

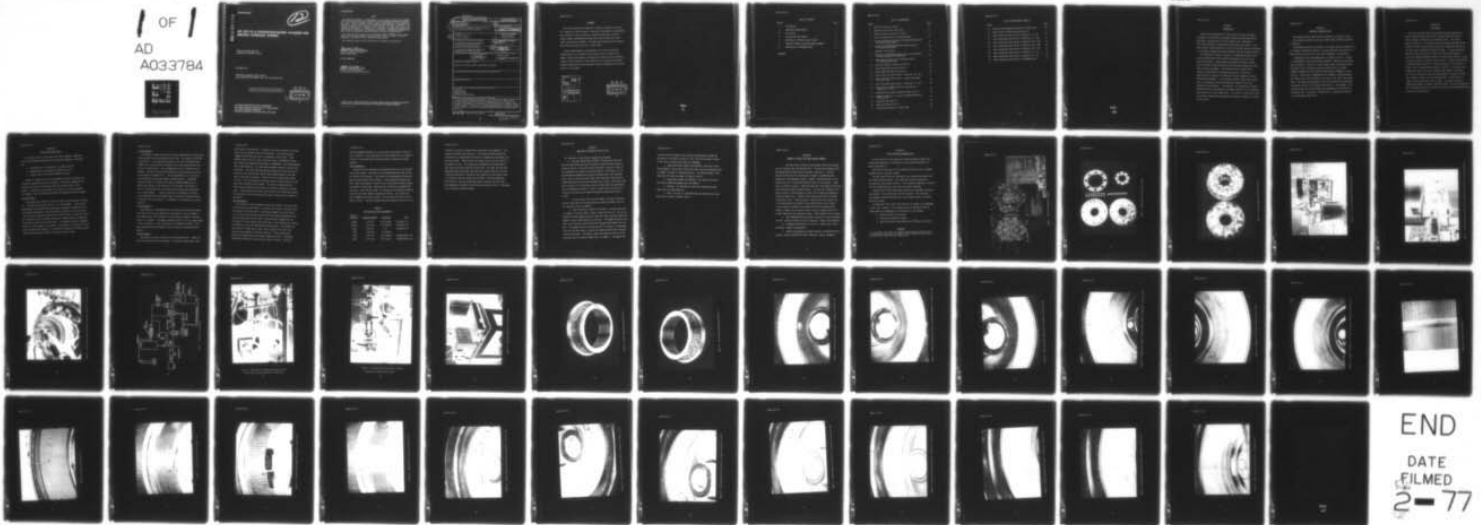
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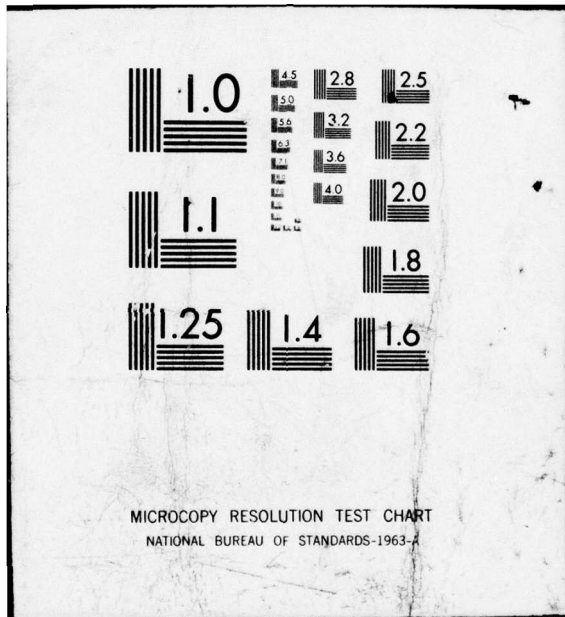
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LIFE TEST OF A DYNAVECTOR ROTARY ACTUATOR FOR AIRCRAFT HYDRAULIC SYSTEMS

VEHICLE POWER BRANCH
AEROSPACE POWER DIVISION

OCTOBER 1976

TECHNICAL REPORT AFAPL-TR-76-58
FINAL REPORT FOR PERIOD JULY 1971 Thru MARCH 1976

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This report has been reviewed by the Information Office (ASD/OIP), and is releasable to the National Technical Information Service (NTIS). At NTIS it will be available to the general public, including foreign nations.

This technical report has been reviewed and is approved for publication.

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REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM	
1. REPORT NUMBER AFAPL-TR-76-58 ✓	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER	
4. TITLE (and Subtitle) Life Test of a Dynavector Rotary Actuator for Aircraft Hydraulic Systems		5. TYPE OF REPORT & PERIOD COVERED Final Report, For Jul 1971 - Mar 1976	
7. AUTHOR(s) Kenneth E. Binns		8. CONTRACT OR GRANT NUMBER(s) 1730	
9. PERFORMING ORGANIZATION NAME AND ADDRESS Air Force Aero Propulsion Laboratory Wright-Patterson AFB, OH 45433		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS 31453007 62203F	
11. CONTROLLING OFFICE NAME AND ADDRESS Air Force Aero Propulsion Laboratory Wright-Patterson AFB, OH 45433		12. REPORT DATE October 1976	
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office) 1250p.		13. NUMBER OF PAGES 43	
		15. SECURITY CLASS. (of this report) Unclassified	
16. DISTRIBUTION STATEMENT (of this Report) Approved for public release; distribution unlimited			
17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)			
18. SUPPLEMENTARY NOTES			
19. KEY WORDS (Continue on reverse side if necessary and identify by block number) Dynavector Rotary actuator Hydraulic motor Aircraft system actuator			
20. ABSTRACT (Continue on reverse side if necessary and identify by block number) This report describes the testing of a hydraulic rotary actuator concept developed by Bendix Research Laboratories under a previous AF R&D contract. The testing included 326 hours and over 400,000 cycles on the actuator. The actuator was designed for a stall torque of 100,000 in-lb at a 3000 psi differential pressure. A discussion of the problems encountered during this program and an inspection analysis of the actuator after testing are included in this report.			

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FOREWORD

This report contains the results of an effort to conduct a life test of a "Dynavector" rotary actuator. The work was performed in the Aerospace Power Division of the Air Force Aero Propulsion Laboratory, Air Force Systems Command, Wright-Patterson AFB, Ohio, under Project 3145, Task 314530, and Work Unit 31453007. The effort was conducted by Mr. Kenneth E. Binns during the period July 1971 to March 1976.

Special acknowledgment is hereby given to Mr. Harold Lee and Mr. Randolph Stahl for the conduct of the reported test; to Captain Joel Bambas, Captain Larry Angelo, and Captain Joel Deluca for their excellent support of and assistance in this program; and to Ron Read of the Bendix Research Laboratories for his excellent technical consultation and overall support of the program.

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SECTION I
INTRODUCTION

Research and development of a rotary actuator concept, the Bendix "Dynavector," was previously conducted by Bendix Research Laboratories, Southfield, Michigan, under AF Contract 33(615)-3431 (Reference 1). Only limited testing was conducted by Bendix under this contract. This report covers testing conducted at the Air Force Aero Propulsion Laboratory on an actuator prototype fabricated by Bendix under the previous contract.

The "Dynavector" concept is basically an integrated hydraulic motor and transmission which offers potential advantages over other rotary actuator techniques. These potential advantages are higher response, higher stiffness, higher efficiency and a more compact design than other rotary actuator techniques. The prototype actuator, Bendix model HH-267-U4 tested under this program was basically a feasibility demonstration unit and was not optimized from the standpoint of weight and overall performance. It did, however, contain a basic motor design which is considered to be the most important element of any future Dynavector actuator design. The purpose of this program was to conduct endurance tests on the prototype to establish potential life of dynavector type actuators for future applications. The results of these tests along with other AF programs being conducted on Dynavector concepts are covered in this report.

SECTION II
PROTOTYPE ACTUATOR DESIGN

The prototype, Bendix model HH-267-U4, actuator is as shown in Figure 1.

This design was basically the same as Bendix model HH-267-U3 described in Reference 1.

The prototype actuator was designed for an output torque of 100,000 in-lb at a 3000 psi differential pressure. The gear reduction ratio was 267 to 1. Design details for the gears can be found in Appendix 1 of Reference 1.

A photograph of the disassembled motor is shown in Figure 2. Figure 3 is a photograph of the motor partially assembled. Referring to this photograph, the motor is made up of a rotor, vanes, output ring and end plates. The output ring is orbited by pressurizing one half of the volumes (chambers) between the vanes and porting the opposite chambers to return pressure. The porting or commutating of the chamber is achieved through the kidney slots in the end plates to the slots in the face of the output plate. The eccentricity between the rotor and output ring is produced by the eccentric rings of the actuator (see Figure 1). Each chamber is controlled by either of the two kidney slots, depending on the position of the output ring. The pressure in these slots is externally controlled by a conventional control valve.

SECTION III

TEST SYSTEM

The first test setup used for testing the actuator consisted of a Denison industrial pump, relief valve, solenoid valves and electric limits switches for controlling the actuator travel. This setup is shown in Figures 4-6. The actuator and circuit experienced considerable vibration with this setup and after 35 hours of testing (71,000 cycles) the test system was modified as shown in Figure 7. An Abex pump (model AP10V) was used as the source of power and a Moog electro-hydraulic servo valve (model 35-S-020) was used for controlling the actuator. Photos of this test system are shown in Figures 8 and 9. A Moog dc Servocontroller Model 82-300 was used with a function generator for the electrical signal input to the servovalve as shown in Figure 10. The actuator was loaded by the load fixture built by Bendix and reported in Reference 1. This fixture utilized torsilastic springs capable of producing a spring rate of 6670 lb-in/deg. The load characteristic of these springs is linear for the travel range of the actuator. The load was varied by changing the number of springs in the load fixture. One spring provided a load of 100,000 in-lb for 30° travel and two springs provided 200,000 in-lb of load for the same travel.

SECTION IV
ACTUATOR TEST AND RESULTS

The original plan for the actuator test was to conduct a repetitive cycle at the following conditions for an equivalent 1000 hours of aircraft life.

- a. 1,500,000 cycles at 60 CPM with $\pm 10,000$ in-lb load
- b. 950,000 cycles at 30 CPM with $\pm 50,000$ in-lb load
- c. 50,000 cycles at 5 CPM with 100,000 in-lb load

Because of problems with the test equipment and with the actuator the testing was changed during the test program. The specific changes will be discussed as part of the particular test runs discussed later in this section. The testing is broken down into test runs in order to describe the changes in test equipment and actuator that occurred during the program.

Test Run Number 1

The actuator was installed in the first test circuit discussed in Section III. The limit switches were set for a $\pm 7.5^\circ$ displacement. A cycle rate of approximately 30 cycles/min was established by adjusting the pump flow rate. The maximum hinge moment in both directions was 50,000 in-lb for this setup, since two load springs were installed in the load fixture. A total of 35 hours and 71,066 cycles were run before the test was stopped because of vibrations and pulsations due to the solenoid valves. The actuator had erratic movement during the latter stages of this testing. Disassembly of the actuator did not reveal any major wear; however, it was decided to replace all bearings because light scoring marks were evident on the inner and outer races.

Test Run Number 2

The actuator was then installed in the test system with an aircraft-type piston pump and an electro-hydraulic servo valve. This system is described in Section III. The actuator was cycled at a rate of 24 cycles/min from 50,000 in-lb in one direction to 50,000 in-lb in the other direction and return for 50,000 cycles. This corresponded to $\pm 7.5^\circ$ of rotation of the actuator. The cycle rate was then reduced to 12 cycles per minute and the load increased to 100,000 in-lb. This corresponded to $\pm 15^\circ$ of rotation. After 3400 cycles the actuator became extremely erratic. Disassembly revealed failure of a tapered roller bearing (TIMKEN #29586 cone and #29522 cup) that was in the upper part of the actuator (see Figures 11 and 12). A similar bearing in the lower part indicated some distress but not as severe damage. Based on contact with both Bendix and Timken, it was determined that the probable cause of failure was improper preload of the bearing during assembly. The remainder of the actuator was in good condition.

Test Run Number 3

The actuator was reassembled with all new bearings and testing resumed. The same test cycling was conducted on the actuator in test run number 2. After 3900 cycles at the 100,000 in-lb test condition, material chips were found in a flow meter. Disassembly revealed a similar failure as experienced in test run number 2. After consultations with Bendix and Timken, it was again determined that the probable cause of failure was improper bearing preload.

