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SEVERE PITTING ATTACK OF PILE PROCESS TUBES AND SLUGS

BY

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Technology - Hanford Processes

AEC RESEARCH AND DEVELOPMENT REPORT

SEVERE PITTING ATTACK OF PILE PROCESS TUBES AND SLUGS

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June 30, 1953

HANFORD ATOMIC PRODUCTS OPERATION
RICHLAND, WASHINGTON

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SEVERE PITTING ATTACK OF PILE PROCESS TUBES AND SLUGS

I. INTRODUCTION

Between October 1951 and October 1952 the F Pile of Hanford Atomic Products Operation was forced a number of times to stop operation temporarily because water leaks in the process tubes allowed large amounts of cooling water to enter the graphite moderator[1,2]. At each of these shutdowns, the tedious and time-consuming operation of pressure-testing individual tubes to find the leaks, and subsequent tube removal, resulted in a serious production loss. When the first few leaking tubes were located they were found to be stuck in their channels and great difficulty was experienced in removing them from the pile. The outside of these tubes was found to be covered with large quantities of corrosion product, and the surfaces were severely corroded. It was concluded that water from previously known leaks, acting as the electrolyte, allowed galvanic corrosion of the tubes. The coupling of the aluminum with the graphite, known to be dangerous to aluminum, provided the necessary driving force. Most of the holes in the leaking tubes that were removed between October 1951 and June 1952 were not located and therefore could not be examined. Those holes that were located definitely started from the outside of the tubes. It is believed, however, that by keeping the outsides of the tubes dry, external attack of this type can be eliminated.

Beginning in June 1952, a different phenomenon was observed. A leaking tube was discovered at F Pile that was not stuck in the channel.

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(1) Foley, D. J., "Water Leaks and Their Effects at F Pile", HW-24440, June 30, 1952.

(2) Foley, D. J., "Tube Leaks and Pitted Slugs at F Pile During June and July, 1952", HW-25417, August 18, 1952.

Furthermore, by a new technique using a dye solution[3], the hole in the tube was found. Large, discrete pits were found on the inside wall of this tube at the point where it leaked. The leak was through a pin hole at the base of one of the pits. Attack on this tube obviously started inside the tube and worked its way out[4]. Most of the tubes that have been removed from F Pile between June 1952 and September 1952, and both leaking tubes that were found in D Pile, were attacked from the inside.

Slug jackets have been found in F Pile with a type of pitting attack that may be caused by the same phenomenon. This slug jacket pitting attack, which is more severe than any that has been encountered to date, occurred concurrently with the pitting attack on the tubes.

A description of the nature of this pitting attack and hypothesis to explain its causes are described in this report.

II. SUMMARY

Several process tubes which were removed from the piles because of water leakage or suspected damage from ruptured slugs were found to be severely pitted on the inside, with penetration of the tube wall occurring where leakage was evident. At about the same time a type of surface attack, not previously observed, was found on some slugs discharged from F Pile. It is possible that this pitting attack observed on both slugs and tubes was caused by the same mechanism. In addition, in at least two instances, both the slugs and the tubes from the same channel showed this type of attack.

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(3) DeHollander, W. R., "A Description of the Acetone-Dye Solution Method of Demarcating a Leak in Process Tubing While in the Pile", HW-25038, July 16, 1952.

(4) Pitzer, E. C., "Technical Activities Report, Corrosion - July, 1952", HW-25059, August 10, 1952.

Incidents of attack in process tubes in the Flow Laboratory were found to be similar to the in-pile phenomenon. The attack on both the tubes and slugs occurred in the vicinity of obstructions to the flow of water in a nine-to-twelve-day period, and appeared to be of a mechanical nature.

The occurrence of this pitting attack, observed in the piles and in the Flow Laboratory, appears to require several conditions, such as: water temperature above 60 C; water velocity above 17 feet per second; and flow irregularities in the annulus. These flow irregularities occur at slug junctions and at misaligned slugs, and are even more serious if loose particulate matter in the tube should become lodged in the annulus.

It is recommended that action be taken to eliminate the causes of misaligned slugs, and to remove the barnacle-like corrosion products that have been found in the front portions of the pile tubes. Because contamination by mercury is a possible cause of the observed attack, all possible sources of mercury contamination of slugs, tubes, and cooling water should be evaluated as to the potential hazard Experimental evidence indicates that the observed attack is inhibited by the presence of dichromate ions in the cooling water.

III. DESCRIPTION OF THE PROBLEM

Between June 4, 1952, and August 25, 1952, six process tubes were removed from the F Pile of HAPO and two from the D Pile in which a severe internal pitting attack was observed. The attack in these eight tubes had progressed far enough to result in perforation of the tubes. Large quantities of water entered the graphite moderator, resulting in serious production losses while the leaks were being located and the piles were being dried. During this period the other three Hanford piles did not have any leaking tubes that could be attributed to this type of pitting attack. However, pitting attack at slug junctions has been found in tubes from B, D, and H Piles.

Since June 22, 1952, severely pitted slugs have been found among the slugs that were discharged from F Pile. In most cases only four or five of the slugs in a tube were pitted, and in no case were there more than 13 pitted slugs in a tube. The tube in which pitted slugs were first found was discharged because of a water leak. A far greater number of tubes were normally discharged without examining the slugs. Large numbers of similarly pitted slugs from the other piles have not been found, although the charges from many tubes have been examined. However, five slugs from H Pile, one from B Pile, and the perforated slugs from the rear of at least two tubes at DR Pile were found to be pitted. All pitted slugs observed from discharges since October 1952 have exhibited a film deposit over the pitted areas, indicating that the pitting attack is no longer active.

Simultaneously with the occurrence of leaking tubes and pitted slugs in the piles, severe pitting of several tubes and slugs occurred in conjunction with the tests that were being run in the Pile Technology Flow Laboratory in the 105-D Building. A tube that contained aluminum dummy slugs and raw river water at 95 C and 20 gallons per minute was perforated by one of the many pits that were subsequently found inside the tube. None of the slugs in the tube were pitted. A tube that contained ferric sulfate treated water at 95 C and 20 gallons per minute was deeply pitted, but not perforated, and the slug at the point of pitting was also attacked. An identical incident occurred in aluminum sulfate treated water. In three other cases, using aluminum sulfate treated water, the slugs were pitted, but the tubes did not appear to be attacked. None of these three incidents occurred in the presence of sodium dichromate inhibitor.

As a result of these occurrences a program of testing to determine the cause of the attack and a solution of the problem was undertaken.

IV. PILE OPERATING DATA

Before October 10, 1951, the cooling water for all Hanford piles was purified by treating Columbia River water with ferric sulfate as a coagulant. Chlorine was added to control algae formation, the pH was controlled at 7.7 with lime for corrosion purposes, and 2 ppm sodium dichromate was added as a corrosion inhibitor. Since that time the following changes have been made in the water treatment procedure at the various piles. On October 10, 1951, aluminum sulfate was substituted for ferric sulfate as the coagulant at F Pile only. The principle difference in the chemical analysis of the water was to decrease the residual iron content from 0.02 to 0.005 ppm and to increase the residual aluminum content from 0.0 to 0.2 ppm. On January 2, 1952, activated silica was added along with the aluminum sulfate at F Pile according to the Bayliss method[5] to aid in the coagulation process. No significant change in the chemical composition of the cooling water occurred at that time.

On April 18, 1952, the addition of sodium dichromate to the water was discontinued at all the piles except F Pile, where it was discontinued one week later. On July 22, 1952, aluminum sulfate was substituted for ferric sulfate at D Pile, resulting in the same changes in chemical composition that occurred at F Pile. Dichromate was again added to the D Pile water at 2 ppm concentration beginning December 24, 1952. Because of the interconnection of the D and DR water plants about 20 per cent of the water fed to DR Pile was aluminum sulfate treated between July 22 and December 24, 1952, at which time it was entirely aluminum sulfate treated with 2 ppm dichromate.

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(5) Fryar, R. M., "Production Test Number 105-503-E, The Use of Activated Silica as a Coagulation Aid for Aluminum Sulfate", HW-22755, November 19, 1951.

During 1952 the water pressure in the headers leading to the process tubes had been increased about 50 pounds per square inch. During the spring of 1952, a program to change the downstream dummy pattern was initiated at all the piles. Perforated slugs were substituted for the solid dummies previously used. These two changes resulted in about 3 per cent increase in the flow rate. The tubes that leaked or contained pitted slugs did not necessarily have the new dummy pattern.

Two purges of F Pile have been carried out since January 22, 1952, and none at D Pile since July 5, 1952. B and H Piles have been purged routinely on about a monthly schedule. Monthly purging at DR Pile was discontinued in January, 1953. C and DR Piles have been purged only when necessary since then.

Certain seasonal changes occur regularly in the characteristics of the cooling water. The most outstanding of these is on the variation in the temperature from near freezing in January to approximately 20 C in August. Because a given temperature rise is maintained from the front to rear of tubes, the outlet temperature is often 15 to 20 F higher in the summer than in the winter.

V. PILE PROCESS TUBE EXAMINATION

Since the appearance of the recent type of pitting attack in pile process tubes, tubes from all operating piles have been examined in the 108-B Tube Examination Facility, which includes equipment to cut, slit lengthwise, and visually examine and photograph the inner and outer surfaces of the pile process tubes. Of the process tubes which were visually examined, ten were suspected or confirmed leakers prior to removal. Holes that penetrated the tube wall were found in nine of the ten leakers, eight of which penetrated the tube from the inside out. The hole in one tube was caused by galvanic corrosion on the outside of the tube which corroded through the tube wall from the outside in. A hole of this type is shown in

 [redacted]

Figure 1. Since this tube suffered an entirely different type of attack, it is included here only for comparison purposes. This tube, 0486-F, was found to be a leaker on February 11, 1952, and was made an air tube until its removal from the pile on July 9, 1952.

Pitting attack as described in this report was first observed on Tube 3573-F, which was reported as a leaker on June 4, 1952. Some general observations obtained from the inspection of the process tubes which tolerated this type pitting attack on the interior surfaces may be summarized as follows:

1. The holes in the process tubes occurred about eight to twelve feet from the rear Van Stone flanges. However, the pitting attack was not limited to areas of tube wall penetrations. Examples of this pitting attack are shown in Figures 2 through 12.
2. The holes occurred at the bottom of internal pits, some as large as one-quarter by three-quarters of an inch at the surface of the pits.
3. No corrosion products could be seen in or adjacent to these pits.
4. No corrosion products could be seen on the outside of the tubes in the immediate vicinity of the holes, as shown in Figures 13, 14, and 15.
5. Some pits have an oblique orientation; i.e., the long axis of the pit is not parallel to the long axis of the process tube. Pits of this type are shown in Figures 2, 9, 16, and 17.
6. Pits generally occurred on or near the ribs; however, this pitting attack has been observed elsewhere on the tubes. Sections of process tubes that did have pits adjacent to the ribs usually also had a severely pitted area along the ribs in the immediate vicinity.

7. Holes and pitted areas were usually observed at or near what appeared to be slug junctions. Three tube wall penetrations have been observed at one pitted "slug junction" in one tube. This type of attack is shown in Figures 6, 7, 9, 12, 17, and 18.

8. Tubes that were pitted usually contained one or both of the following film characteristics: flaked areas in the film on the top or sides of the tube, which may be indicative of a misaligned slug, as shown in Figures 2, 19, 20, 21, and 22; and a film pattern indicating turbulence at "slug junctions" with partial film removal, as shown in Figures 6, 16, 20, and 23. An unusual film pattern that has been observed in the vicinity of perforated slugs is shown in Figure 24.

9. Some tubes containing areas of this pitting attack had spots of white corrosion product, or barnacles, on the sides and tops of the ribs in the front section of the tube upstream from the charge, as shown in Figure 25.

10. The type of pitting attack discussed in this report has been found on the inner surfaces of tubes removed from B, D, F, H, and DR Piles.

Detailed observations of pile process tubes that were associated with this attack, along with those that were routinely examined during this period, are reported elsewhere[7].

VI. PITTED SLUG EXAMINATION

Since start-up, a small percentage of the slugs discharged from the Hanford piles have been visually examined. Prior to July 1952, no pitting attack was reported that was similar to the pitting since observed on the

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(7) Deobald, T. L., "Process Tube Examination at 108-B through February, 1953", HW-27723, April 20, 1953.

jackets of slugs discharged from F Pile. Examples of such pitted slugs are shown in Figures 26 and 36. Irradiated slugs with severely rippled or blistered surfaces have been discharged from all the Hanford piles in the past. The pitting attack does not appear to be associated with this blistering; however, blistered slugs and pitted slugs have been found in the same charges.

Pitting of slug jackets was first observed on two slugs out of the 64 four-inch slugs from Tube 3668-F, discharged on July 19, 1952. This tube was discharged because of a water leak in the process tube. The slugs from this tube received an average exposure of 446 MWD/T. Slugs are normally discharged with an exposure of approximately 600 MWD/T. Radioactivity measurements of and film deposits on these two slugs indicate that they were near the downstream end of the charge. A pit which penetrated the tube wall and apparently caused a water leak in this tube was found about 12 feet from the rear Van Stone flange, or approximately where these two pitted slugs were believed to have been located.

This type of pitting attack was again observed on some of the four-inch slugs discharged from Tube 3773-F on July 29, 1952, with an average exposure of 479 MWD/T. This tube was discharged because of a ruptured slug. The tube was charged with regular group eight metal in the .240 inch orifice zone on December 5, 1951; the metal was canned on October 1, 1951. Twenty slugs from this tube showed some signs of attack - four severely. One slug was pitted and ruptured - an end cap failure. Two of the other severely pitted slugs are shown in Figures 27 and 28. The slug shown in Figure 27 was pitted on the cylindrical surfaces near both ends; the can end is shown here. This attack is not unlike that described in the literature as pitting attack caused by cavitation. The pitting attack on the slug jackets shown in Figure 28 covered about 85 per cent of the cylindrical surface of the slug, was free of corrosion product, and apparently did not penetrate the AlSi bonding layer. An area about three-fourths of an inch wide and parallel to the long axis of the slug was practically unattacked. About ten slugs from this tube showed signs of blistering or rippling on the surface of the slug jackets. Figure 29 shows the most severe attack of this type found in the tube.

The regular four-inch slugs discharged from Tube 3684-F on July 31, 1952, with an average exposure of 383 MWD/T, were attacked in a manner similar to those of Tube 3773-F mentioned above. The tube was charged with group eight metal in the .240 inch orifice zone on January 18, 1951; the metal was canned on December 5, 1951. This tube was also discharged because of a slug failure, but in this case the ruptured slug was not pitted. However, five slugs, or eight per cent of the slugs discharged from this tube, did exhibit signs of pitting attack. The majority of the attack was on the lateral surfaces adjacent to the ends. No attack was found on the slug ends or weld beads. The pits were found to be free of corrosion product and film. Figures 30 through 37, showing slugs from Tube 3684-F, may represent the progress of this type of attack; that is, the slug shown in Figure 37 may have looked previously like the slug shown in Figure 30. Figure 30 shows initial attack. The slugs shown in Figure 31, which is next in the probable progression, shows some pitting. Figures 32 and 33 show areas of more concentrated attack. It is possible that the progress and direction of additional attack depend on, and are accelerated by, pits already present. The pits visible on the slug shown in Figure 33 are not unlike those produced in Flow Laboratory tests (see Figure 53). Because of the similarity it can be deduced that the flow along the slug was from left to right. Fairly severe pitting attack covered about one-half the lateral surface of the slug shown in Figure 34. The area at the lower right was essentially unattacked. The slug shown in Figure 37 was severely attacked over most of the cylindrical surface. Absence of attack was noticed at possible rib contact areas. Pitting attack in longitudinal rows on slug jackets is not uncommon, as shown in Figure 37.

A slug jacket failure which may have been aided by pitting attack was found in Tube 3781-F. This tube was charged in a .240 inch orifice zone on December 5, 1951, with regular, four-inch, group eight metal which was canned October 11, 1951. These 64 slugs were discharged August 24, 1952, with an exposure of 508 MWD/T. The end cap of this rupture is shown in Figures 38 and 39. It appears striking that there is an absence of attack on part of the area of the can adjacent to the cap, between the crack in the jacket and the weld bead. An uneven heat transfer through the cap or uneven flow around the cap may be responsible for this. The entire cylindrical surface was severely attacked. The pits on this slug appear to be flat on the bottom. It may be that the attack was halted at the bonding layer. According to Flow Laboratory observation, as mentioned above, one can deduce that the direction of water flow was from right to left or that the cap end in this case was upstream. Two other slugs from this tube were also pitted. One of these was found to be near the center of the pile flux. This is the first instance of this type attack which was found in the central portion of the tube. Radioactivity measurements and film formation lead one to assume that all other pitted slugs were positioned in the downstream portion of the process tube. There were also nine, or fourteen per cent, of the slugs in Tube 3781-F that were blistered.

A summary of observations that apply to this type of pitting attack on slug jackets includes the following:

1. The pits that are representative of this "F Type" attack are generally tear-shaped as shown in Figures 26, 33, 38, and 42. Results of flow laboratory observations show that the point of the teardrop is upstream[8].

2. The pits, generally, do not contain corrosion products of film. However, slugs have been observed with film deposited in some of the pits.

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(8) Wilson, C. D., "Flow Laboratory Investigation of "F-Type" Pitting of Slugs and Tubes," HW-28207, June 1, 1953.

3. Pitting attack may be concentrated as in Figures 26 and 27 or generally scattered over the lateral surfaces of the slug jackets as in Figure 38. Frequently, slugs have been found with pits located on one side only. Figures 40, 41, and 42 show several views of the same slug. Frequently, the pits have been observed in rows parallel to the long axis of the slug as shown in Figure 37.

4. Pits have not been observed on the can end or the cap end of the slug jacket.

5. Pitting may be severe on one slug, skip several slugs in the charge, and again be severe on another slug.

6. This attack has not been found on slugs other than the four-inch size; however, the percentage of slugs discharged other than four-inch has been small.

7. Blistered slugs and pitted slugs have been observed that were discharged from the same charge. Tubes have been discharged in which no pitted slugs were found but contained some blistered slugs. Others have been discharged in which pitted slugs were found but contained no blistered slugs.

8. Pitted slugs and ruptured slugs have been discharged from the same charge. The ruptured slugs may be pitted or not.

9. This type pitting attack has occurred at exposure levels nearly fifty per cent lower than normal exposure as well as at normal exposure levels.

10. All the severely pitted slugs were located in the 0.240 inch orifice zone except for one slug in the 0.200 inch zone at B Pile.

11. The presence of large numbers of similarly pitted slugs from the other piles has not been found, although the charges from many tubes have been examined. However, five slugs from H Pile, one from B Pile, and the perforated slugs from the rear of at least two tubes at DR Pile were found to be pitted. (See Figure 43)

VII. FLOW LABORATORY DATA[8]

During June and July, 1952, three incidents of severe slug and tube pitting occurred in the 105-D Flow Laboratory. Each incident occurred in mock-up tests using differently treated water, and is briefly described below.

A leaking Alclad process tube was discovered after twelve days operation in a mock-up test to determine corrosion rates in 95 C raw river water at 20 gallons per minute. The average turbidity of the water during this period was 12 ppm. The slugs in the tube were not pitted but the tube was severely pitted as shown in Figures 44, 45, 46, and 47. From flow lines in the film it is apparent that the pits occurred at slug junctions. The similarity of these pits to some of the attacked rib areas in pile tubes that were shown earlier in this report should be noted. All the pits are free of corrosion product. They appear to be related to the direction of water flow. The white areas appear to be points at which the slugs were in physical contact with the tube. The flow pattern beside these white areas indicates that some particulate matter collected on the upstream slug edges and partially blocked the annulus over an arc of about 90^{o}.

The second Flow Laboratory occurrence of severe pitting attack took place in a test using standard process tubes loaded with canned aluminum dummy slugs that was being run to determine the effect of water velocity on slug corrosion rate. Ferric sulfate treated dichromate-free

(8) Wilson, C. D., HW-28207.

water at 95 C and various velocities was being used in this test. The first slug in the highest velocity tube operating at 20 gpm was found to be severely attacked (Figures 48 and 49) after twelve days operation. The tube immediately adjacent to this pitted slug was also severely pitted and is shown in Figure 50. A stainless steel heat exchanger that was used to heat the water for this test had been severely fouled with a brittle calcium carbonate scale in a previous test. Pea size particles of this scale were found to break off and travel through the piping and into the tube. It is possible that these particles lodged at the upstream edge of the slug.

The third incident of severe pitting was observed in a test to determine if corrosion could be accelerated by stresses in stuck or twisted tubes such as could be found at F Pile. Three tubes, each containing pairs of cocked slugs, were fed 95 C dichromate-free aluminum sulfate treated water at 15 to 20 gpm. One tube was stressed in compression, the second was twisted about 10^{o} over its fifteen foot length, and the third was not stressed. Unfortunately, both of the stressed tubes received water from the fouled heat exchanger, while the third was fed by a clean heat exchanger. Except for minute traces of attack that were only visible under magnification, the cocked slugs in the unstressed tube that was fed by the clean heat exchanger were not pitted. However, four of the slugs in the stressed tubes fed from the fouled heat exchanger were severely pitted in less than two weeks, and are shown in Figures 51, 52, 53, 54, 55, 56, and 57. The only tube pitting that was observed in this test occurred opposite the slug pits shown in Figure 52. This pitted area is shown in Figure 58, and is very similar to the tube shown in Figure 50. When this tube was removed from the mockup a large amount of loose calcium carbonate scale from the heat exchanger was found in it. One of the scale particles was much too large to pass through the annulus and was probably lodged on the upstream face of the pitted lead dummy slug. Comparison of the pitting in this test with that in the velocity test described above indicates that the effect of the particles in causing the observed attack was more significant than the effect of stressing the tubes.

In order to evaluate the effect of minute particulate matter in the water, a series of Flow Laboratory tests was carried out with mock-up process tubes containing flow irregularities caused by cocked slugs and by artificial means. The effect of 2 ppm sodium dichromate in preventing pitting was studied in both alum and ferrifloc water containing 0 to 10 ppm added diatomaceous earth to simulate turbidity. The water entered the tubes at 90 C and 15 to 23 gpm. Each test lasted approximately two weeks, at which time the slugs and tubes were visually examined. Only superficial attack was observed in the presence of sodium dichromate. Severe pitting of both tubes and slugs, especially at flow irregularities, occurred in its absence, except when no diatomaceous earth was added to the water. Some similarity was observed between the pitting in this series of tests and that observed in the piles.[8]

The characteristics of the pitting attack observed in the Flow Laboratory include the following:

1. Pitting of slugs and tubes usually occurred at flow irregularities such as slug junctions, cocked slugs, and lodged particles. Occasionally cocked slugs were not attacked even though other slugs in the tube were pitted.

2. The pitting attack was rapid and severe enough to penetrate process tubes and slug jackets in less than two weeks.

3. The pits were relatively clean and free of corrosion product.

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(8) Wilson, C. D., HW-28207.

4. Pitting was concentrated at the upstream edge of the slugs. This is not a characteristic of the in-pile attack, although pits have been found in the flow laboratory over the full length of a slug as shown in Figure 49.

5. In the case of the slugs, only the jacket was penetrated by this attack. The exposed AlSi shown in Figure 49 and the exposed lead (no AlSi present) in Figure 52 were not pitted.

6. The shape of the pits and their orientation appeared to be related to the flow of the water. This phenomenon was also observed on pile slugs and tubes.

7. The pits, even where they overlapped, were sharp and clearly defined as in Figures 49, 50, and 52.

8. The 72S Alcladding, once penetrated, gave little or no galvanic protection to the 2S tube walls.

9. This pitting attack was not observed except at water temperatures above 90 C and water velocities above 15 feet per second.

10. The presence of 0.1 to 10 ppm turbidity resulted in pitting except in the presence of 2 ppm sodium dichromate.

VIII. DATA FROM OTHER LABORATORY TESTS

In order to determine if the observed attack was caused by impingement of a high velocity jet of water on the metal surface, a simple impingement test was carried out. High velocity submerged jets of water from 0.5 mm glass capillaries were allowed to impinge normally from 1/16 inch away on aluminum samples. Forty and fifty feet per second jets at 60 C and 90 C for 3 to 25 days showed pitting of aluminum samples with aluminum sulfate (alum) and ferric sulfate (ferrifloc) treated waters. Alum and ferrifloc waters containing between 0.5 and 2 ppm sodium dichromate showed essentially no pitting up to 25 days under the same conditions. Evidence of incipient pitting was noticed in the 25 day exposures. Under the severe condition caused by air entrapped in the water, pitting was observed even in the presence of the sodium dichromate. A smooth, dark green film was formed on the dichromate samples as compared with a coarse brown film on those without dichromate. A complete description of these tests and the results of them is given elsewhere.[9] It is interesting to note that the pits often were offset from the points of impingement, thus resulting in a dough-nut-shaped area of attack with a slightly raised center.

Discs rotating at high velocity while submerged in water were used to study the impingement attack on aluminum by certain types of water. Such discs, five inches in diameter and cut from 72-S sheet aluminum, were rotated in each of the following waters at 70 C:

1. Aluminum sulfate treated water,
2. Aluminum sulfate treated water with 2 ppm sodium dichromate,
3. Ferric sulfate treated water,
4. Ferric sulfate treated water with 2 ppm sodium dichromate,
5. Raw river water, and
6. Steam condensate.

The water was changed in the containers every four hours. After 96 hours at 1100 rpm plus another 96 hours at 1525 rpm, no attack was apparent except at surface irregularities such as the downstream edges of the stamped numbers and of the screw holes. Another disc was rotated in 90 C aluminum sulfate water at 3600 rpm (peripheral velocity of 80 fps) and showed the same results.

Interrupted jet tests have been described in the literature to provide a mechanical analog for cavitation testing.[10] By rotating narrow specimens

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(9) Houck, W. C. "Pitting and Corrosion of Aluminum by Water Impingement," HW-27929, June 8, 1953.

(10) Mousson, J. M., "Pitting Resistance of Metals Under Cavitation Conditions", Trans. American Society of Mechanical Engineers, vol. 59, p. 399 (1937).

through one or more jets of water at high speeds, the pounding received by the metal surface should correspond to that which is produced by the collapse of the unstable voids in a cavitating medium. An apparatus to accomplish this feat was constructed and a few preliminary tests were run. A disc was rotated in a plane perpendicular to a series of 1/16 inch diameter water jets. Narrow test strips could be fastened to the disc so that they cut the jets at frequencies of 3600, 7200, and 14,400 times per minute. Two 72-S aluminum discs without attached strips were rotated in two preliminary tests with two jet velocities: 80 fps in one test and 40 fps in another, both at 90 C. Extremely severe pitting under the path of the 80 fps jets occurred, actually resulting in 1/4 inch wide channels 20 mils deep gouged into the disc. At 40 fps the attack was in the form of discrete pits with the most severe pitting in the areas where previously stationary jets had impinged on the surface for 24 hours. Even on the 80 fps jet test the pits had an elongated shape that was oriented in the direction in which the metal was rolled, not related to the circular water path. These two facts indicate that the history of the metal surface plays a significant role in determining its resistance to the observed pitting attack.

When the narrow strips described above were used in this test with a jet velocity of 56 fps at 90 C and 7200 impacts per minute, pitting of the strips occurred at the points of impact. The amount of attack varied across each strip, being most severe on the leading edges. Also, the 24-S aluminum disc on which the strips were mounted showed pitted areas only immediately following the strips. These areas were at the points where the jets impinged on the disc after leaving the strips. All these facts indicate the great importance of flow irregularities.

In order to visually study the phenomena occurring in process tubes a glass tube was made up, and various slug arrangements were tested.

Aluminum sulfate treated water at various temperatures, pressures, and flow rates was fed to the tube. Both a clean and a fouled heat exchanger were used in order to observe the behavior of particles. In addition to the effect of cocked slugs in producing cavitation, the effect of artificially restricting the annulus to produce cavitation was studied. High speed motion pictures, at 2,000 to 3,000 frames per second, were taken of areas where cavitation was observed. In this way bubble formation and collapse could be studied. The following observations were made in the glass process tube[8]:

1. Cocked slugs produced violent irregularities in the flow pattern. Bubbles followed in the high speed motion pictures showed sudden changes in direction of as much as 90°.

2. Vapor bubbles originate behind flow obstructions and collapse less than one-fourth inch downstream from their point of formation.

3. The vapor bubbles are sensitive to temperature variations and for a given flow irregularity, require a definite threshold temperature before they appear.

4. Vapor bubbles did not form at bulk water static pressures above 25 psig and temperatures up to 100 C, even though linear velocities of 60 fps were attained.

5. Flow irregularities can be tiny particles, small enough to pass through a normal annulus easily, which become lodged on the leading edge of a cocked slug. They lodge over as much as 90° of arc. They also lodge on the lateral surface of a cocked slug - between the slug and the tube, and between the slug and the ribs.

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(8) Wilson, C. D., HW-28207.

