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TITLE: Mod-C PROGRAM, TURBINE VISCO SEAL CAVITATION TESTSABSTRACT

For the purpose of developing dynamic seal-to-space systems for the SNAP-8 turbine, three rigs were tested which incorporated different space seal designs. One of these designs, which simulated the current seal design, exhibited a much accelerated rate of cavitation damage when compared to actual turbine operation. However, no mercury leakage occurred, thereby extending the seal life, extrapolated to actual turbine conditions, to 60,000 and 70,000 hours. One of the other two designs demonstrated almost negligible cavitation damage, with no evidence of leakage, leading to the prediction of an even more extended life. The third design showed only slight damage and no leakage, but operational difficulties indicated that much more development would be needed in this latter case.

KEY WORDS

Mod-C, Visco Pump, Cavitation

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I. INTRODUCTION

The SNAP-8 turbine is a 4-stage axial impulse machine. The 4 stages are overhung on angular contact ball bearings. The working fluid for the turbine is mercury vapor and the lubricant coolant for the bearings is a polyphenol-ether oil (4P3E).

In order to prevent loss of mercury vapor and contamination between the turbine and the oil lubricated bearings, a dynamic seal-to-space system is employed. This seal is effected by condensing a liquid mercury plug between the shaft element (visco ring) and the housing which in the case of the SNAP-8 turbine contains double helical or herring bone grooves.

The design of the seal system for the turbine was developed during a separate but supporting program run parallel with and subsequent to the turbine design. Several seal designs were tested with the primary objective being the selection of a low leakage seal system. It was observed on several of the designs tested that although good sealing characteristics were obtained, varying degrees of cavitation and erosion on the running ring and housing also occurred indicating instability of the interfaces. Subsequent operation of several turbines in a mercury system demonstrated erosion and cavitation characteristics which in some cases were severe enough to preclude the attainment of the desired 10,000 hour life of the turbine.

In order to determine the life limitations of the visco seal ring and housing, four test rigs were built with the seal elements, visco ring, housing thermal geography, etc., closely simulating that of the SNAP-8 turbine. The primary purpose of the tests was the evaluation of seal elements in regard to cavitation and erosion resistance. Three basic designs were evaluated.

The first design was identical physically and as thermally similar as possible with the current turbine design. This design is known as the Reference design and will be so called throughout the report.

The second design is similar in concept to the Reference design but the sealing surfaces are smaller in diameter, the visco pump and molecular pump being on a common diameter. The slinger face used in Reference design is deleted in this case. This design is known as the Minor Modification (Minor Mod.

The third design represents a more radical departure conceptually from the Reference design in that the mercury condensed in the visco pump is recirculated from the seal area through an external heat exchanger from whence the cooling mercury is returned to the suction sides of the visco pumps. The external heat exchanger uses 4P3E oil as the cooling medium. This design is known as the Major Modification (Major Mod).

The three designs have been operated for the following accumulated periods:

- | | |
|-------------------|----------------|
| 1. Reference Unit | - 3134.1 hours |
| 2. Minor Mod | - 2574 hours |
| 3. Major Mod | - 1528 hours |

The inspection points after the above periods of operation have indicated that the Minor and Major mods exhibit markedly less erosion/cavitation damage than the reference design and as such are considered for inclusion in the turbine.

Of these two designs, the Minor Modification exhibited almost no damage at all and as such indicated that it would be an excellent alternative to the present configuration used in the turbine.

Comparison of the material loss/time data for the reference design and the seal data from TAA 5/4 indicates that for the seal in the turbine to lose as much material as was lost by the Mod-C reference design would require almost 70,000 hours of operation. Even with this amount of material loss no loss of sealing capability is indicated.

II. BACKGROUND

A. Seal-to-Space Program (Known as Mod-B)

The SNAP-8 turbine uses mercury vapor as a working fluid and runs on oil lubricated anti-friction bearings. Because of the proximity of these two fluids on the same shaft, a seal is required to prevent their mixing and restrict the loss of these fluids to space. The seal is located between the turbine and the adjacent bearing.

A seal-to-space program, was initiated early in the SNAP-8 development which investigated analytically and by test the primary seal elements advocated for the dynamic seals-to-space system for leakage criteria. The basic elements were the slinger seal, visco seal, and the molecular pump seal. It was established that three basic functions were required to provide a satisfactory low leakage seal. First, a liquid vapor interface must be established which can act as an effective barrier to the leakage of raw liquid. Secondly, the temperature of the liquid vapor interface must be controlled to maintain a low vapor pressure and thus diminish the quantity of leakage vapors emanating from the liquid vapor interface. Thirdly, the tendency of the interface vapors to leak into the space vent port must be diminished by the most effective flow restriction means available.

Several seal configurations were investigated (References 1 and 2) during this program. The individual elements, slinger, visco, and molecular seals were investigated separately and in combination. The primary objective of this seal program was to develop a low leakage seal-to-space system for inclusion in the SNAP-8 turbine and mercury pump components.

The final configuration for the seal-to-space which was installed in the SNAP-8 turbines is shown in Figure 1. It consists of (1) a visco seal; herringbone grooves in the stationary housing and a smooth running ring, (2) a slinger seal in which a liquid-vapor interface is established, (3) an oil cooled heat exchanger which cools the mercury seal liquid vapor interface and allows the seal to remain filled with mercury condensate, and (4) a Holweck molecular pump which pumps leakage vapors back to the liquid-vapor interface cavity.

Tests of the final configuration of space seal over a period of 1,018 hours demonstrated (Ref. 23) low leakage rates which extrapolated to a loss of less than 1.0 lb. mercury in 10^4 /hours. It was observed on this particular case and on several others tested that although good sealing characteristics were obtained that varying degrees of cavitation and erosion damage were sustained on both the running ring, and on the housing of the visco pump. Figures 2, 3, and 4 indicate the degree of damage.

The configuration of the seal involved in this long duration test differed slightly in detail from the design that was concurrently installed in the SNAP-8 turbine. The major differences were in the L/C flow rate of 3200 pound/hour (1600 pound/hour in turbine) and the seal ring material was AISI 4340 carbon steel (Greek ascoloy - a modified 400 series alloy in the turbine).

B. TAA Experience

Eight TAA's have been tested in their design environment and the degree of damage has been similar generally except for TAA 3/2. The periods of operation were:

<u>TAA</u>	<u>Hours</u>
3/2	826
6/1	117
2/3	143
2/4	165
6/2	1445
5/2	42
5/3	2122
5/4	10,823

The visco seal of TAA 3/2 showed severe damage by cavitation (Figure 5) and there was a light reflection of this damage on the visco seal grooves in the turbine housing. Observation of this degree of damage prompted the following changes for all subsequent TAA units:

1. A change in material from Greek Ascoloy to the more erosion-resistant Stellite 6B.

2. An increase in the radial clearance to balance the pumping coefficients and place the turbine end vapor/liquid interface more directly under the oil heat exchanger (thereby providing improved cooling for the liquid plug); this change also placed the new mercury vapor/liquid interface on the radial slinger face instead of on the cylindrical surface. TAA's 6/1 through 5/3, consequently, showed little or no damage (Figures 6 through 11). What damage there was appears to be similar to a light etching of the surface.

III. DESIGNS CONSIDERED

The decision to proceed with a development program was made after observation of the excessive cavitation damage demonstrated on TAA 3/2 visco ring after only 820 hours of operation.

A basic objective of this seal program known as Mod C was to obtain endurance information on a TAA space seal much sooner than could be obtained from the concurrent TAA system and endurance testing in PCS-1. Periodic examination of the seal as testing progressed would be required to establish bench marks as to life capability and this type of information could not readily be obtained from TAA's in PCS-1 due to the logistic and programmatic consequences of numerous loop shutdowns and component disassemblies. Reactivation of the Mod-B seal tester used in the earlier seal-to-space program was also considered but the reactivation costs and the limitation of being able to only test one seal design at a time eliminated the tester from further consideration.

In addition, if as accumulated run time grew, the periodic examination of the seal in the test rig gave evidence that the life/sealing capability of the seal was questionable, then other designs would have to be tested. In order to test the effectivity of other designs in a timely manner, the modified designs would require testing in parallel with the basic TAA design. This would entail more than one test rig.

An even more basic requirement of the testing is that any cavitation/erosion data generated in solving the space seal cavitation problem, regardless of which of the test rigs were being utilized, should be directly and quantitatively applicable to the TAA. In the same vein and as a prerequisite to establishing the validity of the test program, the initial test rig must not only faithfully reproduce the geometry of the TAA seal but must also demonstrate similarity in regard to damage compared with that sustained on TAA 5/3 tested in PCS-1, preferably in a comparable period of time.

Providing the simulation is satisfactorily demonstrated, then the information gained with the modified designs can be used with confidence. If the cavitation damage measured in this simulation test is distinctly different from that experienced with the TAA, then some correlation will have to be established.

IV. TEST RIG CONCEPT

The Mod-C seal tester primary purpose was to provide a facility for evaluation of cavitation damage of mercury space seals as used in the SNAP-8 TAA's. For a valid test, the geometry of the mercury space seal, thermal environment, and mercury vapor operating conditions must be simulated. The test rigs were designed to permit quick turn-around time and inspection of the seal configuration. Each test unit was identical in respect to a mercury pot boiler, a bearing and shaft assembly and an electric motor. Each rig has a common shaft supported on standard ball bearings. The motor mounted at one end with the space seal elements overhung on the other end. A pot boiler was flange mounted to the rigs so that the condensing mercury vapor collects and forms a liquid plug in the visco seal just as it does in the actual turbine.

V. SEAL DESIGNS CONSIDERED

A. Reference Design

This seal configuration is illustrated in Figures 1 and 15 (Basic TAA 5/3 Mercury Seal). It consists of:

1. A herringbone visco seal which creates a liquid/vapor interface at one end of the liquid mercury seal and prevents centrifuging of the condensing mercury into the turbine wheel cavity due to its inherent stability. The herringbone grooves are in the housing and the visco ring is smooth.
2. An oil-cooled heat exchanger which cools the condensed mercury seal liquid vapor interfaces and allows the seal to remain filled with mercury condensate.
3. A slinger seal which establishes the second liquid vapor interface.
4. A Holweck molecular pump which pumps leakage vapors back into the liquid/vapor interface cavity.

This seal design contains the dimensional modification made after observing the cavitation damage sustained by the first TAA operated with mercury (e.g., TAA 3/2). The radial clearance was increased to balance the pumping coefficients and place the turbine-end vapor liquid interface directly under the oil heat exchanger and provide improved cooling for the liquid plug.

B. Modified Design

(1) Minor Modification

From hydrodynamics of pump design, experience has shown a strong influence of speed on the propensity for the generation of bubbles. This influence is as strong as the 1.5 to 2.0 power. The seal diameter, peripheral velocity, also effect the amount of heat generated and consequently the rate of bubble generation.

This seal modification (Figures 16 and 17) therefore involved the reduction of the visco seal diameter to correspond to that of the molecular pump. This reduction in diameter reduces the seal peripheral velocity from 170 feet/second to 154 feet/second and hence the bubble generation propensity by approximately 30 per cent. Significant also is the effect of temperature level on the bubble formation.

The removal of enough heat can prevent or at least hinder the generation of the vapor that goes to form the bubbles. In this regard, the capability of the oil heat exchanger is important.

Experience with the turbine housing containing the space seal heat exchanger has indicated higher than design pressure drops which have cut the design coolant oil flow rate of 1,600 pound/hour down to 1,200 pound/hour. More important than increasing the coolant oil flow rate, the effect of which is small, is the improvement of the heat transfer from the mercury to the oil. To this end the heat exchanger was redesigned. The helical "fins" were replaced by "fin pins" and the passage height increased in an endeavor to improve the oil side film coefficient which is the major resistance to heat transfer.

(2) Major Modification

This design (Figures 18 and 19) is a more radical departure from the basic reference TAA 5/3 seal design but like the minor modification attempts to minimize the factors responsible for bubble generation; that is, reduced seal peripheral velocity and improved heat transfer (Ref. 4).

The peripheral velocity was reduced by reducing the visco seal ring diameter as in the Minor Mod. The improved heat transfer and consequent cooler running seal have been obtained by using the liquid mercury as the seal coolant. The liquid mercury is pumped out of the seal annulus by the visco pump through an external oil/mercury heat exchanger and then the subcooled liquid mercury is returned and injected into each of the visco pump grooves. In this manner, a more effective cooling of the liquid/vapor interfaces should occur.

It was estimated (Ref. 4) that a mercury recirculation flow rate of at least 200 pound/hour would be required to lower the present space side interface to the region of 230-250°F. In addition, on the turbine side the jets were slightly inset to keep this interface within 20°F of the condensing temperature and reduce the possibility of splashing or disturbances at the interface.

VI. TEST PLAN AND OPERATION

A. Original Test Plan

The original test plan (Ref. 5) called for initial testing for a period of 200 hours of the four test rigs simultaneously, each containing the TAA 5/3 visco pump configuration using 1,018 mild steel for the visco pump material for the rotating member. The purpose of this test was to obtain a distribution of data scatter attributable to dimensional and operational tolerances so that a valid interpretation could be put on single unit tests of other designs. The 1018 mild steel, a recognized inferior cavitation resistance (compared with Stellite 6B, the material used in the TAA seal) was to be used in these controlled tests to accelerate the rate of cavitation damage.

Following this evaluation, a basic TAA 5/3 configuration was to be used to study the effects of coolant flow and temperature in the heat exchanger. At the same time, a similar type of seal in another test rig was to undergo endurance testing for 10,000 hours with several inspections in order to determine a damage rate curve. The visco seal material was to be Stellite 6B in this case. Modified visco pump configurations but using 1,018 mild steel were also to be tested for periods from 200 to 2,000 hours with several inspections enroute in order to determine the degree and rate of cavitation damage. Table 1 reproduced from Reference 5 shows the sequence of tests planned.

B. Initial Loop Operation

The test rigs were designed to operate at the following nominal loop conditions:

L/C flow rate, pound/hr	1,000
L/C inlet temperature, °F	210
Mercury vapor temperature, °F	675
Mercury vapor pressure, psia	14.5
Shaft speed, rpm	12,000

The shakedown tests of the test rigs (which were begun in the fall of 1968) revealed several inadequacies, as follows:

1. Using the full capacity of the heaters a mercury vapor temperature of only 520^oF was attainable.

Analysis of this problem revealed that the cause was twofold. The power level of the heaters was inadequate and based upon erroneous heat input data, 4.5 kw being required instead of 1.5 kw. A thermal analysis based upon the test data revealed that the mechanical design of the pot boiler was such that a high thermal resistance was formed between the aluminum potting compound containing the Cal Rod heaters and the pot containing the mercury. The resistance was either a large void, microporosity of the cast aluminum and/or an oxide film between the stainless steel pot boiler and the aluminum (Ref. 6).

The pot boilers were redesigned using several 1 kw cartridge heaters, in sheaths, which projected directly into the liquid mercury. In addition, the pot capacity was increased to ensure adequate liquid mercury to cover the heaters. This would enable a significant loss of mercury to occur without endangering the heaters which if uncovered for a long while would soon overheat and electrically short out or burn "open".

2. The metal 'V' seals used to seal the oil from the mercury cavities when installing the replaceable heat exchanger (in the housing) were highly unsatisfactory and leakages in both directions frequently occurred. In addition, oil/mercury leakages also occurred past the Flexatallic seal situated between the pot flange and the bearing housing flange.

These leakages were eventually eliminated after many attempts to make the seals work, by welding the heat exchanger sleeve into the housing and increasing the flange bolt torque and applying a high temperature sealant (Copaltite) to the Flexatallic gasket.

3. A bearing phenolic cage failure of the bearing closest to the heat source after an emergency shutdown. This failure was attributed to the loop emergency shutdown mode which allowed a heat soakback from the hot mercury to deteriorate the bearing cage. The emergency shutdown mode shut off all oil coolant flow through the housing and the bearing air/oil mist system. Modification of the loop emergency shutdown sequence prevented the loss of coolant in future circumstances.

4. Subsequent operation of the rigs during shakedown tests also revealed higher than expected loading conditions in the same bearing (wider than anticipated track widths) which were attributed to reduction of bearing radial clearance due to higher than anticipated inner race temperatures.

To avoid a potential failure mode, this bearing was replaced by one with a larger (.001 inch) radial clearance. The other bearing (furthest away from the heat source) performed satisfactorily at all times and showed no evidence of abnormal loads.

The shakedown tests also revealed a failure of the facility lubricant/coolant pump which added to the delay in initiating the planned test schedule. Other difficulties were caused by instrumentation and facility modifications required to ensure a hands-off endurance capability.

Although there were numerous difficulties encountered during this early operation of the test facility, some significant information was obtained in regard to the cavitation damage rate on the TAA 5/3 configuration visco seal runner and housing and an accumulated run time of 1,844 hours was obtained on a single seal unit.

C. Modified Test Plan

The investigation and rectification of the test rig design deficiencies and the modification and additions to the instrumentation and electrical controls consumed a considerable amount of time and money from the program budget and as such, the original test plan had to be somewhat compromised in order to derive maximum benefits within reasonable cost and time limits. Many of the requirements for simplicity on the one hand and the ability to operate hands off and unattended on the otherhand were found to be conflicting, particularly in regard to obtaining reliability and safety of the loop and components. The complexity of the automatic shutdown and monitoring system provided an additional hinderance to the original program schedule.

The original test plan was eventually modified to fit a revised (Ref. 7) budget and schedule. The plan was to be as follows:

1. Run one test rig with the seal configuration corresponding to TAA 5/3, that is, mild steel housing and a 6B visco ring.
2. Run a second rig with the reduced diameter visco pump, mild steel housing and 6B visco ring.

3. Run a third test rig with reduced diameter visco pump, mild steel housing, 6B visco ring, but utilizing an external mercury oil heat exchanger.

4. All three rigs were to be run for 10,000 hours and then inspected. Any inspections other than the one at 10,000 hours would only be for maintenance and repairs of the rings or facility.

This test plan was embarked upon during spring of 1969.

D. Modified Test Plan Operation

The modifications to the units, the operating procedures, and the loop provide better reliability and utilization of the facility and at the program completion. The following hours of operation had been achieved:

Reference Unit	- 3134.1 hours
Minor Modification	- 2574.1 hours
Major Modification	- 1528 hours

There were however numerous shutdowns during this period, the majority of which were related to maintenance of TSE equipment and replacement of cartridge heaters and repair of broken and embrittled heater leads and Edison Company voltage dips. Both the minor and major modification units operated without any failures during this period. There were two failures which caused shutdowns of the reference unit. These failures occurred after only short periods of operation. (141 hours - 11 cycles, 126 hours - 4 cycles) Prior to these failures, the reference unit had operated for over 1500 hours without a problem.

1. Reference Unit

Hexagonal close packed (HCP) form Stellite 6B was included as the reference material in the earlier SNAP-8 turbines due to its good erosion resistant characteristics. This material however is brittle ($< 2\%$ ductility). The two fractures of the visco ring which occurred in Mod-C were attributed to this brittleness.

Examination of the first failed ring revealed a series of cracks. One of the cracks was completely through the ring, both radially and axially (Figure 35). The other cracks were much smaller and were generally located at the free end of the visco ring. Some of these cracks penetrated the entire ring thickness; others were restricted to the outer surfaces. The rub marks indicated that the large crack had existed before the last shutdown. Rubbing was restricted to only one side of the crack.