Test Run Number 4

The actuator was again assembled with new Timken bearings. Timken personnel were present during the assembly. A preload of approximately .002"

was provided to the bearings. A magnetic pickup was installed in the case drain line to indicate failure of the actuator. The testing was then resumed with the same test cycle as conducted in runs 2 and 3. After 68,000 cycles at ± 50 in-lb load, chips were found in the magnetic pickup. Again testing was stopped and the actuator disassembled. The Timken bearings were in good condition. The chips were now coming primarily from the lower ground gear. The debris from the previous bearing failure had resulted in distress to this gear and the load was then causing chipping of the gear teeth in the areas of distress. Figures 13 thru 15 show the gears after this test. As can be seen from the photos shown in Figures 16 thru 18, the lower gears indicate the most damage. This further substantiates the premise that the bearing failure debris initiated the chipping of the gear teeth. A photo (Figure 19) of the ring gear and of the output gear (Figure 20) taken after this test indicates some signs of debris but no chipping of gear teeth.

Test Run Number 5

The actuator was again assembled and the test resumed. The cycle conditions were varied to determine if a variation of cycling in load would stop the chipping of the gear teeth. The load was changed to one load spring. Trial and error type testing indicated that load reversals appeared to produce the chipping of the gear teeth. Cycling was then resumed with the elimination of load reversals during each cycle. Also chipping was virtually eliminated as long as the load was below 33,000 in-lbs. The actuator was then cycled for 10,000 cycles from zero to 33,000 in-lb load in one direction then repeated in the other direction. After 58,300 cycles, testing was stopped because the actuator became very noisy. Disassembly revealed that there was no one particular area of distress. The outer

bearings (KAYDON #KT-B100) and races indicated considerable pitting and loss of material. These bearings had not been changed since run number 2. Therefore, considerable wear particles had been introduced into these bearings.

Test Run Number 6

The outer race was reworked and new bearings were put in the actuator and testing resumed. Chips were still being generated even when no load was applied to the actuator. The actuator was disassembled and pieces of gear teeth were found in the actuator. Close inspection indicated that small cracks were present in certain areas of the teeth and that chipping was imminent in many areas. There were still sufficient undamaged teeth remaining to carry the test loads. A file was used to remove the material from the teeth where imminent chipping was obvious. The actuator was again assembled and testing resumed. The test conditions and cycles are shown in Table 1. While the actuator was being tested at the 9 to 15° CW

Table 1

Test Cycles for Test Run Number 6

<u>Approx. # of Cycles</u>	<u>Actuator Strokes</u>	<u>Cycle Rate</u>	<u>Load</u>
40,000	2-10° CW	19.2 cyc/min	0-33,000 in 1b
40,000	2-10° CCW	19.2 cyc/min	0-33,000 in 1b
4,000	2-15° CW	4.6	0-50,000 in 1b
4,000	2-15° CCW	4.6 cyc/min	
3,168	9-15° CW	16.2 cyc/min	30,000-50,000 in 1b
7,400	9-15° CCW	14.2 cyc/min	30,000-50,000 in 1b

condition, an electrical power failure occurred in the laboratory. This caused the actuator to go hard over. The technician reported that the actuator went to approximately 25° before it stopped and an extremely loud noise was evident. When the test was resumed, large chips were found in the magnetic pickup. The actuator was disassembled and large pieces of gear teeth were missing from the various gears. The shock and high load experienced when the actuator went hard over caused failure of the teeth. A detailed discussion of findings of the inspection of the actuator parts is contained in the next section of the report. The major damage was still evident in the lower gears which again indicates that the teeth were weakened by the debris from the previous bearing failures. The damage was too severe to continue testing.

SECTION V

CONDITION OF ACTUATOR AT END OF TESTS

The inspection of the actuator revealed the following:

a. Ring gear, Bendix Part #2175530 - The gear teeth that mesh with the lower ground gear had five pieces of teeth missing as shown in Figures 21 and 22. The teeth with missing pieces as shown in Figure 22 are separated by six teeth or a multiple thereof. Since there is a six-tooth difference between the ring gear and ground gear, this indicates that a piece of tooth must have lodged itself onto one of the teeth and caused other teeth failures when the gears were in mesh. Other teeth that were a multiple of six teeth away from the failed teeth also had deformation to indicate this contact. In fact, a similar piece of tooth (see Figure 22 for location) was removed by applying light pressure with a scribe.

The gears (see Figure 23) that engage the upper ground gear and the output gear had not experienced any significant damage since the last inspection after run number 4.

b. Lower ground gear, Bendix Part #2175525 - This gear had extensive damage to the gear teeth as shown in Figures 24 thru 28. As could be expected, the most damage occurred at the lower side of the gear where the damaged ring gear teeth meshed with this gear. This damage occurred at the lower side of the gear where the missing ring gear teeth meshes with this gear. This damage occurred for about one half of the gear's circumference. There are also some cracks on some of the remaining teeth which indicates failure was imminent. The numbers shown on the photos at the top of the teeth were used for denoting damage after run number 4. The damage that

occurred during run number 6 can be easily distinguished by comparing the photos of run number 4 (Figures 13 thru 16) with the photos (Figures 24 thru 28) of the gear after tests are completed.

c. Upper ground gear, Bendix Part #2175526 - There was no additional damage or sign of wear found on this gear since the inspection after run number 3 as shown in Figures 29 thru 31. The previous photos of the same area of the gear are shown in Figures 17 and 18.

d. Output gear, Bendix Part #2175524 - This gear did not have any signs of additional damage since run number 4.

e. Bearings - All bearings and races were inspected and were found to be in as-new condition.

f. Motor - No sign of significant wear was found on any of the motor parts as shown in Photos 2 and 3.

SECTION VI

SUMMARY OF RESULTS AND OTHER GENERAL COMMENTS

The total time of testing of the actuator during this program was over 326 hours and over 400,000 cycles. The only parts changed during the program were the bearings as discussed in Section IV. The early bearing failures were very unfortunate in regard to determining the durability of the dynavector concept. However, the motor portion of the actuator was still in excellent condition after all of the tests. These parts are shown in Figure 2. Where the vanes move with respect to the side plate there are slight polishing patterns. The case drain leakage of the motor was below .5 gpm throughout the tests and no change was measurable during the entire test. The motor parts indicate that they are capable of many more cycles. Since the motor is the heart of this concept, this is very encouraging for potential future applications of this concept. It was decided to terminate this program rather than refabricate the actuator, because other contract efforts are now in progress which will further demonstrate the dynavector concept. These programs are as follows:

- a. High Temperature Rotary Hydraulic Actuator for High Performance Aircraft - Contract AF33615-72-C-1187, Contractor - Bendix Electrodynamics.
- b. Prototype Powered Wheel for Aircraft - Contract NAS-1-13787, Contractor - Bendix Electrodynamics.
- c. Digital Electrohydraulic Stepper Actuator for Advanced Missile Systems - Contract AF33615-74-C-2052, Contractor - Bendix, Mishawaka.

SECTION VII
CONCLUSIONS AND RECOMMENDATIONS

The motor portion of the dynavector concept performed extremely well during this program and is considered to offer significant promise for future applications.

The failure of bearings in this program were proven to be an assembly problem and not a technical problem.

The gear teeth failure was considered to be caused by the debris from the failed bearings; however, some additional actuator testing will be required to definitely prove this. This testing as mentioned in Section V will be accomplished under other efforts now being conducted.

Even with the failures experienced there was no catastrophic failure of the actuator. The actuator never failed to operate. This indicates, with properly installed bearings, that a very rugged actuator is possible with this concept.

No additional efforts other than those now in progress are recommended at this time. However, if the present efforts are successful the following areas are recommended for consideration of this concept.

- a. Digital actuators for aircraft
- b. High pressure hydraulic systems
- c. Applications where high response and stiffness are required

REFERENCE

1. K. W. Verge, R.G. Read, N.L. Sikora, "Investigation of Rotary Actuation Technique," Tech Report No. AFAPL-TR-70-52, Wright-Patterson AFB, OH, on contract with Bendix Research Laboratories.

