NASA TMX 54778

ROCKET-MOTOR SPIN-TEST APPARATUS

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Presented at the Second Annual Meeting of the
ICRPC Working Group on Static Testing

Redlands, California
October 21-23, 1964

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SUMMARY

The performance characteristics of some solid-propellant rocket motors have been shown in free-flight and ground testing to be appreciably affected by the dynamic environment encountered during their thrusting period. Principal effects noted are (1) ballistic, associated with alterations to the propellant combustion and flow process, and (2) thermal, resulting from deposition of hot exhaust residue within the motor chamber. Either or both effects may induce motor failure. The NASA-Langley Research Center has fabricated and extensively used a test apparatus capable of subjecting full-scale solid-rocket motors to the dynamic spin or roll environments normally encountered in flight use. This paper describes the design and performance characteristics of this apparatus which have been employed to test fire over 30 solid rockets ranging in weight from 100 to 2800 pounds, diameters to 30 inches, and lengths to 147 inches at roll rates from 100 to 900 rpm under both sea-level and simulated altitude conditions. The apparatus is driven by a timing belt assembly powered by an electrical synchronous motor having an electromagnetic coupling and brake. Changes in motor spin rate during firing are less than 2 percent. The rocket motor is supported fore and aft by roller bearings which do not sustain axial thrust but do permit longitudinal growth of the motor case during firing. Thrust is neutralized by a tapered roller bearing attached to the apparatus spin shaft. The rocket motor transmits its thrust to the spin shaft through a spider assembly. No detectable thrust losses have been observed with this apparatus. Rocket-motor performance is measured through up to 72 low-noise slip rings, and include pressure, temperature, and strain. Comparisons of data between firings of spinning and nonspinning motors have exhibited excellent agreement with no degradation due to the slip rings.

INTRODUCTION

The NASA-Langley Research Center has for many years conducted extensive research in the areas of aerodynamics, materials, communications, reentry physics, etc., through the use of various multistage rocket-powered free-flight vehicles. Many of these vehicles require spinning of one or more boost stages for inertial stabilization or impact dispersion control. Until the advent of the metallic additive in solid propellant a few years ago, no problems had been encountered by NASA-LRC in these free-flight studies resulting from spin effects on rocket-motor performance. In 1959, however, limited spin testing of the Hercules-Allegany Ballistics Laboratory X248 rocket motor by the manufacturer, reference 1, in support of the development of the four-stage Javelin vehicle did indicate a definite performance spin sensitivity, especially in the range of 9 to 12 cycles/sec (540 to 720 rpm). This sensitivity under spinning conditions has been confirmed in numerous NASA-LRC flights employing this motor. The aluminum content of the X248 propellant, a cast double base, is 3 percent.

The NASA Project Fire vehicle utilizing an Atlas-ABL X259 two-stage propulsion system, the latter stage of which was spun at 155 rpm for stabilization, established a firm requirement for determining the spin performance of the X259 rocket motor through ground testing prior to flight use in this environment. The X259 is approximately 30 inches in diameter and contains about 2500 pounds of a highly aluminized composite modified double-base propellant. Due to the basic similarity of the X248 and X259 rocket motors in type of construction, internal grain configuration, and basic type of propellant, a possible problem area was anticipated which required thorough evaluation. An apparatus capable of spin testing an X259 rocket motor about its own principal axis at 200 rpm was designed and fabricated. This paper describes this basic apparatus as employed for the initial X259 spin test and the many versions or modifications subsequently employed in the spin testing of other rocket motors. A summary of the use of this specialized rocket-motor spin-test apparatus is shown in table I.

DESCRIPTION OF EQUIPMENT

Test Apparatus.- Figure 1 shows the entire test apparatus used in the testing of a 15-inch spherical rocket motor and includes all the major components. Thrust cells employed have been single- and dual-bridge Baldwin SR-4 types rigidly mounted to the thrust abutment. As shown in figure 2, a Timken T-311 tapered roller bearing with a 6.375-inch and 3.00-inch outside and inside diameter, respectively, is used to transmit the motor thrust while eliminating the rotational motion. Also shown in figure 2 mounted directly behind the thrust bearing on the spin shaft is a Wendon Model W36-100 slip-ring assembly of 36 low-noise silver slip rings. Two slip-ring assemblies may be employed in tandem on a common spin shaft if required. Two slip rings are allotted to providing ignition current; the remaining 34 may be utilized as required for pressure, temperature, or motor-case strain measurements. Extremely clear signals are obtained using this assembly.

