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TECHNICAL NOTE

No. 1887

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SUMMARY

An investigation was conducted to determine the effect of high shear rates on erosion of common bearing metals. Studies were made with filtered oil flowing at mean surface shear stresses of 11 and 43 pounds per square inch (roughly corresponding to mean surface rates of shear of 1.5×10^6 and 19×10^6 reciprocal sec, respectively) for periods of 6 hours. Under these conditions, specimens of copper, silver, and lead showed no indication of erosion or other surface damage.

Studies were also made by flowing unfiltered oil through a flow path, one surface of which constituted the erosion specimen. Under these conditions, a pseudoerosion was obtained that resembles erosion found in actual aircraft power plants. This pseudoerosion was found by visual observation to be caused by small foreign particles creating a multiplicity of small scores in the specimen surface. It was further observed that particles smaller than the oil-film thickness were capable of producing another type of surface damage if the oil in which the particles were carried was forced to change direction suddenly.

A typical aircraft mineral oil was found to exhibit anomalously high flows when forced through a small flow channel or tube at high values of shear stress.

INTRODUCTION

Journal bearings operating under conditions of high surface velocity and dynamic loading have been found to erode or suffer loss of metal in regions surrounding oil inlet holes or grooves. In some instances, the erosion is extensive enough to reduce the effective bearing area and cause the bearing to fail by overloading. An example of severe erosion adjacent to an oil hole in a high-speed bearing is shown in figure 1. In this case, the erosion created a deep, narrow, curved groove extending from the central oil hole.

In some other cases, however, erosion occurs as large shallow areas, particularly when bearing oil grooves or oil distributing flats on the shaft are employed. Although the actual mechanism by which bearing surfaces are eroded is not definitely known, three suggested causes are: mechanical fatigue of metal, cavitation in the oil film, and high viscous shear stresses. Mechanical fatigue is not considered. The difficulties involved in exploring the phenomena occurring in extremely thin oil films of dynamically loaded high-speed bearings that operate a portion of the time in the boundary lubrication region have hindered fundamental research on the erosion of actual bearings and have necessitated laboratory investigation of the possible erosive mechanisms.

Many researchers have investigated, both analytically and experimentally, the mechanism and the effect of cavitation on the erosion of metals. It has been analytically demonstrated by Rayleigh (reference 1) that the rapid collapse of small cavities in a body of fluid can produce extremely high pressures in the fluid adjacent to the cavity. Gaines (reference 2), Poulter (reference 3), Kornfeld and Suvorov (reference 4), and others have experimentally shown that erosion occurs on metal surfaces that are exposed to collapsing cavities in a fluid and have proposed detailed mechanisms by which the actual removal of the surface metal occurs. Although the existence of cavitation phenomena in actual bearings has not been experimentally demonstrated in a rigorous manner, analysis of the loading conditions found in the bearings of high-speed gear trains suggests that the system comprised of bearing, journal, and oil closely simulates the action found in the well-known cavitation erosion apparatus by Gaines (reference 2).

Bearing erosion is most generally ascribed to the erosive action of oil at high rates of shear and high shear stress; for example, the term "bearing wash" is often used to describe the erosion of lead or bronze bearing surfaces. The appearance of the "washed-out" grooves in the bearing surface seems to justify the use of this terminology. Whereas high surface velocities and dynamic loading admittedly result in extremely high shear rates and shear stresses in actual bearings, a search of the literature indicates a lack of knowledge of the erosive properties of oil at high shear stresses.

The object of this investigation made at the NACA Lewis laboratory was, therefore, to determine whether high shear rates and the corresponding high shear stresses could be a possible source of the erosion found in operating journal bearings. The method employed consisted essentially in flowing oil at high velocity between two closely spaced plates, one of which was made of hardened steel, the other of the bearing metal to be eroded. The experimental apparatus was operated at mean oil pressures between 1000 and 8000 pounds per square inch, which gave rise to oil temperatures from 75° to 220° F.

Shear stresses of 11 and 43 pounds per square inch (roughly corresponding to mean surface rates of shear of 1.5×10^6 and 19×10^6 reciprocal sec) were investigated for as long as 14 hours.

DETERMINATION OF SHEAR STRESS ON EROSION SPECIMENS

The experimental method employed in the erosion studies consists in forcing oil to flow between two parallel surfaces, one of which is composed of the metal to be eroded. The spacing between the plates or surfaces is known, as well as the effective length and breadth of the flow path or channel. In order to obtain some measure of the shear stresses present, it is necessary to measure the oil flow rates corresponding to known pressure differences along the length of the flow path or channel. These values may then be used to calculate the shear stress and shear rate at the surface of the erosion specimen.

The rate of shear in a film of oil flowing between parallel surfaces is (from fluid mechanics) defined by the equation

$$R = \frac{du}{dy} \tag{1}$$

where

R rate of shear, reciprocal seconds

u velocity at any point in oil film, inches per second

y normal distance from either surface, inches

The shear stress at any point in an oil film having a linear velocity profile has been shown by Newton to be

$$S = \mu R = \mu \frac{du}{dy} \tag{2}$$

where

S shear stress, pounds per square inch

μ coefficient of absolute viscosity, pound-seconds per square inch

With the assumption that equation (2) holds for nonlinear velocity profiles and that the viscosity is constant across the oil film, an expression for the shear stress at any point in a fully developed film may be derived.

$$S = \frac{\Delta p(2y - h)}{2L} \qquad (3)$$

where

Δp pressure differential across flow channel, pounds per square inch

h fixed distance between parallel surfaces, inches

L length of flow channel, inches

For the shear stress at either surface, equation (3) reduces to

$$S_W = -\frac{\Delta ph}{2L} \qquad (4)$$

where

S_W surface shear stress, pounds per square inch

The viscosity of the oil flowing between the surfaces may be found from the derived expression (reference 5).

