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FINAL REPORT

MCDONNELL DOUGLAS

SECOND GENERATION HELIOSTAT

WITH HIGH-VOLUME MANUFACTURING FACILITY
DEFINED BY GENERAL MOTORS

MCDONNELL DOUGLAS ASTRONAUTICS COMPANY-HUNTINGTON BEACH

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MCDONNELL DOUGLAS

TEST REPORT

LIFE CYCLE AND OPERATIONAL TORQUE CAPABILITY
OF THE SECOND GENERATION AZIMUTH DRIVE

JULY 15, 1981

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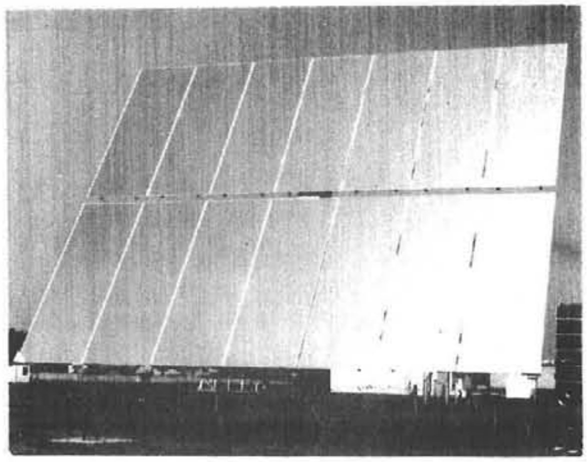

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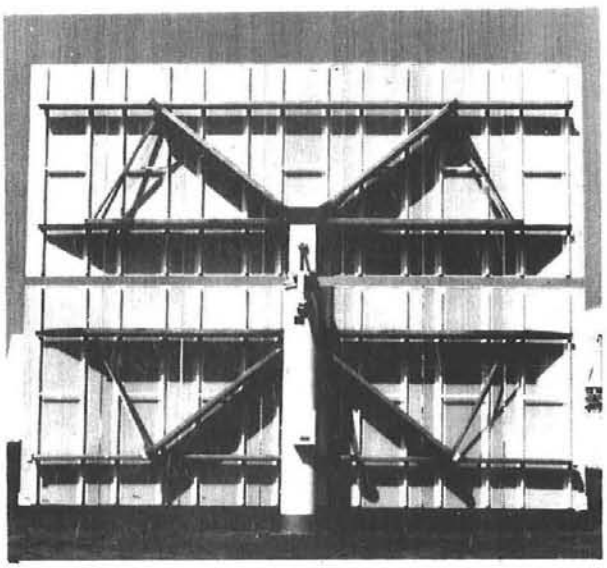

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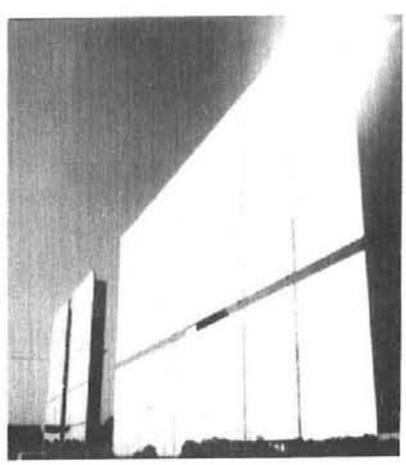

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INTRODUCTION

The design of the McDonnell Douglas Astronautics Company - Huntington Beach (MDAC-HB) Second Generation Heliostat (Figure A) employs a harmonic drive which provides rotational capability around the heliostat vertical centerline (azimuth). The harmonic drive operational torque capability was increased from 100,000 in-lbs to 144,000 in-lbs (corresponds to 50 mph winds in worst orientation).

An accelerated life test was conducted to demonstrate suitable performance over a simulated 30 year life. The increased torque capability was to be demonstrated before and after life cycling. Life testing was intended to demonstrate suitability of the other azimuth drive components, in particular the motor, pinion gear, helicon gear, wire race bearing and seals.

SUMMARY

A harmonic drive unit was evaluated for use in a MDAC-HB designed Second Generation Solar Heliostat. The harmonic drive unit provides rotational capability to a commanded azimuth and reacts loads from the mirror assembly. The harmonic drive operational torque capability was increased from 100,000 in-lbs to 144,000 in-lbs. Evaluation testing consisted of:

1. Demonstration of increased torque capability.
2. Measurement of azimuth drive unit efficiency.
3. Accelerated life testing.

Results of the testing indicate that the azimuth drive will meet the heliostat design requirements. Life testing demonstrated adequate performance over a simulated 30 year life. Torque capability was in excess of 151,000 in-lbs after completing the life tests. The azimuth drive unit efficiency was 7.8% driving against a 40,000 and 86,000 in-lb torque load.

The increased torque capacity azimuth drive unit performed satisfactorily, all design requirements were met, and the structural integrity of the unit was proven.

TEST DESCRIPTION

A. Test Specimen

The harmonic drive unit used for test was a spare unit reworked by United Shoe Machinery Corp. for increased torque capability. The harmonic drive operational torque capability was increased from 100,000 in-lbs to 144,000 in-lbs by modifying the wave generator cam profile and moving the wave generator toward the base of the flex spline. The modified harmonic drive was fitted with new seals throughout and a new wire race bearing for test. The motor (including the helicon pinion) and helicon gear were obtained from azimuth drive #1 previously tested at CRTF. The motor and helicon gear set had approximately 3,000 cycles (equivalent of 10 years of wear) from MDAC heliostat and CRTF testing prior to being installed.

B. Test Setup

The test fixture used was a 1D22425-1 Short Pedestal used with 1T54941 Azimuth Life Test loading structures. Refer to Figure 1 for load test schematic.

C. Test Requirements

1. Ratchet Test

The objective of this test is to demonstrate the increased torque capability of the azimuth drive unit. A progressive torque load shall be applied to the specimen using symmetric hydraulic cylinders, as shown in Figure 2, prior to driving test specimen. The specimen then shall be driven with and against each selected load level for approximately 10 seconds for each rotational direction. The circular spline shall rotate smoothly without binding and harmonic drive should not ratchet or slip for either direction of rotation.

Test torque levels shall be 100,000 in-lbs, 120,000 in-lbs, 130,000 in-lbs, 135,000 in-lbs, 140,000 in-lbs, and 144,000 in-lbs. Measure and record actual applied torque loads for each direction of rotation.

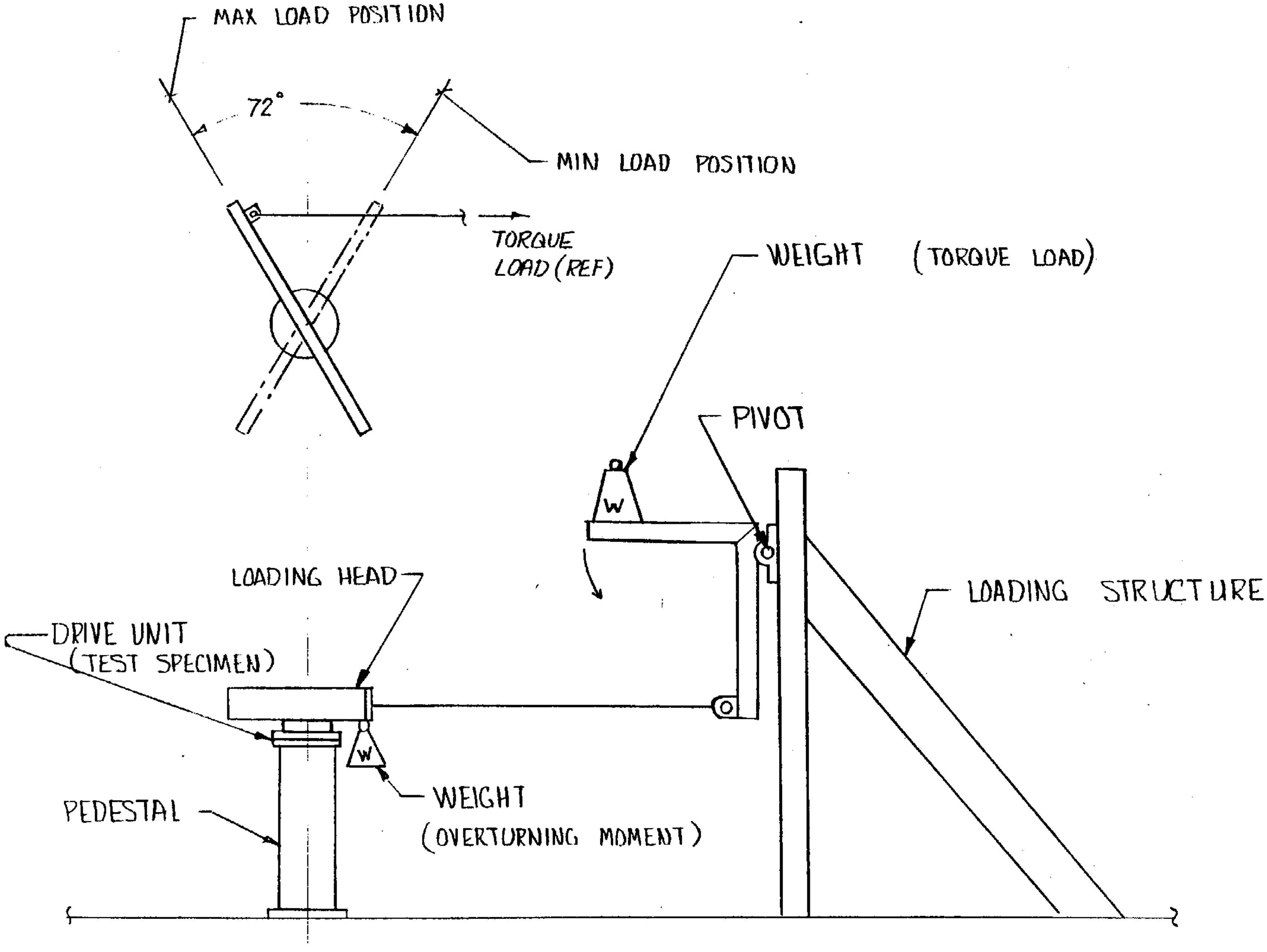
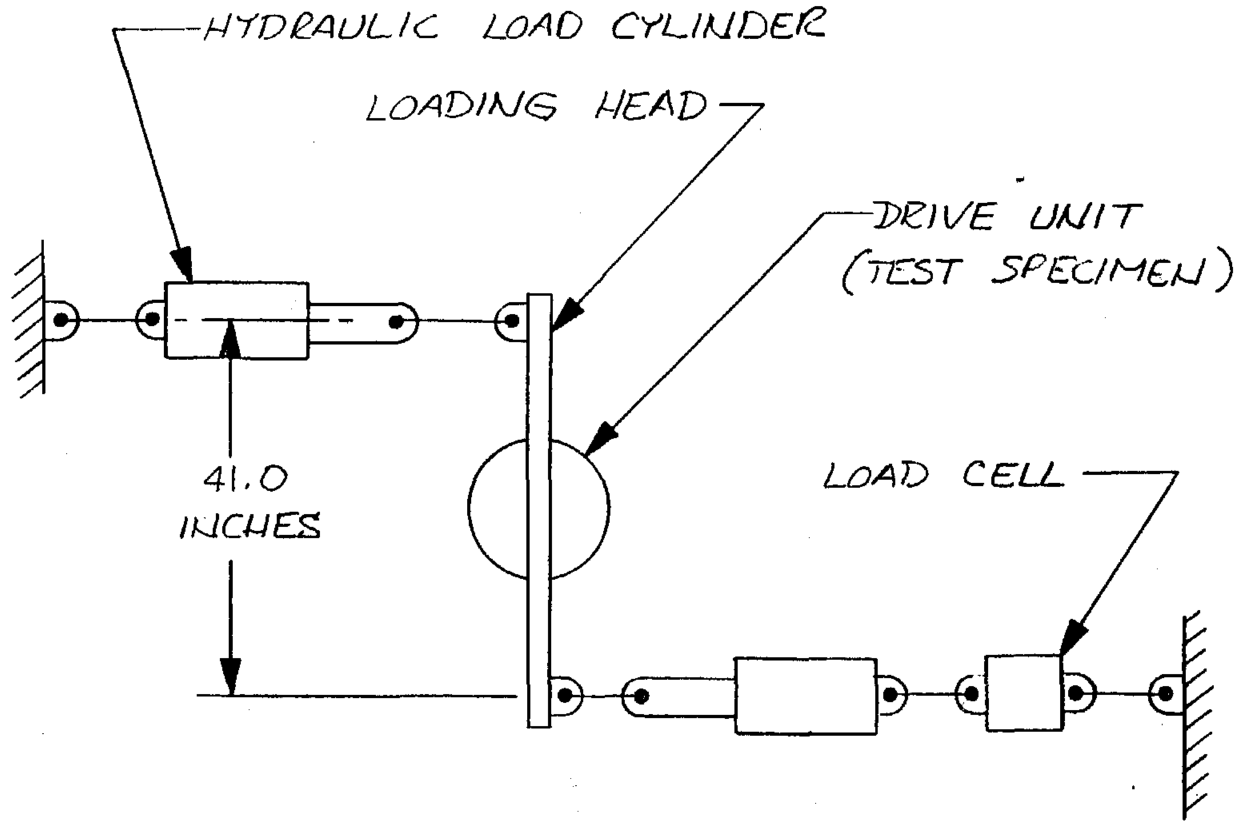


FIGURE 1

AZIMUTH DRIVE LIFE TEST SETUP



RATCHET AND EFFICIENCY TEST SET-UP

FIGURE 2

2. Efficiency Test

The objective of this test is to obtain actual operating efficiency data for the new azimuth drive unit. Using the same test set-up as in the ratchet test, apply 80,900 in-lbs and 40,000 in-lbs torque load. Drive the specimen with and against the torque load for approximately 20 seconds. Measure and record exact operating time, motor current, motor voltage and number of motor revolutions for each load level and each rotational direction.