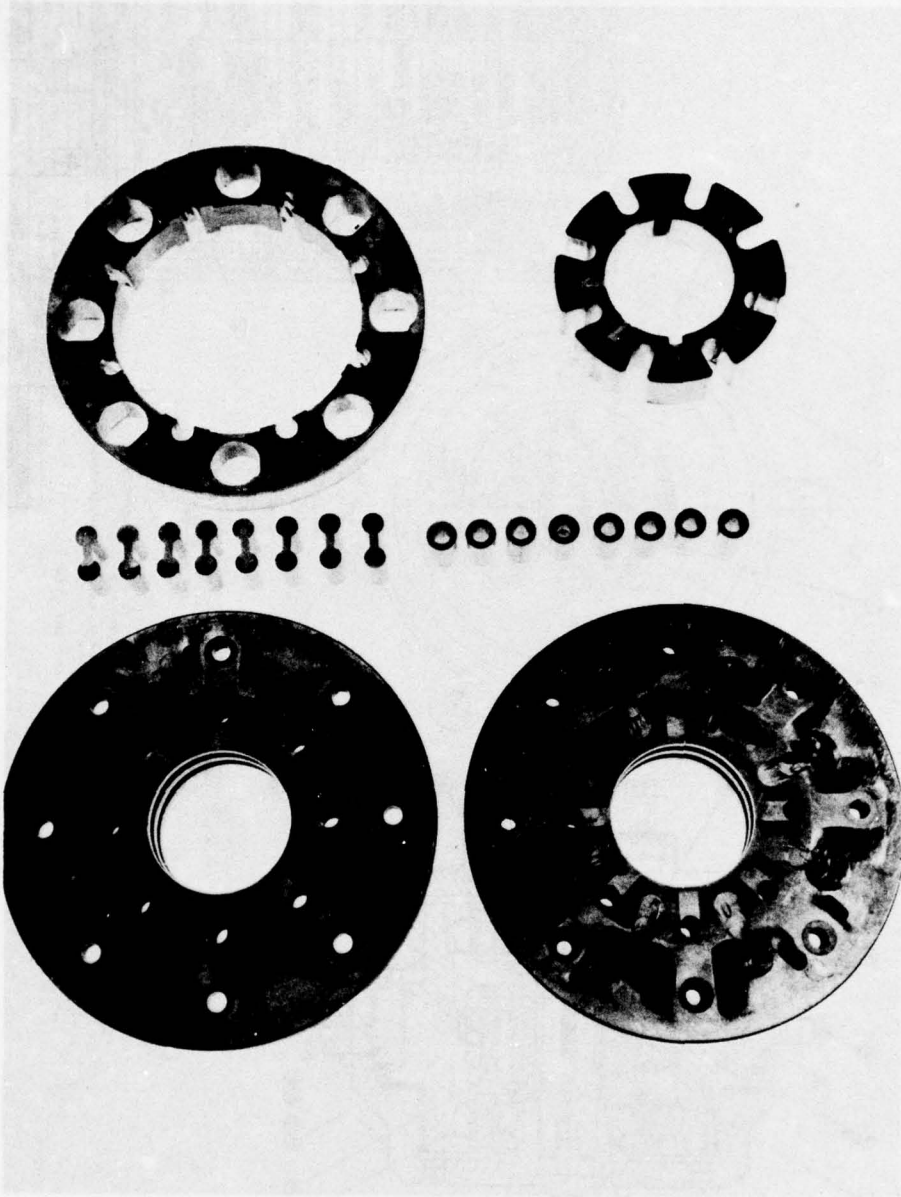


Figure 2. Exploded View of Motor After Tests

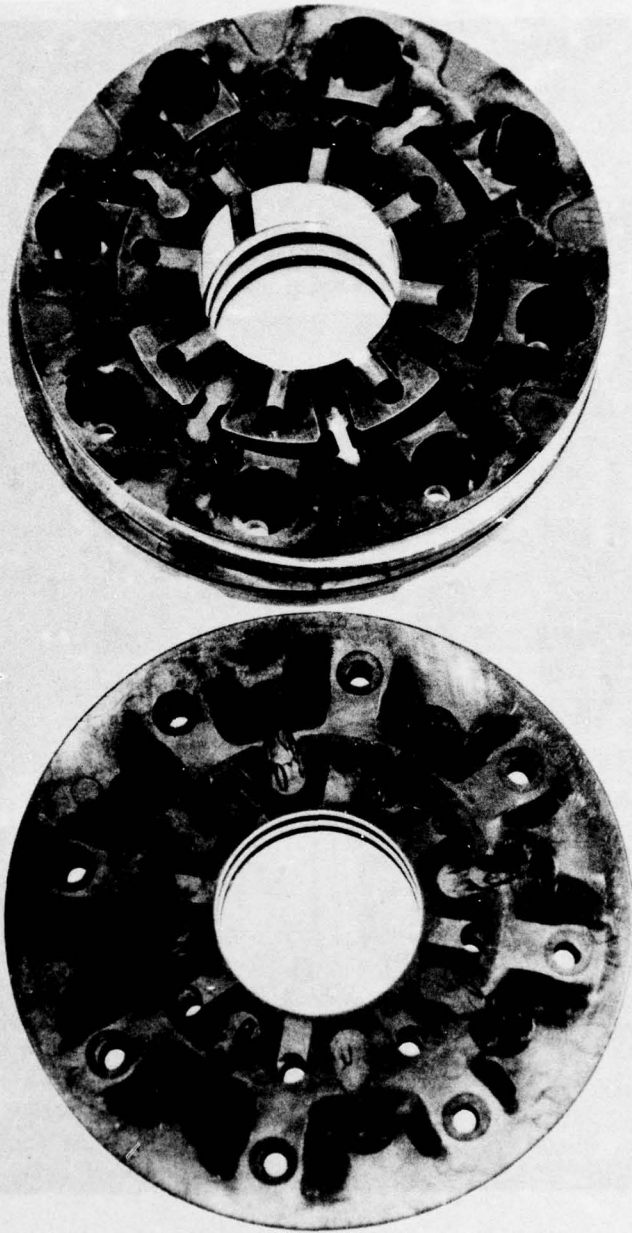


Figure 3. Partial Assembly of Motor After Tests

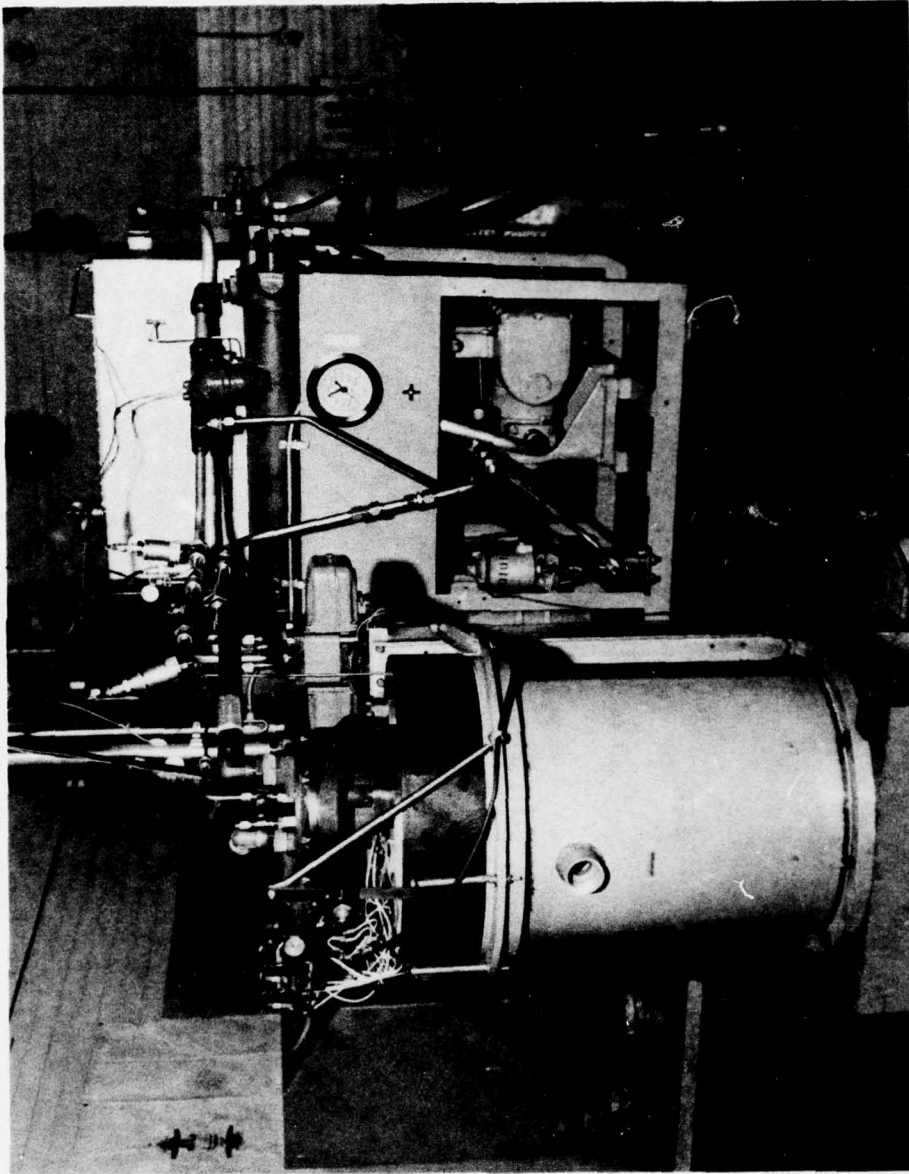


Figure 4. First Test System Used for Testing Actuator

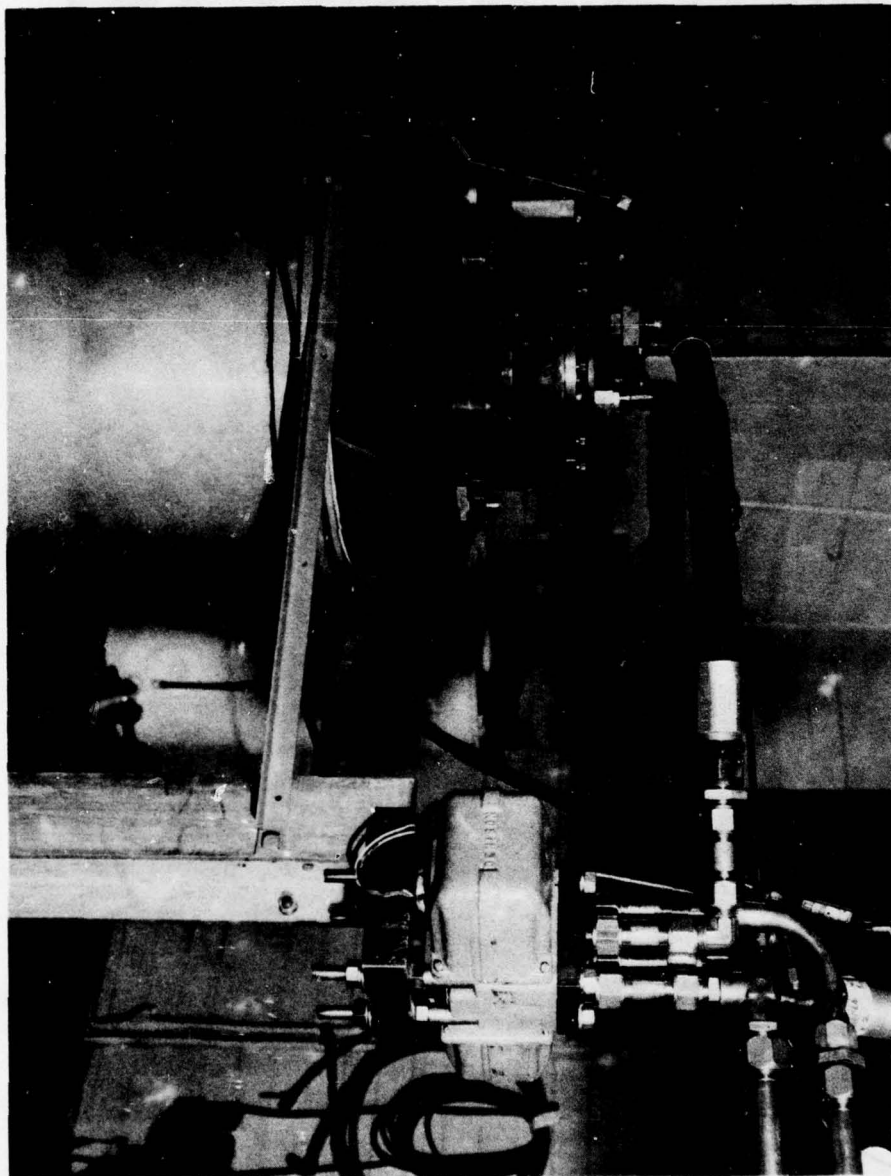


Figure 5. Actuator Installed in Load Rig and Solenoid Valves Used for Controlling Actuator

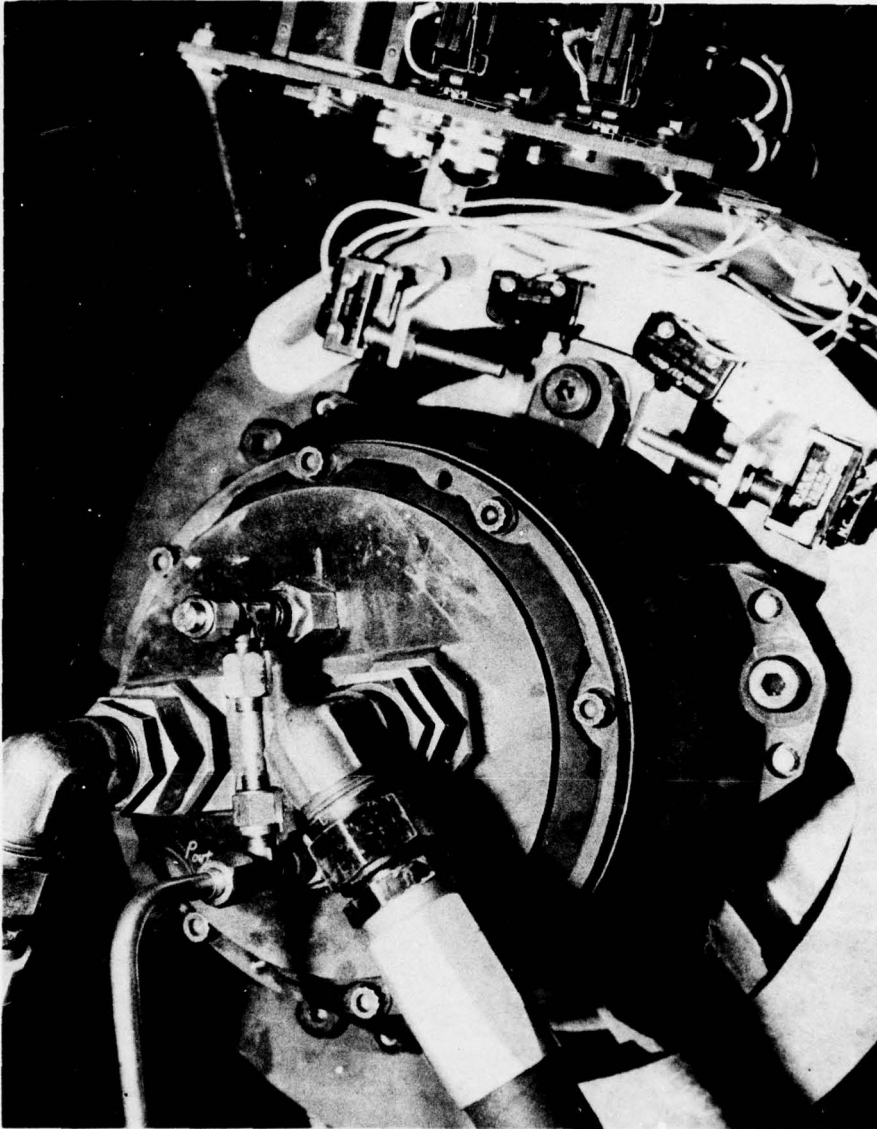


Figure 6. Actuator With Electro-Mechanical Switches Located for Controlling Stroke