In the case of the second failure, removal of the simulated turbine wheel disc revealed that there were cracks in the visco seal ring at its free end. It also appeared that the act of cracking of the visco ring had allowed the free end of the ring to grow radially and become firmly lodged in the housing. The ring was removed from the housing with some difficulty. The ring was apparently in several pieces and was reconstructed on removal from the housing around an epoxy center piece for photographic and examination purposes.

Examination of the complete ring revealed more severe cracking than had been experienced on the first ring to fail. The cracks progressed both radially and axially from the free end through to the thicker fixed end. Also evident was a circumferential crack situated axially about two-thirds of the way back from the free end of the ring. The circumferential crack covered an arc of about 270° . Visual records of the failed part are documented in photographs listed in Table 6.

The analysis of these particular incidents revealed that the failures were the result of adverse thermal gradients, axial, and radial, in the disc portion (Figure 20) of the visco ring that is held on the shaft. Stresses exceeding the yield were calculated to have been reached in the area adjacent to the shaft.

It was the intent that the reference configuration of the visco seal, its material and its immediate environment, would be a close simulation of the configuration currently being used in the SNAP-8 turbine. At this period in time, there had been no failures of this part in a turbine that had been run for some 4,000 hours and subject to 20 thermal cycles and also other turbines that have run for lesser periods. Thus, the question arose as to why no failures of this type had been experienced during turbine operation.

The reason for the absence of a failure in the turbine was not at all obvious. The turbine test data from PCS-1 indicates that at similar L/C flow rates through the space seal heat exchanger that a smaller heat flux (smaller oil temperature rise) compared with the Mod-C unit is passed through to the oil. The heat flux measured in the turbine is approximately 25 to 30% less. Whether this lower heat flux is real is questionable at this point since the seal-to-space heat exchanger outlet temperature in the turbine is measured externally on the plumbing several inches away from the seal housing whereas in the Mod-C unit the outlet temperature is measured directly at the end of the heat exchanger within the unit. It should be noted, however, that the turbine composite housing through which the oil passes is at a similar temperature level to that of the oil and therefore little heat, if any, is added or subtracted from the oil as it leaves the unit. In addition, the plumbing external to the unit in the turbine is well insulated.

If the measured heat flux from the turbine space seal is real, however, it implies (all other things being equal) a liquid Hg plug in the visco seal as well as the visco seal with a lower average temperature. Herein may lie a reason for the absence of visco ring failures in the turbine.

A stress analysis of the ring as a free body compared with it axially restrained or clamped at its smaller diameter indicated a very strong influence of the axial restraint on the stress levels in the ring. This being the case, then the degree of axial restraint or the desire to distort or rotate about the colder corner must be considerably less in the turbine. This could only come about if the temperature level adjacent to the nut and shaft shoulder were lower than in Mod-C and were closer to the level of temperature in the cold corner (Figure 20). The physical and thermal environments at the free end of the ring are likely to be very similar in the turbine and Mod-C. The lower temperatures inferred by the smaller heat flux must therefore occur at the other end of the ring. This lower heat flux measured from the turbine tests in PCS-1 infer a temperature level at least 100 to 150°F lower in this area of the ring than occurs in the part in Mod-C. The tendency to distort or rotate due to axial and radial temperature gradients is therefore much less. The effect of this reduced tendency is that calculated stress levels below the yield occur. In general, over a 30% reduction in stress level occurs in the area of concern: a safer condition than exists in the Mod-C rig but not necessarily safe enough if the effects of material and surface defects are considered.

Again, the reasons why such a situation should occur are not obvious. The region in close proximity to the visco seal ring is identical in the turbine assembly and the Mod-C test rig. The heat exchangers are identical, the nut retaining the ring on the shaft is the same as used on the turbine. The only region where there is an obvious and significant difference lies in the heat path to the underside of the ring where it fits on the shaft. The shaft in the Mod-C unit is solid whereas on the turbine it is essentially a hollow shaft. In addition, the end of the solid shaft in the Mod-C unit, which is relatively close to the ring, is exposed to the 675°F mercury vapor whereas in the turbine the end of the hollow shaft, albeit at a much higher temperature, is far removed from the area of the ring. The heat conduction path is therefore much poorer in the turbine than in the Mod-C and, as a consequence, the material in contact with the I.D. of the visco ring in Mod-C is distinctly hotter. Although this fact was recognized earlier and an effort was made to provide a similar heat path to the Mod-C ring, it is possible that in reality, the effort was not completely successful.

A significant factor regarding these failures was the material used for the visco ring, Stellite 6B. Stellite 6B in the HCP form was initially used for the SNAP-8 turbine rotors and was responsible for two turbine failures (Ref. 9 and 10). Although stresses in the visco seal ring would be much lower, nevertheless, the small elongation property of this material was considered to be a major contributor to making this part prone to failure. Therefore, in order to obtain a greater margin of safety, it was recommended that Stellite 6B be used stabilized in the more ductile FCC form. The recommendation was adopted on the next assembly of the unit and this unit ran without failure for over 3100 hours and numerous thermal cycles.

2. Minor Modification

This unit operated entirely satisfactorily without any failures whatsoever. The shutdowns that did occur were either for maintenance or for reasons external to the rig.

3. Major Modification

There were no mechanical failures associated with this unit during operation, and again the majority of shutdowns were for general maintenance. However, there were several shutdowns which were precipitated by a loss of mercury flow during operation.

Since the design was an entirely new concept, tests were first run without any heat input to the mercury and the visco pump was primed, while running, from an external liquid mercury reservoir. This was done primarily to see if the visco pump would pump at all and also to see if a stable plug of mercury could be maintained in the pump. The visco seal successfully demonstrated a pumping capability but was unable to maintain a stable plug of mercury which was quickly lost from the seal. The inability to maintain a plug of mercury was not disturbing considering the different pressure and temperature environment compared with the designed for hot operating conditions.

The initial hot operation also satisfied some questions in regard to the feasibility of the seal concept and its ability to prime itself; that is, to establish a stable flow by condensing and pumping into the heat exchanger sufficient liquid mercury to fill the heat exchanger, associated plumbing and the visco seal itself prior to heating up of the shaft and surrounding housing. It was felt that if the system was unable to establish a stable operating pattern, with a continuous liquid seal prior to the heatup of the housing to the point where mercury vapor is not condensed in sufficient quantity, then large quantities of mercury may be pumped out of the system through the space seal (due to the differential pressure across the seal).

The first few tests indicated the sensitivity of the configuration to the initial housing and shaft temperatures. In the first test the current to the heaters was increased slowly and this allowed the shaft and more particularly the surrounding housing temperature to rise almost as rapidly as the mercury temperature. By the time mercury vapor was being produced, the housing temperature had reached a level whereby the condensation rate was below that level required to prime the system and gain the advantage of the cooling mercury flow which would maintain a relatively lower housing temperature and allow a liquid mercury plug to form.

The second test produced quite different results. The current to the heaters was increased almost immediately to the anticipated level for the operating temperature required. Mercury vapor condensation occurred at much lower housing temperatures, the system primed itself and set up a liquid mercury flow and a stable plug of mercury in the visco seal. The mercury flow rate was observed to increase from zero to over 1,000 pound/hour (off the scale of the recording instrument) in approximately 30-45 seconds.

The flow was then throttled down to 800-900 pound/hour by partially closing the flow control valve on the discharge side of the visco pump in order to observe the variations in the flow. The flow appeared to be unstable in that high frequency variations in flow were occurring. The amplitude of these variations were reduced considerably when the flow was reduced further to 400-500 pound/hour. Under these conditions, this configuration of space seal functioned well. Tests were also conducted under hot operating conditions wherein the mercury flow control valve was completely closed for at least 20-30 seconds. The valve was then reopened fully and it was observed that the seal primed itself and continued flowing mercury. The flow was regained some 10-12 seconds after opening the valve.

Two problems however shortly revealed themselves:

a. Increasing outer race temperature of the bearing situated closest to the seal and mercury pot boiler. Normal operating temperatures for this bearing on the other rigs and initially on this one had been 230-240°F. Over a few hours this temperature rose to 295-310°F, the recommended upper limit for this bearing being 300°F. Investigation indicated that this problem was peculiar and particular to this housing configuration. It appeared that a considerable amount of heat was being conducted axially through the housing to the bearing area. Removing from the housing the internal oil heat exchanger (as is present on the reference design and minor modification) from surrounding the visco seal and replacing it with an external oil/mercury heat exchanger removed the thermal barrier and heat sink for a considerable portion of the heat that was now able to reach the bearing.

A temporary arrangement was made by blowing air over the housing which was partially successful. A more permanent arrangement was later made by silver soldering copper cooling coils to the conical rear face of the housing and passing cooling oil (as used in the heat exchanger) through them.

Subsequent Operation - There were several shutdowns and disassemblies of the unit that occurred at intervals of 300-600 hours. Replacement of the carbon face seals, which provide the seal between the bearing and lubricant system and the space seal vacuum cavity, were involved in a few of these shutdowns but more disturbing was the loss of liquid mercury flow on several occasions. The loss of mercury flow was observed to occur over several hours on one occasion but were generally over a period of 2-3 days.

Where a loss of flow was observed, the subsequent disassemblies revealed that in the housing the small discharge holes of the visco pump were either partially or completely blocked, and occasionally the mercury line (0.125 inch diameter stainless steel tubing) in the heat exchanger was also blocked. Analysis of the material blocking these paths showed it to be a gummy substance formed apparently by the agglomeration of oil and mercury. The oil was found to be the coolant, 4P3E, used in the heat exchanger and the housing flange. Investigation revealed two possible sources of oil, the flexitallic gasket between the boiler and housing flange which seals the flange coolant oil from the mercury vapor or the oil/mercury heat exchanger. Inspection of the flange faces indicated adequate compression of the seal, and the flange surfaces were not scored or warped in any way. A helium leak check of the heat exchanger (at room temperature) indicated no leakage was present. It was suggested that it might be possible that the flange may distort at temperature and allow oil to leak into the mercury boiler, or that perhaps a leak in the heat exchanger only occurred when at temperature. Several times it was possible to flush the heat exchanger, and more particularly the visco pump inlet and exit passage in situ but this did not eliminate the congesting material completely, although it did temporarily alleviate the blockage. The testing of this unit was suspended after 1585 hours of operation due to evidence of more significant cavitation damage than was being obtained on the minor modification and a growing conviction that although the concept had been proven, more development was required to make the concept acceptable for a TAA than either funds and/or time left in the program would allow.

VII. TEST RESULTS

The primary purpose of this particular seal program was to provide either a design or information that would lead to a design of the visco pump component of the space seal that would be less susceptible to cavitation and erosion damage than the design currently used in the SNAP-8 turbine.

Before examining the test results, it would be well to discuss the phenomena of cavitation and some of the contributing factors.

Cavitation is defined as the formation of voids within a moving body of liquid when the particles of liquid fail to adhere to the boundaries of the passage. These voids occur when there is insufficient internal pressure to overcome the inertia of the particles of the flowing liquid to force them to follow the changing boundary. The voids thus formed become filled with vapor of the liquid or entrained air and cause the formation of bubbles.

Over the past decade, extensive research has established that by far the major part of the damage associated with cavitation is due to a mechanical erosion of material. Studies (Ref. 11 through 15) of the cavitation phenomena has shown this erosion is brought about by the collapse of the entrained air or vapor bubbles or the collapse of bubbles formed by dissolved air in the fluid. It has also been demonstrated that the collapse of a bubble against a solid boundary will cause a pressure against that boundary (Ref. 12). Although the entire life of these bubbles is only a few microseconds, the pin-point shock pressure produced by the bubble collapse is extremely intense and damage to the material with which they are in contact either by direct destruction or by producing a fatigue type failure (Ref. 14). The intensity of bubble collapse, the number of bubbles formed, their size, etc., dictate the amount of damage done in a given material. In addition, the surface roughness of the boundary and surface tension of the fluid contribute to the propensity for bubble formation and consequent damage. The regions in which cavitation damage generally occurs is turbulent and the random nature of the turbulent flow patterns and the difficulties in establishing gas content make a quantitative solution to the problem almost impossible.

Investigation by numerous authors have only served in many instances to give rise to more questions such as what factors cause the bubbles to form in the first place, where they are most likely to form and where they are most likely to collapse. Apart from the hydrodynamic considerations, the boundary material resistance to the forces created by the collapse of the bubbles is a matter of the metallurgical composition and structure of the material itself.

The treatment of these factors either separately or together by numerous investigators has not been sufficiently accurate to permit their use quantitatively with any high degree of confidence.

The basic contention put forward by the majority of investigators in general is that the formation of a void in a liquid flowing over a changing boundary depends upon the velocity of flow and the surrounding pressure. In an attempt, therefore, to reduce the propensity to cause the formation of bubbles and subsequent cavitation damage, the modified visco pump designs tested in this program were of smaller diameter (reduced velocity) than the configuration currently in use, and had either an improved internal heat exchanger (minor modification) or recirculating mercury and an external oil/mercury heat exchanger to lower the general fluid temperature hence vapor pressure level in the visco pump.

A. Reference Design

1. Mod-C

This is the configuration that is currently in use in the SNAP-8 turbine and it is this design that has exhibited significant cavitation damage in actual operation of the TAA 3/2. The visco seal ring removed from 5/3 (which included the design changes described in Paragraph II-B) is shown after 2122 hours of operation in Figures 9, 10, and 11. This is noted to have quite moderate surface damage.

Characteristically, there was no damage to the housings in the turbine (Figure 15); all the damage occurred on the visco ring itself. The damage on the ring has also been localized to the side of the ring that supports the pumping of fluid away from the turbine. As Figure 11 shows, the damage is fairly uniform, and may be described as a light etching of the surface. The interface between the damaged and undamaged portions of the rings show extensions of the etched-like area which appear to be a reflection of the grooves in the housing and are at almost the same angle of inclination to the ring center line.

Returning now to Reference design in the seal test rig, this visco ring was examined on five occasions during the 3134.1 hours operation (Figures 21 through 31). The examinations were made after 45 hours, 154 hours, 501 hours, 1844 hours, and at the completion of testing.

The progress of the damage is very evident from the photographs. Again, as in the turbine visco seal, damage has occurred in the same region and shows reflection of the housing grooves. There was evidence however in the early portion of the test, of damage occurring on the narrow portion of the visco pump which pumps toward the turbine. No damage of this kind was in evidence on the visco seal from the turbine. As testing progressed, this latter damage did not worsen but the damage on the broad portion of the pump which pumps away from the turbine grew steadily worse and heavier than experienced with the turbine.

The initial conclusion reached was that the damage to the visco ring in the seal (at 1884 hours) was decidedly worse than that experienced in the turbine at 2122 hours. The cavitation damage in the Mod-C unit appeared to give an accelerated version of the actual turbine damage. The intended simulation of the TAA visco seal conditions and damage were therefore not correct.

The weight loss curves for this particular visco seal are shown in Figure 32. Also, significant is the damage to the housing grooves, damage that was not present in the turbine. Figures 33 and 34 show the local depths of penetration on various areas of the ring and comparable data for the TAA 5/4.

The reasons for the accelerated heavier damage in the seal test rig visco seal ring are obscure. The heavier damage within a similar period of time can suggest more intense bubble collapse, more bubbles, and/or larger bubbles or even a physical difference such as annular clearance and/or shaft eccentricity. Build-up records indicate annular clearance and shaft runouts well within tolerance and almost identical with the turbine dimensions. This leaves only possibilities of thermodynamic and hydrodynamic differences.

A preliminary thermal analysis indicated that perhaps the visco seal ring was running hotter than its counter part in the turbine; anywhere from 70 to 100°F hotter. This of course would affect the material properties and create larger bubbles. There was evidence of hydrodynamic or thermodynamically induced instability as evidence by the large variations in motor current. The nominal 5-6 amps fluctuated up to 10-12 amps several times a minute.

The reasons for ragged interface between the etched and unetched portions of the ring are equally obscure. One would normally expect uniform peripheral damage since the part is rotating. However, the location of the fingers or promontories of damage and angle of inclination suggest a cyclic phenomena that is a function of rotational speed. The inference here being the possibility of cyclic recirculatory flow within the grooves in the housing. A certain amount of recirculation is expected

due to the pressure differences from one side of a groove land to the other. The cyclic nature of the flow could be induced by shaft or visco ring eccentricity or very small dimensional differences.

Evidently, after the 501 hour inspection and reassembly, the dimensional and buildup changes were sufficient to disrupt a greater part of the cyclic nature of the cavitation phenomena to the extent that the damage produced became comparatively uniform circumferentially (Figure 28) and the promontories of damage were obliterated.

The damage to the grooves in the housing, which became evident after 154 hours of operation, was only slightly worse at 501 hours of operation. Beyond this point in time there was no further damage to this part.

The amount of damage sustained in the housing was equivalent to that occurring in the TAA 5/3 after 2122 hours of operation. Judging by the photographic evidence, the vast majority of the damage in the Mod-C housing occurred during the first 150 hours of operation. A comparison of Figures 23 and 30 (154 hours and 1844 hours of operation) shows no evidence of increasing damage.

The damage to the visco ring is understandable to the extent that the mechanics of the situation will dictate that the cavitation bubbles will remain next to the visco ring rather than the liquid mercury. Under these circumstances, the damage to the grooves and lands in the housings can only be explained by the presence of a recirculatory flow which allows a void or bubble to be formed toward the trailing edge of a land.

It was at this point that the fits, clearances and areas of contact of the visco ring with the shaft and turbine wheel simulator were reviewed with the object of making the heat input to and hence the temperature of the visco pump sleeve simulate those conditions as they occur in the turbine as closely as possible. The significant physical change involved here was the simulation of the contact area of the curvic coupling teeth of the fourth-stage wheel of the turbine on the free end of visco ring. Similar teeth were cut on the rear hub of the turbine wheel. In addition, an identical nut as used on the turbine was used to retain the seal ring on the shaft.

Subsequent operation of two seal rings of Stellite 6B resulted in thermal cracks and test rig seizures. The remedy for these failures was to replace the visco ring with one using the more ductile form of Stellite 6B material, the face centered cubic (FCC). The more brittle hexagonal close packed form (HCP) had been used previously.

With an FCC visco ring installed, the unit was run for an accumulated run time of 3134 hours with an inspection period at 1683.9 hours.

A comparison of Figure 29 and Figure 41 shows that the FCC visco ring, although run for a slightly shorter period (1684 hours) than the HCP ring (1844 hours), experienced somewhat greater damage, notably, the larger diameter which pumps toward the turbine at the rear of the ring. A major portion of this lip has been removed by the cavitation damage. In addition, the damage on the larger diameter, which pumps away from the turbine, contains pits and cavities far deeper than those occurring on the harder (HCP) Stellite ring. Since the operating conditions were similar, a possible major contributor to the more severe damage was the change to the more ductile material.

This latter ring was reinstalled in the unit and run for a further 1451 hours. Looking at Figure 44 reveals that the additional running did not produce proportionally more damage; in fact, there appears to be very little additional damage except in one particular area. The damage to the O. D. of the lip which pumps toward the turbine while superficially showing no more damage, contains pits and cavities whose depth has been considerably increased; increased to the extent that some of the cavities have broken through the slinger face of the ring (Figure 46).

The weight loss characteristic of this ring compared with the data obtained from the long operation (10,823 hours) of a ring from TAA 5/4 shown in Figure 32.

2. TAA Operation

The visco ring taken from the 10,823 hour turbine assembly shows remarkably little cavitation damage. The increase in observable damage between the 2122 hour and 10,823 hour data points is small.