$$\mu = \frac{h^3}{12} \frac{\Delta pb}{QL} \qquad (5)$$

where

Q measured flow, cubic inches per second

b width of flow channel, inches

The rate of shear at either surface may be found by combining equations (2), (4), and (5).

$$R_W = \frac{\Delta ph}{2\mu L} = \frac{6Q}{h^2 b} \qquad (6)$$

where

R_W rate of shear at surface, reciprocal seconds

For the case of oil flowing from a relatively large reservoir into a small channel, the maximum value of the surface shear stress is not that given by equation (4), but reaches a much larger value in the vicinity of the entrance to the channel. Just inside the entrance to the channel the velocity is uniform at all of the points across the film except for an extremely thin boundary layer at the surface. As the oil proceeds downstream, viscous forces retard the motion near the walls until the velocity profile assumes the parabolic form common to fully developed laminar flow (reference 6). Because the slope of the velocity profile is very large at the surfaces near the channel entrance, the rate of shear, and hence the shear stress, must also be very large. Inasmuch as this flow condition does not lend itself to analytical or experimental treatment, the mean wall stress along the channel, as found from equation (4), is used in presenting the data of these experiments. It should be remembered, however, that erosion is more likely to be found in the region of maximum shear stress near the channel entrance than further downstream.

APPARATUS

A schematic diagram of the basic apparatus employed in this investigation is shown in figure 2. This apparatus consisted essentially of a high-pressure reciprocating oil pump, a spring-loaded pressure accumulator for damping pump pulsations, a high-pressure oil filter capable of removing all particles larger than 1 micron, and a combined flow nozzle and specimen holder. The oil pump was driven at constant speed and the oil flow through the nozzle was regulated by adjusting a bypass valve in the oil delivery line. The action of the pressure accumulator could be varied from zero damping to maximum damping by adjusting the spring loading while the pump was in operation.

A disassembled view of the flow-nozzle and specimen-holder assembly is shown in figure 3. Provision was made for interchangeability of flow nozzles in order to permit investigation of a variety of entrance conditions. The flow channel in the face of each nozzle was proportioned to permit attainment of the maximum mean shear rate possible with the available high-pressure oil supply. The flow channels were formed by milling a rectangular slot in the face of each nozzle, the slot extending from the central oil-inlet hole to the outer rim of the nozzle face. The nozzle face was then hardened and the surface ground away until the remaining channel was of the desired depth. The channels ranged from 0.020 to 0.040 inch in width and were 3/16 inch in length. Two depths were used, 0.001 and 0.002 inch. All nozzles were originally constructed with sharp-edged entries from the central oil holes and were later modified by carefully rounding and smoothing the entries. The surfaces of the steel nozzles were hardened to a value of Rockwell C-60 and the faces were metallographically polished. All test specimens were in the form of small disks of the metal to be investigated, as shown in figure 3.

The arrangement shown in figure 4 was employed to study flow conditions within the flow channel. A thin disk of the specimen metal was sweat-soldered to the unchanneled face of a flow nozzle. A disk of glass replaced the usual specimen in the apparatus. A slotted steel spacer, 0.001 inch thick, was clamped between the nozzle face and the glass disk to form a flow channel similar to that described in the preceding paragraph. A low-powered microscope was mounted in the manner shown in figure 4, so that the oil flow within the channel could be viewed clearly when illuminated from the side.

The specimens, disks of 9/16-inch diameter and 1/8 inch thick, were prepared by machining the faces parallel and finishing on standard metallographic polishing equipment. Three materials were investigated: annealed copper, silver, and lead. These materials were chosen as being fairly representative of actual bearing materials, as being ductile and of low shear strength to facilitate the rapid erosion in the laboratory apparatus, and for the uniformity of structure necessary to obtain reproducible results. The annealed copper specimens and the silver specimens were cut from solid stock, whereas the lead specimens were made by "tinning" or coating copper specimens with lead, then machining the lead to a layer approximately 0.015 inch thick, followed by hand-lapping on metallographic polishing papers. Two types of surface finish were investigated: (1) surfaces metallographically polished with random motion on 4/0 rouge paper, and (2) surfaces finished by unidirectional motion on 120-grit emery paper. Precautions were taken to keep the specimen faces flat in order to insure good sealing between the specimen and the nozzle face.

PROCEDURE

In order to make a typical erosion run, the prepared face of the specimen was clamped firmly against the face of the flow nozzle so that all oil entering the nozzle passed through the shallow rectangular flow channel formed by the nozzle and the specimen. The oil pump was started and the oil bypass valve closed until the oil flow out of the flow channel, which was determined by measuring the time required to collect a known quantity of oil, was sufficient to produce the desired mean shear rate within the flow channel. The temperature rise and the pressure drop across the nozzle were measured with thermocouples and a pressure gage, respectively. In some cases, the temperature at the face of the specimens was obtained with a thermocouple peened into the surface of the specimen.

The oil used in the investigation was an uncompounded mineral oil similar to that used in the lubrication systems of aircraft gas turbines. The temperature-viscosity relation for this oil is shown in figure 5. The design of the high-pressure oil pump was such that the use of oils of higher viscosity was inadvisable. No attempt was made to control oil temperature during the erosion investigation.