3. Life Test

Perform an accelerated life cycle test to simulate the fatigue effects of 30 years of field use on the azimuth drive unit. Azimuth torque loads to be applied shall be based on wind loads versus percentage of time the loads are expected to occur. The wind loads were based upon a condensed wind speed frequency profile of Sandia Specification A10772, Appendix 1, and heliostat geometry. The life cycle test shall consist primarily of high load cycling to induce fatigue in azimuth drive components. The cycling at wind speed loads less than 18 mph were abbreviated because no contribution to azimuth drive fatigue was expected at these low levels. A 150,000 in-lb asymmetrical dead weight overturning moment shall be applied throughout the life test to represent loads equivalent to the heliostat with mirror oriented in a vertical plane. A cycle shall consist of a 72° maximum travel in each rotational direction ($\pm 36^{\circ}$ around south and back) with the final angular excursion adjusted to provide 10 minutes per cycle. Redundant limit switches shall be provided 45° on either side of center to provide a safety power cutoff in the event of a control system malfunction. A counter device shall be mounted on the specimen to accurately determine the actual number of cycles for each load level. The load test arrangement is designed to provide a peak torque load at one end of the specimen travel and a minimum load (near zero) at the opposite end. Adjust the weight magnitude and position to provide the required peak load. The test load schedule is divided to provide life test results in 10 year increments in order to establish when wear related failures present themselves. The load head shall be removed for visual inspection of the harmonic drive following the high wind conditions of the first 10 years of life and again completing approximately 15 years of life testing. During the two intermediate visual inspections, an input hysteresis test shall be performed. The loading sequence for the life test shall be in accordance with Table 1. Upon completing life test, remove load head and perform visual inspection and input hysteresis test.

4. Ratchet Test (Post Life Test)

Repeat ratchet test following completion of life test. Repeat torque levels specified to a minimum of 144,000 in-lbs or until ratcheting is observed. Measure and record actual applied torque loads for each direction of rotation.

5. Disassembly Inspection

Remove azimuth drive unit from pedestal and perform tear-down inspection. Provide photographic coverage of any significant findings. Note any wear or anomalous characteristics noted. Prepare silicone inspection molds of circular spline and flex spline for shadow graph analysis of tooth wear. Retain all test hardware for reassembly of unit for future testing.

TABLE 1

AZIMUTH LIFE TEST, LOADING SEQUENCE

Test No.	Approx. Peak Load (In-Lbs)	No. Test Cycles	Simulated Wind Speed Range	% of Simulated Life at Specified Load Level	Estimated Time Required
1	102,000	16	>32 mph	16%	2 Hrs., 40 Min.
2	60,000	50	27-32 mph	16%	8 Hrs., 20 Min.
3	42,000	430	18-27 mph	33%	71 Hrs., 40 Min.
4	19,000	800	9-18 mph	25%	133 Hrs., 20 Min.
5	5,000	500	0-9 mph	10%	83 Hrs., 20 Min.
6	60,000	50	27-32 mph	16%	8 Hrs., 20 Min.
7	102,000	32	>32 mph	33%	5 Hrs., 20 Min.
8	60,000	50	27-32 mph	16%	8 Hrs., 20 Min.
9	42,000	430	18-27 mph	33%	71 Hrs., 40 Min.
10	60,000	50	27-32 mph	16%	8 Hrs., 20 Min.
11	102,000	32	>32 mph	33%	5 Hrs., 20 Min.
12	60,000	50	27-32 mph	16%	8 Hrs., 20 Min.
13	42,000	430	18-27 mph	33%	71 Hrs., 40 Min.
14	60,000	50	27-32 mph	16%	8 Hrs., 20 Min.
15	102,000	16	>32 mph	16%	2 Hrs., 40 Min.
		2,986			497 Hrs., 40 Min.

Note: 100% of expected high wind conditions have been simulated for the 30 year life test.

TEST RESULTS

A. Ratchet Test

The azimuth drive unit successfully completed this demonstration of increased torque capability. The modified harmonic drive exhibited no ratcheting when driving with or against torque loads reaching 144,000 in-lbs. The actual test data is presented in Table 2. The loads were applied prior to driving the test specimen.

B. Efficiency Test

The azimuth drive output member was loaded to 40,000 in-lbs and 80,900 in-lbs. The load was maintained while the motor was driven against the load and with the load for 20 seconds. An electrical power meter monitored voltage and current to the motor. A counter was used to monitor the number of motor turns. The results of the efficiency test of the new harmonic drive reworked for 144,000 in-lb torque capability are presented in Table 3.

C. Life Cycle Test

Life cycle testing went according to plan without problems developing. The load sequence schedule was altered slightly, in that testing that should have ended at an inconvenient time was extended or shortened so that load level changes could be made during regular working hours. Excess cycles were subtracted from the next group of cycles for that particular load so that the total at completion would be correct. In one instance a short fall at 5,000 in-lb peak torque load (0-9 mph simulated wind speed range) was made up by performing additional cycles at higher load. The test plan called for conducting 2,986 cycles and precisely 2,986 cycles were accomplished. Refer to Table 4 for the actual azimuth life test history.

The loading head was removed after completing the first 10 years of life of the high wind load conditions. The gear oil in the harmonic drive section was clear with no evidence of metallic chips or wear particulate.

TABLE 2

RATCHET TEST - PRELIFE CYCLE TEST

Load Cell Force (LBF)	Actual Torque Applied (In-Lb)	Wind Speed* (MPH)	Drive Direction WRT Load	Results/Comments
2,580	105,800	42.9	Against	Rotation smooth, no ratcheting
2,870	117,800	45.3		
3,157	128,500	47.4		
3,305	135,500	48.5		
3,415	140,000	49.4		
3,525	144,500	50.1	Against	Rotation smooth, no ratcheting

Note A: WRT = "With Respect To"

B: Load cell force applied through a 41 inch moment arm.

C: Actual torque loads were applied prior to driving specimen.

*Equivalent wind speed at worst orientation.

TABLE 3

AZIMUTH DRIVE EFFICIENCY TEST

Load (In-Lb)	Time (Sec)	Motor Turns	Power In (In-Lb/Sec)	Power Out (In-Lb/Sec)	Efficiency (%)
40,000 In-Lb Against	20	600	2,213	174	7.8
29,000 In-Lb With	20	614	1,770	-	-
84,665 In-Lb Against	20	360	2,832	221	7.8
70,684 In-Lb With	20	393	1,770	-	-

TABLE 4

ACTUAL AZIMUTH LIFE TEST HISTORY

Planned Test No.	Peak Torque Load (In-Lbs)	Planned Cycles	Actual Cycles	Comments
1	102,000	16	16	
2	60,000	50	50	
3	42,000	430	522	Loading head removed and visual inspection and input hysteresis test performed.
4	19,000	800	830	
5	5,000	500	435	
6	60,000	50	50	
7	102,000	32	33	Loading head removed and visual inspection and input hysteresis test performed.
8	60,000	50	100	
9	42,000	430	575	
10	60,000	50	-	
11	102,000	32	32	
12	60,000	50	50	
13	42,000	430	225	
14	60,000	50	51	
15	102,000	16	17	Loading head removed and visual inspection and input hysteresis test performed.
		2,986	2,986	

