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LOX/GOX RELATED FAILURES DURING SPACE SHUTTLE MAIN ENGINE DEVELOPMENT

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16. ABSTRACT

Specific rocket engine hardware and test facility system failures are described which were caused by high pressure liquid and/or gaseous oxygen reactions. The failures described were encountered during the development and testing of the Space Shuttle Main Engine. Failure mechanisms are discussed as well as corrective actions taken to prevent or reduce the potential of future failures.

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TECHNICAL MEMORANDUM

LOX/GOX RELATED FAILURES DURING SPACE SHUTTLE MAIN ENGINE DEVELOPMENT

SUMMARY

The various types of lox/gox related failures encountered in the Space Shuttle Main Engine program have illustrated the need for extreme caution in designing and fabricating systems for high pressure high flow oxygen systems. The selection and processing of structural materials are critical factors in component development. The failures encountered have been resolved and appropriate changes made to ensure safe operation with respect to the use of high pressure oxygen.

INTRODUCTION

Throughout the development and testing of rocket engines and related hardware, a variety of component failures has been attributed to reactions of materials with liquid or gaseous oxygen.

The Marshall Space Flight Center, because of its role in rocket engine development, has been a pioneering organization in research on liquid and gaseous oxygen compatibility with materials. The research dates back to the predecessor organization, the Army Ballistic Missile Agency, during the early 1950's development of the Redstone and Jupiter missiles, and subsequently the large Saturn rockets that were used in the Apollo program.

The Space Shuttle Main Engine development program has had the benefit of past experience in designing for high pressure lox/gox applications; yet, for several reasons, failures have been encountered during the development phase of the program. Test facility problems have been encountered because of the use of existing test equipment not specifically designed for the higher pressures of the SSME. Some component failures have occurred because of extremely high flowrates of oxygen through ducts and valves which were not fully optimized to reduce flow induced vibrations.

This report describes in narrative form the specific failures encountered, and discusses some of the corrective actions taken to prevent or reduce the potential of future failures.

FAILURE HISTORY

The following chronology lists the significant failures that have occurred:

1) March 1975 - Santa Susana Coca 4 Facility Valve

2) February 1976 - Santa Susana Coca 1A Facility Valve

3) March 1977 - Engine 0003, High Pressure Oxidizer Turbopump Primary Seal

4) June 1977 - Santa Susana Coca 1B Facility Valve

5) September 1977 - Engine 0004, High Pressure Oxidizer Turbopump Instrumentation

6) April 1978 - Engine 0002, Injector Lox Posts

7) June 1978 - Engine 0005, Injector Lox Posts

8) July 1978 - Engine 0101, High Pressure Oxidizer Pump

9) September 1978 - Engine 0005, Lox High Pressure Duct Flowguide

10) December 1978 - Engine 0007, Heat Exchanger

11) December 1978 - Engine 2001, Main Oxidizer Valve

12) February 1979 - Engine 0201, Main Oxidizer Valve Seal.

FAILURE DESCRIPTIONS

March 1975 - Santa Susana Coca 4B Facility Valve

On March 7, 1975, an SSME Powerhead test (014) was underway at the Rocketdyne Santa Susana Test Facility in Los Angeles, California, when the test was terminated by an explosion. The test objective was to complete a preburner ignition and main combustion chamber ignition. The failure resulted in moderate to extensive damage to several components of the assembly. Most of the damage resulted from a combustion wave propagating through the system from the ignition of mixed gases at the nozzle exit. Figure 1 is a simplified schematic of the test assembly. However, the propellant feed lines contained numerous ball valves, filters, and flowmeters, as shown in Figure 2, which is an isometric schematic of the oxidizer system. Note the flow of lox from the lox tank to the oxidizer preburner (OPB). LB-7 is a 2 in. 7800 series Annin valve used as a lox bleed valve, and is located on a stub line to the main flow line. A schematic of this valve and associated components and materials is shown in Figure 3. This particular valve was found to have a burned bonnet seal (Teflon). There was no evidence of significant prior contamination. Note that the valve was installed such that lox/gox pressure was over the ball. The downstream valves were reversed, with the low pressure under the ball; thus, protecting the stem packing and seals from exposure to lox while in the closed position.

It was concluded that primary velocities and surges in the unprimed stub bleed line, caused by main line surges, could have resulted in pressures of 20,000 psi and velocities of 400 ft/sec. This would have resulted in high temperatures, generated by adiabatic gox compression in the stub line. Temperatures on the order of 1220°F were calculated because of this effect. The ignition temperature of Teflon at 3060 psi is approximately 850°F. The Teflon seal was a static bonnet seal (Rayco) of TFE Teflon with an internal spring, used between the cap and body of the valve. The spring and seal were burned; no other damage occurred to the valve. No other cause, other than adiabatic compression, was found to explain the Teflon ignition.

The explosion and major assembly damage were not attributed to the Teflon ignition in the valve but to surges and overpressure in the system. The Teflon ignition was caused by the pressure surge because of erratic main lox valve opening, and the installation of the valve such that the Teflon was exposed to the surge pressure.

Corrective action involved changing the main valve opening instrumentation, servo-systems instrumentation, redesign of flowmeters to withstand higher surge pressures, redesign of filters, and reversal of several Annin valves to protect seal areas from pressure surges while in the closed position.

February 1976 Santa Susana Coca 1A Facility Valve

On February 4, 1976, a verification test of the SSME Low Pressure Oxidizer Turbopump (LPOTP) and the High Pressure Oxidizer Turbopump (HPOTP) was being conducted at the Rocketdyne Santa Susana Coca 1A Test Facility, when a fire occurred at approximately 14 sec into a programmed mainstage duration of a 35 sec test. Much of the total damage to the test hardware and the test stand resulted from sustained burning of hydraulic oil from a ruptured manifold and tubing supplying the control valves.

The LPOTP sustained minor internal damage. The HPOTP was extensively damaged throughout. Facility lines and valves downstream of the HPOTP were ruptured and burned through in several areas. These parts were damaged by lox fires, but most of the test stand damage was a result of burning of the spilled hydraulic oil.

A simplified schematic of the test hardware is shown in Figure 4. The test set up and annotations as to post test observations are shown in Figure 5. Extensive burning occurred in the SA-5 Annin Throttling valve, as illustrated in Figures 6 and 7. Also, damage was observed in a flowmeter (LA-71). The meter lost two adjacent rotor blades; a retaining ring was dislodged; and two anti-rotation pins were missing (Fig. 8 and 9).

The 6-in. diameter flowmeter, made by Flow Technology, Inc., Tempe, Arizona, was of 1970 vintage and had been previously used in development testing (16 tests and 413 sec test time). The ten blade rotor was SAE 9310 steel, nickel plated. Most other parts were 302 and 304 CRES. Following the failure, two adjacent blades were missing; the 308 CRES anti-rotation pins were missing; the 440C CRES rotor bearing was free, but rough running; and the Sprialoc ring, which held the flow straighteners in place, was out of its groove and bent over the downstream vanes. Analysis of the rotor blades showed them to be AMS 6260 aircraft quality 9310 steel, with a hardness of RB 93-96. Some globular oxides and sulfides were evident in the microstructure, and the material showed a typical air melted structure. Failure in both blades initiated at the leading face. The leading failed blade had numerous scratches from sanding and a portion of the fractured edge followed a large scratch. The fractures were primarily cleavage type, and were found to be identical to samples broken in the laboratory by bending LN_2 soaked specimens. Some other blades on the rotor were slightly undercut at the root; the second fractured blade was 0.0001 out of spec; and part of the fracture ran through this area (Fig. 10). Stress calculations on the blade showed that the combined torque load on the blade and a load calculated from the impact of a loose anti-rotation pin would approach the yield strength of the alloy.

The 6-in. Annin valve was of typical construction and was used as a throttling valve with a fail open mode. The poppet shaft seals were on the low pressure side of the valve. The valve body material was 316 CRES and the lip seal of the valve was an integral part of the body. The poppet material was also 316 CRES, containing an AMPCO aluminum bronze seal ring which mated against the 316 body for sealing. The poppet shaft rode in an aluminum bronze bushing and was sealed by a battery of Teflon chevron seals in the shank.

The Grayloc fittings at each end of the Annin valve had 316 CRES hubs welded to the valve body. The T-seal was 17-4 ph CRES coated with Teflon and the clamps were 304 CRES.

The accident investigation board concluded that the probable cause of the accident was the loss of blades from the LA 71 facility flowmeter and subsequent ignition from the impact of the blades with downstream components, probably the SA-5 valve. It was also concluded that this valve operated with a cavitation condition just downstream of the throat. This condition would tend to propagate burning once ignition occurred. The resulting internal fire would restrict flow from the HPOTP causing excessive pressures in the ducting, loss of flow in the preburner pump, subsequent overspeeding and fire, and cavitation in the HPOTP leading to overspeeding and fire. Hydraulic lines used for control of servo valves were severed and the spilled hydraulic fluid caused secondary damage to the test stand and associated instrumentation.

Significant corrective actions taken as a result of this accident were as follows:

1) The flowmeter was redesigned to minimize the risk of blade breakage and loss of pins and retainer rings due to mechanical vibrations.

2) Revised procedures were implemented in the operation of throttling valves. The procedures were developed to minimize valve position changes during high lox flow conditions; cavitation conditions were avoided; and additional screens were employed to intercept foreign particles.

3) More stringent inspection procedures were employed to reduce the risk of outside contamination entering the system.

4) Additional structural supports were added to reduce flow induced vibrations.

5) The design of the hydraulic oil system was modified to permit quick isolation in case of a fire on the stand.

6) New and improved instrumentation cabling and protective covers were designed. Spray-on and bond-on insulations were extensively employed.

7) Additional instrumentation was added to detect abnormal flow, vibration, or temperature conditions.

General Remarks

No positive conclusion was reached as to the direct initiator of this accident, although many possible contributors were studied. Laboratory impact tests of the flowmeter blades in lox demonstrated that ignition could have occurred because of this failure mechanism. Calculations also showed that cavitation in the throttling valve could have been severe enough to cause ignition from adiabatic compression, especially if small particles of contaminants were present. Just downstream of the throttling valve, a Grayloc fitting was coated with Teflon. Vibrations in the system were calculated to be of sufficient magnitude to have caused an ignition at the seal mating faces, if some contaminant had been present to result in a localized reaction. Some traces of sand and other contaminants were found in the ducts, probably introduced during assembly or during modifications. Any of these factors could have caused the fire; however, the conclusions reached by the investigation were based on the most logical sequence of events as constructed from the evidence. Many changes were made in the system during reactivation to eliminate most of the problems mentioned, and no further difficulties were encountered during the ensuing test program.

March 1977 - Engine 0003 - High Pressure Oxidizer Turbopump Primary Seal Failure

On March 24, 1977, during a test of SSME Engine 0003, at Test Stand A-1, National Space Technology Laboratory (NSTL) at Bay St. Louis, Mississippi, a fire occurred in the area of the high pressure oxidizer turbopump (HPOTP) at approximately 74 sec into the test.

The planned test duration was 520 sec and the test was planned to cover various power levels. Test designation was 901-110.

The first indication of a problem was the observance of a fire at the exit of the lox primary seal cavity drain tube followed by a large fire at the lox turbopump which engulfed the engine. The engine controller initiated cutoff of the engine and the test facility firex system suppressed the fire within 30 sec.

A schematic of the HPOTP is shown in Figure 11. The major external fire damage is illustrated in Figures 12, 13, and 14. Because of the extensive internal burning of the turbopump, the task of determining the specific cause of the fire was very difficult, as is usual for lox fire accidents. Many possible causes were considered, analyzed, and failure scenarios developed and studied.

The investigation board was unable to positively identify the actual origin of ignition. Extensive post accident laboratory tests and experiments were conducted at Rocketdyne and at MSFC to simulate component operational conditions and to determine safety margins and sensitivities of the various components to ignition. The sources that were determined to have the potential of causing ignition were:

1) Loss of hydrodynamic lift in the primary lox seal, causing rubbing of a carbon seal against a stainless steel mating ring, creating frictional heat and ignition of the carbon composite. Figure 15 illustrates the configuration of the primary seal area of the HPOTP, and the associated materials of construction.

2) Primary oxidizer seal bellows (Inco 718) weld failure, allowing oxygen leakage.

3) Ignition of the interface of the bellows and its vibration damper as a result of friction.

4) Contamination in the seal cavity.

5) Hot gas leakage past the intermediate seal into the primary seal area.

6) Vibration of the carbon seal against the mating ring.

7) Insufficient intermediate seal purge gas.

8) Dimensional tolerances in the seal area.

Since no direct cause could be identified, design changes of major importance were implemented to correct all deficiencies defined. A new primary seal concept was employed using a labyrinth concept, and the carbon seal concept was eliminated.

The experimental studies supporting this investigation are briefly described below:

The major materials used in the HPOTP seal package are listed in Table 1. Oxygen compatibility for each material was confirmed by laboratory tests under the environmental conditions experienced. Three extensive studies were made: (1) ignition studies of the primary lox seal carbon (P-692) ring by rubbing and overheating; (2) ignition of the thin metal bellows (Inco 718) by fretting against the damper ring, fatigue failure, or adiabatic compression of trapped oxygen gas; and (3) particulate contamination of either carbon seal or bellows, producing fresh surfaces and local hot spots under the dynamic use conditions. Post accident examination showed that the metal bellows and damper spring had burned completely, but the carbon seal was only partially burned.

The laboratory tests were designed to study the combustion characteristics of the two materials involved. The results were as follows:

Summary of Carbon Seal Tests

1) The P-692 carbon material autoignites at 560°C in O_2 at one atmosphere under normal equilibrium conditions

2) It is possible to ignite carbon P-692 by ignition of adjacent in-contact Inconel 718 in 400 psi O_2.

3) Once ignited, P-692 carbon will normally sustain combustion in 50 psi O_2 at room temperature.

4) Burning P-692 carbon can also ignite adjacent in-contact Inconel 718 foil.

5) An excess quantity of liquid oxygen can quench the combustion of P-692 carbon.

Summary of Inconel 718 and Inconel X750 Tests

1) Inconel X750 is considerably more difficult to ignite than Inconel 718 at 400 psi O_2.

2) Once ignited, Inconel 718 (5 mils) will sistain combustion over 50 percent of the time, whether at 50 or 400 psi O_2.

3) Secondary ignition of Inconel 718 foil can occur by contact with burning droplets of Inconel 718.

4) Temperatures near the melting point (2300 to 2500°F) are required for initial ignition of Inconel 718 in 50 psi oxygen.

5) Rupture of an Inconel 718 bellows by fatigue vibration, while exposed to 400 psi O_2, did not produce a fire. (However, other tests made on samples of this material show that ignition can occur under similar conditions if the fresh broken edges are excited sufficiently to result in very localized high temperature areas).

June 29, 1977 - Santa Susana Coca 1B - Preburner Facility Oxidizer Throttle Valve (SB-1)

Test 018, an SSME Preburner assembly test, was conducted on June 29, 1977, at the Coca 1B Test Facility. The test was planned for a duration of 10 sec mainstage operation. A fire occurred in the preburner main oxidizer throttle valve during the start transition and there was a subsequent burn-through of the facility lox line.

A sketch of the basic facility system is shown in Figure 16. A sketch of the SB-1 valve seat and stem assembly is shown in Figure 17.

Post-test inspection revealed that the SB-1 throttling valve plug and body (4-in. Annin oriented with flow over the plug) were burned at the plug seat area, downstream of the seat area and the facility ducting downstream of the valve. The valve body was eroded internally to a depth of approximately 1-in. Figure 18 is a photo of the burned body.

The investigating team for this incident concluded that induced vibration coupled with flow induced erosion of the seat resulted in ignition of the material.

Analysis of the hot fire data for the test series showed that the SB-1 valve throttling characteristics had changed throughout the test series, indicating progressive plug erosion. The vibration, induced by cavitation at the valve seat area, caused intense impact between the plug and seat, resulting in an impact mechanism with lox on a fresh unoxidized surface of metal.

The investigation found no evidence of foreign contamination in any associated component. No other material deficiencies were found in any other part of the system that could have attributed to the SB-1 valve failure. There was no evidence of impact from any migrating particles. No materials incompatibility was found in the survey; all valve softgoods were appropriately batch tested and found acceptable.

The valve plug material was Ampco 18 and the body material was 21-6-9 CRES. Both of these materials had been previously certified for lox service by testing in 8500 psi gox at 600°F and 10 Kgm. Some Teflon flakes (which came from the valve stem spacer and that were sandwiched between the Ampco 18 and 21-6-9) were tested in 7000 psi gox at RT and 10 Kgm without any reactions. A study of the heat of combustion of Teflon was made and the possibility of this material serving as an ignition source for the metal was discounted.

Another similar valve was examined and evidence of a discoloration on the plug was noted. This was identified as an oxide film which normally forms from an exposure to 400 to 800°F. This indicated that the flow conditions within the valve are capable of producing sufficient energy to increase the temperature to a high level.

Thermal studies of the valve showed that the 1-in. eroded depth of the valve body could have taken place in approximately 750 msec. This corresponds to the test parameters and observations.

Corrective actions taken as a result of this incident were as follows:

1) Valves were reversed in this and similar usages to result in flow under the plug. This would reduce cavitation and induced vibration, prevent damage to the shaft seal during shutdown surges, and result in the valve seat being upstream of any shaft stem seal debris.

2) Clearances of plug and seats were changed to minimize impact during vibration and dwell times at positions that would permit impact were minimized.

3) Assembly bolts were modified to provide positive retention.

September 1977 - National Space Technology Laboratory-
Test Stand A-1 SSME Engine 0004 High Pressure Oxidizer Turbopump

On September 8, 1977, during a test firing of SSME Engine 0004 at the National Space Technology Laboratory, Bay St. Louis, Mississippi, a fire occurred in the area of the high pressure oxidizer turbopump at 300 sec into the planned duration of 320 sec.

The initial fire was observed at the HPOTP inlet duct. This duct immediately ruptured and separated from the engine at the inlet and at an internally restrained bellows joint assembly, approximately two ft upstream of the HPOTP inlet point. The low pressure pump housing ruptured at this point causing a general conflagration around the LPOTP and HPOTP area, resulting in extensive external burning of the engine. The fire was suppressed within 5 sec by the facility firex system.

The major damage was confined to the HPOTP, LPOTP, and connecting duct work (Fig. 19). The HPOTP was almost completely destroyed by fire; the LPOTP, as well as portions of the duct work, appeared to have ruptured from overpressure. Damage to the discharge section of the HPOTP was less than at the inlet side. Other small feed lines were ruptured, primarily as secondary failures because of the extensive burning. Also, many instrument lines, sensors, and valves were damaged.

The investigating board concluded that the failure was caused by a bearing failure in the HPOTP. A load imbalance of the four bearings apparently occurred because of liquid oxygen coolant flow characteristics. The flow was such that the axial and radial loads on the pump end pair of bearings were not shared, but were concentrated on the inboard bearing. Also, the inboard turbine end bearing was not cooled adequately to provide satisfactory bearing life. The board also found inadequacies in the pump rotor balancing that needed more improvement. A cross-sectional view of the HPOTP is shown in Figure 20. A sketch of the HPOTP is shown in Figure 21 showing the principal areas of damage.

1. <u>HPOTP Housing</u> - The Inconel 718 housing had accumulated 2693 sec of test time, having been rebuilt several times. No discrepancies were found to indict the housing as the cause of failure.

2. <u>HPOTP Shaft</u> - Little damage occurred to the Waspalloy TMP shaft. It was judged not to have contributed to the failure.

3. <u>HPOTP Turbine Rotor and Blades</u> - (Material: Waspalloy TMP Rotor; MAR-M-246 Hf Blades). Both the first and second stage rotors were intact and no burning occurred in this area of the turbopump. Many blades were damaged mechanically by rubbing, caused by bearing failure and shaft unbalance, but no blades were missing from the rotors. Several bolt failures in the rotors were attributed to high centrifugal forces as the pump oversped during failure.

4. <u>HPOTP Honeycomb Tip Seals and Interstage Seals - Turbine End</u> - (Material: Tip Seals, Haynes 188 and Inconel 625; Interstage Seals, Incoloy 903). The honeycomb seals were destroyed by the blades and the labyrinth seals were worn away by the eccentric rotation of the shaft and rotor. No burning occurred in this area.

5. <u>HPOTP Seal Package</u> - The primary lox seal labyrinth (Kel-F and Inconel 718) was partially burned. A portion of the Kel-F remained intact in its housing, and the shaft part of the labyrinth was intact and in good condition. It was concluded that this area was not the source of ignition.

6. <u>HPOTP Bearings</u> - (Material 440C Balls and Races, Figure 22). All bearings (Nos. 1 and 2 on the pump end and Nos. 3 and 4 on the turbine end) were burned and essentially destroyed except for parts of the inner and outer races. All balls were missing and assumed destroyed

by fire. Examination of the remaining races indicated moderate to heavy synchronous radial loads and non-uniform wear, indicating an unbalanced condition. It appeared that the worst fire damage occurred between the two sets of bearings, in the inducer area, and was more severe on the No.2 bearing side.

7. HPOTP Bearing Cartridge - (Material: Cr plated Hastelloy B, overcoated with Dry-Film Lubricant). The pump end cartridge was consumed by fire. The turbine end cartridge was intact. Spalling of the coating and improper plating were discovered on this cartridge, but this discrepancy was judged not to have caused bearing failure.

8. HPOTP Main Impeller - (Material: Inconel 718). The impeller was severely burned with only a thick hub remaining. Contribution to the failure could not be determined.

9. HPOTP Preburner Impeller - (Material: Inconel 718). This impeller was also consumed, with only a hub remaining in contact with the shaft.

Failure Sequence

The most probable failure sequence leading to the HPOTP fire was concluded to be as follows: The bearings at the pump end received too much cooling from the lox flow and the bearings at the turbine end too little cooling. At the pump end the excessive flow caused unequal axial loading between the two bearings resulting in the No. 2 bearing (inboard) carrying approximately 90 percent of the radial loads. At the turbine end, the flow caused No. 3 bearing (inboard) to carry about 75 percent of the axial load, and at the same time, the flow was inadequate for proper cooling. With these conditions, a gradual degradation occurred causing an unbalanced condition and subsequent vibrations in the pump. The bearings continued to lose stiffness and the shaft dropped into a synchronous speed range. Then, the loads increased significantly, leading to increased degradation rate of the bearings, eventual rubbing of the shaft and labyrinth seals, higher lox flow to the pump end bearings, and rubbing at the turbine end. At approximately 300 sec, sufficient heat was generated by rubbing of metal parts to initiate a fire.

Corrective actions were taken to improve the coolant flow in the pump and to refine the pump balance to equalize bearing loads.

April 1978 - SSME Engine 0002 and Engine 0005 Main Injector Failures at National Space Technology Laboratories

SSME Engine 0002 was undergoing its ninety-third mainstage test at National Space Technology Laboratories, Bay St. Louis, Mississippi, in April 1978, when failure occurred in the main injector. The engine had accumulated 93 tests and 6125 sec total test time, and the failure occurred at 200 sec into test 901-173.

Damage was limited to a burnthrough of the injector secondary and primary face plates, burning of lox posts, and retainer and nozzle tube ruptures.

Post-test examination revealed a crack in the radius of a lox post, and several lox posts were bent, up to 1/4-in. in line with the outside hot gas transfer ducts. Some damage was observed on 18 lox posts and retainers. Cracks were found in the interpropellant plate.

A sketch of the injector and posts is shown in Figure 23. A lox post illustration and a cross-section is shown in Figure 24. Figure 25 shows several bent lox posts and Figure 26 shows general damage to the post tips and injector face.

