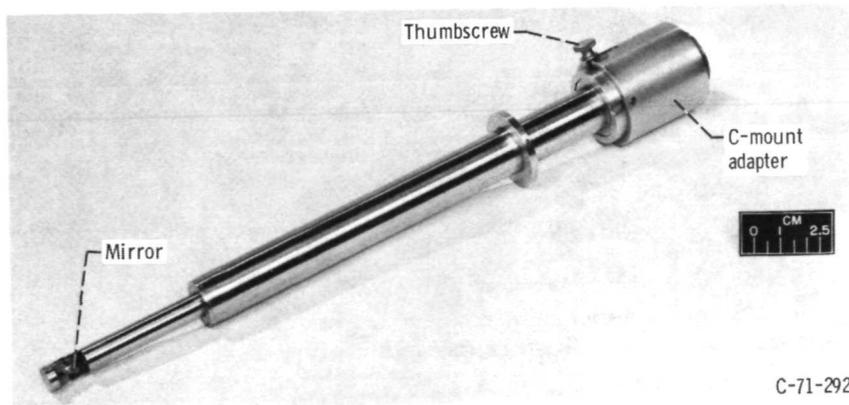


Figure 2. - Light tube for single-flash and double flash operation.



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Figure 3. - Fiber optic light tube.



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Figure 4. - X1.5 borescope.

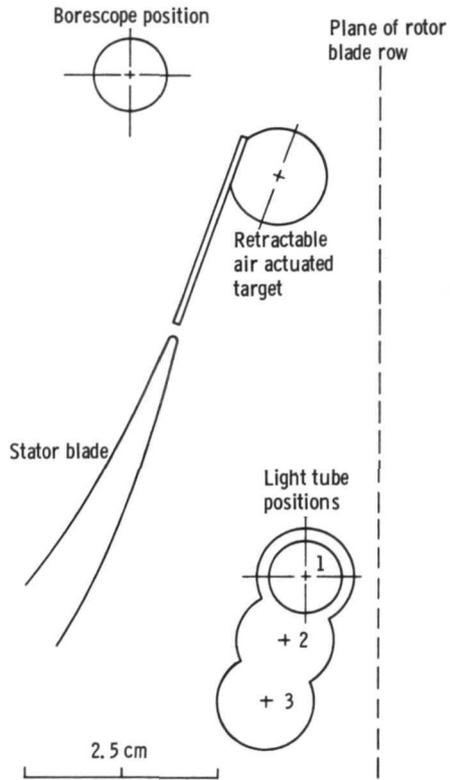


Figure 5. - Plan view for drop photography configuration.

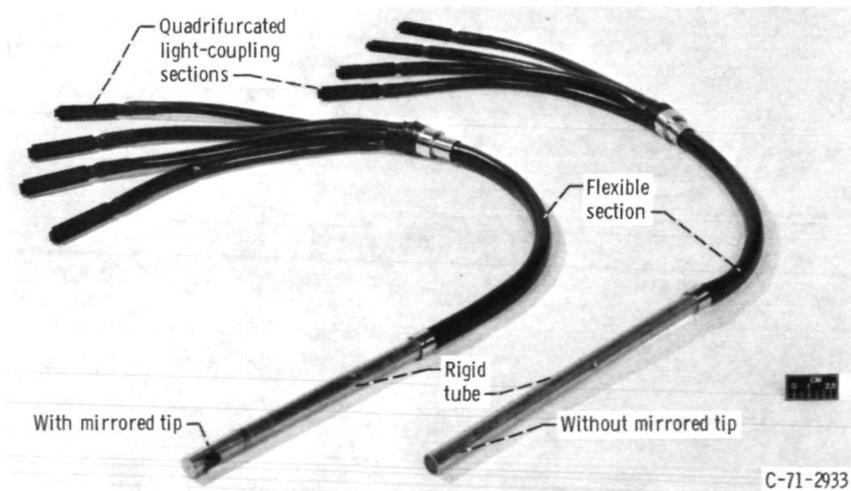


Figure 6. - Fiber optic light tubes.