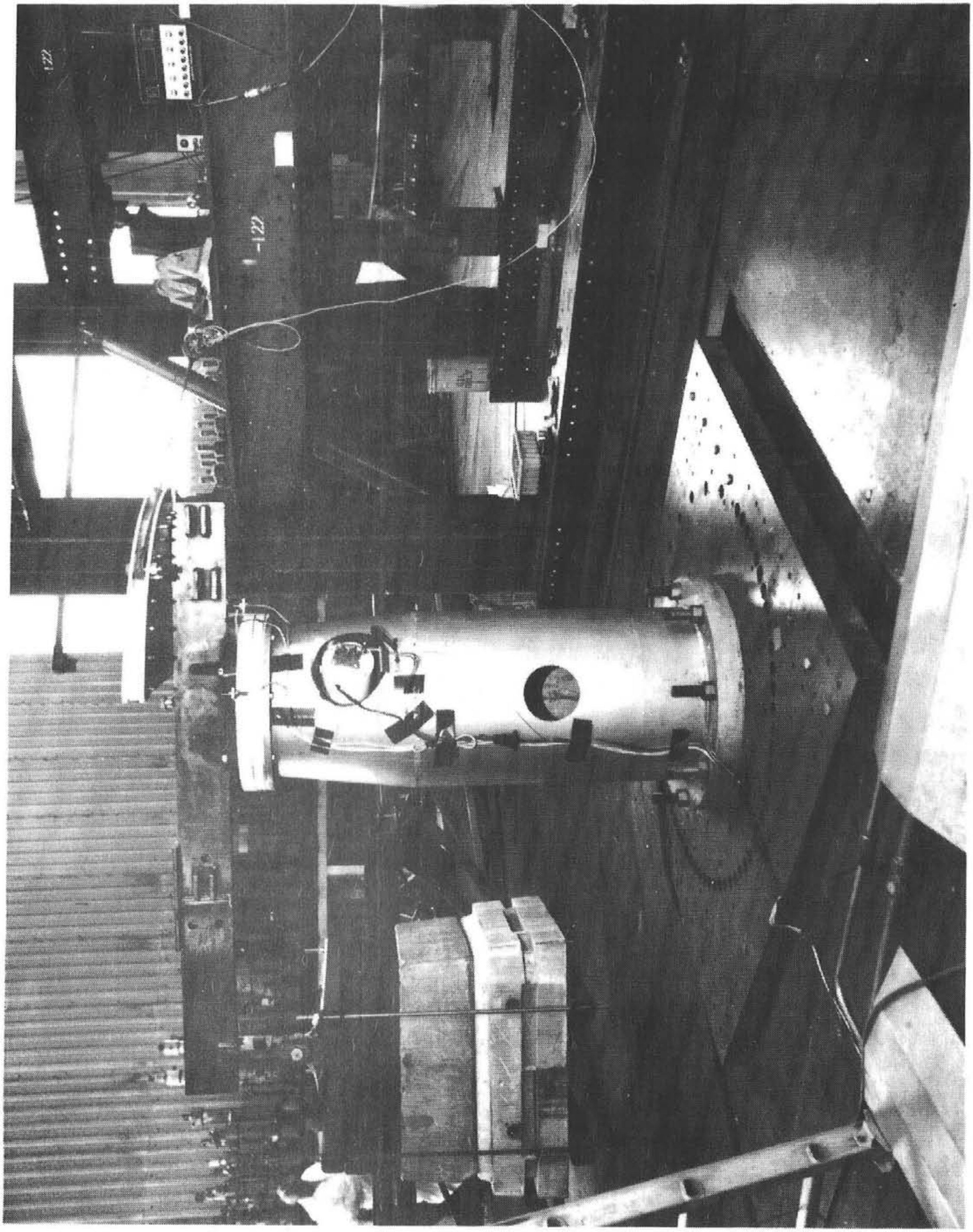


FIGURE 3 - TEST SET-UP

FIGURE 4 - TORQUE LOADING PENDULUM

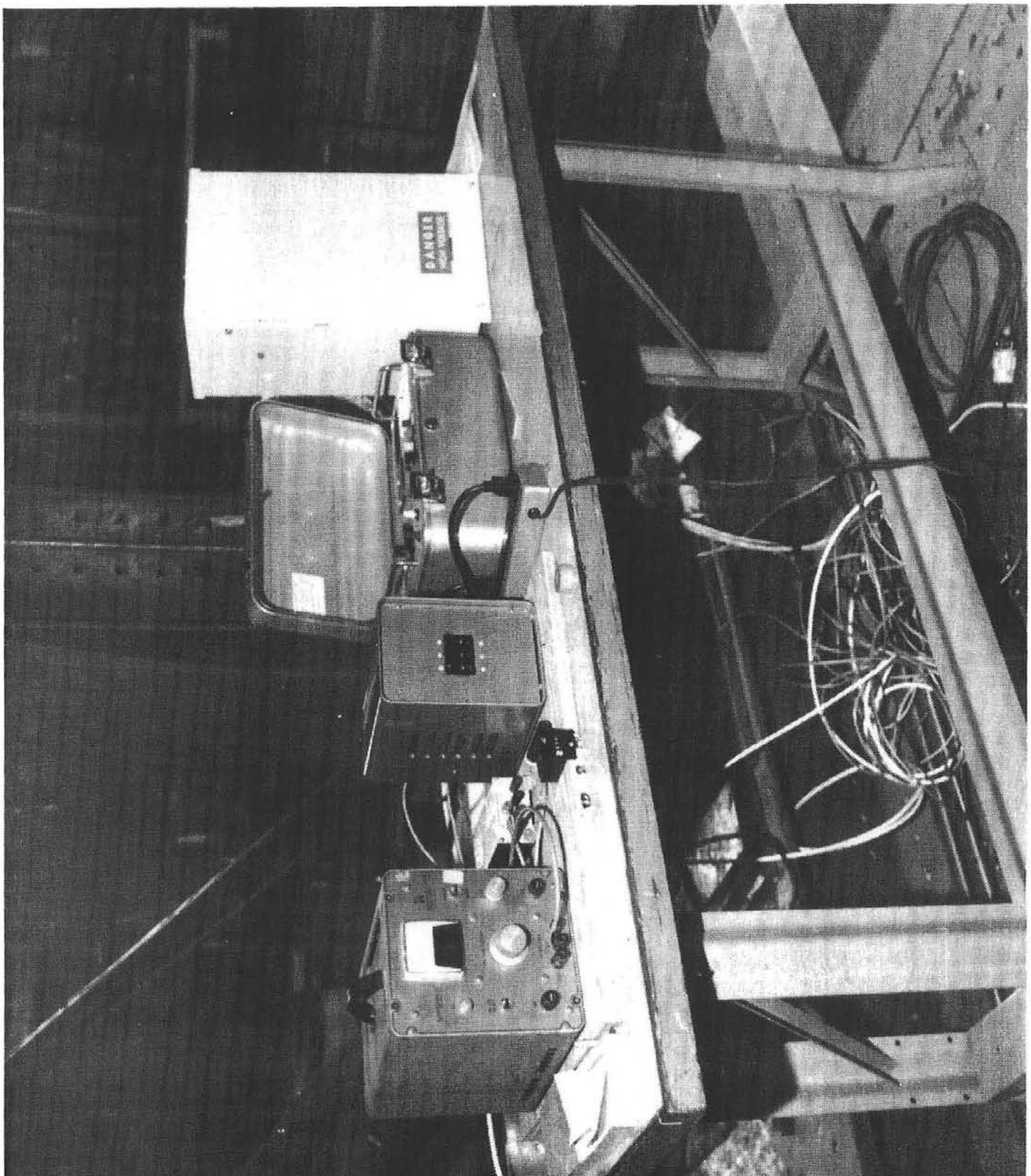


FIGURE 5 - ELECTRICAL DRIVE EQUIPMENT

During this inspection, it was noted that the oil level did not fully cover the flex spline/circular spline tooth engagement area. Interrogation of the assembly technicians indicated that they merely set the oil level slightly above the wave generator upper surface. In order to completely cover the tooth engagement area, the oil level was adjusted to 0.5 inches above the wave generator surface. It should be pointed out that harmonic drive teeth were fully wetted with oil due to capillary action even with the initial low oil level. An input hysteresis test was performed and measured to be 1.5 motor turns. This is in comparison with 1.0 motor turn measured prior to starting the life testing.

A second load head removal and harmonic drive inspection was made at approximately the 15 year point. All scheduled low wind condition cycles were completed and half of the high wind condition cycles. In terms of total cycles, 65% were completed. The oil in the harmonic drive was found to be blackened by grease which had worked its way up the annular area between the wave generator shaft and the lube pan tube. A bead of grease was found at the top of the wave generator shaft bushing. A sufficient quantity of the dark grease dissolved in the oil to create the discoloration observed. Mixing of the oil and grease does not pose a problem, in fact, during assembly of the harmonic drive, grease is packed in the annular area between the wave generator shaft and the azimuth drive support housing. The purpose of the grease in this area is to prevent wear particulate from entering the lower oil seals and provide a grease seal to prevent oil intrusion into the helicon gear set. The oil level was measured to be 0.5 inches above the wave generator surface indicating that no oil leakage was present. A magnet was placed in the oil bath to attempt to pick-up any metallic wear particles. None were found. The grease expansion chamber and motor were removed. No oil was found in the lower grease chamber. The grease appeared to be smooth and fresh and have a new appearance with no discernable discoloration present. No chips or metal contamination could be observed. The helicon gear looked excellent with no discernable wear pattern. The motor pinion was in excellent condition with a very polished and smooth tooth surface. The azimuth drive input hysteresis test was repeated and measured to be 1.8 motor turns.

No further interruption of the life cycle testing was made. After completion, the loading head was removed and visual inspection performed. The bead of grease at the top of the wave generator shaft increased in size and the oil showed continued trend toward darkening from the grease intrusion. A magnet passed into the oil bath picked up some metallic particles most probably coming from wear in the harmonic drive spline teeth. The oil level was measured and found to be 0.5 inches above the wave generator top surface indicating a stable level throughout the test. The input hysteresis test was repeated and resulted in 2.0 motor turns.

D. Ratchet Test (Post Life Test)

The azimuth drive unit successfully completed this demonstration of increased torque capacity. Due to the extremely good condition of the harmonic drive found during the post life visual inspection, the ratchet test objective of 144,000 in-lb torque capability was increased. The modified harmonic drive exhibited no ratcheting when driving against or with torque loads reaching 151,500 in-lbs. The actual load levels are presented in Table 5.

E. Disassembly Inspection

The azimuth drive was removed from the pedestal and routed to the assembly area where functional parts were observed for wear.

1. Azimuth Drive Unit

The drive unit wire race bearing retainer bolts were torque striped prior to starting test. All sixteen bolts maintained the installed position without any evidence of torque stripe misalignment following the 30 year life test.

TABLE 5

RATCHET TEST - POST-LIFE CYCLE

Load Cell Force (LBF)	Actual Torque Applied (In-Lb)	Wind Speed* (MPH)	Drive Direction WRT Load	Results/Comments
2,440	100,000	41.7	Against	Rotation smooth, no ratcheting
2,980	122,100	46.1	Against	
2,780	114,000	44.5	With	
3,080	126,400	47.0	With	
3,240	133,000	48.1	Against	
3,315	136,300	48.8	With	
3,330	136,700	48.8	With	
3,560	146,000	50.5	Against	
3,525	144,500	50.1	With	
3,695	151,500	41.4	Against	
3,650	149,800	51.1	With	Rotation smooth, no ratcheting

Note A: WRT = "With Respect To"

B: Load cell force applied through a 41.0 inch moment arm.

C: Actual torque loads were applied prior to driving specimen.

*Equivalent wind speed at worst orientation.

2. Motor/Pinion/Helicon Gear

The motor performed satisfactorily throughout the life test. No disassembly of the motor was performed because the unit would require return to the supplier, Emerson Electric, for reassembly. The pinion and helicon gear were in excellent condition following the life test. The pinion had a very polished appearance with no evidence of pitting. The helicon gear was found in excellent condition without any significant wear pattern evident on the teeth for either direction of rotation. These units will be used as is when the azimuth drive unit is reassembled for future testing. Refer to photographs presented in Figures 6, 7 and 8 for close-ups of the noted components.

3. Grease

The grease (Shell Alvania EP) in the lower azimuth drive chamber appeared to be in excellent condition. The texture was smooth without any evidence of overheating. No discoloration or oxidation was found. Sufficient grease was available for lubricating the helicon gear set and no evidence of chips or wear particles could be found. No evidence of oil from the harmonic drive was found in the grease chamber.

4. Wire Race Bearing

The wire races were found to be highly polished in the loaded areas. The surfaces were highly burnished from the repeated ball travel and had an appearance similar to a decorative chrome plate. No evidence of pitting or surface failure could be detected. The back sides of the races and grooves that they rested in also showed some burnishing. The burnishing was a surface leveling of the machining on the new parts and most probably the result of the high loads during the ratchet test and the superimposed overturning moment applied throughout the 30 year life test. No pitting or surface failure was found. The wire race bearing balls were in good condition with slight scratches