At 2122 hours of operation, Figure 11, there is light surface etching at the leading edge of the ring and immediately adjacent slightly heavier etching with promontories of roughened surface inclined to the axis of rotation and corresponding to the angle of the grooves in the housing. The amount of material removal in the radial direction is of the order of tenths of thousandths. At 10,823 hours, there has been no extension in the axial direction of the area of damage. However, radially the increase in depth has increased as indicated in Figures 69 and 70. The increase is about .010 to .012 inches circumferentially at a specific axial distance from the hot end of the ring. The width of the band of cavitation damage is probably the result of operation of the turbine with various exhaust pressures. The boundary of the damage area furthest from the hot end exhibits the characteristic promontories of damage at angles to the axis of rotation approximating to the angle of the grooves in the housing. Elsewhere the ring is unmarked. The single pits shown in Figure 71 are no more than .010 - .012 inches in depth.

A comparison of the damage at 2122 hours and at 10,823 hours (Figures 11 and 70) show that the rate of progress of the damage is comparatively slow and that a considerable period of operation in a TAA would be required before damage comparable to that sustained by the reference design would occur.

B. Minor Modification

This configuration was initially run for a period of 2001 hours. As Figures 50 through 53 show, the cavitation damage sustained was light indicating that this configuration promised a distinct improvement in its ability to resist cavitation and provide a long life seal when compared to the reference design in Mod-C.

However, a review of the inability (initially at least) of the major modification to hold a stable plug of mercury in the visco pump led to the installation of a ring (Figure 54) at the turbine end of the visco pump which effectively closed the 'open' thread starts in the housing. These open thread starts allowed liquid mercury in the plug to spill and/or splash out of the plug thereby providing an instability and eventual loss of fluid. Since the basic configuration of these seals was similar it was concluded that a similar modification to the minor modification would be advantageous.

The second minor modification with this ring included was run for 2574 hours before a worn carbon face seal and a bearing failure terminated the testing.

Figure 49 shows no evidence of cavitation damage, a marked improvement over the original configuration. There is some discoloration of the visco seal ring and a light etching of the surface corresponding to that portion of the visco pump that pumps toward the turbine. Close examination of the ring indicates that the bearing failure probably allowed the ring over its entire periphery to lightly touch the housing with a more emphatic interference in only one place. The light touching of seal ring and housing appears to have removed some of the etched surface as evidence by the circumferentially interrupted but continued islands or promontories (corresponding to the housing grooves) of etched surface. The housing also shows no evidence of cavitation damage.

Thus, the latter form of the minor modification is by design therefore a distinct improvement over the reference seal design in regard to its ability to resist cavitation damage.

C. Major Modification

The major modification was operated for a total of 1528 hours before the testing was terminated. During this period, the unit was disassembled several times in order to clear the plugged visco pump discharge and inlet passages. These disassemblies enabled the visco pump to be inspected frequently during its run life. Figures 54 through 67 show the visco pump ring and housing at significant stages during the run period.

Significantly, up to 421 hours of operation (Figures 54-58) there is very slight etching of the surface circumferentially in the region of the visco pumps which pump to and from the turbine. The marks take the form of parallel lines at angles to the axis of rotation corresponding to the angle of the screw thread in the housing. The etching is more strongly pronounced in the region of the exit channel into which both halves of the visco pump discharge.

This level of damage may be roughly compared with the reference unit visco pump after 501 hours, Figure 26 and 27, which show much more cavitation pitting damage.

The unit was next inspected after a further 520.9 hours of operation (Figures 59 and 60) at 941.9 hours of operation without any further etching or damage being evident either to the visco seal ring or the housing.

The next 640 hours of operation were plagued with numerous shutdowns due to blockage of the heat exchanger and visco pumps inlet and exit holes with an oil mercury mixture.

It was during this latter period of operation that the most significant changes in the condition of the seal occurred. As Figures 61, 62, 65, 66, 67, and 68 show, large areas of localized pitting due to cavitation are evident, principally in the region corresponding to the visco pump half which pumps away from the turbine and in the region of the discharge channel (in the housing). Damage was also present (Figure 63) on the ring insert (which closes off the open grooves) in the housing.

Comparing the major modification damage with that sustained by the minor modification after 1580 hours and 3134.1 hours of operation respectively, indicates that major modification does have the same capability of resisting cavitation damage as does the minor modification. The major modification is however distinctly better in this respect than the reference seal design as can be seen by comparing Figures 61 and 44.

While the period of operation with the major modification has proved that the basic concept works (that is, the ability to circulate mercury and create a seal) experience has shown that considerable development work would be required before a completely workable form would be available.

VIII. DISCUSSION

Concern for the turbine visco seal ring to survive 10,000 hours of operation in a turbine was precipitated by the observed damage sustained by the Greek Ascoloy visco ring from TAA 3/2 which ran for 822 hours. The degree of damage was such as to provide grave doubts about the mechanical structural integrity and sealing capabilities of the seal for periods of use exceeding 1000 hours.

Examination of this seal ring indicated that the liquid/vapor interfaces were not in the correct position on the ring. Proceeding from the turbine end, the interface was too far back from the leading edge of ring, and the second interface was located on the cylindrical portion of the ring instead of on the radial surface. A design change increasing the radial clearance to reduce the pumping coefficient of the visco seal that pumps toward the turbine was made and a material change to the more erosion/cavitation resistant Stellite 6B was also included.

Even though these changes radically improved (diminished) the cavitation picture on subsequent TAA's, the damage sustained was still cause for concern, hence the decision to proceed with the turbine visco pump seal program in view of the lengthy cavitation time needed to accumulate operating hours in the mercury system facility.

Relationship between the three seal configurations:

A. Cavitation Damage

The basic requirement regarding the value of these tests was that the operating conditions as experienced by the visco seal elements in the test fixtures would approximate as closely as possible those conditions that exist in an actual turbine. Initial operation of the reference unit indicated that the simulation fell short of producing similar damage patterns. Minor changes to produce a better simulation of the turbine seal environment did not give the desired close correlation. The damage pattern however was vaguely similar in the region of the visco pump that pumps away from the hot mercury.

The damage sustained on the TAA visco pump occurred on the forward (turbine end) part of the diameter which pumps away from the turbine whereas on the reference Mod-C unit the damage occurred more towards the rear portion of this same diameter. Differences in axial location relative to the heat exchanger in the housing in both TAA and Mod-C could contribute to this difference however measurement and observation indicate differences of only a few thousandths of an inch are involved. The damage sustained at the top of the slinger face and on the immediately adjacent cylindrical surface at the slinger O.D. was severe. This however was not at all present on any of the turbine visco pumps thus indicating the location of an unwanted interface.

The housing damage in both instances was also different being significant in the Mod-C reference unit and with no observable damage in the turbine. The lack of damage on the turbine 5/4 housing is a good indication that the vapor bubbles were effectively centrifuged toward the shaft.

The reason for the radical difference between the two is obscure and is probably a result of a combination of thermal and physical differences which are probably very slight since they are not readily discernable.

The rate of material removal and damage in the Mod-C Reference unit was greatly accelerated compared with that sustained in the turbine (compare TAA 5/3 damage at 2122 hours). However, this in itself may not be entirely detrimental to the investigation at hand if a time/wear correlation factor between the two situations can be determined. The weight loss curves of Figure 32 provide some feel for the order of magnitude of this factor. This curve indicates that for a given operating period of operation, the Mod-C reference design lost approximately 25 times as much material (by weight) than did the same design in the turbine. On this basis alone, to lose as much weight in the turbine as was lost by the Mod-C reference design in 3134 hours would require almost 65,000 hours of operation (assuming a linear, time/material loss relationship) in the turbine proper.

The amount of material removal sustained by the minor mod was substantially less than that of the reference design. Evidently, the reduction in diameter of the seal ring and (to a lesser extent) the new heat exchanger configuration were changes in the right direction. Unfortunately, the interference of the visco ring and housing during the last period of operation of the minor mod obscured the true weight loss. However, on a subjective basis, one can readily see hundreds of thousands of hours required for equivalent material loss. The indicated position of the liquid mercury/vapor interfaces also appears to be satisfactory. The actual

contribution of the redesigned heat exchanger is unassessable from a practical standpoint due to failure of the special thermocouple used to reach (internally) the heat exchanger outlet. Analytically, the modified heat exchanger is only marginally better.

The major modification, as Figure 65 shows, sustained significant local damage after only 1528 hours of operation. Even at 941 hours, the damage is greater than that sustained by the minor mod at 313⁴ hours of operation. This fact alone puts this seal configuration out of contention. While the concept embodied in this particular configuration has essentially been proven, the practical difficulties experienced (heat exchanger and visco pump hole blockage, oil injection into the mercury system, unsteady mercury flow rates) have indicated that considerable development of the seal and the test rig itself would be required before a satisfactory design could be established.

B. Mercury Leakage

The primary purpose of the seal-to-space system in the SNAP-8 turbine is to prevent leakage of mercury out of the system. The visco pump provides the liquid plug of condensed fluid which forms part of this seal. The characteristic leakage rates of seals of the nature considered here is basically low (that is, of the order of 10-20 pounds in 10⁴ hours) and to accurately determine these small leakage rates requires more sophisticated test equipment than the space seal (Mod-C) program could support. The only indication of leakage rates that could be obtained was to observe the change in the liquid mercury level indicator which shows the level of mercury in the pot boiler. This level-indicating device consisted of a differential pressure transducer with liquid mercury in both legs. One leg was connected to the bottom of the pot boiler and the other to a standing leg containing an equal height of mercury. The only unbalance possible therefore coming about by loss of mercury in the pot boiler.

This provided only an extremely coarse measurement of space seal leakage loss by relating this to a change liquid level in the pot boiler. Its primary objective was to provide protection for the cartridge heaters in the boiler. Normally run immersed in the liquid mercury, if uncovered by loss of mercury (via leakage past the space seal) the heaters would burn out and fail.

Observations during extended run periods (500 hours) indicated imperceptible loss of liquid in both the reference and minor modification unit. Even the reference unit with severe cavitation damage indicated no perceptible loss of mercury. This last observation is particularly important since it indicates that from a sealing standpoint alone (considering the comparatively little damage sustained by the visco pump ring in TAA 5/4 in 10,823 hours) that the TAA visco seal could probably operate for several times its design life before any question of loss of sealing capability could be raised.

IX. CONCLUSIONS

As a result of the visco seal test program, the following conclusions can be drawn:

1. Under similar operating conditions in the Mod-C test facility, the minor modification visco seal exhibited little or no cavitation damage than the reference design and as such, indicates an excellent alternative to the present configuration in the turbine.

2. It is suggested that although the pattern of damage sustained by the reference design is distinctly different from that sustained in a TAA, that the magnitude of the damage and material loss may be an accelerated version of that damage that is presently being experienced in a TAA. If this is the case, an extrapolation (linear) of the weight loss data indicates that the visco pump in the TAA can run for over 65,000 hours before an equivalent degree of damage would be sustained.

3. The concept of a double visco pump which circulates liquid mercury through an external heat exchanger and maintains a seal was satisfactorily demonstrated. However, before an entirely satisfactory version could be obtained, a great deal of development work is required. The amount of cavitation damage that did occur with this configuration, considering the shorter period of operation, was slightly worse than that obtained on the minor modification although it is acknowledged that the designs were probably not optimized.

4. Although the leakage capability of each of the seal configurations was not specifically tested for, the indications are that even with significant cavitation damage as sustained by the reference design, no leakage was discernible. Also, although the reference design elements suffered extensive damage during Mod-C testing, there appeared to be no indication that disintegration of the seal ring would occur nor did there appear to be a likelihood of a catastrophic seizure taking place.

5. The simulation by the Mod-C Reference design of the visco seal damage as sustained in TAA 5/3 was obtained only in the broadest sense. The degree of simulation was less than that aimed for. Additional regions of damage were observed on the Mod-C Reference design and the magnitude of the damage was markedly greater at 3134 hours of operation than that sustained by the TAA visco seal after 10,823 hours of operation.

6. Examination of the thermal and physical layout of the Mod-C Reference configuration and comparison with the corresponding TAA layout suggests that the difference in degree of damage sustained in the two circumstances is related to only small thermal and dimensional differences. This further suggests that a second turbine alternator assembly apparently identical in the region of the space seal may produce a cavitation damage pattern significantly different than that experienced by TAA 5/4.

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12. Symposium on Erosion and Cavitation, ASTM Special Technical Publication #307
13. Experimental Investigations of Some Properties of Cavitating Flow,
J. Varga, Gy Sebestyen
14. Cavitation Bubble Collapse Observations in a Venturi,
R. D. Ivany, F. G. Hammitt, T. M. Mitchell
Journal of Basic Engineering - September 1966
15. Cavitation Along Surfaces of Separation, D. W. Apel
ASME Preprint 60-WA-265