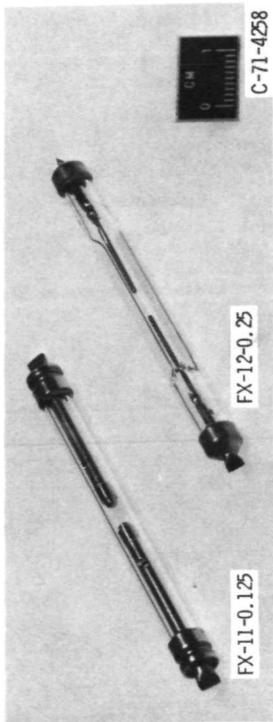


Figure 7. - Xenon flashtubes.

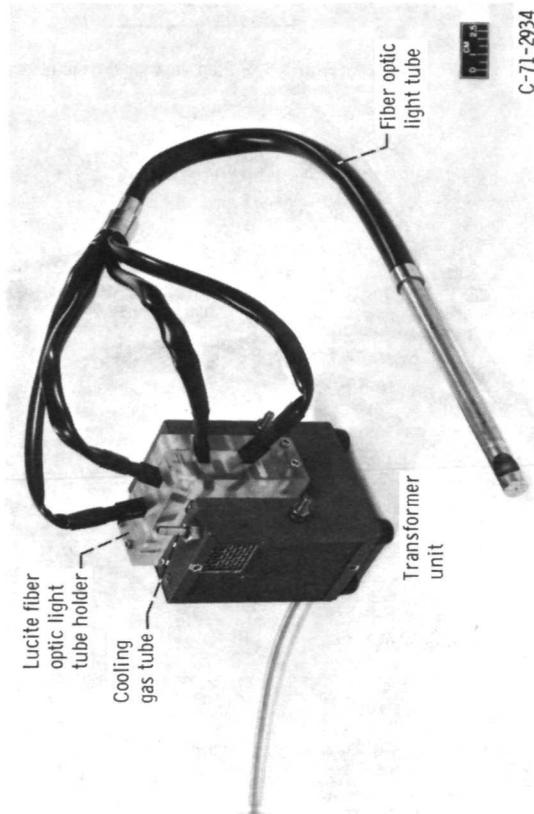


Figure 8. - Modified transformer unit.

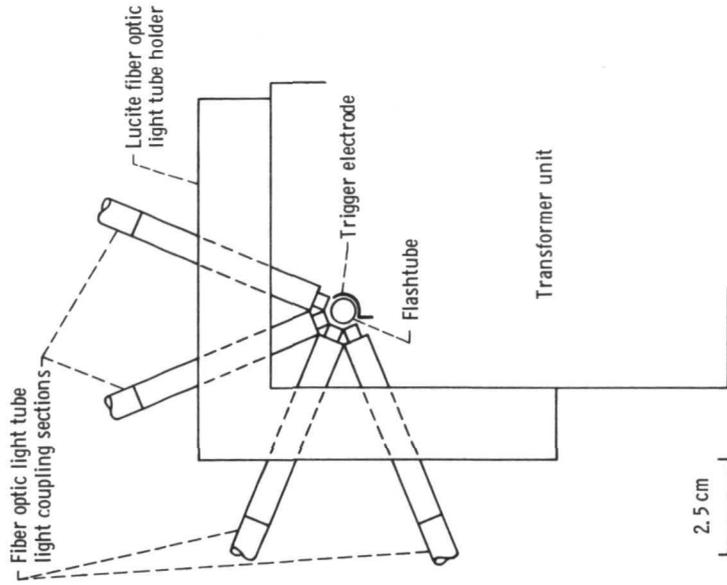


Figure 9. - Arrangement of fiber-optic light tube ends around flashtube.