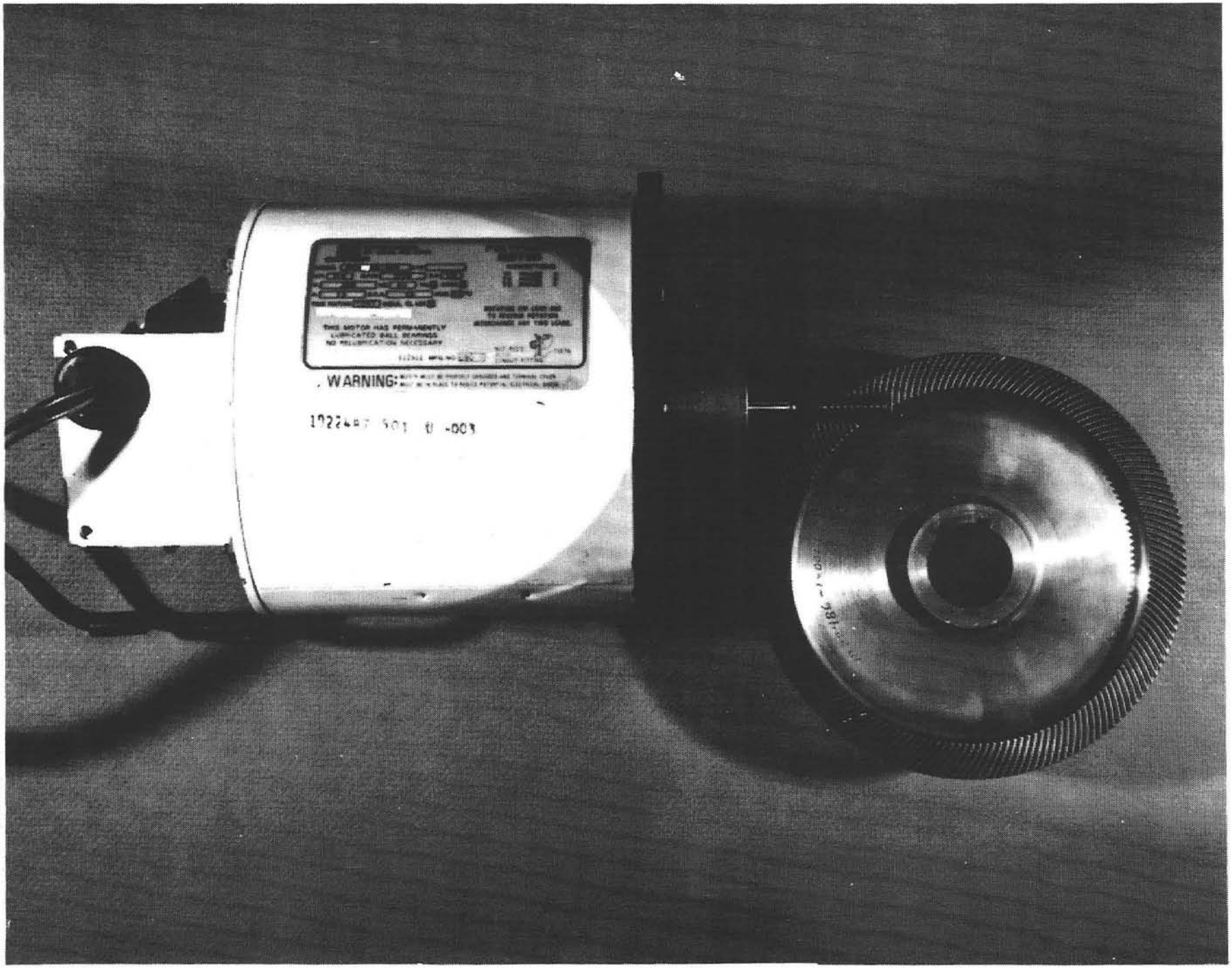


FIGURE 6 - MOTOR AND HELICON GEAR SET

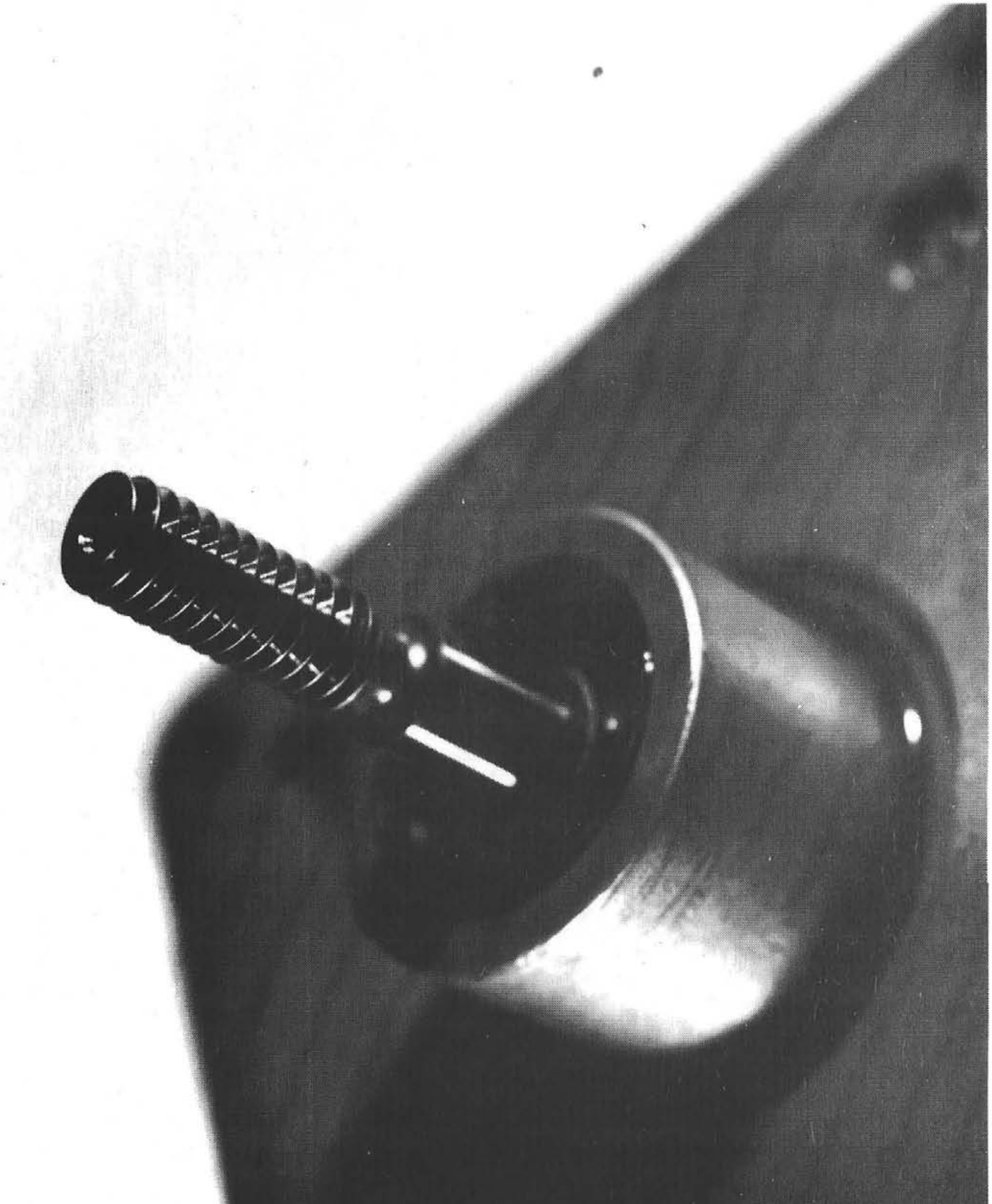


FIGURE 7 - HELICON PINION GEAR

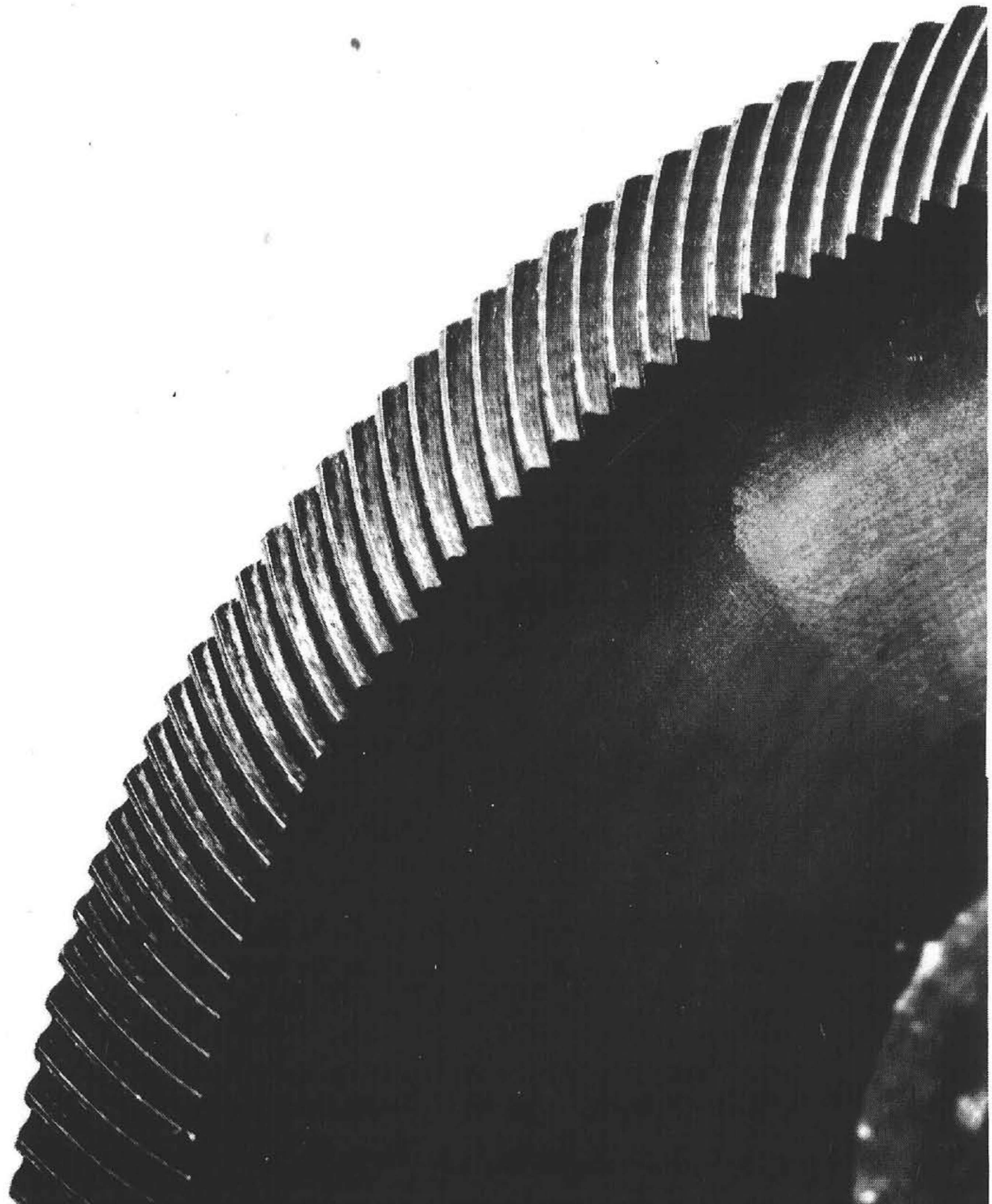


FIGURE 8 - HELICON GEAR

on their surfaces. The scratches are most probably caused by ball-to-ball rubbing seen in previous tests conducted on the wire race bearing. The overall condition the wire race bearing and related components is good and these parts will be installed in the azimuth drive unit for future testing. Post life details are shown in Figures 9, 10 and 11.

5. Oil

The oil in the harmonic drive section was discolored due to grease working its way up the wave generator shaft. Some metallic wear particles could be extracted from the oil by using a magnet. The metallic particles were very fine in size, but not present in large numbers. The metallic content appears to be consistent with the wear found on the circular spline. After draining the oil, very few metal chips were found in the bottom of the oil chamber indicating that most of the metal chips were sufficiently fine to be held in suspension by the oil. The predominant contaminate on the bottom of the oil chamber was polyurethane varnish from the wood blocks used to reduce the oil quantity in the chamber.

6. Harmonic Drive

The flex spline teeth were in excellent condition with practically no evidence of wear. Silicone molds of the splines were obtained and sectioned slices were projected on a shadowgraph. Refer to photographic coverage in Figures 14 and 15 for flex spline details. The respective slices were obtained .25, .50 and 1.00 inches down from the top of the flex spline as shown in Figure 13. No readily discernable wear can be seen. The flex spline/wave generator interface looked good. The contact area was burnished, but no deep grooves or other damage were found.

The circular spline photos in Figure 16 shows a slight narrowing of the spline teeth approximately .375 inch from the top. The top .25