The rocket motor and holding fixture weight is supported by forward and aft bearings as shown in figure 1. The forward bearing is a roller type, Rollway MC S-200 with a 7.086-inch and 6.6-inch outside and inside diameter, respectively, which provides a rigid support for the spin drive input. Figure 3 shows this bearing in detail. Two different bearing assemblies, ball type, have been used for the aft support. The first is a Kaydon "A" 169 B-1 with a 31-inch and 29-inch outside and inside diameter, respectively, and is primarily used for large-diameter motors requiring low spin rates, 400 rpm or less. This bearing is shown in figure 4. The second type of aft bearing assembly incorporates a Heavy Duty Kaydon KG 250-XR bearing with a 25-inch and 23-inch outside and inside diameter, respectively. This bearing is shown in figure 5 and is used whenever possible, especially in the high spin applications. An oil spray is provided for cooling and lubrication in the high rpm tests as shown in figure 5. For testing of very long rocket motors, a third support bearing assembly as shown in figure 5 is employed. This bearing does not normally contact the motor case and is primarily a safety measure to retain the casing should excessive deflection or failure occur. This bearing, also oil-spray cooled, is identical to the Heavy Duty Kaydon KG 250-XR employed in the aft bearing assembly.

A total of three Thomson A-406080 linear bearings 4.5 inches long and 3.75 inches and 2.5 inches in outside and inside diameter, respectively, are used to support the aft bearing assembly as shown in figure 5 and provides for linear expansion of the rocket motor up to 1 inch.

Small ball-bearing rollers are employed on the forward support structure as shown in figures 3 and 4 to support the weight of the motor attachment fixture and any portion of motor remaining affixed in the event a motor failure should occur. These bearings do not normally contact the rotating assembly and are primarily a safety measure to protect equipment in the event of malfunction.

A small thrust preload is maintained on the floating rotating assembly against the forward tapered roller thrust bearing through the use of three equally spaced springs with adjustable tension as shown in figure 6. These springs connect the rigid portion of the test apparatus and the structure supporting the aft bearing assembly which floats on the linear bearing cited previously.

The transmission of power to rotate the test assembly is accomplished using a timing belt drive system from the electric drive motor to the spin shaft as shown in figure 1. The power is supplied by a 10-horsepower Westinghouse eddy-current coupled squirrel-cage induction motor which runs at a constant speed of 1735 rpm. This motor may be wired for either 220-volt or 440-volt operation, drawing 25.6 amperes or 12.8 amperes, respectively. Integral to this motor is a Westinghouse type ACMV-256-906B electromagnetic coupling and brake with a regulated speed of the output shaft of 30 rpm to 1200 rpm. A speed reducer is supplied for operation between 30 and 100 rpm. Output speed, or torque, may be regulated to provide a constant test roll rate despite load changes within the system. The coupling operates on 110 volts a-c and draws 1.27 amperes. The entire drive unit is in a dripproof enclosure designed for vertical or horizontal operation on a minimum level of vacuum of 0.5 mm Hg for a period of 10 minutes without overheating or experiencing arc-over. The unit also contains an integrally mounted tachometer generator to measure shaft output speed.

A control console, figure 7, as supplied by the Eaton Manufacturing Company, Dynamatic Controls Division, is employed for system power control. Direct-current power is supplied to the electromagnetic clutch by a Tyhratron rectifier. The Tyhratron tube is also used as a speed control by electronically maintaining the preset speed. The console contains an on-off switch for the electric drive motor, a potentiometer (variable voltage divider) for speed control on the coupling, and a frequency meter to indicate output shaft speed.

The entire test assembly, including the drive motor system, is rigidly mounted to a heavy I-beam rail structure as shown in figure 1 which permits easy transportation and setup in various test cells as required. Careful alinement of the test assembly and the thrust load cell is required to prevent rotational flexure of the load cell diaphragm which yields poor quality data. Spacing of the forward and aft bearing to accommodate rocket motors of various lengths is accomplished by positioning the aft bearing structure on the I-beam rails as required. Stiffness of the assembly is obtained through use of I-beams along each side joining the forward and aft bearing structures.