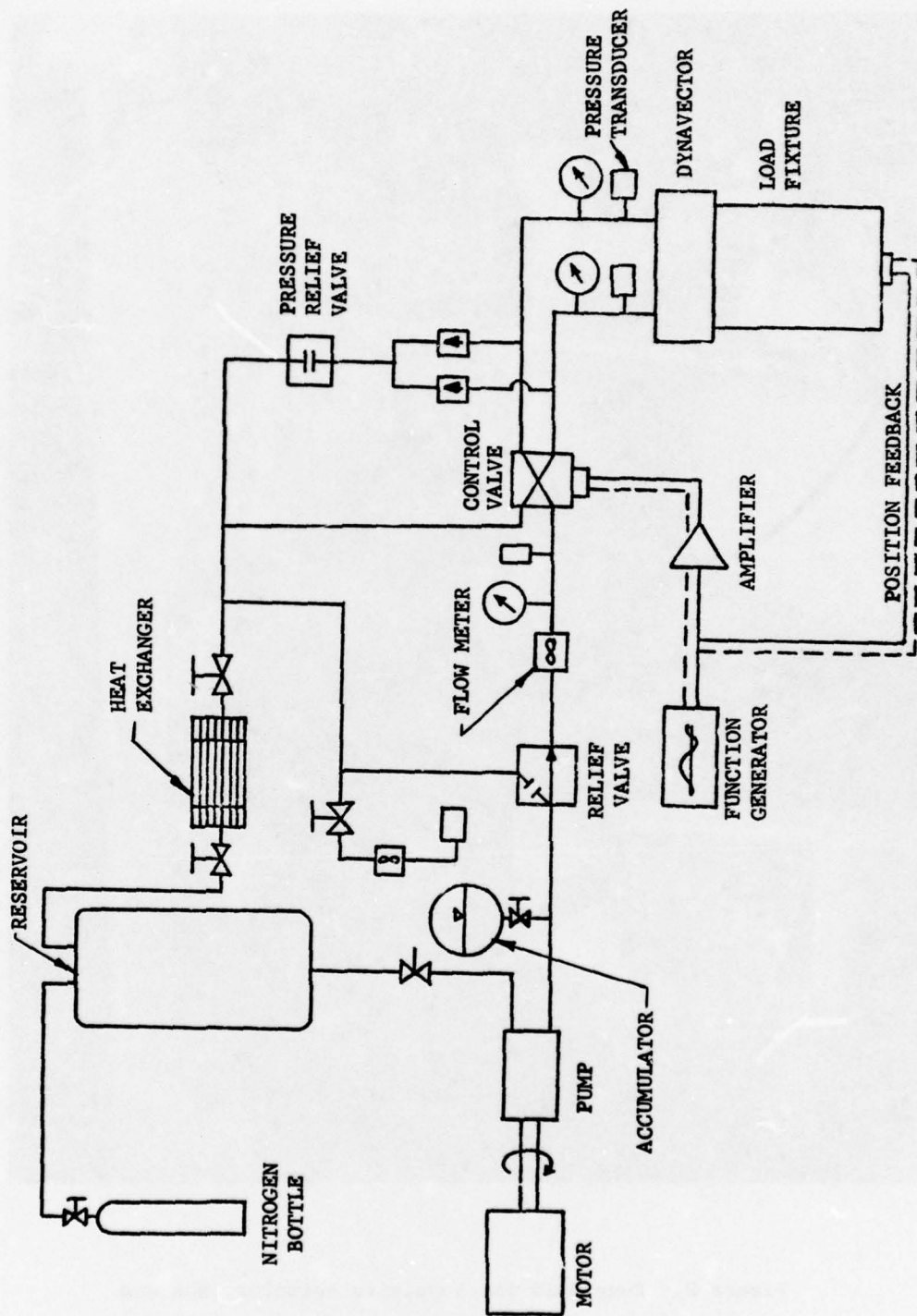


Figure 7. Schematic of Test Setup

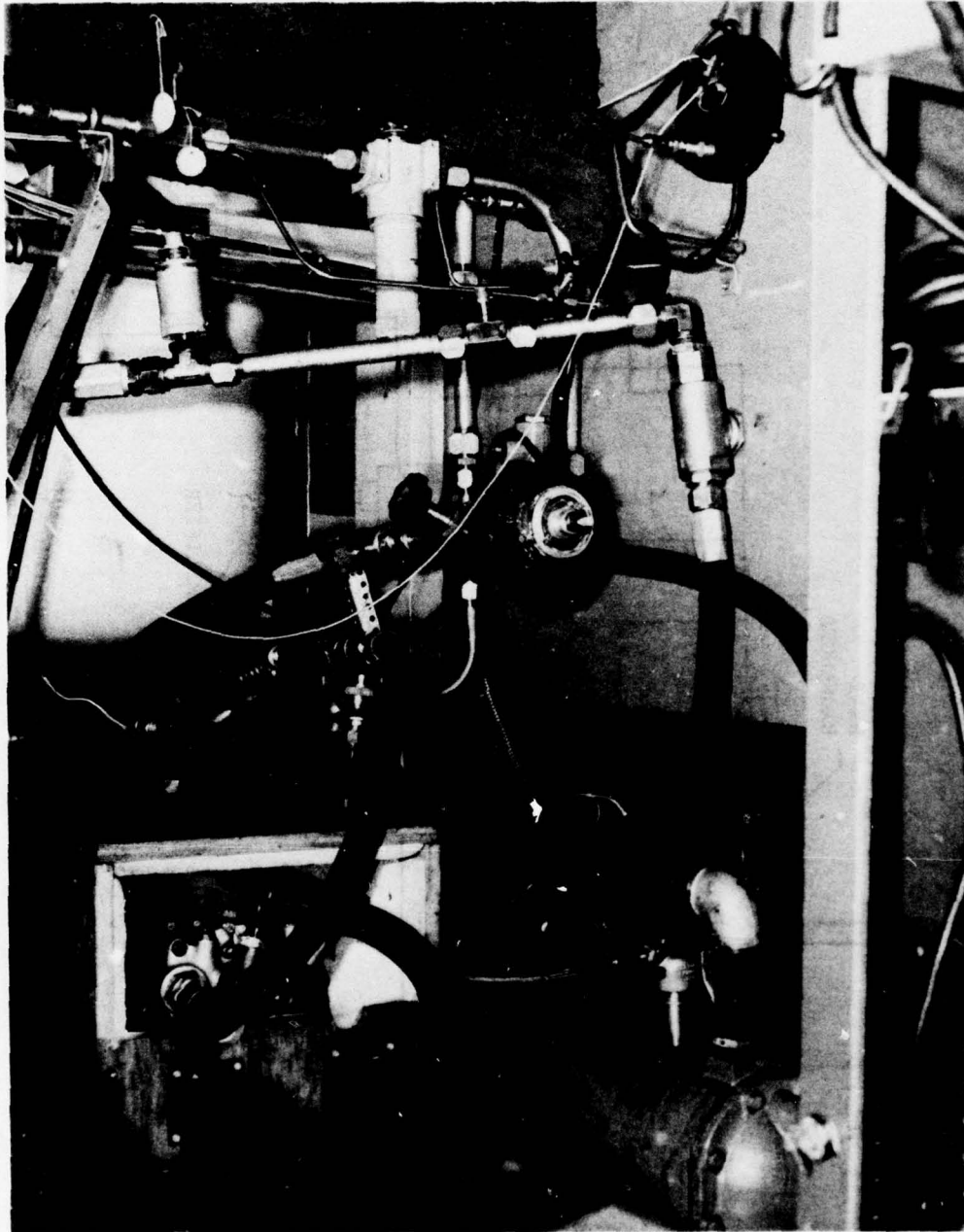


Figure 8. Pump Used for Supplying Actuator (Box and Installation Provided Reduction of Pump Noise)

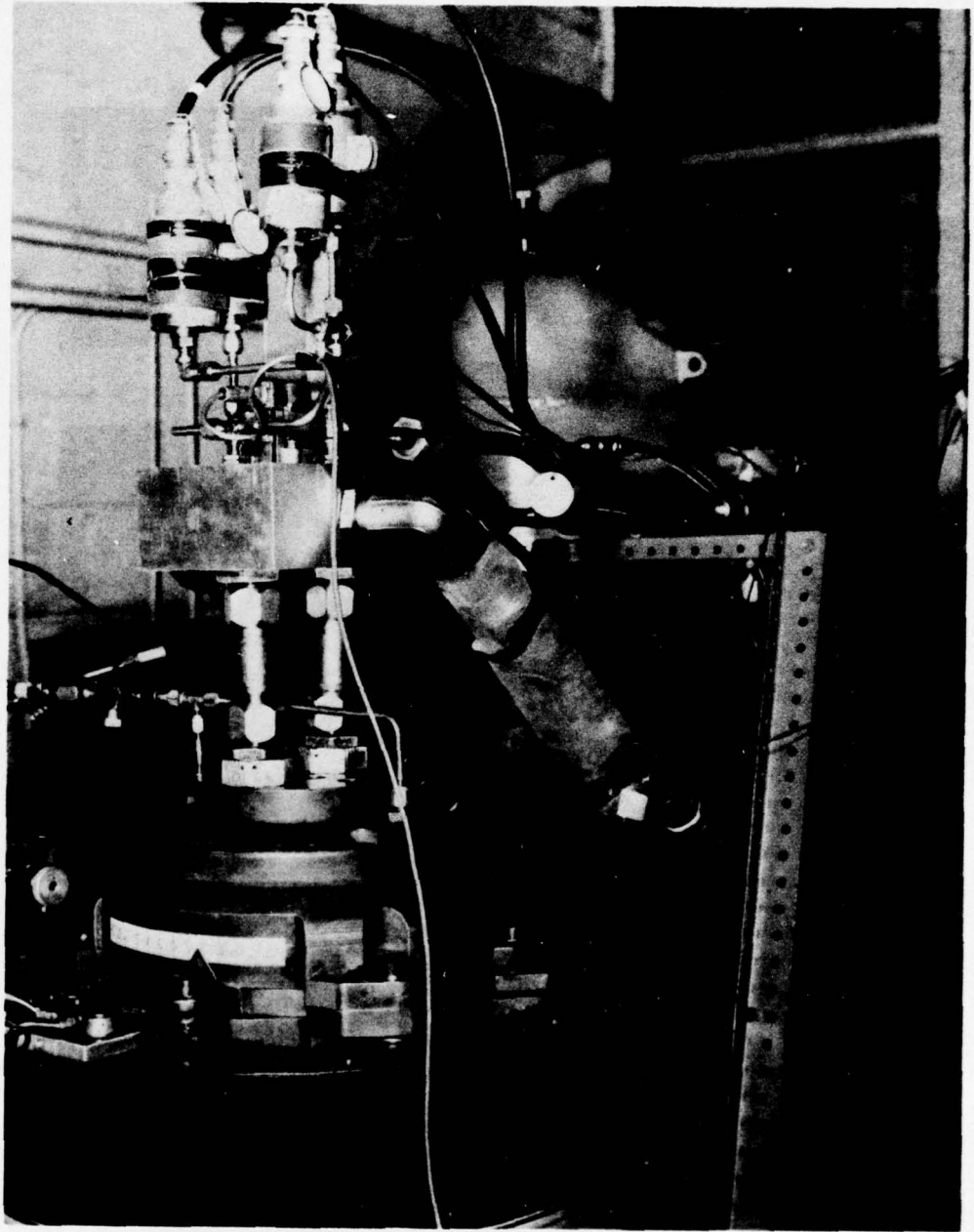


Figure 9. Installation of Servo Valve and Manifold Block for Controlling Actuator