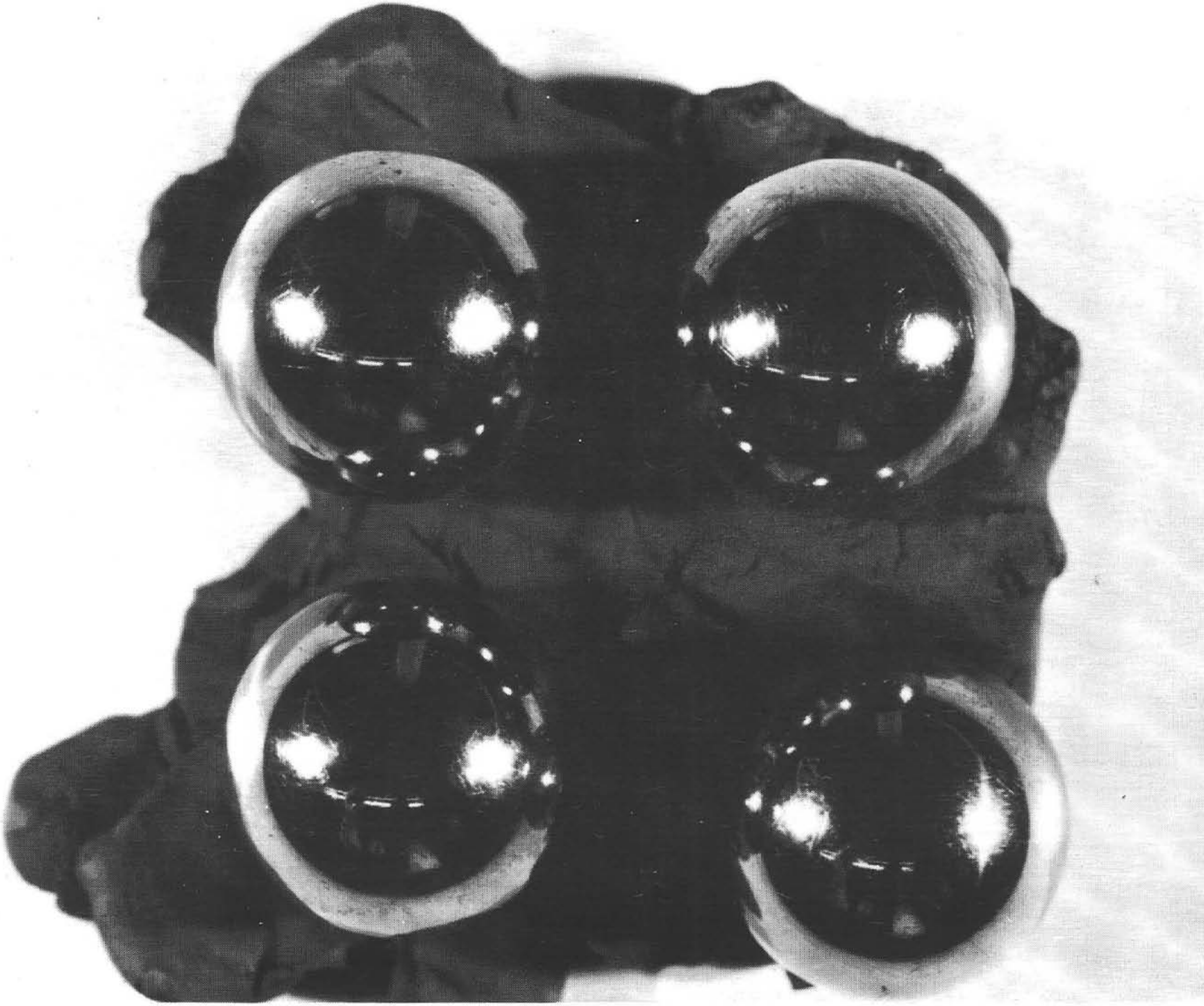


FIGURE 9 - TYPICAL WIRE RACE BEARING BALLS

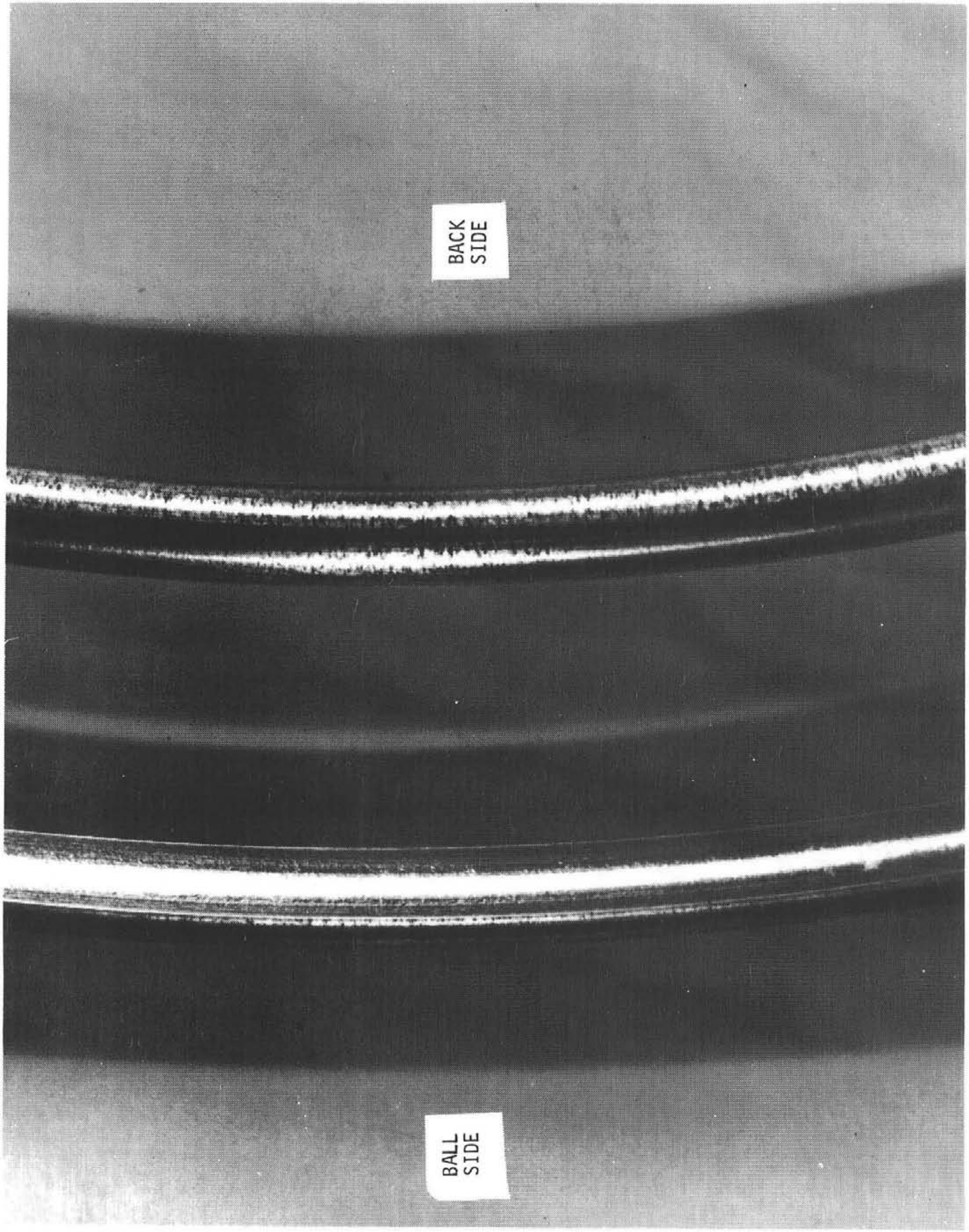


FIGURE 10 - WIRE RACES

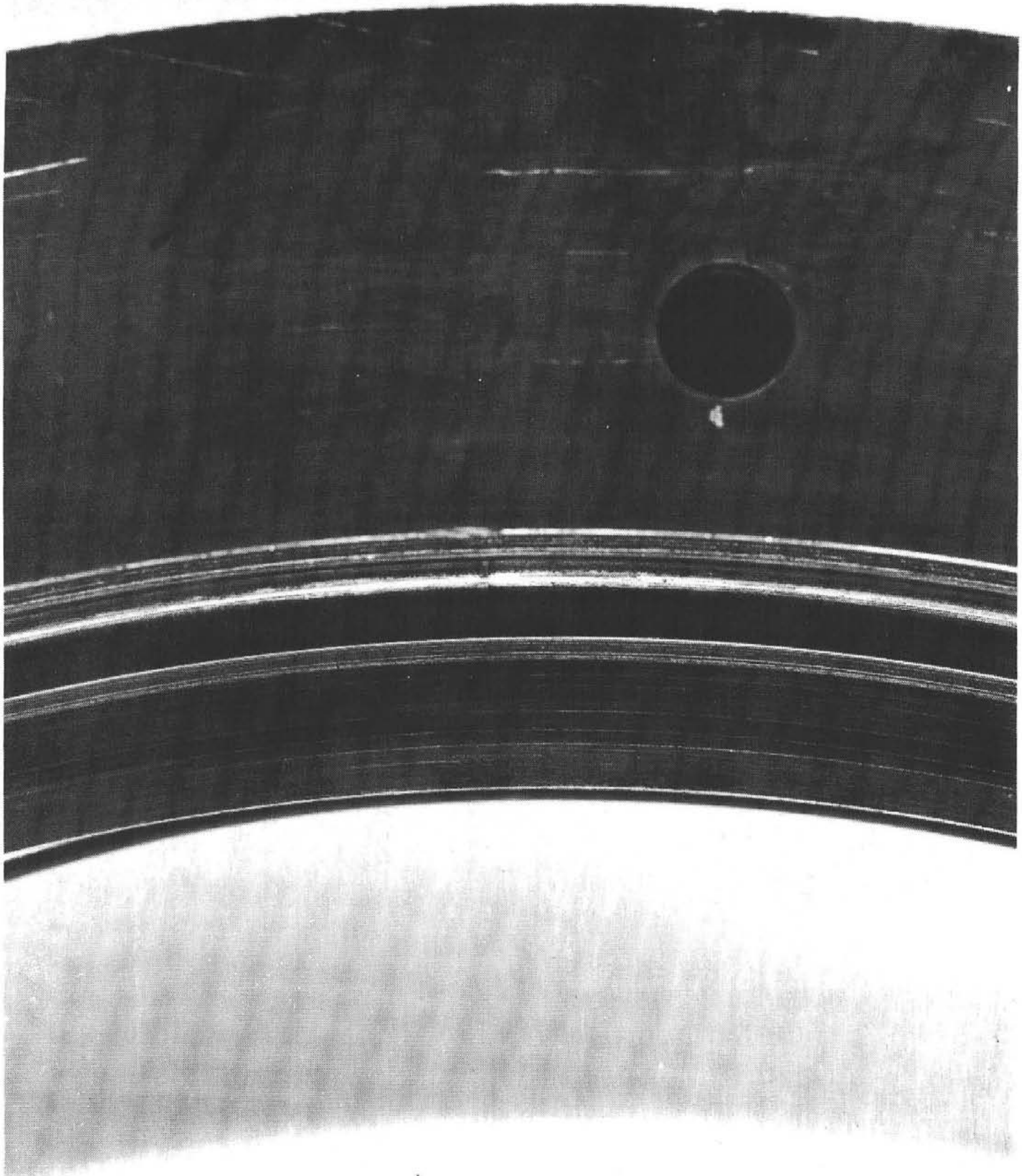


FIGURE 11 - WIRE RACE RETAINER GROOVE

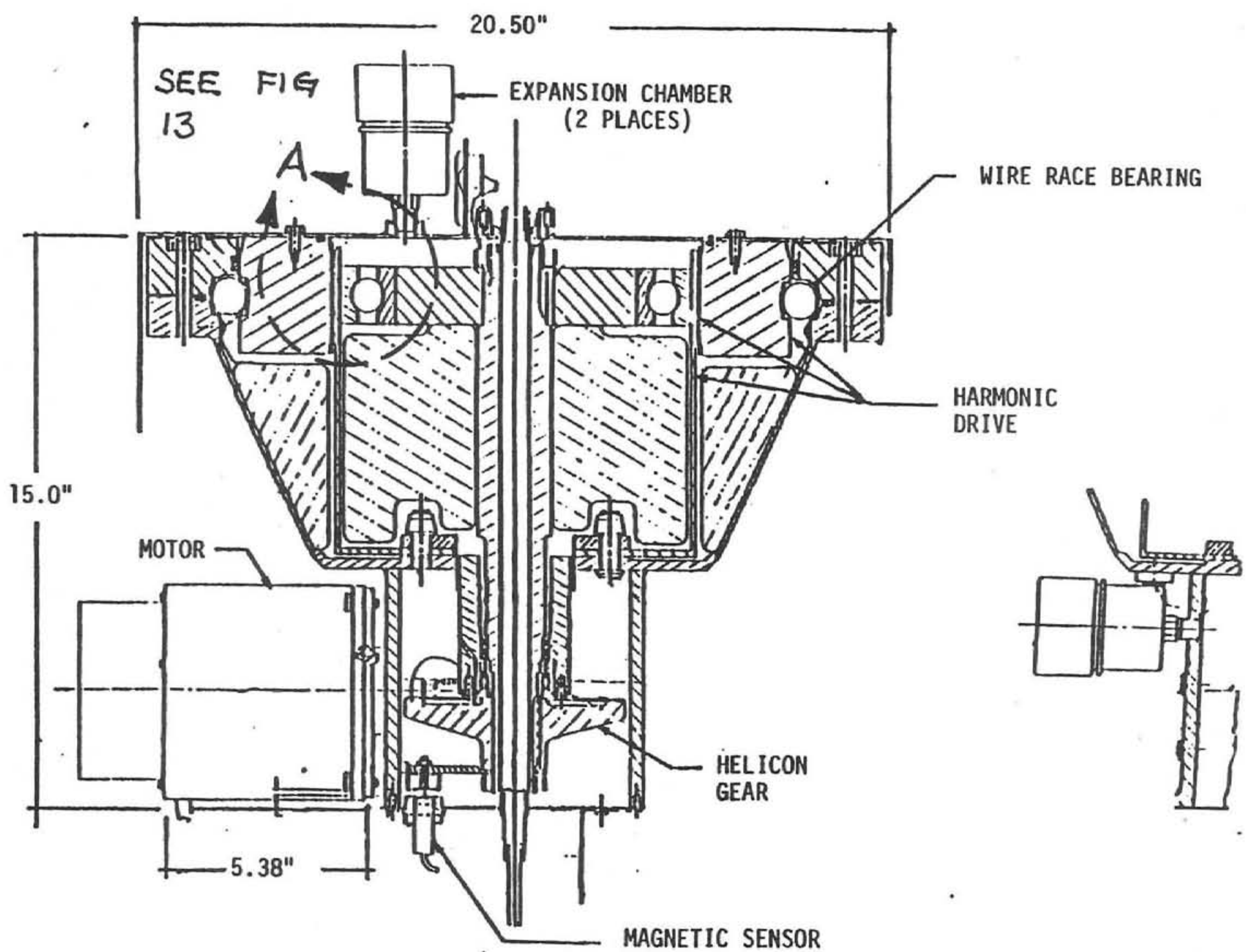
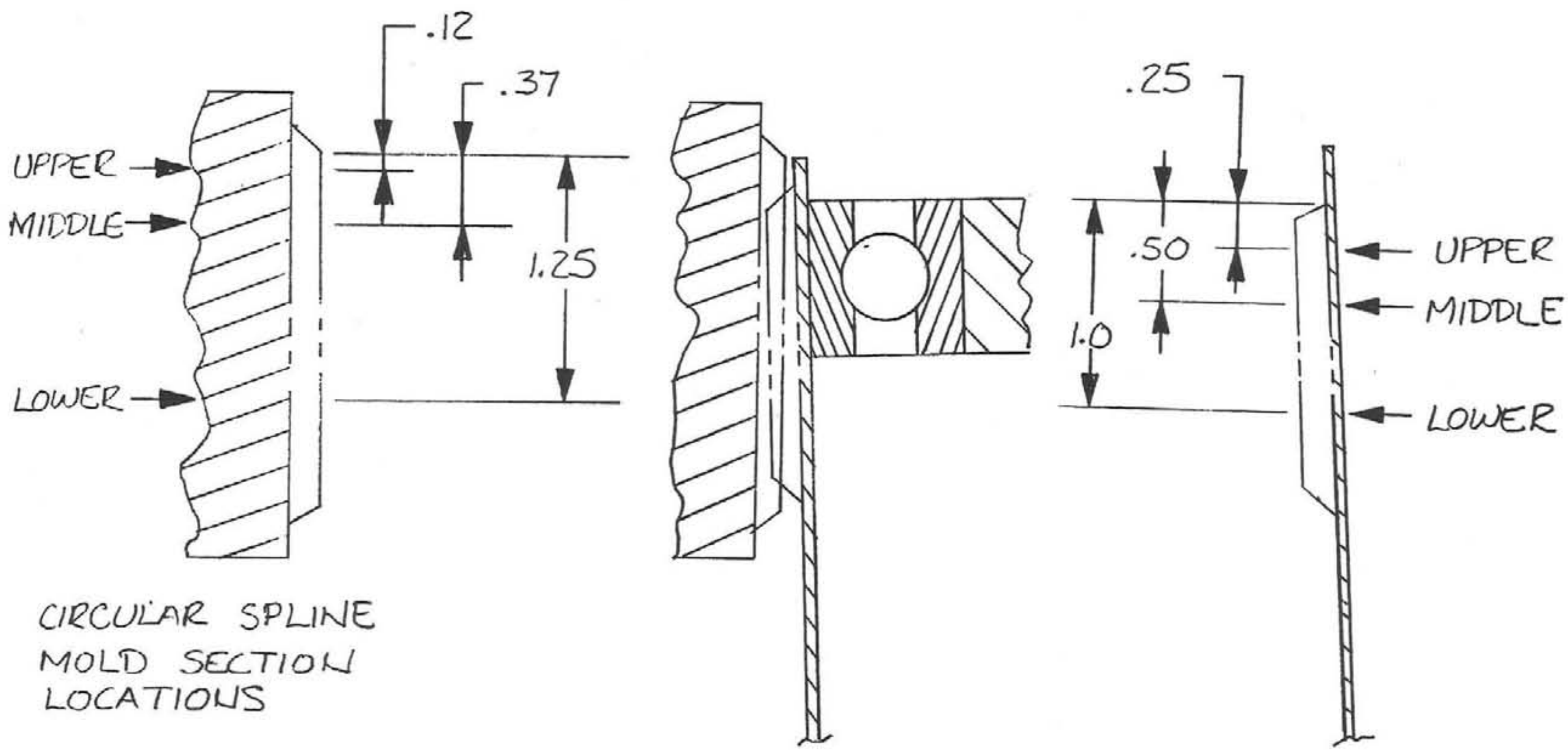


FIGURE 12 AZIMUTH DRIVE CROSS SECTION



CIRCULAR SPLINE
MOLD SECTION
LOCATIONS

DETAIL A FROM
FIGURE 12.