For safety purposes in installation and checkout operations, an ignition shorting block is employed, providing a dead short for both the rocket initiator system and the firing power supply if accidentally energized. The short is manually removed immediately prior to final system spin-up for test firing. This shorting block is shown mounted on the thrust spider in figure 1.

Instrumentation.- Conventional test cell instrumentation is employed in conjunction with the described test apparatus. Included as sensors are wire strain-gage load cells, wire strain-gage pressure transducers, magnetic reluctance pickup to measure rotational speed, and thermocouples for temperature measurements. The load cells principally employed are the Baldwin Model U-1 type, accurate to 0.25 percent of full scale, hermetically sealed, temperature compensated, with a dual bridge circuit. The pressure transducers used are Dynesco Model PT 121 with a balanced, bonded, four-arm bridge with the sensing element hermetically sealed and temperature compensated from -65° to 250° F.

The spin rate of the test assembly is continuously monitored through the use of an Elcor Model 3040 reluctance pickup mounted to the forward structure as shown in figure 3. Ten equally spaced steel pins are so oriented on the rotating structure as shown as to pass within the field of the sensing pickup, generating a pulse. Ten pulses per revolution are obtained and directly recorded for spin rate determination.

Conventional thermocouples employed are iron constantan and chromel-alumel. Typical installations are shown in figure 8. For most applications, 30-gage wire has been used successfully for temperature measurements which have exceeded 2000° F in some tests. A specially constructed 42-channel Royson Company thermocouple calibration unit is used with built-in signal conditioning unit.

The strain-gage-type thrust and pressure transducer power are supplied from a common external strain-gage power source. The excitation voltage for each channel is adjusted manually by use of a pot. Balance control is provided through the use of a NACA designed and built balance box of 18 channels each. Extreme sensitivity of zero balance is accomplished through the use of a Minneapolis-Honeywell drum-type potentiometer with 0- to 1-millivolt full-scale deflection. A fixed resistor is used for electrical calibration which when applied to the circuit the resistor shunts a predetermined arm of the bridge circuit. The conditioned signals are then fed into three CEC model 114 recorders of 18 channels each. Some data are printed on film-drum records while other data use Data-Rite.

DISCUSSION OF RESULTS

Equipment.- Excellent results in the testing of rocket motors in the spinning environment have been obtained with the cited test apparatus. Both mobility and flexibility have been demonstrated with firings conducted on the NASA-LRC apparatus at the Langley Research Center, Virginia, at the Vacuum Test Facilities of the Arnold Engineering and Development Center, Tennessee, and at the Solid Rocket Plant of Aerojet General Corporation, Sacramento, California. Rocket motors as listed in table I of a wide range of weights and dimensions have been fired while spinning over a wide range of roll rates at both sea-level, ambient, and simulated altitude conditions. Some test results are formally reported in references 2 through 7. The results of NASA-LRC tests are not yet formally reported.

The range of propellant weight for motors tested is from 100 pounds for a CYGNUS-15 (15-inch-diameter spherical rocket) to 2500 pounds for a Hercules X259 motor. The X259 with a 30-inch motor diameter represents the maximum diameter tested. The Lockheed HYDAC rocket motor with a length of 147 inches is the longest tested and required the use of the third bearing, previously mentioned. Roll-rate range has varied from 100 rpm to 900 rpm to meet test requirements. Roll rate is not varied during a given test run and the test apparatus is well able to maintain a roll rate within 2 percent of the set rate while under thrusting operation. The thrust levels of the motors tested have ranged from several hundred pounds force to over 20,000 pounds force with no loss of equipment operation or performance data.

The figures supporting the earlier description of the test apparatus show a range of rocket motors tested and the flexibility of the test apparatus. Figure 1 shows the system as used in the testing of the CYGNUS-15, the CETUS-17, and the XM-85 rocket motors wherein the motor is mounted in a can which is then attached to the fore and aft bearings. The installation in figure 1 is at NASA-LRC. Figure 3 shows a Hercules X258 motor in the test stand. Figure 4 is a photograph of a Hercules X259 motor in the test apparatus prior to firing. It should be noted that wherever possible in sea-level firings of upper-stage motors, the nozzles were cut off to yield full flow, hence good thrust performance data.