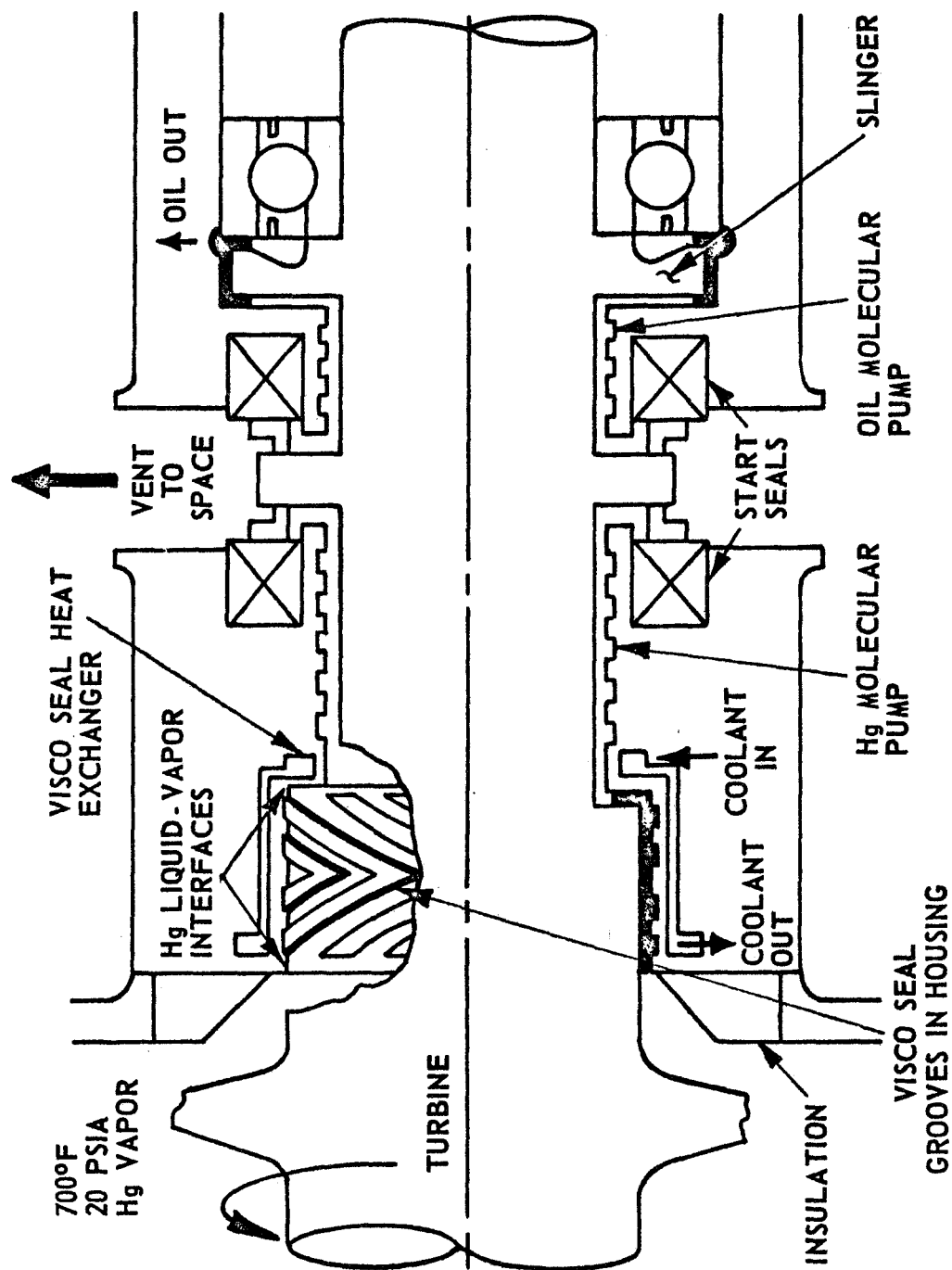


Figure 1

Seal to Space - Slinger Seal Liquid-Vapor Interface

664-834



Figure 2

Mod-'C' Visco Ring After Approximately 1300 Hours in the TAA Seal Simulator Test

664-835



Housing from Mod-'B' Test

Figure 3

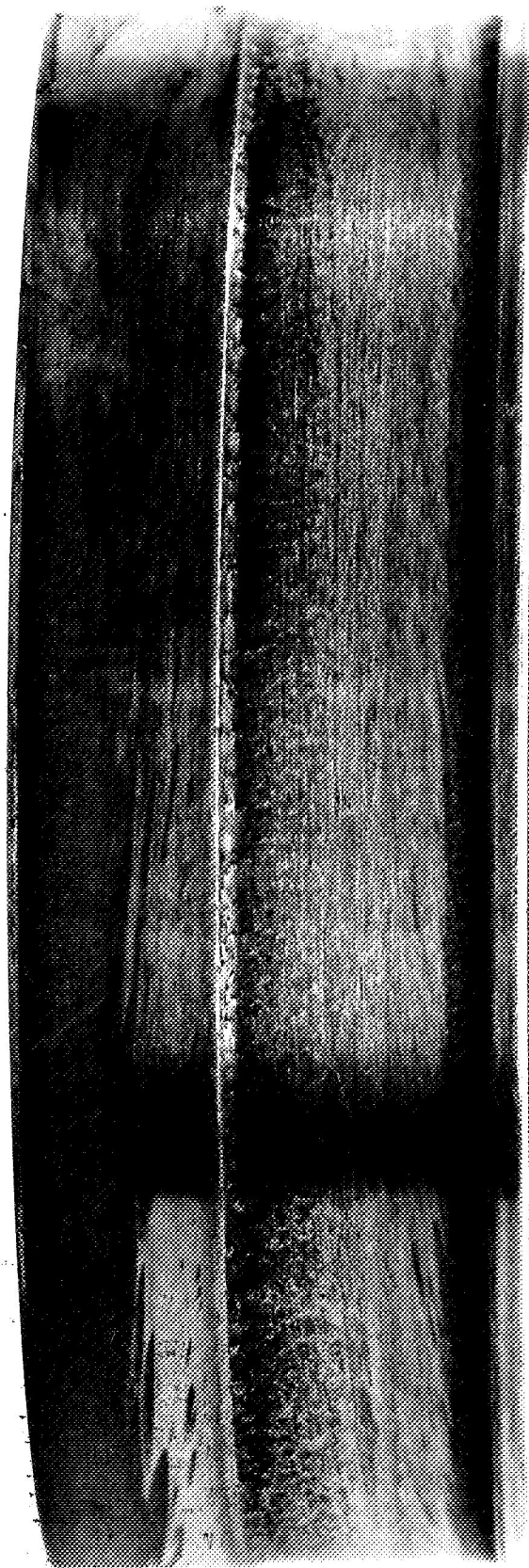
765-571



Figure 5

Visco Seal Ring on TAA 3/2

567-074



RUB MARKS AND CAVITATION DAMAGE
ON VISCO SEAL RING
TA 1 / 5 AFTER SHUTDOWN 4-25-67

Figure 6

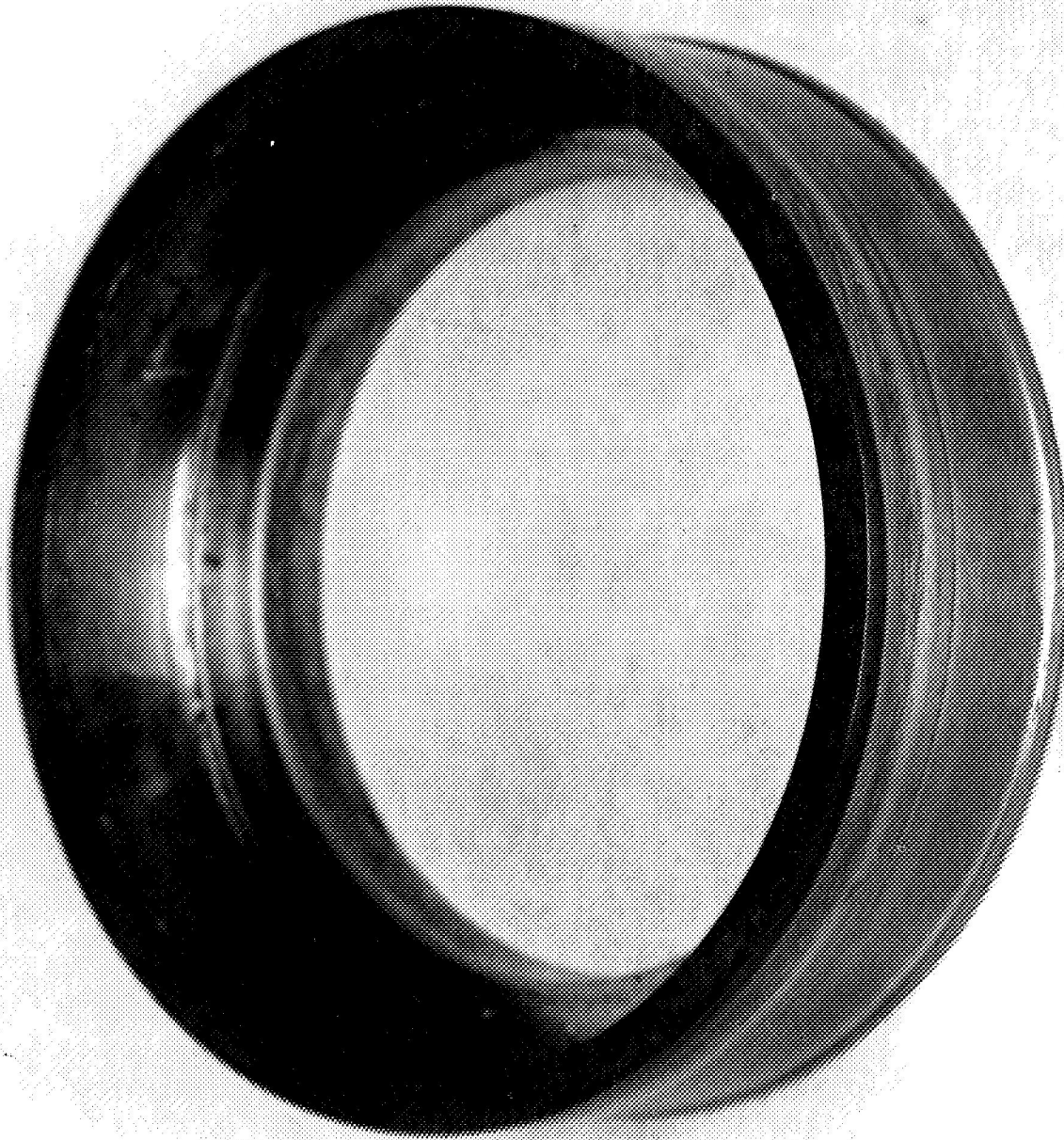
366-050



SNAP 8 TURBINE-ALTERNATOR ASSEMBLY 2/3
P/N 096800-1, S/N A2 141 HRS. OPERATION
VISCO SEAL RING. SLINGER SIDE

Figure 7

366-049



SNAP 8 TURBINE-ALTERNATOR ASSEMBLY 2/3
P/N 096800-1, S/N A2 141 HRS. OPERATION
VISCO SEAL RING. TURBINE END

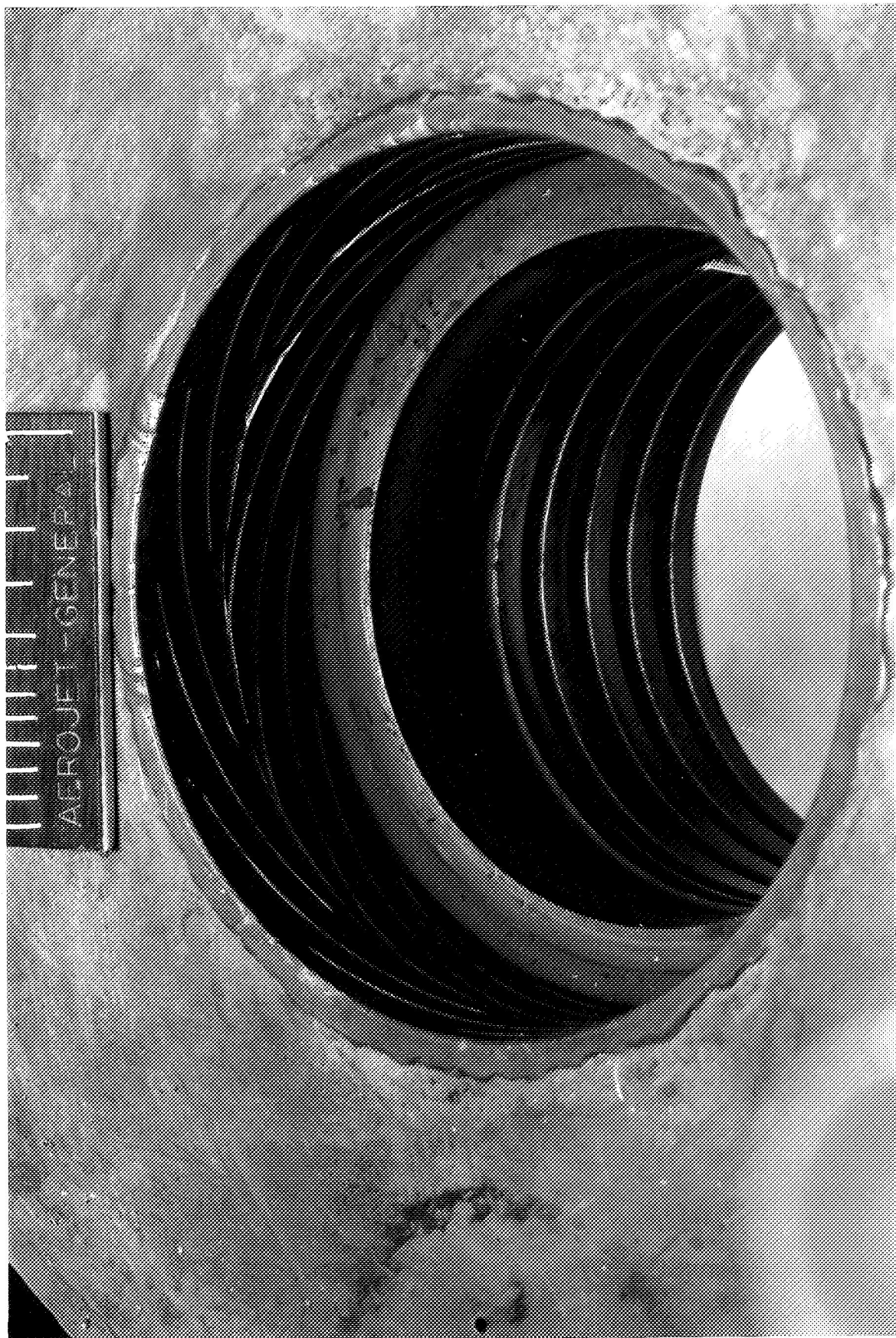
Figure 8

1267-444



(CLEANED) TURBINE 5/3 AFTER 2122 HOURS OF TESTING
IN PCS-1 PHASE IV STEP 3 VISCO SEAL RING

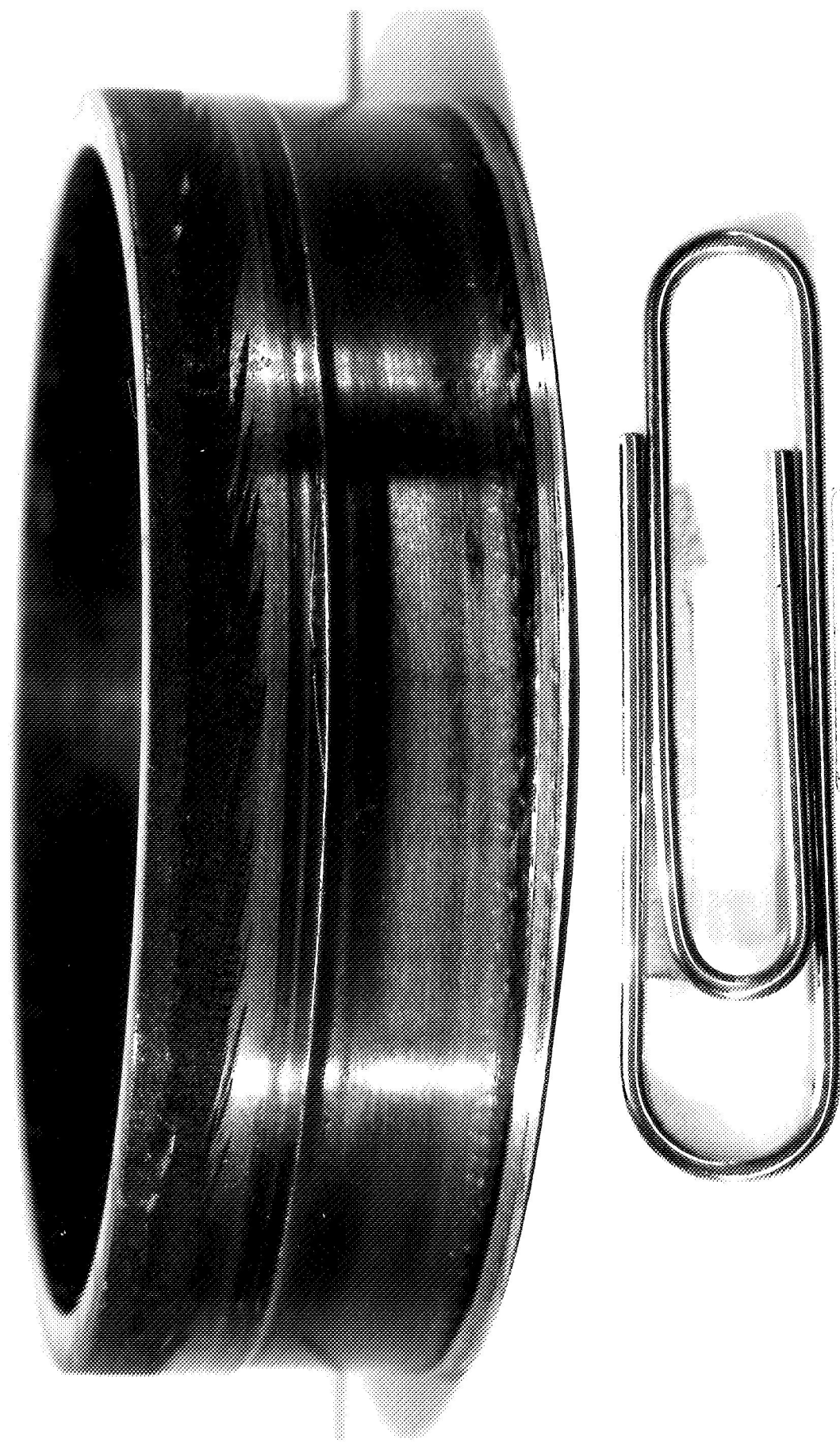
Figure 9



SNAP-8 TURBINE-ALTERNATOR ASSEMBLY. UNIT NO. 5/3
P/N 096800-5 AFTER 2123 HOURS OPERATION
SEAL HOUSING PORTION OF TURBINE CASE
SHOWING VISCO PUMP AND MOLECULAR PUMP
(SPACE SEALS)

Figure 10

1167-642



SNAP-8 TURBINE-ALTERNATOR ASSEMBLY. UNIT NO. 5/3
P/N 096800-5 AFTER 2123 HOURS OPERATION
VISCO PUMP RING P/N 098084-3 S/N A1