FLEXIBLE SPLINE
MOLD SECTION
LOCATIONS

MOLD SECTION LOCATIONS

FIGURE 13

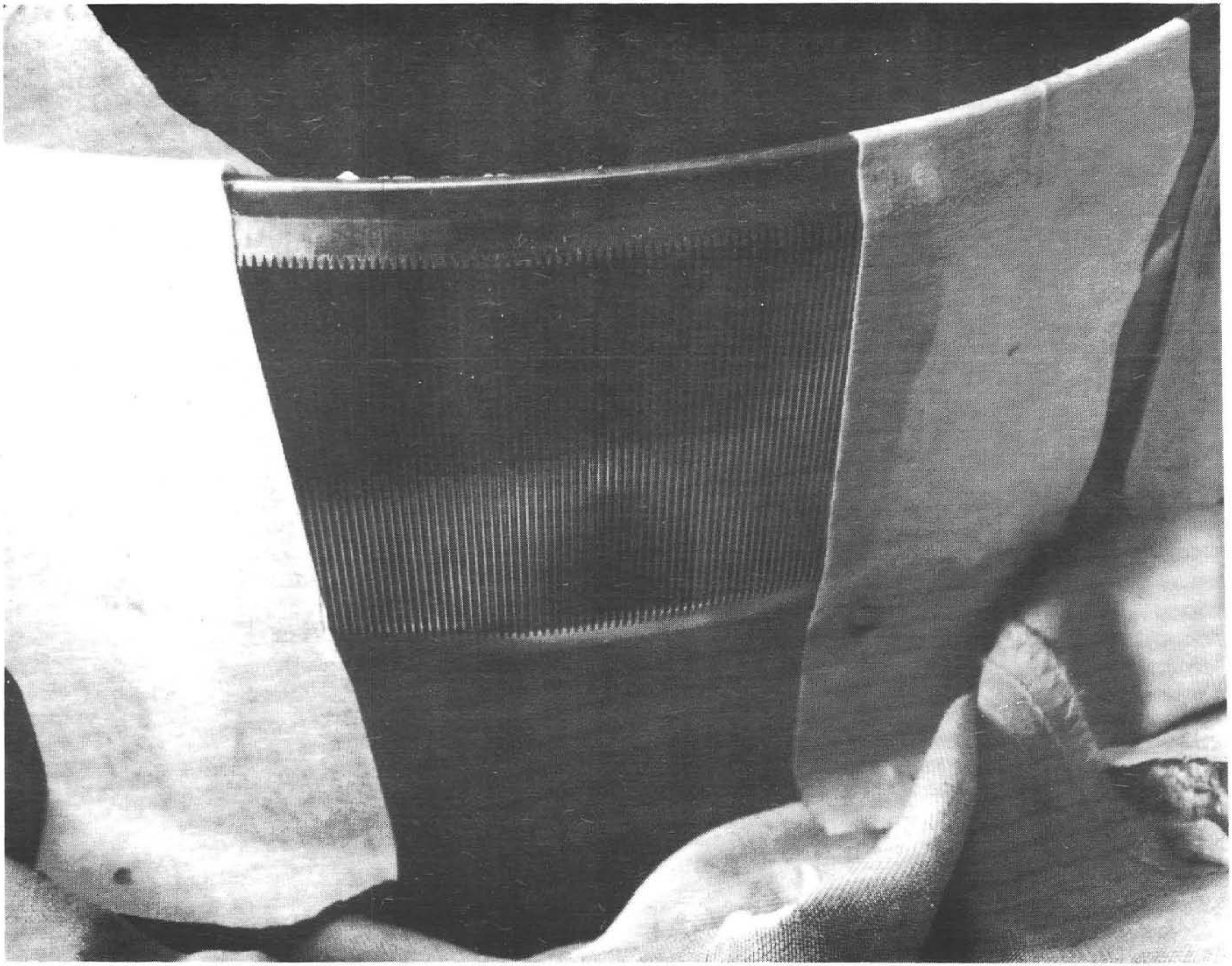


FIGURE 14 - FLEX SPLINE (POST LIFE CYCLE)

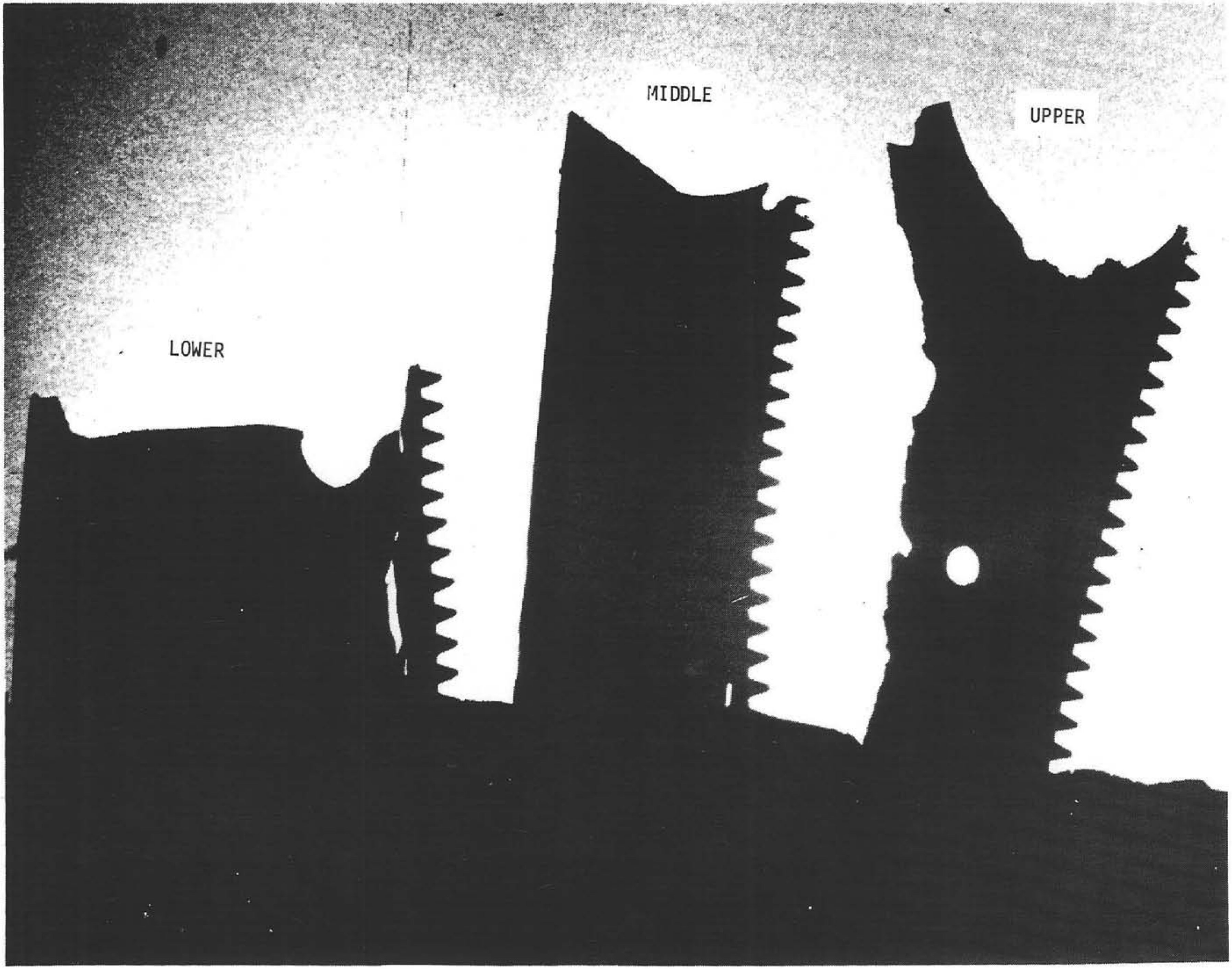


FIGURE 15 - FLEX SPLINE MOLD SECTIONS

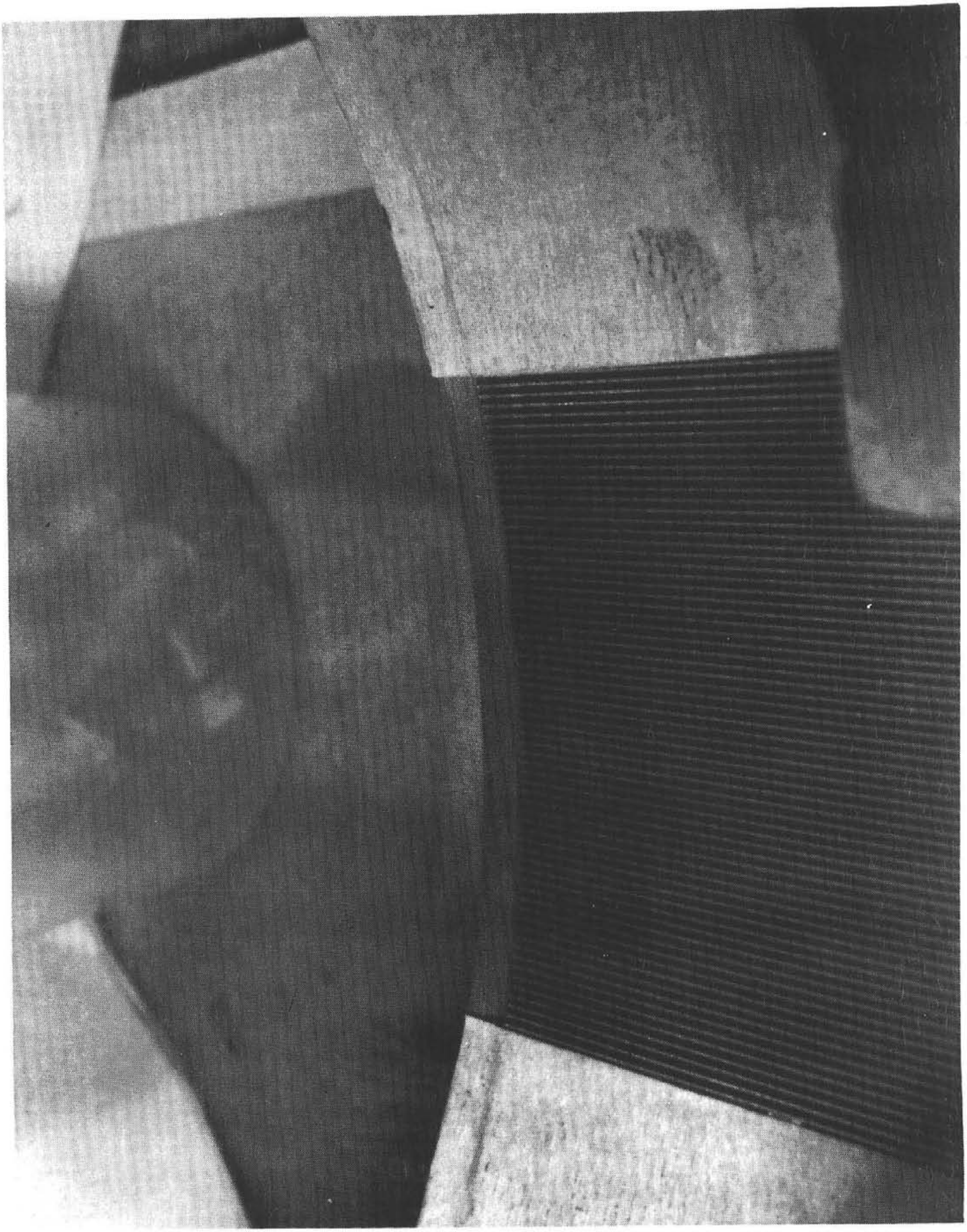


FIGURE 16 - CIRCULAR SPLINE

inch of the circular spline is not in mesh with the flex spline and represents no wear. The shadowgraph sections in Figure 17 are taken .12, .375 and 1.25 inches from the top of the circular spline. The .12 inch slice represents the control since no wear is achieved at this point. Comparison of the .12 slice with the .375 inch slice shows some narrowing of the spline teeth. The .375 inch slice should show the greatest wear because this area achieves the greatest deflection and highest load. The slight wear observed suggests that considerable life remains in the harmonic drive.

The wave generator anti-friction bearing was in excellent condition. The ball separator, balls and races did not show any damage and are satisfactory for further testing.