The investigation of this failure concluded that the crack in the tip of lox post No. 77 (in No. 13 outer row) was caused by high cycle fatigue. This particular crack was not a through crack; it had progressed 0.010 through a 0.020 in. wall. The bent posts were caused by high temperature, high velocity, hot gas impingement. The lox posts were made from 316L CRES and apparently lacked sufficient high temperature strength to be structurally adequate. The Inconel 718 interpropellant plates were cracked parallel to the post axis and the cracks were attributed to low cycle thermal fatigue. One other post (post 8, row 12) was found to have failed at the friction weld, on the 316L side, by hot tensile failure, primarily because of overheating after the burning began. Early in the development program, the lox posts were made from HS-188, and no bending or cracking was encountered during testing. The 316L posts were used after the first three injectors, since the structural and thermal analysis showed them to be adequate, and considerable difficulties had been experienced in manufacturing the HS-188 units. The high loads and temperature effects and subsequent bending of the 316L posts had not been anticipated.

Laboratory studies made in support of the failure investigation further defined the lox post vibration frequencies and mode shapes. Dynamic and structural models were made to simulate the failure mode. Vortex flow models were made and studied. It was concluded that the lox posts in line with the outer gas ducts failed first because of higher dynamic forces and higher temperatures. Thermal bending of the post caused increased tip loading. Vibration was most severe in the outer row of the posts. Consequently, several modifications were made to the main injector, including the incorporation of larger propellant face plate nuts, and better GH_2 cooling of the lox posts by using larger GH_2 orifices.

June 1978 - SSME Engine 0005 Main Injector Lox Post Failure at National Space Technology Laboratories

Following the failure of the injector posts in Engine 0002, fatigue cracks occurred in the thread roots of some posts in Engine 0005. A through crack developed in one outer row post and some burning resulted downstream of the crack. The failure was a typical high cycle fatigue crack, resulting from similar high frequencies, temperatures, and loads as experienced on Engine 0002. Some face plate cracking and interpropellant plate cracking were also experienced.

Extensive dynamic, structural, and thermo dynamics tests and analyses resulted in a decision to reinforce the outer row posts in-line with the inlet ducts to strengthen them. This was done on an interim basis; later the outer two rows of posts were strengthened by brazing tips of HS-188 alloy onto the 316L and still later, these parts were changed to an all HS-188 machined post.

July 1978 - Engine 0101 High Pressure Oxidizer Pump Failure at National Space Technology Laboratories

On July 18, 1978, SSME Engine 0101 experienced a high pressure lox pump failure during test 902-120. The test was programmed for 300 sec and was terminated at 41.8 sec due to the failure. The specific turbopump, No. 0301, had undergone approximately 1280 sec hot firing time in previous tests on various engines, but had been modified for this latest series of tests with a capacitance type speed sensor in the pump. There were also some internal accelerometers and strain gages installed in this unit, with the first pump so instrumented.

The engine was operating at 100 percent rated power level when the failure occurred. Damage to the engine was extensive. The low pressure oxidizer pump (LPOTP) housing fractured and separated with multiple fractures, but no evidence of primary burning was found in this pump. The connecting duct work and flexible joints between the low pressure and high pressure pumps fractured. All burned segments were concluded to be caused by secondary burning. The high pressure oxidizer turbopump (HPOTP) sustained extensive burning, more severe at the pump end. The preburner end showed relatively little damage. Other minor components were both mechanically and fire damaged, as well as many lines and instrumentation cables. Minor damage to the test stand facility occurred.

Within the HPOTP, there was major damage and loss of material consumed by the lox fed fire (Fig 27). Essentially all damage at the turbine end of the pump was caused by mechanical failure during spin down. The turbine wheels rubbed and damaged the blades severely. The interstage seals were destroyed by rubbing and impact loads. The turbine shaft seal and intermediate seal were not burned. The primary lox seal area was burned extensively, but the Kel-F labyrinth seal was only charred (approximately 95 percent intact). There was no burning downstream of the labyrinth. It did not appear that the fire initiated in the primary seal package, but that fire came through the bearings from the pump end area. The bearings were heavily damaged on the pump end. The capacitor speed sensor device was completely consumed, as well as the flow turning vanes. The inlet area of the housing was heavily burned; the main impeller vanes and shroud as well as the preburner impeller were destroyed. The preburner pump housing was completely burned away inside and several burnthroughs occurred.

The investigating team concluded that the fire initiated in the area of the capacitor speed probe which was installed for R&D purposes only, and that the fire was most likely the result of rubbing of the device against the rotating shaft. Analysis of the data from this test and from the preceding test led to the conclusion that a fire had also initiated on the previous test, but self quenched without any hardware damage.

The capacitor device was studied in detail with respect to construction, materials, amount of energy to ignite and energy liberated by burning, and dynamic characteristics. Many other causes of ignition were postulated and each considered in detail. After consideration of all modes of failure, it was concluded that the most likely cause of failure was the deformation of a part of the capacitor device because of high lox flow forces, and subsequent rubbing of the deformed part against a speed nut on the pump shaft. A sketch of the speed device is shown in Figure 28. The mode of deformation is depicted in Figure 29. The materials used in its construction were adequate for use in lox under normal circumstances. However, small particles of abraded 303 stainless steel which could result from rubbing of the speed pad against the shaft nut could be ignited from the frictional heating. The ignition point in 50 to 800 psi oxygen would approach the melting point, 2500°F, but freshly abraded particles could ignite at a lower temperature. Simultaneously, frictional heat on the probe pads caused by rubbing would be conducted to the Armalon (Teflon) insulation which could ignite at about 870°F at this pressure. This Armalon ignition would trigger a rapid and massive combustion of the entire probe and surrounding structure.

Extensive laboratory testing was accomplished to support the conclusions reached by the investigating team. These tests included friction/wear tests, dynamic flow tests, ignition tests in oxygen, structural testing of the capacitance probe, electrical measurements, and thermal conductivity tests.

One failure mechanism postulated was the rubbing of an Inconel 718 slinger on a mating silver surface (silver plated Inco 718). However, silver has been determined to be extremely difficult to burn in lox or gox. It melts and relieves frictional heating long before the combustion temperature is reached; thus, it is an excellent wear-seal material.

The speed device has not been used in subsequent engine tests.

September 1978 - Engine 0005 High Pressure Lox Duct Flow Guide

During SSME Engine 0005 tests 901-185 and 186 at National Space Technology Laboratories in September 1978, a rather unusual failure occurred in a high pressure lox duct. Although an internal fire was experienced, the burning did not propagate extensively and apparently self-extinguished.

The high pressure duct system involved is shown in Figure 30. The flow guide was located immediately upstream of the main oxidizer valve (MOV). The guide was made of annealed Inconel 718. The major damage was a crack approximately 0.8-in. long which was ignited and melted for about half its length, as shown in Figures 31, 32, and 33.

Examination of the flow guide disclosed extensive cracking around the circumference because of high cycle fatigue. Figures 34 and 35 show dye penetrant indications of these multiple but small cracks. The largest crack had ignited as a result of heat generated by severe vibration and rubbing together of the fresh fractured surfaces, and some of the metal had melted and eroded away. The burning apparently stopped prior to engine shutdown, probably because of quenching by the flow of oxygen through the burned opening into a low pressure cavity region surrounding the flow guide.

Some ignition and burning rate tests at Southern Research Institute indicated that specimens of materials such as Inconel 718 can burn to a distance of 1/4-in. in approximately 0.006 sec after ignition. Thus, the burning in the flow guide probably was sustained for an extremely short period, perhaps on the order of 0.01 sec. The test time for the duct was 290 sec, thus the fatigue cracks occurred during that time. Scanning electron microscopic examination of the fractured surfaces showed a mixture of melted material, ductile overload fracture surfaces, and high cycle fatigue fracture surfaces.

A redesign of this component was made to eliminate the resonance cavity behind the flow guide. Later units were made solid, omitting the cavity. No further occurrences of this specific mode of failure have been encountered in this duct.

December 1978 - Engine 0007 - Heat Exchanger Coil Failure

On December 6, 1978, during SSME Engine 0007 test firing 901-222, at the National Space Technology Laboratories, a fire occurred in the vicinity of the heat exchanger discharge line before a premature cutoff at 4.33 sec. The test had been programmed for a duration of 50 sec.

A teardown inspection of the engine, a review of motion picture film, and data evaluation indicated that the fire initiated in the lox heat exchanger. Major damage resulted to the heat exchanger, the high pressure oxidizer pump, the hot gas minifold, and the main injector. No significant damage was sustained by the test stand. Damage external to the engine was slight, although major internal damage occurred.

Figure 36 is a schematic of the powerhead showing the heat exchanger location.

Figures 37 through 41 illustrate the damage caused to the heat exchanger assembly, manifolds, and preburner. The heat exchanger coil was destroyed, the preburner liner and walls were burned through, and the overall powerhead was severely burned. The turbine support housing in the high pressure lox pump was burned through to the internal nozzle area.

The failure investigating board concluded that the failure initiated in the heat exchanger, as a result of a leak in the coil. Ignition of the lox rich plume probably severed an adjacent coil allowing massive quantities of lox/gox into the turbine exhaust stream. The ignition and detonation of this lox rich mixture caused a shock extending the damage. The metal/oxygen fire then extended from the ruptured coils downstream to the hot gas manifold, to the transfer tubes, and on to the main injector. Subsequently the external HEX/gox discharge line ruptured, causing superficial external fire damage; before engine shutdown.

No positive decision was reached as to the cause of the initial heat exchanger tubing leak; however, several possible reasons were found. The most likely cause was damage to the coil by an electrical arc during a local weld repair.

Laboratory tests were made to demonstrate that a weld high frequency arc jumping between the coils and its supporting bracketry could result in a pinhole leak. Many welds are made during the course of fabrication of the heat exchanger unit, thus particular care in welding was specified. However, it was determined, for one particular series of modifications, that the welder failed to use the recommended procedure of grounding the welder to the closest point of the structure to the torch; instead, the ground was clamped to the external protrusion of the tubing. The resultant electrical path could have caused a pinhole leak by arcing between the coil and the bracketry, on which the repair was being made.

To prevent future occurrences of this kind, several corrective actions were taken:

1) Welding procedures were reviewed and techniques to prevent this type of problem were re-emphasized to welders.

2) Improved leak detection methods for heat exchanger coils were employed.

3) Higher pressures for proofing the coils were employed.

4) Modified coil forming methods were developed and new cleaning procedures used.

December 1978 - Engine 2001 - Main Oxidizer Valve Failure

On December 27, 1978, SSME Engine 2001 was tested on Test Stand A-1 at the National Space Technology Laboratories. The test was designated 901-225 and was scheduled to be the final acceptance test for this engine.

The scheduled 520 sec test proceeded normally until 255.6 sec when premature shutdown occurred because of high fuel turbine discharge temperature. Simultaneously, the main combustion chamber lox injector manifold ruptured and a general fire enveloped the engine.

The engine sustained extensive damage, internally and externally. Facility damage was limited to burning of electrical and instrumentation cables, pneumatic and hydraulic tubing, cameras, and general smoke damage. No damage to structural members resulted.

Analysis of high speed film and engine data showed that the initial failure occurred in the Main Oxidizer Valve (MOV). Recovery of the almost intact valve permitted a detailed inspection and it was concluded that the burning began in an interface joint between two parts of the MOV inlet area due to severe vibration and fretting and subsequent reaction with lox/gox. It was apparent that a screw had loosened allowing fine threads to rub across thin shims exposing fresh metal raised to elevated temperatures to high pressure flowing lox, leading to ignition.

An overall view of the engine showing the high pressure oxidizer pump area, and the missing pump discharge duct and main oxidizer valve is shown in Figure 42. Figure 43 shows the MOV and attached discharge duct as recovered after the incident.

A cross-sectional of the MOV is shown in Figure 44. Figure 45 is a sketch of the MOV and duct assembly with notations of the damage observed and other observations relative to the failure cause.

Figure 46 is a photograph of the inlet sleeve removed from the burned MOV. Note the thin shims used at the flange and the eroded flange section originating at a screw hole. This evidence and other observations led the failure investigation team to conclude that:

1) The MOV was undergoing severe vibrations due to an acoustic/flow characteristic of the propellant flow through the valve. (This vibration characteristic, predominantly in the 7200 Hz range, was later eliminated by closing the small gap at the inlet flange interface.)

2) The A286 steel screw loosened sufficiently to allow fretting of the mating parts, and the generation of localized heat where the screw threads fretted against the thin 302 CRES shims in the flange area (Fig. 46).

3) Ignition of the shims occurred and the burning propagated to the 21-6-9 CRES inlet liner and subsequently to the Inconel 718 bellows surrounding the liner.

4) The burning began to erode the downstream duct and simultaneously increased the pressure in the duct and injector manifold to a pressure exceeding the strength of the hot Inconel 718 ducting, resulting in rupture of the duct.

This failure scenario was supported by the pressure/temperature timelines in the test. Also, subsequent examinations of other MOV's in different engines substantiated that the severe vibrations and fretting were occurring in these units also. Figures 47 and 48 show an MOV inlet liner and bellows assembly removed from another valve and the evidence of severe fretting in the flange area. In addition to the design changes made subsequently to reduce the high frequency vibrations, most all close fit mating parts in the valves were dry film lubricated with lox compatible lubricants. Various types of lubricants were used for the several applications. Inlox 88, a phosphoric bonded moly-disulfide type was applied to several close fitting parts; Everlube 811, a silicate bonded moly-disulfide type was used where thicker films could be allowed.

Discussion

The MOV delivers oxygen to the injector dome at a pressure of approximately 4600 psia, and the flowrate is approximately 1060 lb/sec. Thus, the metal/oxygen reaction potential is increased considerably because of this high pressure and flow. A previous failure incident was described in this report in which the duct liner immediately upstream of the MOV vibrated and cracked and subsequently ignited and burned. In that case, the burning was self-extinguished before any significant damage was done.

Both incidents point to a requirement for extreme caution in designing components for this level of oxygen pressure and flow. As a general rule, the following precautions should be taken:

1) Mating parts and materials must be carefully selected to avoid high frictional heat.

2) Care must be exercised to avoid exposure of thin parts to oxygen because of heat absorption capabilities and burning characteristics.

3) Bolted parts should be torqued correctly with locking fasteners to prevent loosening and localized impact or fretting of metals.

4) Consideration must be given to the possibility of cracks in thin metals, which could allow rubbing together of fresh metal surfaces. Fatigue cracks in thin bellows may be particularly dangerous in high vibration applications.

5) The use of compatible dry film lubricants can significantly reduce metal fretting and wear in close fit design applications.

6) The use of the best fretting resistant metal combinations must be a design requirement where rubbing actions are likely to occur.

February 1979 - SSME Engine 0201 - Main Oxidizer Valve Seal Failure

On February 12, 1979, SSME Engine 0201 was tested at Santa Susana Test Facility for a 300 sec duration firing. This was the first test using S/N 0006 Main Oxidizer Valve (MOV). Following the successful test, disassembly of the MOV revealed severe erosion of the MOV Kel-F ball seal.

Figure 49 is a cross-section of the MOV showing the location of the Kel-F ball seal. Figure 50 shows the original configuration of the seal and Figure 51 is the damaged seal from the 0201 test. Approximately 120 degrees of the seal circumference remained; the other material was washed downstream by the lox flow into the lox dome and injector. The seal appeared to have been heated to the melting point beneath the surface. Many small pieces were recovered from the backside of the injector and all showed evidence of erosion and/or melting.

Examination of the other parts of the MOV showed that many dry film lubricated parts were worn and impacted in many places. The end of the ball shaft showed severe wear and galling. The mating guide sleeve showed evidence of spinning on the shaft and external wear. The seal opening cam surfaces were brinelled to some extent. Instrumentation showed that the MOV had experienced a 7400 Hz vibration. This particular MOV had incorporated some design change features employed to reduce these vibrations, but the modifications were not entirely effective. The energy level measured in this valve seemed to increase with test time.

It was concluded that the Kel-F seal experienced internal melting due to the high vibrational frequency encountered in this test. The material softened internally although the surface remained solid due to the high lox flow across it. The internal softening eventually caused sufficient strength loss to crack the cold brittle thin skin and subsequent mechanical failure occurred.

Discussion

This was the first time a failure of this nature had occurred in SSME components; however, a re-examination of some parts from previous tests showed slight indications of surface heating and cavitation erosion on some MOV seals.

The melting temperature of Kel-F is approximately 600°F and the ignition temperature is 640°F at ambient pressures in oxygen. This ignition temperature may be somewhat lower at higher pressures. Several possible heat sources were considered in the course of the investigation of this failure, such as:

1) Vibratory pounding of ball to seal.

2) Flexing of the bellows assembly.

3) Friction caused by oxygen flow.

4) Oxygen flow cavitation/bubble collapse.

5) Acoustic whistling

6) Compression heating.

Calculations were made to determine the heat generated in melting the MOV seal assuming a heat of fusion of 17 Btu/lb for Kel-F. Other calculations were made to show that the seal could have reached 600°F in 29 to 40 sec, assuming that the heat flowrate was constant. Yet, none of these calculations accounted for the source of the heat.

To support this failure investigation, high frequency fatigue tests on Kel-F samples were made at Hydronautics, Inc. These tests showed that, at a frequency of 8 KHZ, 0.0003-in. axial amplitude, some local melting resulted in the Kel-F after 10 sec. The test specimen external surface temperature reached 170°F in 10 sec.

These high frequency fatigue tests did not produce overall melting of the test specimens, but served to show that the material could have been heated to the melting point, even immersed in lox, by the application of sufficient high frequency energy.

Other laboratory tests supporting this investigation evaluated the mechanical erosion of a high pressure water "laser" jet on Kel-F, and several other materials. Water pressure was increased to actually penetrate a 1/4-in. thick Kel-F plate and the resultant damage appearance compared with the failed Kel-F MOV seal. The eroded surfaces did not compare, further supporting the conclusion that th MOV seal had melted, rather than eroded.

DISCUSSION

The failures described in these narrative accounts are recorded in detailed reports of Investigation Boards and Failure Investigation Teams.

As a group, these failures can be attributed primarily to the severe conditions encountered in high pressure high flow oxygen systems. The dynamic conditions existing in such a system are difficult to determine with conventional instrumentation and even more difficult to analyze. High-flow conditions cause complex boundary layer phenomena, gas pockets in many components, cavitation phenomena, localized friction, etc. The known reaction mechanisms of materials with lox or gox become difficult to relate to some conditions that exist in a complex, high-pressure high-flow system.

Corrective actions taken for the failures described have involved design, systems operations, and materials changes. In many cases, analytical techniques could be employed to direct these changes; in others, experimental trial and error type programs were implemented to solve the particular problem encountered.

The impact sensitivity of both metals and non-metals with lox or gox has been studied extensively by MSFC. In 1980, only two other facilities in the U.S. were active in routine impact testing of materials: Rocketdyne, Canoga Park, California, and White Sands Testing Laboratories, New Mexico. All of these laboratories were testing materials in support of the Space Shuttle development. All three groups have the capability to test at pressures up to 10,000 psi.

In addition to impact sensitivity, some oxygen reactivity sensitivity studies are being made by the National Bureau of Standards, Boulder, Colorado, under contract to NASA-MSFC. However, there is a paucity of information available on basic reaction mechanisms, thresholds of reactivity, and inhibiting conditions. Additional technology must be developed to support any new designs employing oxygen systems over 10,000 psi.

With respect to the selection of materials for oxygen systems, very few materials have been developed specifically for such systems. For the most part, existing materials have been characterized for use with oxygen, not developed for this purpose. Among the metallic materials, there seems to be little need to undertake the development of new alloys for oxygen systems of the foreseeable future. This is not the case for nonmetals. Less reactive seal materials, adhesives, fillers, paints, insulations, and protective coatings are needed, as well as more efficient, lox compatible lubricants.

An initial SSME program guideline was based on the use of state-of-the-art materials and processes, and this approach has been adhered to with very few exceptions. No extensive alloy or nonmetallic materials development program has been undertaken; but a very thorough materials characterization program has supported the SSME development to assure that the materials and processes used provided the materials compatibility assurance necessary for safe operation.

TABLE 1

LIST OF MATERIALS USED IN HPOTP PRIMARY SEAL AREA AND USAGE CONDITIONS

Material	Usage Maximum Pressure (psi)	Maximum Temperature (°F)
Carbon P-692	510	-300
Inconel 600	510	-300
Inconel 718	510	+500
Inconel X750	500	+500
321 CRES	400	+130
K-Monel	400	+500
Chromium (Plating)	400	+500

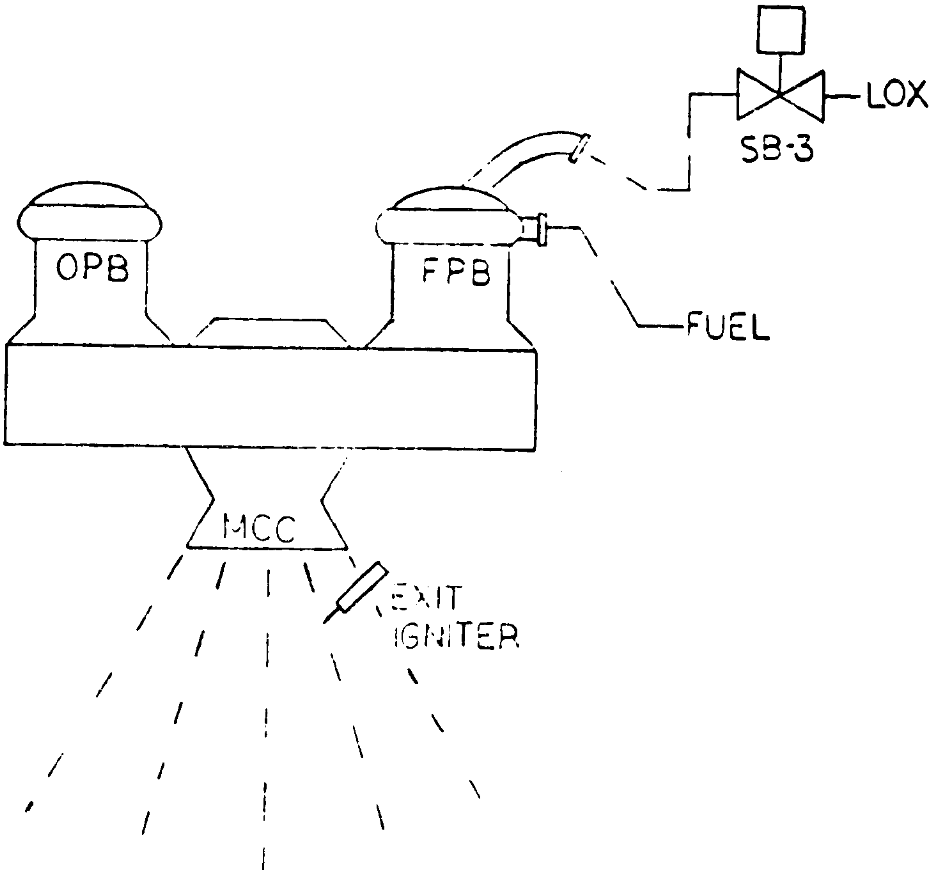


Figure 1. Coca 4B Test 014

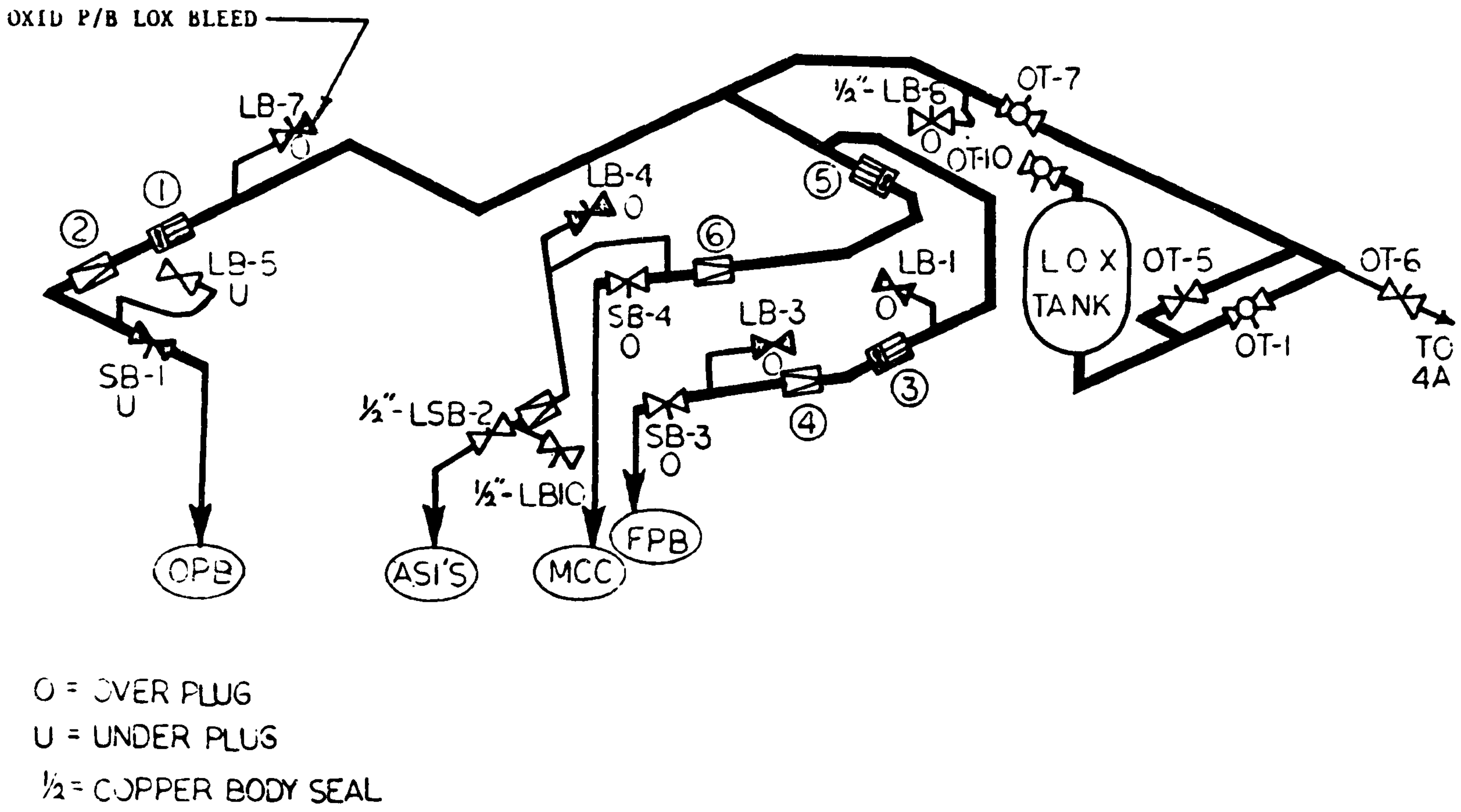


Figure 2. Isometric schematic C4B oxidizer system.