In the first series of experiments with the rectangular flow channels and filtered oil, each erosion specimen was subjected to investigation at mean surface shear stresses of 11 pounds per square inch and 43 pounds per square inch, corresponding approximately to mean surface shear rates of 1.5×10^6 and 19×10^6 reciprocal seconds, respectively. Inasmuch as bearings in aircraft power plants have been found to erode in less than 3 hours of operation, the duration of each erosion run was arbitarily set at 6 hours. One specimen of lead was subjected to the 43 pound-per-square-inch shear stress for 14 hours. Another lead specimen was subjected to the action of a highly pulsating flow for 6 hours. This pulsating flow was obtained by removing all damping from the oil system so that the reciprocating pump delivered 120 distinct pulses per minute. Separate runs were made with unidirectionally finished copper specimens oriented with the surface finish marks parallel to the direction of flow as well as perpendicular to the direction of flow. The aforementioned phenomena were studied visually by rearranging the apparatus as shown in figure 4. A bright light source was focused on the edge of the glass disk and the resulting diffuse illumination permitted visual examination of the surface of the specimen at a magnification of X10 during an experimental run.

In a further series of experiments, the high-pressure filter was removed from the oil circulating system. The channeled flow nozzles were replaced by a smooth disk-like nozzle with a smoothly blended central oil hole. A polished specimen of annealed copper was forced against the nozzle face until the desired operating pressure was attained and the oil leaving the central hole in the nozzle was forced to flow radially outward between the parallel surfaces of the specimen and the nozzle. Visual studies of flow were also made, as in the preceding series of experiments.

RESULTS AND DISCUSSION

Erosion Phenomena

Microscopic examination of the erosion specimens from the series of experiments with the rectangular flow channel and filtered oil indicated that no combination of the conditions investigated eroded or otherwise altered the surface of the specimens. Small scratches and indentations, intentionally made on the otherwise smooth surface of the specimens, failed to act as nuclei for surface erosion and sharp edges left at the scratches were not rounded or smoothed by the oil flow.

The results obtained from the series of experiments in which the unfiltered oil was caused to flow radially outward between parallel surfaces of specimen and nozzle showed that foreign particles produced the pseudoerosion shown in figure 6. These particles were probably wear particles from the high-pressure pump. As might be expected, this damage began to occur soon after the pump was started and occurred regardless of the size or shape of the central oil hole. Figure 7 shows the types of flow nozzle used in the erosion studies. When the oil-film thickness was 0.001 inch and a central oil hole 1/64 inch in diameter was used, the small wear particles were able to pass between the surfaces without interference and the long extended scratches ceased to occur. However, a "sandblast" effect was evident on the specimen in the region opposite the central oil hole, as shown in figure 8. This effect is caused by the small particles striking the specimen surface and abrading it as they flow out of the central hole and change direction to flow out between the nozzle and the specimen. The nature of these occurrences was verified by visual observation with the apparatus of figure 4, the foreign particles appearing as points of light in the oil. Replacing the high-pressure oil filter in the oil system completely eliminated this form of surface damage.

It is possible that a part of the erosion found in the bearings of actual power plants is of this nature, inasmuch as wear and dirt particles are present to some degree in all lubrication systems. It is of interest to note that metal removal can be caused by particles of a size well below the filtration limits of standard aircraft filters if these particles are carried by an oil stream that is forced to make sudden changes in direction of flow. In this manner a bearing may be eroded by particles whose diameter is smaller than the minimum film thickness of the bearing. On the other hand, particles small enough to pass through typical aircraft filters may still be of a size that is too large to pass through the point of closest approach in a highly loaded bearing without scoring the surface to some degree.

Pressure-Viscosity Phenomena

The results obtained from a typical run in which the pressure difference across the flow channel was set and the resulting flow recorded are shown in figure 9. These data were for the oil of figure 5 and a flow channel 0.002 inch deep, 0.020 inch wide, and 0.188 inch long, with smoothly blended entrance conditions. The pressure differential was measured between inlet and atmosphere. The temperature was obtained with an iron-constantan thermocouple embedded in the surface of the erosion specimen. The mean surface shear stress as computed from equation (4) is also indicated in figure 9. The pressure-flow relation of figure 9 follows equation (5) up to a pressure differential of approximately 4000 pounds per square inch. Beyond this value, the flow increases at an increasing rate with pressure differential. At a pressure differential of 8000 pounds per square inch, the mean surface shear stress reaches a value of 43 pounds per square inch. The increase in flow at an increasing rate suggests a variation in viscosity contrary to the classic assumptions on which equation (5) is based. At this value of pressure differential, the pressure in the upstream region of the flow channel is large enough to have considerable influence on the viscosity of the oil flowing in the channel. The viscosity of an oil depends upon its chemical structure, its temperature, and its pressure. Inasmuch as a number of these factors are unknown for the case in question, no exact treatment of the pressure-viscosity change along the length of the flow channel is attempted. The viscosity as calculated from the measured surface temperature at a pressure drop of 8000 pounds per square inch across the channel ends is 2.25×10^{-6} pound-seconds per square inch. With this value, the shear rate at the surface of the erosion specimen under a pressure drop of 8000 pounds per square inch is 19×10^{6} reciprocal seconds. This shear rate represents a minimum value of the mean rate at the wall because the measured temperature will indicate a higher viscosity than that actually existing in the oil film.

Any theoretical explanation of the anomalous flows at pressure drops greater than 4000 pounds per square inch is beyond the scope of this report. A detailed analysis of conditions within the flow channel would necessitate consideration of pressure-viscosity relations for the oil, nonuniform temperature distribution within the oil film, critical conditions for the onset of turbulent flow, and the possibility of shear-induced viscosity reduction.

SUMMARY OF RESULTS

From experiments conducted with oil flowing at very high shear rates and corresponding high shear stresses, the following results were obtained:

1. Annealed copper, silver, and lead specimens showed no indication of erosion or other surface damage when exposed to flowing oil at mean surface shear stresses as high as 43 pounds per square inch (roughly corresponding to a mean surface rate of shear of 19×10^6 reciprocal sec) for periods of 6 hours. A lead specimen showed no damage under similar conditions after 14 hours. Surface finish marks, scratches, and indentations failed to act as nuclei for erosion.