6. The lodged particles may intensify any attack or not, depending on their location and arrangement.

Because of the screens in the pile front face crossheaders and the orifice cone screens, particles large enough to lodge in the annulus could not enter a process tube. The corrosion product barnacles that are known to form on the cap-supported shielding pieces and the blank upstream tube sections provide a sufficient source of such particles. It is suspected that these corrosion products appeared in greater size and frequency after the elimination of sodium dichromate from the cooling water.[11] A typical section of tubing showing barnacles can be seen in Figure 25.

IX. DISCUSSION

Several hypotheses have been proposed to explain the foregoing observations of pile and flow laboratory phenomena. The cavitation hypothesis and the erosion-corrosion hypothesis, which have been considered the most plausible, are briefly discussed and evaluated along with other hypotheses.

A. The Cavitation Hypothesis

Static pressures lower than the vapor pressure may exist in the vicinity of flow irregularities in a stream of high velocity liquid. The liquid may flash into the vapor phase at such low pressure points. The unstable bubbles of vapor have only transitory existence, and may collapse on the surface of the flow channel. This phenomenon is known as cavitation. The pressure surges from the collapsing bubbles can cause stresses that exceed the tensile strength of the material. The violent implosions progressively blast out particles of solid and produce a severe pitting attack.

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(11) DeHollander, W. R., "Interim Report Front Tube Corrosion Problem", HW-26537, p. 9, December 20, 1952.

It is possible that cavitation was the cause of the observed pitting attack reported in this document. The observations reported for the glass process tube test showed that cavitation could be made to occur in a process tube and that pitting occurred at the point of vapor bubble collapse. It should be pointed out that the necessary static pressures (less than 25 psig) with velocities up to 60 fps and temperatures up to 100 C are extremely unlikely in an operating pile tube. Pitting attack all over the surface of a slug is also a remote possibility by cavitation, a highly localized phenomenon.

B. Erosion-Corrosion Hypothesis

The observed features of the pitting attack could well be explained by a hypothesis that combines mechanical with chemical attack. Such a hypothesis, here called erosion-corrosion, fits the facts quite well, and for an electropositive metal such as aluminum may be more realistic than cavitation. The principle of this hypothesis involves the rupturing of the protective aluminum oxide coat by mechanical means with the subsequent reaction of the unprotected metallic aluminum with the water, or with the oxidizing agents dissolved in the water. Turbidity in the water could contribute to the damage of the oxide coat on the aluminum. The physical configuration of the slugs in the tubes that led to cavitation would also be conducive to erosion-corrosion. Flow irregularities would still be of prime importance in causing the attack. The fundamental difference between the two hypotheses lies in the fact that one calls for purely mechanical attack while the other also involves chemical action. It is conceivable that the presence of a corrosion inhibitor in the water could minimize the attack by erosion-corrosion, but would not be expected to affect attack by cavitation alone. Sodium dichromate was found to stop the attack by turbid water as reported earlier in this document.

C. Electrochemical Hypothesis

Another possible explanation of the observed facts is based upon purely chemical attack. In this case, the presence of irregularities in the flow, hot spots on cocked slugs, and differential aeration on the metal surfaces would cause potential differences to exist from spot to spot on the metal. These potential differences would result in pitting of the anodic areas. The hypothesis requires that the inevitable corrosion product be washed away to leave the pits clean as observed in both the in-pile and flow laboratory cases. The observed rapid rate of attack is a little greater than might be expected for electrochemical attack, but such a mechanism cannot yet be overlooked. For example, a tube about 1/2 inch in diameter, with a wall thickness of 40 mils, was perforated in six months in the pile by corrosion thought to be caused by an oxygen concentration cell.[12]

D. Film Removal Hypothesis

Since aluminum sulfate treated water has been introduced at F and D Piles, a noticeable decrease in the amount of pressure drop film has occurred at those piles. It has been suggested that the lack of this film may be the fundamental cause of the observed attack. A gelatinous film has been suggested as a protective barrier against cavitation in the same way that rubber coating of turbine blades protects them from damage by cavitation. Furthermore, if the pressure drop film is removed, then the more firmly adherent protective film that has been found on flow laboratory slugs and tubes may also be removed. The loss of this film, if it is not uniform, may leave unprotected areas that are subject to pitting attack, by such mechanisms as oxygen concentration cells.

E. Mercury Hypothesis

The presence of mercury or its salts has long been recognized as dangerous to aluminum equipment. The mercury, when it amalgamates with the aluminum, prevents the protective aluminum oxide coat from forming, and the aluminum may then readily be dissolved even by the

(12) DeHollander, W. R., Private Communications.

moisture in humid air. According to R. H. Brown of the Aluminum Company of America, when a piece of aluminum equipment has operated satisfactorily for an extended period, and suddenly deteriorates corrosionwise for no apparent reason, the cause is often due to mercury contamination.[13] Mercury has been shown to be present in the 300 Canning Area[14] and contamination of slugs has been suspected. Mercury has also been found on the work area floor at 105-D.[15]

Four of the severely pitted slugs from the pile were analyzed for mercury by the Analytical Research groups, and "above background" amounts were reported.[16] The presence of sufficient mercury alone or in combination with the action of violently turbulent water, or cavitating water, could account for the severe attack that is reported here. Mercury contamination of the pile process tubes could take place by the contact of a contaminated cocked slug with the tube wall. Such contact would most likely occur on the walls and ribs of the tubes in the vicinity of slug junctions. The ribs also could be contaminated at other points, but the area between the ribs could not be so contaminated. These points of most probable contamination correspond with the observed areas of attack in process tubes.

X. CONCLUSIONS AND RECOMMENDATIONS

The severe pitting attack that was observed on slugs and tubes in the Hanford piles and flow laboratories during the summer of 1952 appeared to require the following conditions for its occurrence:

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(13) Fryar, R. M., "Trip Report", HW-25602, September 10, 1952.

(14) Dalrymple, R. S., "Mercury and Slug Jacket Corrosion", HW-24458, May 14, 1952.

(15) Jaffe, R. J., "Survey for Mercury in the 100 Areas", HW-26861, January 23, 1953.

(16) Ward, R., "Technical Activities Report, Metallurgy, Applied Research Unit, October, 1952", HW-26173, November 3, 1952.

(1) Water temperatures above 60 C.

(2) Water velocities greater than 17 feet per second.

(3) Flow irregularities in the water annulus.

Because the attack occurred only during a period when sodium dichromate was not being added to the water, and has not been observed during the six months since dichromate addition started again, it is concluded that 2 ppm dichromate inhibits the pitting attack. Flow Laboratory studies on the effect of dichromate support this conclusion.

It is recommended that:

(1) Action be taken to eliminate the causes of flow irregularities such as misaligned slugs and loose particulate matter in the tubes.

(2) Sodium dichromate or an equivalent inhibitor continue to be added to the cooling water.

(3) Possible sources of mercury contamination of slugs, tubes, and cooling water be evaluated as to the potential hazard.

M. Lewis

M. Lewis

R. A. Rohrbacher

R. A. Rohrbacher

ML:RAR:lj

Photograph Unclassified
AEC-GE RICHLAND, WASH.

FIGURE 1

OUTSIDE VIEW OF TUBE 0486-F, REMOVED FROM THE PILE ABOUT JULY 9, 1952

The pit which penetrated the tube wall from the outside is shown in this figure. This penetration occurred about nine feet from the rear Van Stone flange.

SECRET

Photograph Unclassified
AEC-GE RICHLAND, WASH.

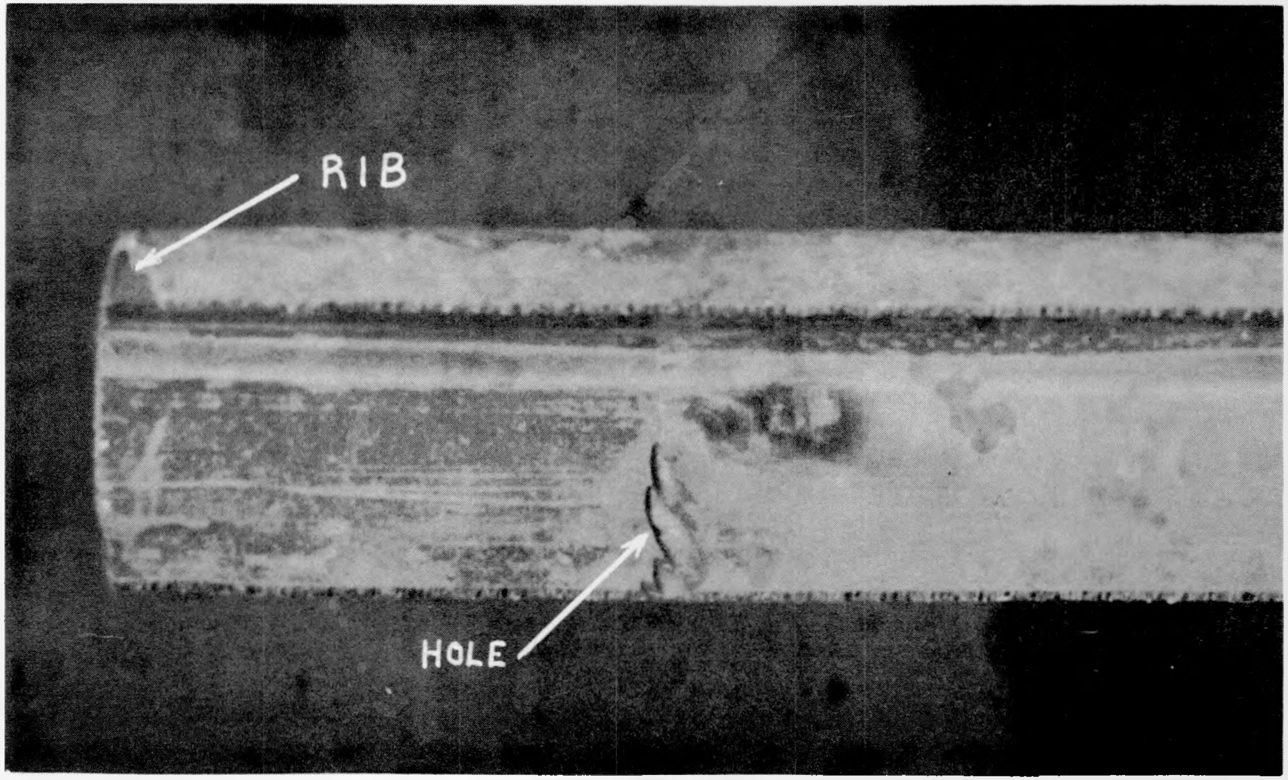

FIGURE 2

INSIDE VIEW OF TUBE 3883-F, REMOVED FROM THE PILE ABOUT JULY 21, 1952

The tube section where pitting attack penetrated the tube wall.
Note orientation of the pits in this attack area.

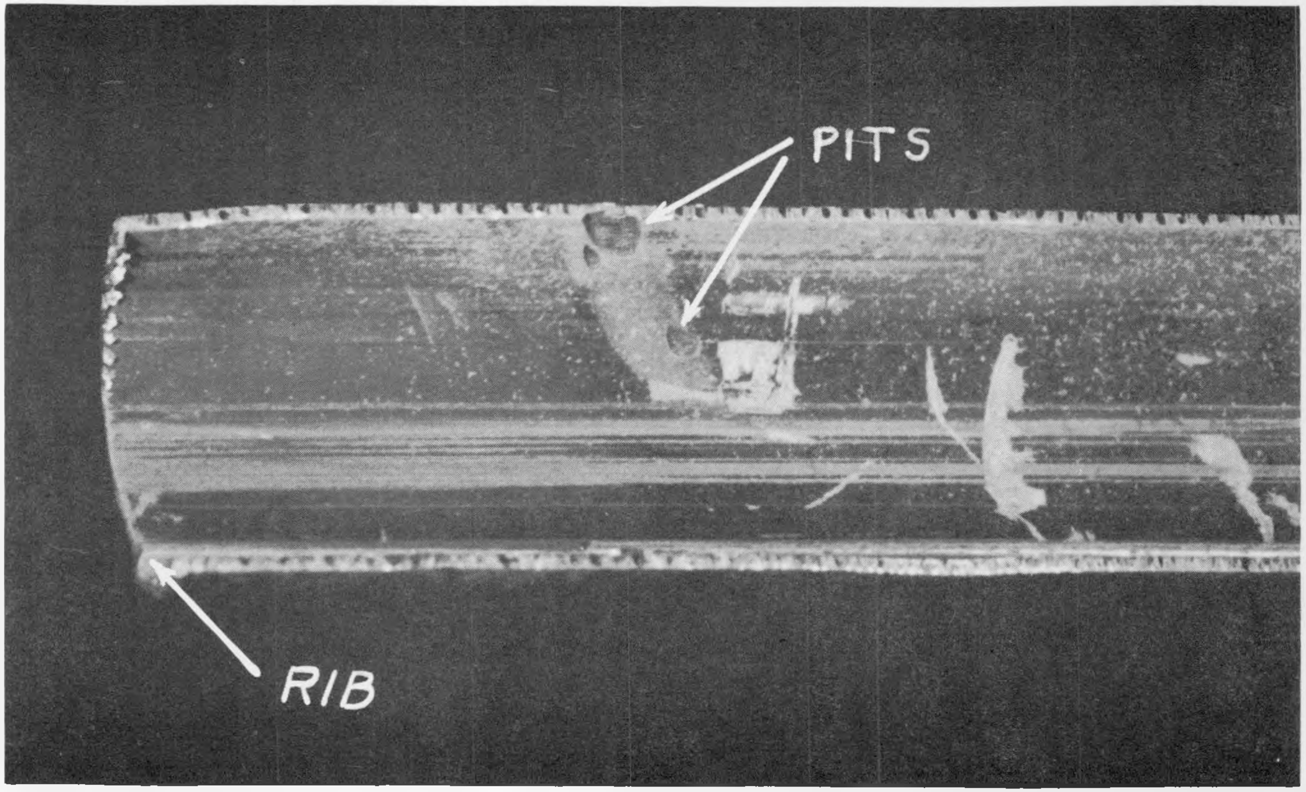

FIGURE 3

INSIDE VIEW OF TUBE 3883-F, REMOVED FROM THE PILE ABOUT JULY 21, 1952

Pitting attack shown here is opposite the hole shown in Figure 2.
The light colored areas are scratches made during or after tube removal.

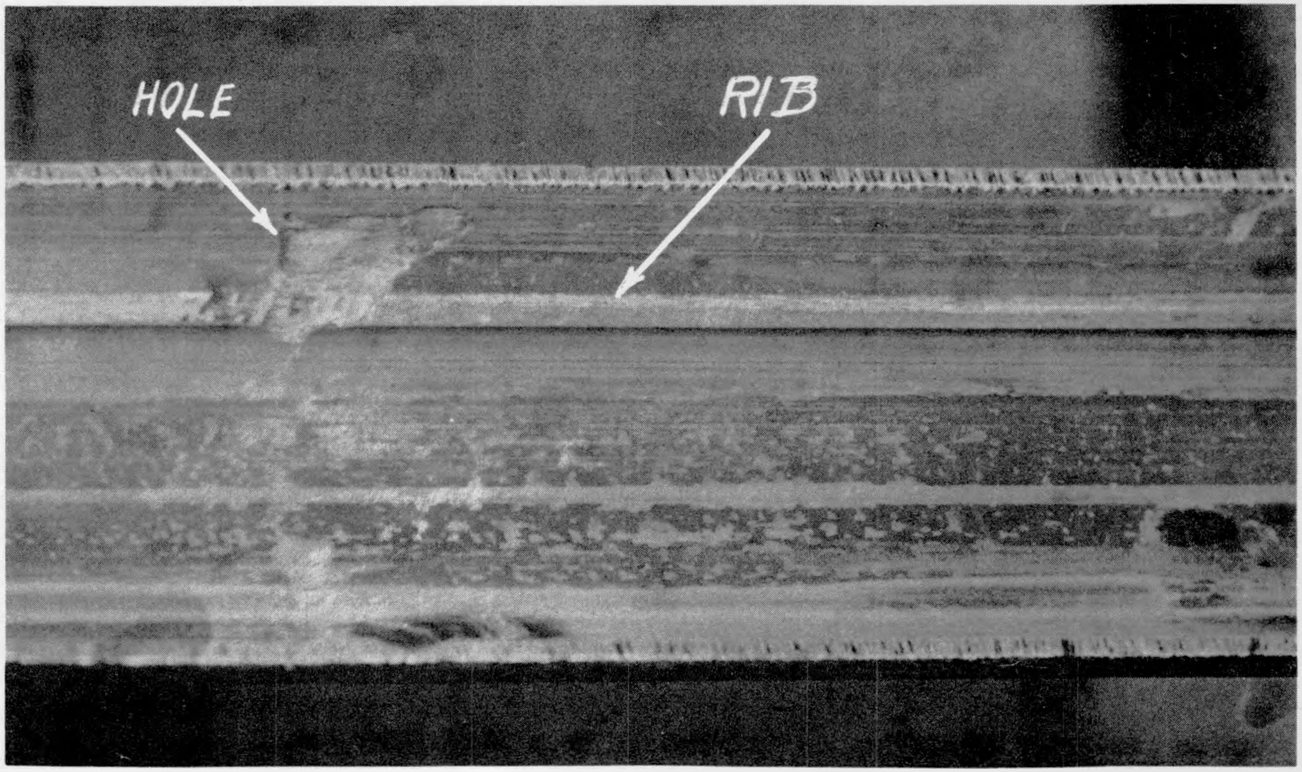

FIGURE 4

INSIDE VIEW OF TUBE 3883-F, REMOVED FROM THE PILE ABOUT JULY 21, 1952

Another area of pitting attack inside this tube. The attack area is well defined, relatively smooth, and free of film and corrosion product.

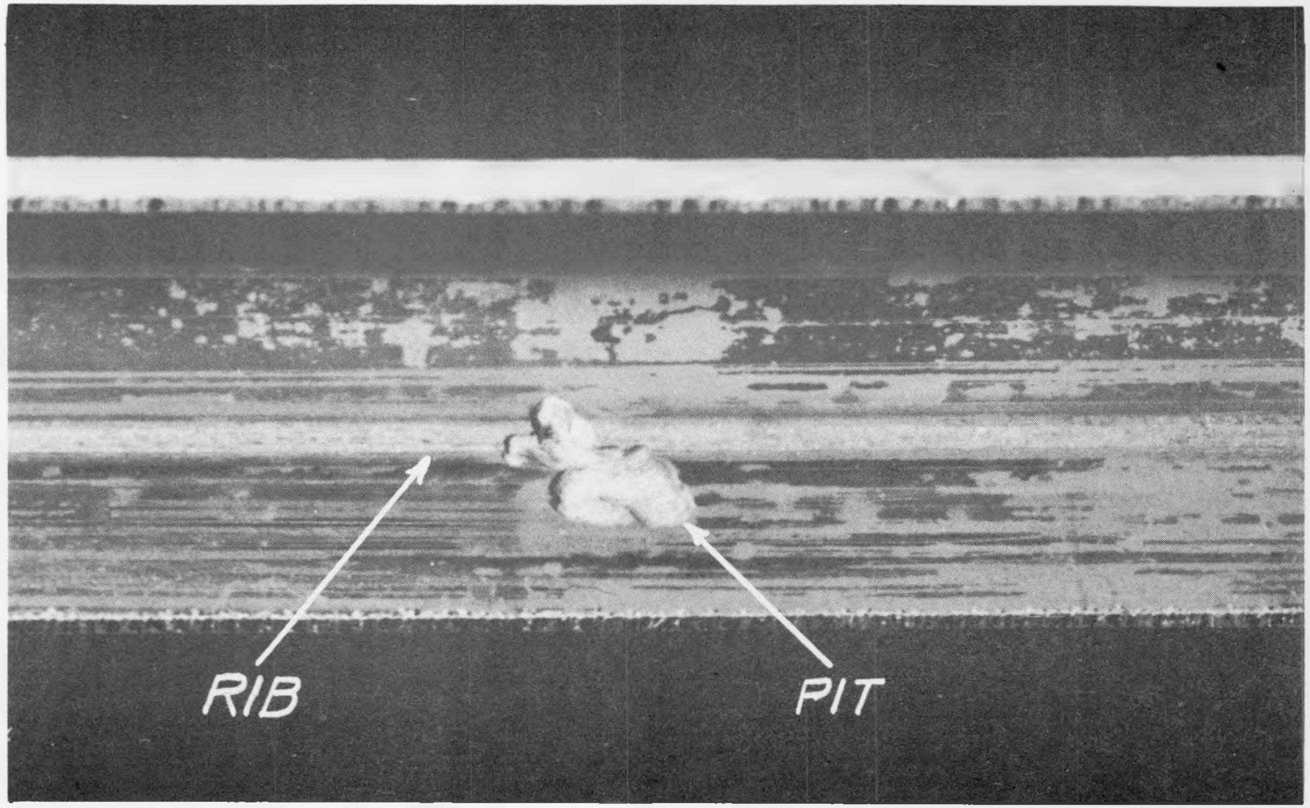

FIGURE 5

INSIDE VIEW OF TUBE 3883-F, REMOVED FROM THE PILE ABOUT JULY 21, 1952

The area in the vicinity of the pit is essentially void of film.

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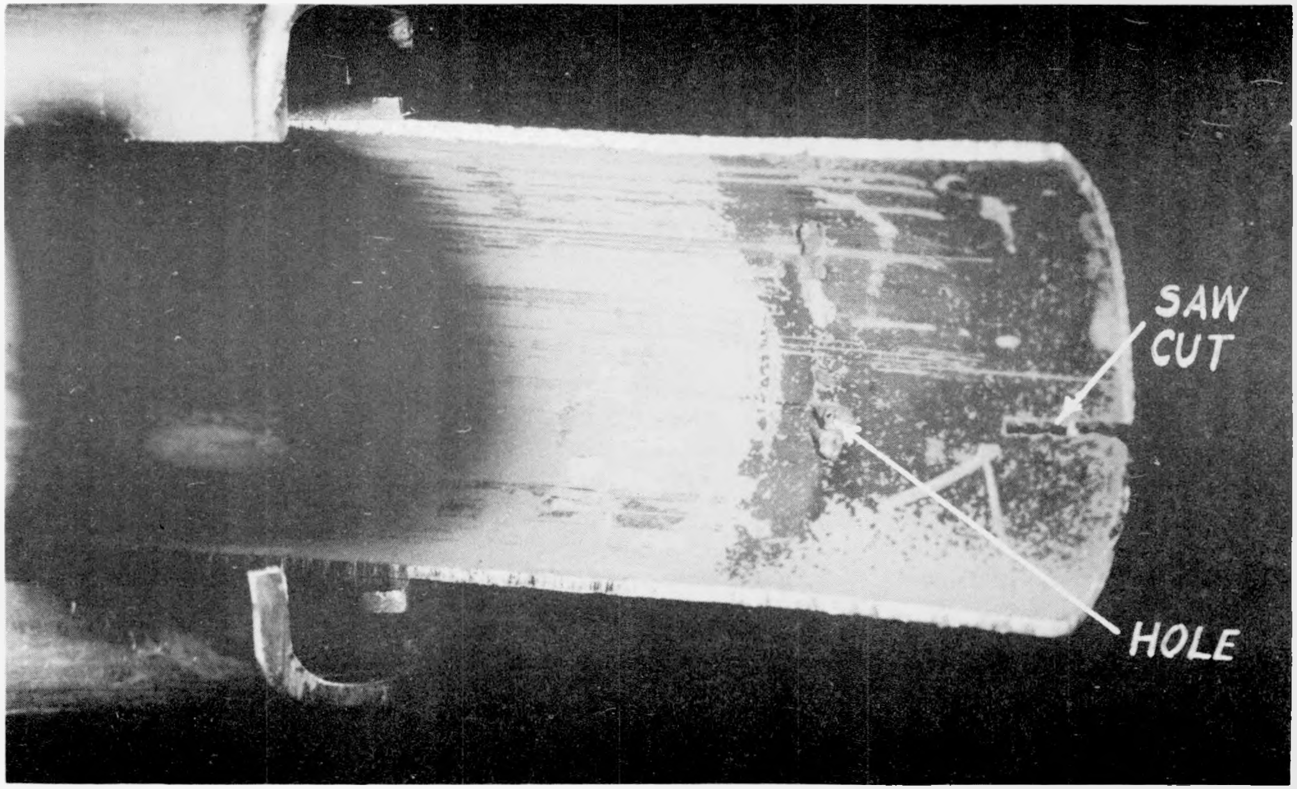

FIGURE 6

INSIDE VIEW OF TUBE 1475-F, REMOVED FROM THE PILE ABOUT JULY 21, 1952

The light colored area to the left of the pitting attack is essentially devoid of film.

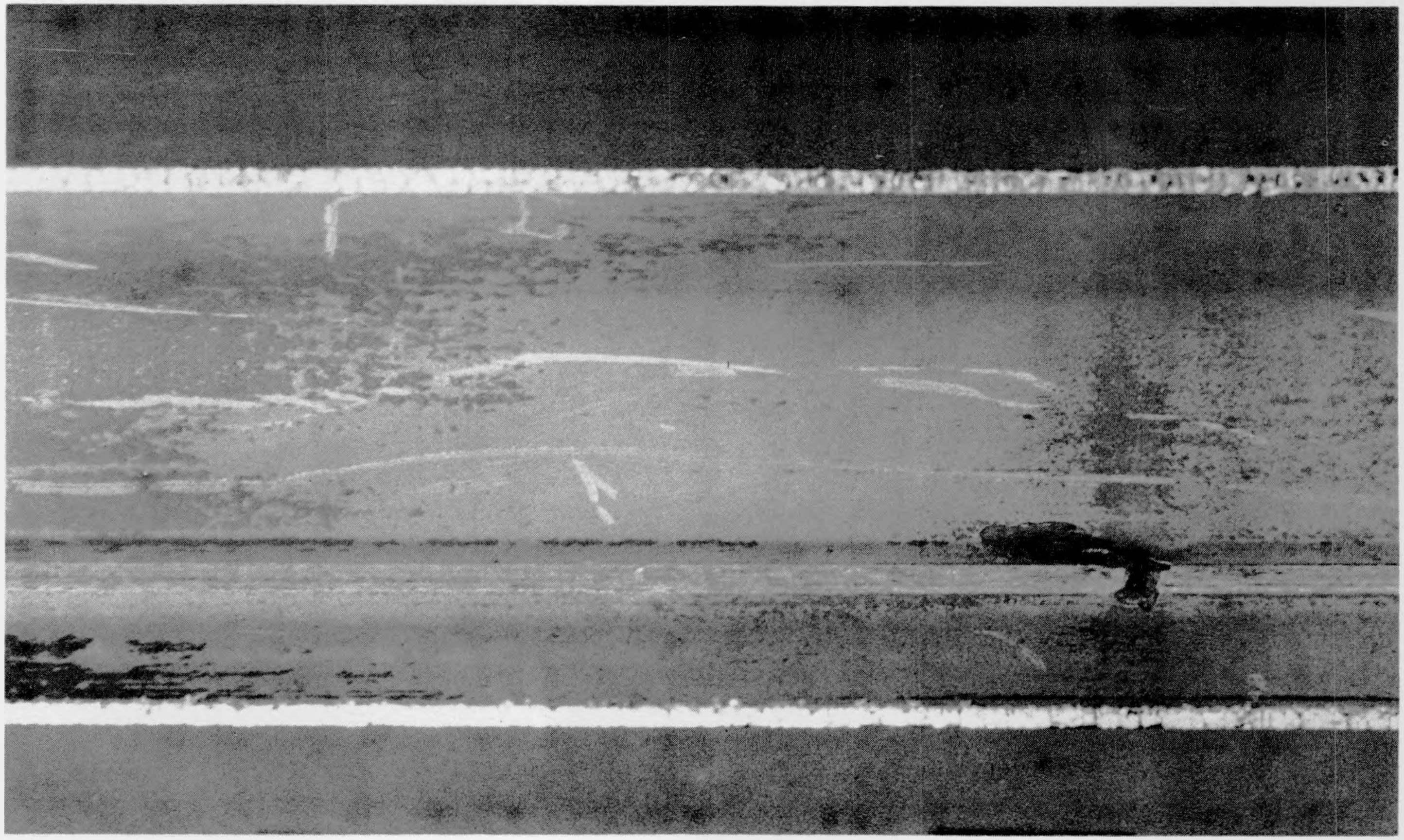

FIGURE 7

INSIDE VIEW OF TUBE 3684-F, REMOVED FROM THE PILE ABOUT AUGUST 8, 1952

The area where this pit occurred is about nine or ten feet from the rear Van Stone flange. Note that the pit occurred at a "slug junction". Downstream is to the left.