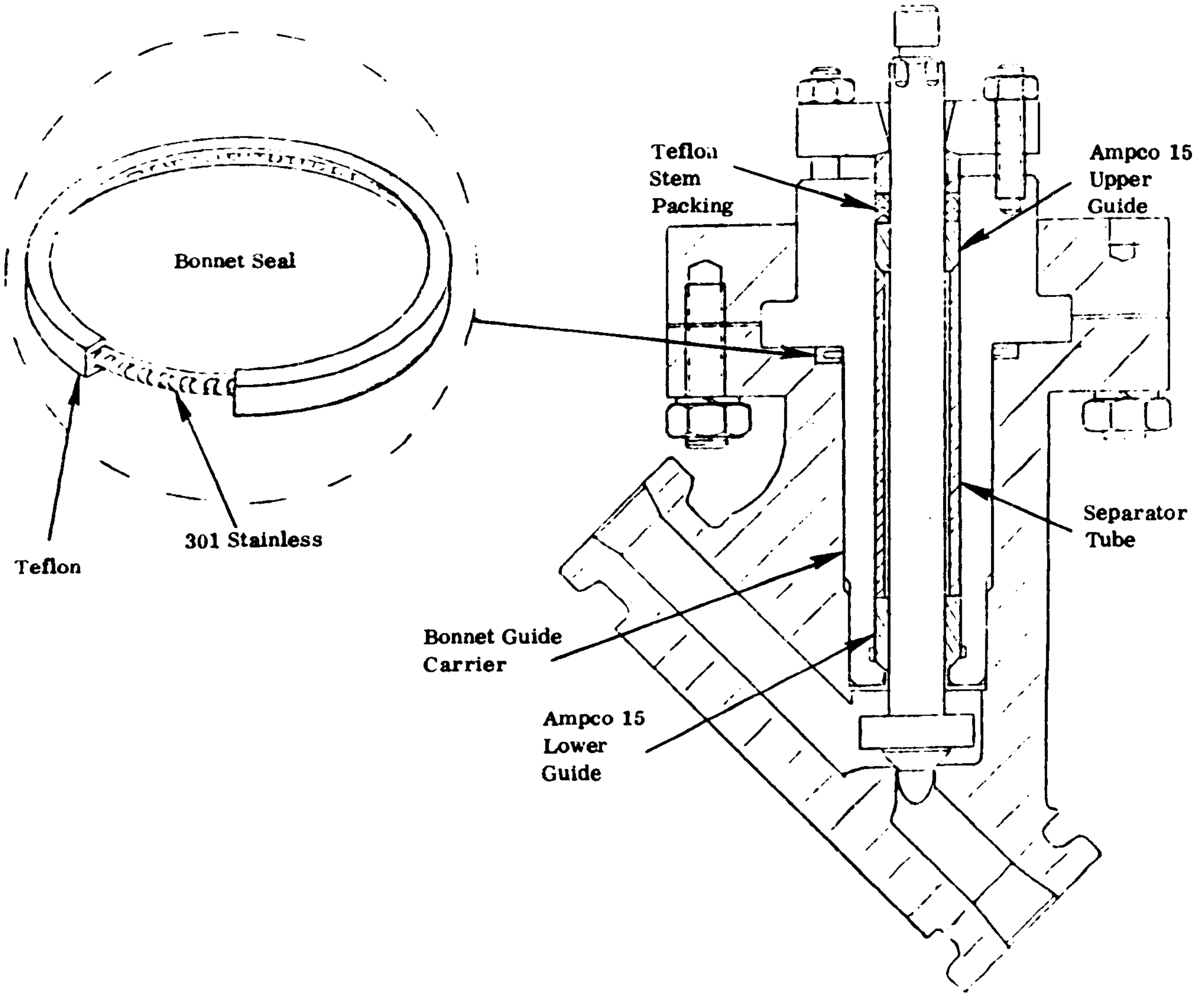


Figure 3. Coca 4B oxidizer P/B F/M lox bleed.

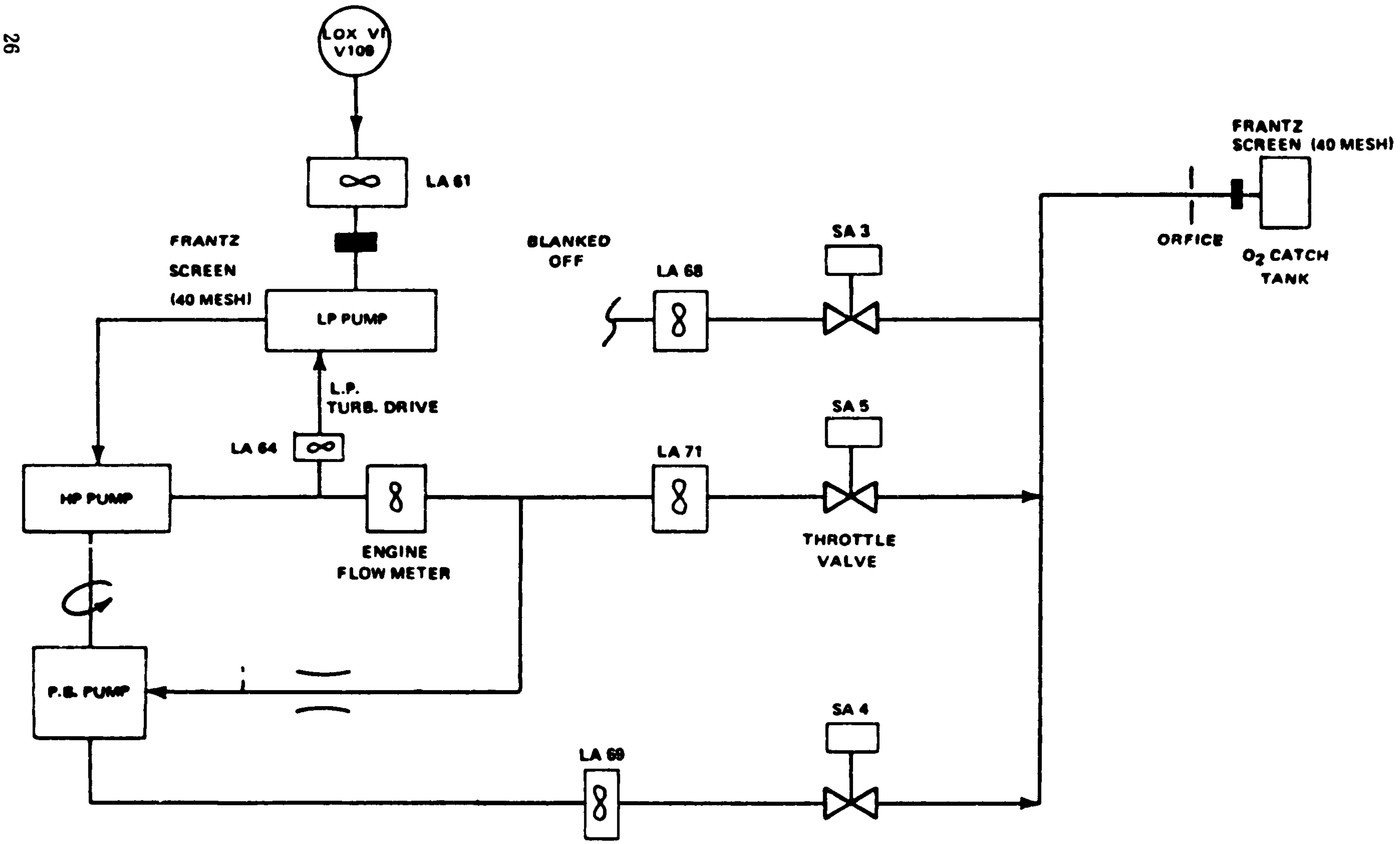


Figure 4. Coca 1A simplified schematic of test hardware.

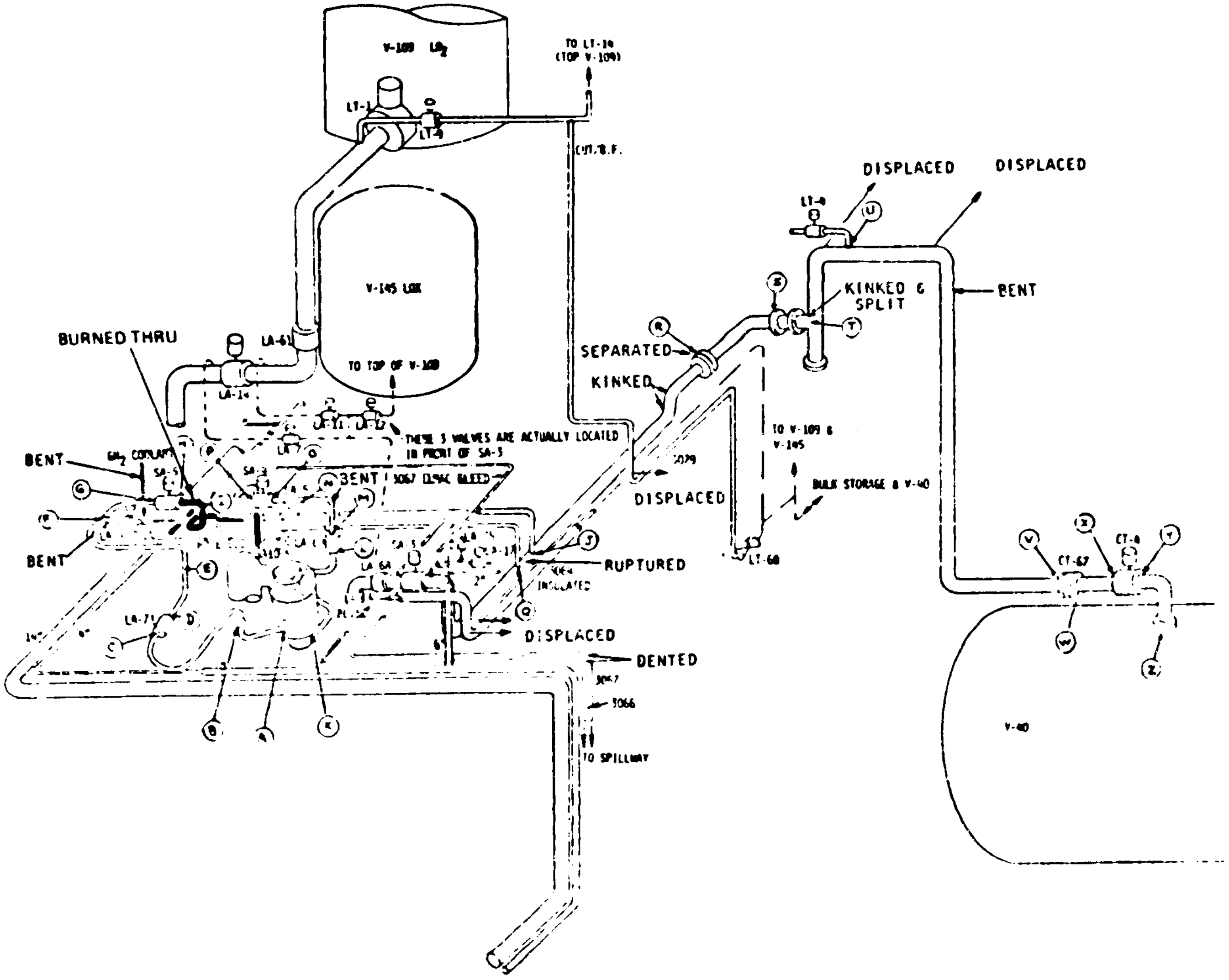


Figure 5. Coca 1A test set up - LPOTP not shown.

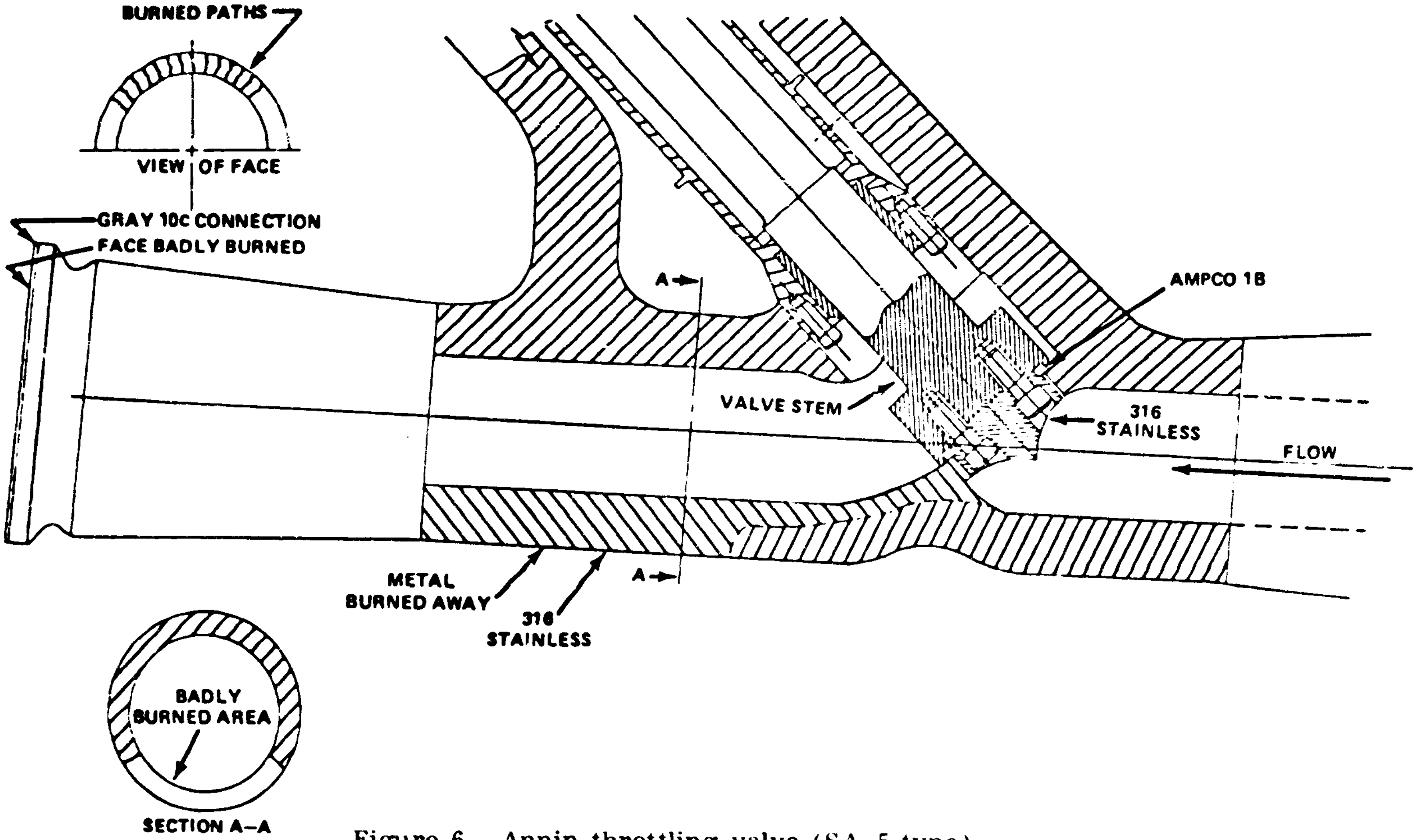


Figure 6. Annin throttling valve (SA 5 type).

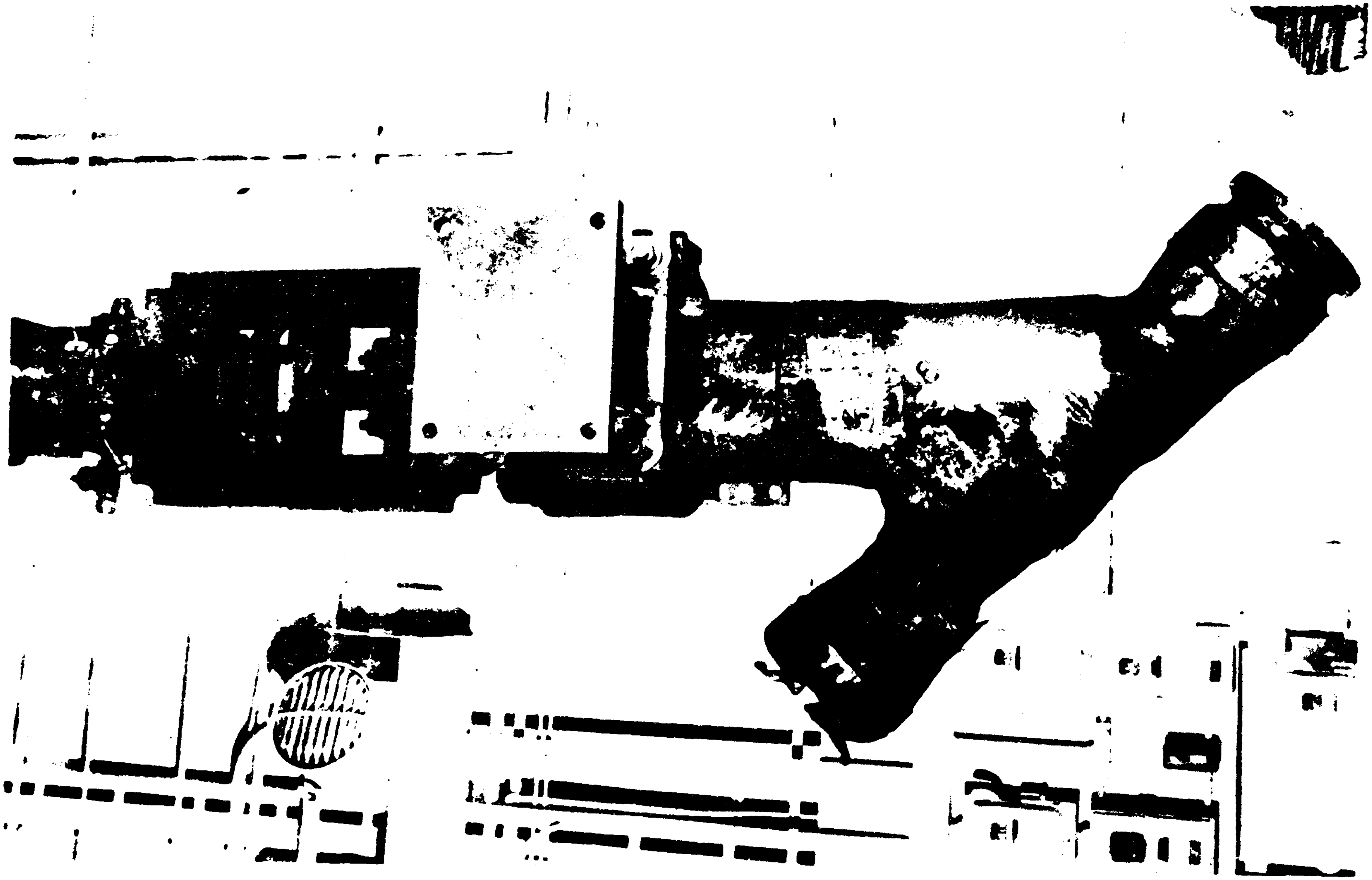


Figure 7. Annin valve SA5 - post test.