2. A pseudoerosion was caused by the accumulation of a large number of small scores created by forcing of foreign particles through the flow path. Another type of erosion was caused by the sandblast action of small particles in the oil striking the surface of the erosion specimen at regions where the oil flow was forced to change direction. In this case erosion was caused by particles smaller than the oil-film thickness. Part of the erosion found in actual power plants may be of this nature.

3. Data are presented to show the anomalously large flows found under conditions of high shear stress for a typical aircraft mineral oil. Because of the complexity of flow conditions in the flow channel and a lack of knowledge of the true temperatures in the oil film, no valid explanation of the anomalous flows can be offered nor can the existence of a shear-induced viscosity reduction be verified.

Lewis Flight Propulsion Laboratory,
National Advisory Committee for Aeronautics,
Cleveland, Ohio, March 7, 1949.

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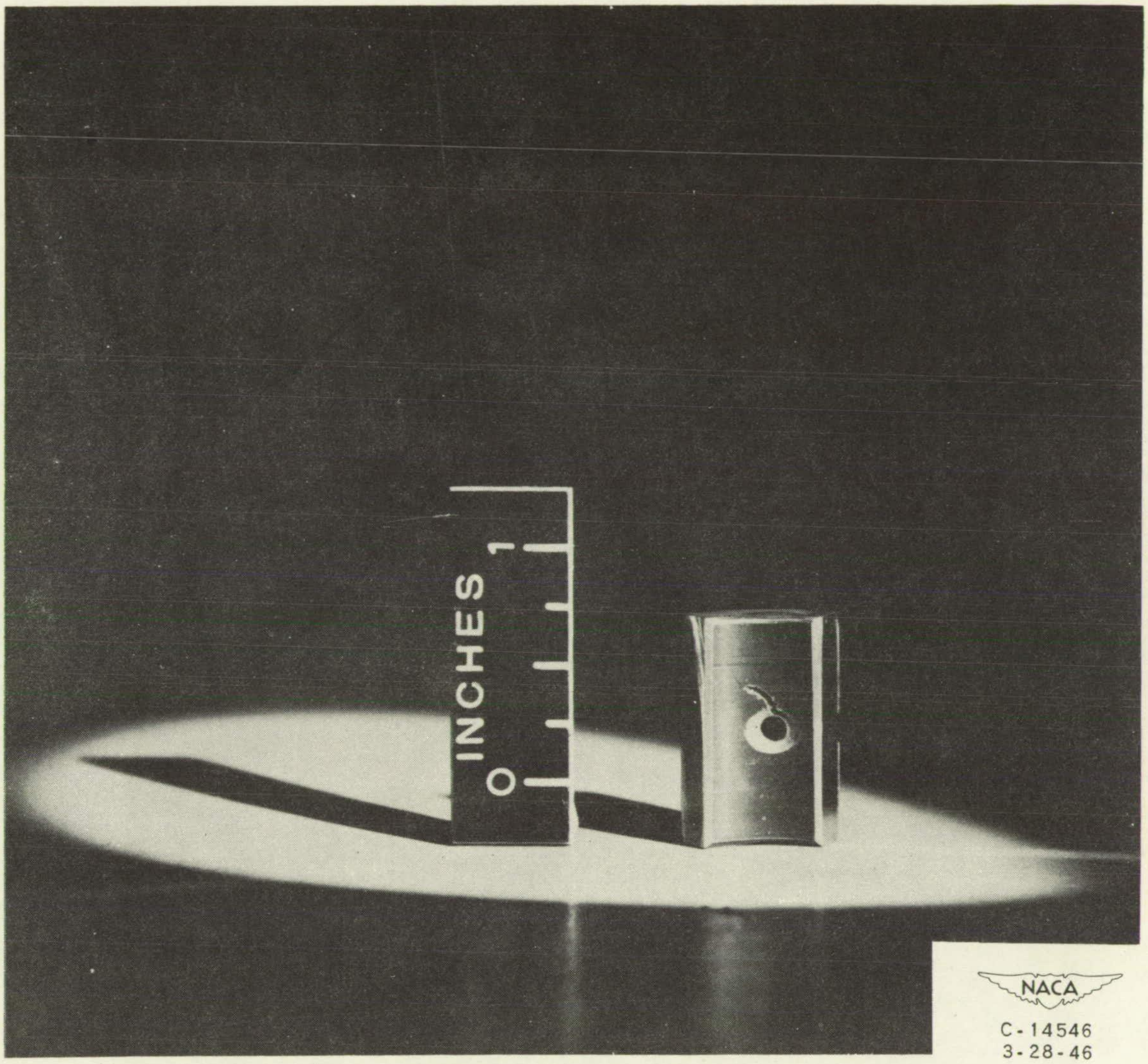

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Figure 1. - Severe erosion adjacent to oil hole of bearing.