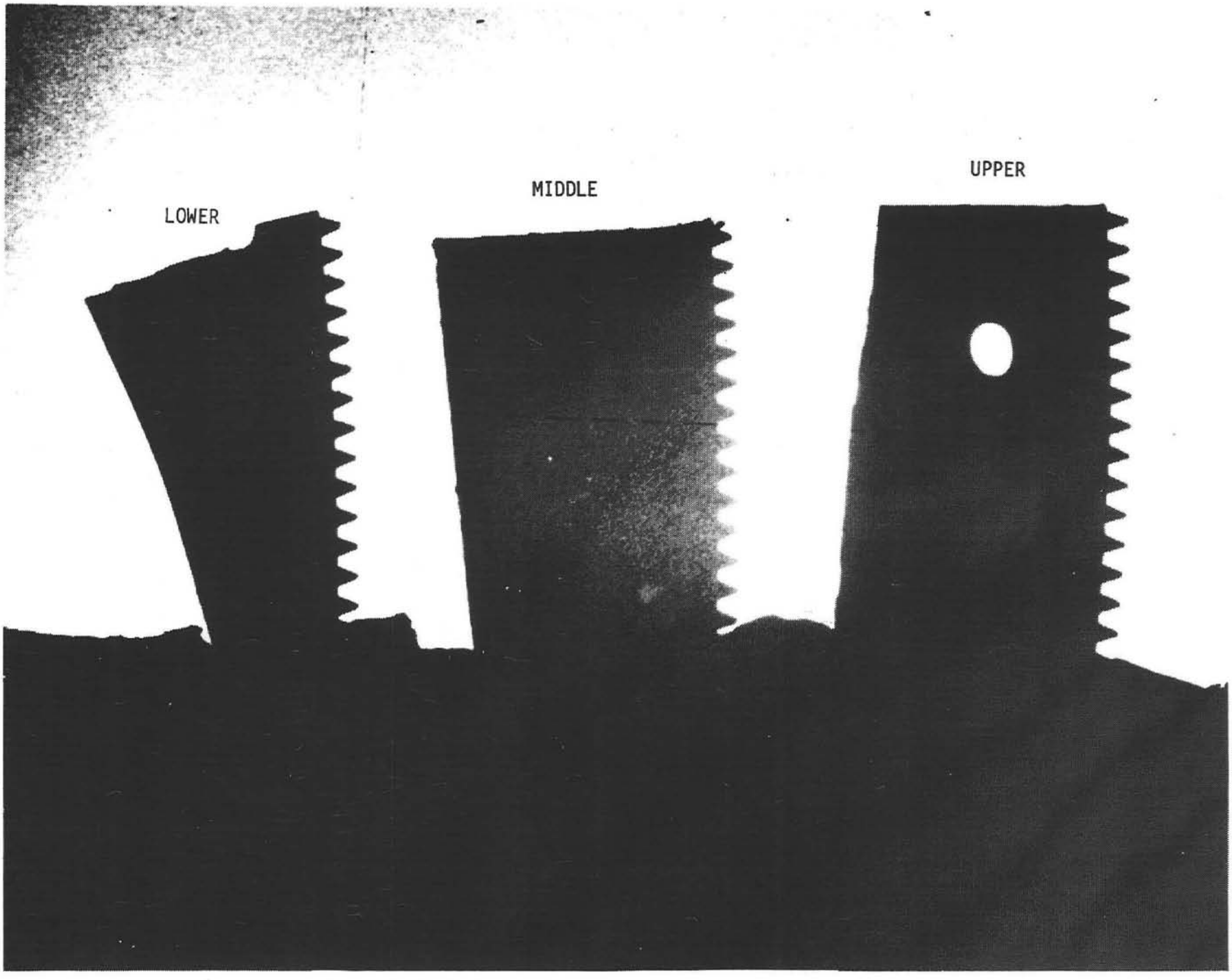


FIGURE 17 - CIRCULAR SPLINE MOLD SECTIONS

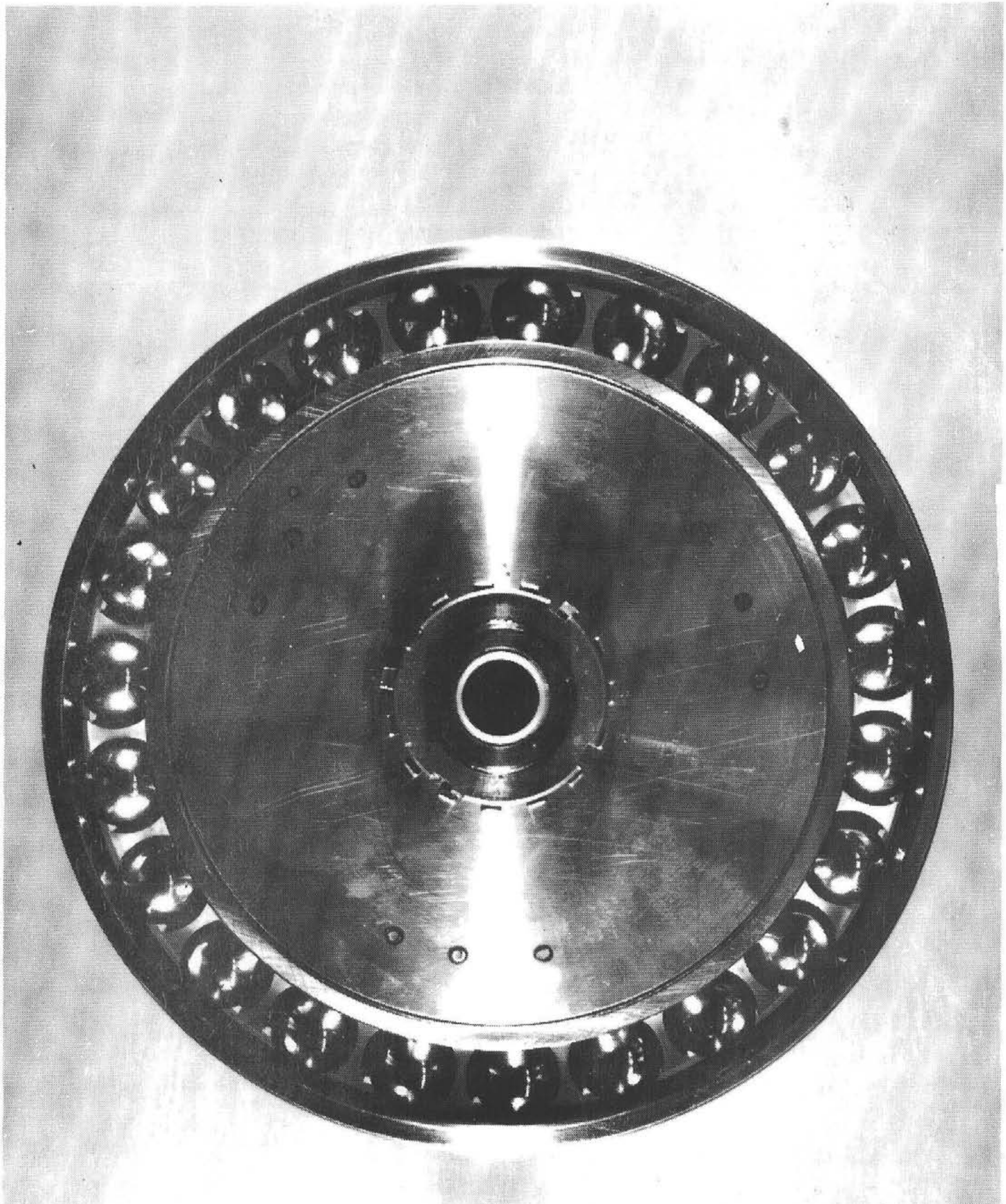


FIGURE 18 - WAVE GENERATOR

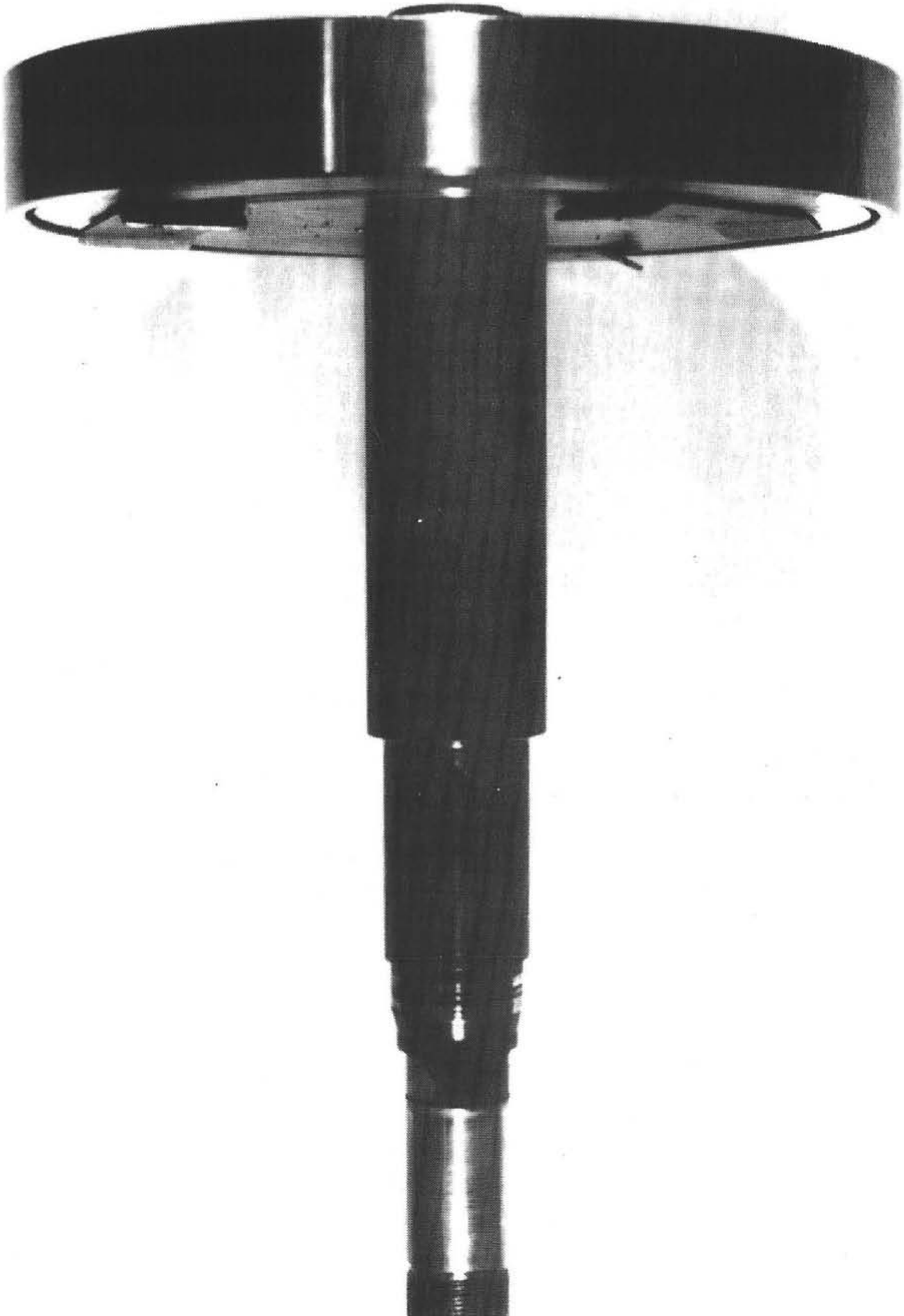


FIGURE 19 - WAVE GENERATOR (PROFILE)

CONCLUSIONS

Based upon the preceding test results, the following conclusions are offered.

1. Testing of the azimuth drive unit has demonstrated the integrity of the design and performance of the assembly meets all specified requirements.
2. The ratchet test prior to the life cycle verified increased operational torque capability of 144,000 in-lbs (50 mph wind speed).
3. The azimuth drive successfully completed the 30 year life testing. Post test inspection of all parts showed them to be in excellent condition with considerable life remaining.
4. The azimuth drive successfully demonstrated greater than 150,000 in-lb operational torque capability (51.4 mph wind speed) following the 30 year life cycle test.
5. The motor/pinion/helicon gear were found in excellent condition in the post test inspection. These parts had been previously used in the heliostat at MDAC Huntington Beach and CRTF. The prior heliostat testing had an accumulated life exposure of approximately 10 years and following the 30 year life cycle exposure, these parts had demonstrated 40 year life capability.
6. The maximum overturning moment applied throughout the 30 year life cycle test yielded a second wire race bearing life test. All parts of the wire race bearing were in excellent condition as noted in the post test inspection.

MCDONNELL DOUGLAS

TEST REPORT

ELEVATION ACTUATOR, MDAC SECOND GENERATION HELIOSTAT

1 AUGUST 1981

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Approved by: R. K. Knowles
Chief Program Engineer
Solar Collector Subsystems

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INTRODUCTION

The design of the McDonnell Douglas Astronautics Company-Huntington Beach (MDAC-HB) Second Generation Heliostat employs a ball screw actuator which provides elevation control of the mirror surface position. The elevation actuator is supplied by the Duff-Norton Company with the screw, ball, and nut components being supplied by the Saginaw Steering Gear Division of General Motors.

Accelerated life testing was conducted on the elevation actuator screw, recirculating balls and nut in order to obtain test information on life expectancy for various ball screw configurations. Testing was initiated as a result of inspection of the current configuration actuator following heliostat life cycling at MDAC-HB and CRTF Albuquerque, New Mexico, which showed some pitting on the screw after the cycling. The cycling equated to approximately 10 years of service life and the pitting was relagated to a small portion of the screw that corresponded to the high load area. No failure was experienced with the actuator, however, the pitting did provide questions as to the margin/ability to meet the 30 year life requirement. Hence, testing on the current and alternate configurations was initiated to provide a better assessment of the life expectancy and to provide a recommended configuration of ball, screw and nut that would be demonstrated to meet the 30 year life requirement.

Testing was conducted at the Saginaw Steering Gear Division of General Motors. Testing was successful and resulted in a recommended configuration that is interchangeable with the current design. This report details the results of that test activity.

SUMMARY AND CONCLUSIONS

Several ball, screw, and nut configurations were life cycle tested and evaluated for use in the elevation actuator for the MDAC-HB designed Second Generation Solar Heliostat. The ball, screw, and nut are half of the two-stage elevation actuator which provides position control of the mirror assembly. The evaluation testing consisted of:

1. Evaluation of lubrication on life.
2. Evaluation of ball screw race hardness on life.
3. Evaluation of screw diameter on life.

A total of eight test configurations were run and a detailed discussion of each test is provided in the following text. A summary of the results and conclusions, based on the test results of this activity, are as follows:

- A 1½" diameter 4150 screw provides significant margin against pitting over the 1¼" diameter screw employed in the original design.
- Test results showed that the recommended 1½" diameter 4150 rolled screw with the ground nut provided operational life in excess of 30 years for all three components.
- Test results did not show any significant difference between the lubricated system and a non-lubricated system. It did show that the felt wiper lubrication method worked very satisfactorily and, therefore, was retained in the recommended design configuration.
- As expected, a ground nut is required to guarantee the ball fatigue life as opposed to a tapped nut.
- While the testing did not show a clear relationship of reduced pitting with increased material hardness in all cases, the increased hardness of RC58 minimum in the recommended configuration is a further improvement over the original configuration.

- Recognizing the limited ability of accurate theoretical analysis for this fatigue problem, the theoretical data was in harmony with the test results and the maximum calculated Hertz stresses for the recommended 1½" diameter screw are less than the calculated Hertz stresses where pitting occurred on the original 1¼" diameter screws utilized at CRTF.

BACKGROUND DISCUSSION

In February 1981, the elevation actuator from Heliostat #1 was disassembled. The prototype actuator had undergone testing at MDAC-HB and Sandia Central Receiver Test Facility (CRTF). The unit had accumulated over 3,300 operating cycles which is the equivalent of 10 years service life. The life requirement for the elevation actuator is 30 years.

Disassembly of the prototype unit revealed pitting of the ball screw at the extend end. The highest actuator loads are encountered when the unit is fully extended or when mirror normal is horizontal which corresponded to the pitted area of the screw. The load is primarily a gravity load of the mirror assembly and is approximately linear throughout the actuator stroke. With the mirror face up, the load is zero, and with the mirror vertical the maximum load is 8,500 pounds.