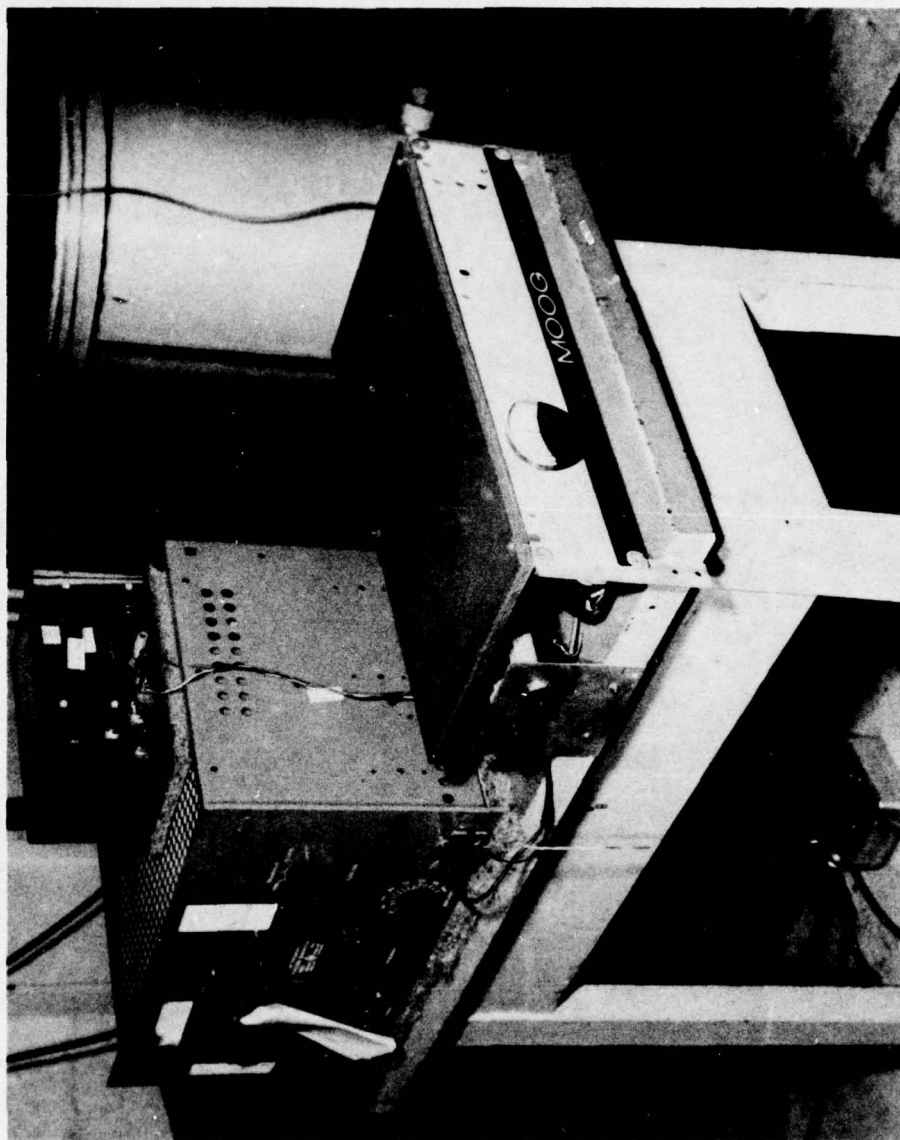


Figure 10. Frequency Generator and Servo Controller

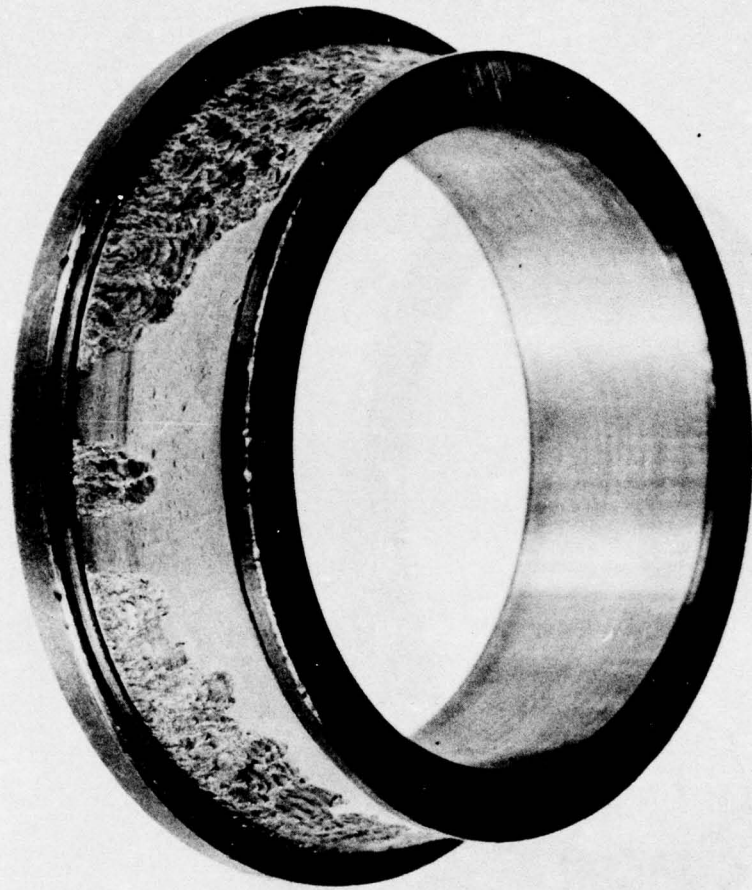


Figure 11. Failed Timken Bearing After Run No. 2

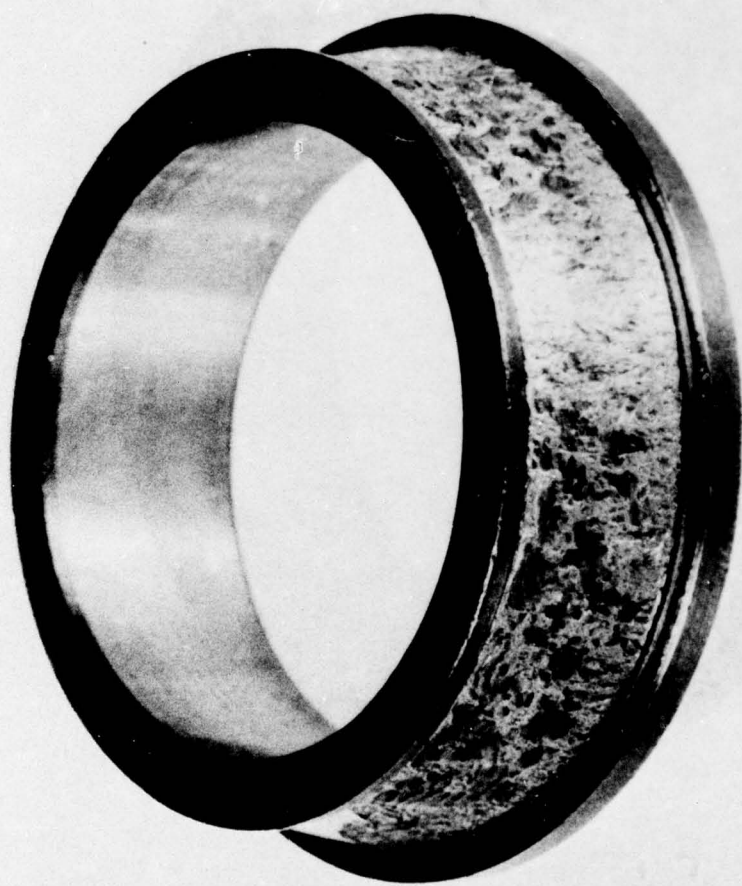


Figure 12. Failed Timken Bearing After Run No. 2

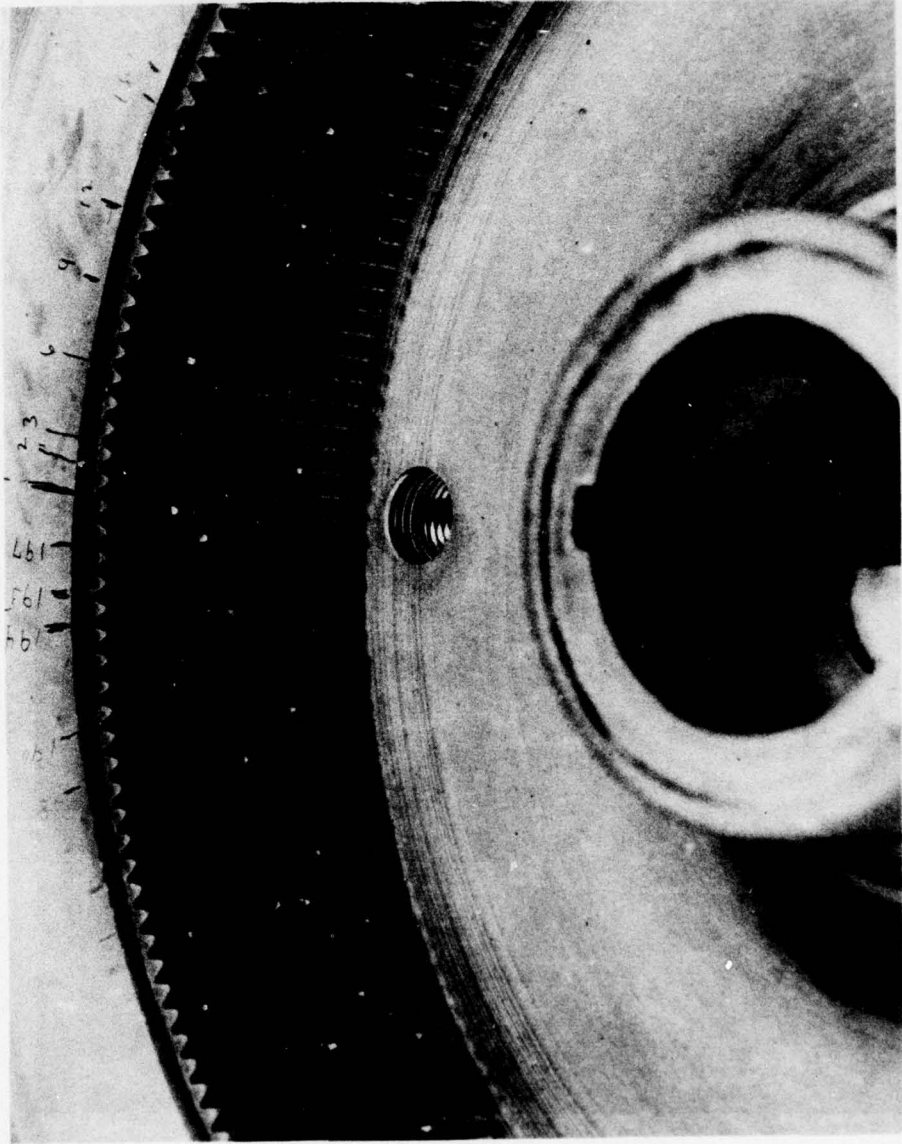


Figure 13. Lower Ground Gear After Run No. 4 (Teeth No. 70 Thru No. 20)

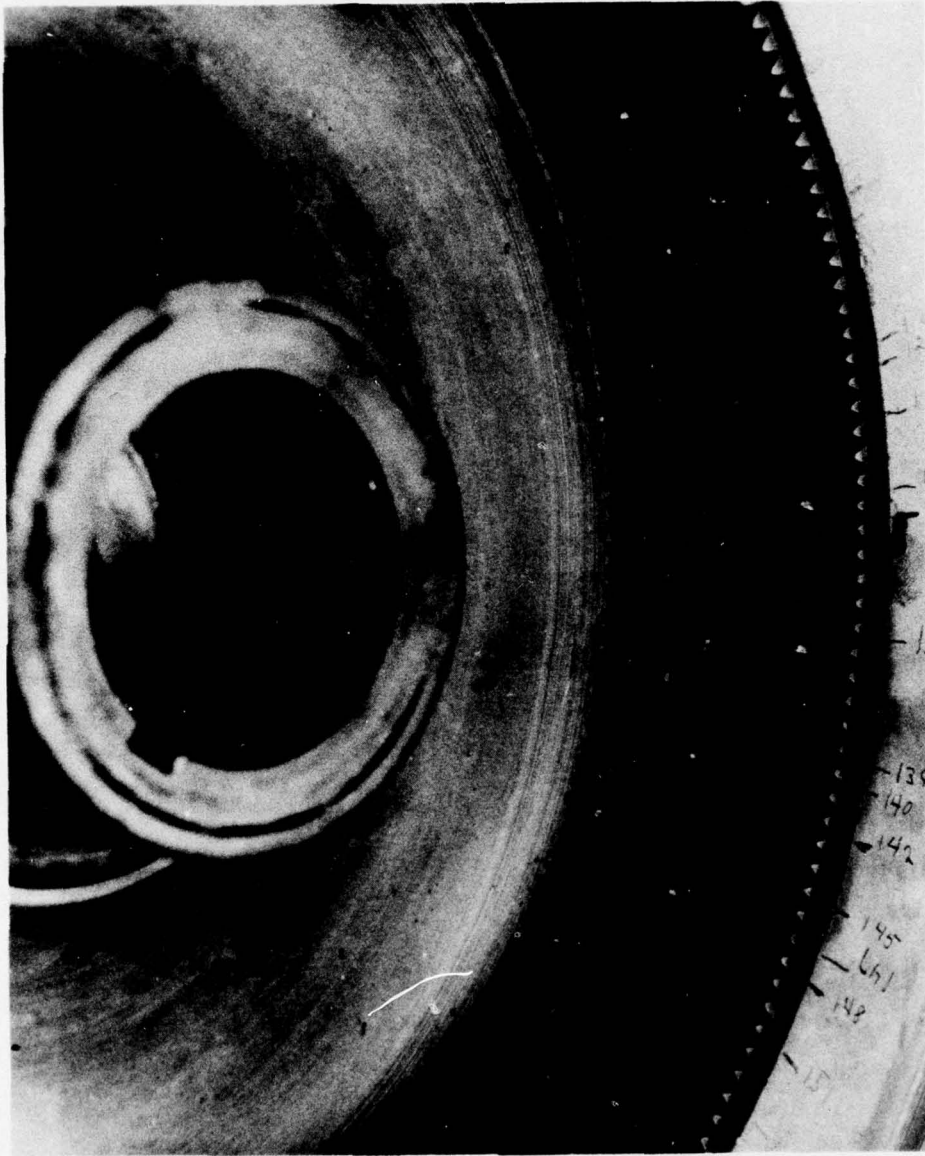


Figure 14. Lower Ground Gear After Run No. 4 (Teeth from Approx No. 110 Thru No. 155)