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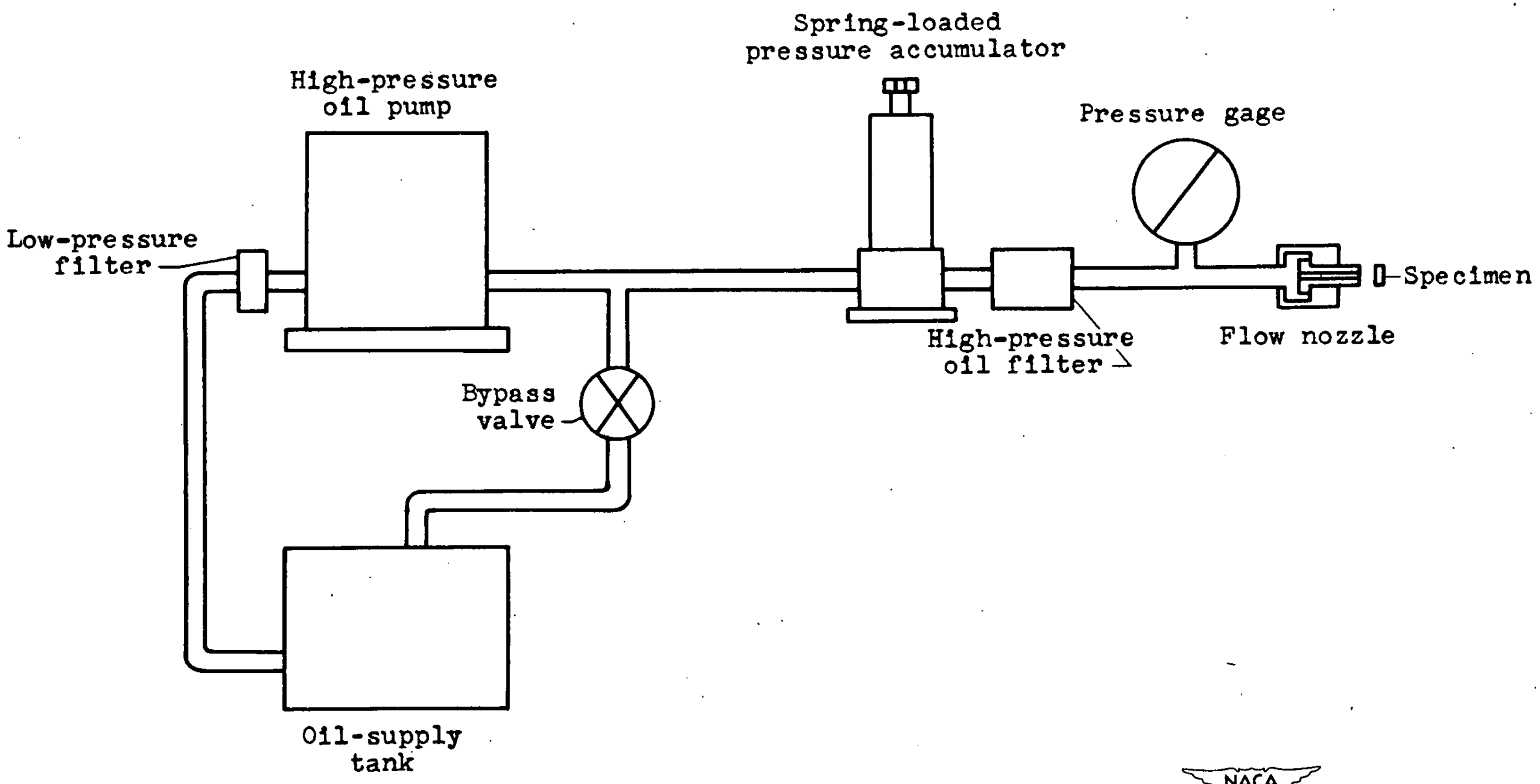

Figure 2. - Schematic diagram of erosion apparatus.

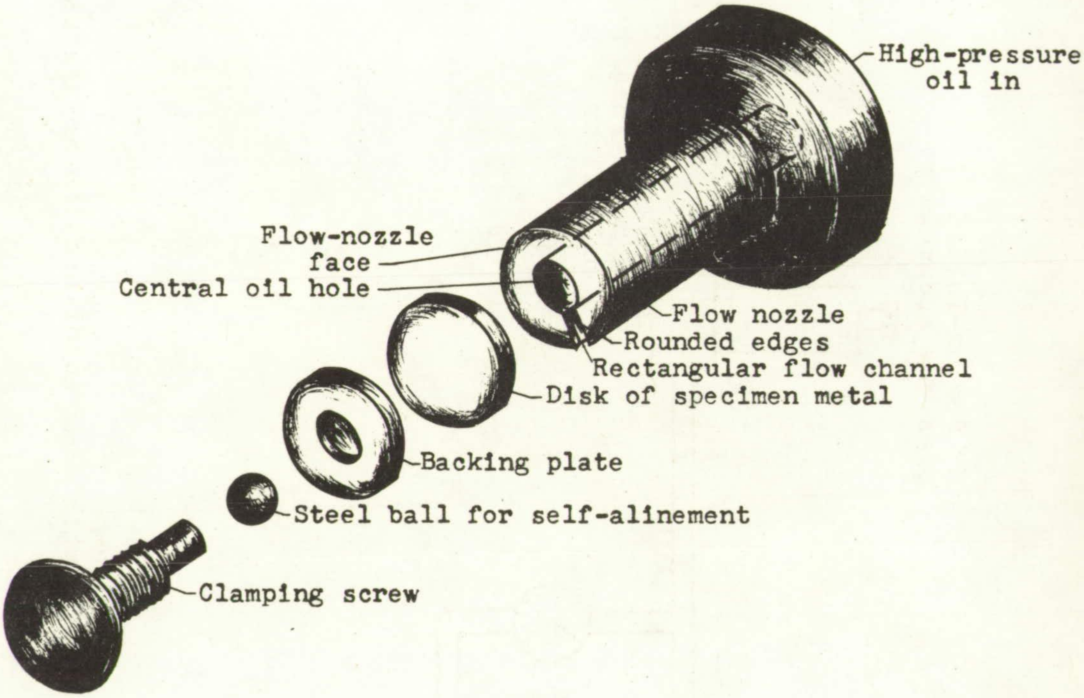

Figure 3. - Disassembled view of flow-nozzle and specimen arrangement.