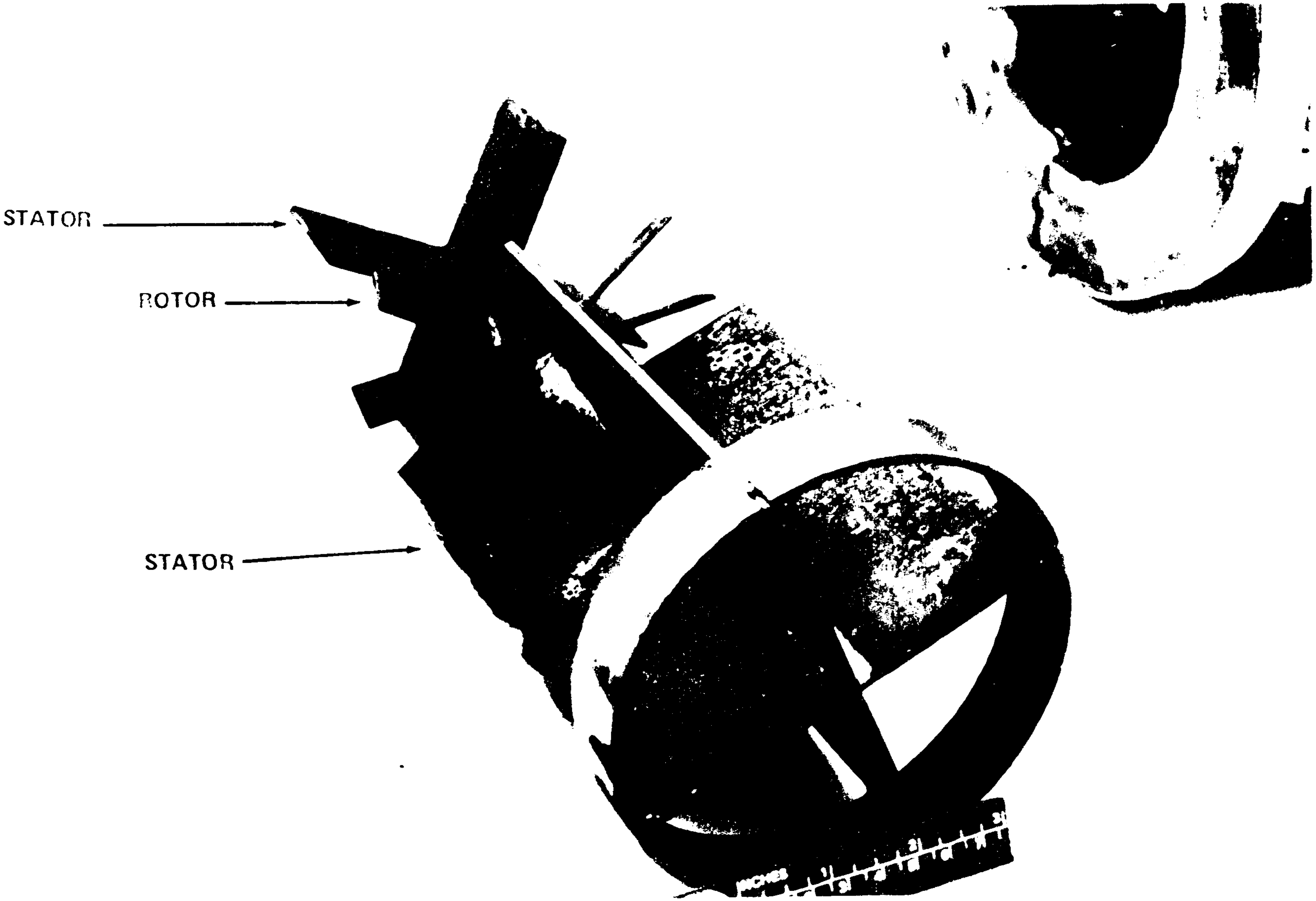


Figure 8. Coca 1A facility flowmeter LA71 - post test.

Figure 9. Coca 1A facility flowmeter SA71 retaining ring - post test.

Figure 10. Blade root of leading face of trailing blade.

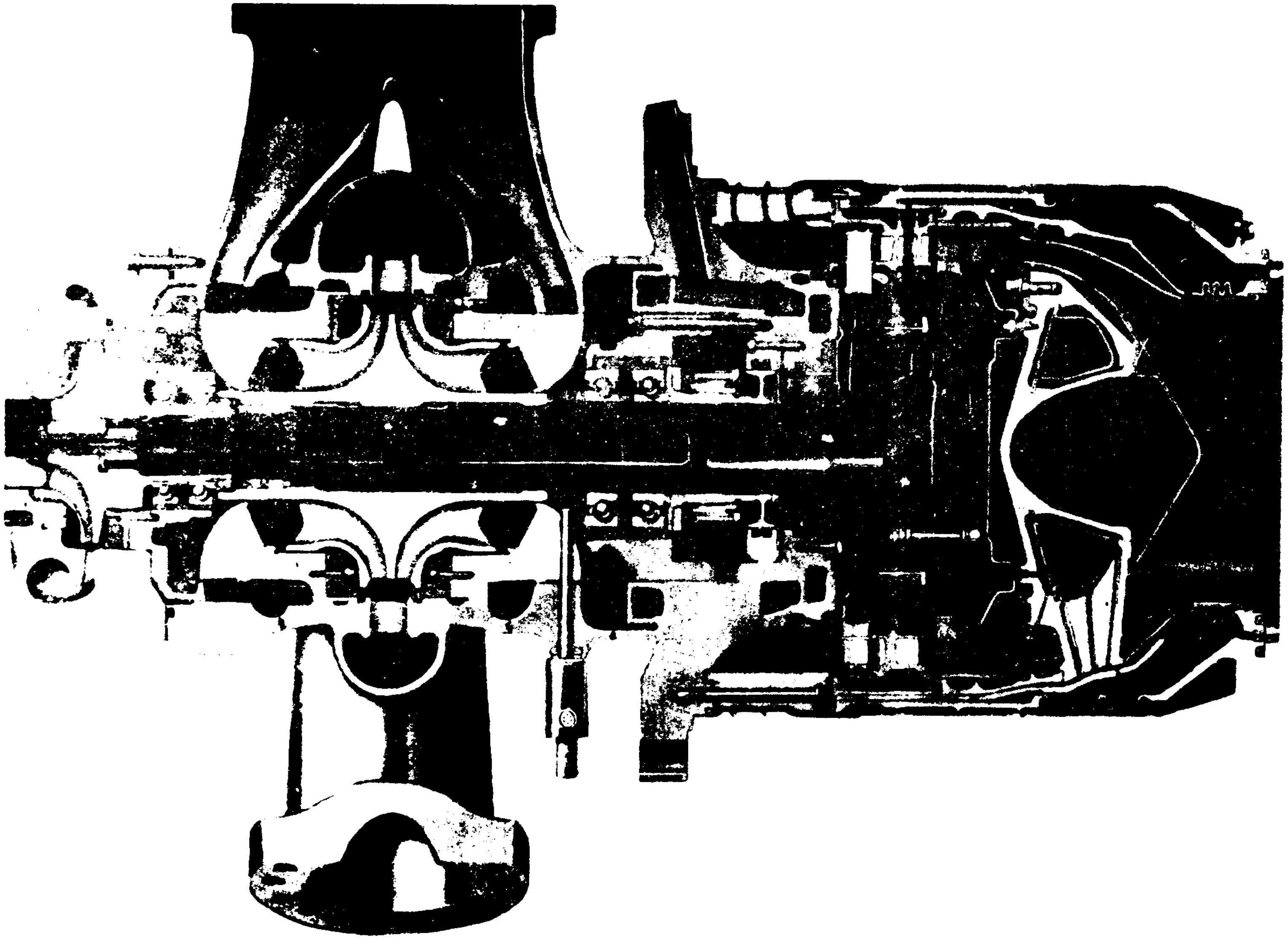


Figure 11. Schematic of HPOTP.

Figure 12. High pressure oxidizer pump inlet duct.

Figure 13. High pressure oxidizer pump discharge duct.

Figure 14. High pressure oxidizer pump.

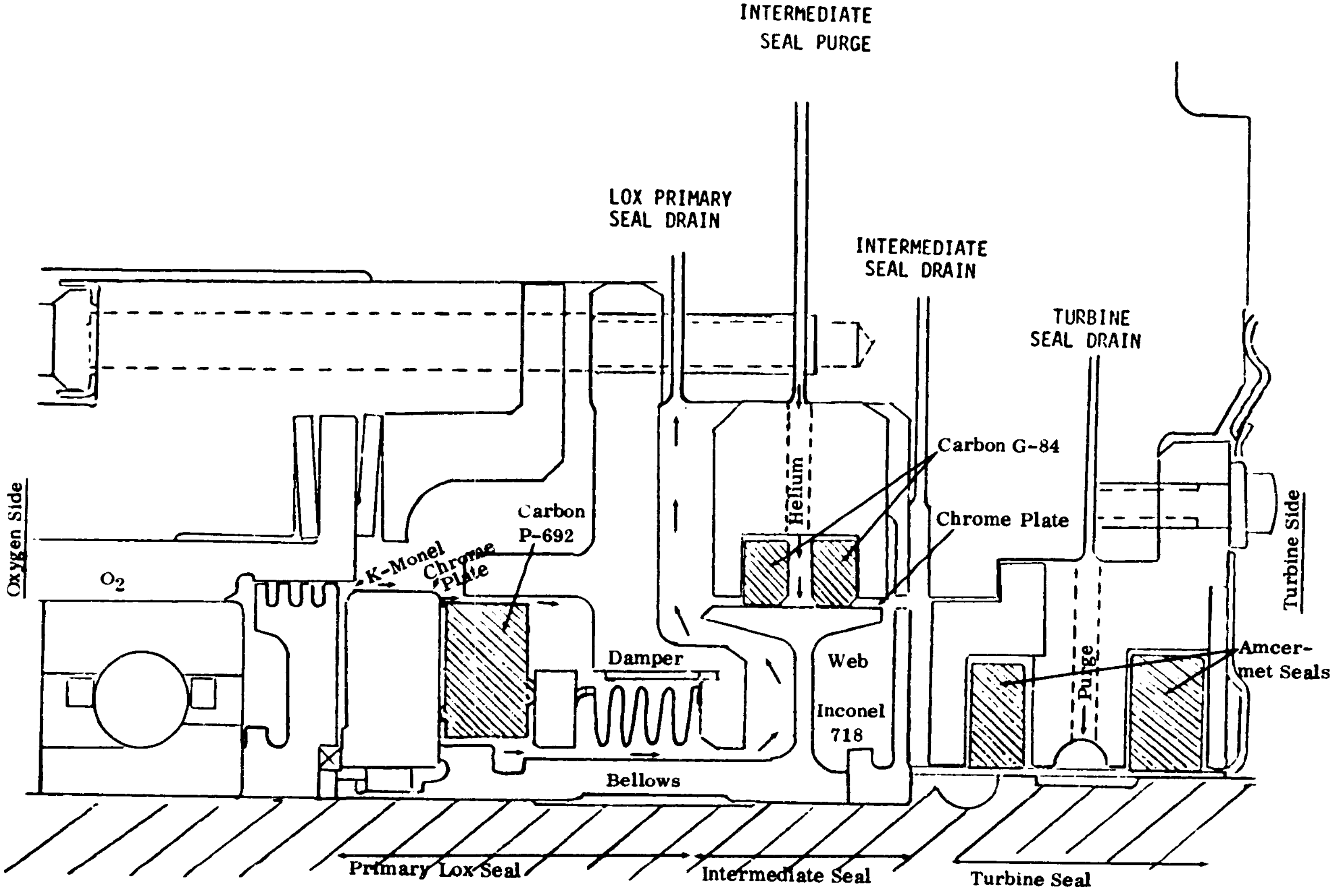
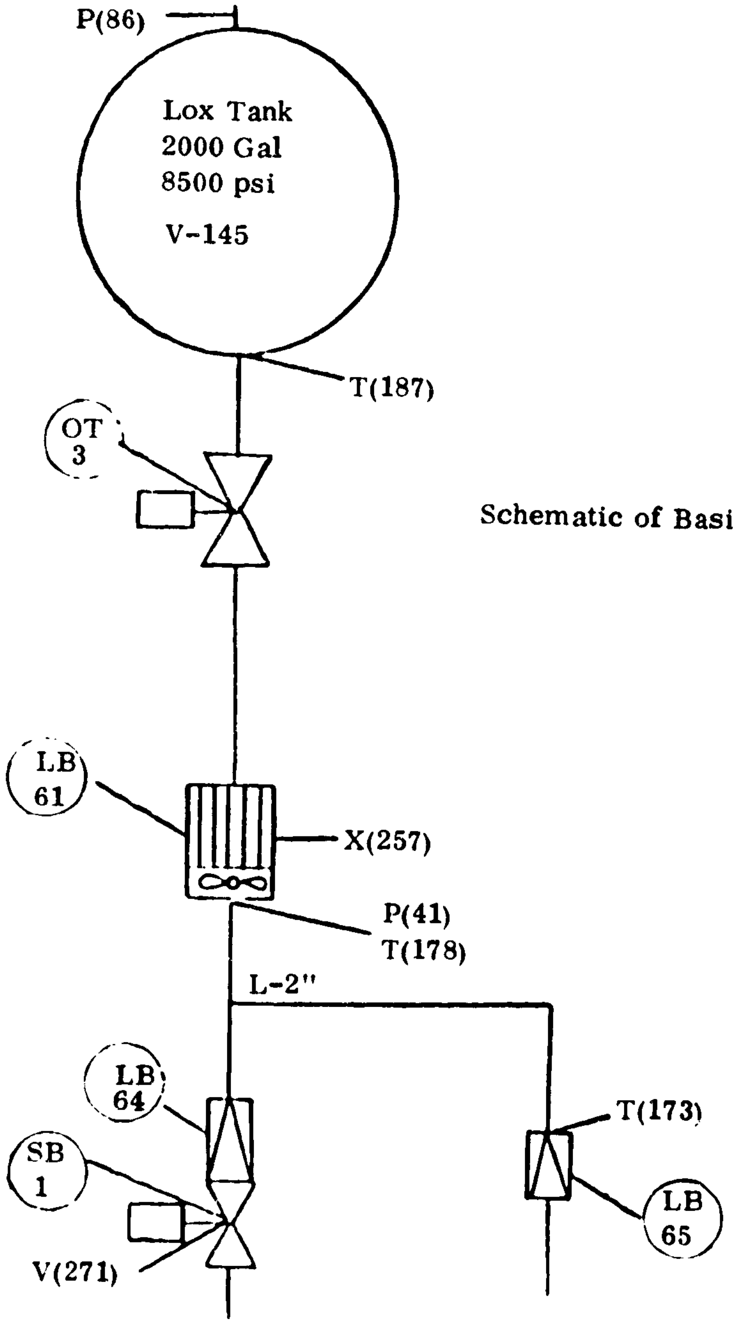


Figure 15. Configuration of the primary seal area of the HPOTP and the associated materials of construction.



Schematic of Basic Test Facility

Figure 16. Coca IB test 018 system schematic.

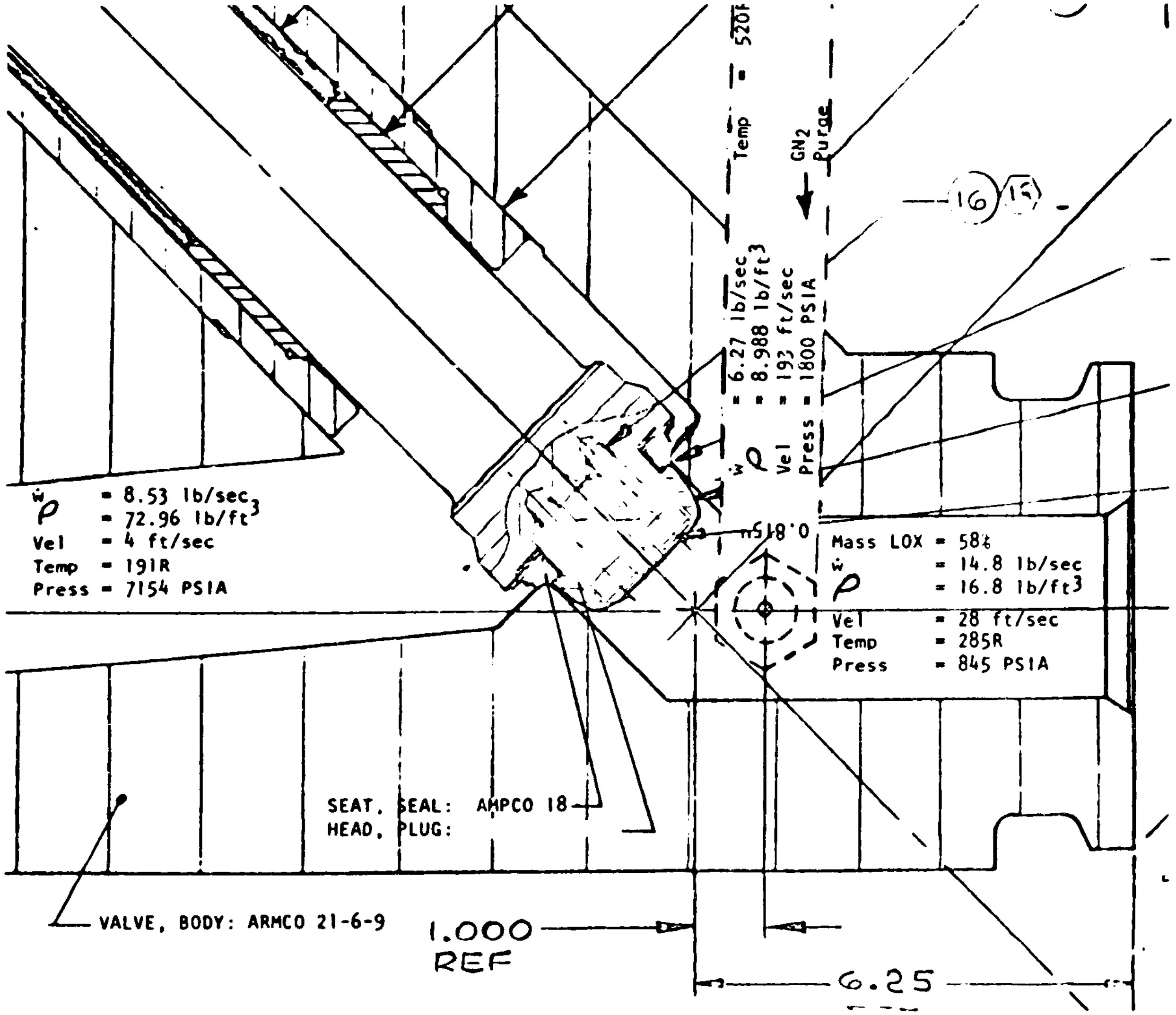


Figure 17. SB-1 valve seat and stem assembly.

Figure 18. Burned valve body.

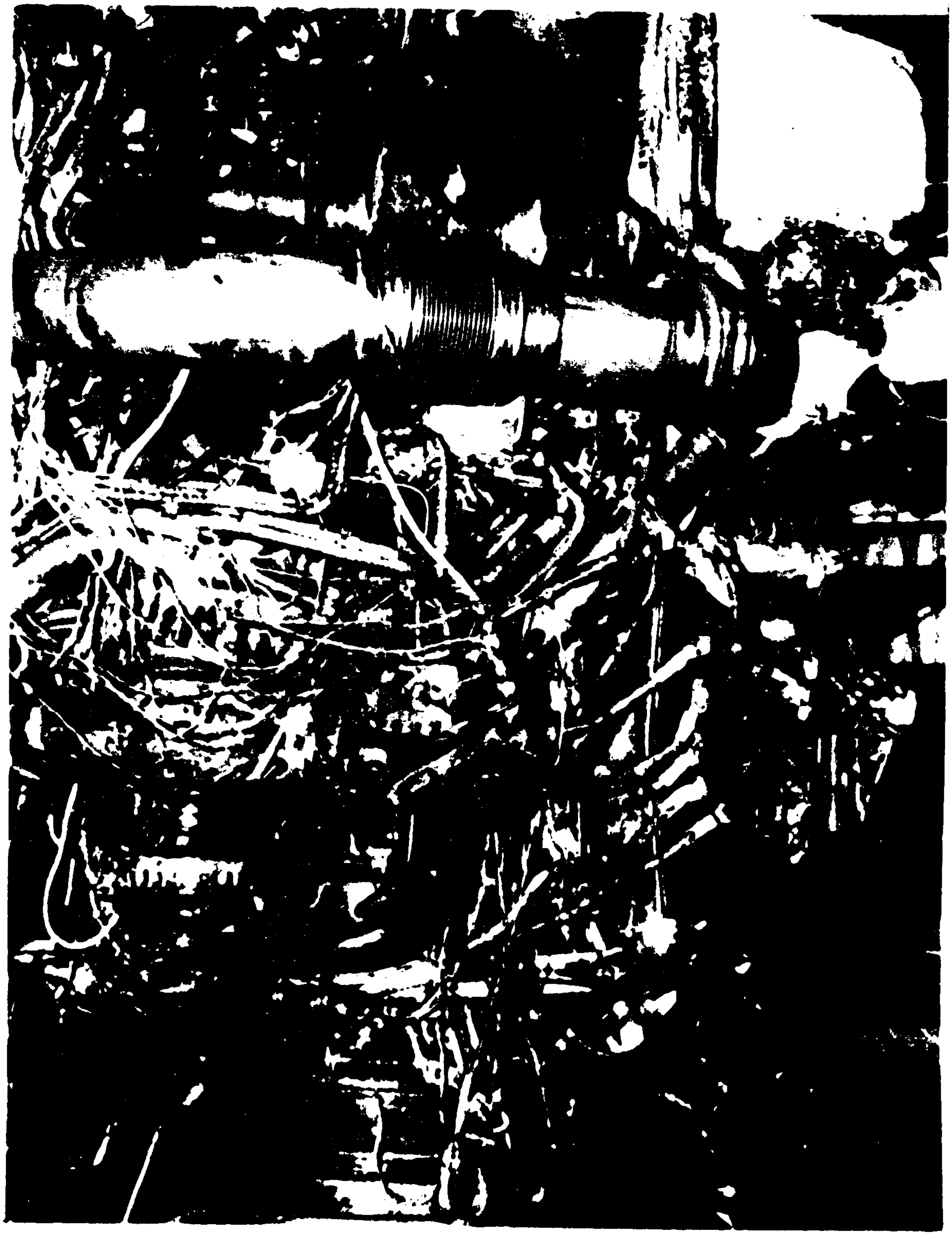


Figure 19. SSME 0004 after test 136 showing damage to HPOTP.

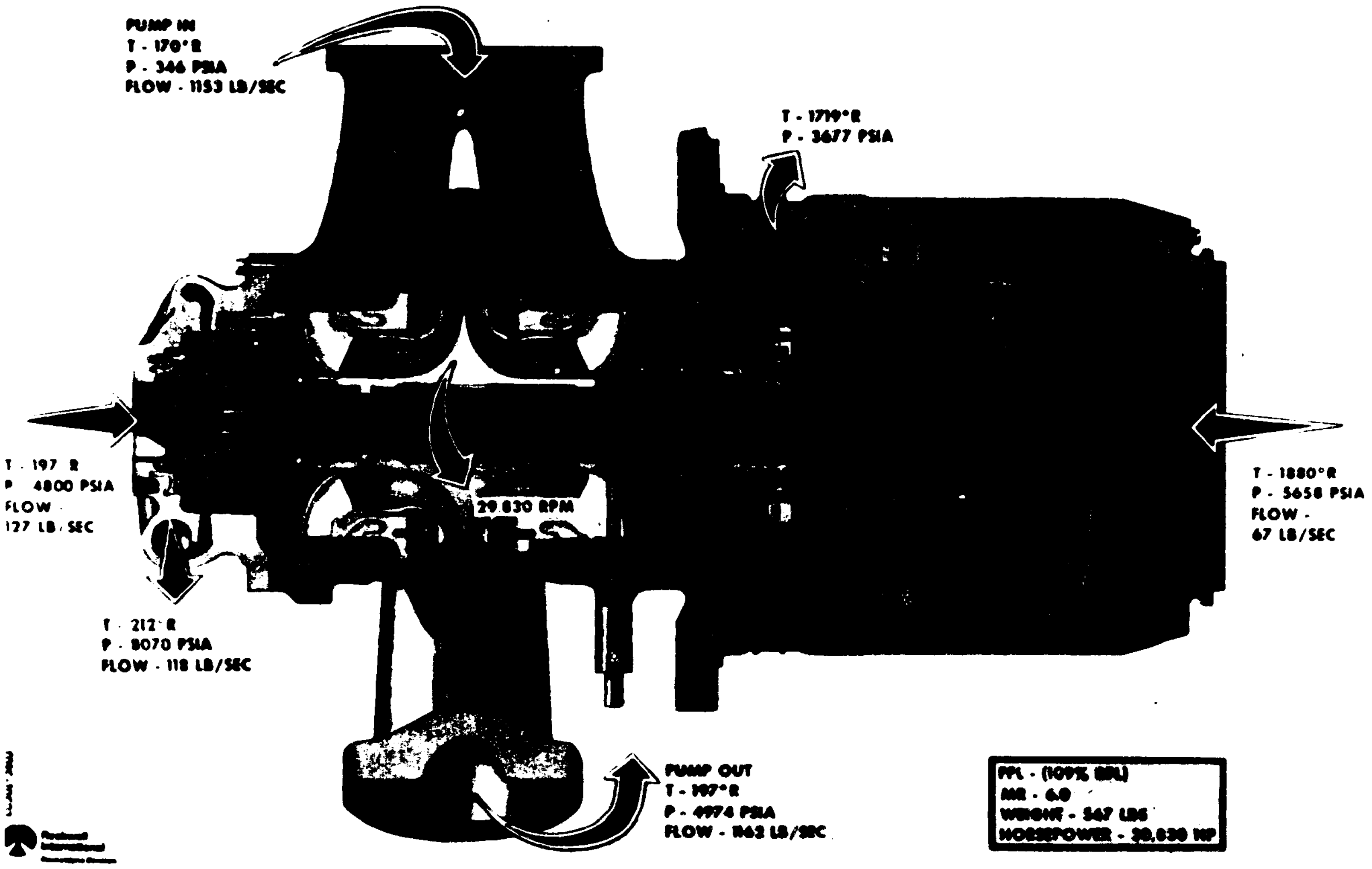


Figure 20. High pressure oxygen turbopump.