The Lockheed HYDAC motor is shown in figure 5 illustrating the system flexibility. Figures 6 and 8 are closeups of the motors shown in figures 3 and 4, respectively. Figure 9 shows the test apparatus as employed in the Aerojet testing of the ALCOR IA rocket motor. Figure 10 (ref. 6) shows the LRC test apparatus as installed in T-3 test cell at AEDC for simulated altitude firings. The rocket is a Hercules X258 which has been wrapped with aluminum foil to meet Thor-Delta flight requirements.

The test apparatus is rugged and has satisfactorily sustained violent motor failures without severe component damage.

During initial operations using this test machine, some noise was experienced in the thrust channels which was a direct result of the rotational motion. The noise was cylic in nature with one signal representing the natural frequency of the machine imposed on a cylic signal whose frequency was exactly equal to the rotational velocity. Careful alinement of the test machine components with the thrust transducer, balancing of the various components to some extent, and more rigid mounting of the machine to the existing test fixtures virtually eliminated all noise in the thrust channels on subsequent test firings.

Rocket-Motor Performance.- The value of the testing accomplished on the apparatus can clearly be shown by figures 11 and 12. These figures show the post-fire condition of a Hercules X258 rocket motor after spin testing at 250 rpm. At the time of testing the X258 rocket had completed development and PFRT programs. The actual motor shown was recalled from the launch station for test firing. The motor was completely severed as shown in figure 12. With this type test information the manufacturer was able to modify the motor design and produce a motor able to function satisfactorily in the dynamic spin environment. The typical spin sensitivity of the X258 rocket motor as derived from both NASA AND AEDC testing is shown in figure 13.

Figures 14 and 15 compare the pre-fire and post-fire condition of the NOTS 551 rocket motor. As seen in figure 15, case wall burn throughs were experienced in several locations. Figures 16 and 17 show the pre-fire and the post-fire remains of an Aerojet CYGNUS-15 spherical rocket motor after spin testing at 900 rpm. The propellant was highly aluminized and produced thermal failure at the motor equator as shown. This motor had completed extensive development testing and was ready for flight use.

Figure 18 shows a United Technology TM-3 test evaluation motor in the LRC test apparatus at Langley. The objective of tests at 0, 200, and 400 rpm was to determine the spin sensitivity of a particular propellant formulation, grain configuration, and internal insulator thickness applicable to a motor under development. The test results (ref. 5) are shown in figure 19 and clearly define the importance of this testing. These tests dictated a change in propellant formulation.

The drawing of conclusions as to the effect of spin environments on rocket-motor performance is beyond the scope of this paper. These typical test results are included herein only to indicate clearly the value of this type testing in motor development programs.

CONCLUSIONS

A test apparatus capable of subjecting full-scale solid rocket motors to the dynamic spin or roll environments encountered in flight use has been fabricated and extensively used by the NASA-LRC. A wide range of rocket motors with propellant weights to 2500 pounds, diameters to 30 inches, and lengths to 147 inches have been fired at roll rates from 100 rpm to 900 rpm at both sea-level, ambient, and simulated altitude conditions. Motor thrust levels of 20,000 pounds force have been encountered. The spin apparatus is mobile and flexible, permitting spin testing in a number of test sites and accommodating a wide range of motors. Provisions are available for direct motor instrumentation through the use of high-quality, low-noise, silver slip rings which yield excellent data. The value of spin testing on this type apparatus has been clearly demonstrated in test firings to date wherein motor failures and drastic ballistic performance effects under the spin environment have been demonstrated on motors normally considered ready for flight use.

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"Simulated Altitude Test of Atlantic Research Corporation XM-85 Solid-Propellant Rocket Motor (s/n T1-3) Spinning at 200 rpm." By A. A. Cimino, RTF ARO, Inc., Technical Documentary Report No. AEDC-TDR-64-122, June 1964, Program Element 62405184/3059.