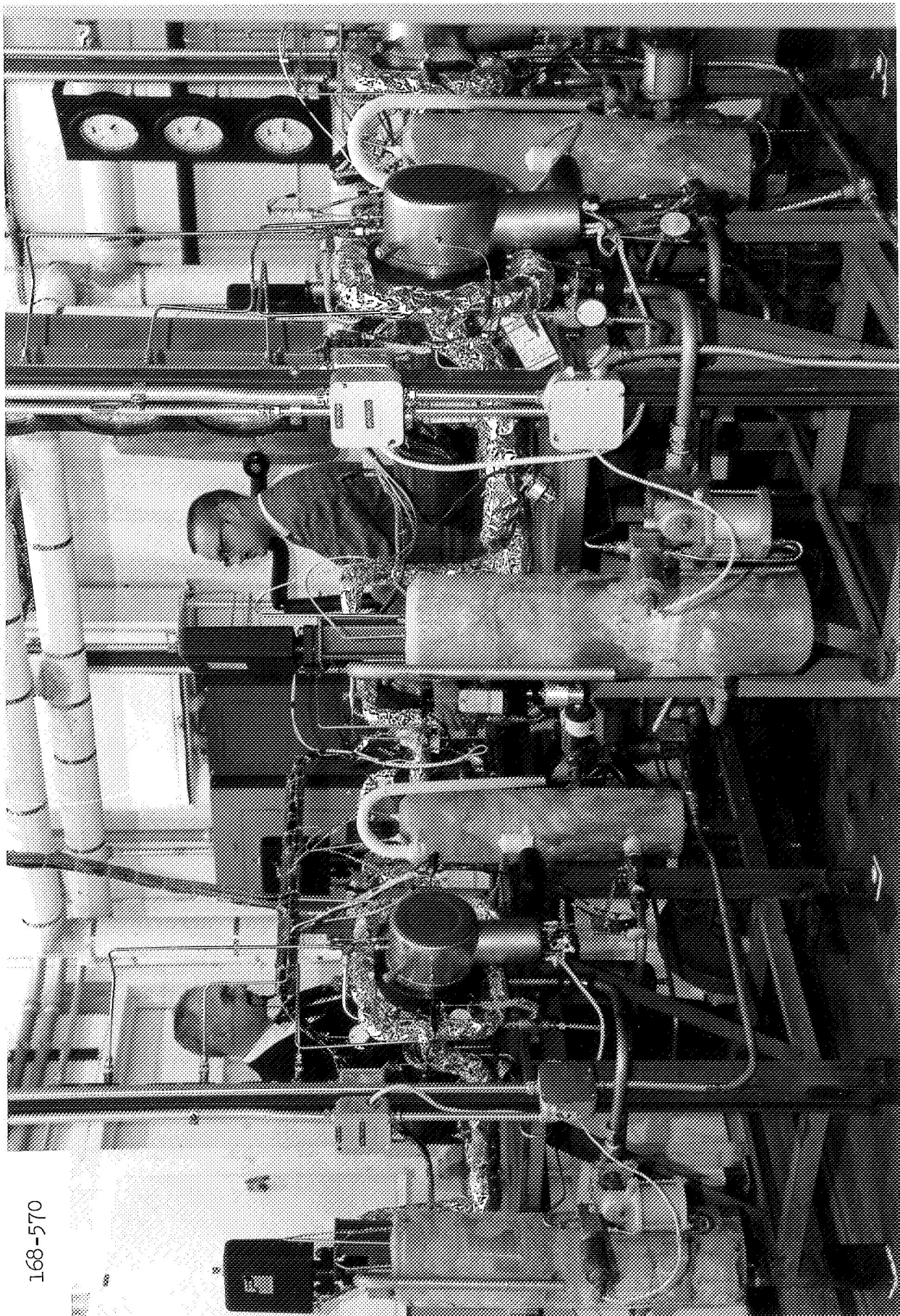
Figure 11



168-573

SNAP-8 SPACE SEAL
TEST FIXTURE

Figure 12

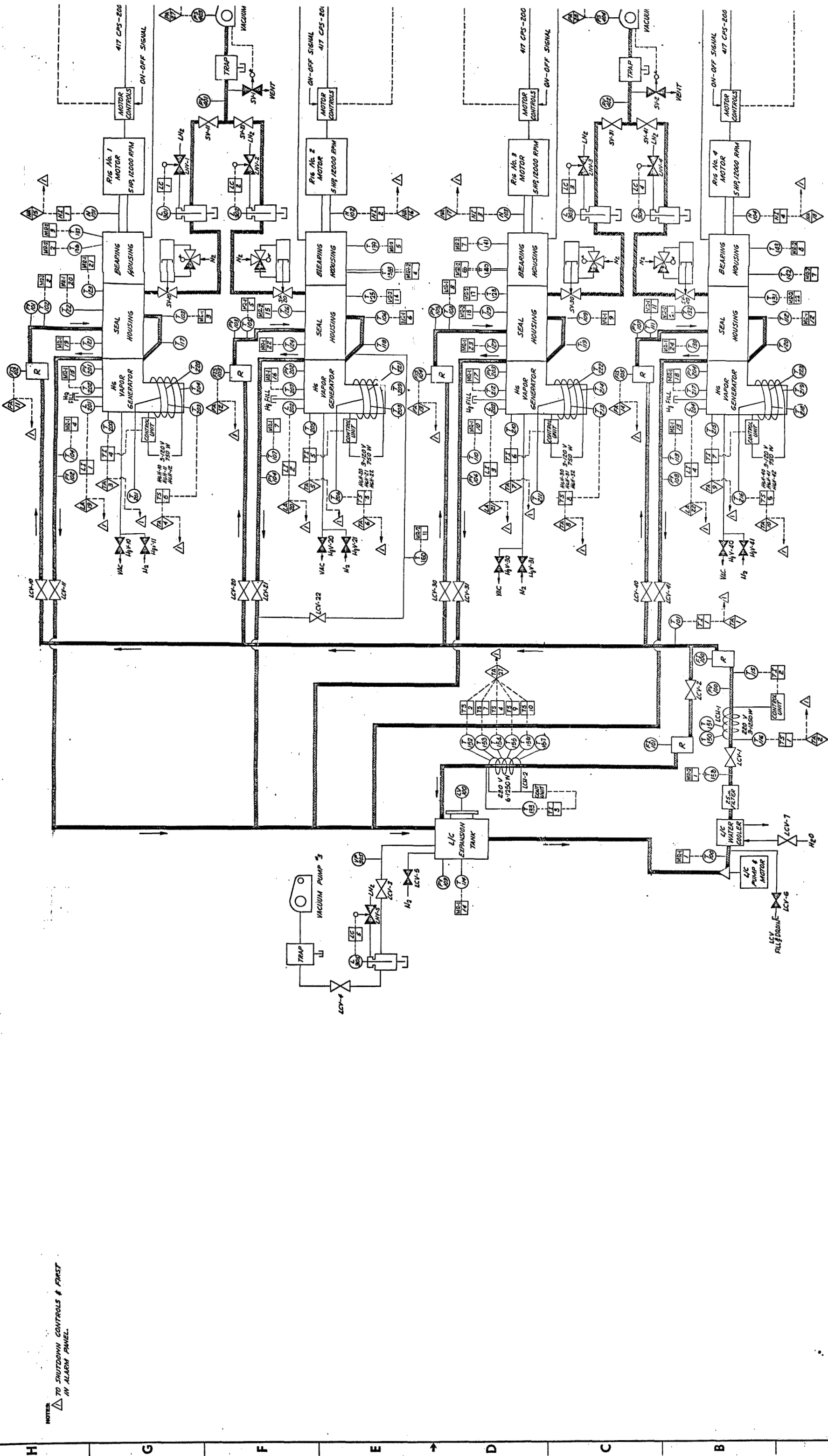


168-570

MULTIPOSITION TEST STANDS
FOR SNAP-8 SPACE SEAL

Figure 13

NOTES
△ TO SHUTDOWN CONTROLS & FIRST
IN ALARM PANEL



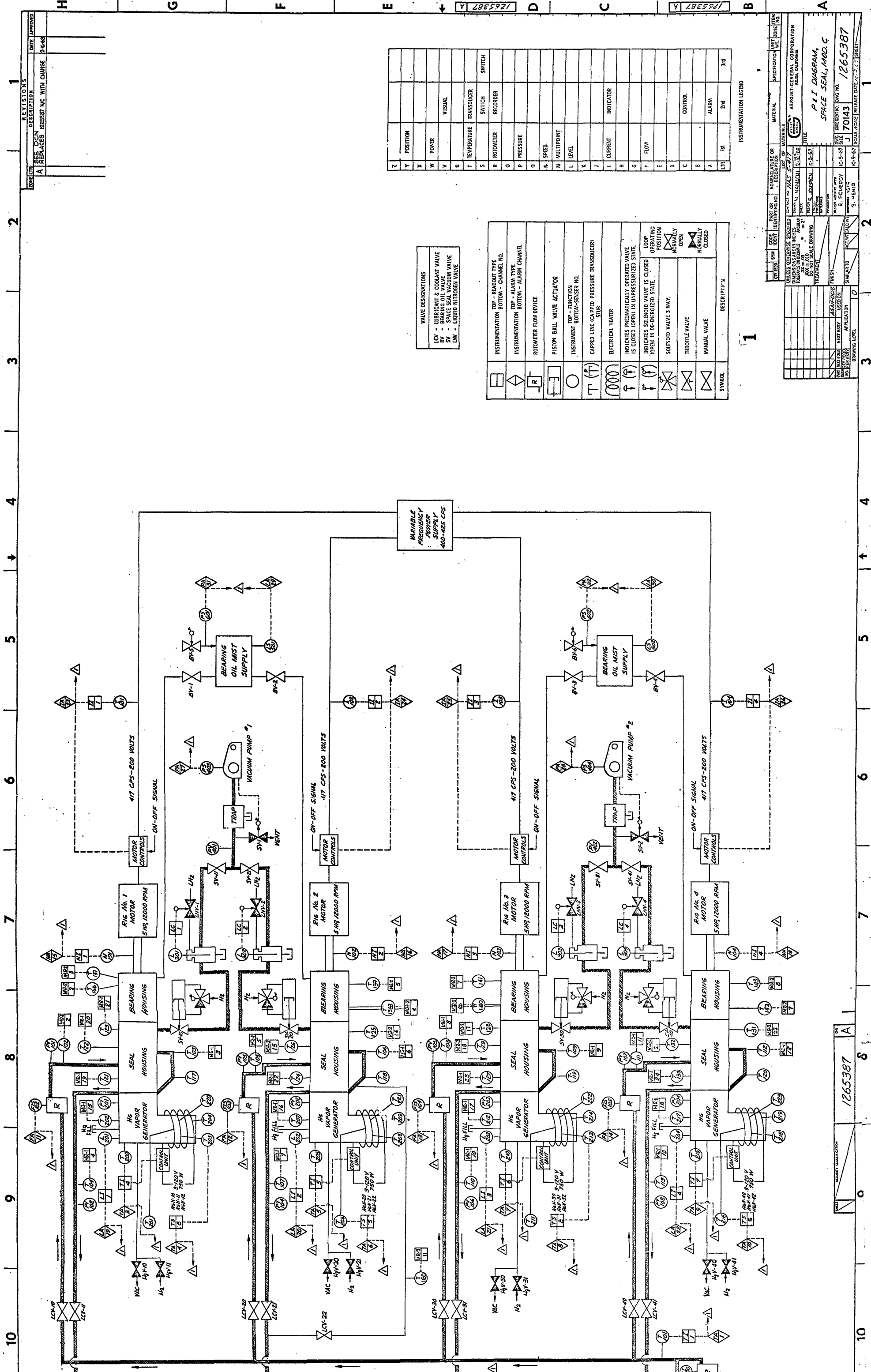


Figure 14. P&I Diagram, Space Seal, Mod-'C'

370-X-1121

1266513

2 ASSY ONLY

1266513

1266513

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1266513

1266513

1266513

1266513

Technical drawing of a mechanical assembly, likely a turbine or engine component, showing a cross-section view. The drawing includes numerous callouts (1 through 60) identifying various parts and features. Key dimensions and specifications are provided:

- 1**: MATCHED SET CONSISTS OF: 1131709-9, 1131715-1, TAPERED DOWEL
- 4**: TORQUE 350-370 IN LB.
- 11**: 1133709 REF.
- 12**: TORQUE TO 40-50 FT. LBS.
- 13**: 1133715 REF.
- 14**: TORQUE TO 40-60 FT. LBS.
- 15**: TORQUE TO 55-60 FT. LBS.
- 16**: 1133715 REF.
- 17**: TORQUE TO 12-17 IN. LBS.
- 18**: TORQUE TO 180-200 IN. LBS.
- 19**: TORQUE TO 10-15 IN. LBS.
- 20**: TORQUE TO 85-95 FT. LBS.
- 21**: 1133715 REF.
- 22**: TORQUE TO 40-50 FT. LBS.
- 23**: TORQUE TO 55-60 FT. LBS.
- 24**: TORQUE TO 12-17 IN. LBS.
- 25**: TORQUE TO 180-200 IN. LBS.
- 26**: TORQUE TO 10-15 IN. LBS.
- 27**: TORQUE TO 85-95 FT. LBS.
- 28**: TORQUE TO 40-50 FT. LBS.
- 29**: TORQUE TO 55-60 FT. LBS.
- 30**: TORQUE TO 12-17 IN. LBS.
- 31**: TORQUE TO 180-200 IN. LBS.
- 32**: TORQUE TO 10-15 IN. LBS.
- 33**: TORQUE TO 85-95 FT. LBS.
- 34**: TORQUE TO 40-50 FT. LBS.
- 35**: TORQUE TO 55-60 FT. LBS.
- 36**: TORQUE TO 12-17 IN. LBS.
- 37**: TORQUE TO 180-200 IN. LBS.
- 38**: TORQUE TO 10-15 IN. LBS.
- 39**: TORQUE TO 85-95 FT. LBS.
- 40**: TORQUE TO 40-50 FT. LBS.
- 41**: TORQUE TO 55-60 FT. LBS.
- 42**: TORQUE TO 12-17 IN. LBS.
- 43**: TORQUE TO 180-200 IN. LBS.
- 44**: TORQUE TO 10-15 IN. LBS.
- 45**: TORQUE TO 85-95 FT. LBS.
- 46**: TORQUE TO 40-50 FT. LBS.
- 47**: TORQUE TO 55-60 FT. LBS.
- 48**: TORQUE TO 12-17 IN. LBS.
- 49**: TORQUE TO 180-200 IN. LBS.
- 50**: TORQUE TO 10-15 IN. LBS.
- 51**: TORQUE TO 85-95 FT. LBS.
- 52**: TORQUE TO 40-50 FT. LBS.
- 53**: TORQUE TO 55-60 FT. LBS.
- 54**: TORQUE TO 12-17 IN. LBS.
- 55**: TORQUE TO 180-200 IN. LBS.
- 56**: TORQUE TO 10-15 IN. LBS.
- 57**: TORQUE TO 85-95 FT. LBS.
- 58**: TORQUE TO 40-50 FT. LBS.
- 59**: TORQUE TO 55-60 FT. LBS.
- 60**: TORQUE TO 12-17 IN. LBS.

Additional notes and dimensions:

- 250 DIA DOWEL x 2.50 LONG FOR TORQUEING ITEM (41)**
- 5.125 5.000**
- 4.42**
- ANISO 40 FT TORQUE 12 FT IN LB REF**
- CONIL PROD 220-3030-1005 REF**
- 21**: 1133715 REF.
- 22**: TORQUE TO 40-50 FT. LBS.
- 23**: TORQUE TO 55-60 FT. LBS.
- 24**: TORQUE TO 12-17 IN. LBS.
- 25**: TORQUE TO 180-200 IN. LBS.
- 26**: TORQUE TO 10-15 IN. LBS.
- 27**: TORQUE TO 85-95 FT. LBS.
- 28**: TORQUE TO 40-50 FT. LBS.
- 29**: TORQUE TO 55-60 FT. LBS.
- 30**: TORQUE TO 12-17 IN. LBS.
- 31**: TORQUE TO 180-200 IN. LBS.
- 32**: TORQUE TO 10-15 IN. LBS.
- 33**: TORQUE TO 85-95 FT. LBS.
- 34**: TORQUE TO 40-50 FT. LBS.
- 35**: TORQUE TO 55-60 FT. LBS.
- 36**: TORQUE TO 12-17 IN. LBS.
- 37**: TORQUE TO 180-200 IN. LBS.
- 38**: TORQUE TO 10-15 IN. LBS.
- 39**: TORQUE TO 85-95 FT. LBS.
- 40**: TORQUE TO 40-50 FT. LBS.
- 41**: TORQUE TO 55-60 FT. LBS.
- 42**: TORQUE TO 12-17 IN. LBS.
- 43**: TORQUE TO 180-200 IN. LBS.
- 44**: TORQUE TO 10-15 IN. LBS.
- 45**: TORQUE TO 85-95 FT. LBS.
- 46**: TORQUE TO 40-50 FT. LBS.
- 47**: TORQUE TO 55-60 FT. LBS.
- 48**: TORQUE TO 12-17 IN. LBS.
- 49**: TORQUE TO 180-200 IN. LBS.
- 50**: TORQUE TO 10-15 IN. LBS.
- 51**: TORQUE TO 85-95 FT. LBS.
- 52**: TORQUE TO 40-50 FT. LBS.
- 53**: TORQUE TO 55-60 FT. LBS.
- 54**: TORQUE TO 12-17 IN. LBS.
- 55**: TORQUE TO 180-200 IN. LBS.
- 56**: TORQUE TO 10-15 IN. LBS.
- 57**: TORQUE TO 85-95 FT. LBS.
- 58**: TORQUE TO 40-50 FT. LBS.
- 59**: TORQUE TO 55-60 FT. LBS.
- 60**: TORQUE TO 12-17 IN. LBS.

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70143 E	3	1266513
DATE REC'D, NO.	DATE	CHRG NO.

Figure 15. Mod-'c' Reference Design

⑦ 9 REQD

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70143	1266513
DATE REC'D	DATE REC'D