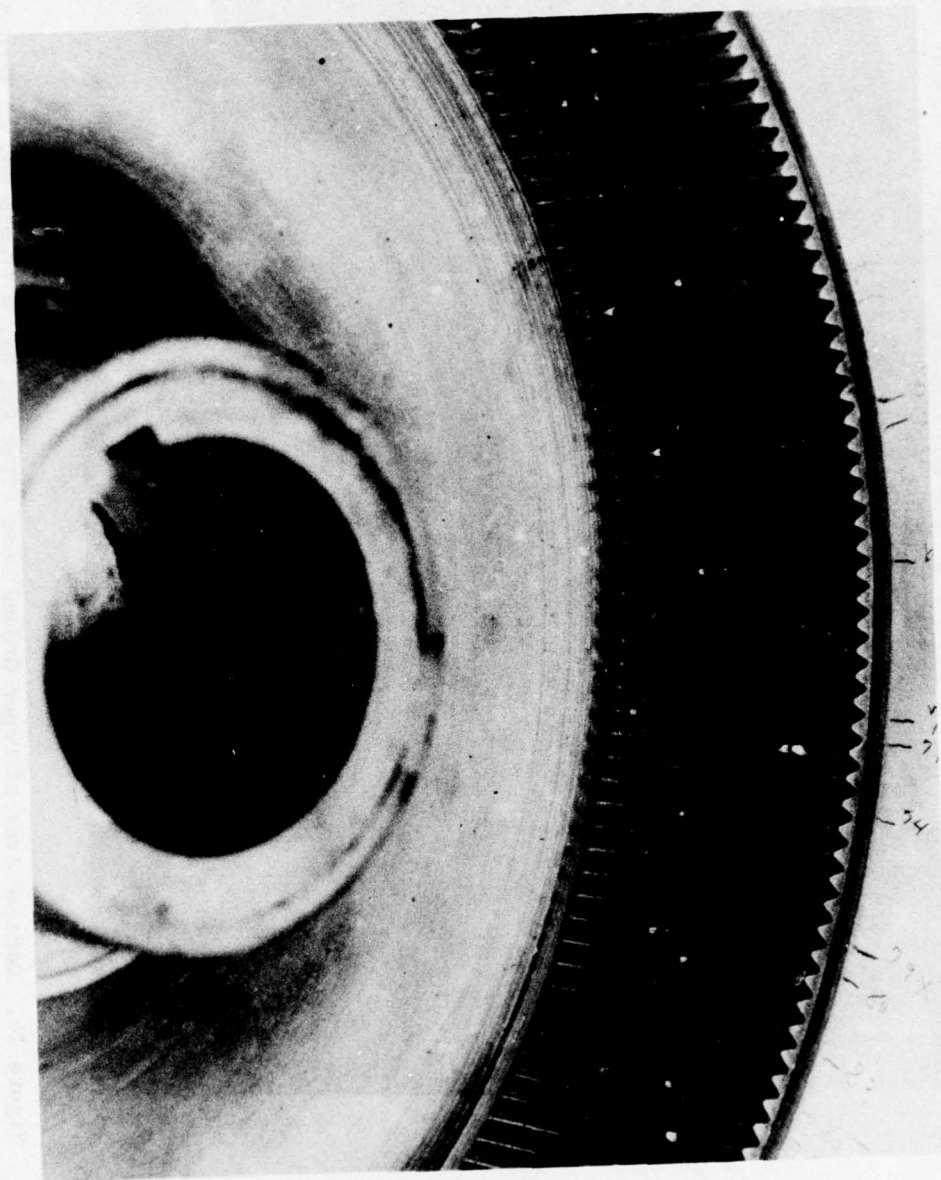


Figure 15. Lower Ground Gear After Run No. 4 (Teeth No. 40 Thru No. 88)

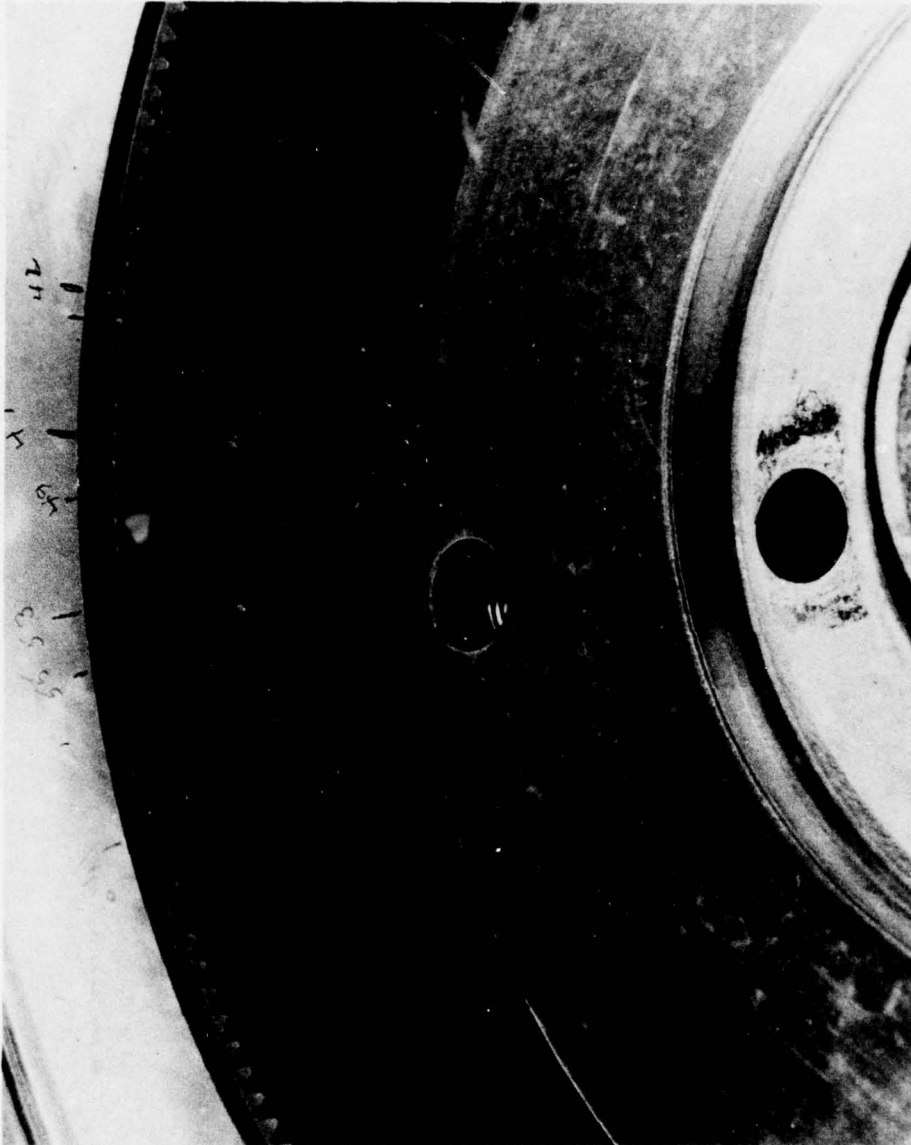


Figure 16. Damaged Area of Upper Ground Gear After Run No. 4 (Teeth No. 42 Thru No. 55)