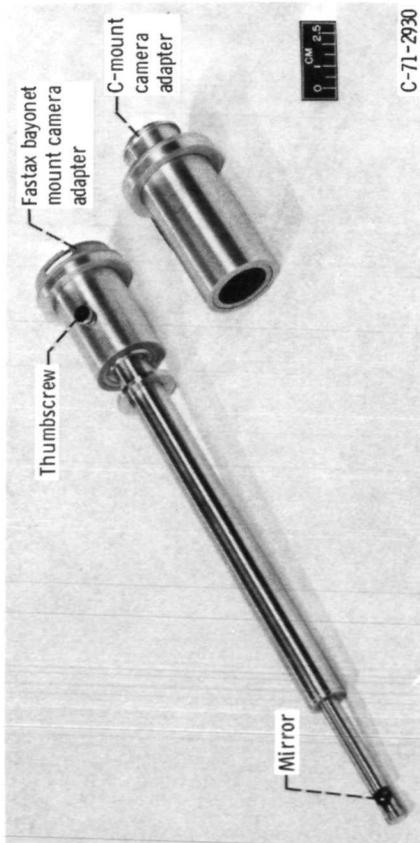


Figure 10. - X0.2 borescope.

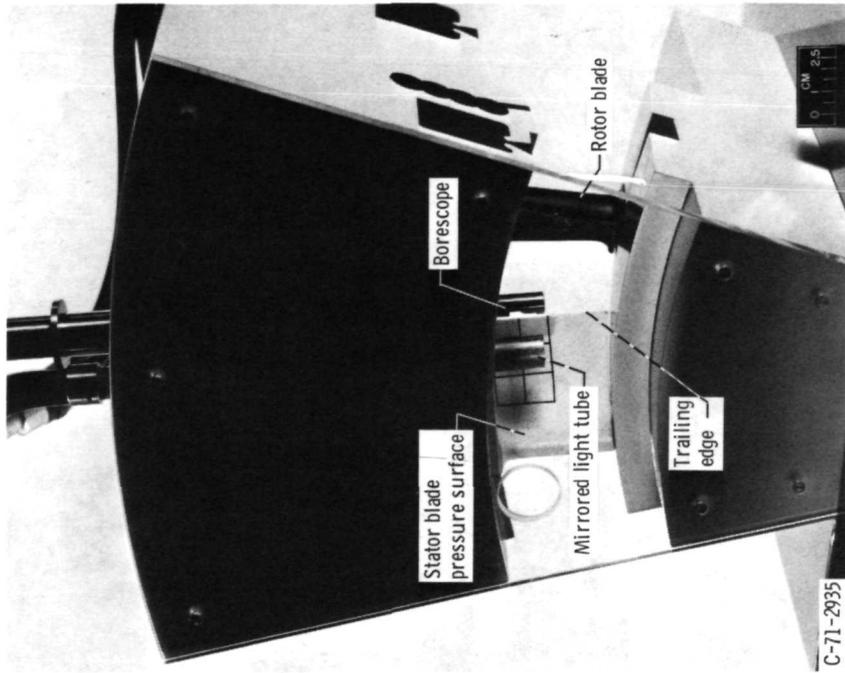


Figure 12. - Pressure surface view configuration.