Figure 16. Mod-'C' Minor Modification

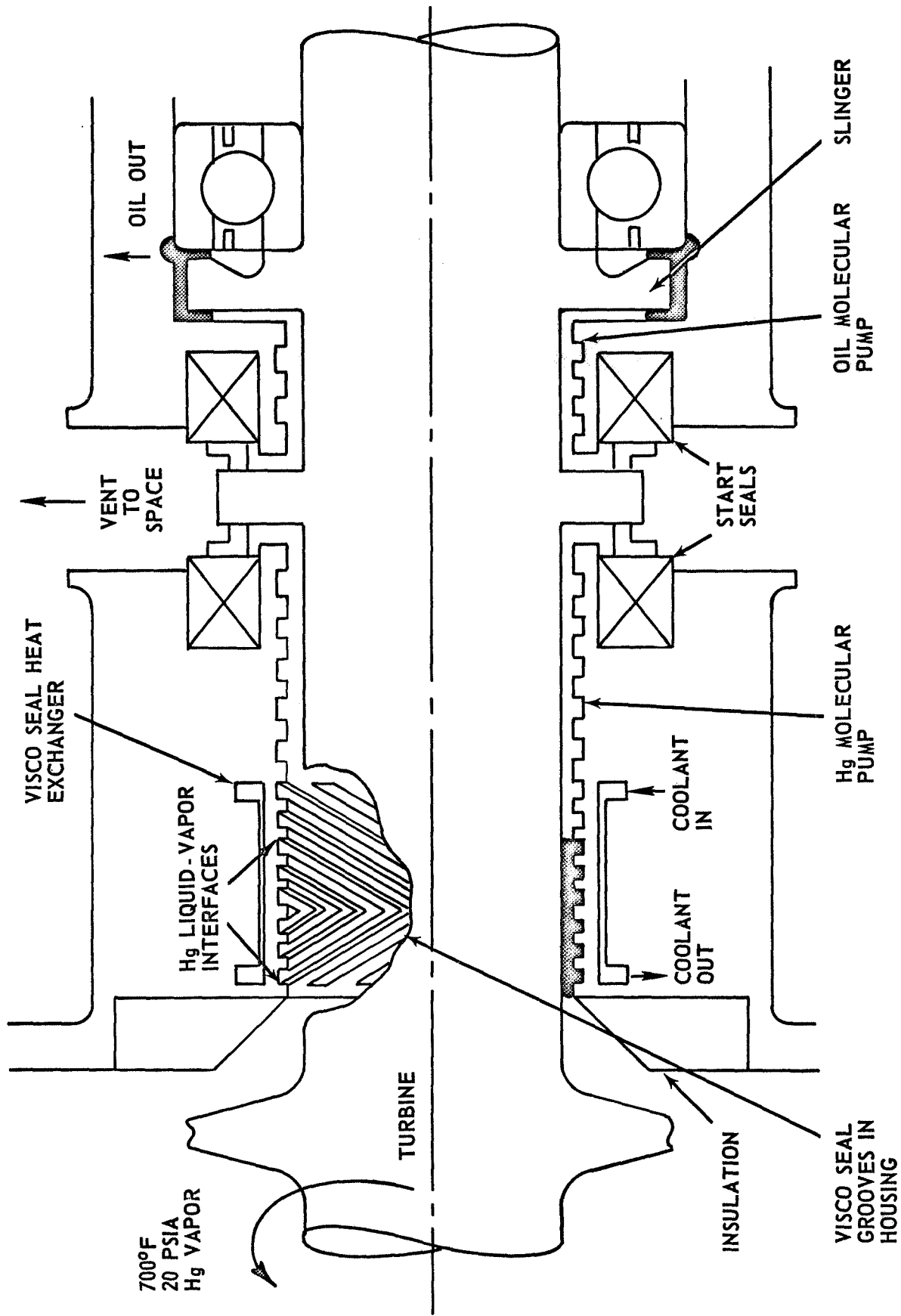


Figure 17. Minor Modification

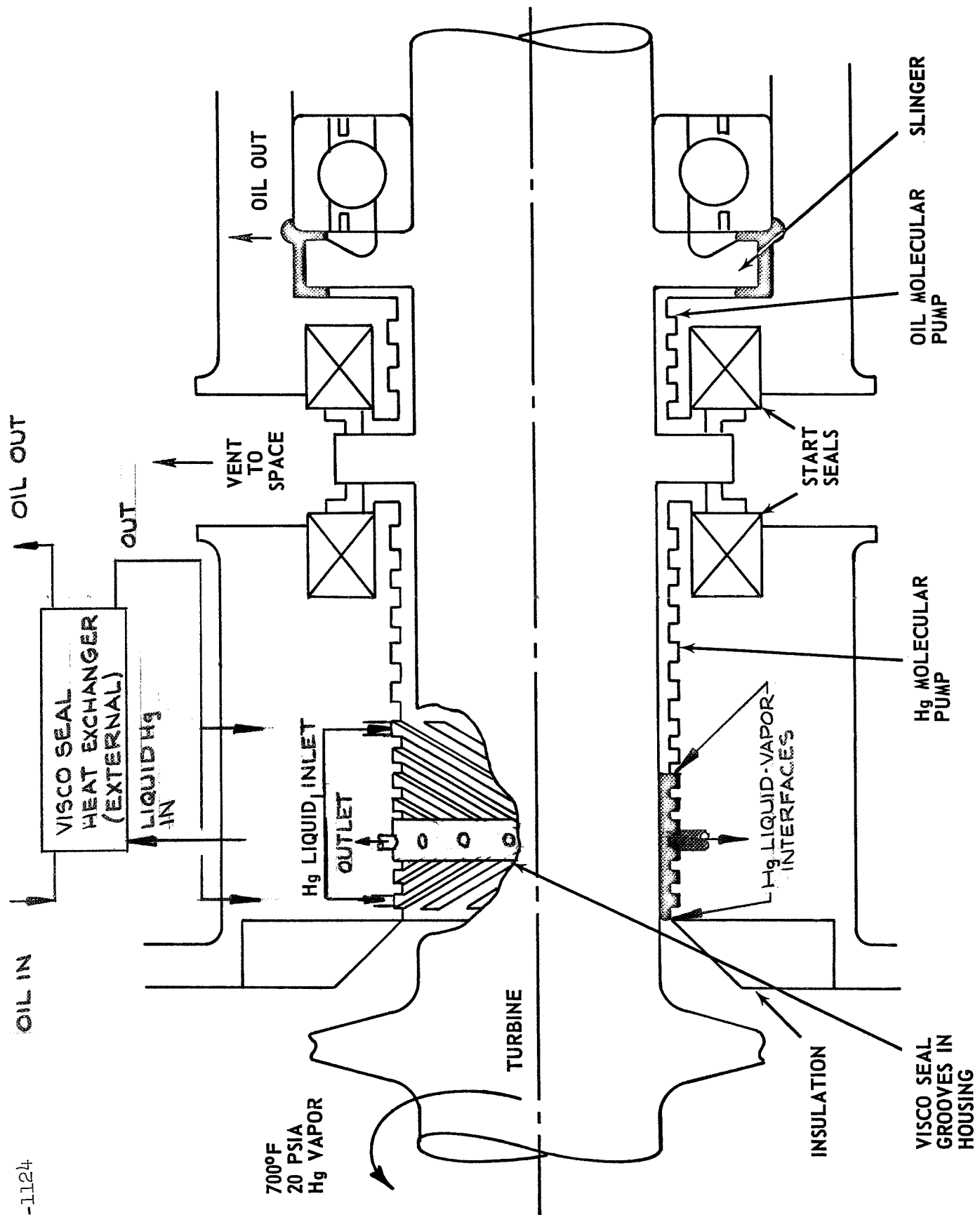


Figure 18

370-X-1126

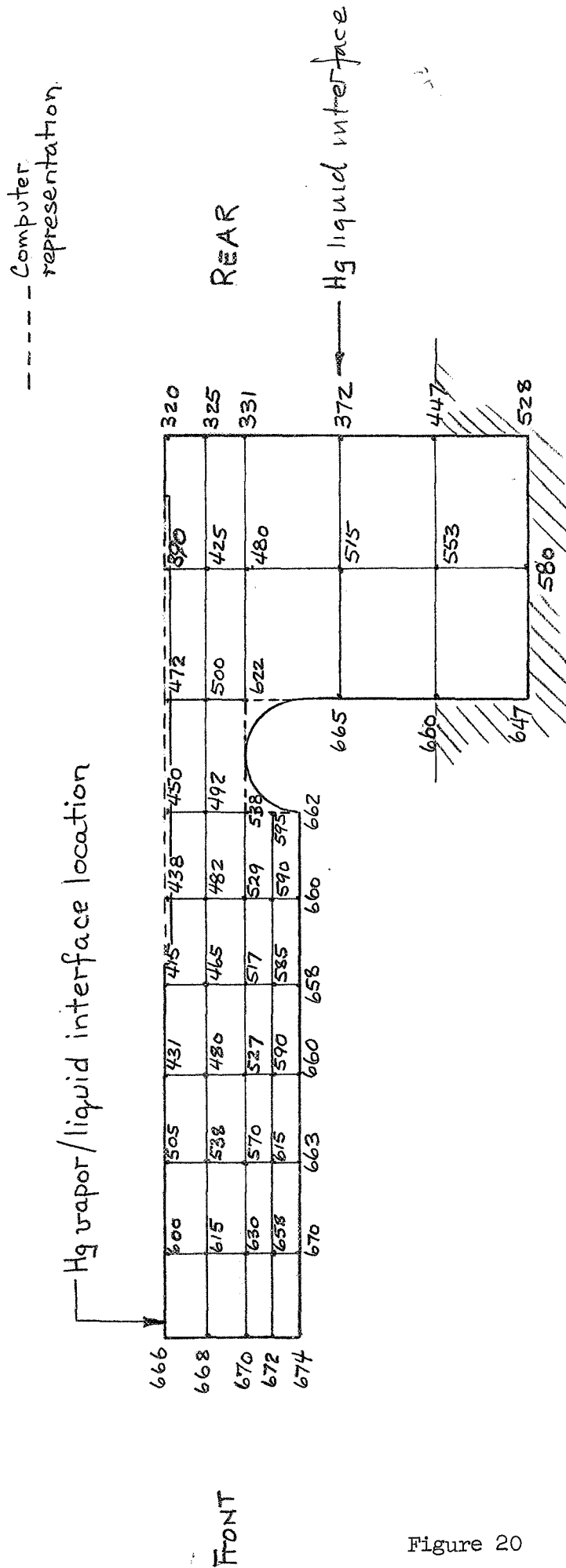
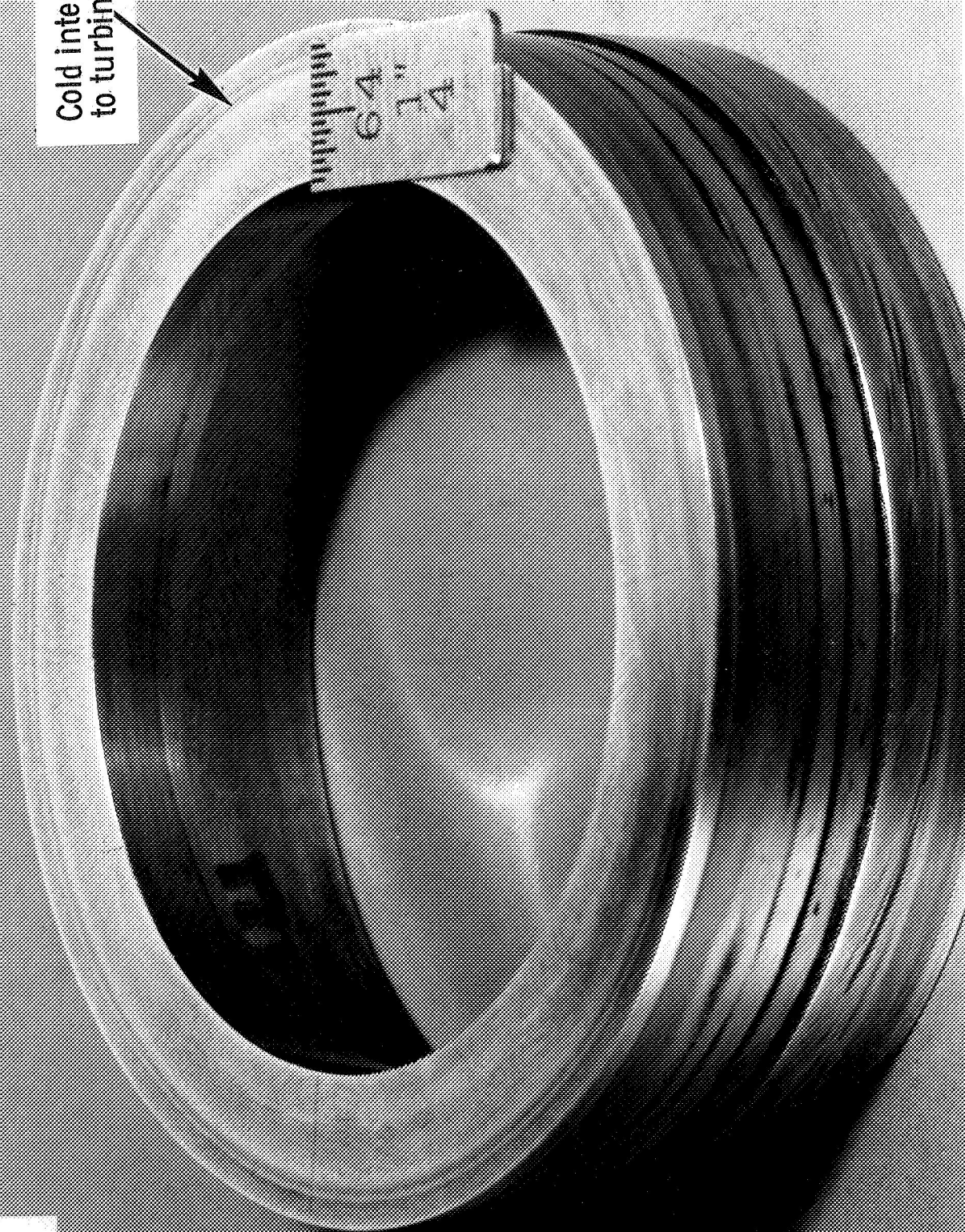


Figure 20

368-337

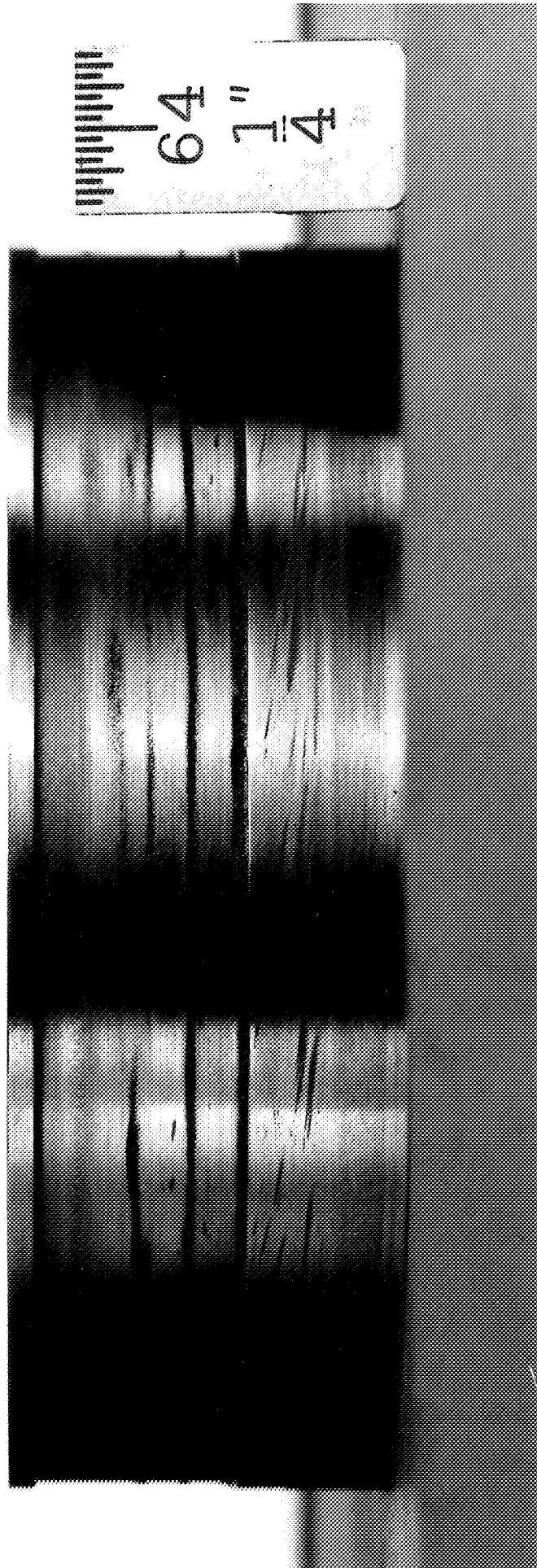
Cold interface similar
to turbine



VISCO SEAL RING (STELLITE 6B) FROM MOD C TEST RIG NO. 1
SHOWING CAVITATION DAMAGE AFTER APPROXIMATELY
45 TEST HOURS (P/N 098084, S/N A-11)

Figure 21

368-338



VISCO SEAL RING (STELLITE 6B) FROM MOD C TEST RIG NO. 1
SHOWING CAVITATION DAMAGE AFTER APPROXIMATELY
45 TEST HOURS (P/N 098084, S/N A-11)

368-552



SNAP-8 MOD-C SEAL TEST RIG NO. 1
CAVITATION DAMAGE ON MILD STEEL HERRING BONE PUMP
AFTER APPROXIMATELY 154 TEST HOURS (3-26-68)

368-549



Figure 24

VISCO SEAL RING (STELLITE 6B) FROM MOD-C TEST RIG NO. 1
SHOWING CAVITATION DAMAGE AFTER APPROXIMATELY
154 TEST HOURS (P/N 098084, S/N A-11) (3-26-68)

368-550



VISCO SEAL RING (STELLITE 6B) FROM MOD-C TEST RIG NO. 1
SHOWING CAVITATION DAMAGE AFTER APPROXIMATELY
154 HOURS (P/N 098084, S/N A-11) (3-26-68)

468-579



VISCO SEAL RING (STELLITE 6B) FROM MOD-C TEST RIG NO. 1
SHOWING CAVITATION DAMAGE AFTER APPROXIMATELY
501 HOURS 4 MINUTE TEST (P/N 098084, S/N A-11) 4-23-68

Figure 26

468-578



VISCO SEAL RING (STELLITE6B) FROM MOD-C TEST RIG NO. 1
SHOWING CAVITATION DAMAGE AFTER APPROXIMATELY
501 HOURS 4 MINUTES TEST (P/N 098084, S/N A-11) 4-23-68

Figure 27

468-577



SNAP-8 MOD C TEST UNIT NO. 1
P/N 096800-5 AFTER 501 HOURS 4 MINUTES OPERATION
VISCO PUMP RING P/N 098084-3 S/N AI 4-23-68



VISCO SEAL RING (STELLITE 6B) FROM MOD C TEST RIG NO. 1/6
SHOWING CAVITATION DAMAGE AFTER 1844 HOURS OPERATION
(P/N 098084-3 S/N A-11) 7-17-68



SNAP-8 MOD C SEAL TEST RIG NO. 1/6
SHOWING CAVITATION DAMAGE ON MILD STEEL HERRING BONE PUMP
AFTER 1844 HOURS OPERATION 7-17-68



VISCO SEAL RING (STELLITE 6B) FROM MOD C TEST RIG NO. 1/6
SHOWING CAVITATION DAMAGE AFTER 1844 HOURS OPERATION
(P/N 098084-3 S/N A-11) 7-17-68

VISCO SEAL RING WT. LOSS

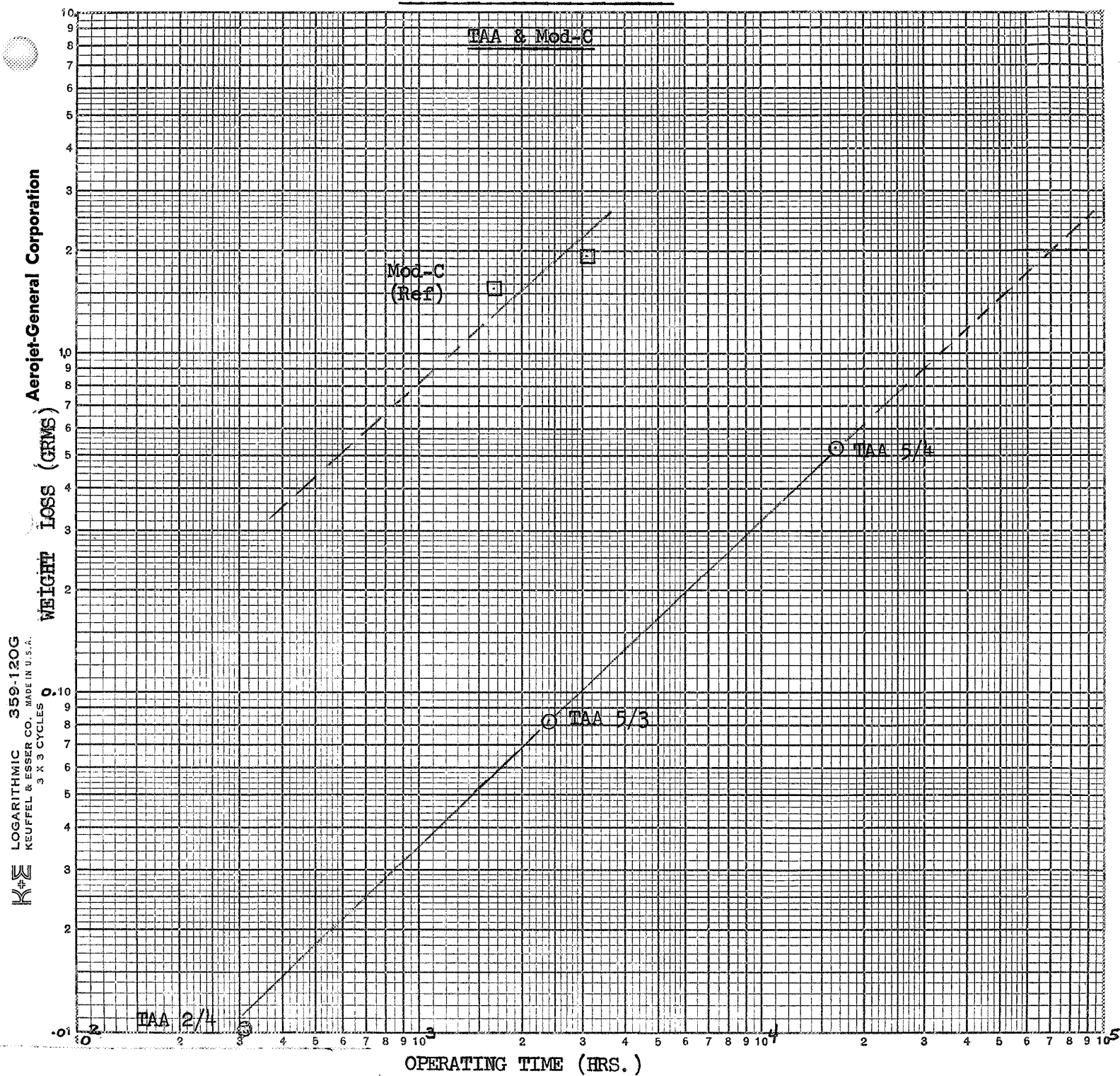


Figure 32



Figure 33

VISCO SEAL RING & HOUSING

K&E LOGARITHMIC 359-120G
 KEUFFEL & ESSER CO. MADE IN U.S.A.
 DEPTH OF LOCAL PENETRATION AS PERCENTAGE OF WALL THICKNESS

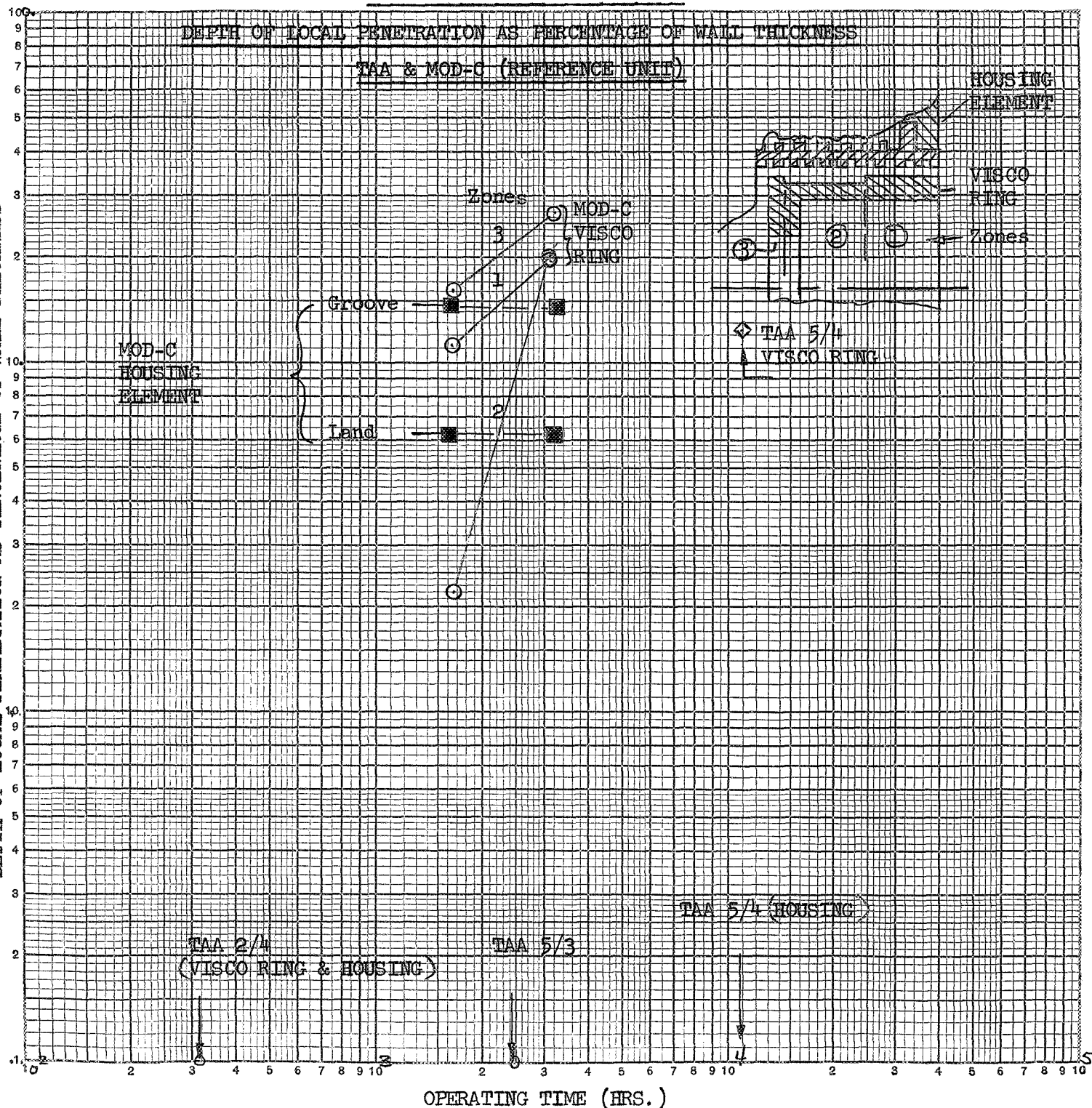


Figure 34



Figure 35

VISCO SEAL RING (STELLITE 6B) FROM MOD C TEST RIG NO. 414
AFTER 120 HOURS (P/N 098084-3 S/N A9) 8-9-68
TEST WAS TERMINATED DUE TO RING SEIZURE IN HOUSING