Figure 17. Undamaged Area of Upper Ground Gear After Run No. 4



Figure 18. Damage to Teeth No. 1, 6, and 13 of Upper Ground Gear After Run No. 4

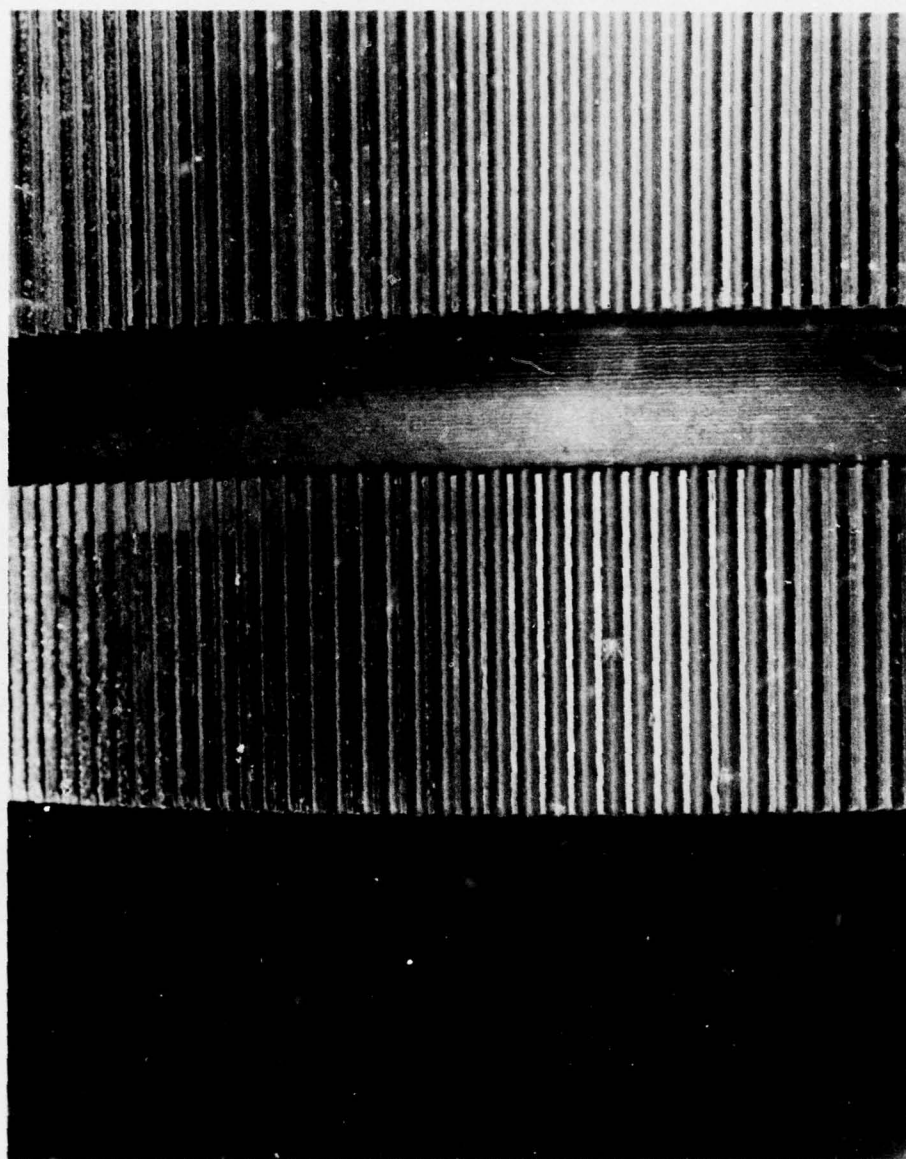


Figure 19. Ring Gear After Run No. 4

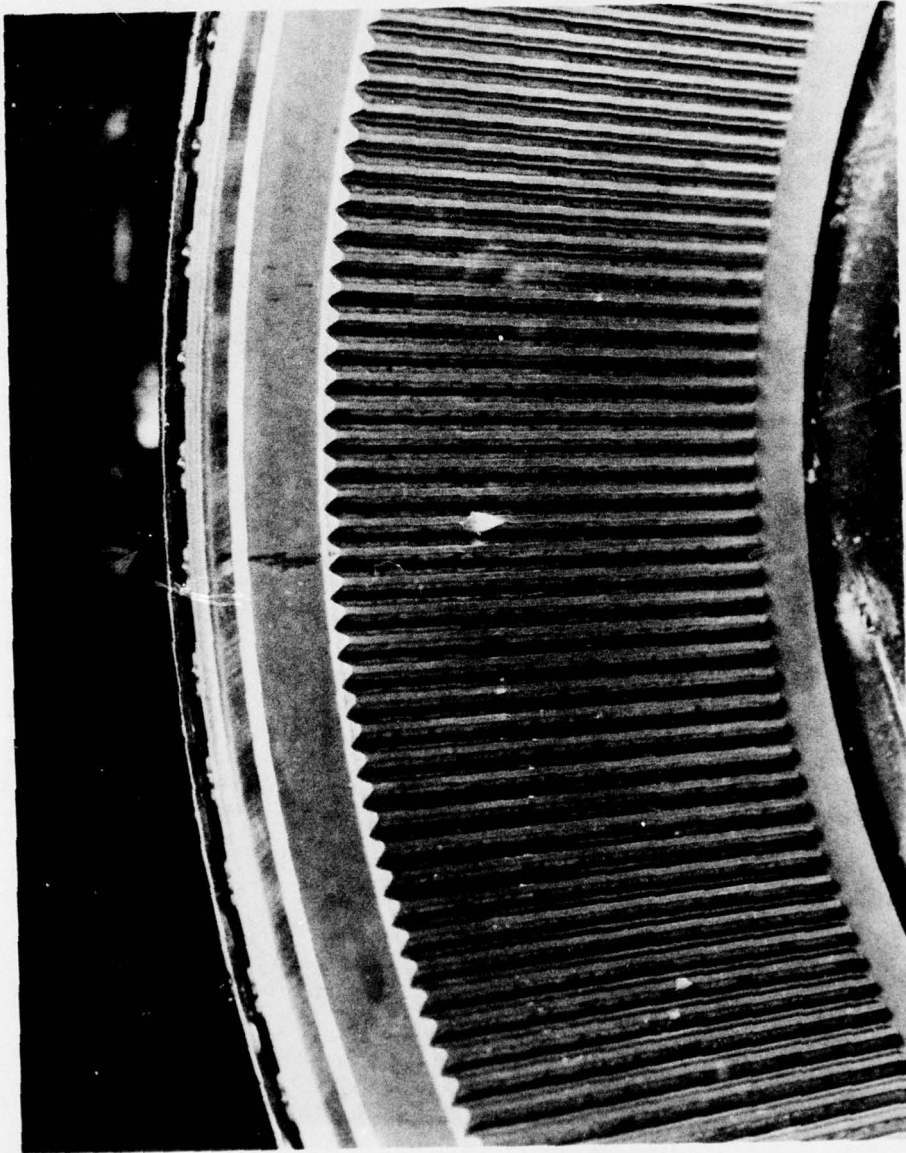


Figure 20. Output Gear After Run No. 4

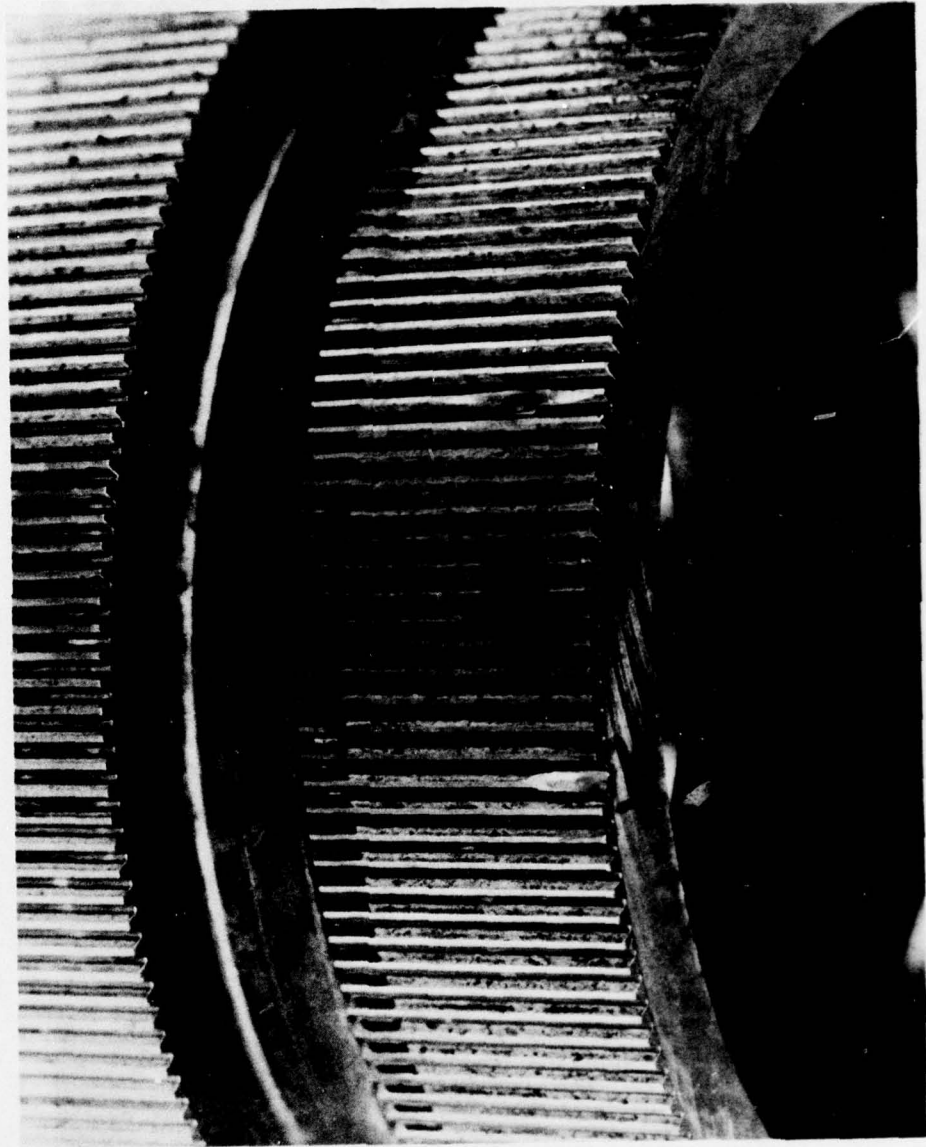


Figure 21. Ring Gear After Run No. 6 (Lower Gear)

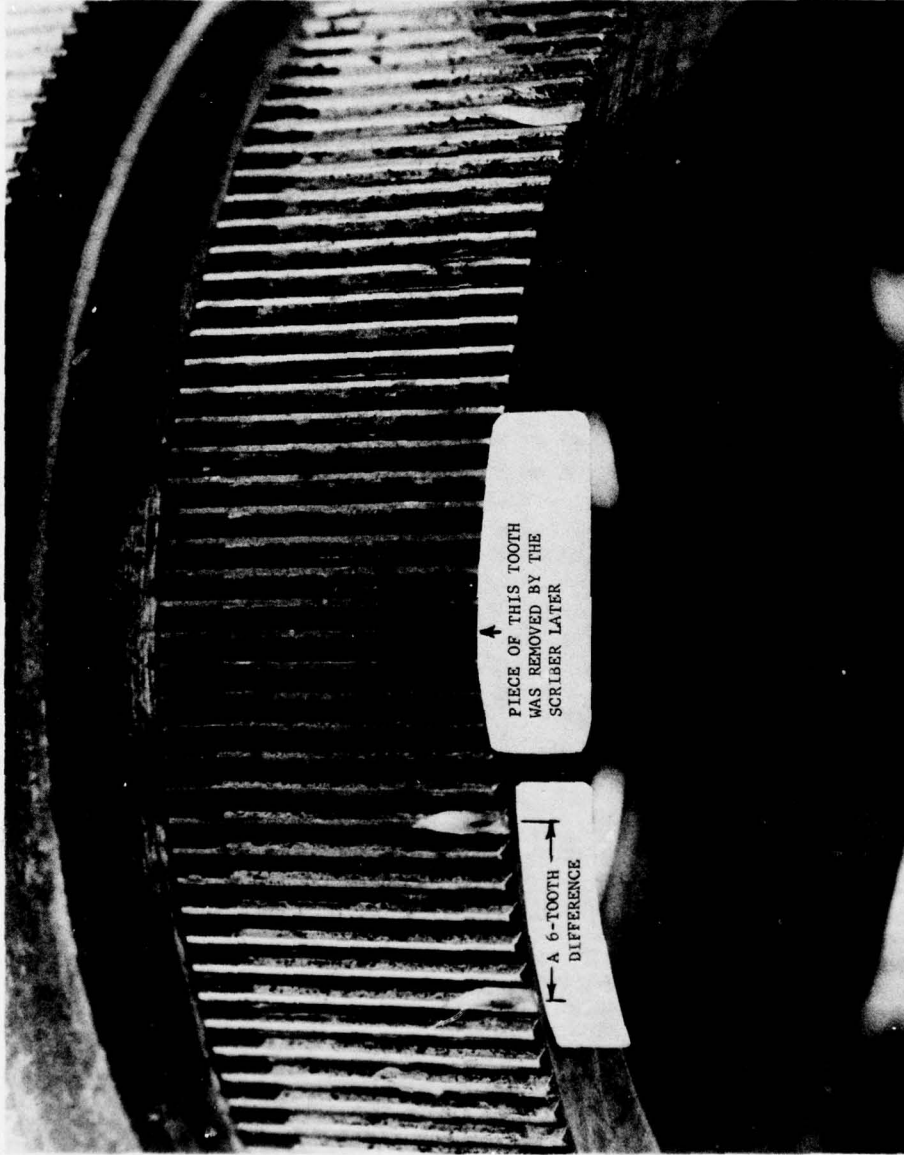


Figure 22. Ring Gear Teeth Damage After Run No. 6 (Lower Gear)