Photograph Unclassified
AEC-GE-RICHLAND, WASH

[redacted]

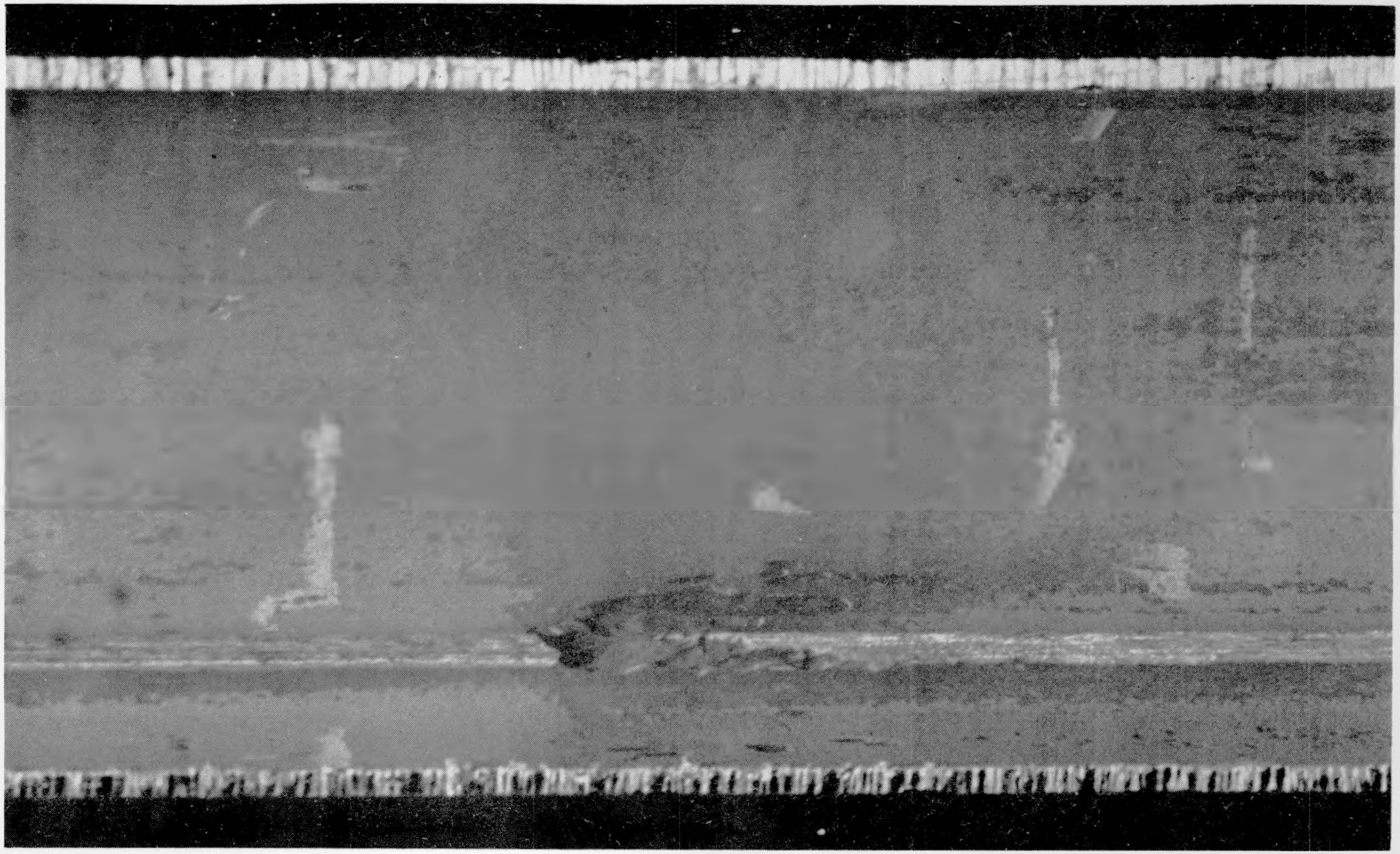

FIGURE 8

INSIDE VIEW OF TUBE 3684-F, REMOVED FROM THE PILE ABOUT AUGUST 8, 1952

This pitting attack occurred at the same "slug junction" as the pitting attack shown in Figure 7. Downstream is to the right.

[redacted]

Photograph Unclassified
AEC-GE-RICHLAND, WASH.

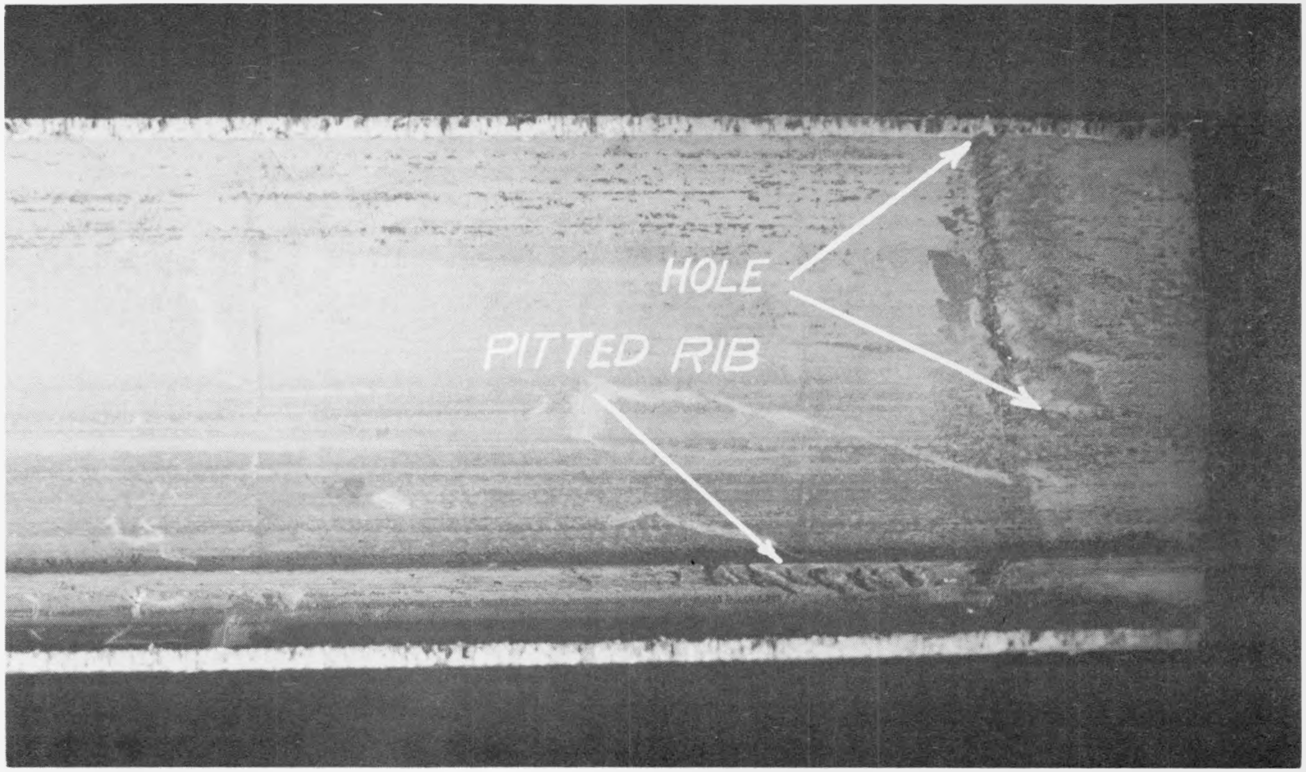

FIGURE 9

INSIDE VIEW OF TUBE 3668-F, REMOVED FROM THE PILE ABOUT JULY 21, 1952

The pitting attack at this "slug junction" extends beyond the top of the tube. Three holes were found at this "slug junction". Two are indicated here, the third was located on the other side of the tube.

Photograph Unclassified
AEC-GE-RICHLAND, WASH

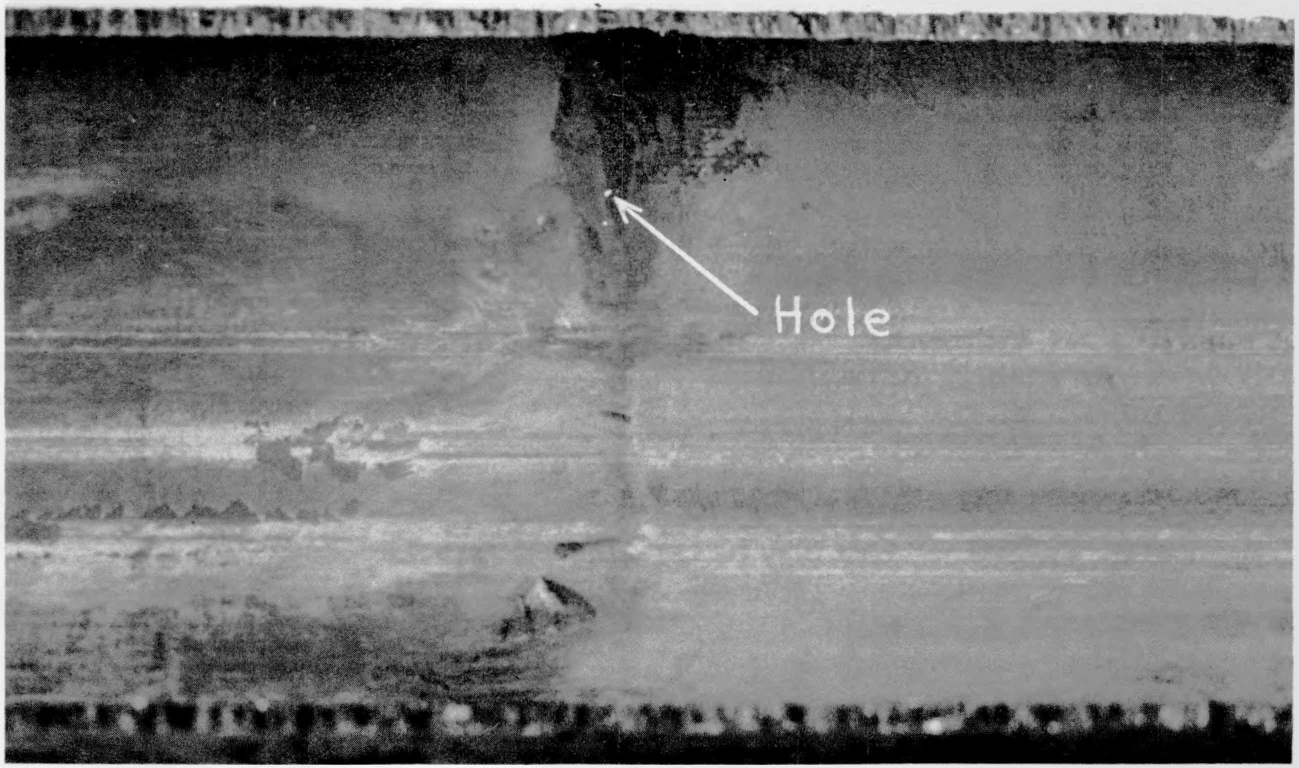

FIGURE 10

INSIDE VIEW OF TUBE 0867-F, REMOVED FROM THE PILE ABOUT JULY 9, 1952

The hole in this tube is at the bottom of the pit. This area is about twelve feet from the rear Van Stone flange.

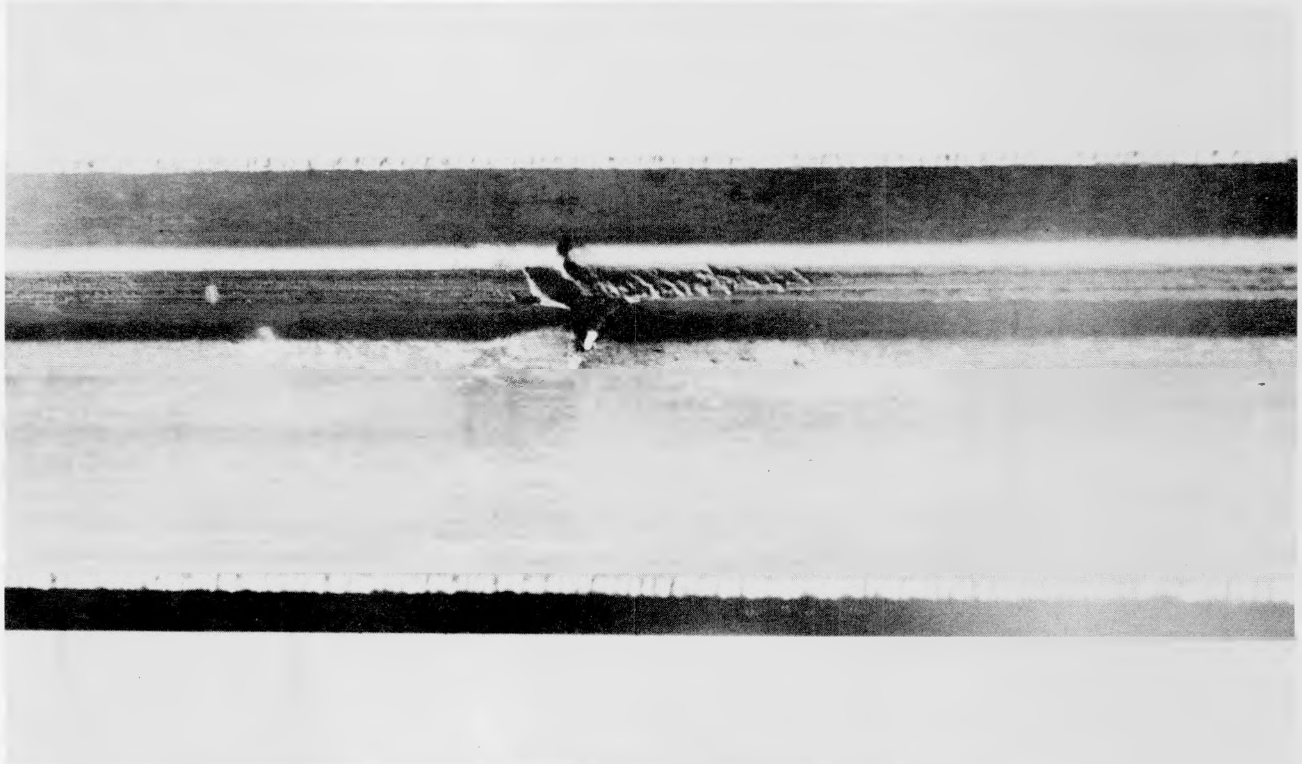

FIGURE 11

INSIDE VIEW OF TUBE 3175-D, REMOVED FROM THE PILE ON AUGUST 8, 1952

The pit, which penetrated the tube about eight feet from the rear Van Stone flange, is just below the badly pitted rib. Downstream is to the left.

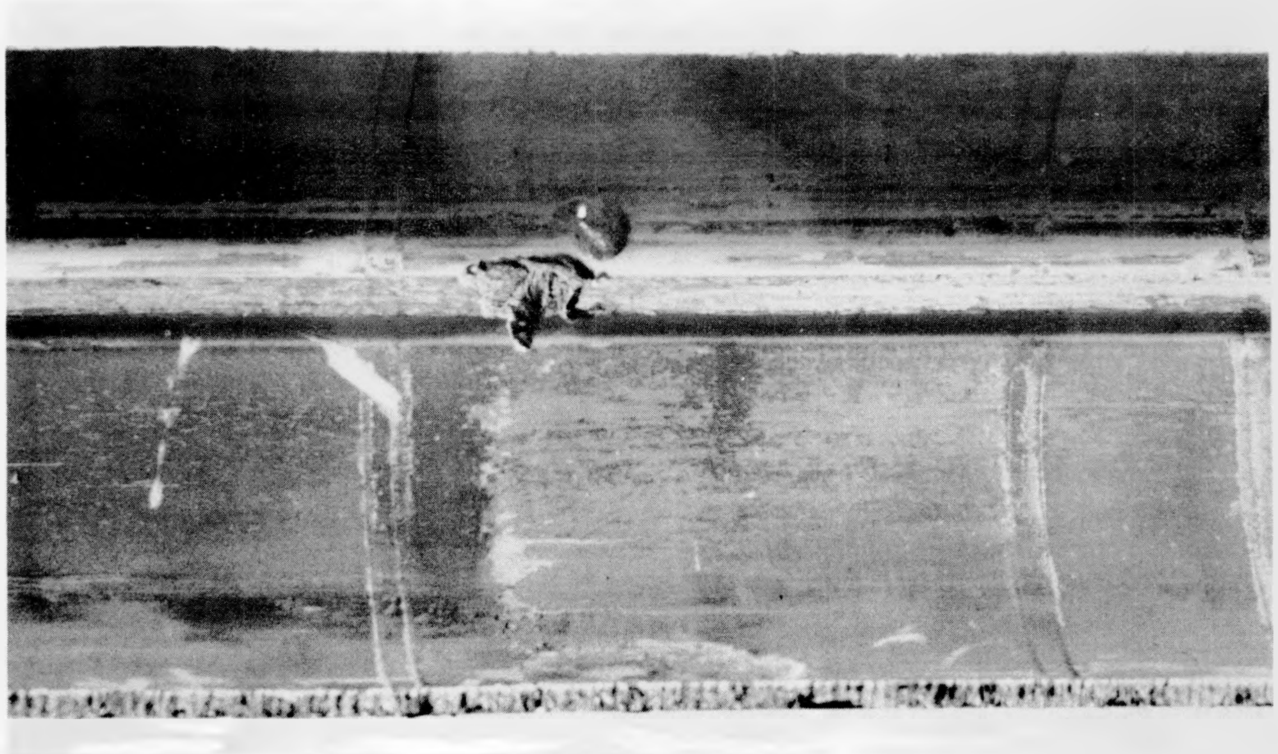

FIGURE 12

INSIDE VIEW OF TUBE 1692-D, REMOVED FROM THE PILE ON AUGUST 26, 1952

This pit penetrated the tube wall between the ribs about eight and one half feet from the rear Van Stone flange. Downstream is to the right.

[redacted]

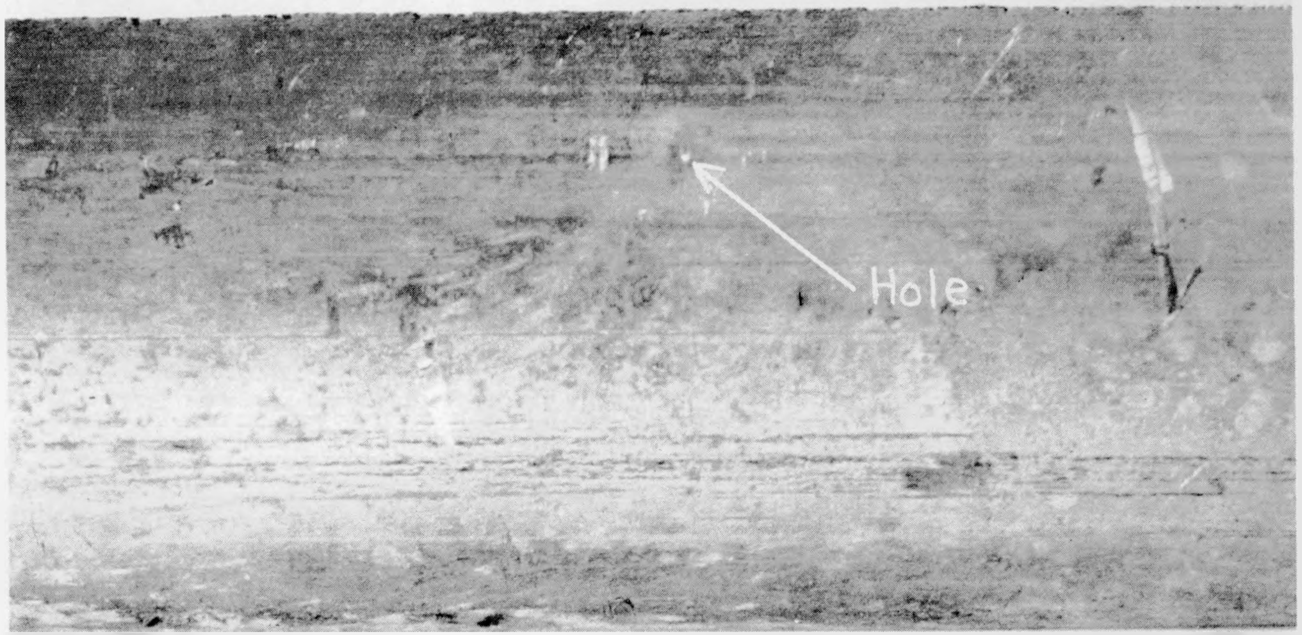

FIGURE 13

OUTSIDE VIEW OF TUBE 0867-F, REMOVED FROM THE PILE ABOUT JULY 9, 1952

The galvanic attack which is usually visible on leakers of this type was not apparent on this tube.

[redacted]

Photograph Unclassified
AEC-GE RICHLAND, WASH.

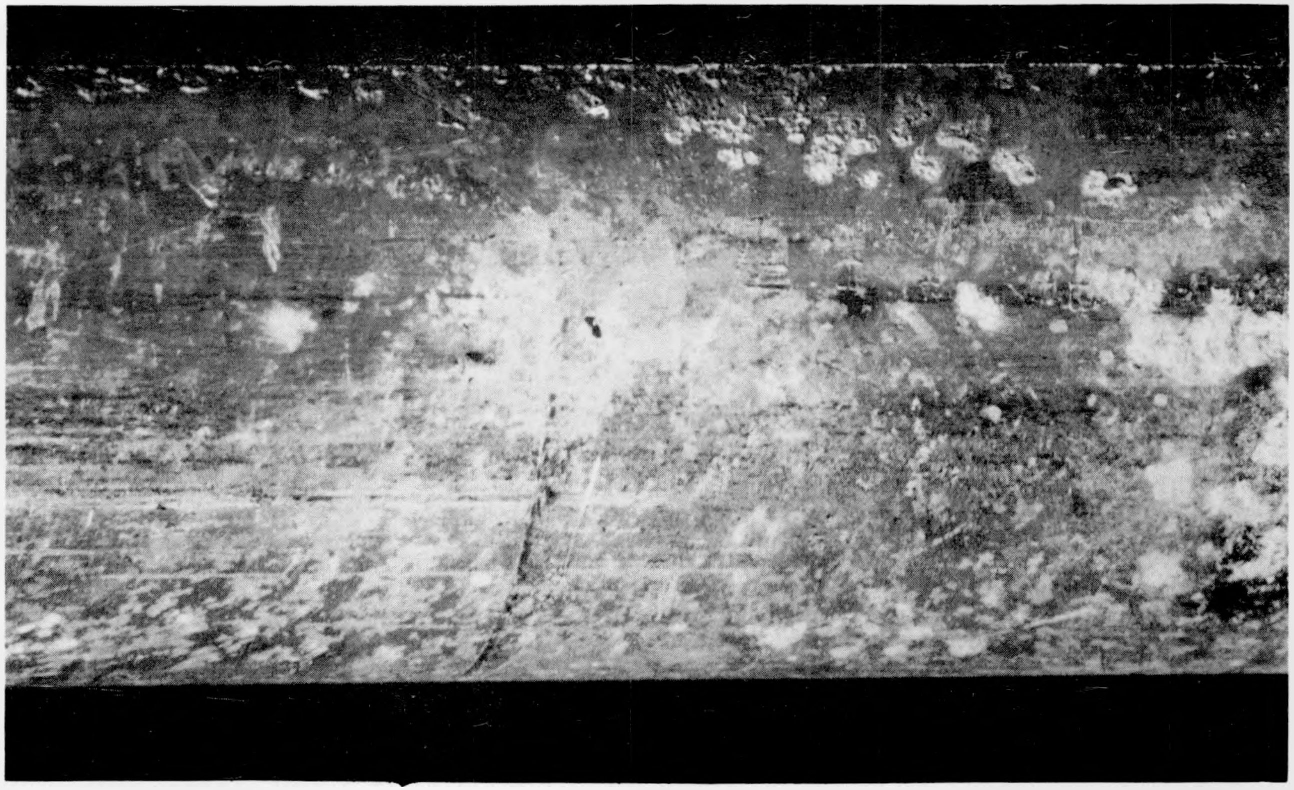

FIGURE 14

OUTSIDE VIEW OF TUBE 3175-D, REMOVED FROM THE PILE ON AUGUST 8, 1952

This figure shows the condition of the outside tube surface around the hole shown in Figure 11. The white spots are mounds of corrosion product. Downstream is to the right.

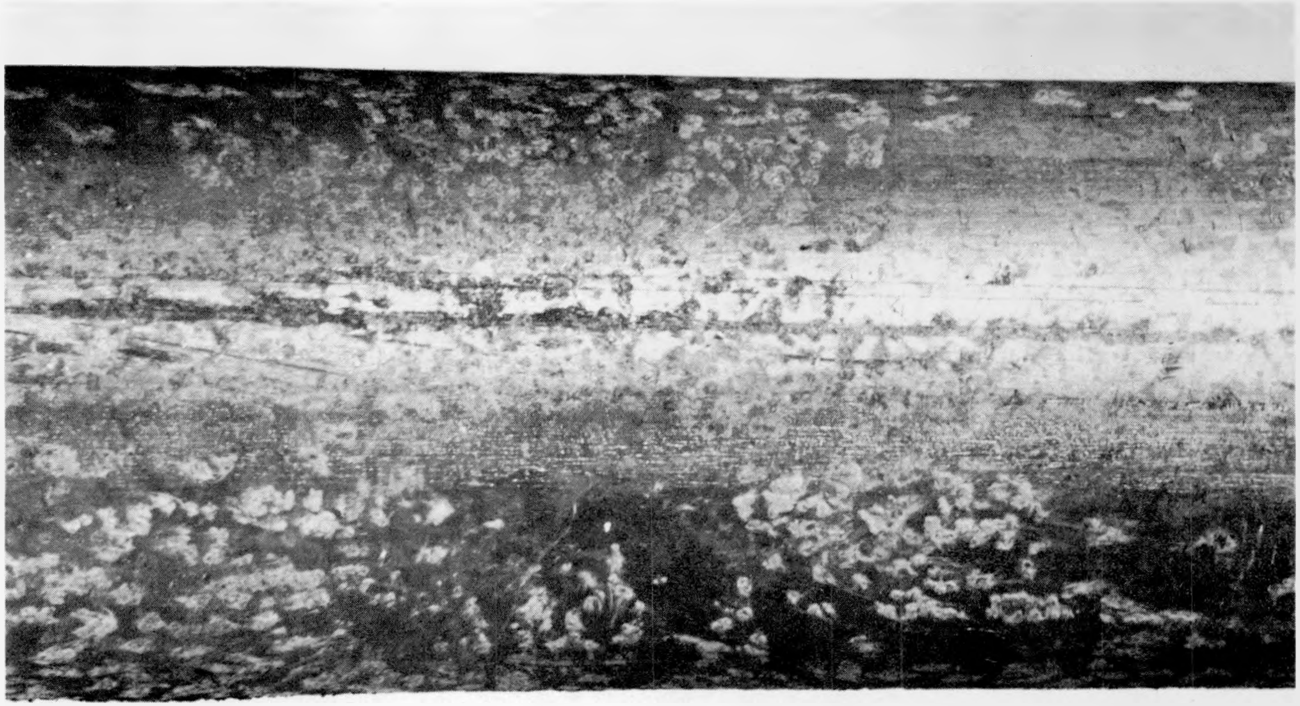

FIGURE 15

OUTSIDE VIEW OF TUBE 1692-D, REMOVED FROM THE PILE ON AUGUST 26, 1952.

This figure shows the outside surface of the section of tubing shown in Figure 12. The hole can be seen as a white dot at the center of the figure in the lower half of the tube. Downstream is to the right.