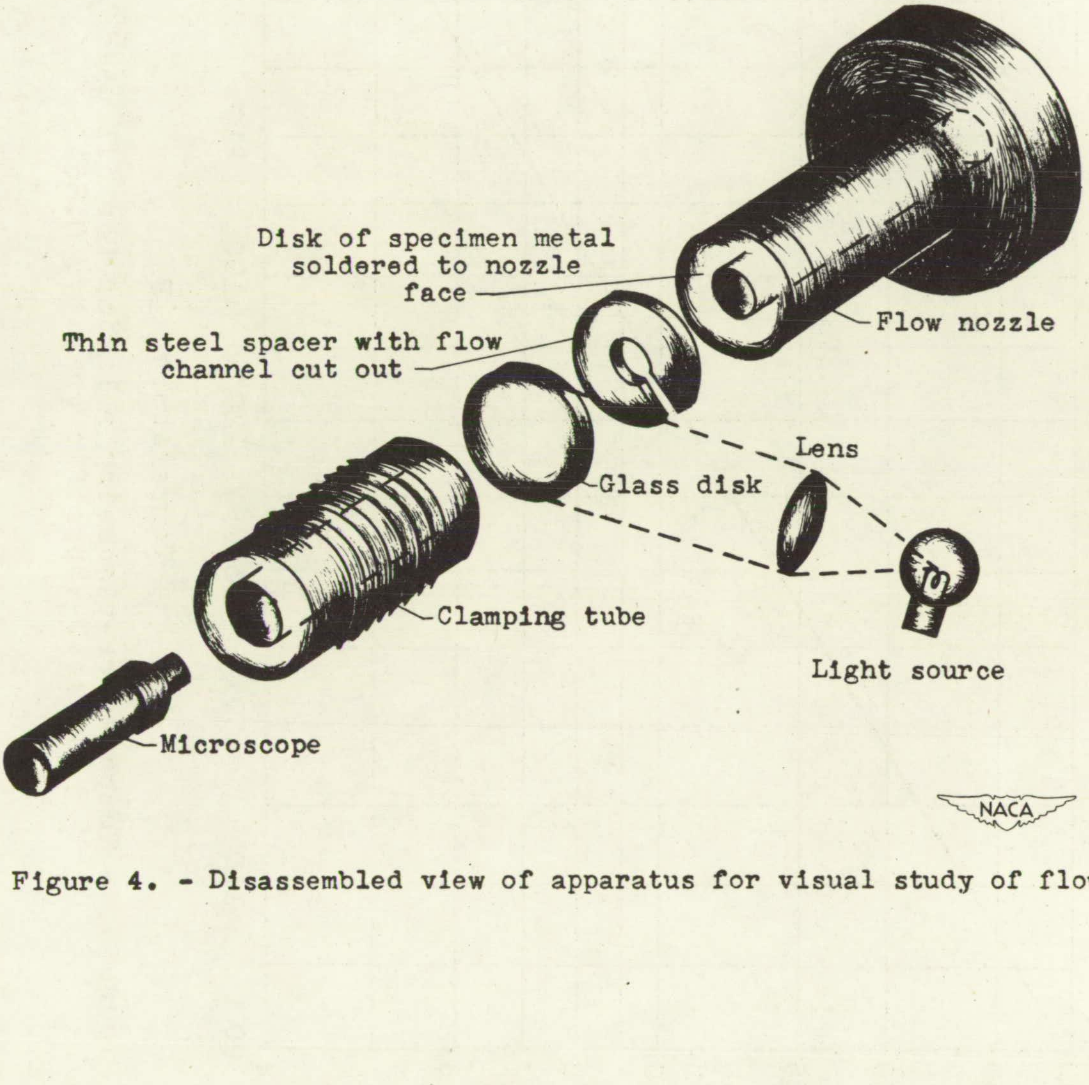

Figure 4. - Disassembled view of apparatus for visual study of flow.