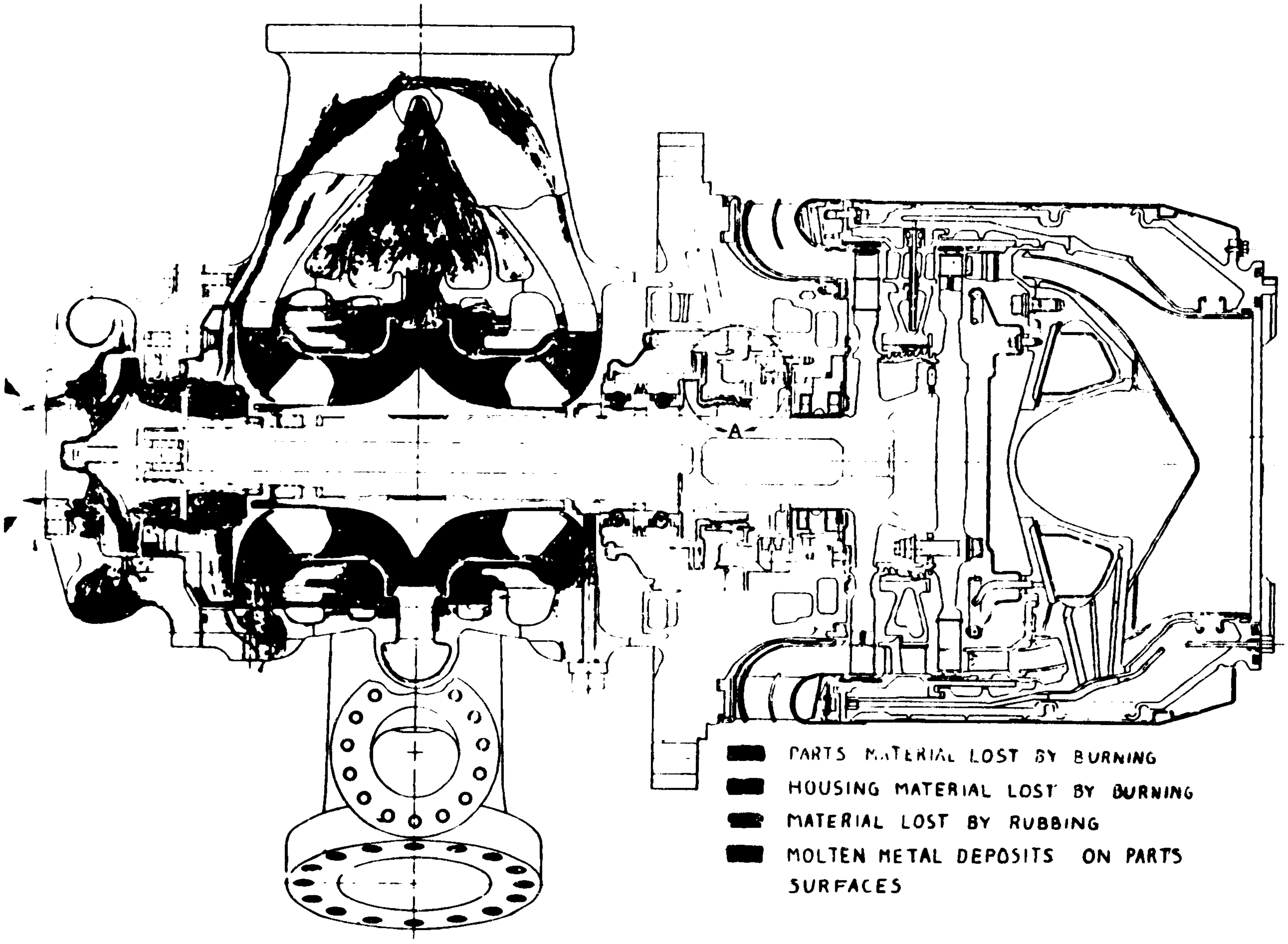


Figure 21. Cross-sectional drawing of high-pressure oxidizer turbopump after fire showing area of damage.

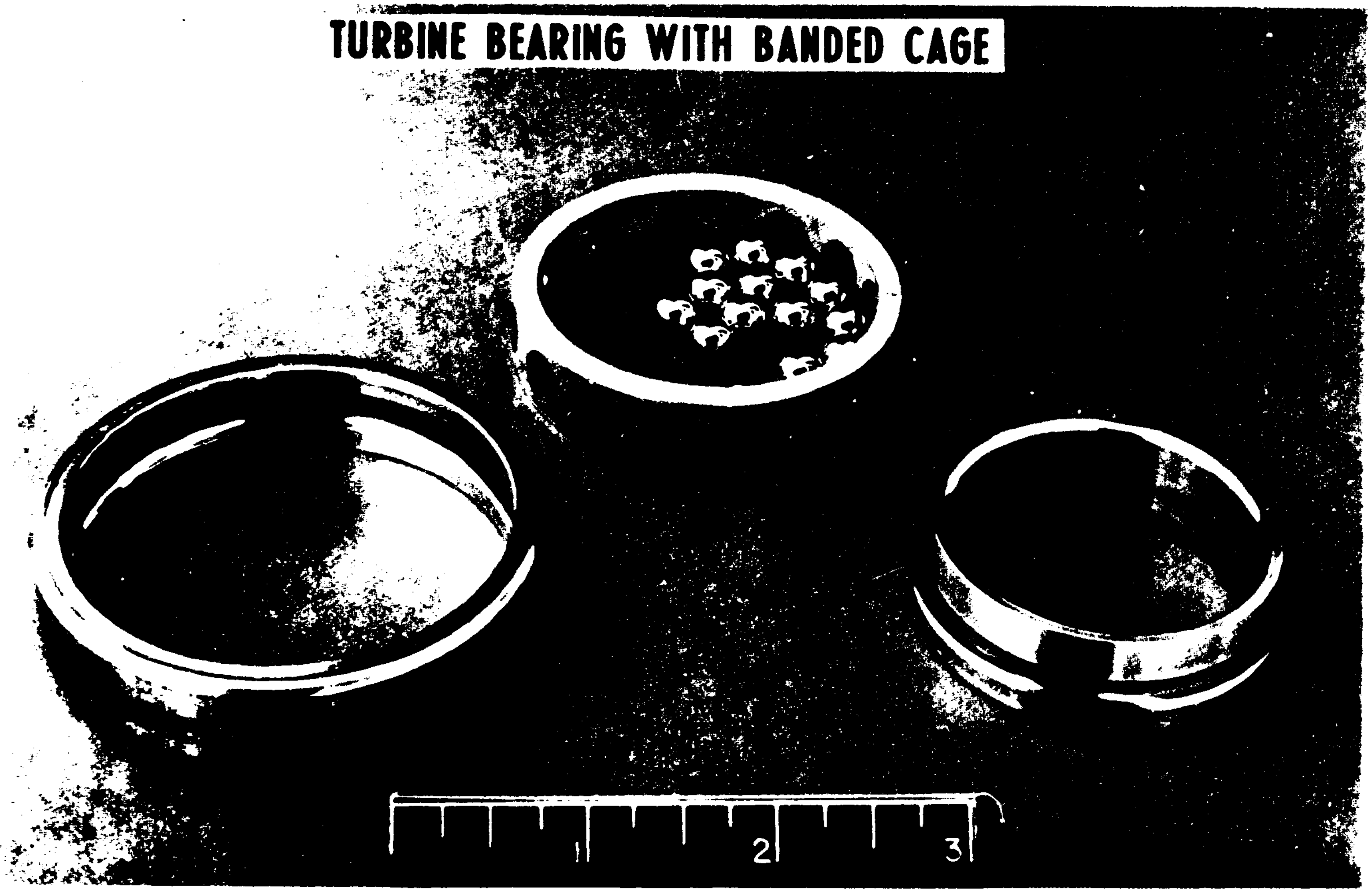


Figure 22. HPOTP bearings.

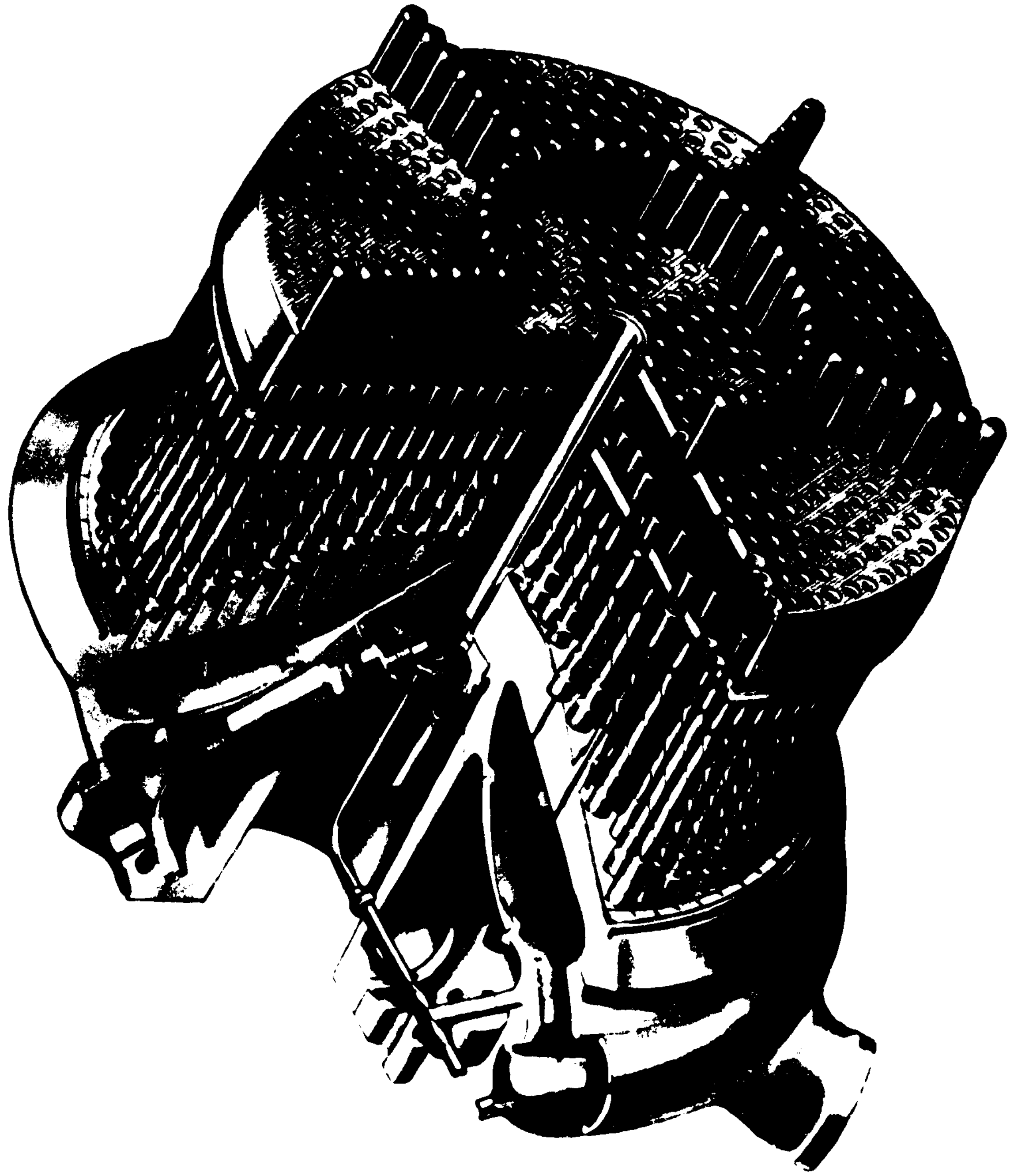


Figure 23. Injector and lox posts.

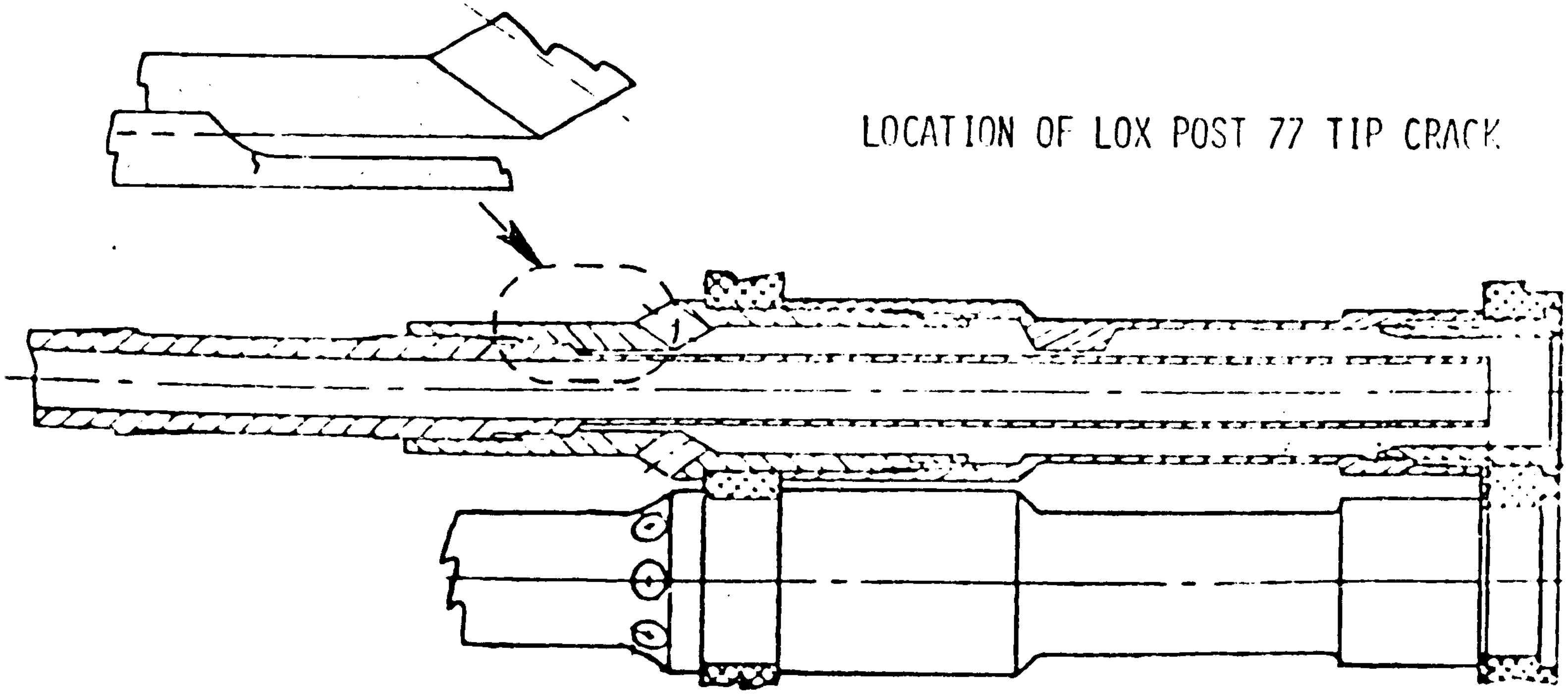


Figure 24. Main injector 0002, lox post failure.

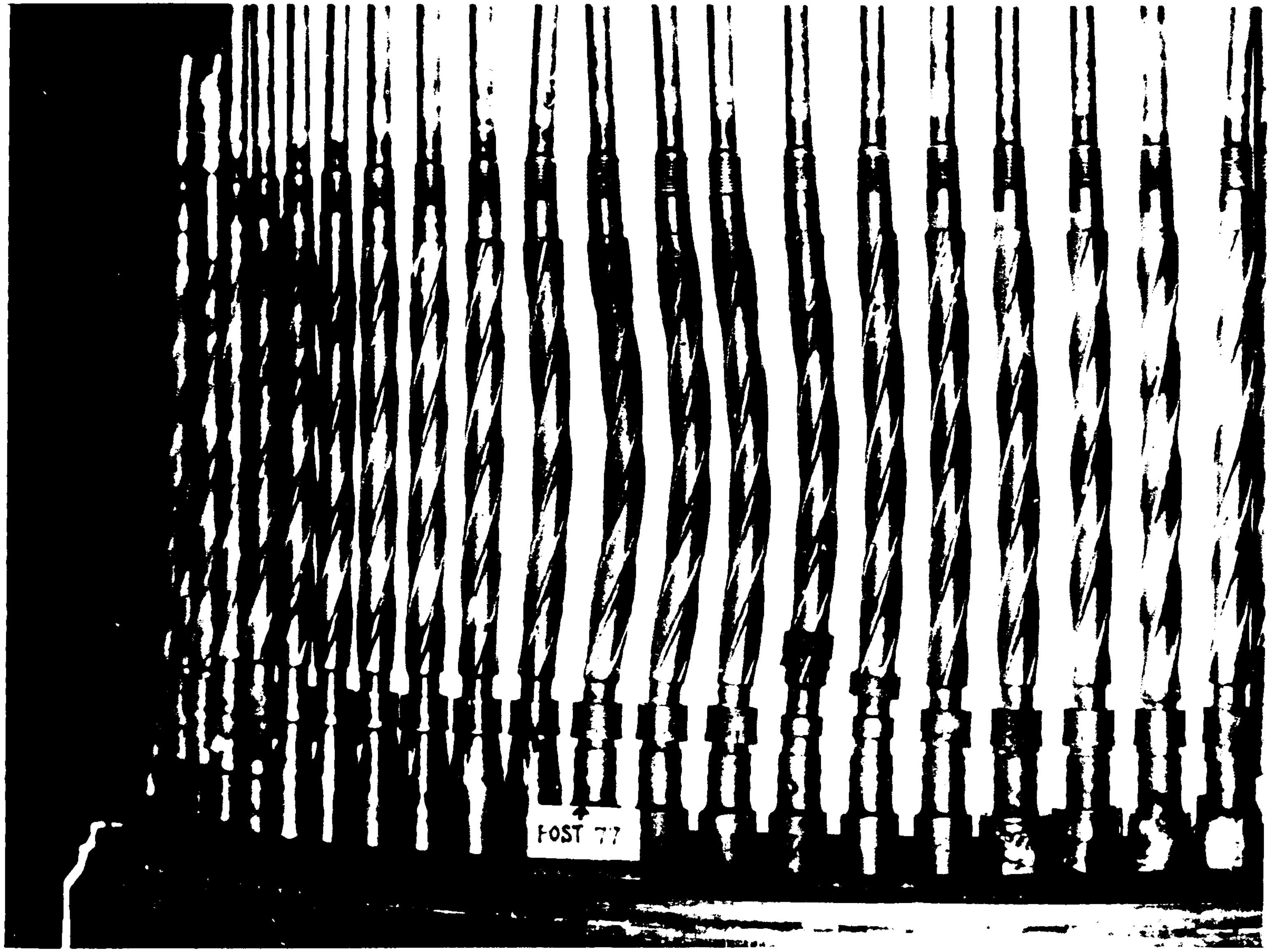


Figure 25. Deformation of lox posts.

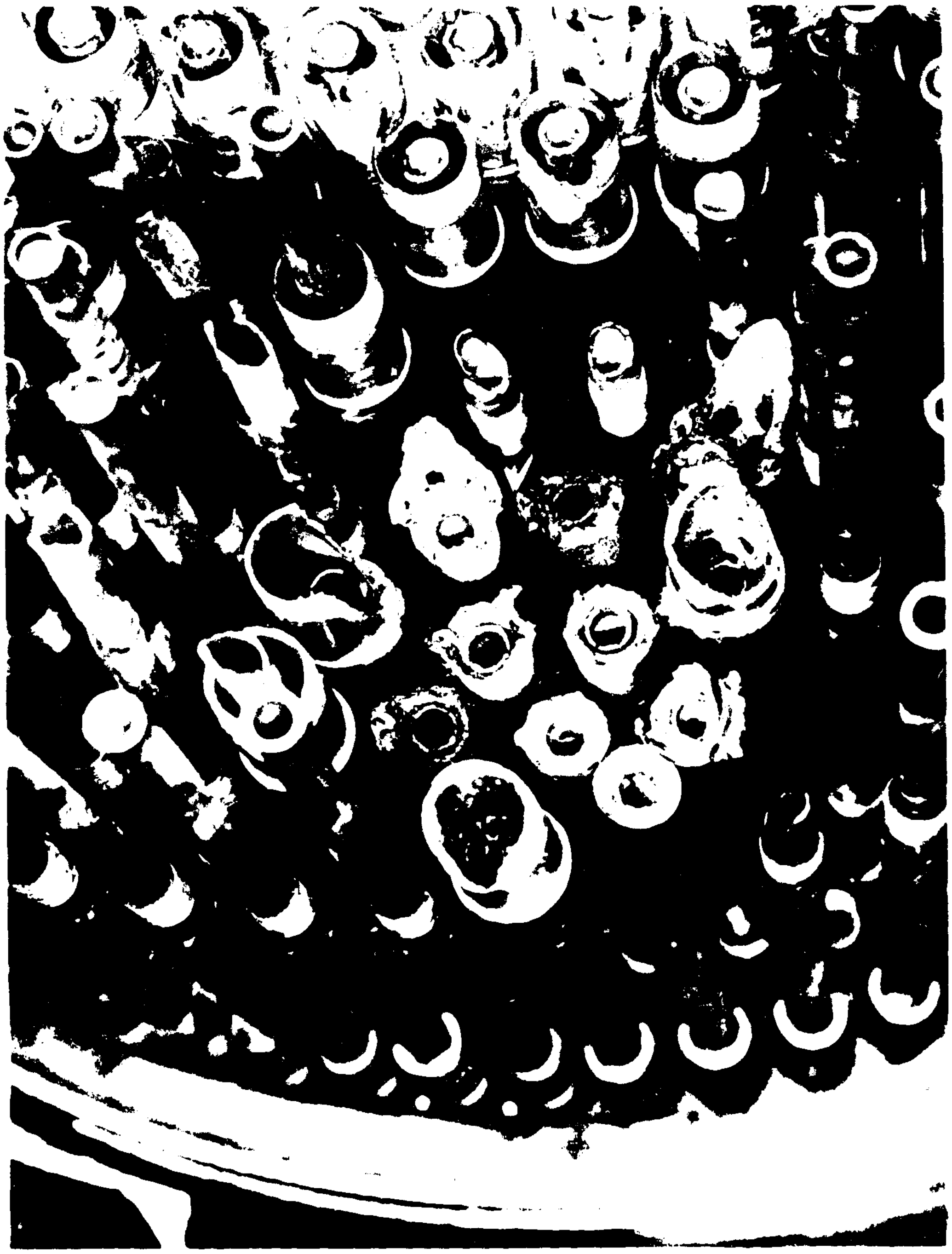


Figure 26. Post tips and injector face.