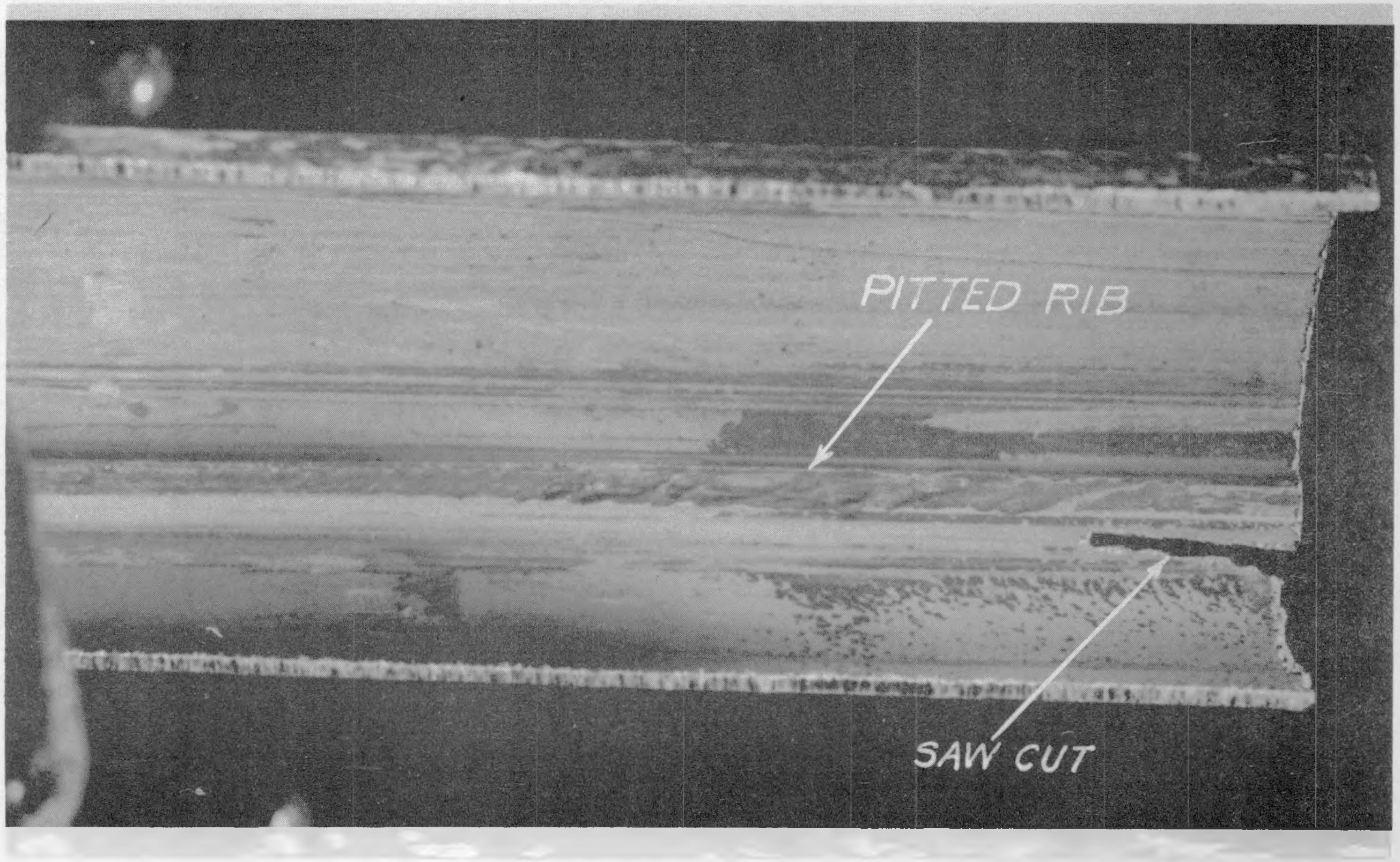

FIGURE 16

INSIDE VIEW OF TUBE 1475-F, REMOVED FROM THE PILE ABOUT JULY 21, 1952

This pitted rib is opposite the hole shown in Figure 6. The dark patches above the pitted rib, as well as the spots below, are brown film.

[redacted]

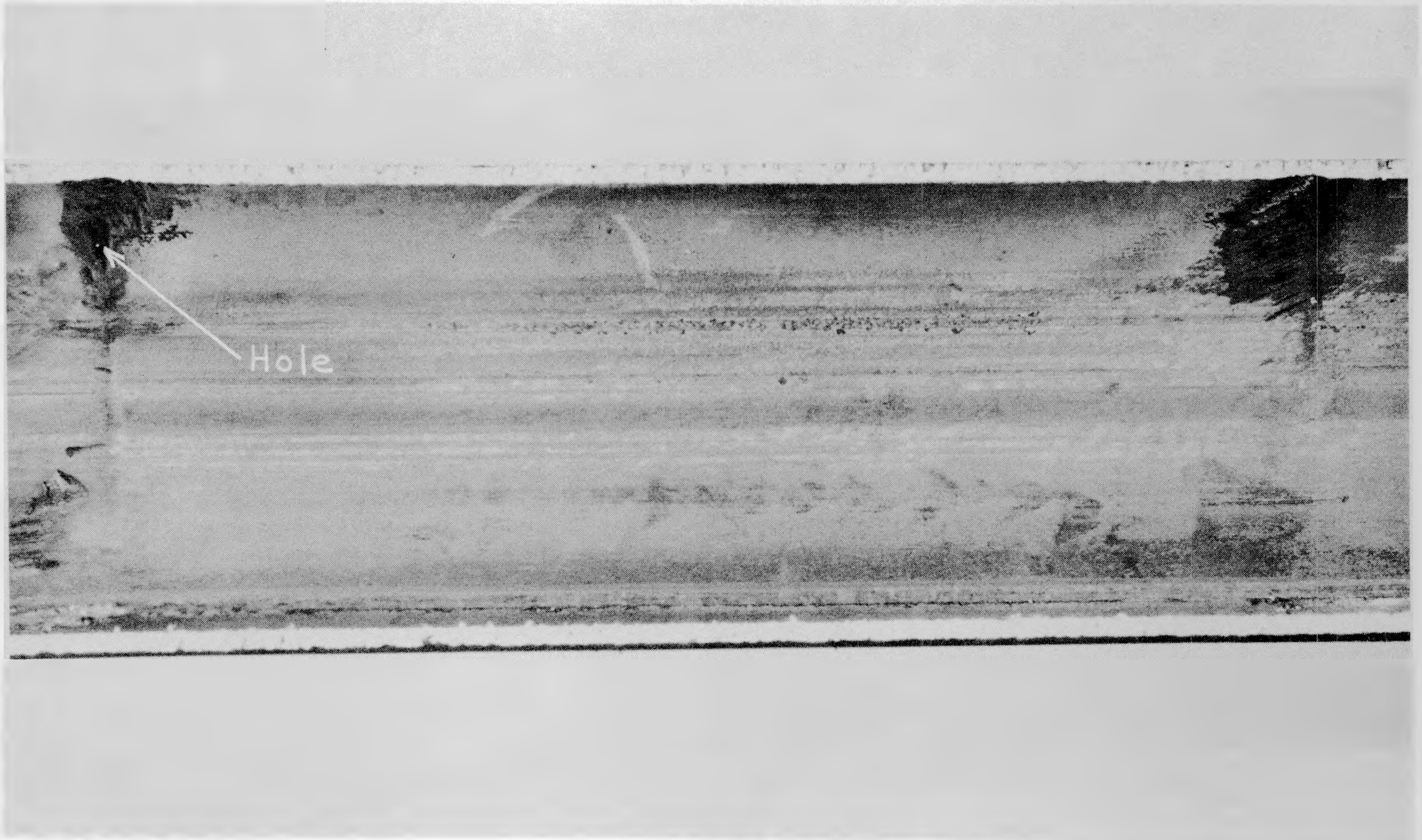

FIGURE 17

INSIDE VIEW OF TUBE 0867-F, REMOVED FROM THE PILE ABOUT JULY 9, 1952

The pit which penetrated the tube can be seen at the left side of the figure. The pitting attack at the right is about four to five inches from the hole area. The dark areas are the surfaces of the pit which are covered with film.

[redacted]

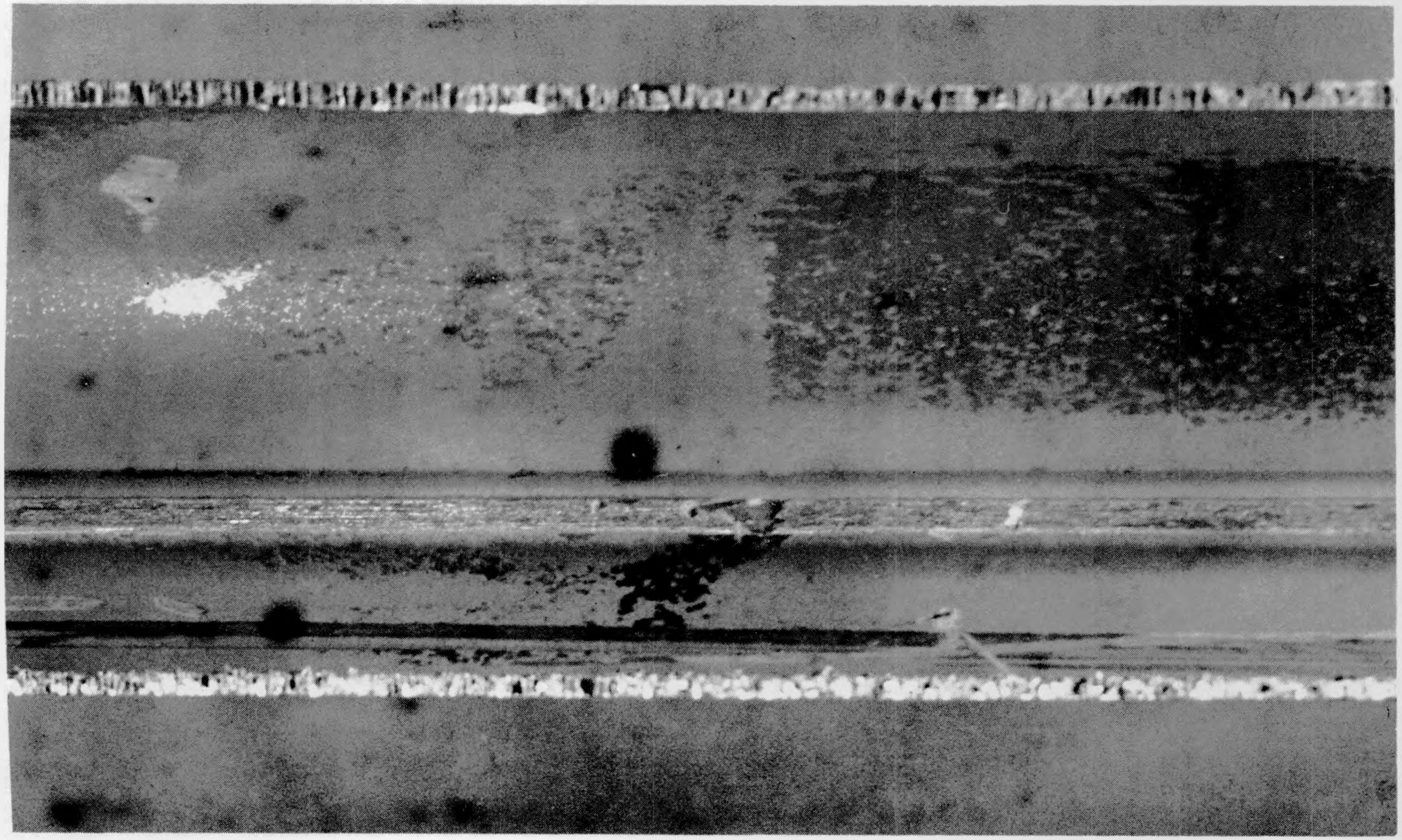

FIGURE 18

INSIDE VIEW OF TUBE 3684-F, REMOVED FROM THE PILE ABOUT AUGUST 8, 1952

The pit on the rib in this figure is about eight or nine inches upstream from the pit on the rib shown in Figure 7. Evidence of a "slug junction" is also apparent in this figure. The small bright spot at the left of the figure is essentially free of film. Downstream is to the left.

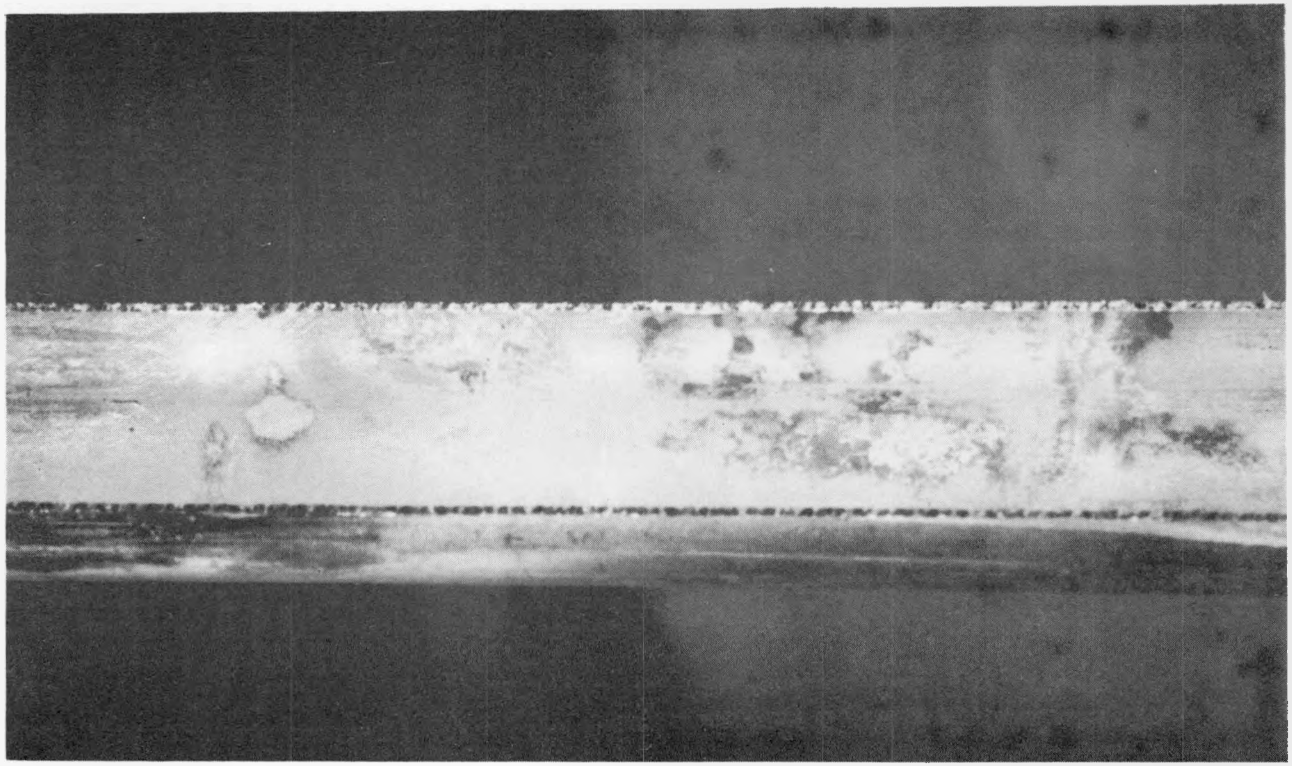

FIGURE 19

INSIDE VIEW OF TUBE 3773-F, REMOVED FROM THE PILE ABOUT AUGUST 8, 1952

This section is about 21 feet from the rear Van Stone flange. The patch of film near the center of this figure may indicate that a slug was close to or in contact with the tube at this point.

Photograph Unclassified
AEC-GE-RICHLAND, WASH

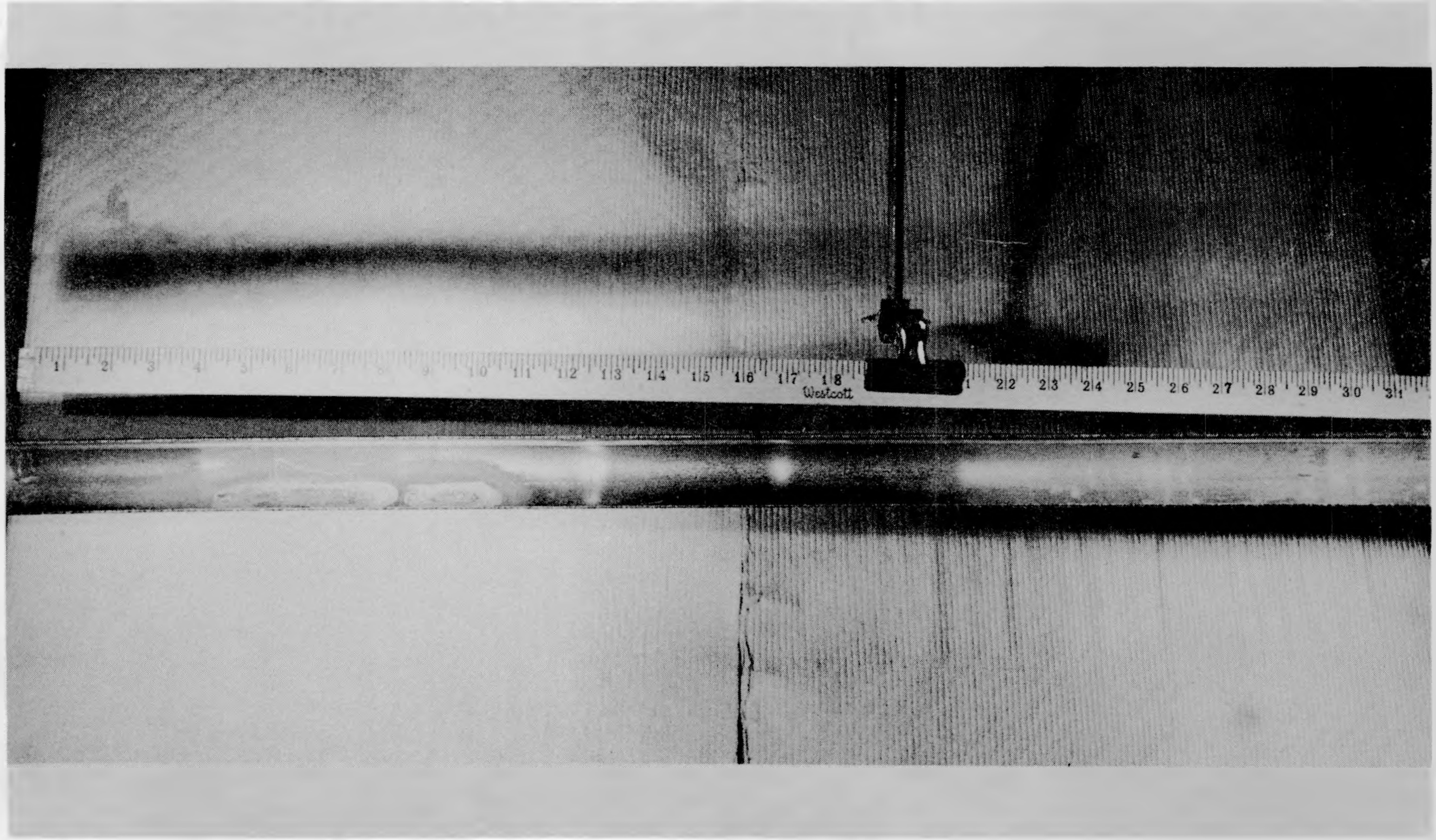

FIGURE 20

INSIDE VIEW OF TUBE 3175-D, REMOVED FROM THE PILE ON AUGUST 8, 1952

The two film patches at the left are "burned" areas where slugs may have been close to or made contact with the tube wall. Downstream is to the left.

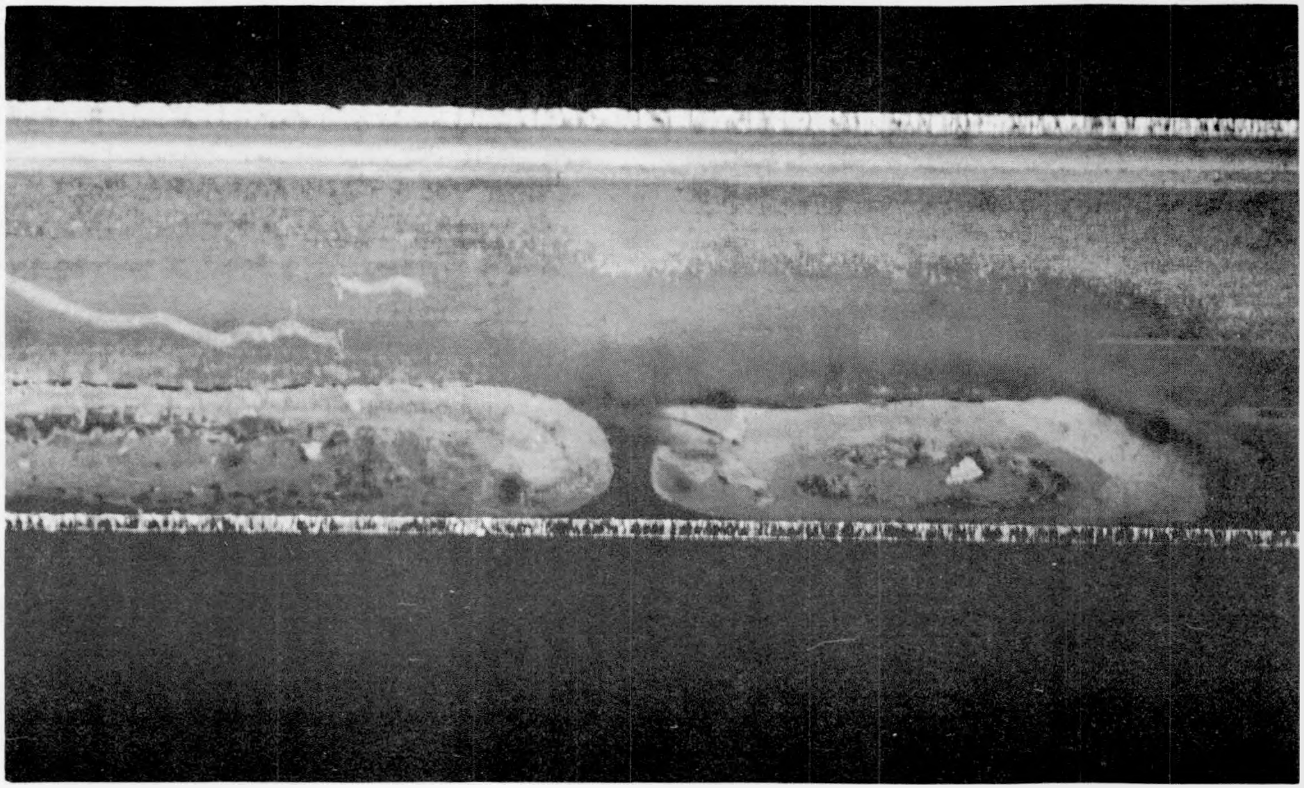

FIGURE 21

INSIDE VIEW OF TUBE 3175-D, REMOVED FROM THE PILE ABOUT AUGUST 8, 1952

This is an enlarged view of the film patches shown in Figure 20. Note the flaky appearance of this film formation, especially at the edged of the "patches". Downstream is to the left.

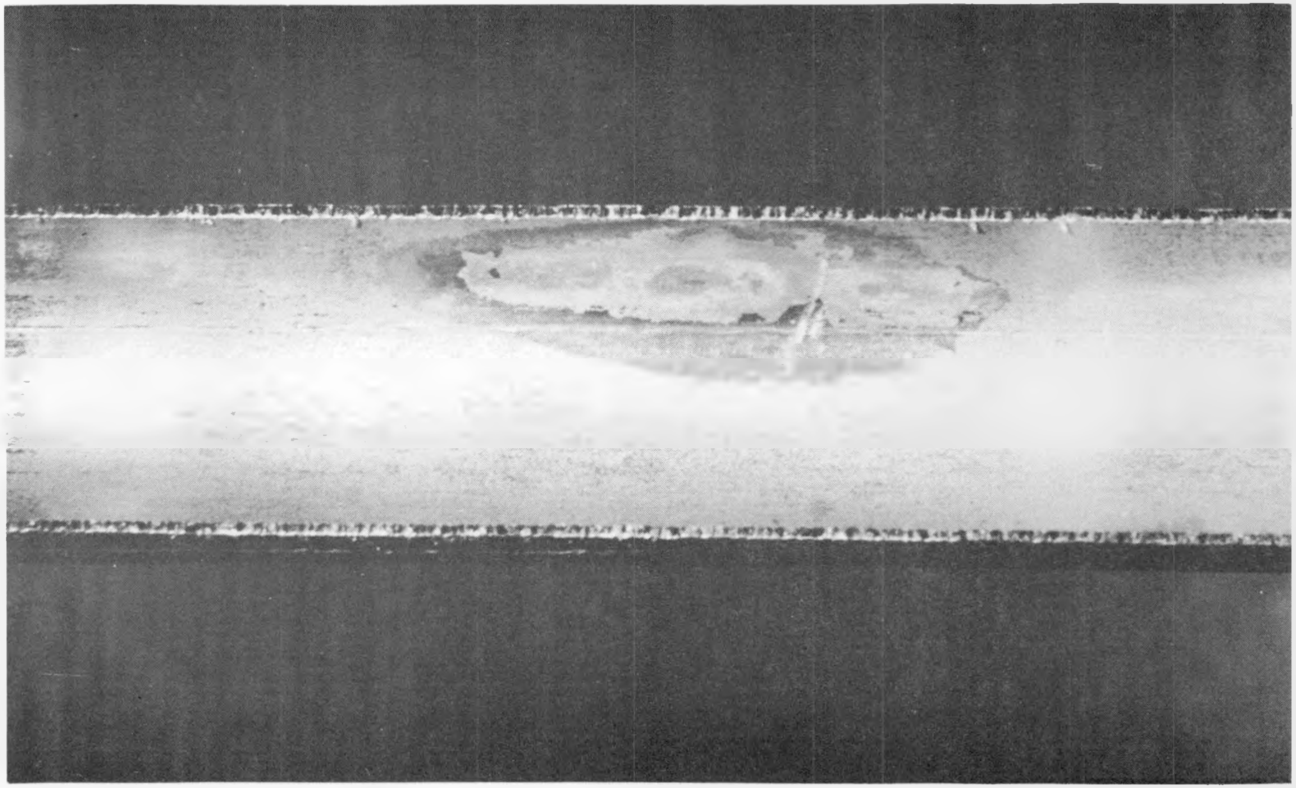

FIGURE 22

INSIDE VIEW OF TUBE 3175-D, REMOVED FROM THE PILE ON AUGUST 8, 1952

The flaky film patch shown in this figure is just opposite those shown in Figure 21. Note that the area around this film patch is almost completely void of film and has a bright metallic luster.

[redacted]

Photograph Unclassified
AEC-GE-RICHLAND, WASH.

[redacted]

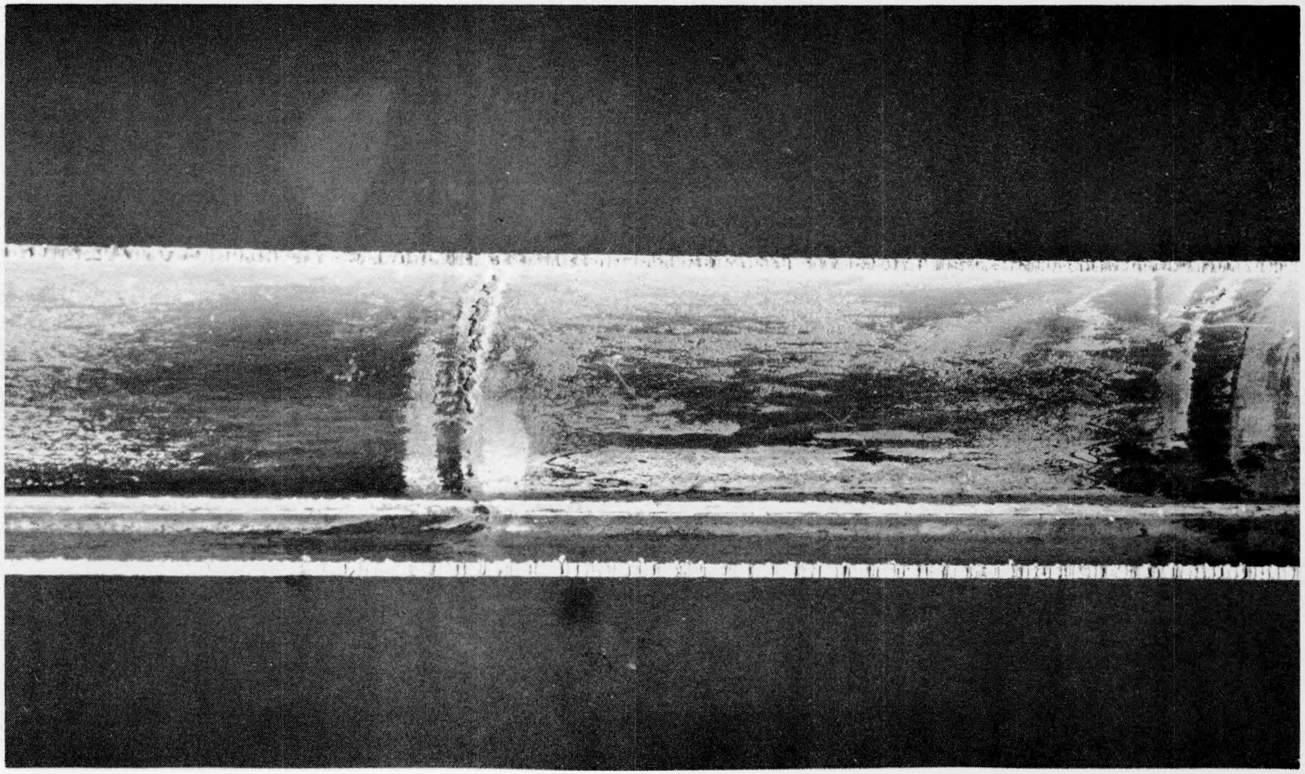

FIGURE 23

INSIDE VIEW OF TUBE 3178-DR, REMOVED FROM THE PILE ABOUT SEPTEMBER 6, 1952

The exact location in the pile of this pitting at a "slug junction" is not known.