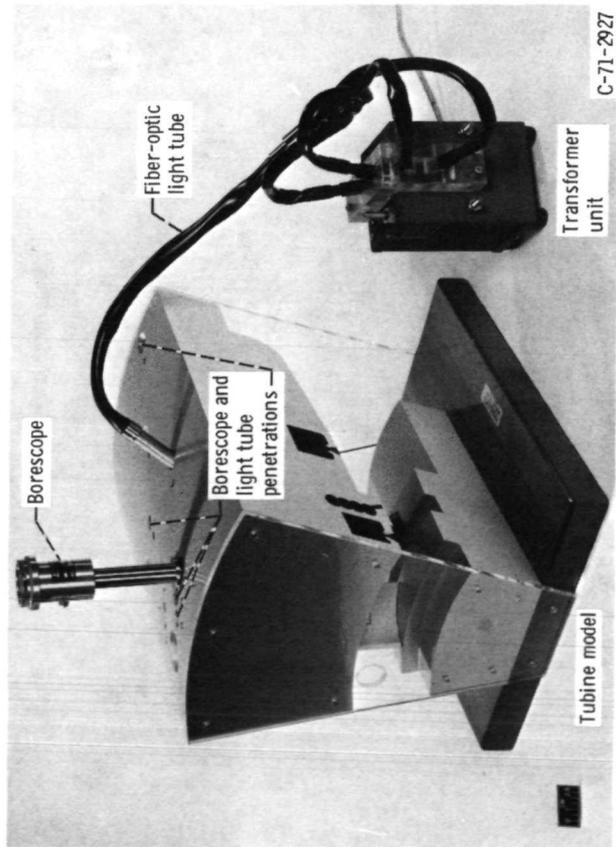


Figure 11. - Turbine model - including photographic instrumentation.

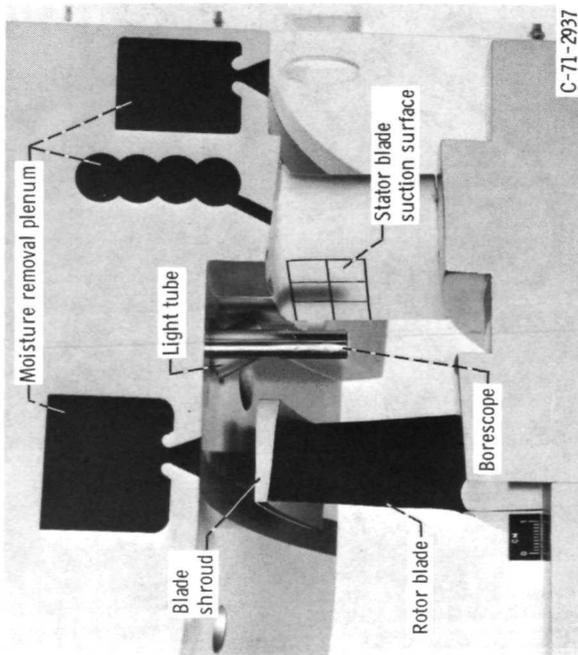


Figure 13. - Suction surface view configuration.

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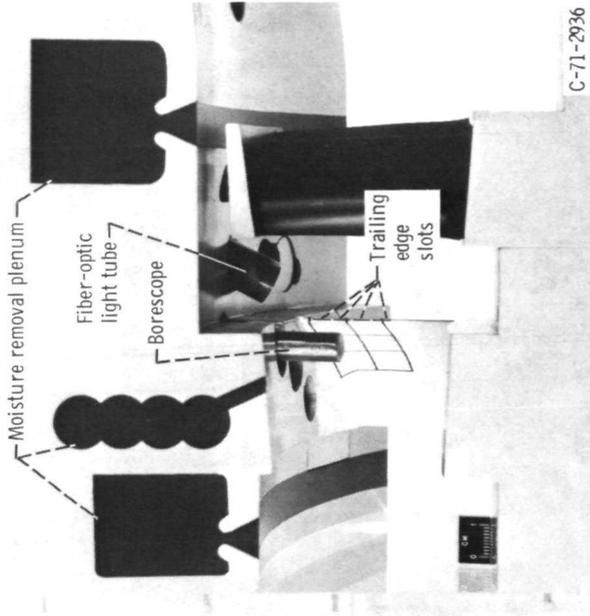


Figure 14. - Trailing-edge view configuration.