SNAP-8 MOD C SEAL TEST RIG NO. 4/4 SHOWING MILD STEEL
HERRING BONE PUMP AFTER 120 HOURS OPERATION 8-9-68
TEST WAS TERMINATED DUE TO RING SEIZURE IN HOUSING

Figure 36



Figure 37

VISCO SEAL RING (STELLITE 6B) FROM MOD C TEST RIG NO. 4/4
AFTER 120 HOURS (P/N 098084-3 S/N A9) 8-9-68
TEST WAS TERMINATED DUE TO RING SEIZURE IN HOUSING

868-268



VISCO SEAL RING (STELLITE 6B) FROM MOD C TEST RIG NO. 4/4
AFTER 120 HOURS (P/N 098084-3 S/N A9) 8-9-68
TEST WAS TERMINATED DUE TO RING SEIZURE IN HOUSING

Figure 38

369-334



MOD-C TESTER (REFERENCE UNIT)
HOUSING, VISCO PUMP GROOVES
1683.9 HRS OPERATION 3/13/69

Figure 39

369-333



MOD-C TESTER (REFERENCE UNIT)
HOUSING, VISCO PUMP GROOVES
1683.9 HRS OPERATION 3/13/69

Figure 40

369-336

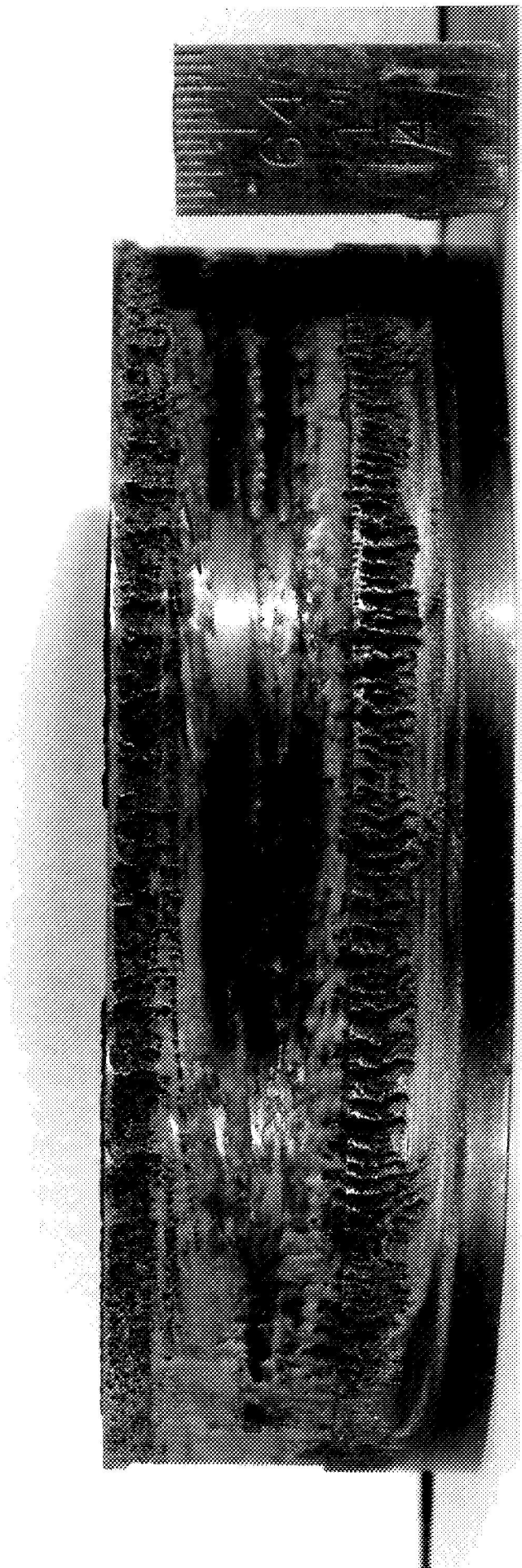


Figure 41

MOD-C TESTER (REFERENCE UNIT)
VISCO RING AFTER 1683.9 HRS OPERATION 3/13/69

369-338



Figure 42

MOD-C TESTER (REFERENCE UNIT)
VISCO RING AFTER 1683.9 HRS OPERATION 3/13/69



MOD-C TESTER (REFERENCE UNIT)
HOUSING, MOLECULAR PUMP GROOVES
1683.9 HRS OPERATION 3/13/69

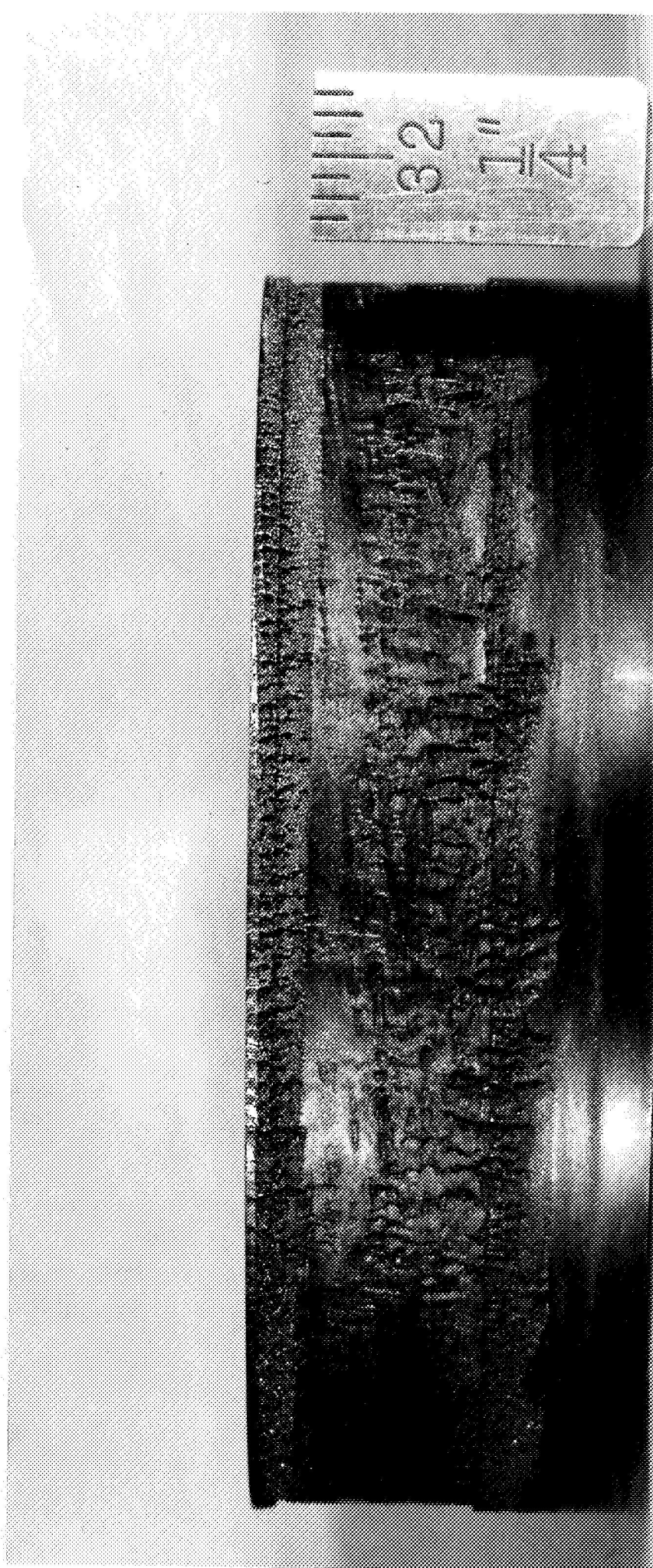
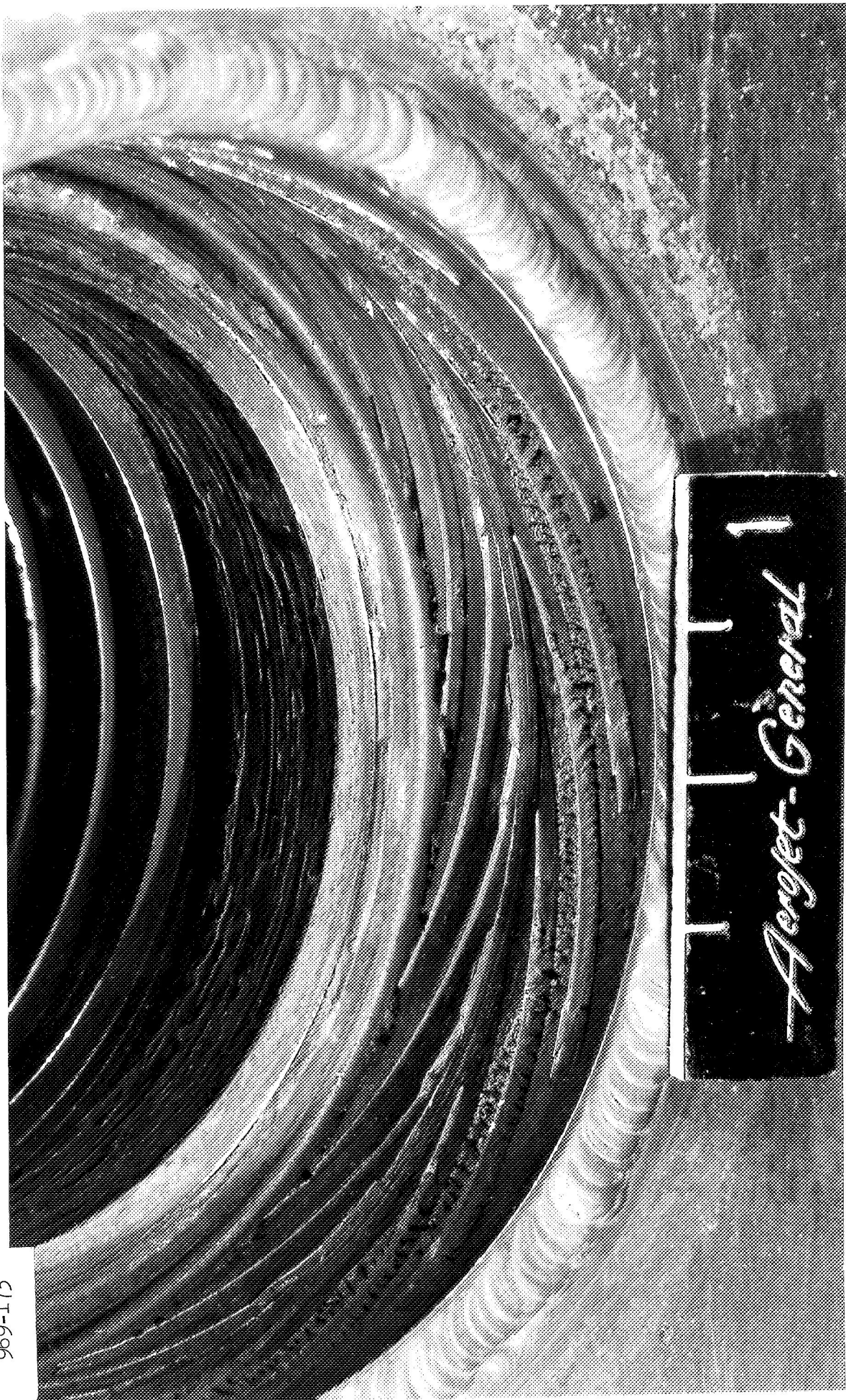


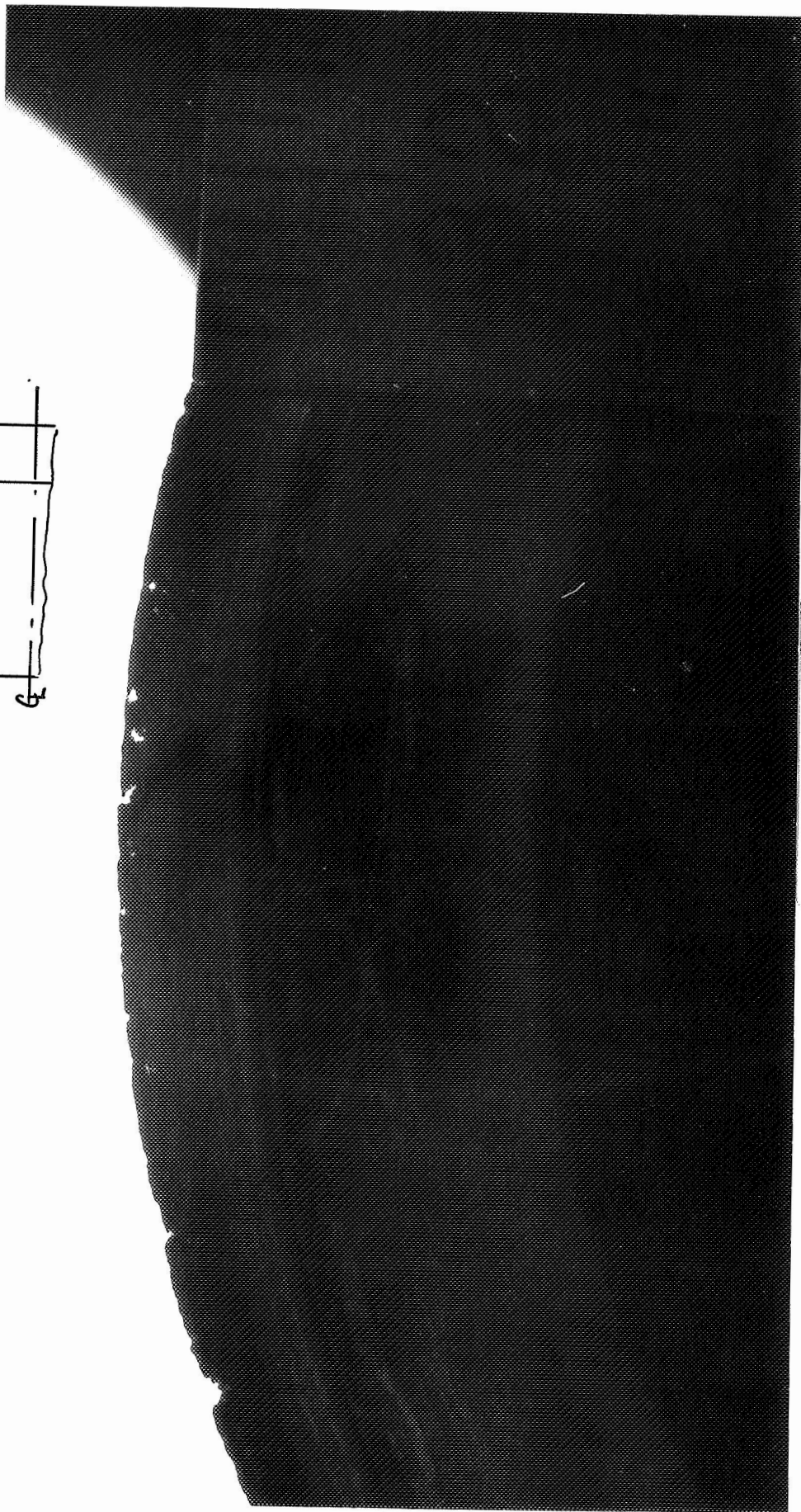
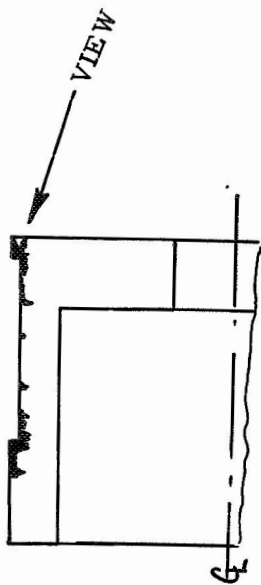
Figure 44

969-173



MOD-C TESTER (REFERENCE UNIT)
HOUSING, VISCO PUMP GROOVES
AFTER 3134.1 HRS. OF OPERATION 9/12/69

969-171 A



MOD-C TESTER (REFERENCE UNIT)
VISCO RING
AFTER 3134.1 HRS. OF OPERATION 9/12/69

Figure 46

969-350



MOD-C TESTER (MINOR MOD)
VISCO SEAL (LIGHTLY RUBBED AREA)
AFTER 2574.1 HRS. OF OPERATION 9/12/69

Figure 47

969-174



MOD-C TESTER (REFERENCE UNIT)

VISCO RING

AFTER 3134.1 HRS. OF OPERATION 9/12/69

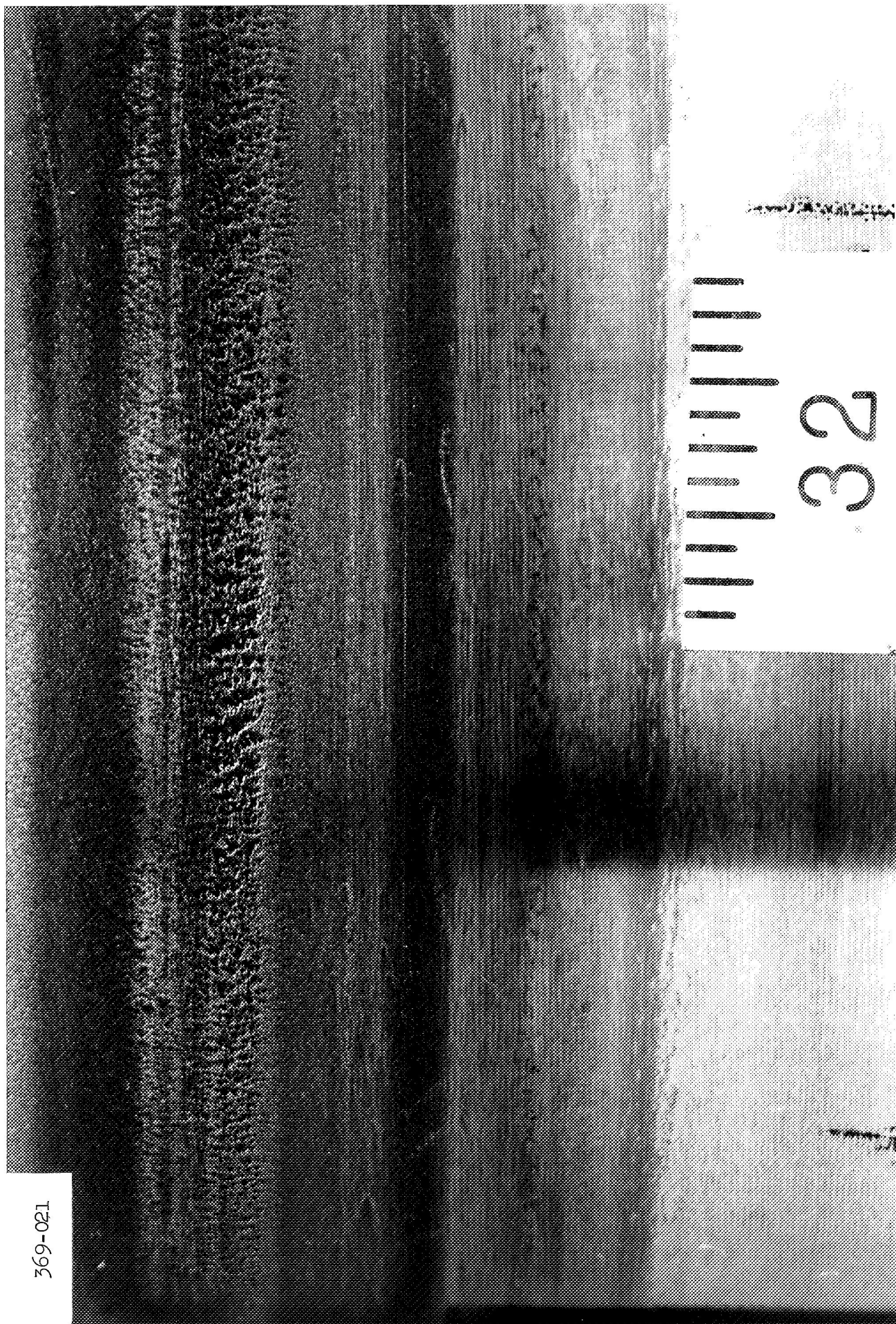
Figure 48

969-348



MOD-C TESTER (MINOR MOD)
VISCO SEAL
AFTER 2574.1 HRS. OPERATION 9/12/69

369-021



MOD-C (MINOR MOD) 2001 HOURS OF OPERATION
20 FEBRUARY 1969 VISCO RING DAMAGE (3)