[redacted]

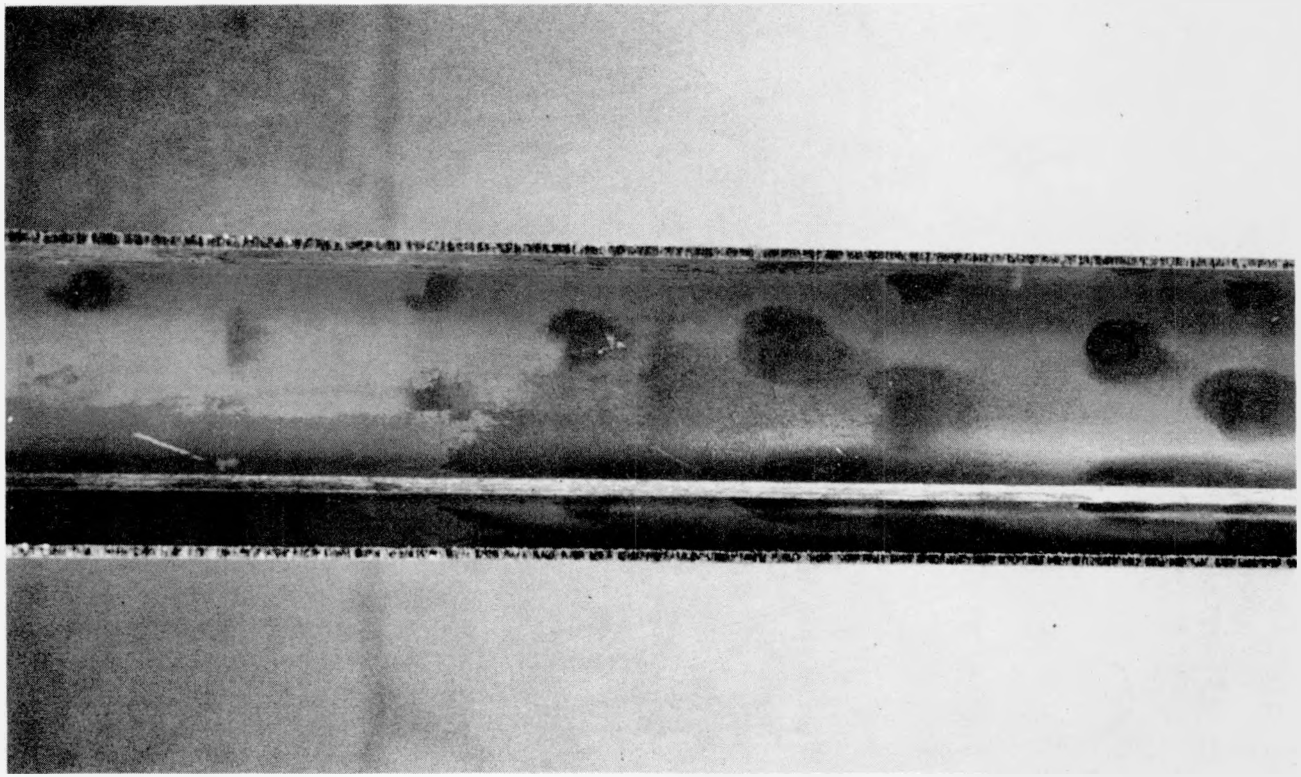

FIGURE 24

INSIDE VIEW OF TUBE 3773-F, REMOVED FROM THE PILE ABOUT AUGUST 8, 1952

This section is about three feet from the rear Van Stone flange. The black spots on the tube conform to holes in the perforated dummy slugs which were located in this section of the tube. Downstream is to the right.

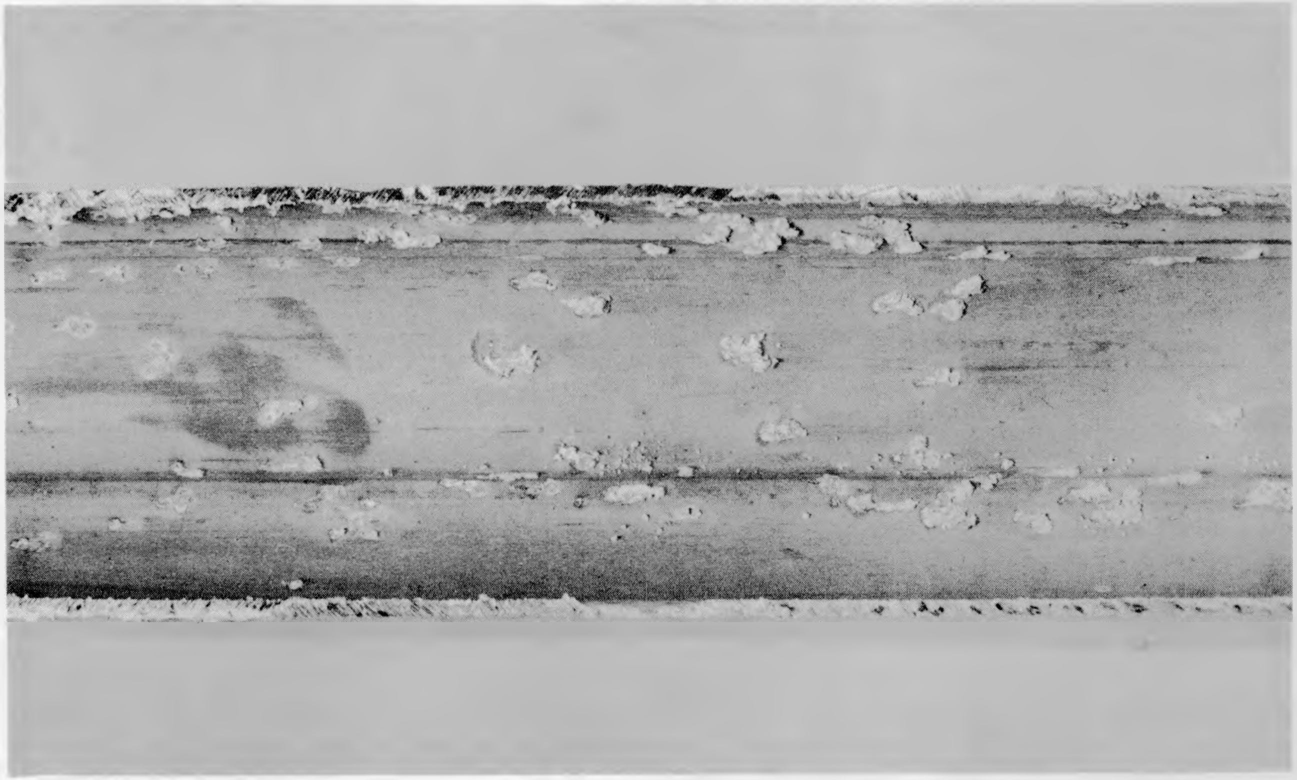

FIGURE 25

SECTION OF PROCESS TUBING CONTAINING CORROSION PRODUCT "BARNACLES" ON INSIDE OF TUBE

Eighteen gallons per minute of cold ferric sulfate treated, dichromate-free water flowed through this empty tube section for two and one-half months.

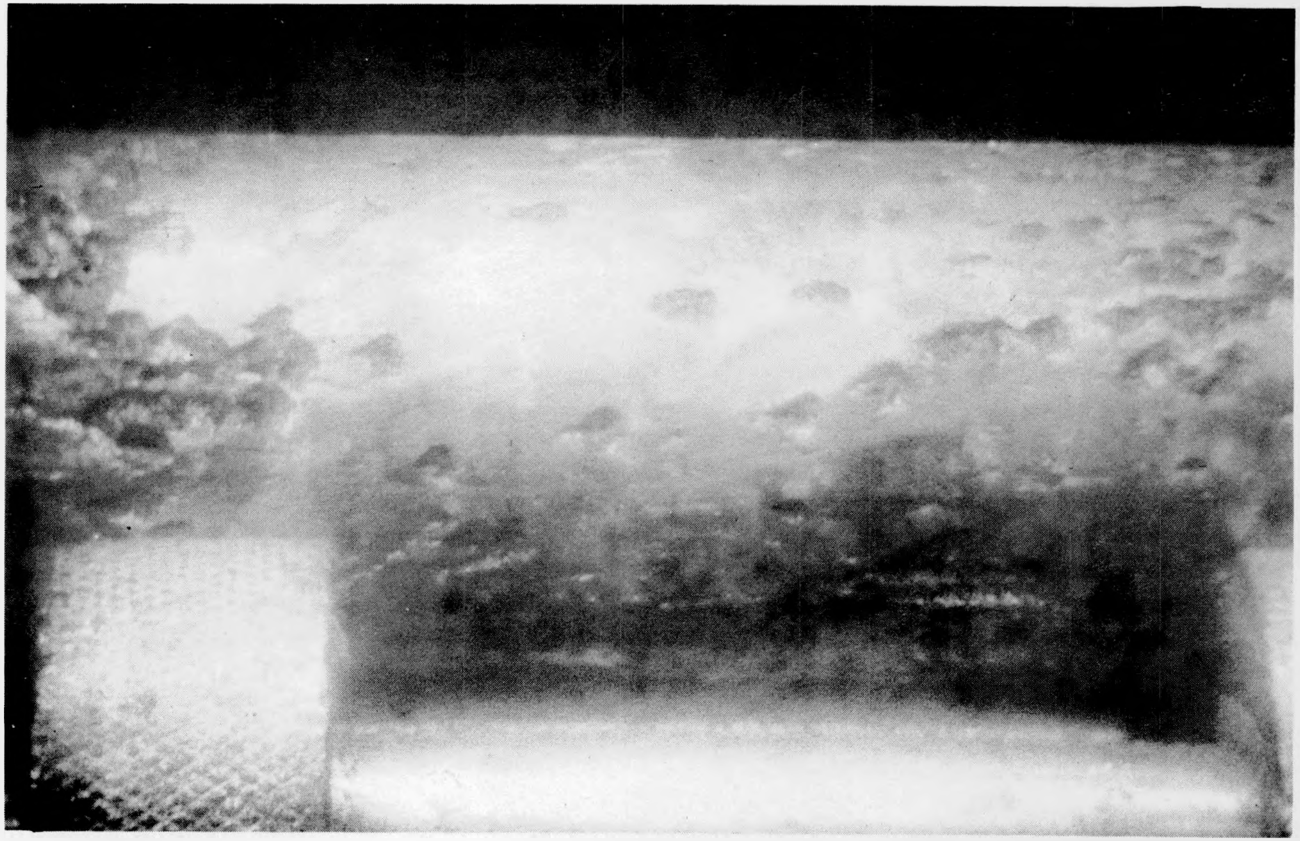

FIGURE 26

SLUG DISCHARGED AUGUST 30, 1952, FROM TUBE 3879-F

Note discrete pits.

Photograph Unclassified
AEC-GE RICHLAND, WASH.

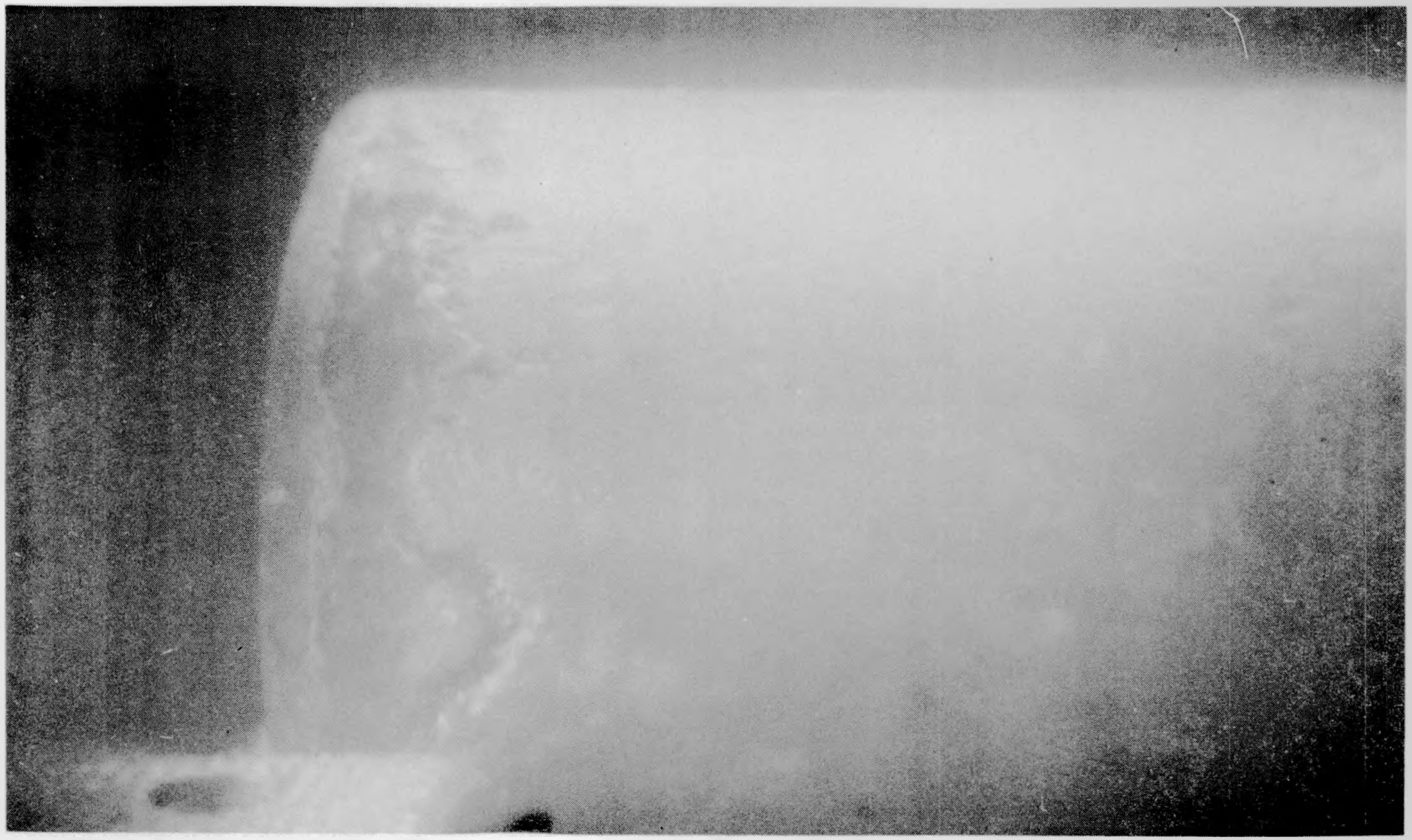

FIGURE 27

SLUG DISCHARGED JULY 29, 1952, FROM TUBE 3773-F

Pitting attack is concentrated near both ends. Can end is shown here.

[redacted]

Photograph Unclassifed
AEC-GE-RICHLAND, WASH

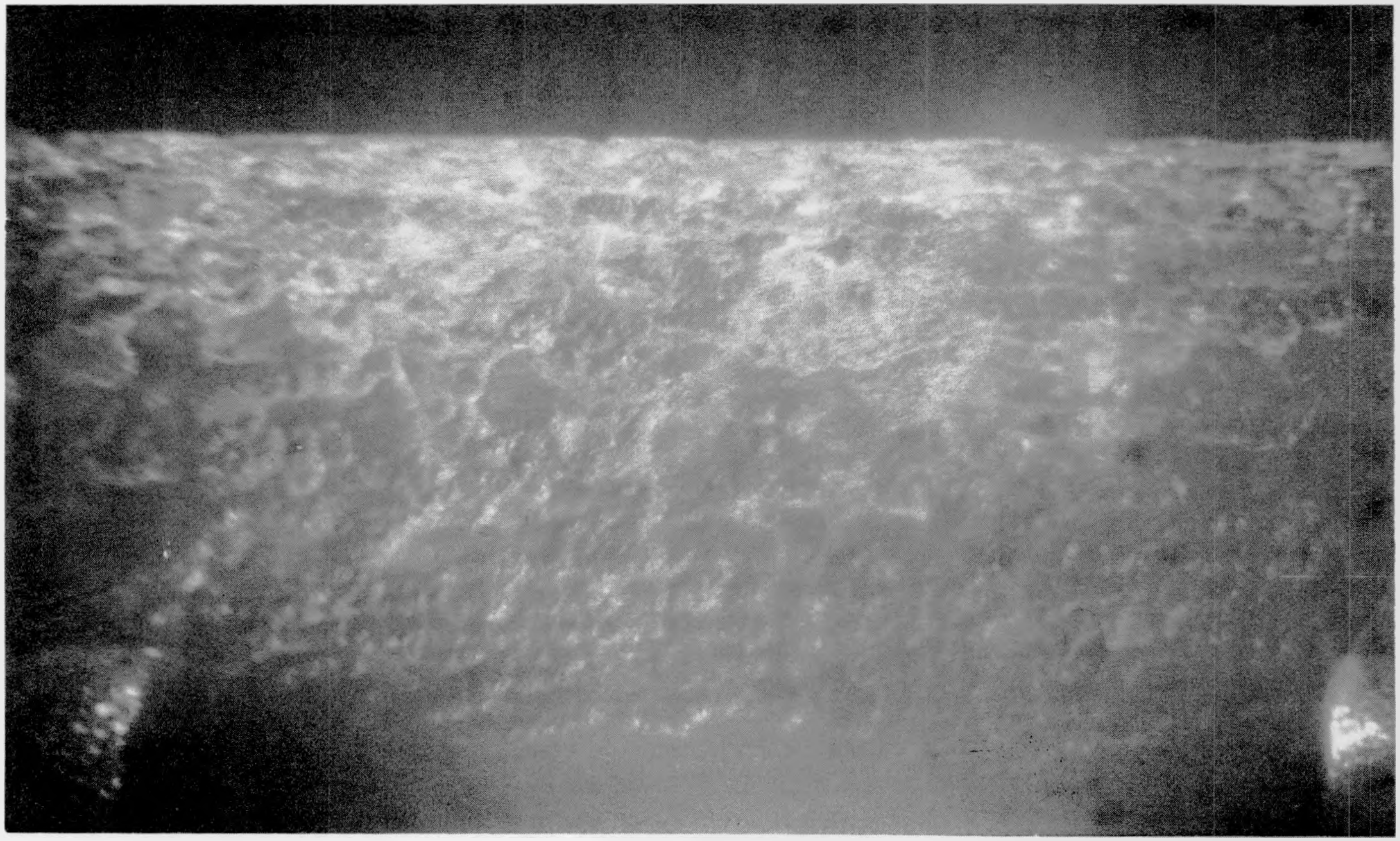

FIGURE 28

SLUG DISCHARGED JULY 29, 1952, FROM TUBE 3773-F

About 85 per cent of the jacket surface was attacked.

SECRET

Photograph Unclassified
AEC-GE-RICHLAND, WASH.

[redacted]

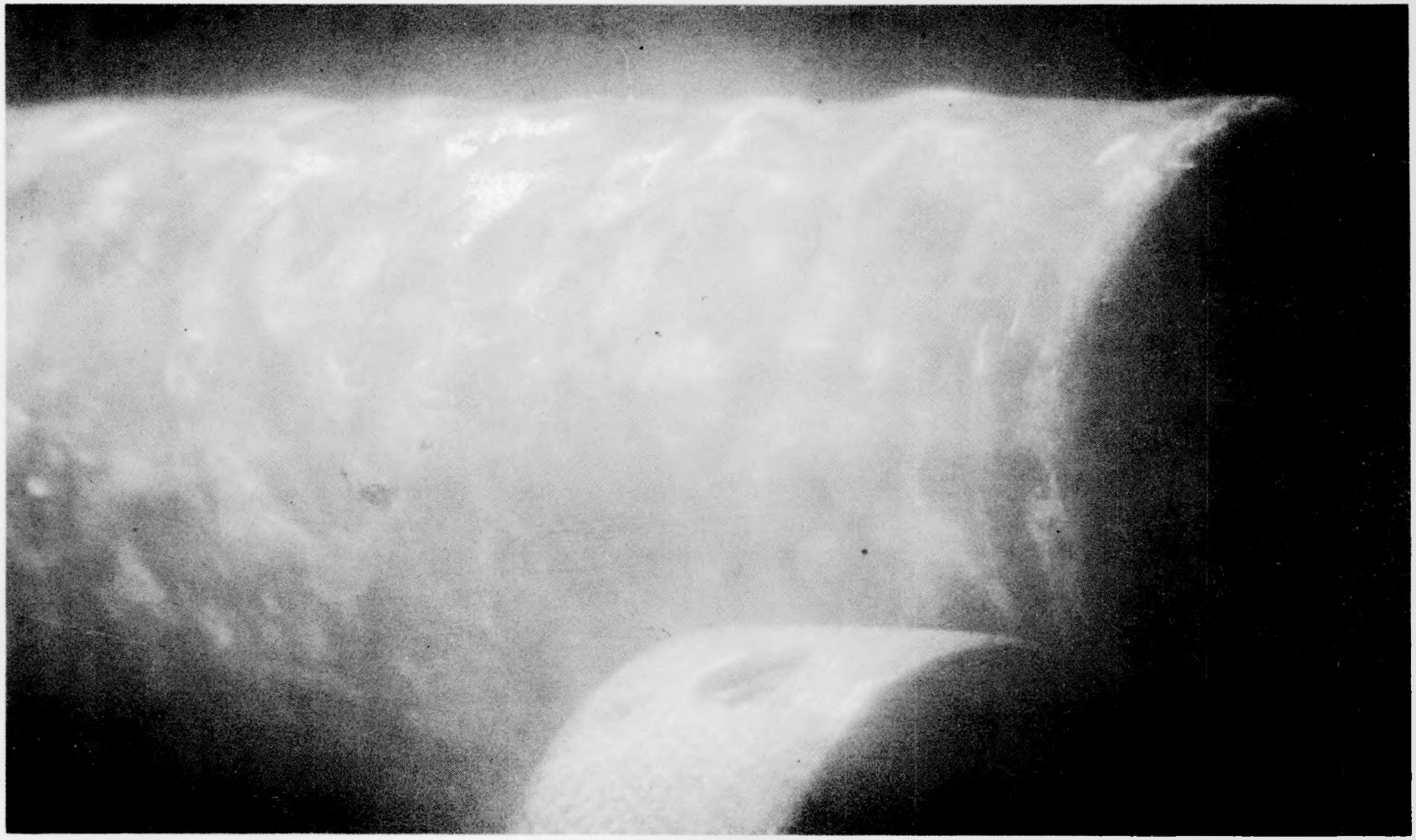

FIGURE 29

SLUG DISCHARGED JULY 29, 1952, FROM TUBE 3773-F

Ten slugs in this charge were blistered similarly to this slug.

[redacted]

Photograph Unclassified
AEC-GE-RICHLAND, WASH

FIGURE 30

SLUG DISCHARGED JULY 31, 1952, FROM TUBE 3684-F

Incipient pitting - not readily discernible without magnification.

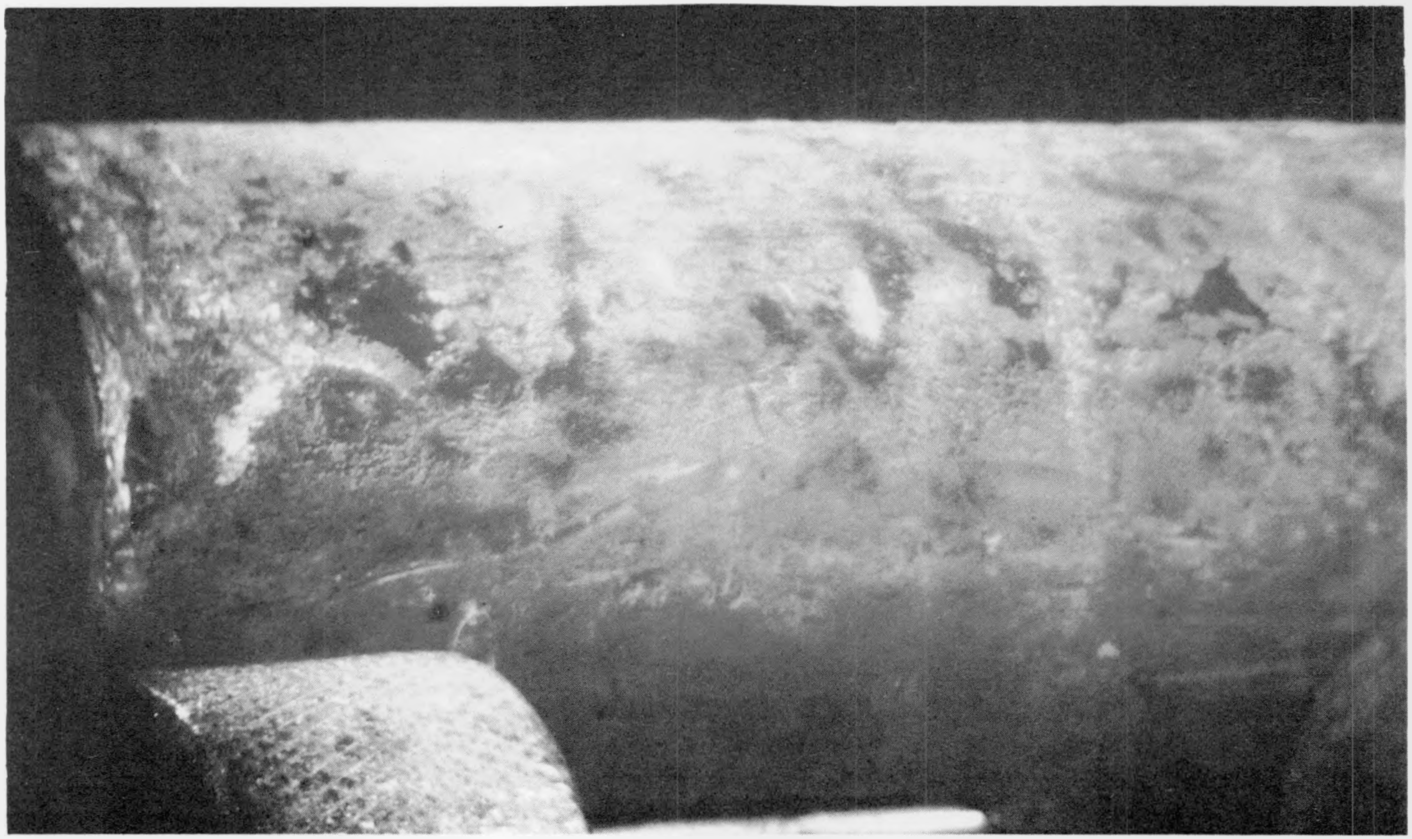

FIGURE 31

SLUG DISCHARGED JULY 31, 1952, FROM TUBE 3684-F

The bright areas at the left end of the slug are small pits.

Photograph Unclassified
AEC-GE-RICHLAND, WASH.

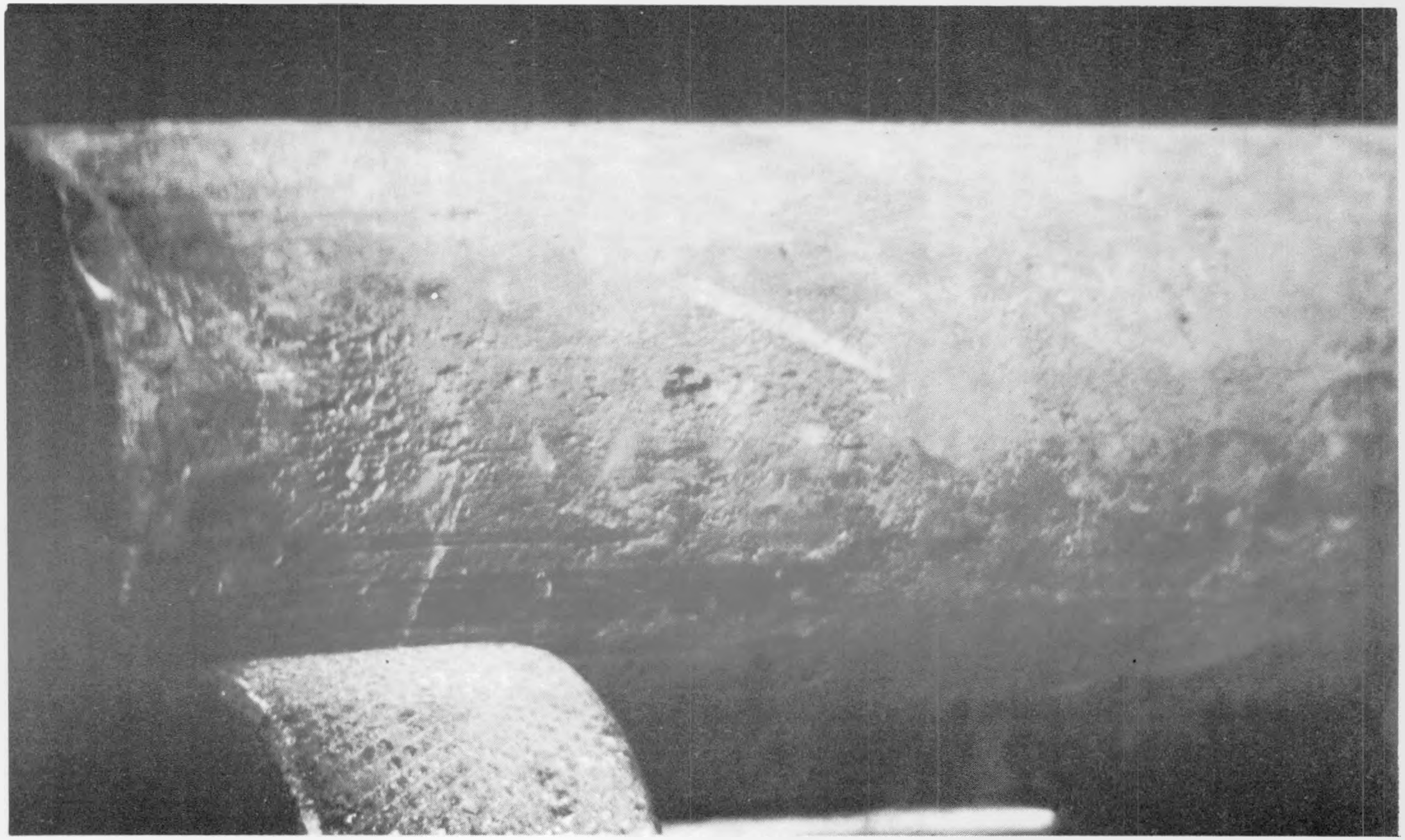

FIGURE 32

SLUG DISCHARGED JULY 31, 1952, FROM TUBE 3684-F

The attack appears to be concentrated near one end of the slug.