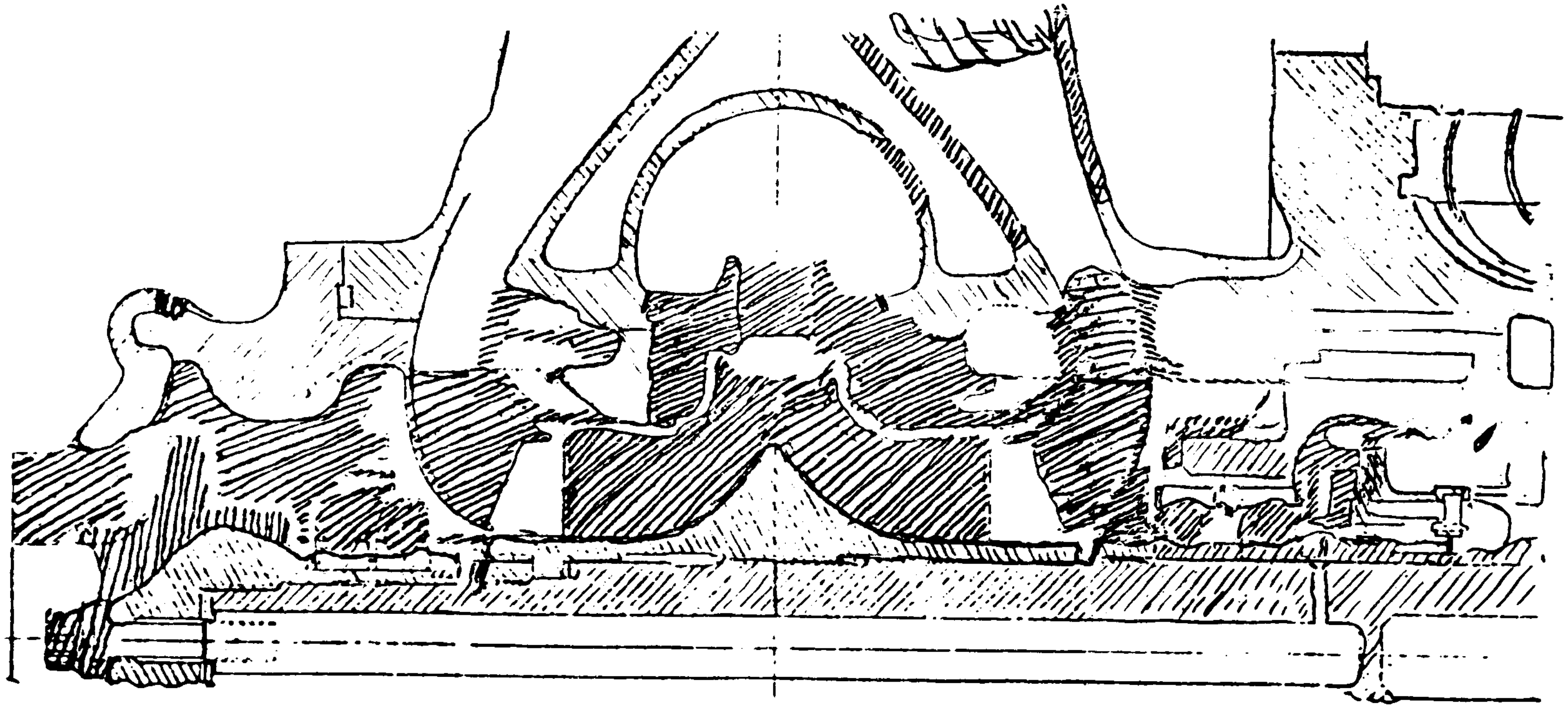


Figure 27. HPOTP 0301 burn patterns.

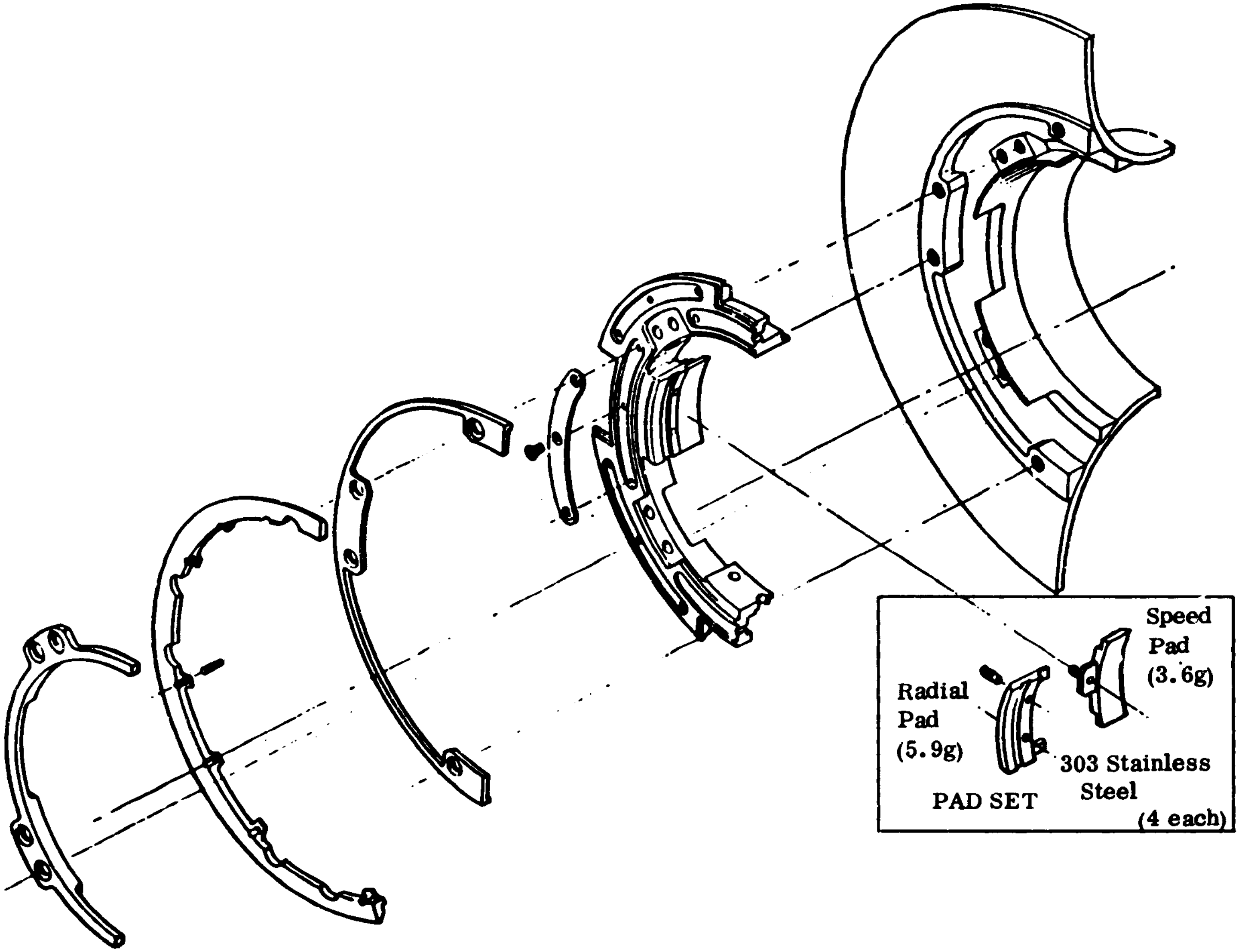
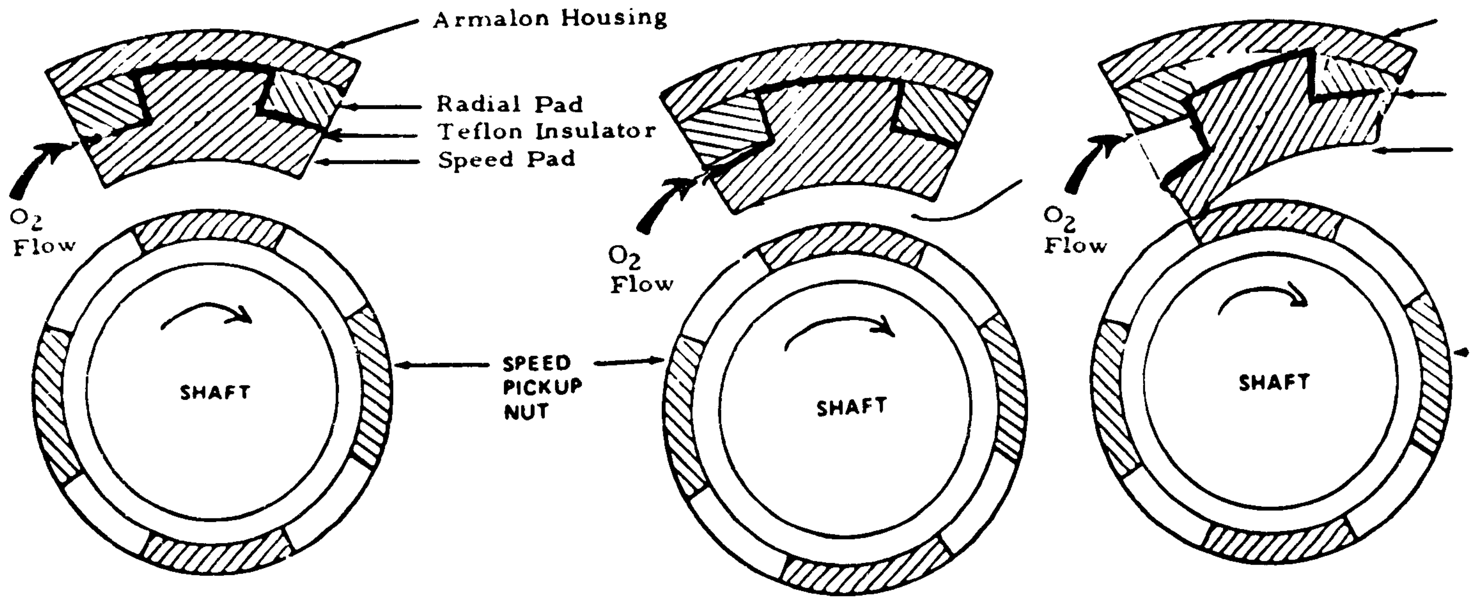


Figure 28. Capacitance device.



INITIAL

INITIAL BREAKAWAY OR DEFORMATION

RUBBING CONTACT

Figure 29. Assumed rubbing mechanism.

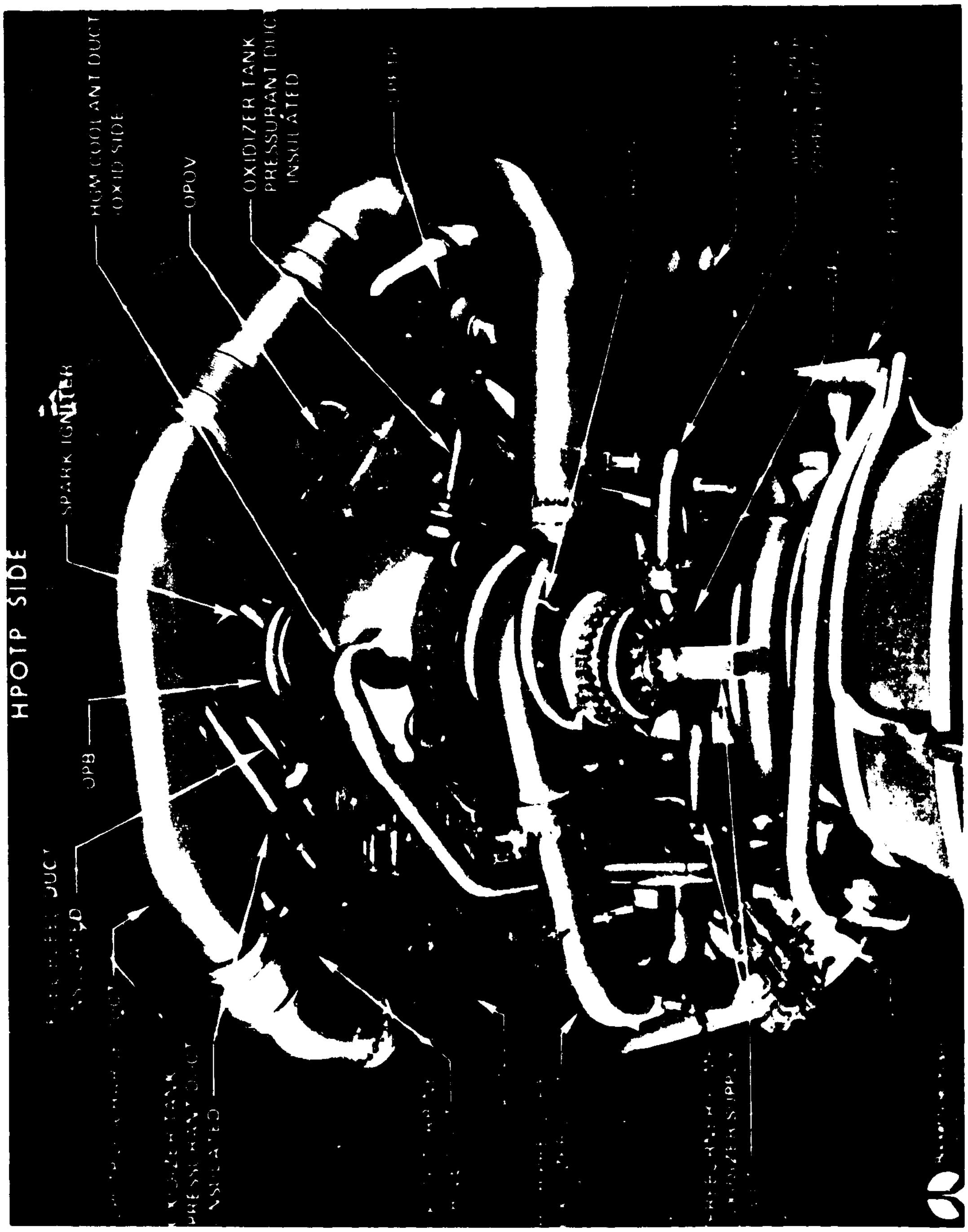


Figure 30. High pressure duct system.

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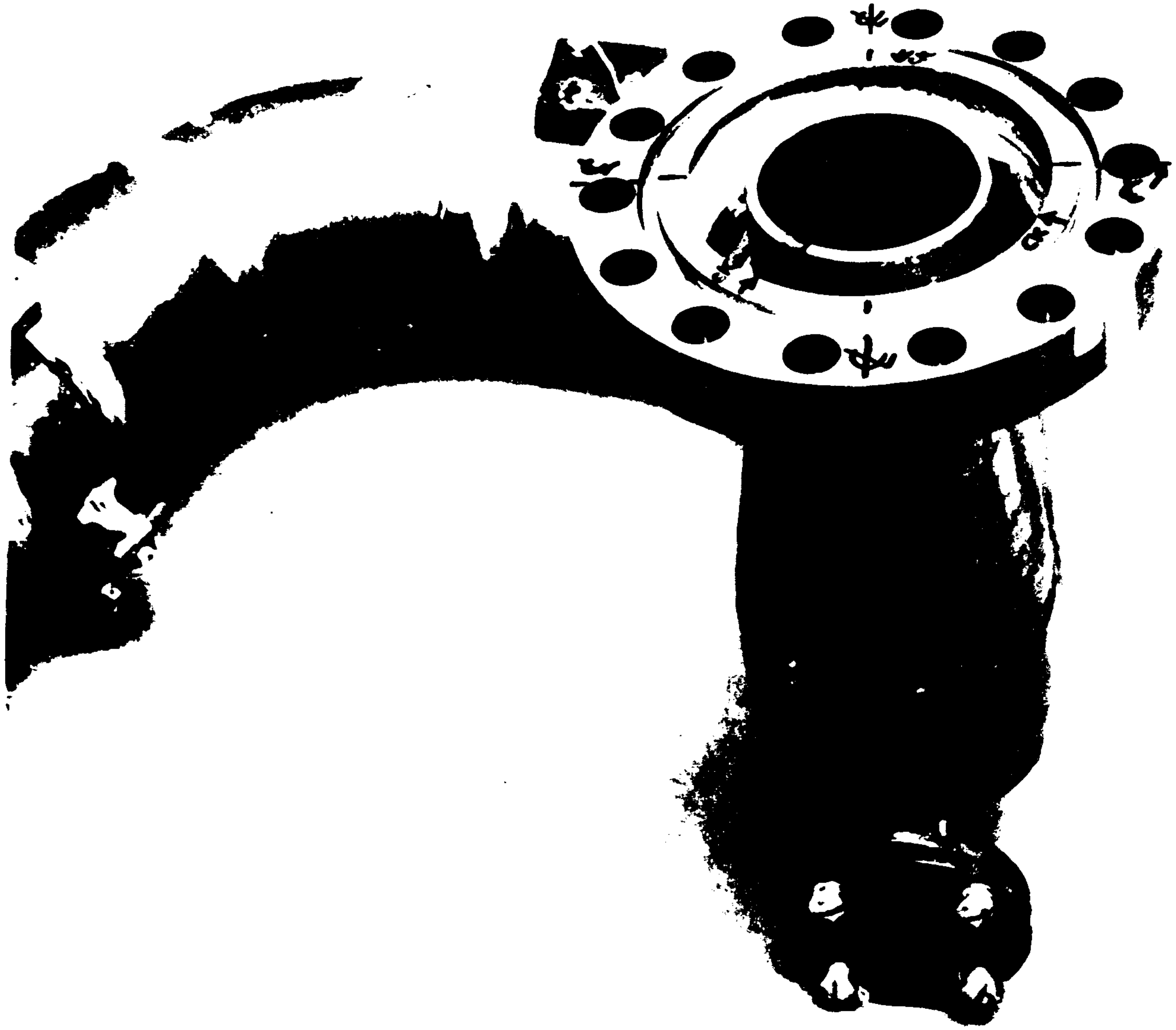


Figure 31. Flow guide in duct showing burned region.

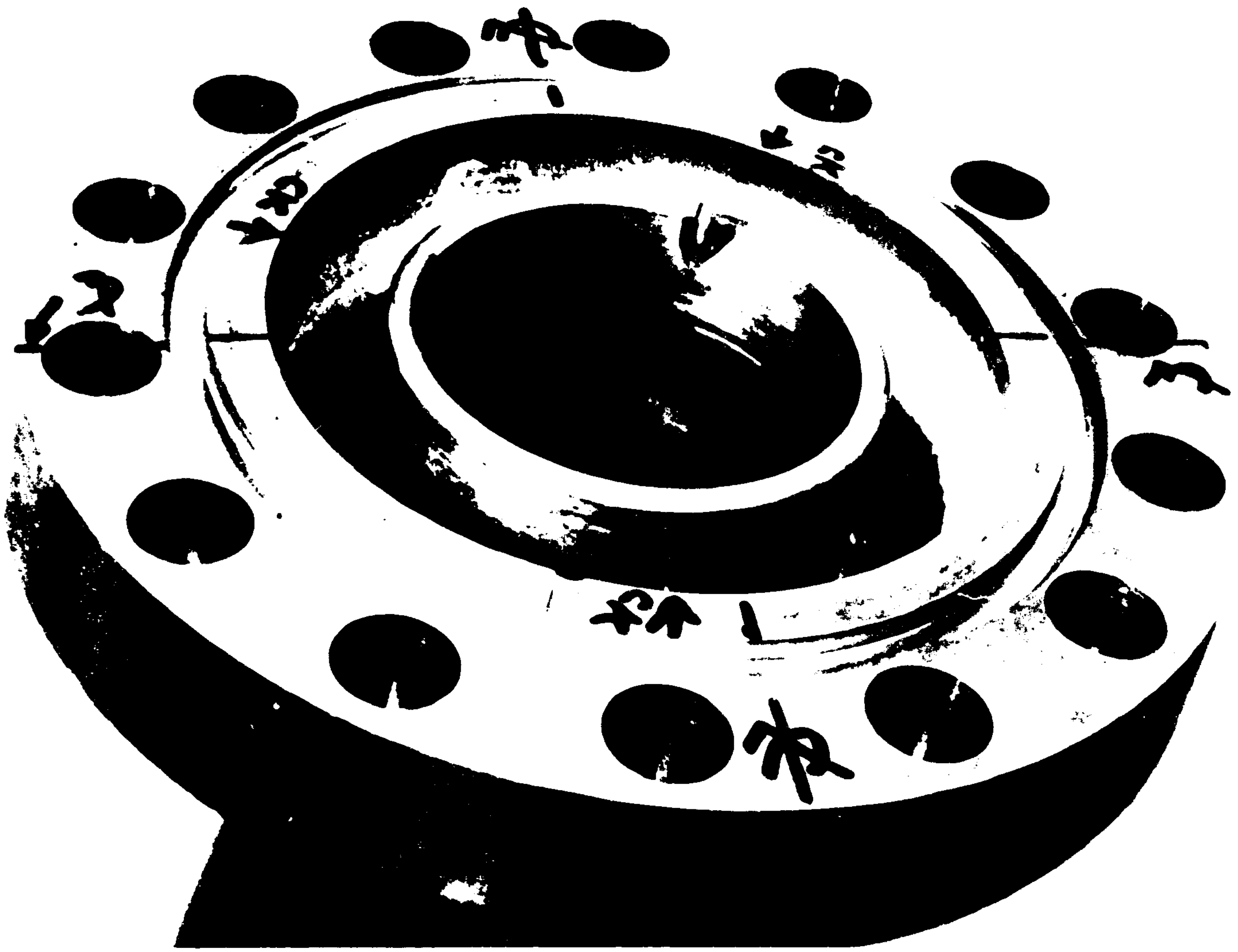


Figure 32. Burned region at inside of flow guide.

Figure 33. Close-up of burned region.