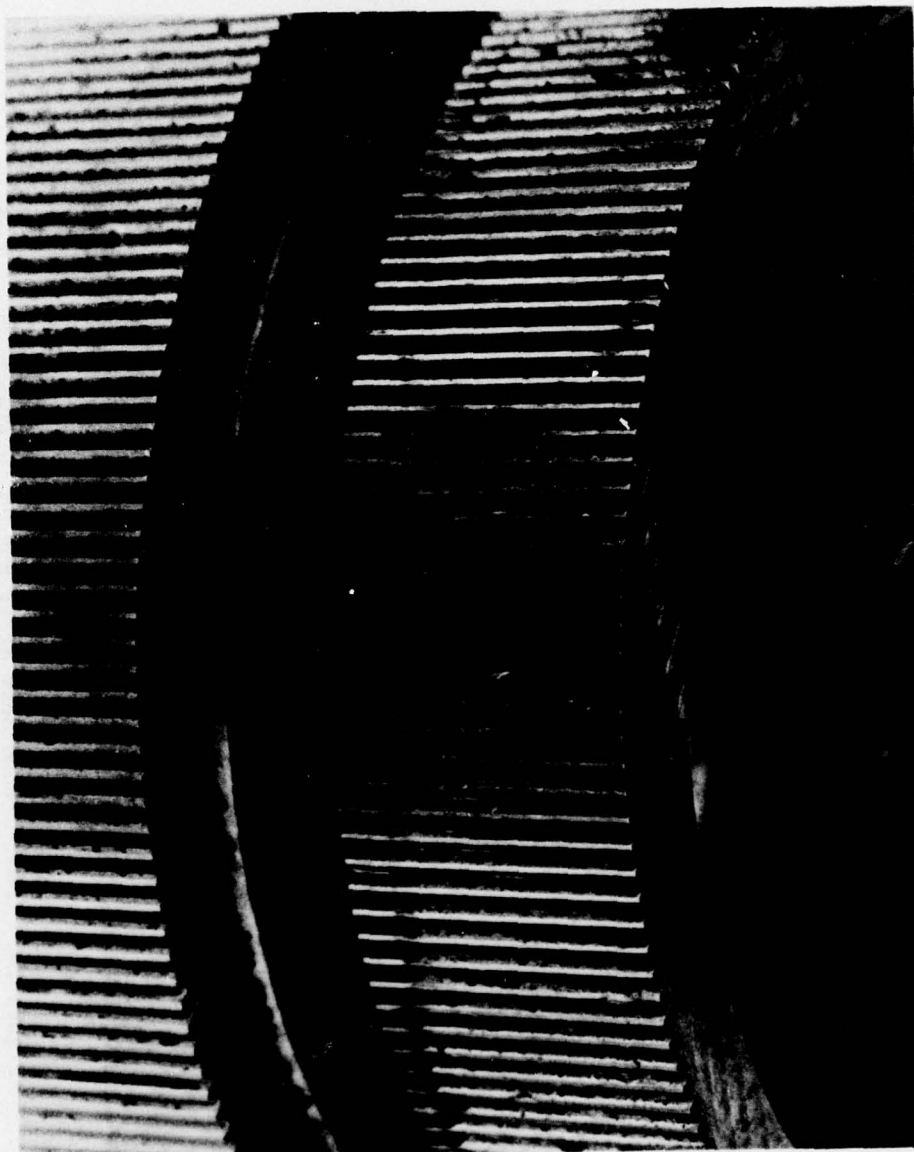


Figure 23. Upper Portion of Ring Gear After Run No. 6

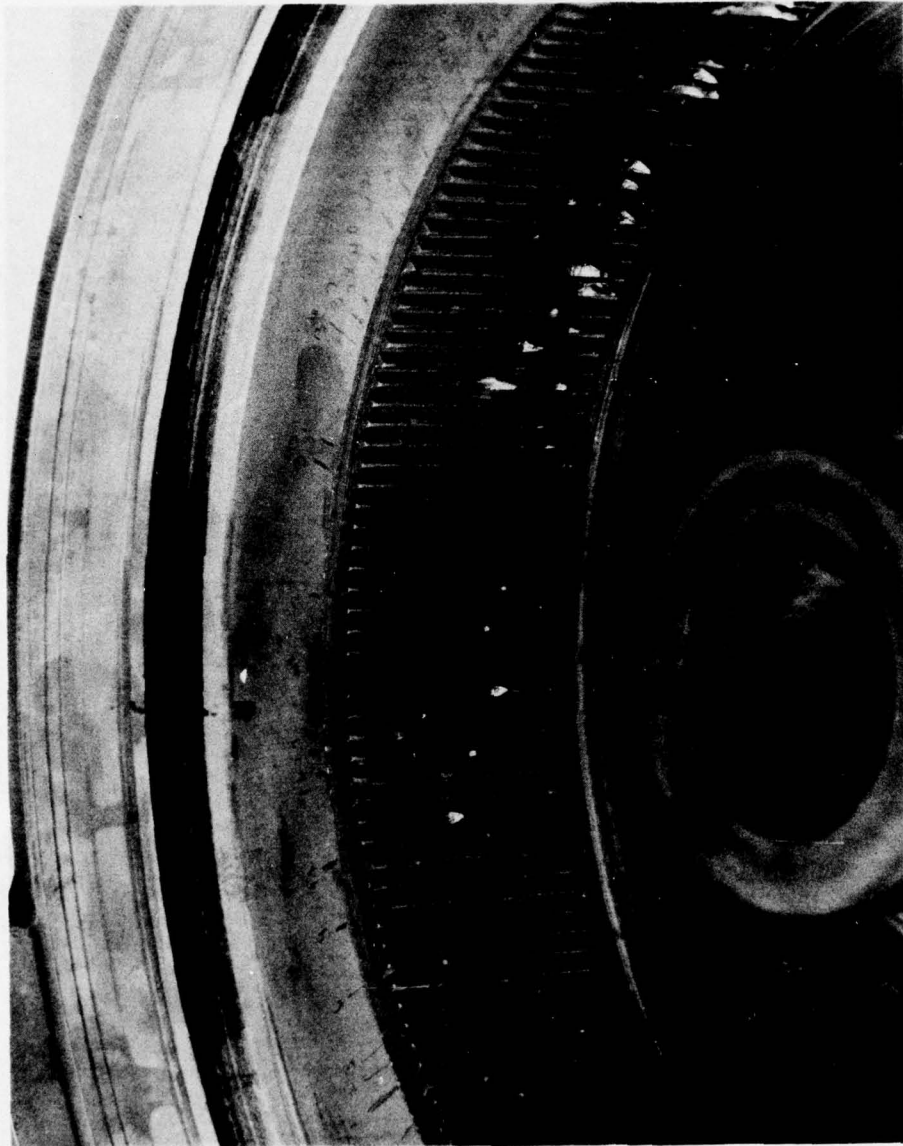


Figure 24. Lower Ground Gear After Run No. 6 (Teeth No. 1 Thru No. 60)

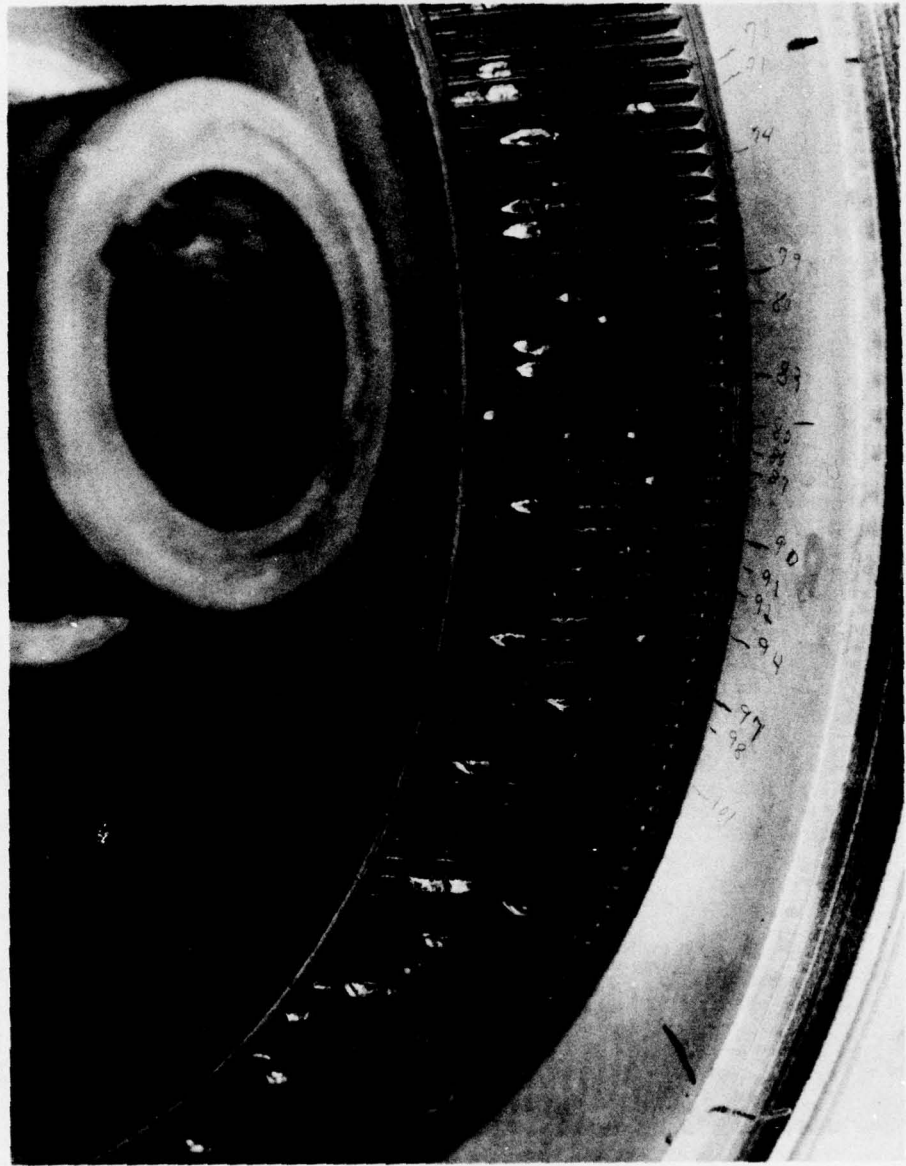


Figure 25. Lower Ground Gear After Run No. 6 (Teeth No. 67 Thru No. 120)

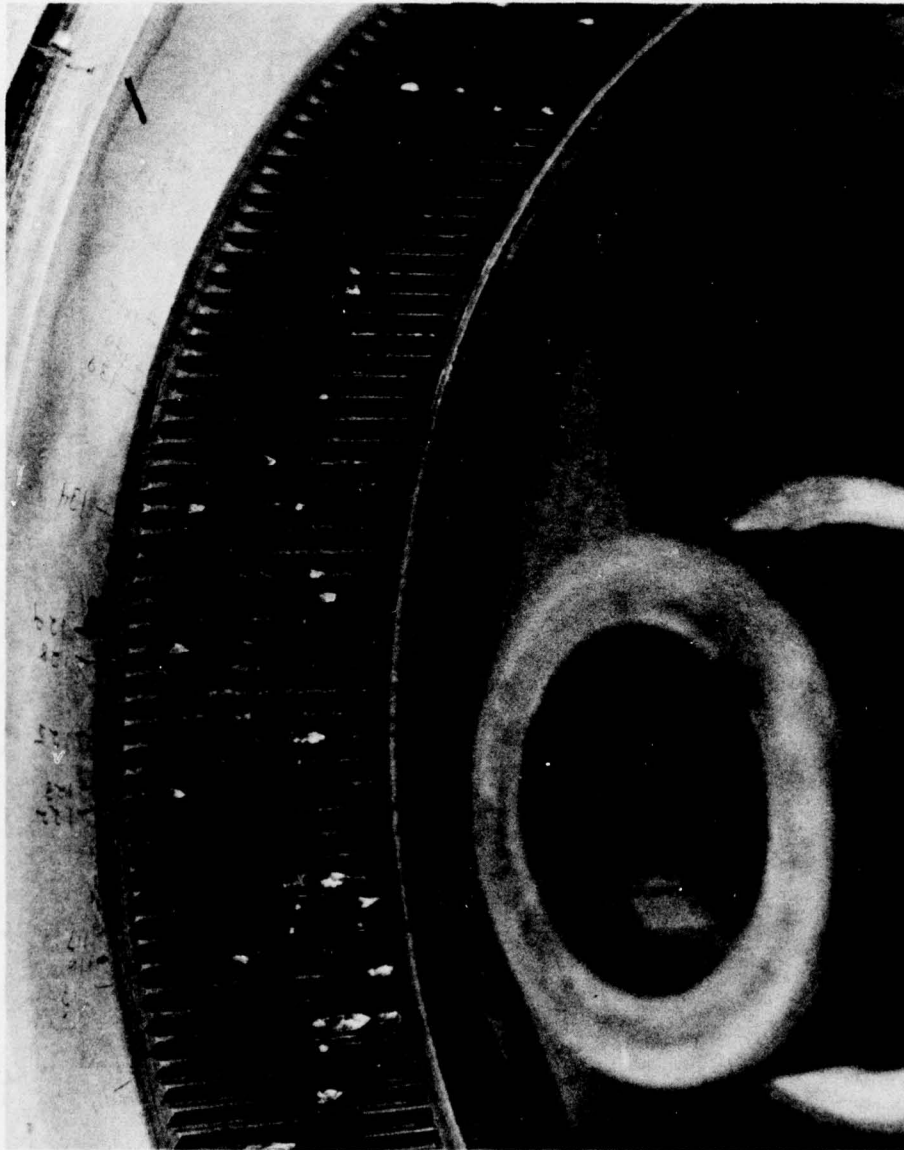


Figure 26. Lower Ground Gear After Run No. 6 (Teeth No. 106 Thru No. 160)

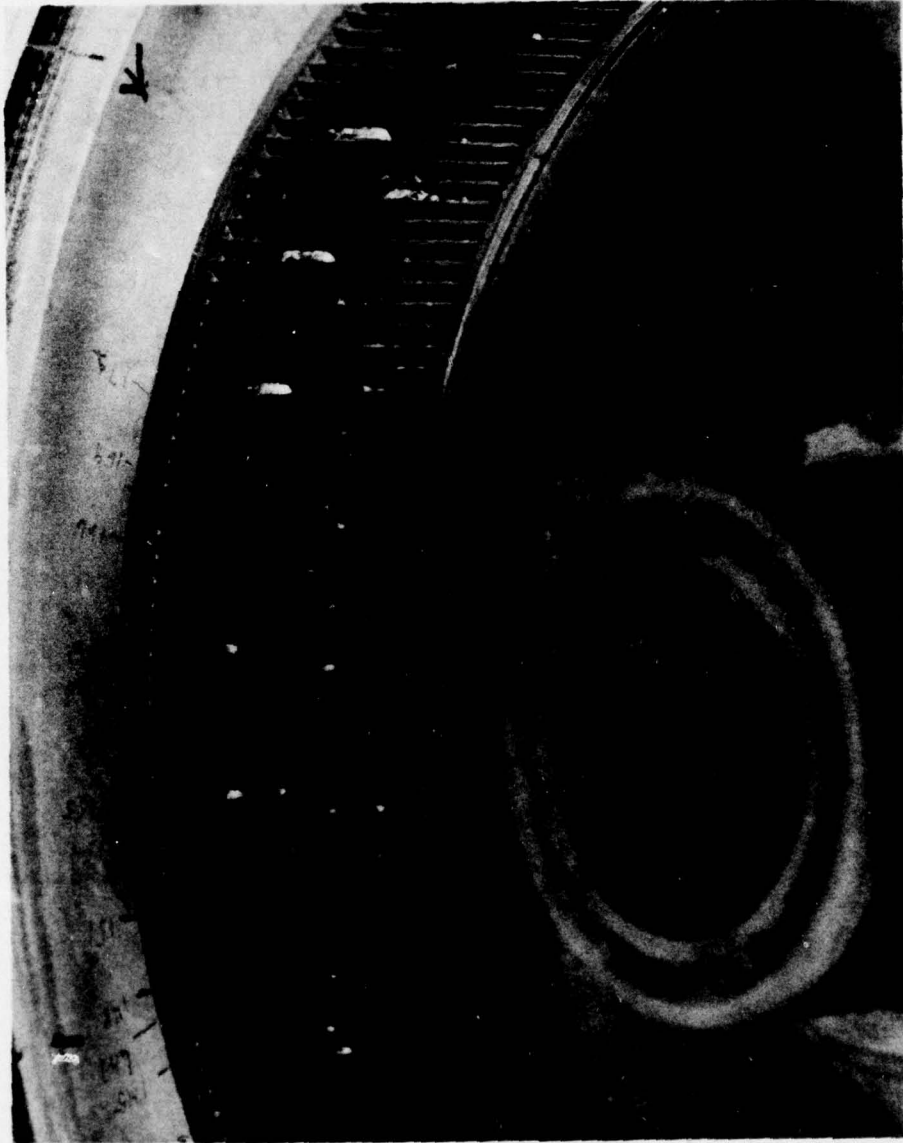


Figure 27. Lower Ground Gear After Run No. 6 (Teeth No. 100 Thru No. 190)



Figure 28. Lower Ground Gear After Run No. 6 (Teeth No. 177 Thru No. 20)



Figure 29. Upper Ground Gear After Run No. 6 (Teeth No. 42 Thru No. 55)



Figure 30. Upper Ground Gear After Run No. 6 (Teeth No. 6 and No. 13)



Figure 31. Upper Ground Gear After Run No. 6 (Undamaged Area)

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