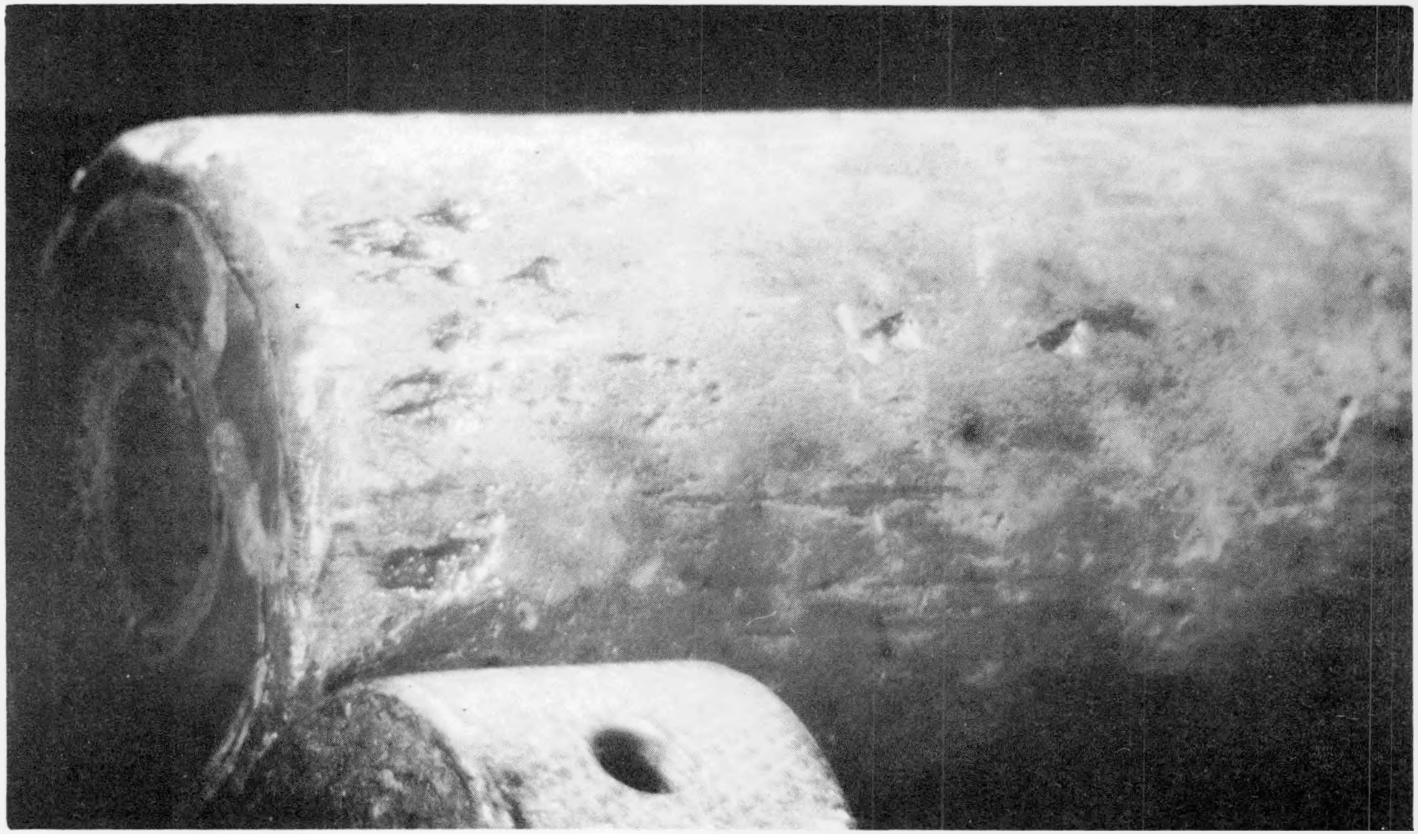

FIGURE 33

SLUG DISCHARGED JULY 31, 1952, FROM TUBE 3684-F

Another view of the slug shown in Figure 32.

SECRET

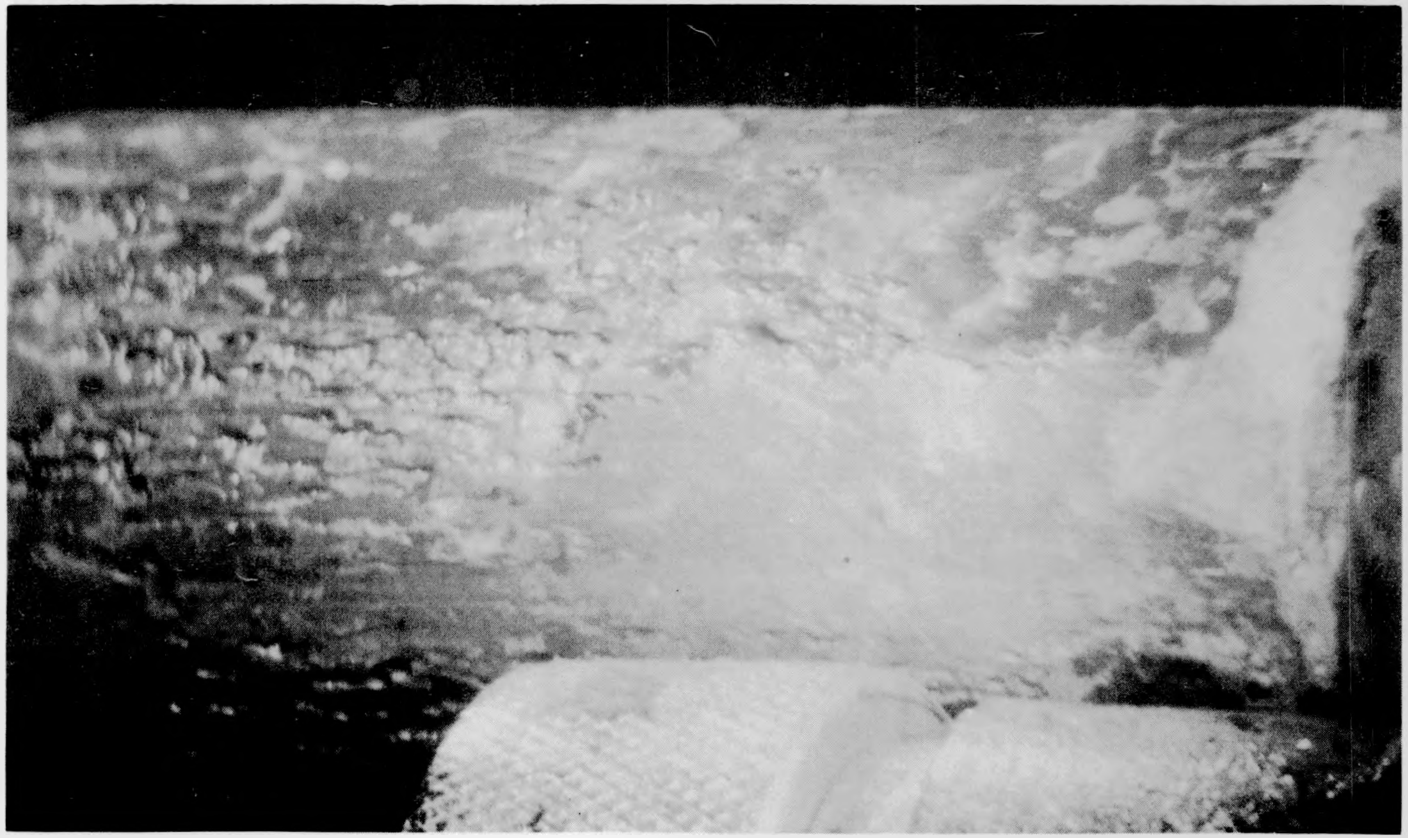

FIGURE 34

SLUG DISCHARGED JULY 31, 1952, FROM TUBE 3684-F

This fairly severe pitting attack covered about half of the cylindrical surface of the slug.

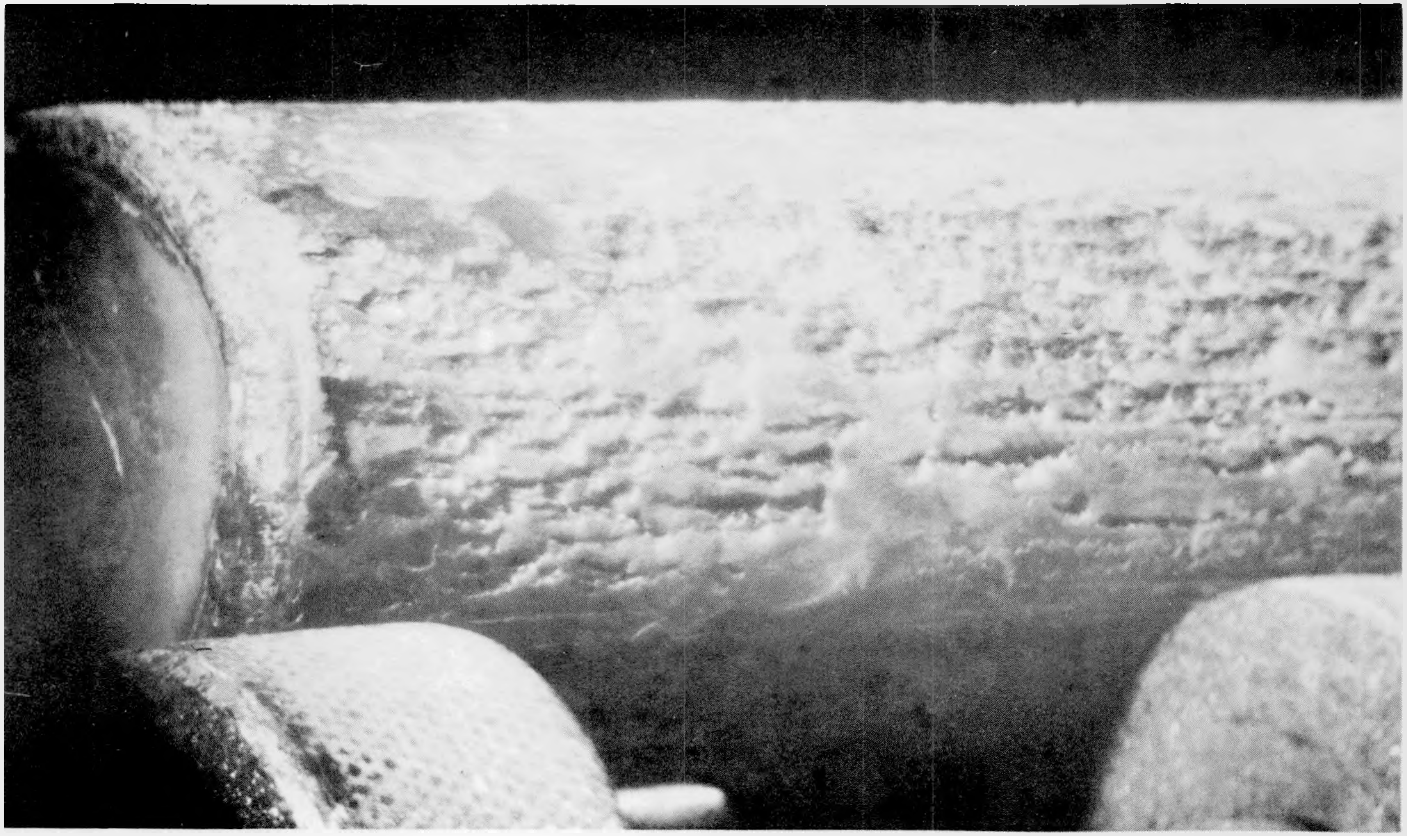

FIGURE 35

SLUG DISCHARGED JULY 31, 1952, FROM TUBE 3684-F

Another view of the slug shown in Figure 34.

Photograph Unclassified
AEC-GE-RICHLAND, WASH.

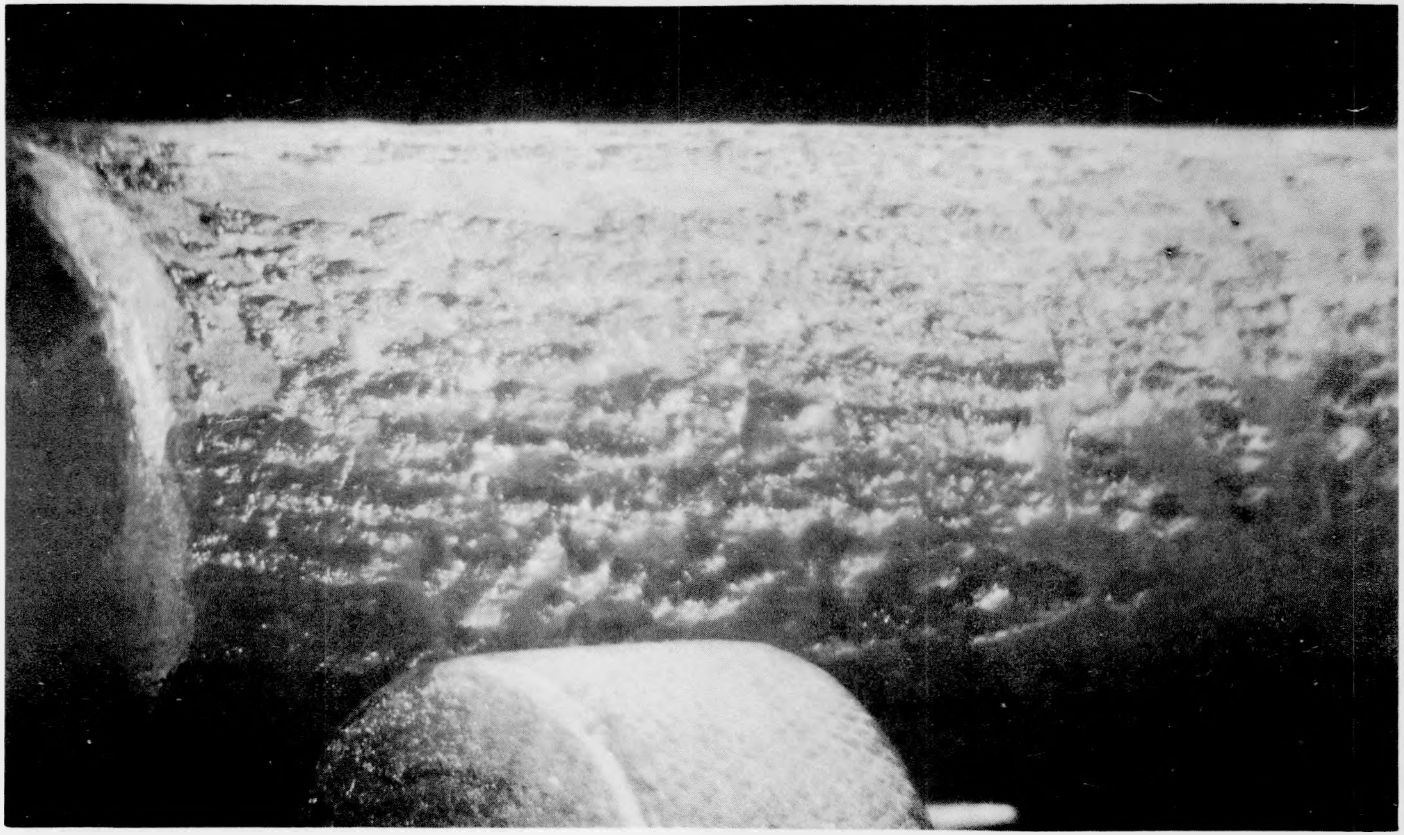

FIGURE 36

SLUG DISCHARGED JULY 31, 1952, FROM TUBE 3684-F

General severe attack covered most of the cylindrical surface of the slug.

Photograph Unclassified
AEC-GE-RICHLAND, WASH.

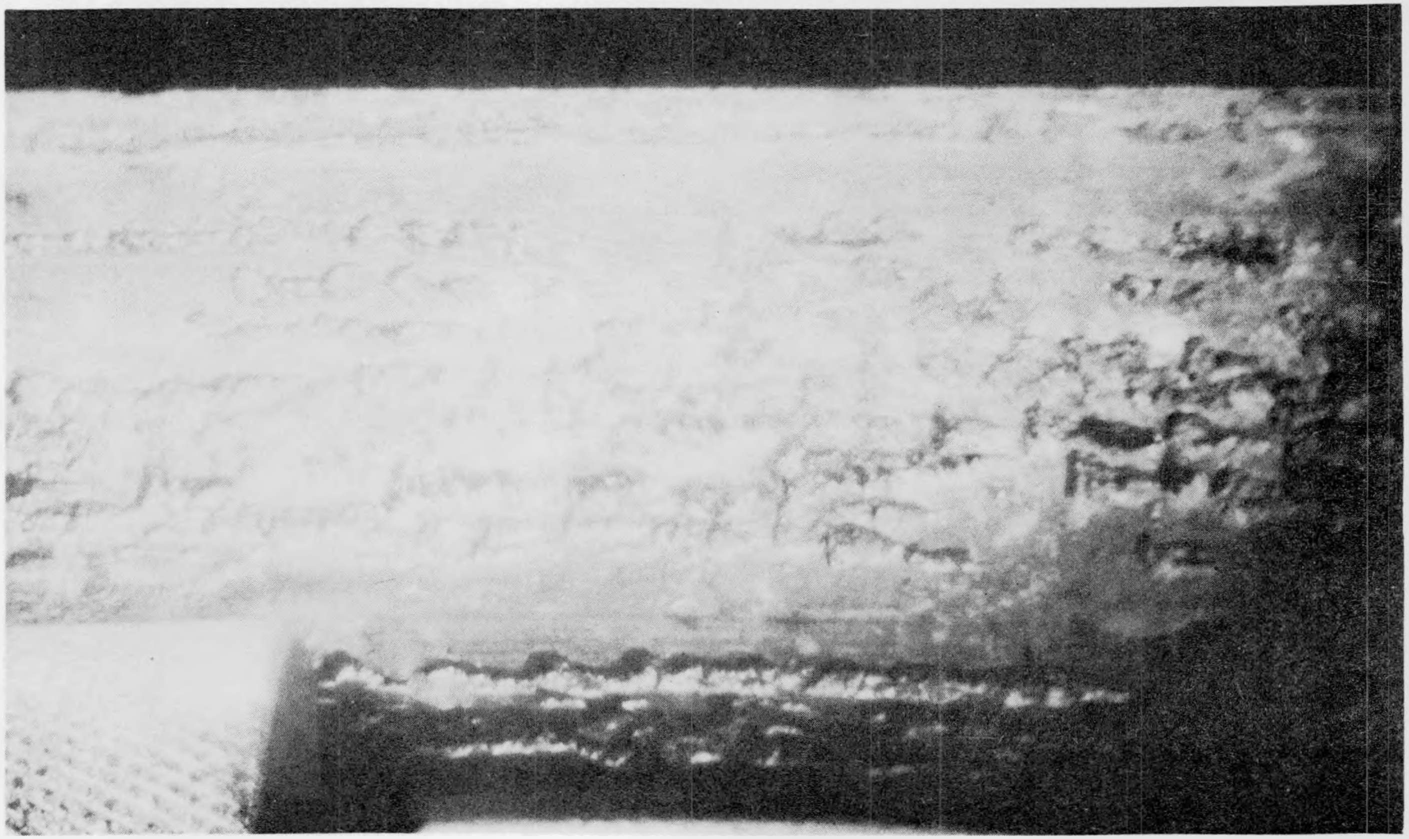

FIGURE 37

SLUG DISCHARGED JULY 31, 1952, FROM TUBE 3684-F

Another view of the slug shown in Figure 36. Note absence of attack at possible process tube rib contacts.

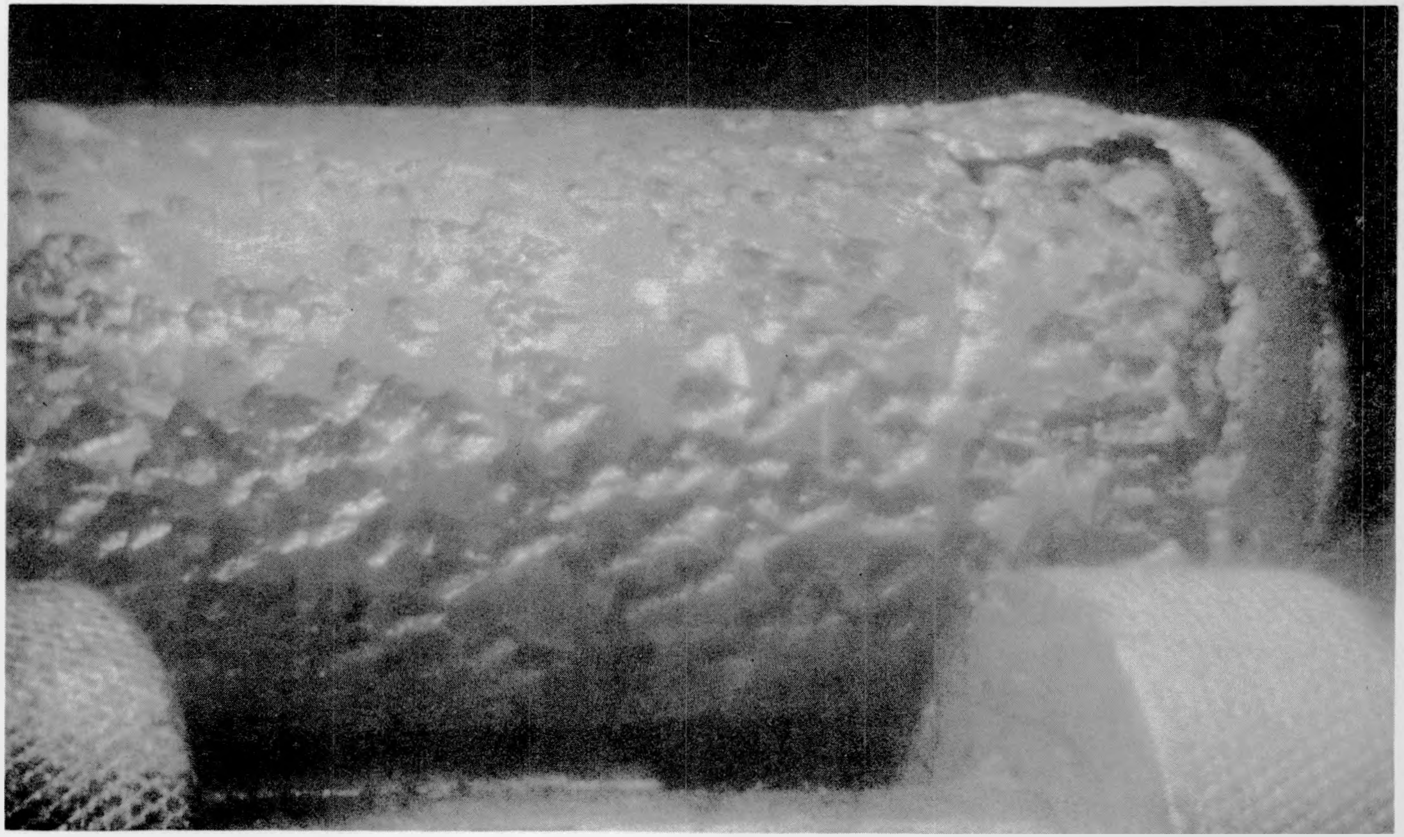

FIGURE 38

SLUG DISCHARGED AUGUST 24, 1952, FROM TUBE 3781-F

Note concentration of attack at the break. There was no attack on the part of the cap edge shown in this picture. The pits appear to be flat-bottomed.

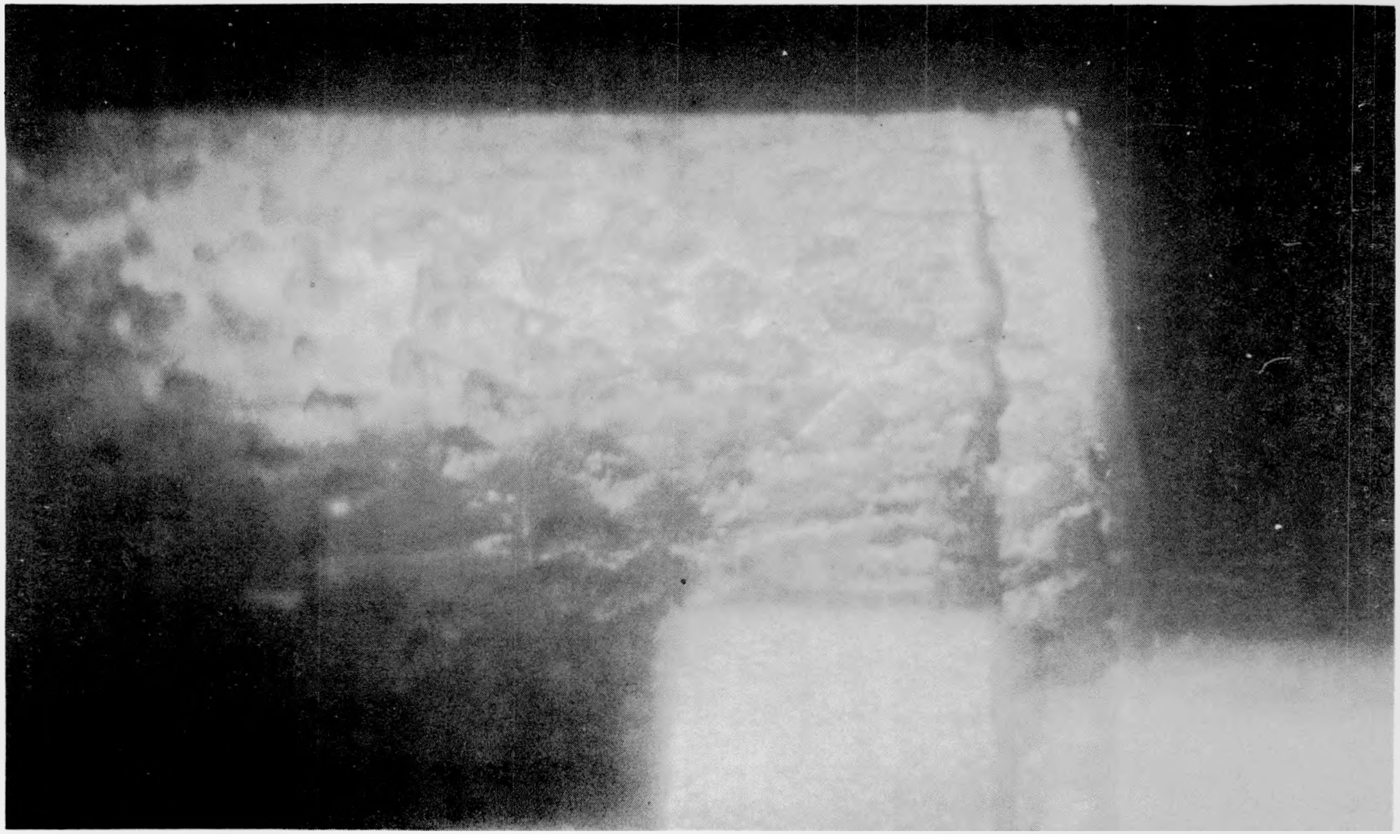

FIGURE 39

SLUG DISCHARGED AUGUST 24, 1952, FROM TUBE 3781-F

Another view of the slug shown in Figure 38.