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TABLE I. SUMMARY OF TESTS CONDUCTED ON LRC ROCKET SPIN-TEST APPARATUS

Type motor	Manufacturer	Number tested	Spin rate, rpm	Approximate propellant wt., lb.	Exhaust alt., ft.
X259	Hercules-ABL	2	200, 300	2500	S.L.
X258	Hercules-ABL	7	100, 200, 250	500	S.L. and 110 k
X248	Naval Prop. Plant	1	250	450	S.L.
CYGNUS-15 (spherical)	NASA-LRC	7	900	100	S.L. and 120 k
CYGNUS-15 (spherical)	Aerojet General	4	900	100	S.L.
CETUS-17 (spherical)	Naval Prop. Plant	5	200	135	S.L. and 110 k
XM-85	Atlantic Research	2	200	130	110 k
ALCOR IA	Aerojet General	2	300, 480	900	S.L.
TM-3	United Technology	4	0, 200, 400	600	S.L.
HYDAC	Lockheed Propulsion	1	900	410	S.L.
NOTS 551	Naval Ordnance Testing Station	1	480	700	S.L.

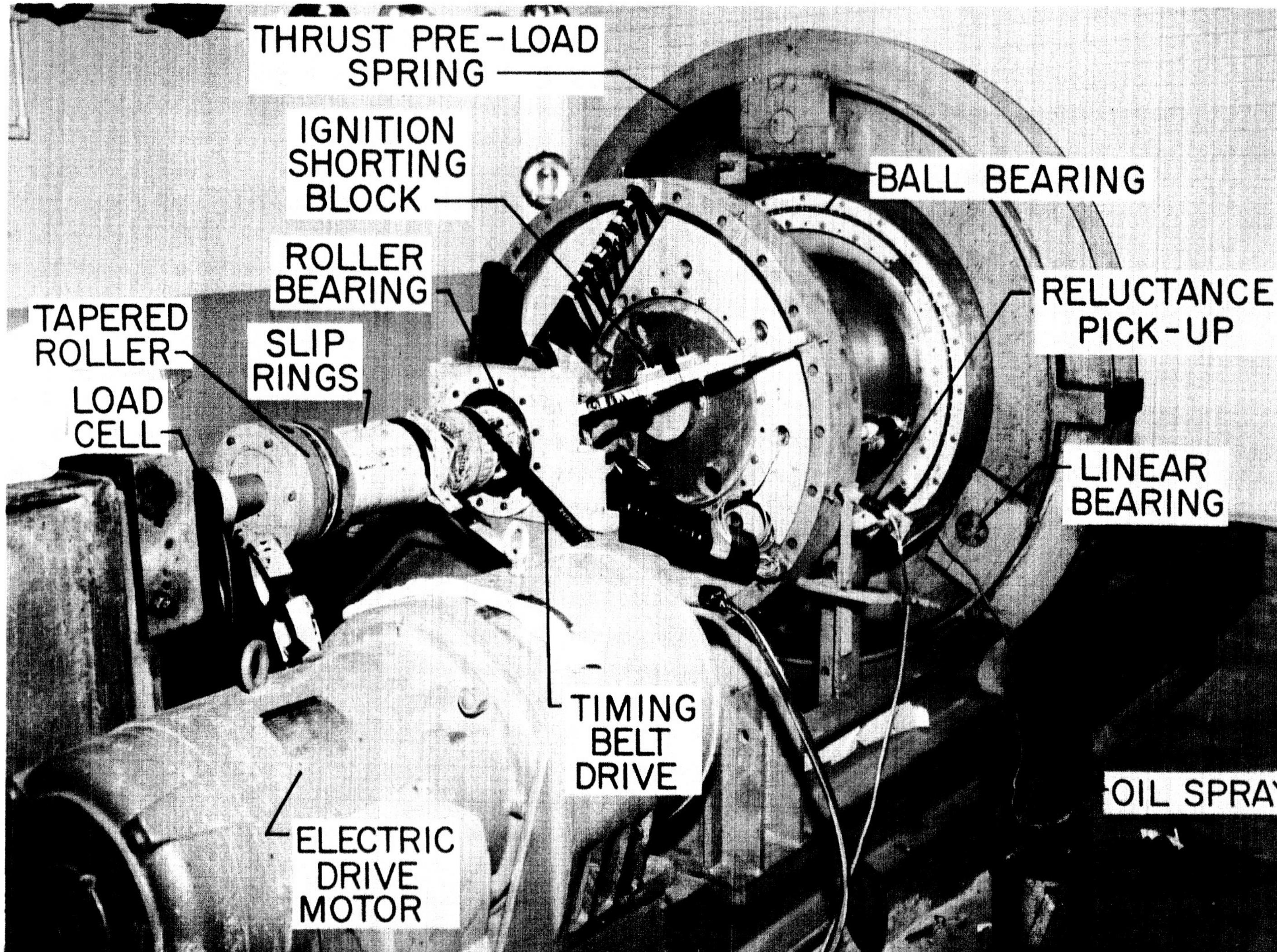

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Figure 1.- Spin test apparatus - overall view.

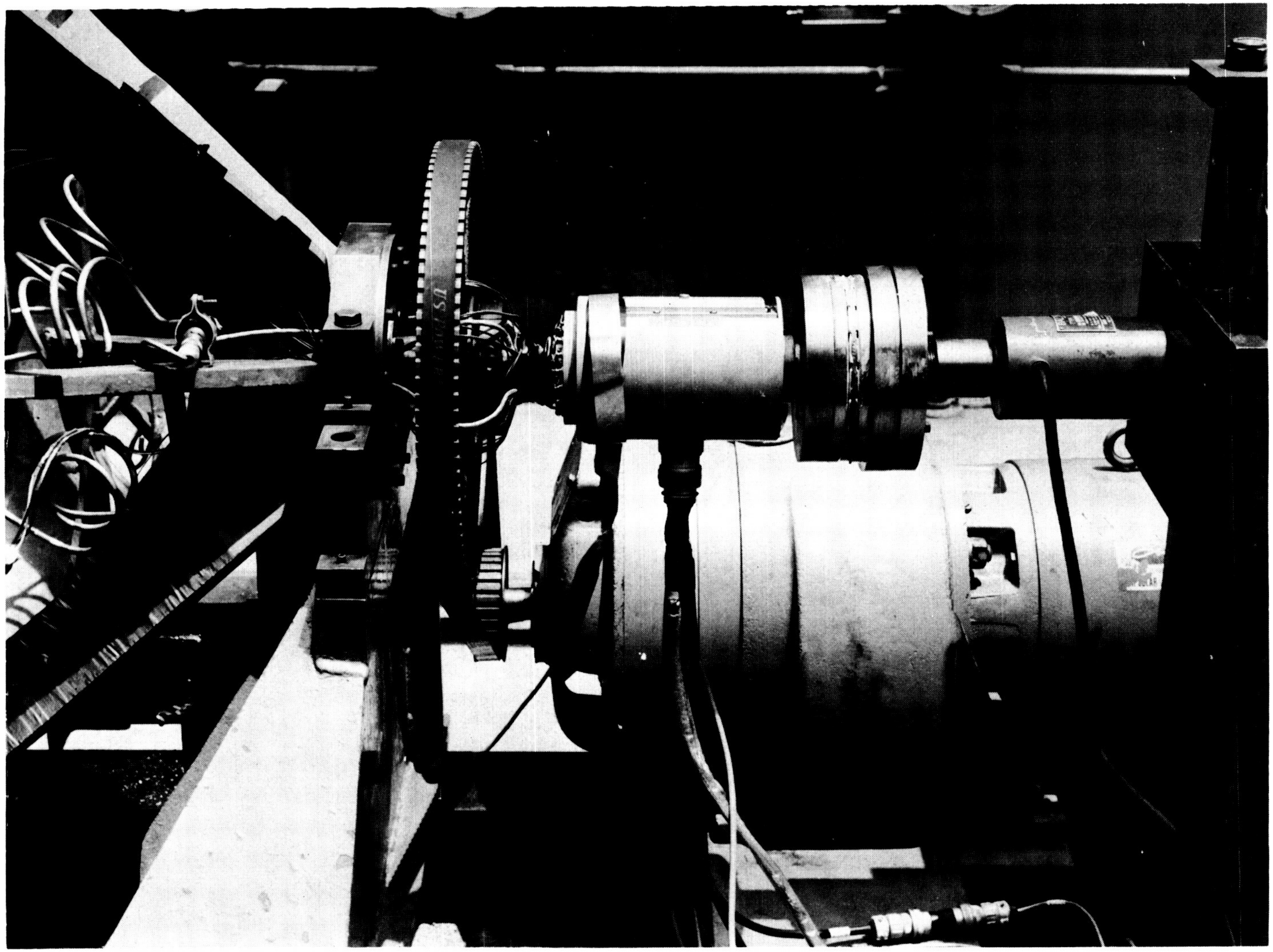

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Figure 2.- Forward bearing assembly - spin test apparatus.