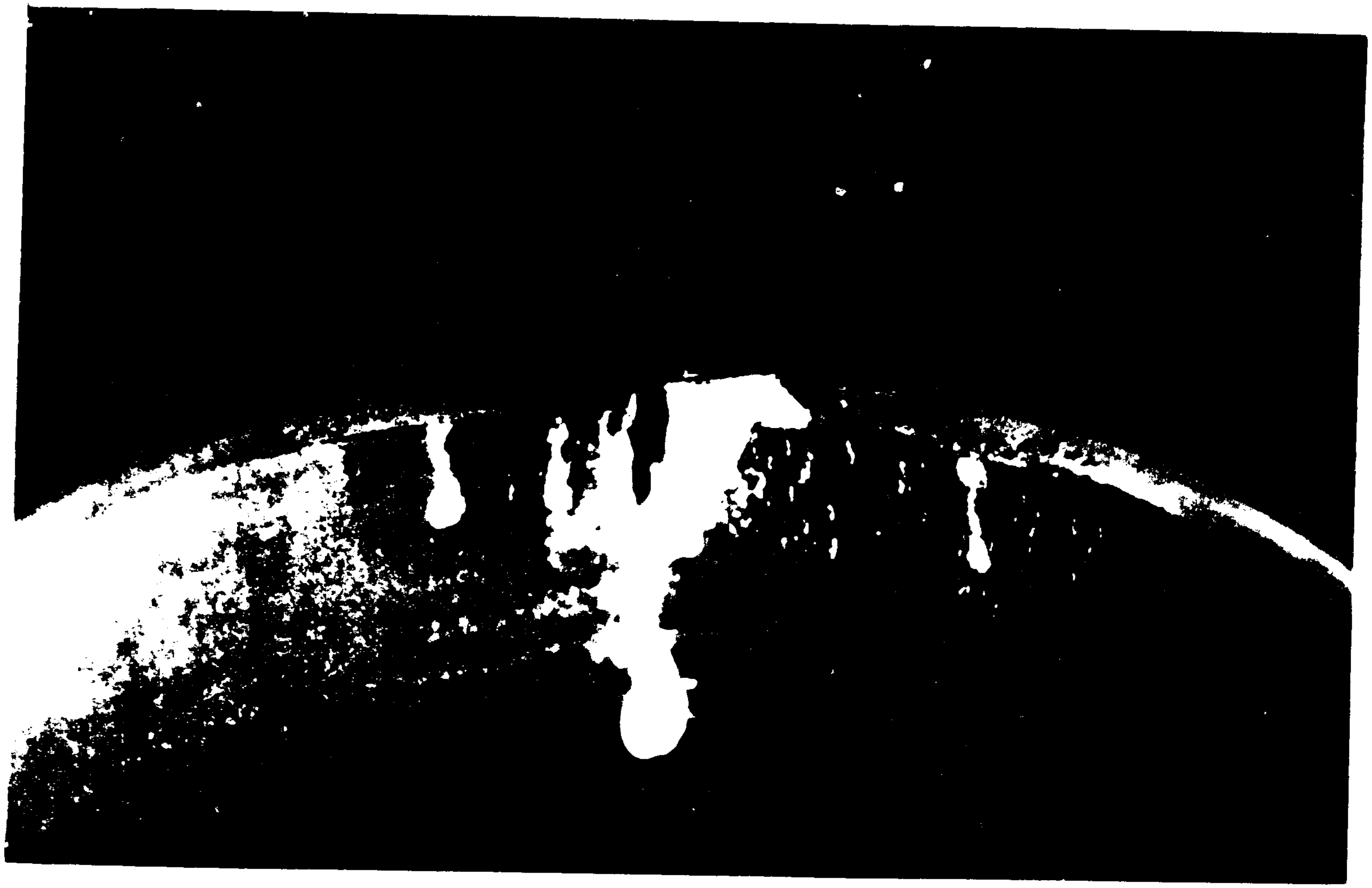


Figure 34. Inner surface of dye penetrant treated flow guide at region of burned crack.

Figure 35. Inner surface of dye penetrant treated flow guide.

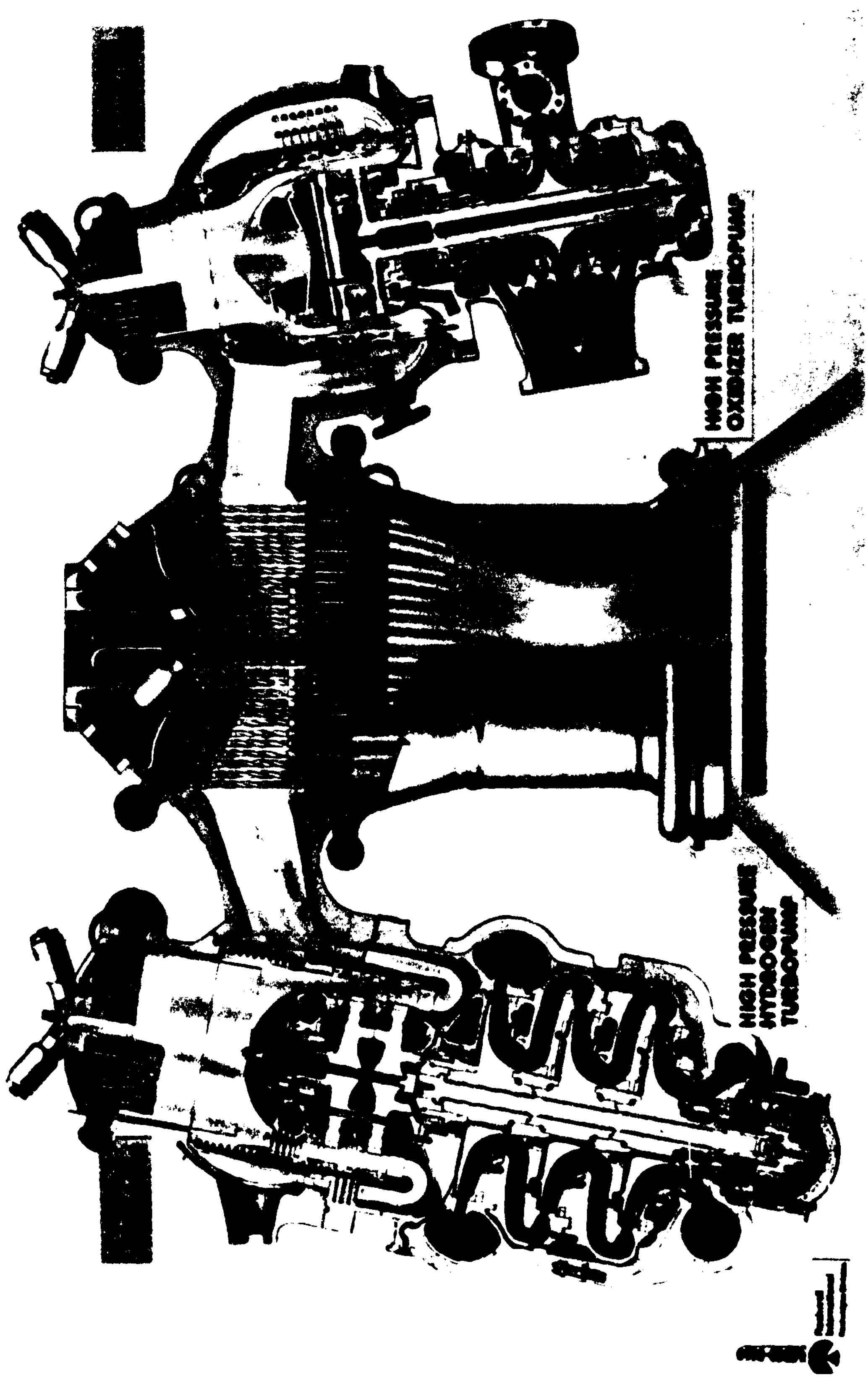


Figure 36. SSME powerhead schematic.

Figure 37. Heat exchanger assembly damage.

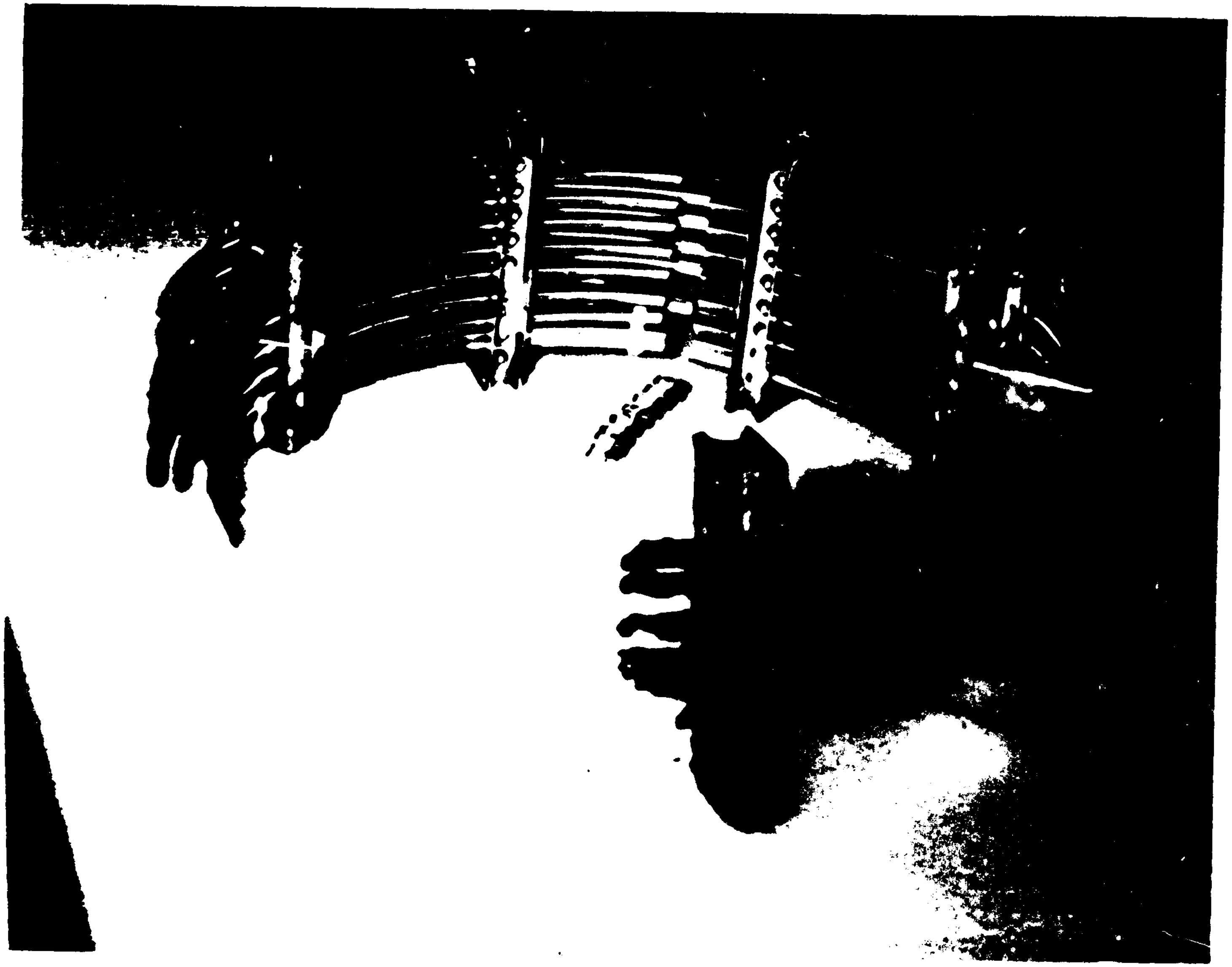


Figure 38. Heat exchanger coil removed from assembly.

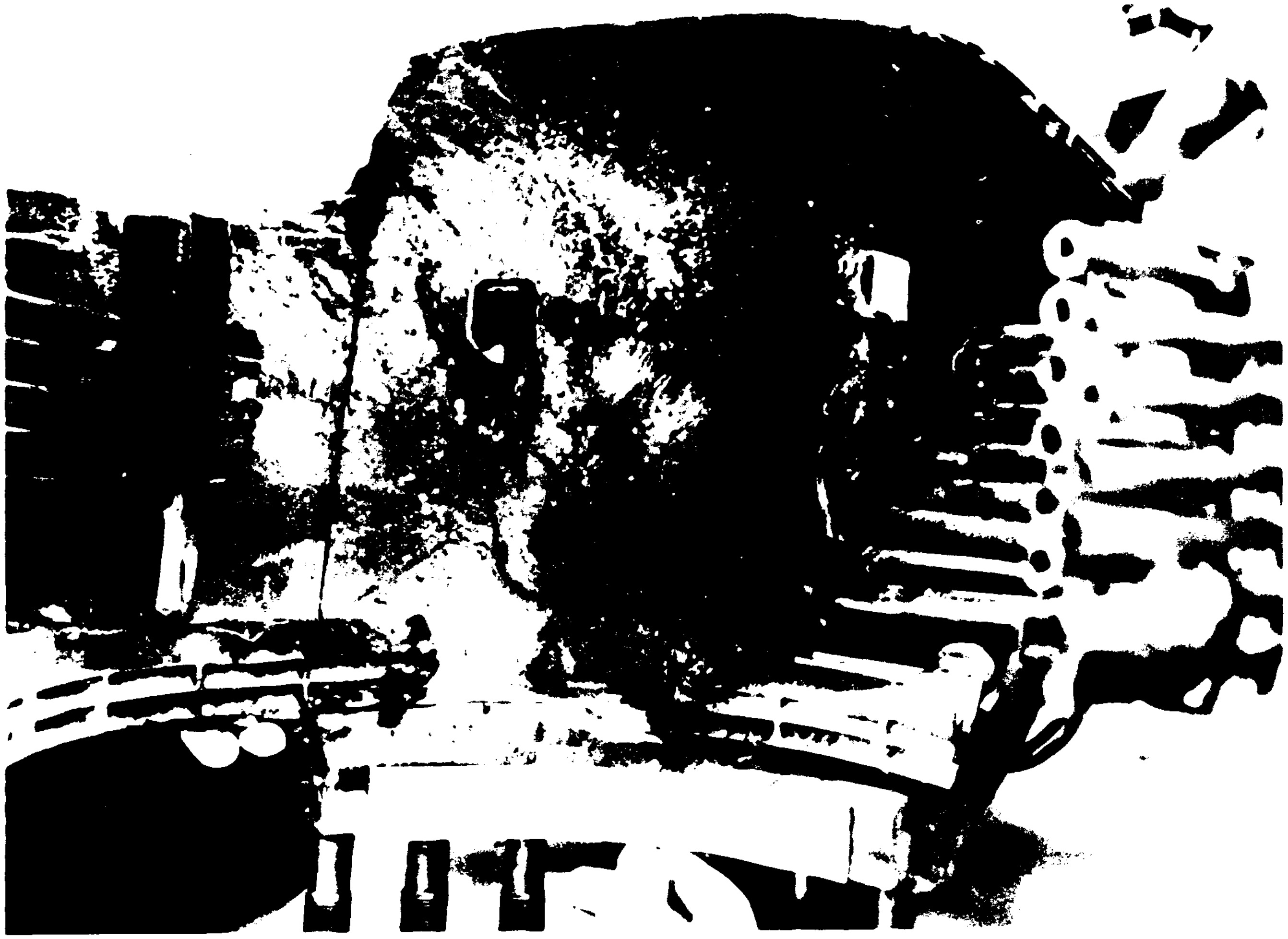


Figure 39. Internal section of preburner wall and burned HEX coils.

Figure 40. Preburner liner and manifold damage.

Figure 41. Heat exchanger assembly, preburner liner and bellows.

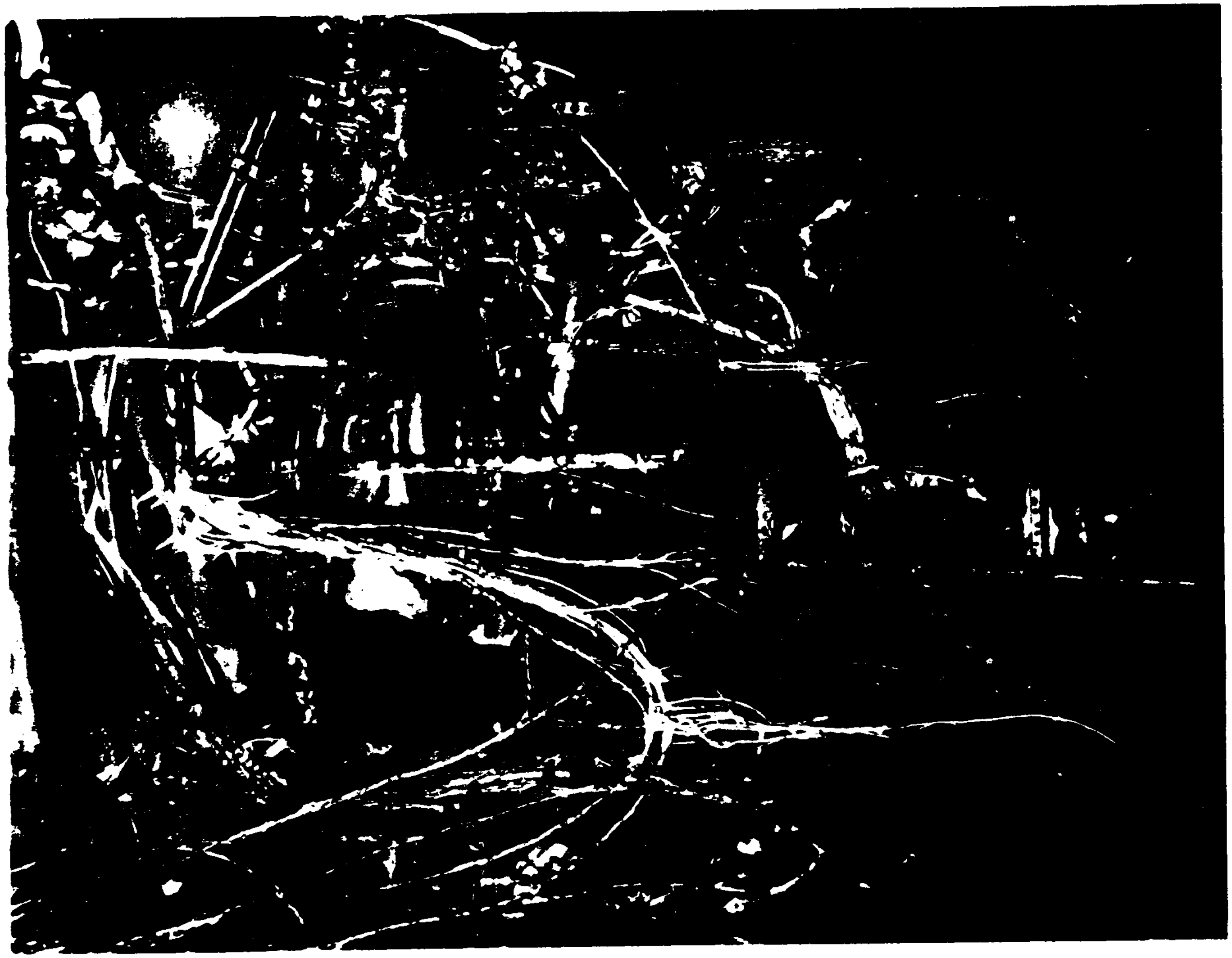


Figure 42. Overall view of the engine showing the high pressure oxidizer and the missing pump discharge duct and main oxidizer valve.

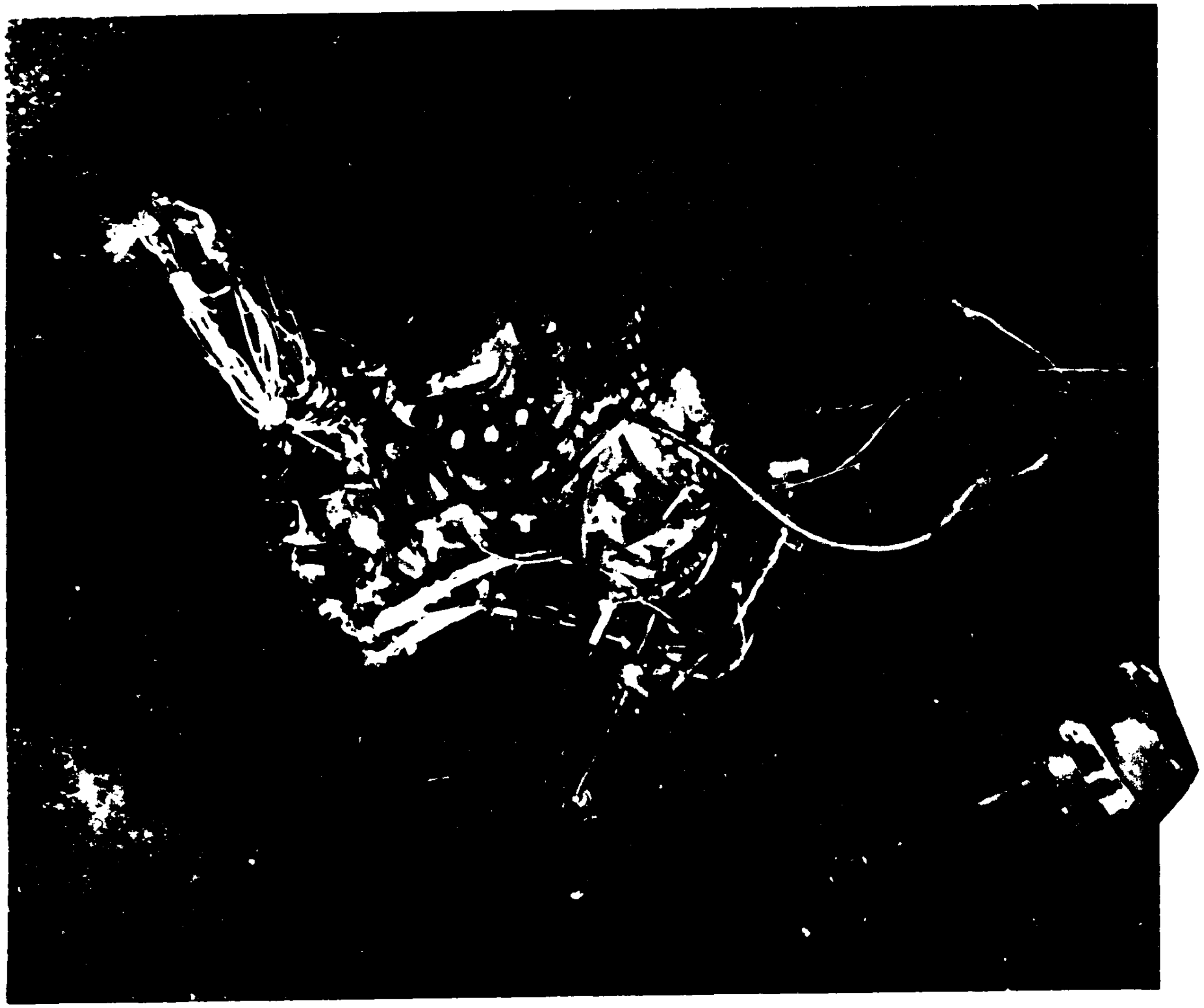


Figure 43. MOV and HPOP discharge duct as found in the flame deflector spillway.

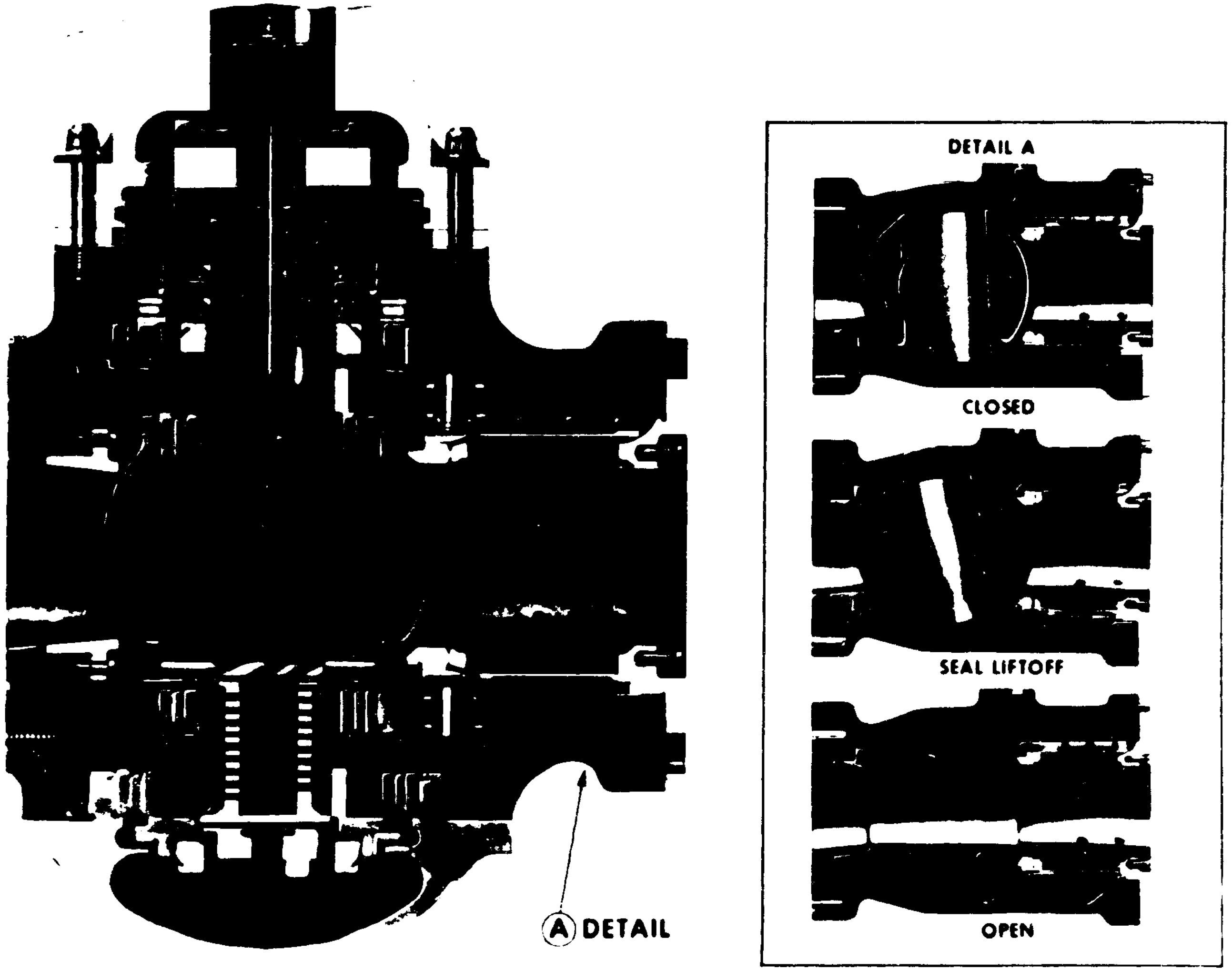


Figure 44. SSME main oxidizer valve assembly.