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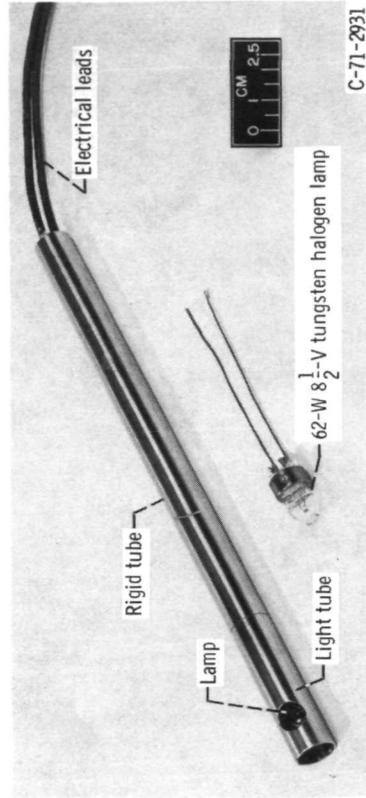


Figure 15. - Tungsten halogen light tube.

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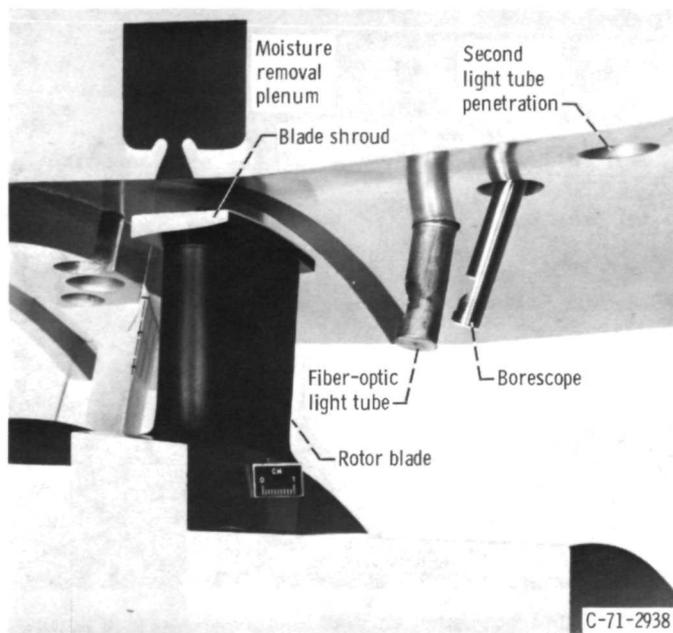


Figure 16. - Rotor blade row view configuration.