The ability of the elevation actuator to meet the 30 year life requirement was discussed with Duff-Norton Company (actuator supplier to MDC) and Saginaw (ball screw and nut supplier). The peak high loading associated with the present application was beyond the experience of Saginaw and no substantive data was available to make an unqualified recommendation on the proper method of increasing life. An evaluation test program was established as the best means of testing possible candidates for improving ball screw life. The items selected for improving life were:

1. Ball Screw Surface Hardness

   The wear life of bearings and gears generally improves when harder materials are used in contact. The 4150 steel material used by Saginaw to make the ball screw is induction hardened to RC56 minimum. The test plan included evaluation of 4150 screw material hardened to RC60 in order to find an optimum hardness.

2. Lubrication

   The ball screw is delivered with a manganese phosphate treatment which serves a role in lubrication. Also, the elevation actuator is filled with Mobil SHC-630 lubricating oil upon installation in the heliostat. In operation the lubricating oil congregates toward the motor end of the elevation actuator. The ball nut receives lubrication only when retracted (no load end of stroke) and no requirements exist as to how often the actuator is retracted. The actuator, as presently designed, did not incorporate a positive lubrication feature. It was desired to obtain definitive information as to whether a method of positive lubrication was needed and whether positive lubrication would substantially increase life.

3. Ball Screw Diameter

The standard rolled thread screw is available in different diameters while maintaining the same lead. A larger diameter screw permits more balls to carry the load and thus reduce contact stresses. A larger diameter screw also requires the balls to make more revolutions per screw turn increasing the required ball inches traveled. Increased life requires a balanced design in which the screw, nut and balls have a suitable life for the required duty cycle.

4. Screw Material

The nut material is 8620 steel that is case carburized to RC60-62. The fact that the nut never experienced pitting failure lead to the possibility of using this material for the screw in order to increase life.

While 8620 steel was considered a candidate in the early phases of this investigation, and in fact two 8620 screws were fabricated, it turned out that the 8620 material was not a cost effective solution to the problem. Heat treatment, subsequent straightening and lead match of screw and nut with 4150 material are standard processes with Saginaw and permit a suitable configuration with a rolled screw. Characteristics of the 8620 material and resulting processes for heat treat, carburizing and maintaining screw straightness required additional processes, over that needed for 4150 material and would require a ground screw configuration to obtain the required straightness. As a result, a viable 8620 configuration is significantly more expensive and was dropped as a candidate solution.

DETAILED TEST RESULTS

The overall test results summary is contained in Table 1 and may be used in conjunction with the detail test summaries that follow.

Cycles, as defined in this test report, shall mean one elevation actuator extension and retraction under a tension load. This means that only the tension side of the screw is used for wear evaluation which is precisely the way the elevation actuator is used in a heliostat application.

The Saginaw test equipment loads the ball screw in tension for half the stroke and in compression for the return stroke. Therefore, Saginaw applied twice the number of cycles, per their count, in order to duplicate an actual cycle as experienced by a field installed unit. Table 1 records the actual imposed test loads for each travel direction, however, only the tension flank results are appropriate and reported in the detailed test summaries for the elevation actuator.

Test 1

This test incorporated a felt wiper for lubrication of the ball screw and nut. Lubrication was performed at test start and again at 2,250 cycles.

Results: This test was aimed at duplicating the CRTF screw problem under laboratory test conditions. The screw exhibited heavy pitting on tension flank at 3,300 cycles, similar to the CRTF screw. The addition of a positive lubrication scheme did not improve ball screw life.

Test 2

This test maintained the use of the ball screw and nut lubrication system as the same nut was to be used. The screw hardness was changed from RC55 to RC60. The load was also reduced to correspond to possible elevation system kinematics revisions to reduce actuator loads and thus increase life.

Results: The felt wiper was oiled at test start at 1,000 cycles and again at 2,400 cycles. The tension flank exhibited light pitting after 3,390 cycles even with the tension load reduced from 6,600 pounds to 5,000 pounds. It appears that broad spectrum approach of (1) lubrication, (2) increased screw hardness, and (3) reduced load, would not produce the desired life increase. The same nut was used for Test 1 and 2. The nut had completed 6,690 cycles and looked very good with only slight pitting observed. It was felt that the 30 year goal or 10,000 cycles could be obtained and that the nut was not a problem. The balls, since they are loaded in each direction, require only 5,000 cycles to reach the 30 year goal. The balls were in very good condition following both tests and were estimated to have sufficient life. The problem of life appears to be solely screw related as the other components performed well.

Test 3

This was the first test of a 1½" diameter screw. Conditions for this test were the same as Test 2, namely:

a. Reduced load of 5,000 pounds tension.
b. Screw hardened to RC60.
c. Lubrication wiper used.

An additional configuration variation was made due to time limitations. A production nut was used that was a tapped thread rather than a ground thread. The life of the ball screw is appreciably extended when a nut is ground to the screw lead as currently practiced by Saginaw. Use of a tapped nut will not produce representative test results, but if the balls remain undamaged will allow comparative assessment of the screw life. Increased screw diameter appears to afford a solution to reducing screw pitting.

Results: The screw exhibited no pits or problems. Based upon Test 3, the screw size diameter increase exhibited promise with regard to extending life. This test was terminated at 3,377 cycles when pitting was observed in one circuit of the nut.

Basically, Tests 1 and 4 were aimed at duplicating the CRTF problem and evaluating the effects of the selected life improvement candidates. The subsequent testing was aimed at developing a method and then demonstrating a 30 year life capability.

Test 4

This test returned to the original conditions that the present evaluation actuator encounters. The peak tension load was increased to 8,500 pounds in order to simulate the mirror assembly dead weight in the worst condition. The lubrication system was eliminated to provide a worst case test. No lubrication was used other than grease used in assembling ball in the nut tracks. The screw was actually wiped clean after 2 cycles. The original 1¼" diameter and RC55 hardness ball screw was utilized in order to establish a baseline configuration from which to make improvement comparisons.

Results: The screw showed light pitting on the tension flank after 3,300 cycles. The results are somewhat peculiar in that Test 1, run at lower load and with a lubrication system, yielded higher wear. Due to the limited number of tests involved, it may not be possible to reach a statistically significant conclusion. It would not be appropriate to conclude that higher loads and less lubrication result in increased life. The data from this test run probably should be viewed as an optimistic result which is not on average representative. However, the lack of positive results in using a lubrication resulted in the decision to delete this as possible method of obtaining greater screw life. This was the last test to utilize a lubrication system.

Test 5

This test was essentially a repeat of Test 4, except the screw hardness was RC60.

Results: The test was stopped at 3,300 cycles in order to inspect the ball screw components for abnormal wear or unusual conditions. The screw pitting was worse than Test 4 at the same number of cycles. Cycling was resumed and terminated at 5,527 cycles when the screw resembled the CRTF specimen. Continued cycling would only produce a higher wear rate and no reasonable hope of reaching the 10,000 cycle life goal could be expected. This test demonstrated that simply increasing screw surface hardness would not produce the required life.

At this point it was also concluded that the 1¼" diameter screw was not a reasonable candidate to meet the life requirement. If the 1¼" screw could have demonstrated life capability exceeding 20 years, a higher cost ground screw may have been considered as a method of obtaining the required life. It was estimated by Saginaw that approximately 9 years additional life could be obtained by selecting a ground screw. Since significant screw pitting was obtained in all test instances at 10 years or less (3,300 cycles), the remaining tests were conducted on 1½" diameter screws which held promise with regard to reducing screw surface pitting.

Test 6

This test was performed with a tapped nut which, as noted in Test 3, would probably not provide good results in terms of nut or ball life. It was felt that despite reduced ball and nut life, an estimate of screw life could be determined.

Results: The test was terminated at 1,710 cycles and disassembly inspection made. The screw and nut were free of pitting. The balls were spalled and one ball was found broken.

Reassembly was made with a new nut and a new complement of balls. The ball screw was noted to be running rough and began making unusual noises. Testing was terminated at only 460 cycles. No pitting was found on the nut or screw, however, one ball was found cracked. A new set of balls were installed and test cycling resumed. The cycling was stopped following 2,983 cycles (5,153 cumulative cycles on screw) and disassembly inspection performed on the ball screw components. No pitting was evident on the screw or nut. The balls were spalled as found in previous testing, but no broken balls were found.

New balls were installed and cycling resumed. The test specimen was disassembled again at approximately 7,200 cumulative screw cycles with similar results. The balls were found spalled and replaced with new parts. Testing was finally terminated after completion of 10,985 cumulative cycles on the screw and 9,275 cumulative cycles on the nut. Inspection of the screw found intermittent pitting on the tension side. The screw life goal of 10,000 cycles was surpassed by a comfortable margin. Based upon previous testing, numerous additional cycles could be made on this screw. The nut circuits exhibited some minor pitting, but considering that 9,275 cycles were accumulated and the good condition of the nut, this item was also considered to have demonstrated adequate life performance.

The 1½" diameter screw has demonstrated 30 year life cycle capability at the standard Saginaw heat treatment of RC56 minimum and without the need for a positive lubrication system.

Test 7

Saginaw had decided to raise the minimum hardness from RC56 to RC58 throughout their product line for the purpose of increased life. This test included a screw heat treated to the new standard production level of RC58 minimum. This was also the first test of a ground nut in conjunction with the 1½" diameter screw.

Results: Since suitable screw and nut life were demonstrated in Test 6, the remaining objective was to demonstrate adequate ball life. Since the balls are loaded in both travel directions, 5,000 cycles are necessary to demonstrate 30 year ball life capability. This test was terminated after 5,090 cycles. The balls were in excellent condition after test. The balls were free from pitting or any other surface irregularities. The screw and nut were in excellent condition with no evidence of pitting.

Test 8

Test 7 was primarily a ball fatigue test conducted at the peak elevation actuator load and at a limited 6" stroke. Test 7, therefore, demonstrates high load fatigue capability with the actuator fully extended. In general, the elevation actuator operates over a longer stroke and at a lower load. Test 8 was constructed to demonstrate adequate life over a more representative operating cycle, similar to what may be encountered in field operation. A 6,600 pound constant load and 13-3/4" stroke were selected to be representative of the operating duty cycle.

Results: The test was periodically stopped and component inspections conducted at 2,500 to 5,000 cycle intervals. Only results from key inspections or significant milestones are presented in detail.

- 5,000 Cycles - All components in perfect condition with no evidence of wear.
- 10,000 Cycles - The screw was in excellent condition with no evidence of pitting or surface irregularities. The nut was in excellent condition. The balls, which are loaded during tension and compression strokes and thus received double life, were in satisfactory condition and appeared like new. Following successful demonstration of life capability for the screw, nut and balls during an operational duty cycle, it was considered beneficial to continue cycling the test specimen to establish remaining margin.
- 15,000 Cycles - The screw and nut continues to look good with no evidence of pitting. One ball shows some spalling but no loss of efficiency or impairment of function is evident.

- 17,500 Cycles - The screw is beginning to show some slight pitting. The pits are very small and insignificant. The nut continues to look good with no pitting in evidence. Eleven balls show some spalling.
- 30,000+ Cycles - The testing was terminated without failure. The screw shows evidence of slight pitting along the length. The nut shows moderate pitting in both circuits and all of the balls are spalled. The unit continues to operate in a satisfactory manner with the same hardware that started test. Efficiency is slightly down due to pitting and wear on the balls.

Analytical Comparisons

Concurrent with the test program, the CRTF screw was examined by Duff-Norton and Saginaw. Based upon the load stroke profile of the screw and measurement of the point on the screw where pitting started, it was determined that the Hertz contact stress at pitting onset was 326,000 psi. The Hertz contact stress at the peak load of 8,500 pounds was 338,000 psi. A second screw from a second actuator at CRTF, which had similar load and cycle history, exhibited pitting onset at the same point. From the two data samples available, it would be necessary to reduce Hertz contact stress for the 4150 material below 326,000 psi throughout the elevation actuator stroke in order to eliminate pitting. The 1½" diameter screw has a Hertz contact stress of 316,000 psi at 8,500 pounds load. The agreement between theory and test data appears in good correlation on this point. With the stress below the level where start of pitting was observed on the CRTF screws, no pitting was found on any 1½" screw during all testing. It could be concluded that the point of pitting on the 1½" diameter screw would occur beyond the present possible stroke.

Table 1

Ball Screw Test Results Summary

Test No.	Screw Size	Screw Hard.	Nut Type	Test Load Ten.	Test Load Compr.	Test Cycles Per Flank	Post Test Screw Condition	Remarks
1	1¼"	RC55	Ground	6,600	8,500	3,300	Heavy pitting on tension flank.	Felt wiper for lubrication.
2	1¼"	RC60	Ground	5,000	8,500	3,390	Light pitting on tension flank.	Felt wiper for lubrication.
3	1½"	RC60	Tapped	5,000	8,500	3,377	No pitting.	Felt wiper for lubrication. One bad circuit in nut.
4	1¼"	RC55	Ground	8,500	6,600	3,300	Light pitting on tension flank.	No lubrication.
5	1¼"	RC60	Ground	8,500	6,600	5,527	Heavy pitting equivalent to CRTF screw.	
6	1½"	RC56	Tapped	8,500	6,600	10,985	Slight pitting on tension flank.	Proved screw and nut life capability.
7	1½"	RC58	Ground	8,500	6,600	5,090	No pitting on screw or nut.	Max load ball fatigue test. Proved ball life.
8	1½"	RC58	Ground	6,600	6,600	15,000+	Screw and nut in good condition. One ball spalled.	13-3/4" stroke.
						30,000+	Test terminated. Unit still functioning. All balls spalled and pitting on nut and screw.	

Note: All screws tested were rolled thread construction made from 4150 steel. All nuts tested were 8620 steel heat treated to RC62.

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