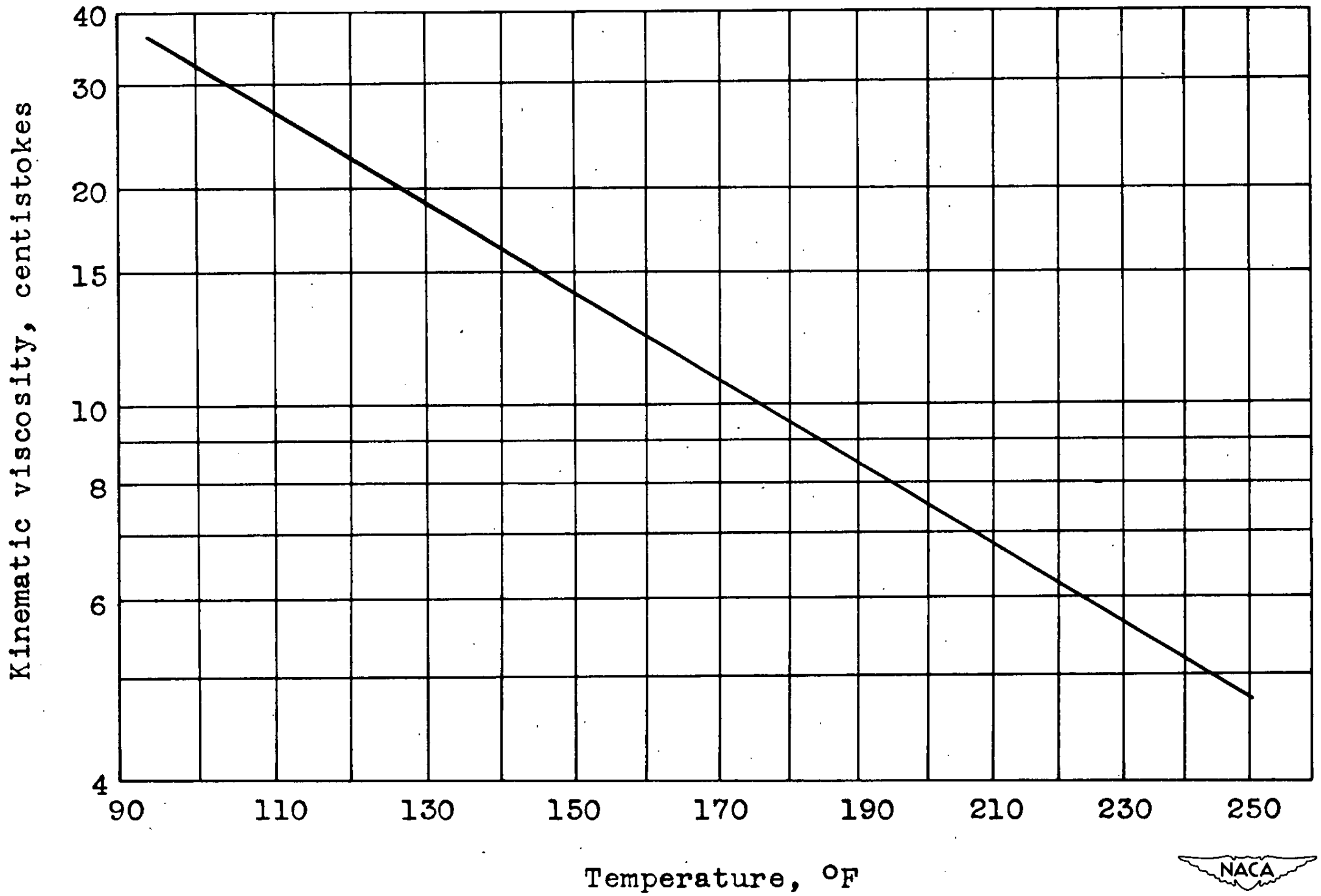

Figure 5. - Temperature-viscosity relation for oil used in erosion studies. Specific gravity, 0.86.

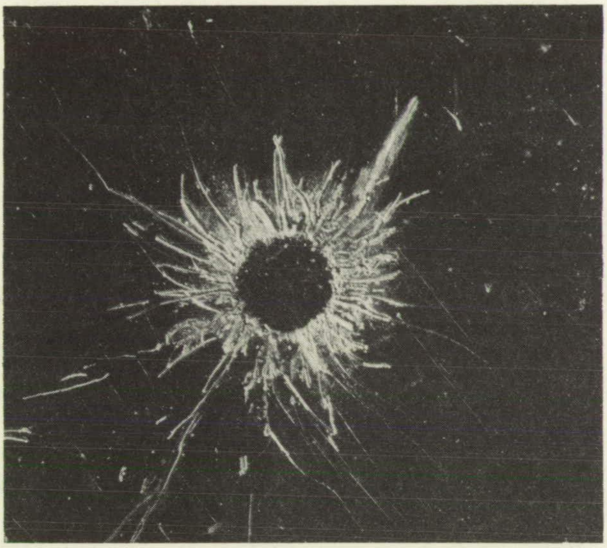

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Figure 6. - Pseudoerosion caused by scoring of particles carried in oil. Particles large compared with oil-film thickness; oblique illumination. X10

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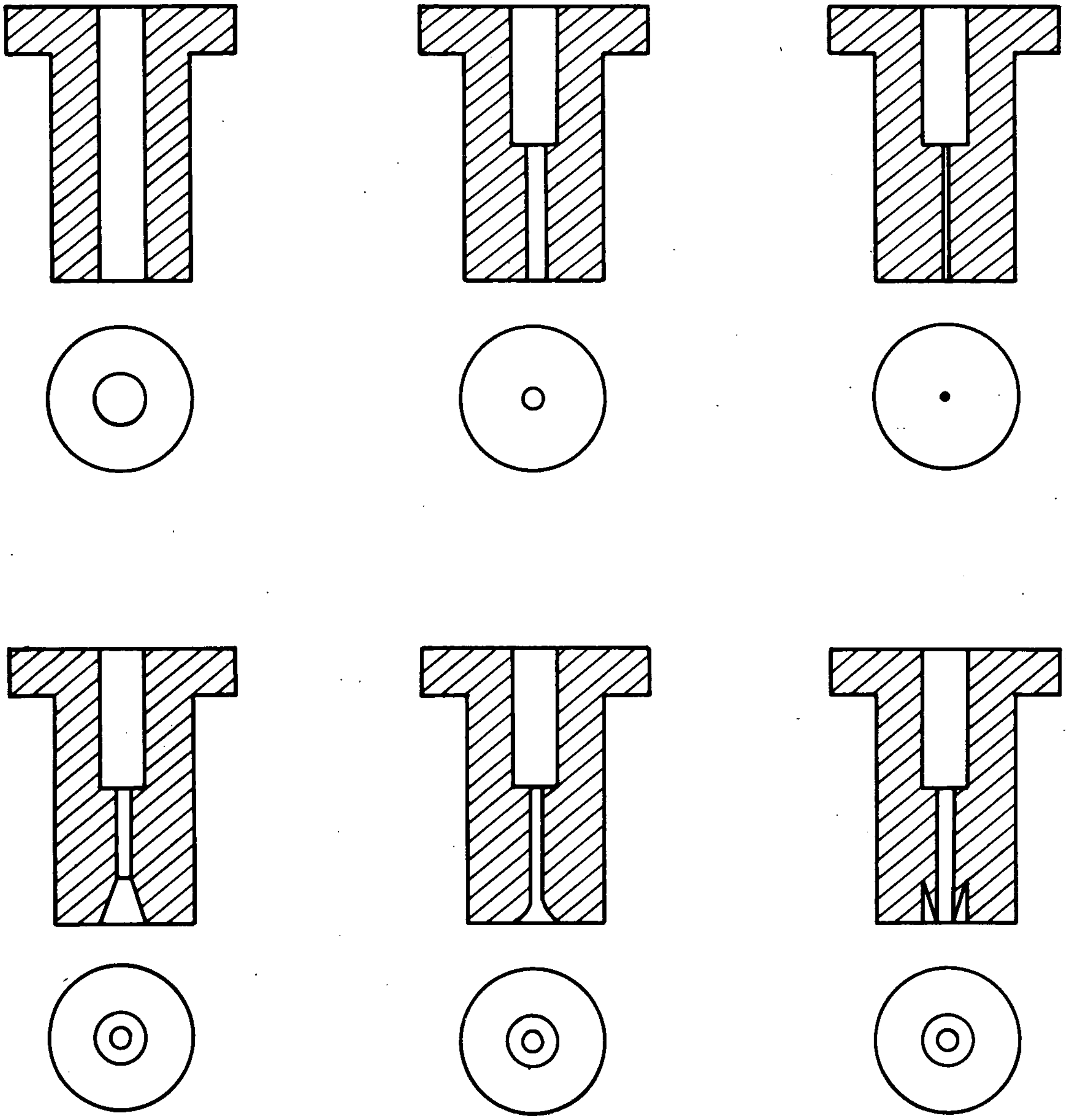