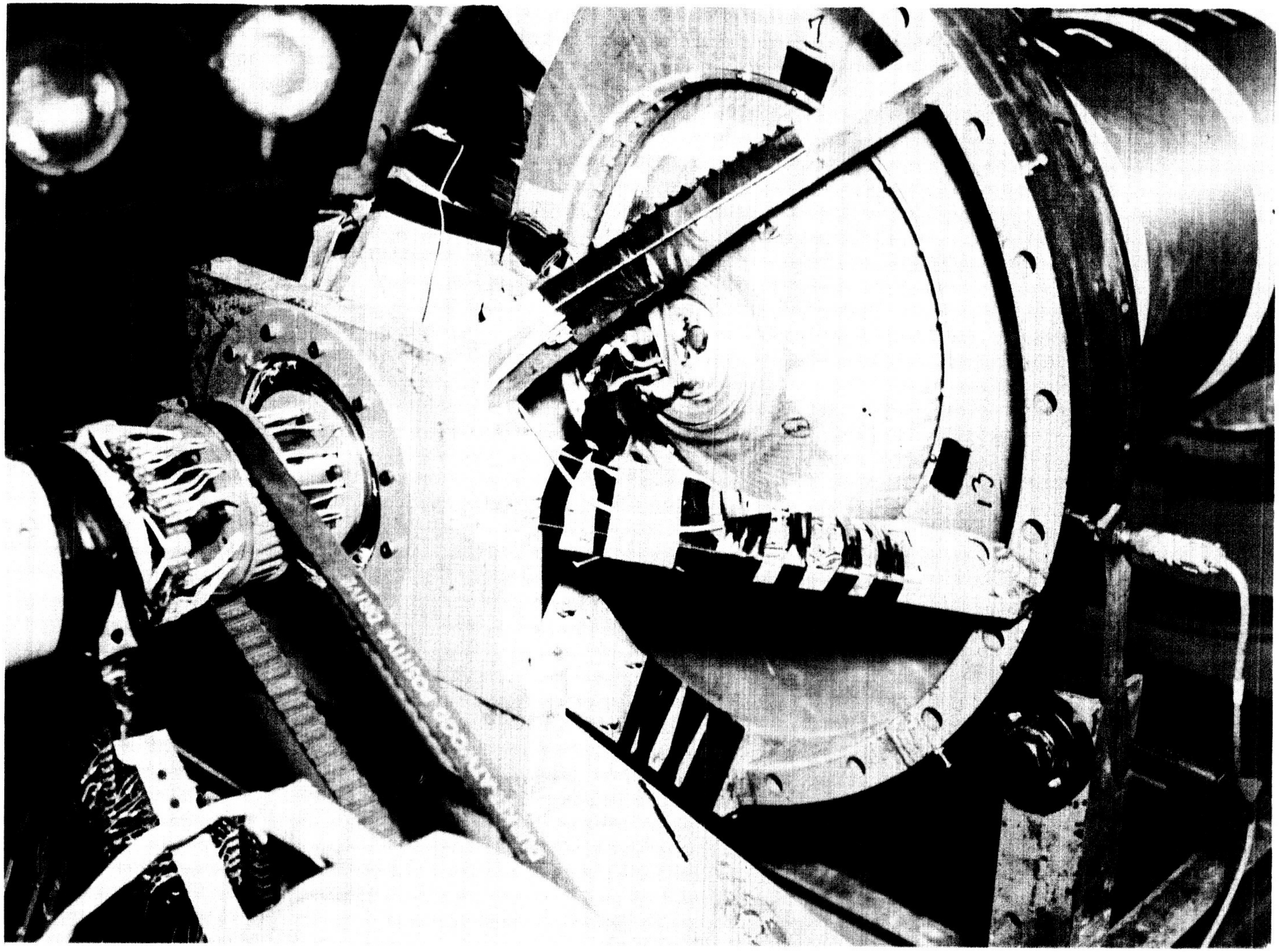

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Figure 3.- Detail of forward roller bearing - spin test apparatus.