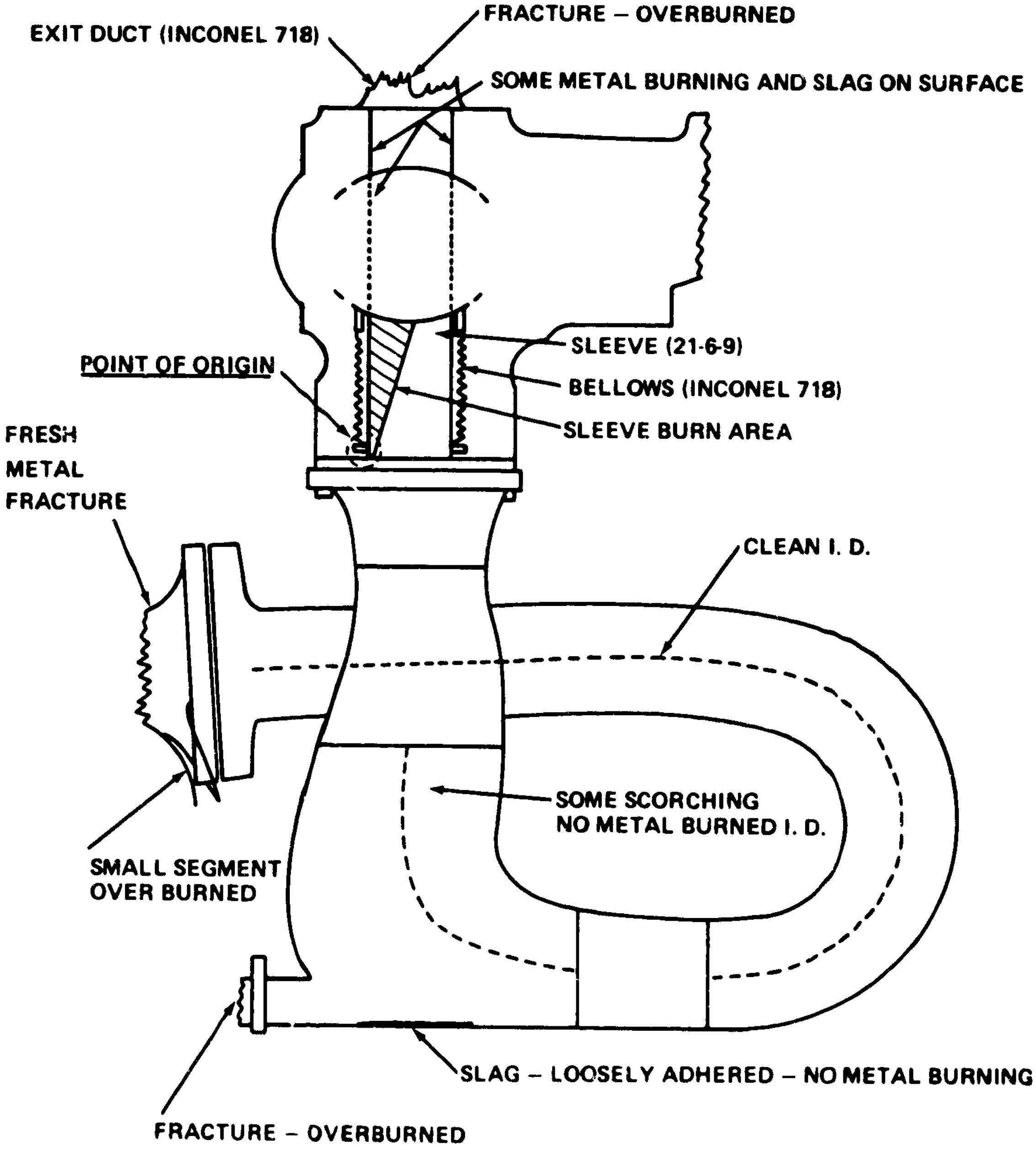


Figure 45. Origin of fire.

Figure 46. Inlet sleeve removed from the burned MOV.

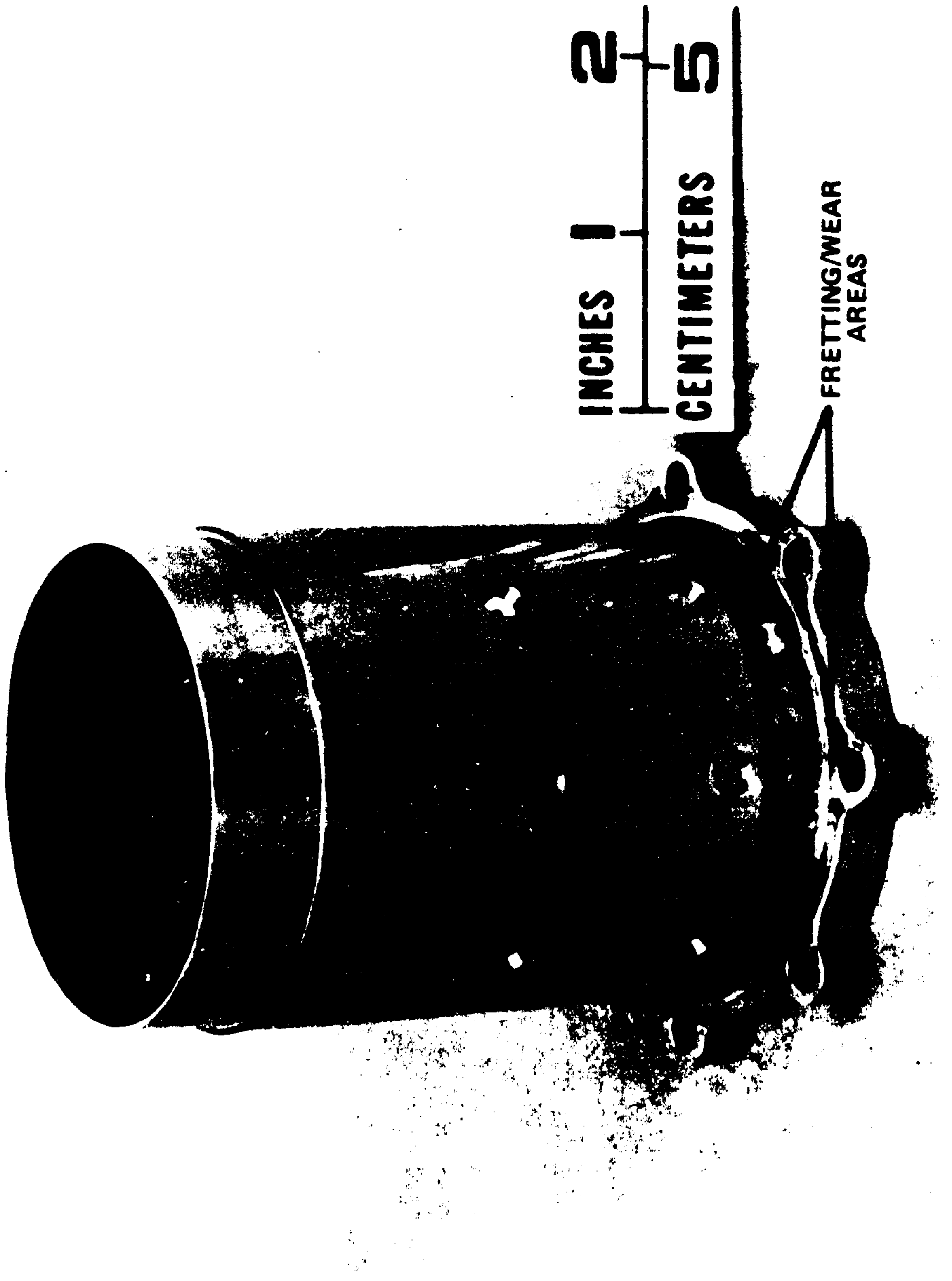


Figure 47. Unburned sleeve.

Figure 48. MOV inlet liner and bellows assembly removed from another valve and the evidence of severe fretting in the flange area.

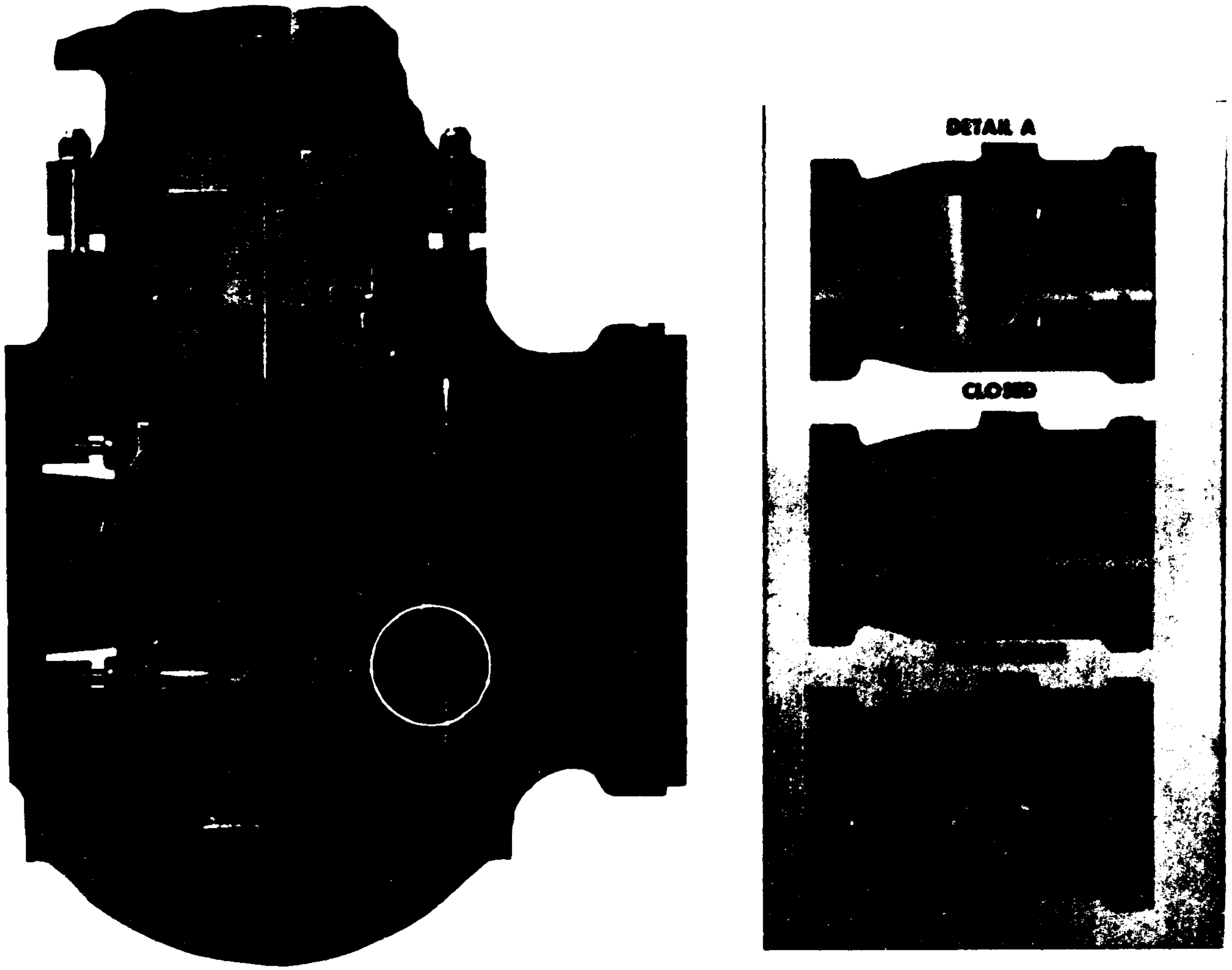


Figure 49. MOV cross-section. (same as Fig. 44 except encircled area shown).

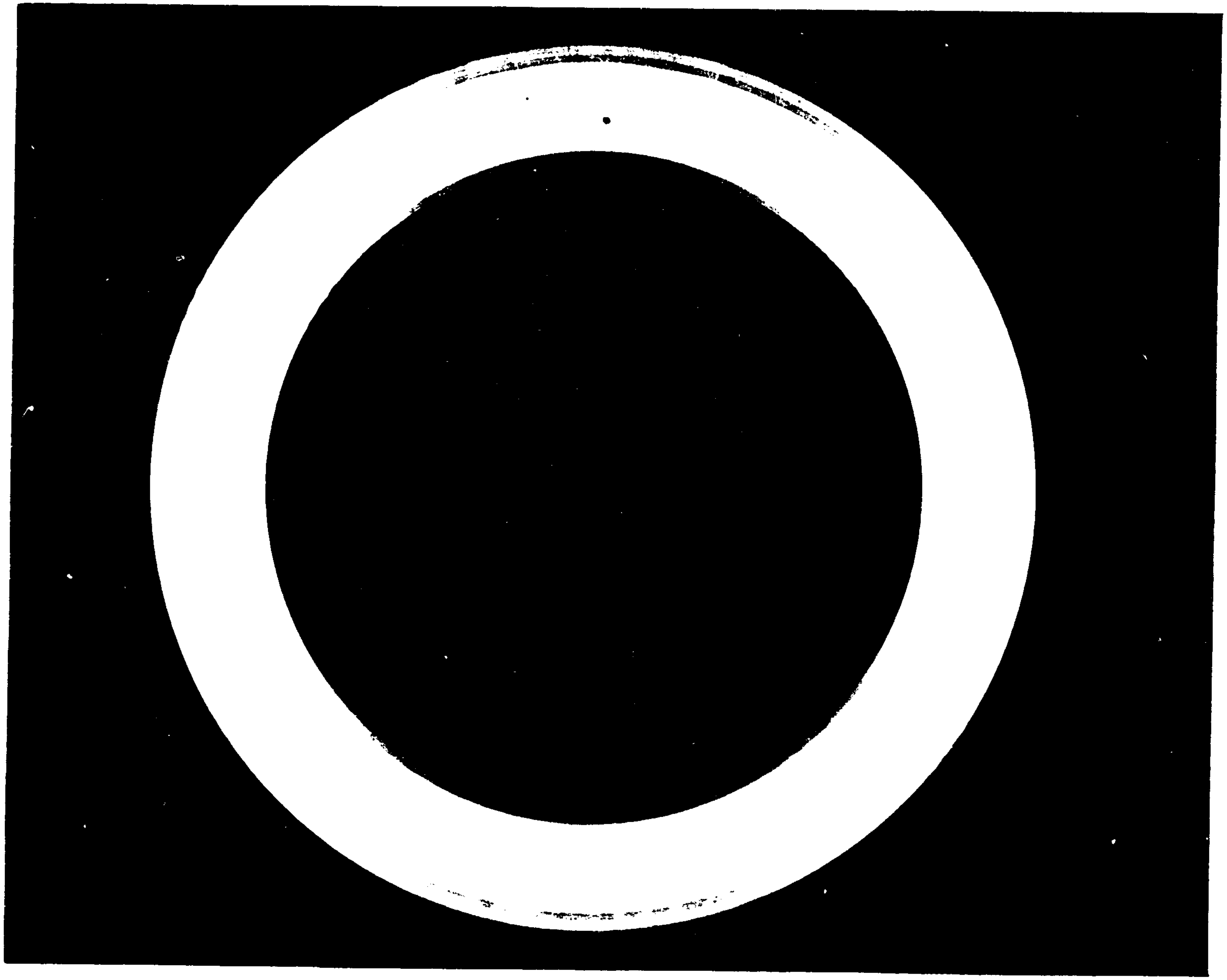


Figure 50. MOV Kel-F ball seal configuration.

SEAL FROM MOV 0006

PORTION REMAINING IN VALVE ≃ 1X

CROSS SECTION ≃ 5x

SEM PHOTOS OF PIECE FROM INJECTOR
(Au - Pd COATED)

MACHINING LINES IN SEALING SURFACE (14x)

MELTING ON INSIDE SURFACE (13x)

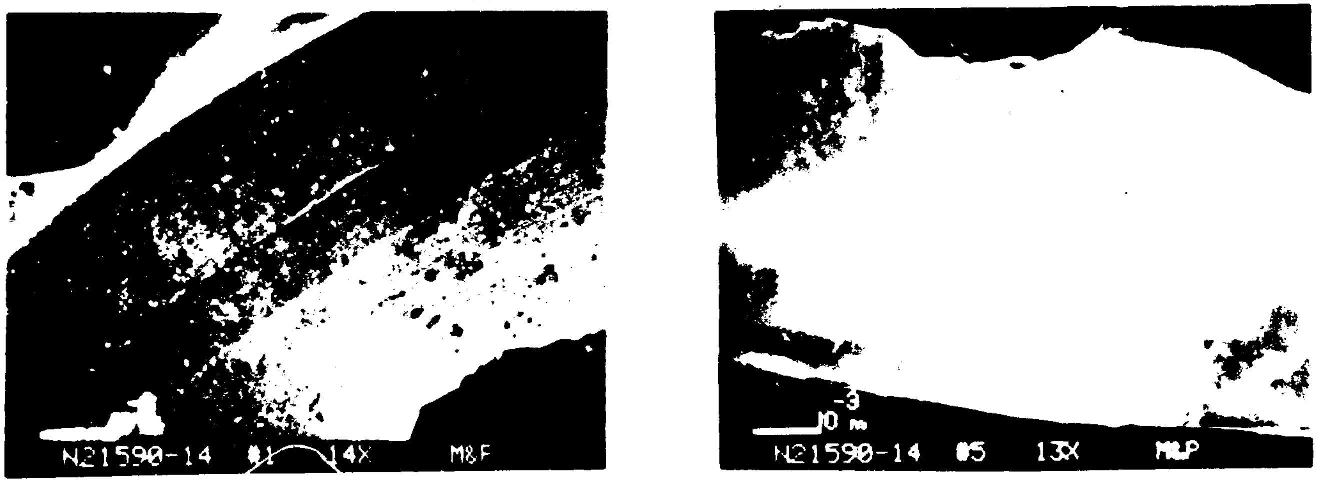


Figure 51. MOV Kel-F seal from engine 0201 after test.

APPROVAL

LOX/GOX RELATED FAILURES DURING SPACE SHUTTLE MAIN ENGINE DEVELOPMENT

By C. E. Cataldo

The information in this report has been reviewed for technical content. Review of any information concerning Department of Defense or nuclear energy activities or programs has been made by the MSFC Security Classification Officer. This report, in its entirety, has been determined to be unclassified.

R.J. Schwinghamer

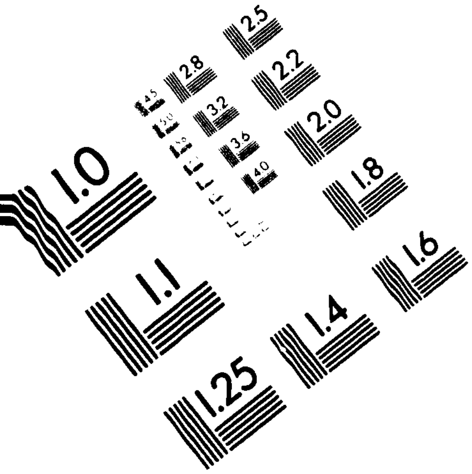
R.J. SCHWINGHAMER
Director
Materials & Processes Laboratory

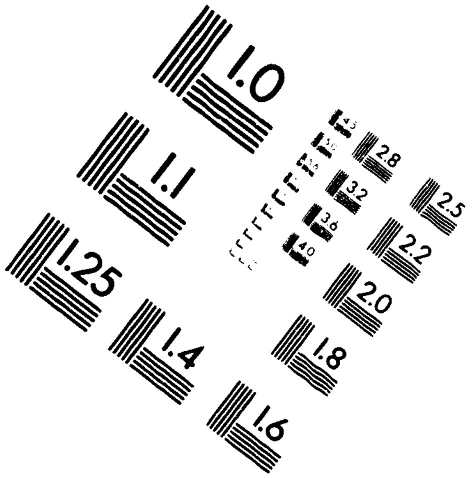
END

DATE

FILMED

JUN 8 1994





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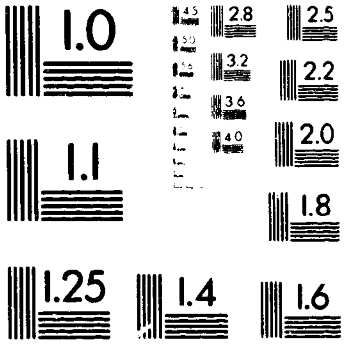

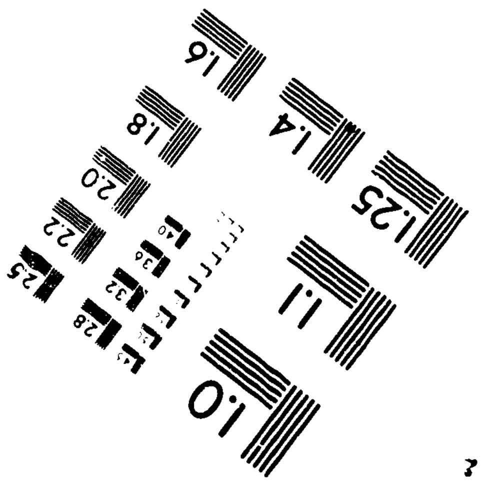

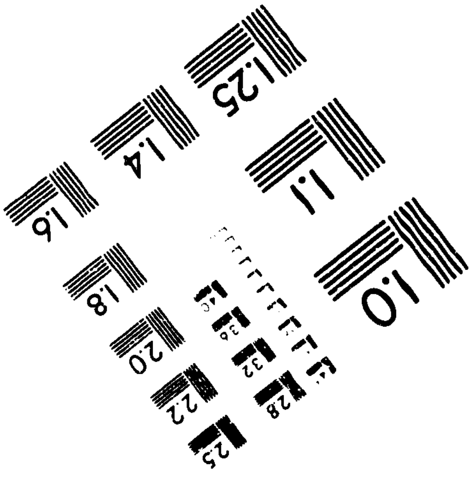

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