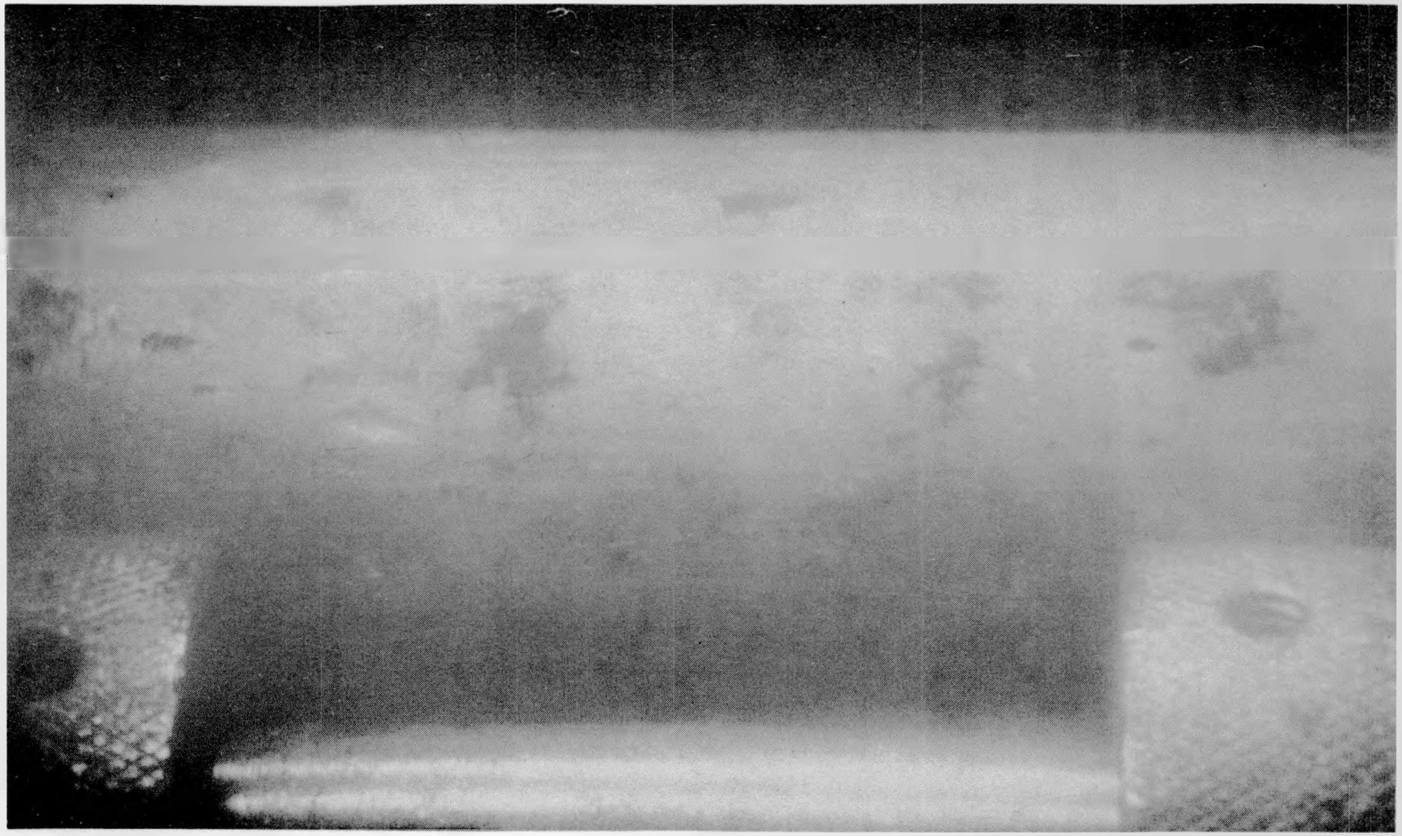

FIGURE 40

SLUG DISCHARGED AUGUST 31, 1952, FROM TUBE 3582-F

Note absence of attack. The small dark areas are patches of film.

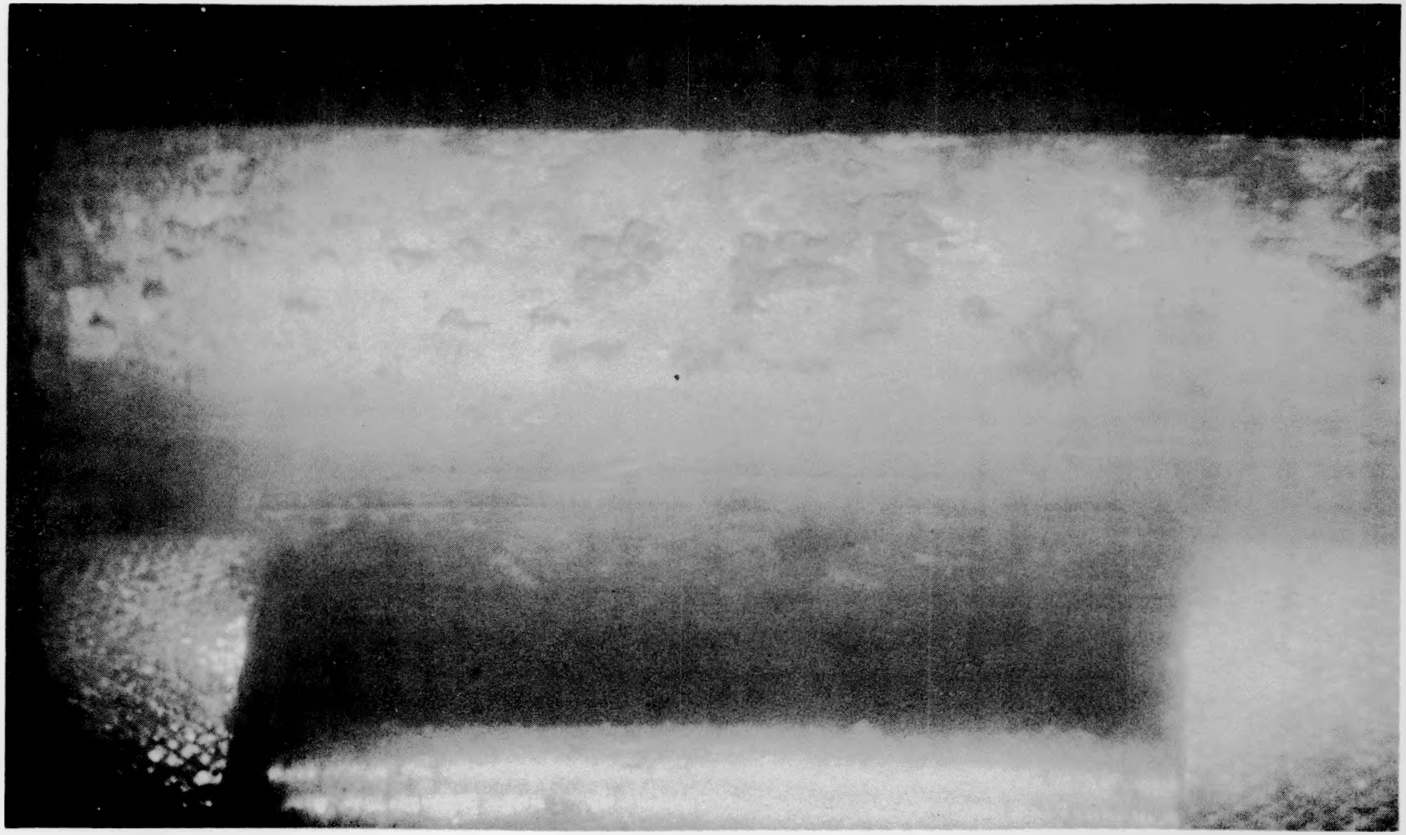

FIGURE 41

SLUG DISCHARGED AUGUST 31, 1952, FROM TUBE 3582-F

Another view of the slug shown in Figure 40.

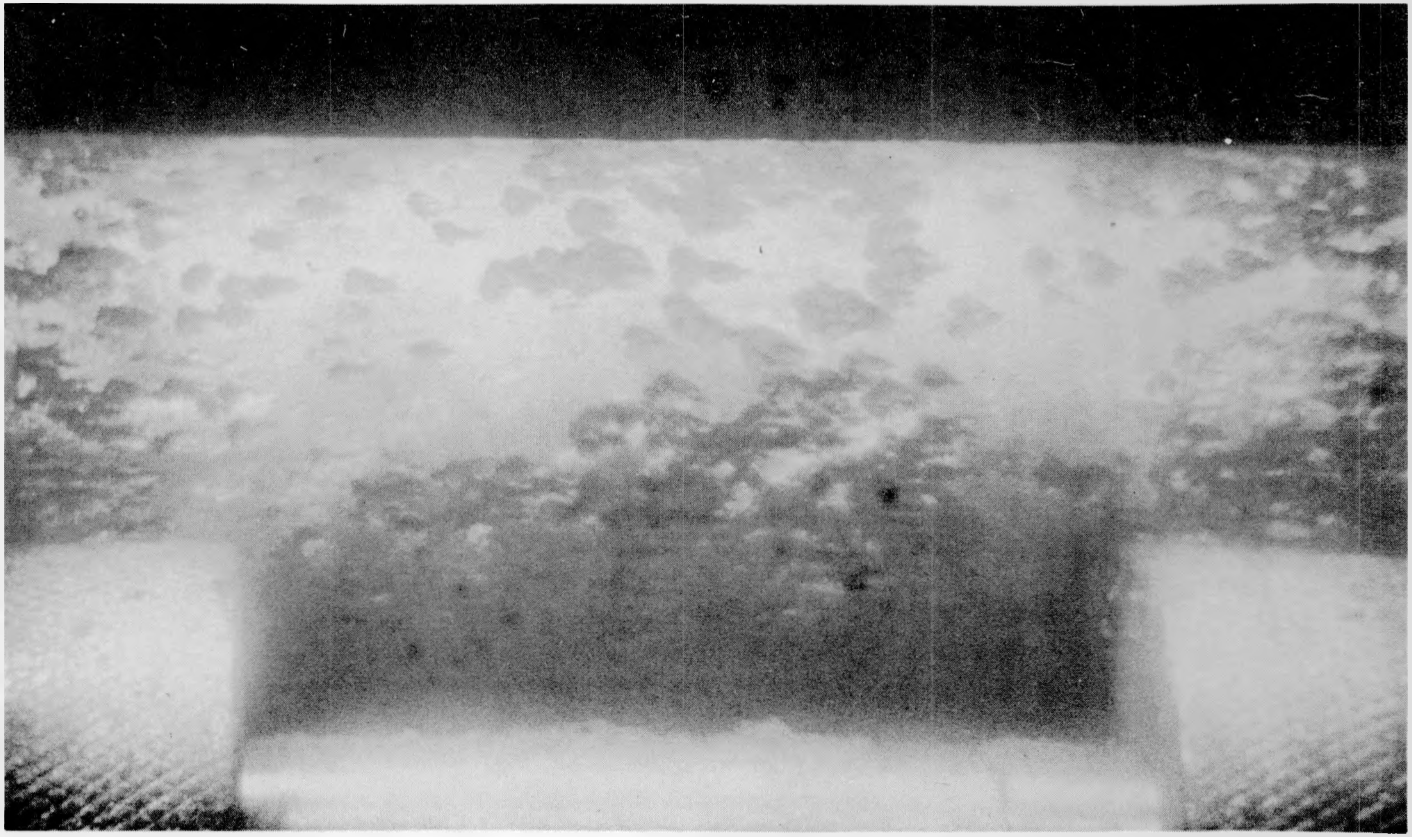

FIGURE 42

SLUG DISCHARGED AUGUST 31, 1952, FROM TUBE 3582-F

Another view of the slug shown in Figures 40 and 41.
Note the concentration of pitting attack on this portion of the slug.

Photograph Unclassified
AEC-GE-RICHLAND, WASH.

FIGURE 43

PERFORATED DUMMY SLUGS DISCHARGED FROM TUBE 3178-DR ON AUGUST 6, 1952

Note that the pitting attack on these dummy slugs is very similar to that shown in earlier figures which resulted in holes in process tube walls. The attack occurred only adjacent to the edge of the holes.

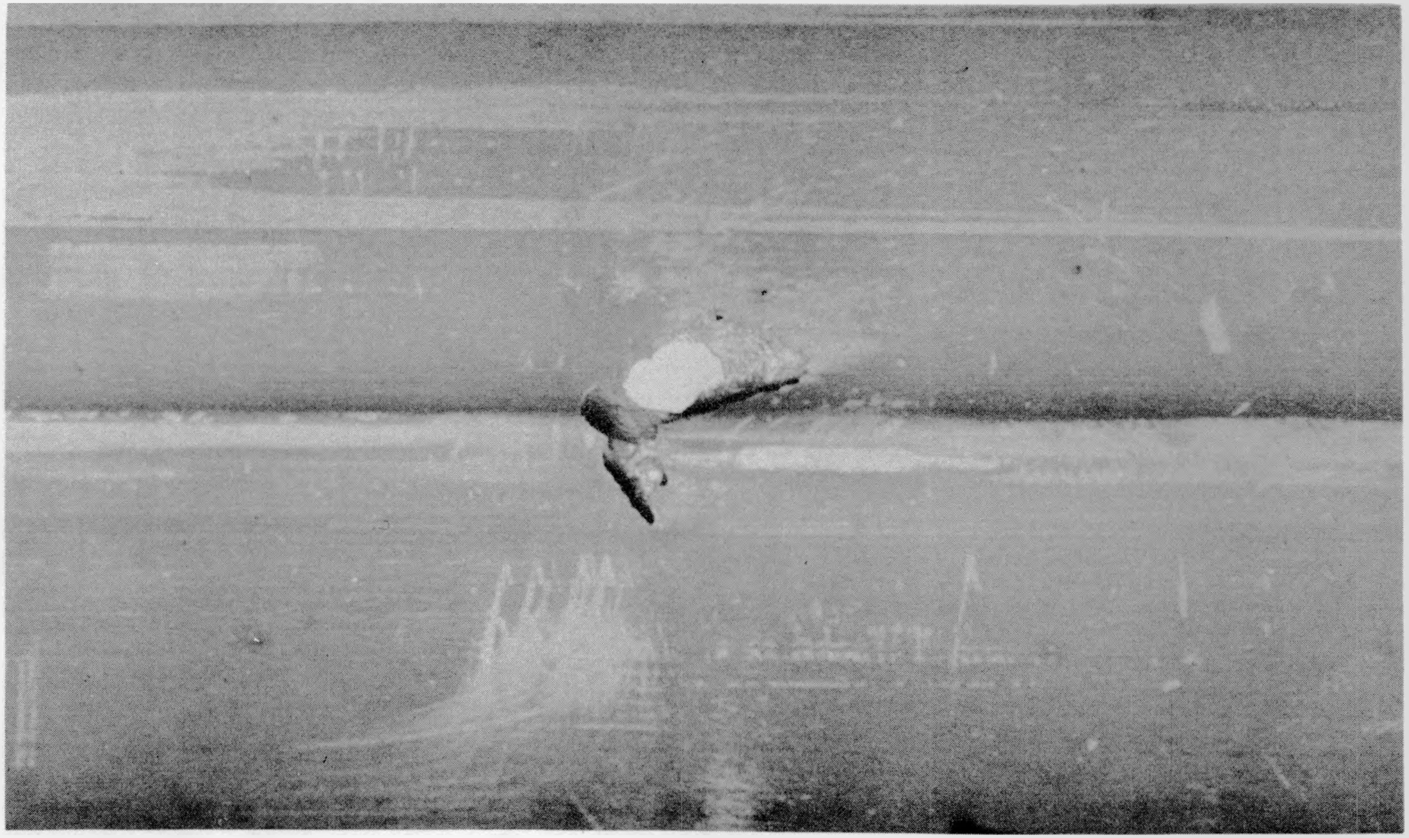

FIGURE 44

HOLE ADJACENT TO RIB INSIDE FLOW LABORATORY TUBE

Raw Columbia River water flowed from left to right in this tube at 20 gallons per minute and 95 C. Note the straddling of the rib by the pits. Compare with Figure 11.

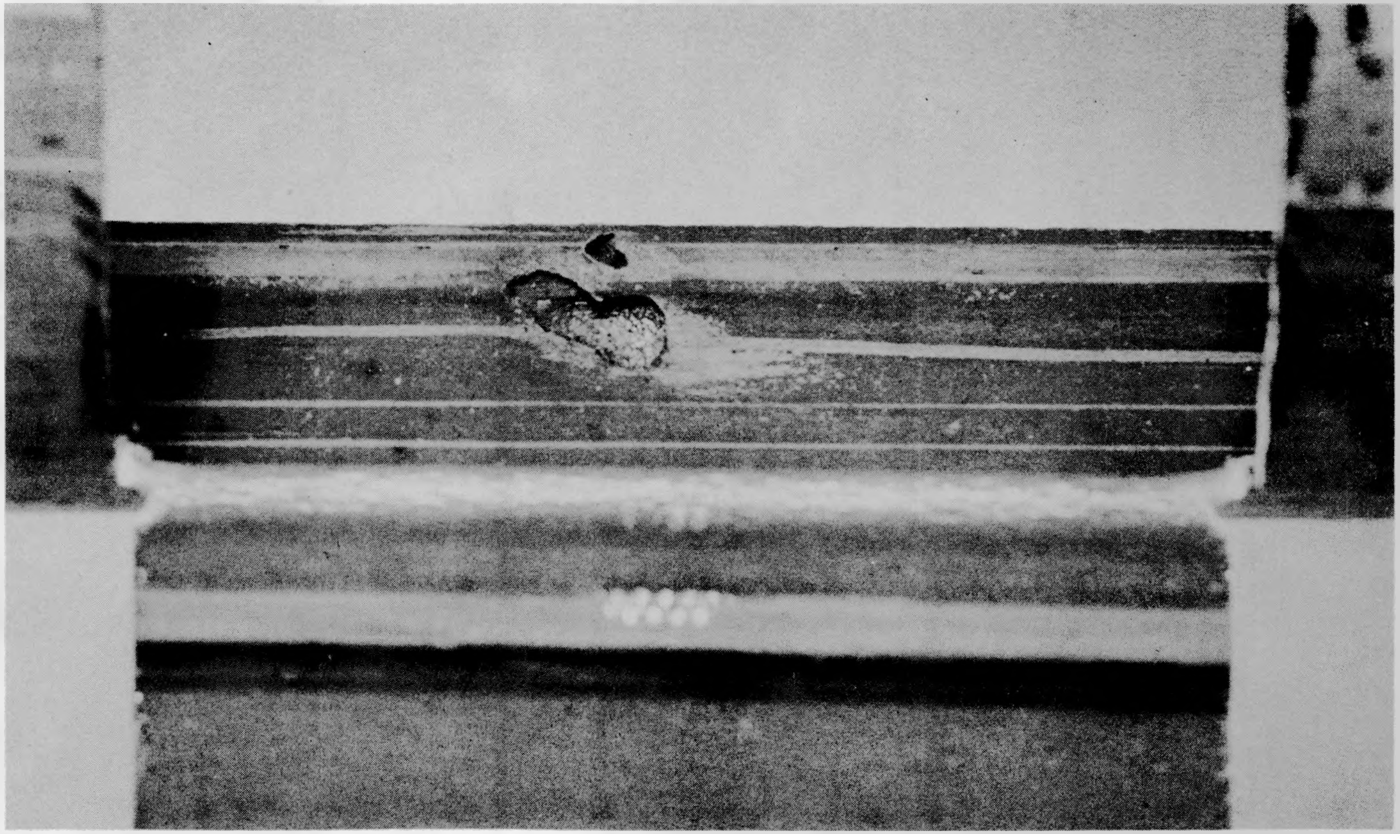

FIGURE 45

PITS ADJACENT TO RIB INSIDE FLOW LABORATORY TUBE

Same tube as Figure 44. These pits are located on opposite rib and one slug length upstream from the hole in Figure 44. Downstream is to the right.

Photograph Unclassified
AEC-GE-RICHLAND, WASH.

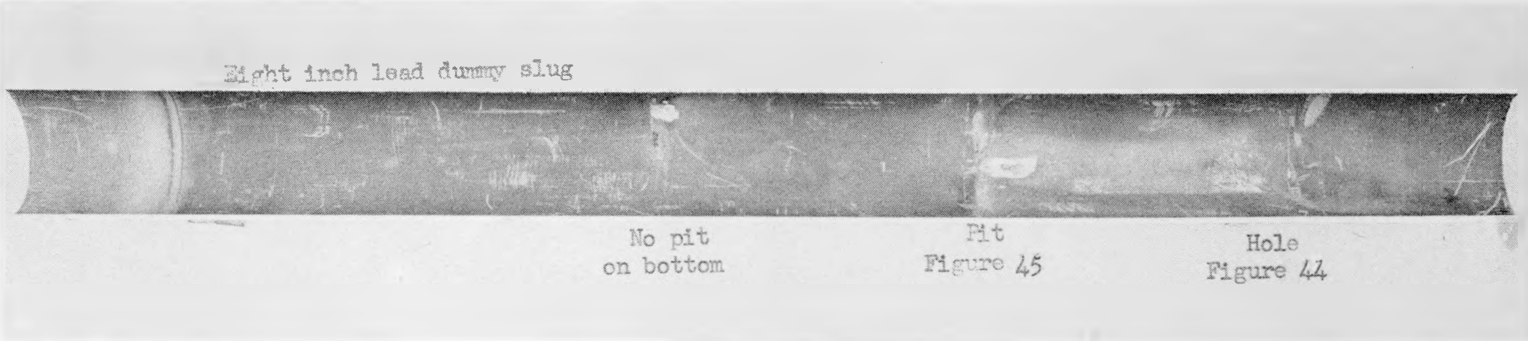

FIGURE 46

PITS INSIDE TOP OF FLOW LABORATORY TUBE

Same tube as Figures 44 and 45. Note relative location of pits and hole shown in previous figures. Note similarity of film color at pitted areas and in the low velocity region upstream of lead dummy which was the first slug in the tube.

[redacted]

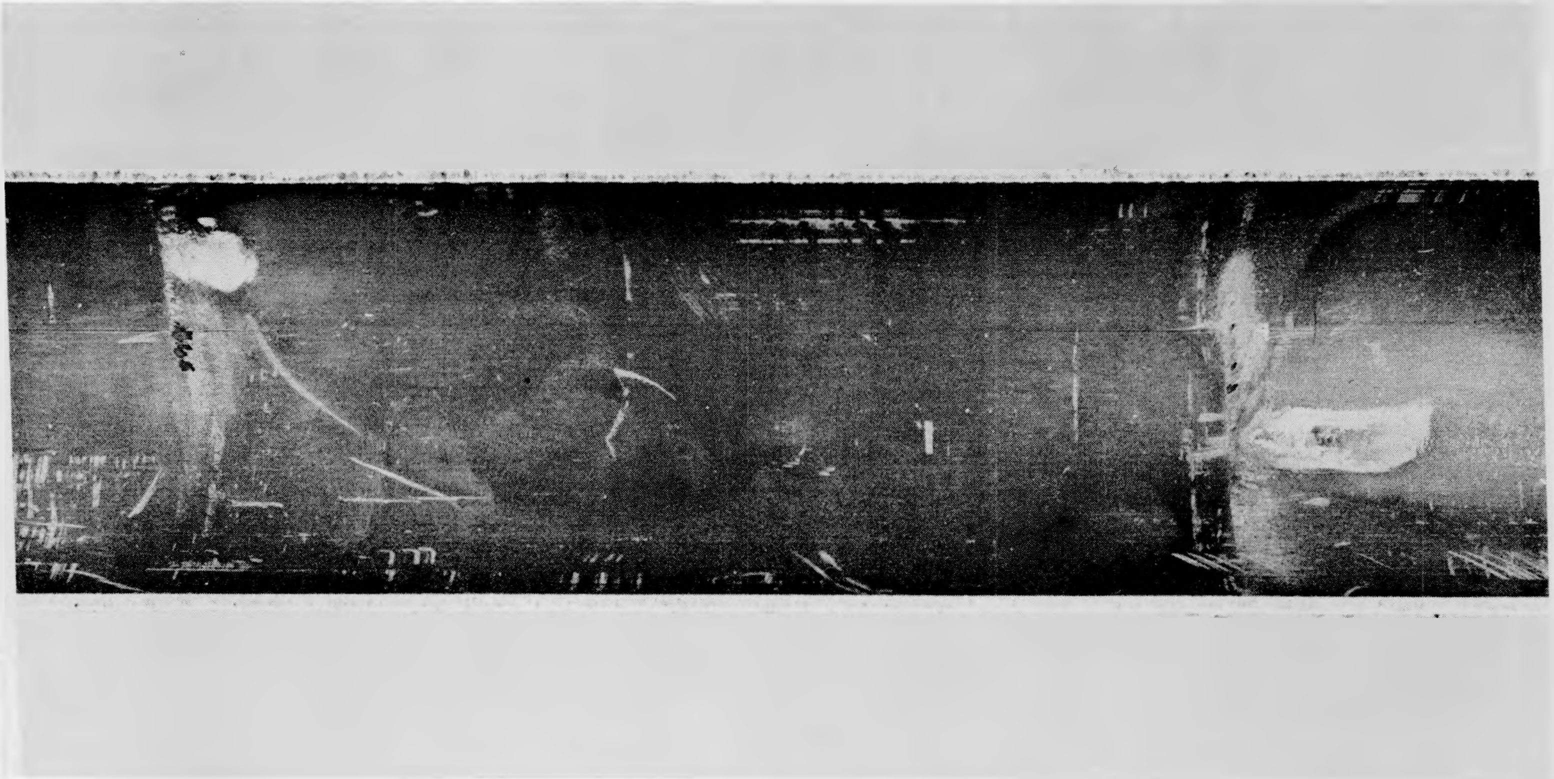

FIGURE 47

CLOSE-UP OF PITS INSIDE TOP OF FLOW LABORATORY TUBE

White areas appear to be regions of contact between slugs and tube. Film was dark brown except in vicinity of pits where it was tan. Downstream is to the right.

[redacted]

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[redacted]

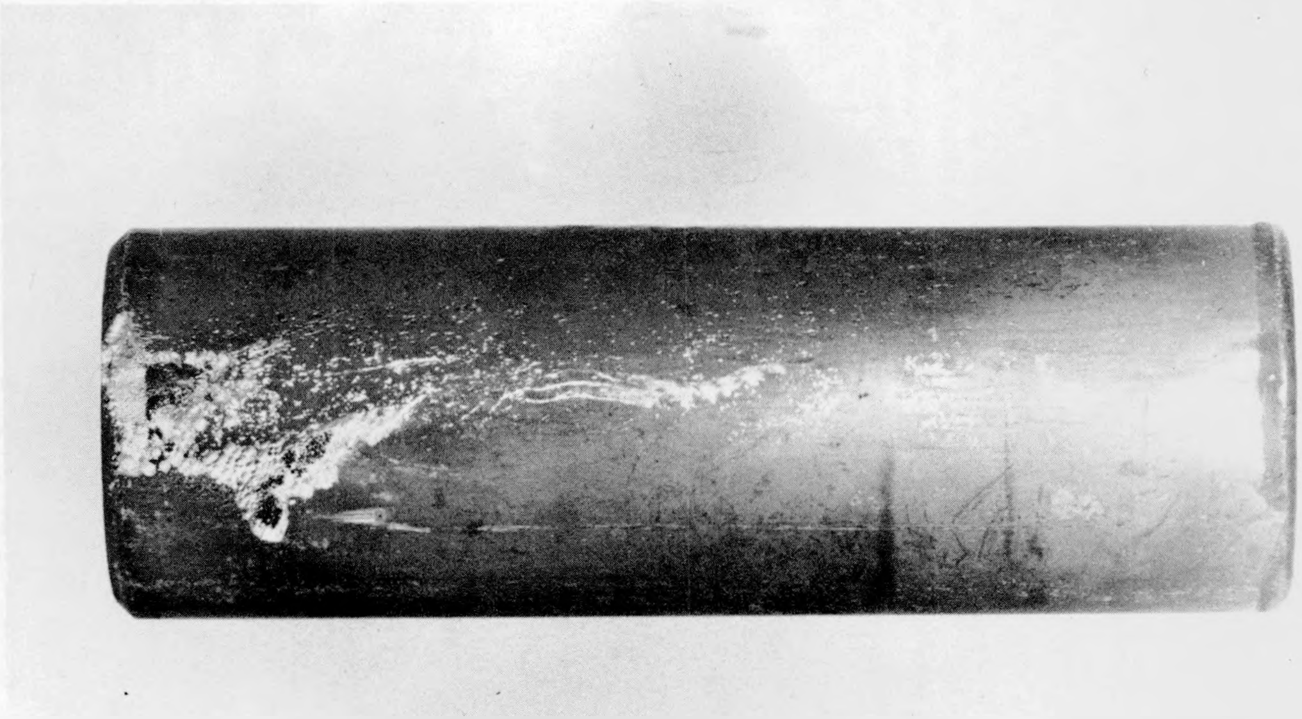

FIGURE 48

PITTED SLUG FROM FLOW LABORATORY TUBE

This slug was the first upstream slug in a tube through which ferric sulfate treated, dichromate-free water flowed at 20 gallons per minute and 95 C. The pitted end was upstream.

[redacted]

UNCLASSIFIED

[redacted]

Photograph Unclassified
AEC-GE RICHLAND, WASH.

FIGURE 49

ENLARGEMENT OF PITTED SLUG IN FIGURE 48

This enlargement of the upstream end of the slug shows the discrete nature of the pits. The black areas are AlSi.

[redacted]

UNCLASSIFIED

[redacted]

FIGURE 50

PITS INSIDE TOP OF FLOW LABORATORY TUBE

These pits were immediately opposite the pitted area on the slug shown in Figure 48. Note the triangular shape of the broad, shallow pits at the top, center. Downstream is to the right.