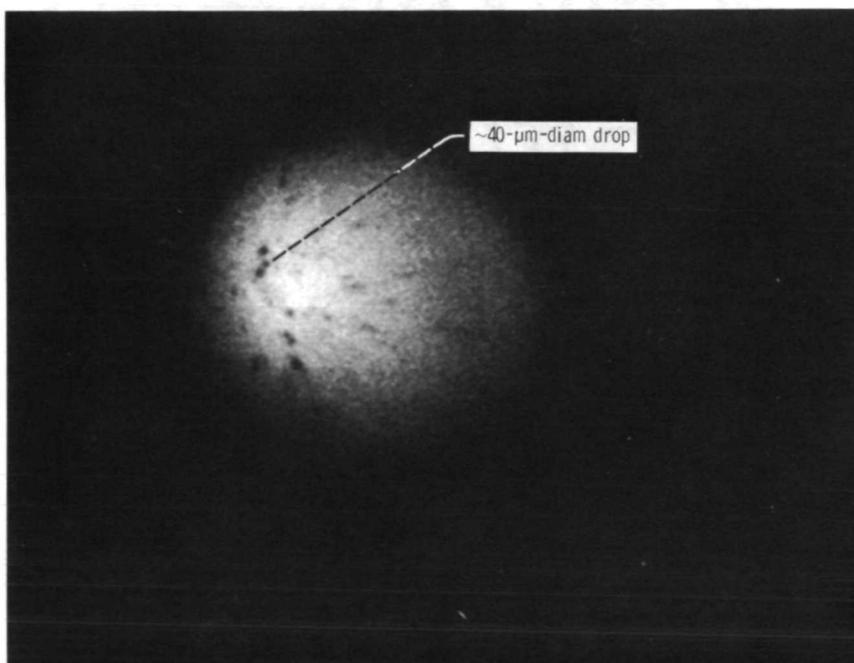
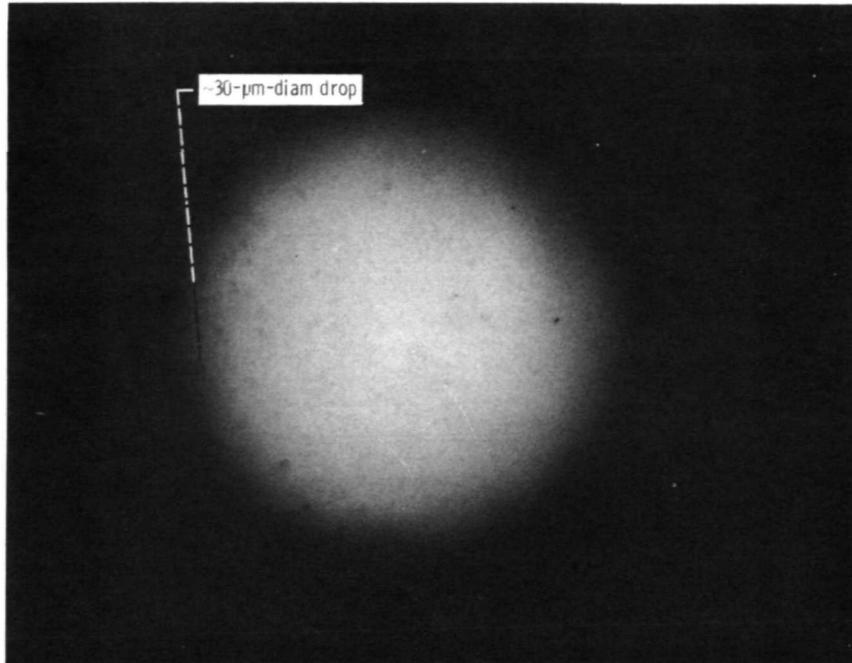
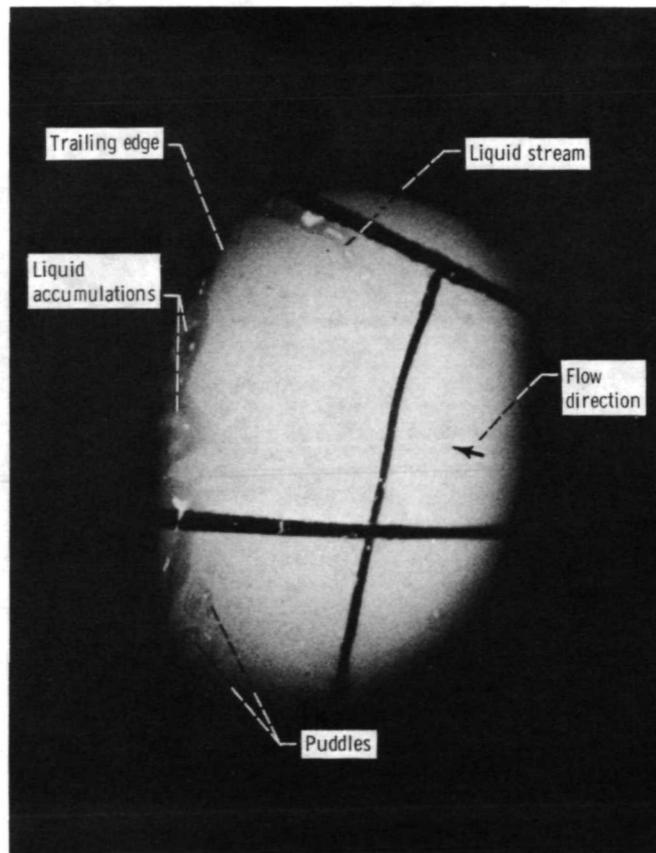


Figure 17. - Drop photograph; EG&G model 2307 light tube ((single flash operation.



-30- μ m-diam drop

Figure 18. - Drop photograph; EG&G model 501 high-speed strobe light source.