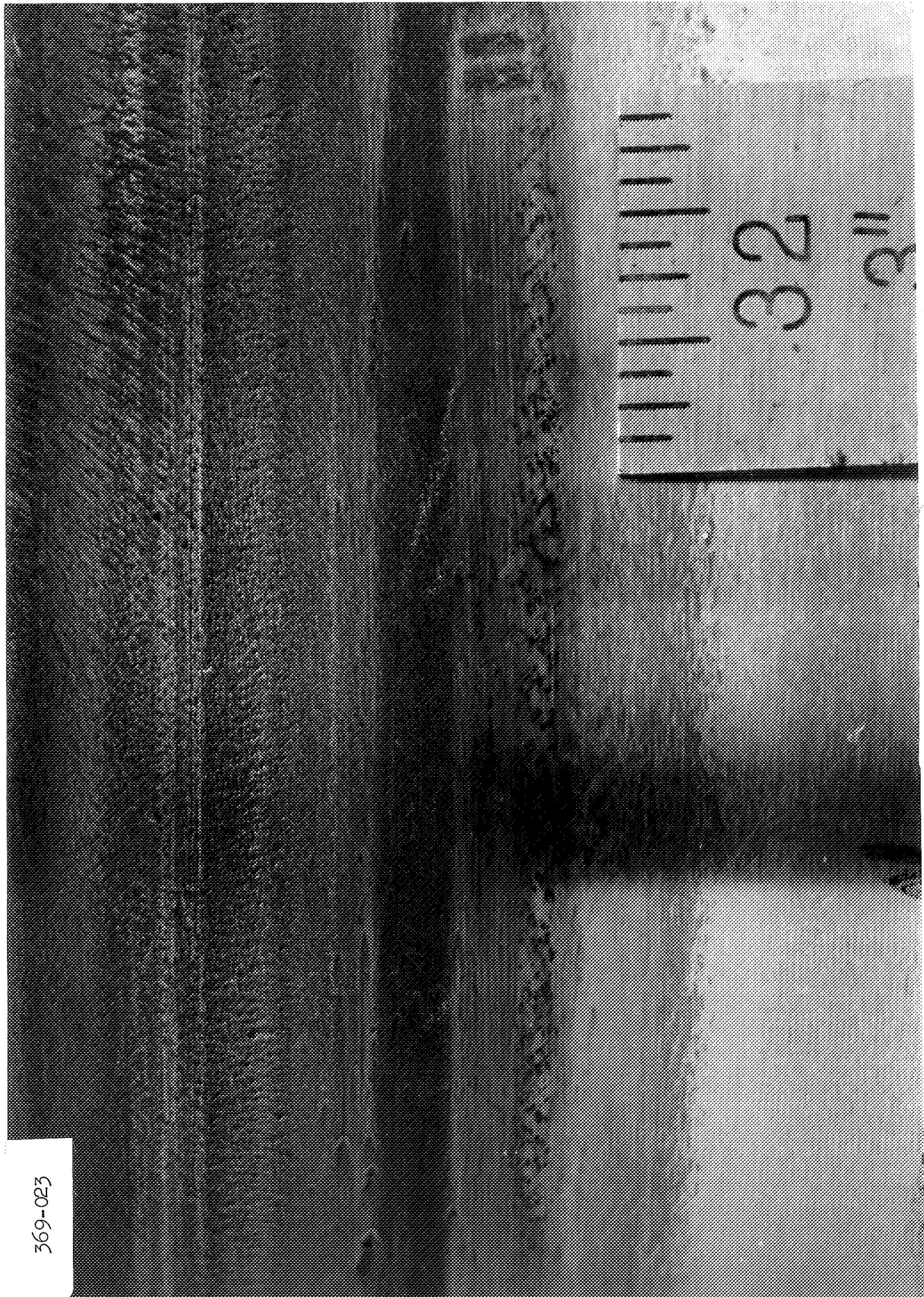
Figure 50

369-020



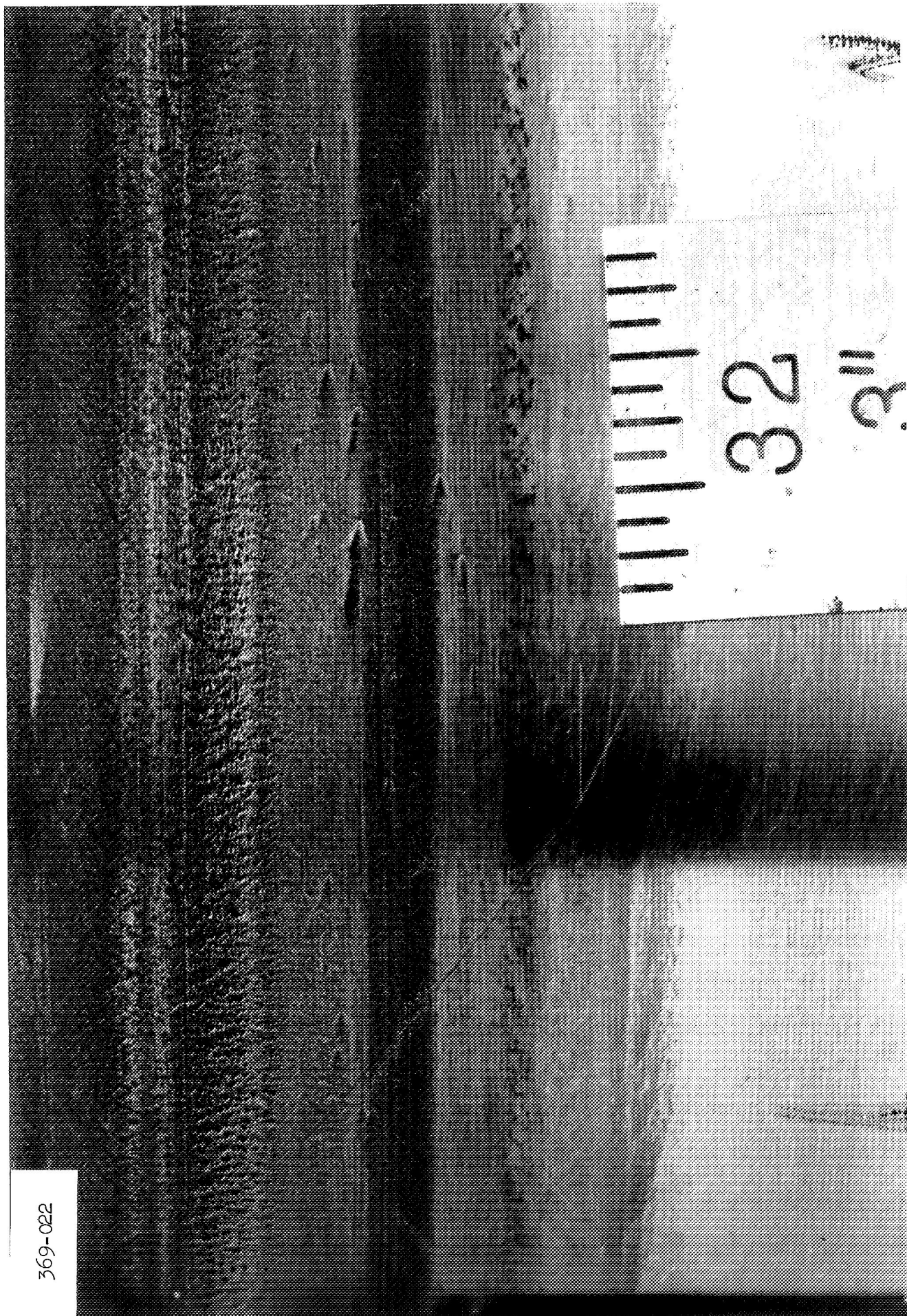
MOD-C (MINOR MOD) 2001 HOURS OF OPERATION
20 FEBRUARY 1969 VISCO RING DAMAGE (4)

369-023



MOD-C (MINOR MOD) 2001 HOURS OF OPERATION
20 FEBRUARY 1969 VISCO RING DAMAGE (1)

369-022



MOD-C (MINOR MOD) 2001 HOURS OF OPERATION
20 FEBRUARY 1969 VISCO RING DAMAGE (2)



MOD-C (MAJOR MOD) VISCO PUMP HOUSING (i)
AFTER 421 HRS. 1-16-69



169-499

MOD-C (MAJOR MOD) VISCO PUMP HOUSING (ii)
AFTER 421 HRS. 1-16-69

169-501



Figure 56

MOD-C (MAJOR MOD) VISCO PUMP RING (iii)
AFTER 421 HRS. 1-16-69

169-502



MOD-C (MAJOR MOD) VISCO PUMP RING (ii)
AFTER 421 HRS. 1-16-69

Figure 57

169-503



MOD-C (MAJOR MOD) VISCO PUMP RING (i)
AFTER 421 HRS. 1-16-69

Figure 58

469-015



MOD-C (MAJOR MOD) VISCO PUMP RING
AFTER 941.9 HRS. 3-23-69

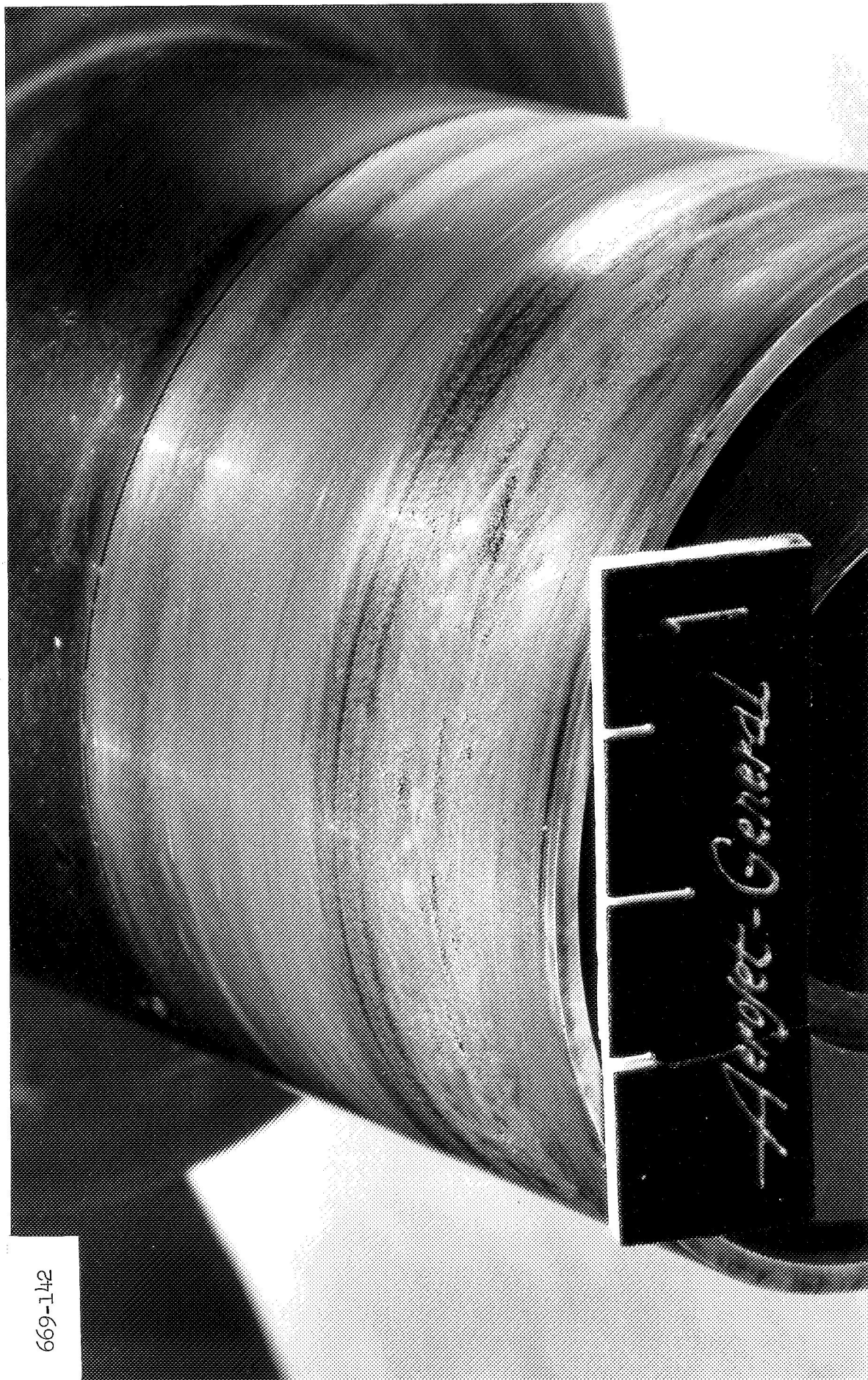
469-016



MOD-C (MAJOR MOD) VISCO PUMP RING
AFTER 941.9 HRS. 3-23-69

Figure 60

669-142



MOD-C, MAJOR MOD.
VISCO SEAL RING DAMAGE
1580 HRS. OF OPERATION, 4 JUNE 1969

Figure 61



669-140

MOD-C, MAJOR MOD.
VISCO SEAL RING FLOW PATTERNS
1580 HRS. OPERATION, 4 JUNE 1969

Figure 62

669-141



MOD-C, MAJOR MOD.
VISCO SEAL HOUSING DAMAGE
1580 HRS. OF OPERATION, 4 JUNE 1969

669-139



MOD-C, MAJOR MOD.
VISCO SEAL HOUSING DAMAGE

Figure 64

669-143



MOD-C, MAJOR MOD.
VISCO SEAL RING DAMAGE
1580 HRS. OF OPERATION, 4 JUNE 1969

669-144



MOD-C, MAJOR MOD.
VISCO SEAL RING DAMAGE
1580 HRS. OF OPERATION, 4 JUNE 1969

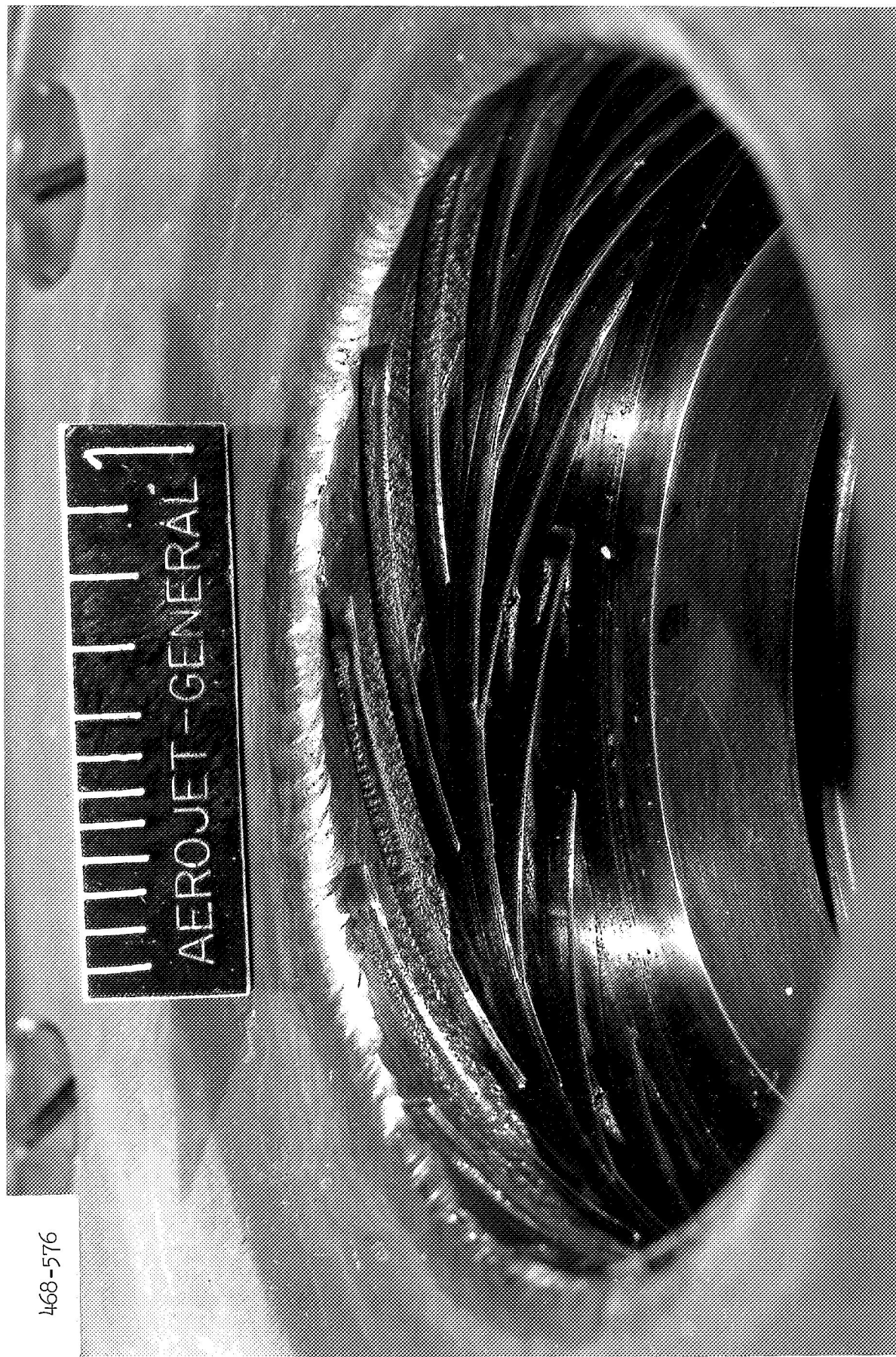
Figure 66

669-146



MOD-C, MAJOR MOD.
VISCO SEAL RING DAMAGE
1580 HRS. OF OPERATION, 4 JUNE 1969

468-576



SNAP-8 MOD-C SEAL TEST RIG NO. 1
CAVITATION DAMAGE ON MILD STEEL HERRING BONE PUMP
4-23-68

Figure 68



SNAP-8 TURBINE ALTERNATOR ASSEMBLY, UNIT 5/4
P/N 096800-5 AFTER 10,822 HOURS OPERATION
VISCO RING

Figure 69



Figure 70

SNAP-8 TURBINE ALTERNATOR ASSEMBLY, UNIT 5/4
P/N 096800-5 AFTER 10,822 HOURS OPERATION
VISCO PUMP RING