[redacted]

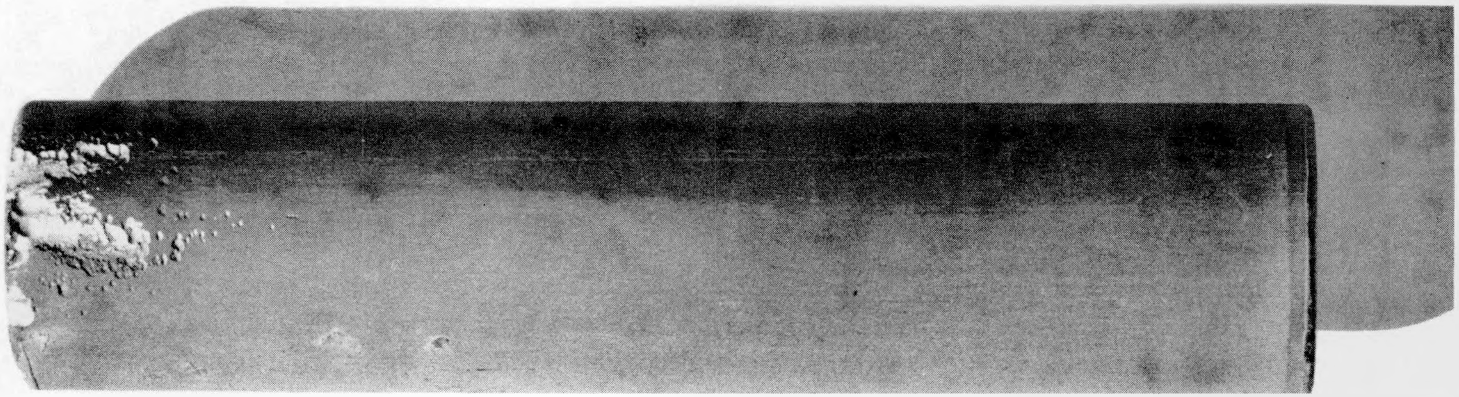

FIGURE 51

PITTED LEAD DUMMY SLUG FROM FLOW LABORATORY TUBE

This slug was the first upstream slug in a tube through which aluminum sulfate treated, dichromate-free water flowed at 20 gallons per minute and 95 C. The pitted end was upstream.

[redacted]

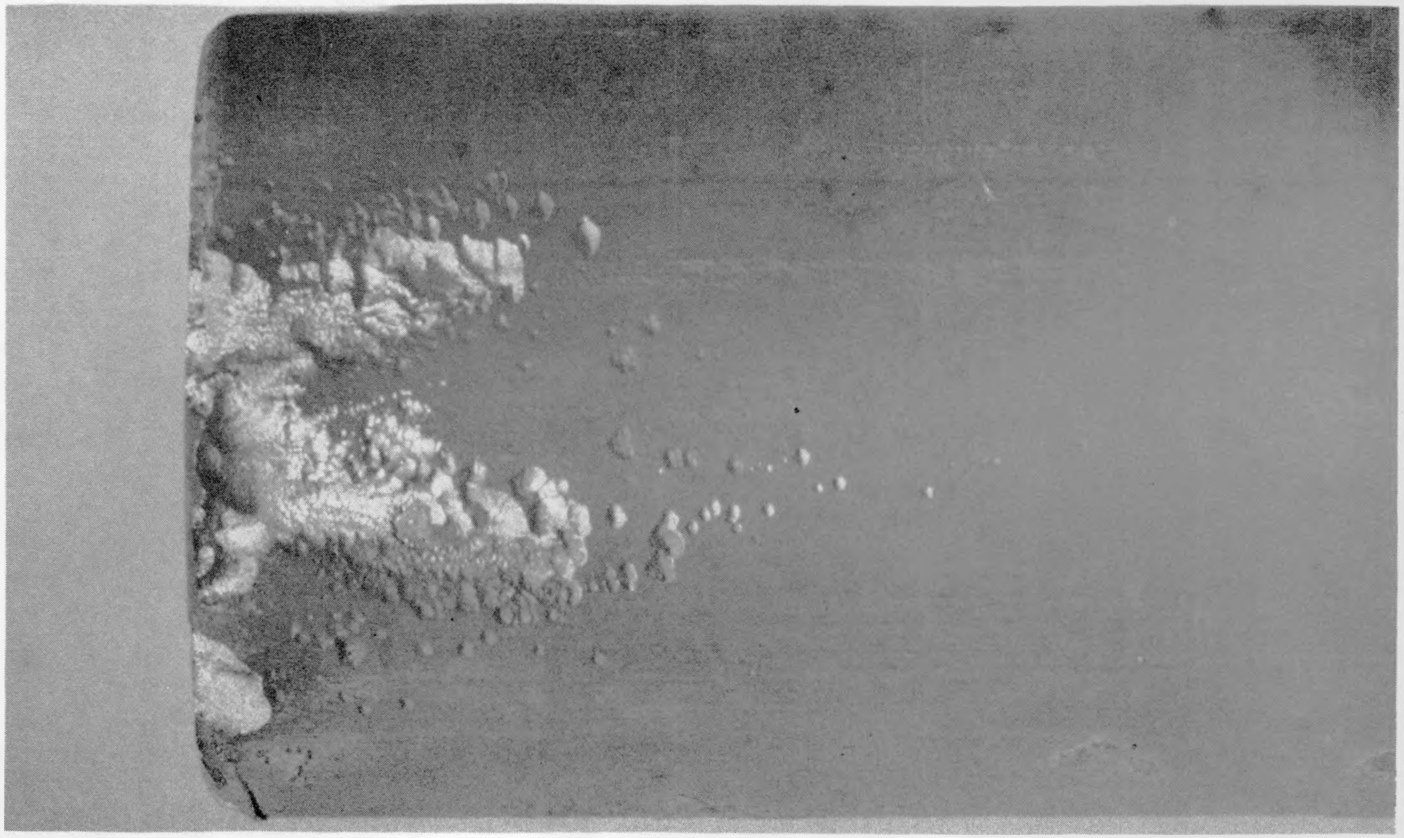

FIGURE 52

ENLARGEMENT OF PITTED SLUG IN FIGURE 51

This enlargement of the upstream end of the slug shows the discrete, triangular-shaped pits that have been observed on irradiated slugs. The apex of the triangles, as in Figure 50, is always upstream.

[redacted]

[redacted]

Photograph Unclassified
AEC-GE-RICHLAND, WASH.

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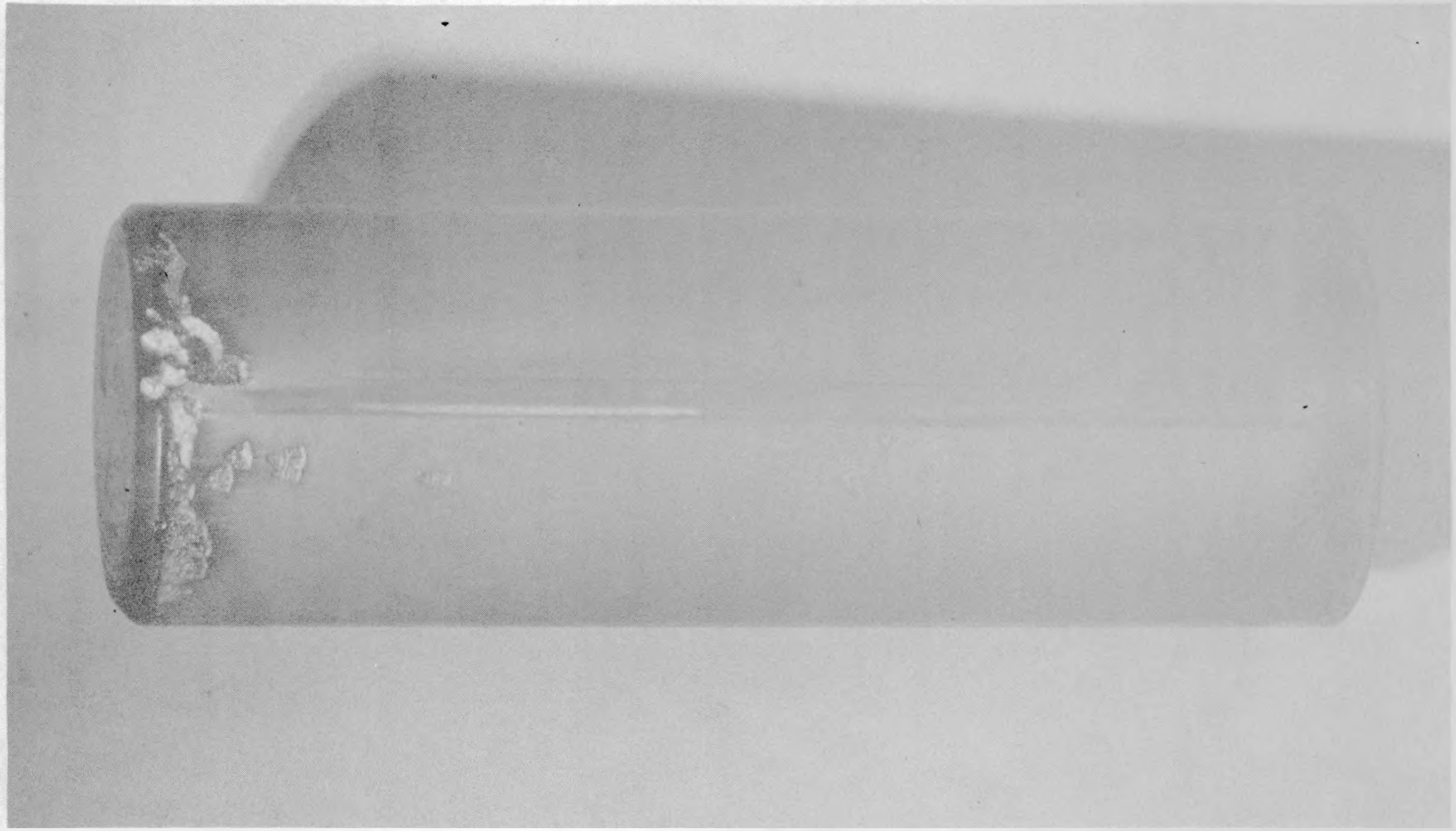

FIGURE 53

PITTED SLUG FROM FLOW LABORATORY TUBE

Aluminum sulfate treated, dichromate-free water flowed past this intentionally cocked slug at 15 gallons per minute and 95 C. Note similarity of attacked area on upstream end to that on pile discharged slug, Figure 27.

[redacted]

[redacted]

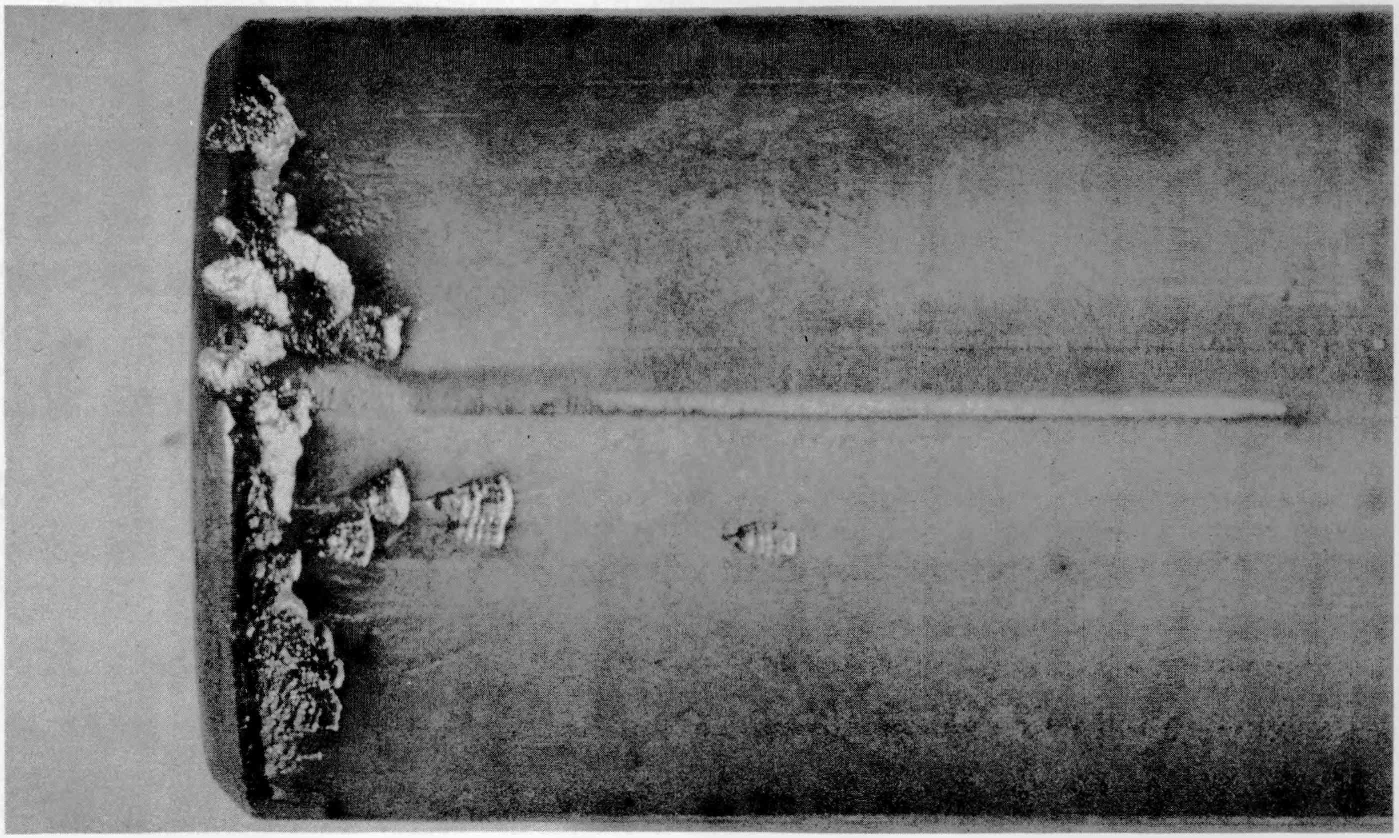

FIGURE 54

ENLARGEMENT OF PITTED SLUG IN FIGURE 53

Note the sharply defined, triangular pits with apexes pointing upstream. Note the sharp line of demarcation where the pitted area starts at the downstream edge of the bevel.

[redacted]

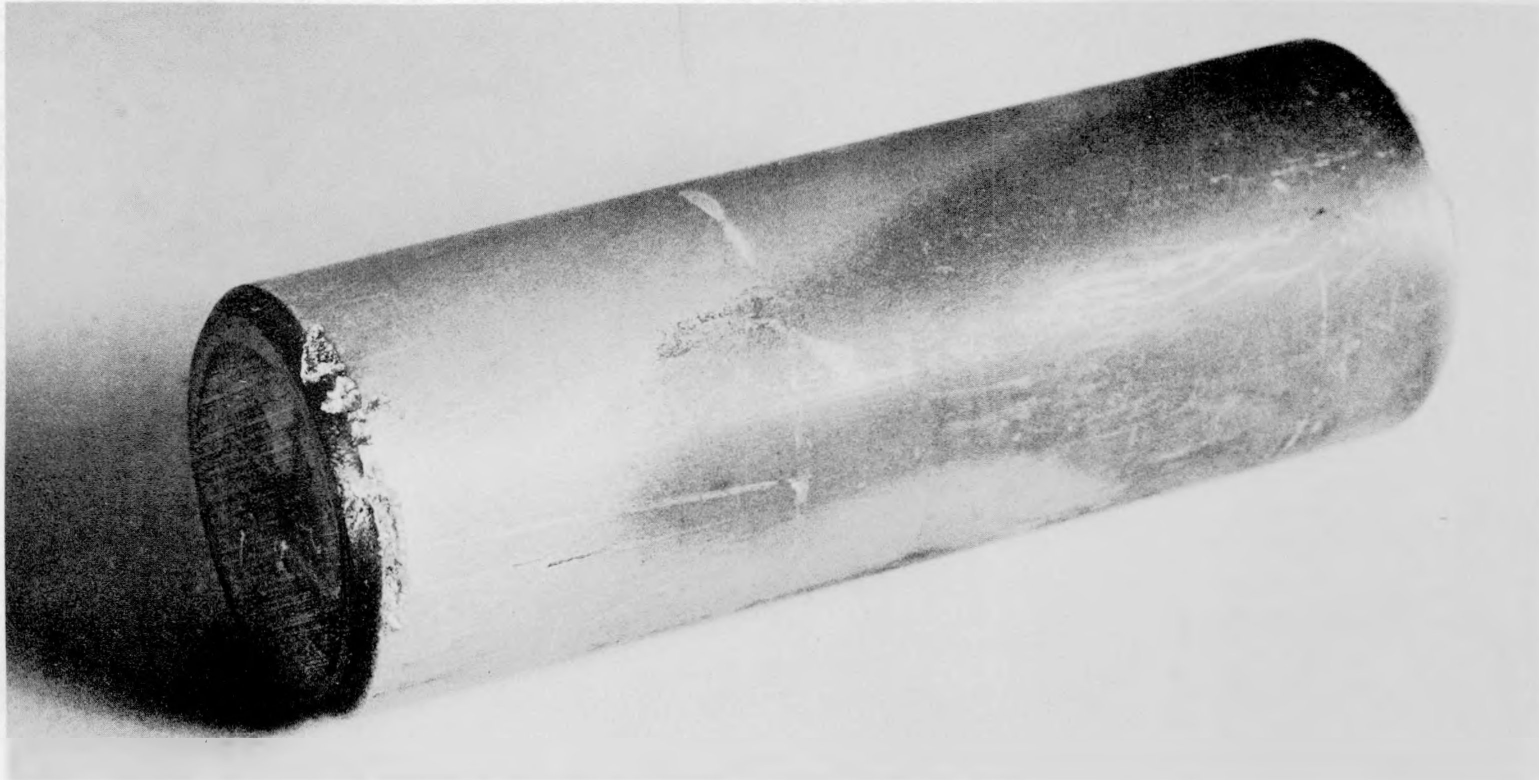

FIGURE 55

PITTED SLUG FROM SAME TUBE AS SLUG IN FIGURE 53

This intentionally cocked slug from the same tube as the slug shown in Figure 53 shows similar pitting on the upstream edge. Note flow pattern shown by varicolored film deposit.

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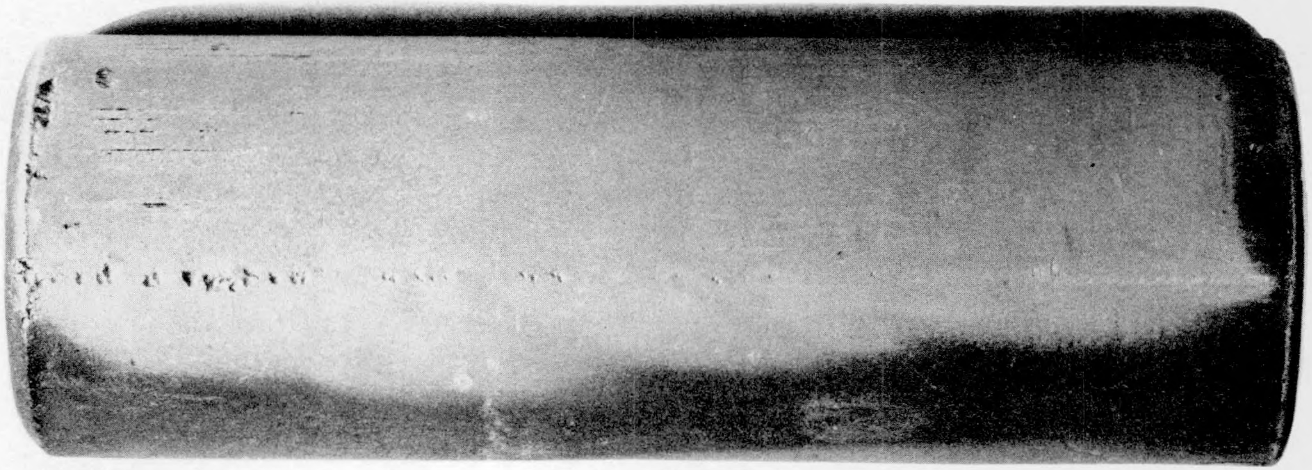

FIGURE 56

OPPOSITE SIDE OF SLUG IN FIGURE 55

Note additional pits immediately downstream from bevel, and pits along line opposite tube rib. Particles that may have lodged between slug and rib may have caused pits. Rib and slug were in direct contact at downstream end.

[redacted]

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Photograph Unclassified
AEC-GE RICHLAND, WASH.

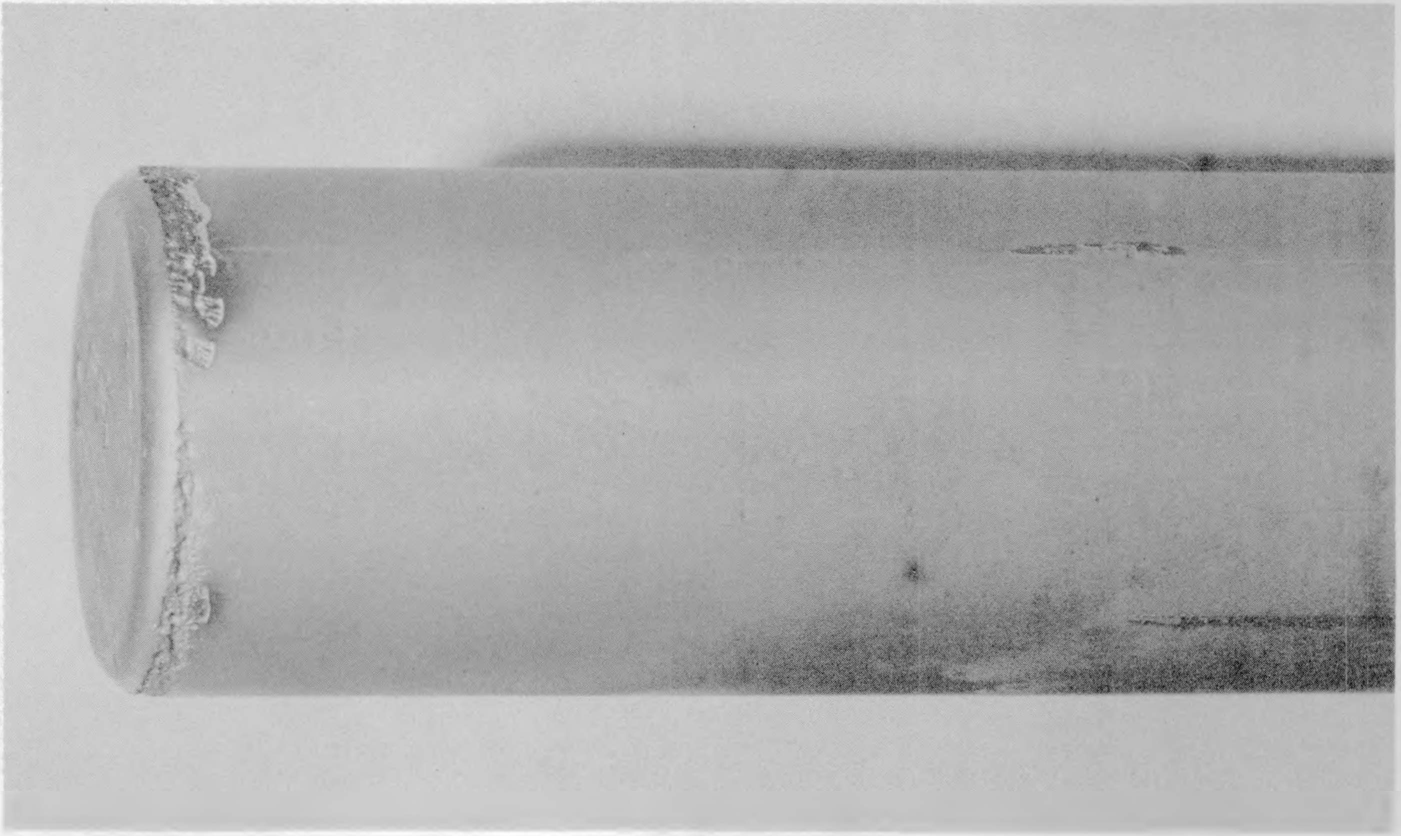

FIGURE 57

PITTED SLUG FROM TUBE SHOWN IN FIGURE 58

This slug was not intentionally cocked and may not have been cocked at all. A cocked slug located two slug lengths upstream of this one was not pitted nor was the slug between them. Note sharp demarcation of pitted areas immediately downstream of the bevel.

UNCLASSIFIED

[redacted]

UNCLASSIFIED

[redacted]

Photograph Unclassified
AEC-GE-RICHLAND, WASH.

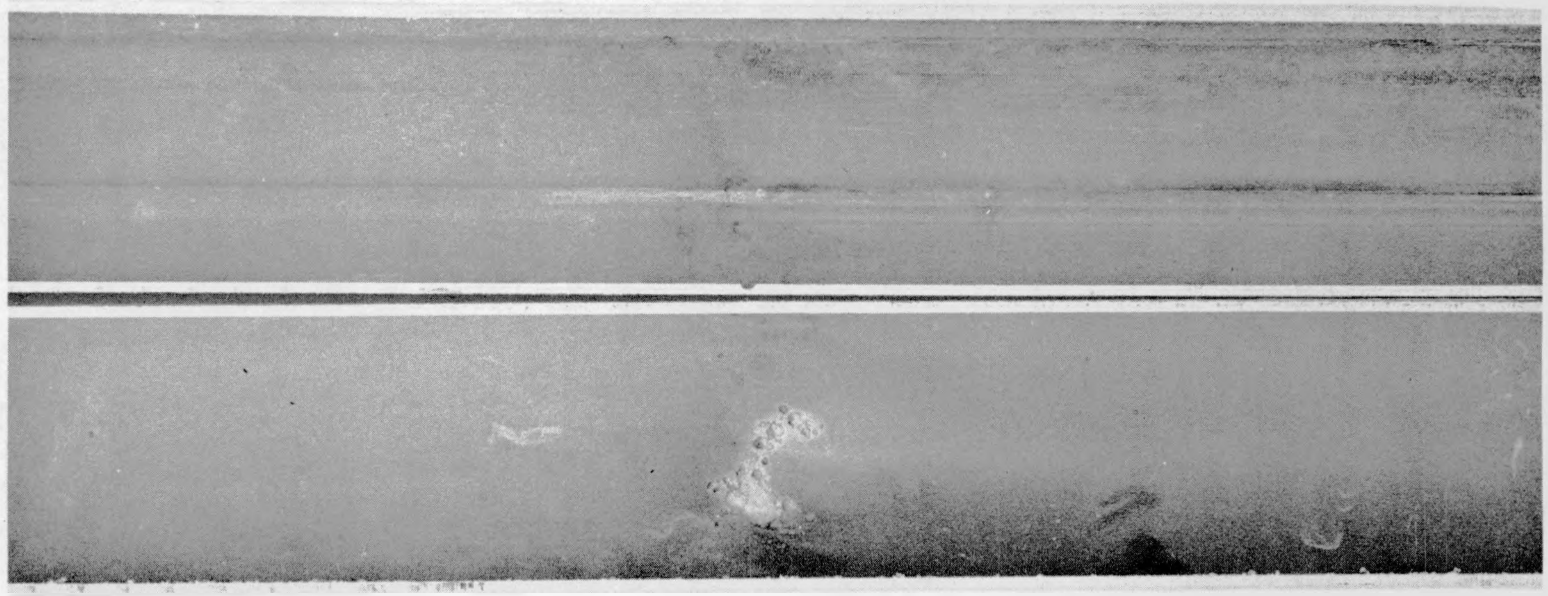

FIGURE 58

PITTED AREA INSIDE TOP OF TUBE

The pits shown here are discrete and irregularly shaped. They are somewhat undercut and the bottoms of the pits are pebbled in appearance. The pitted area on the slug shown in Figure 51 was located opposite the pits shown here.

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[redacted]

ABSTRACT

The severe pitting attack of pile process tubes and slug jackets that occurred at HAPO during the summer of 1952 was investigated. Several process tubes that were removed from the piles because of water leakage or suspected damage from ruptured slugs were found to be severely pitted on the inside, with penetration of the tube wall occurring where leakage was evident. At about the same time a type of surface attack, not previously observed, was found on some slugs discharged from F Pile. In some instances, both the slugs and tubes from the same channel showed this type of attack. Incidents of attack in process tubes in the Flow Laboratory were found to be similar to the in-pile phenomenon. The attack on both the tubes and slugs in the Flow Laboratory occurred in the vicinity of obstructions to the flow of water, took place in nine to twelve days, and appeared to be of a mechanical nature. The occurrence of this pitting attack, observed in the piles and in the Flow Laboratory appears to require several conditions, such as: water temperature above 60 C, water velocity above 17 feet per second, and flow irregularities in the annulus. These flow irregularities occur at slug junctions and at misaligned slugs, and are even more serious if loose particulate matter in the tube should become lodged in the annulus. Experimental evidence indicates that the observed attack is inhibited by the presence of dichromate ions in the cooling water.