Trailing edge

Liquid stream

Liquid accumulations

Flow direction

Puddles

Figure 19. - Liquid flow on stator blade pressure surface.

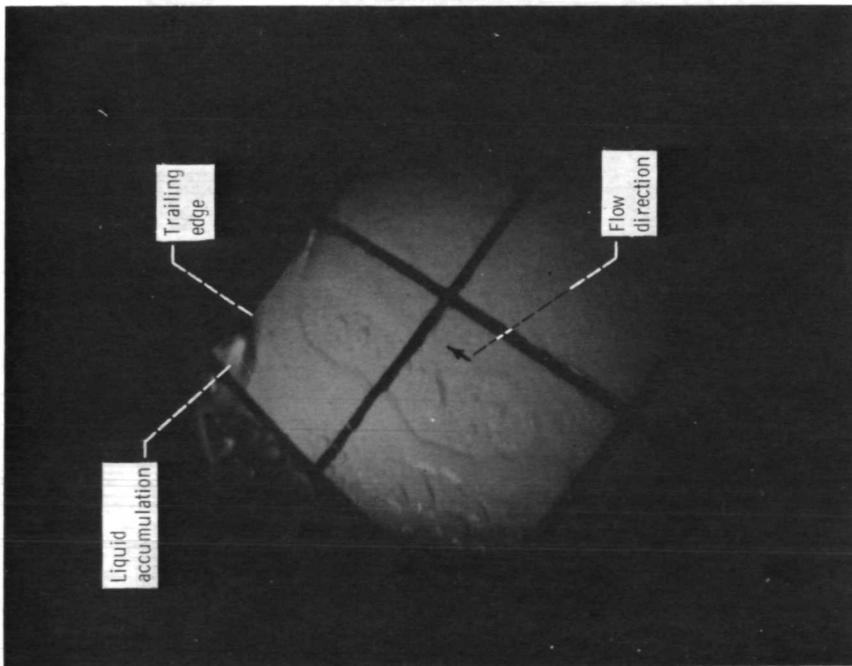


Figure 20. - Liquid flow on stator blade suction surface.

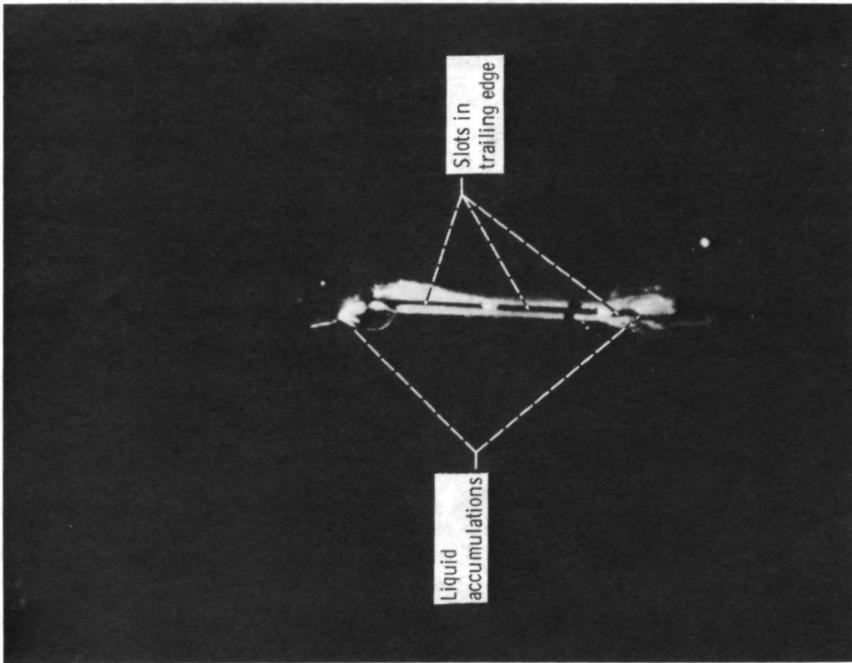


Figure 21. - Liquid flow at stator blade trailing edge.