Figure 7. - Types of flow nozzle used in erosion studies.

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Figure 8. - "Sandblast" surface damage caused by small particles in oil impinging upon surface in regions where oil is forced to change direction of flow. Particles small with respect to oil-film thickness; oblique illumination. X10

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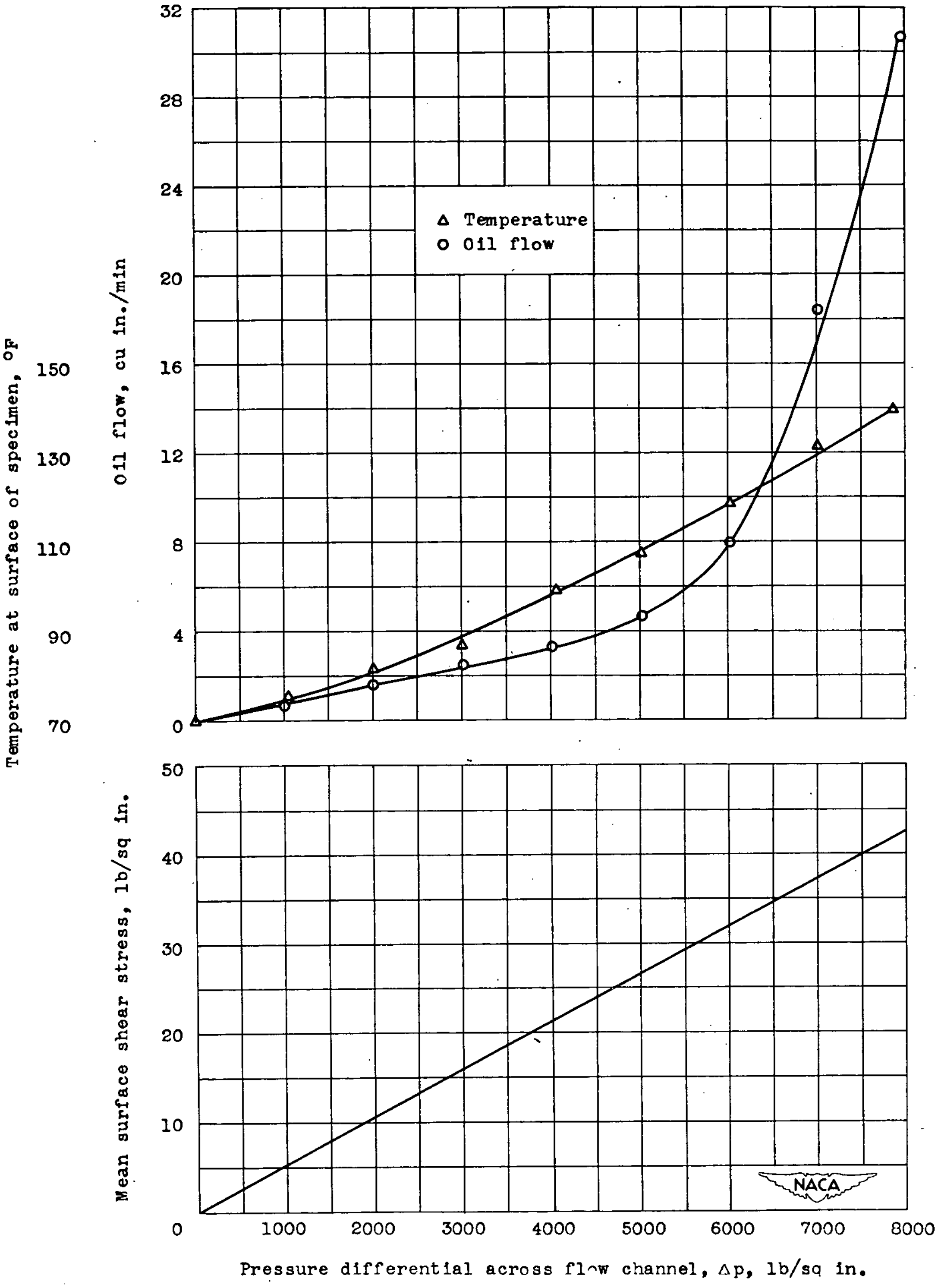

Figure 9. - Effect of pressure differential on mean surface shear stress, measured oil flow, and measured oil temperature for rectangular, rounded-entry flow channel 0.002 inch deep, 0.020 inch wide, and 0.188 inch long. Mean surface shear stress is based on equation (4).