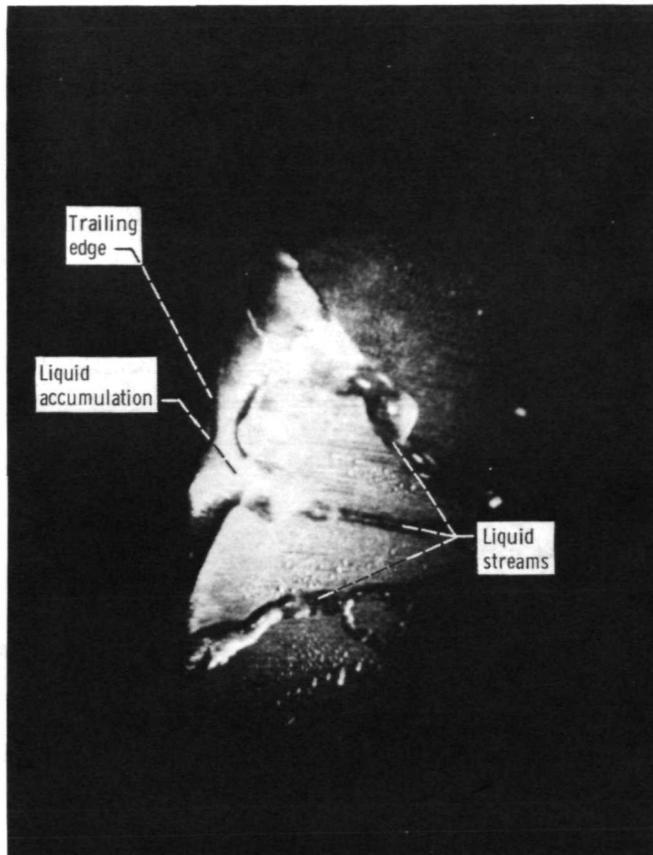


Figure 22. - Liquid flow on unpainted blade pressure surface.

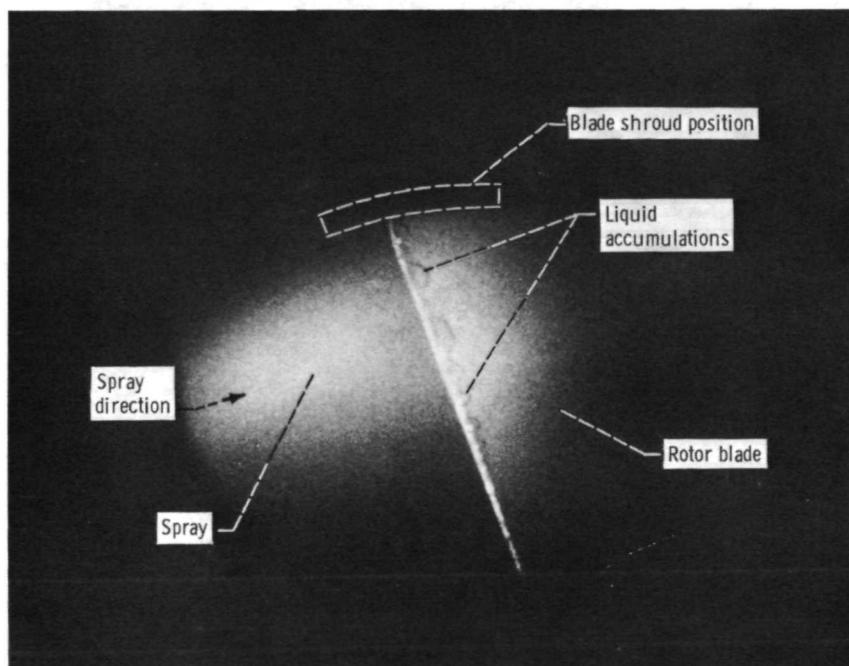


Figure 23. - Liquid spray at rotor blade row trailing edge.

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