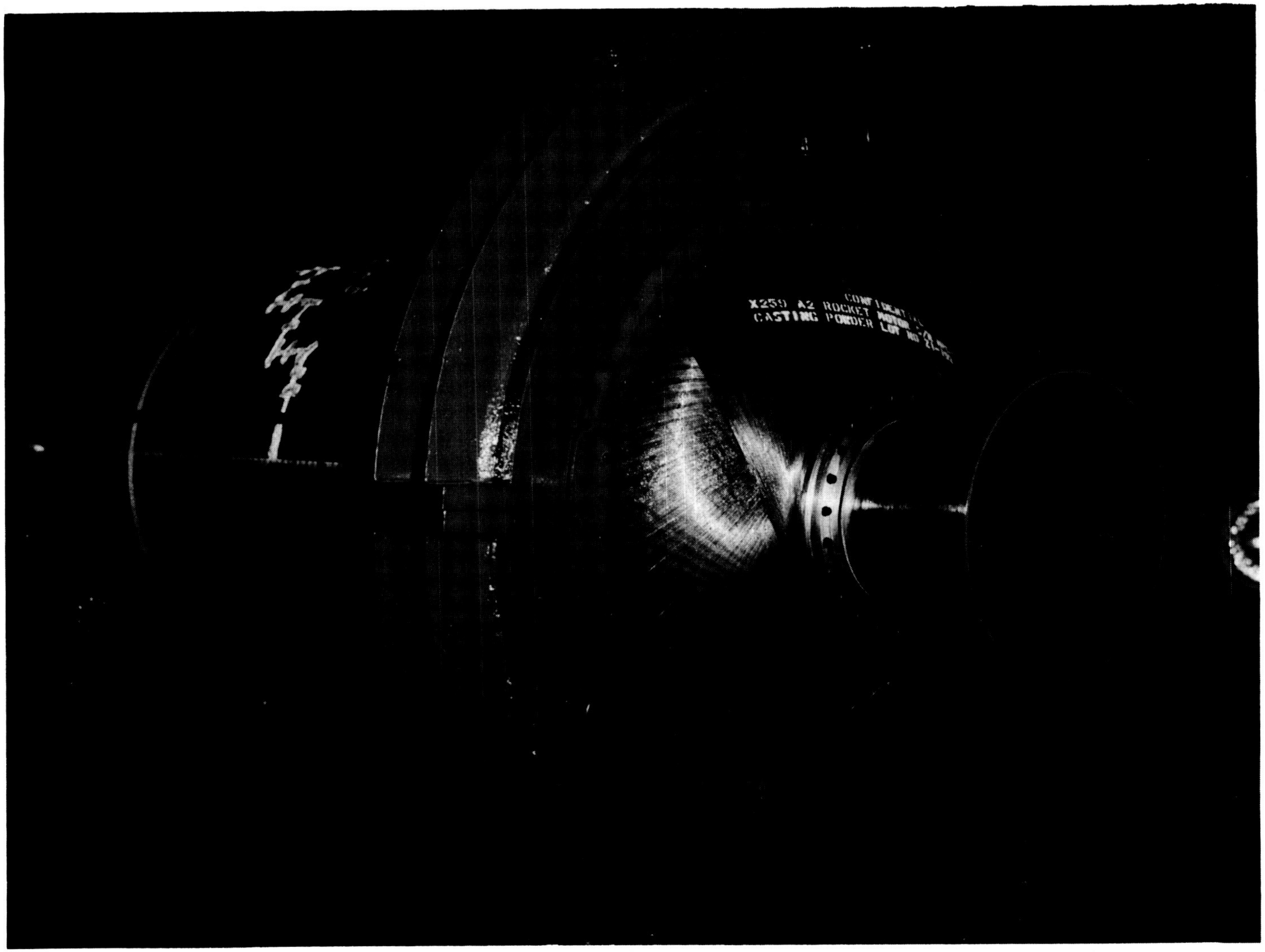

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Figure 4.- Detail of aft ball bearing - spin test apparatus.

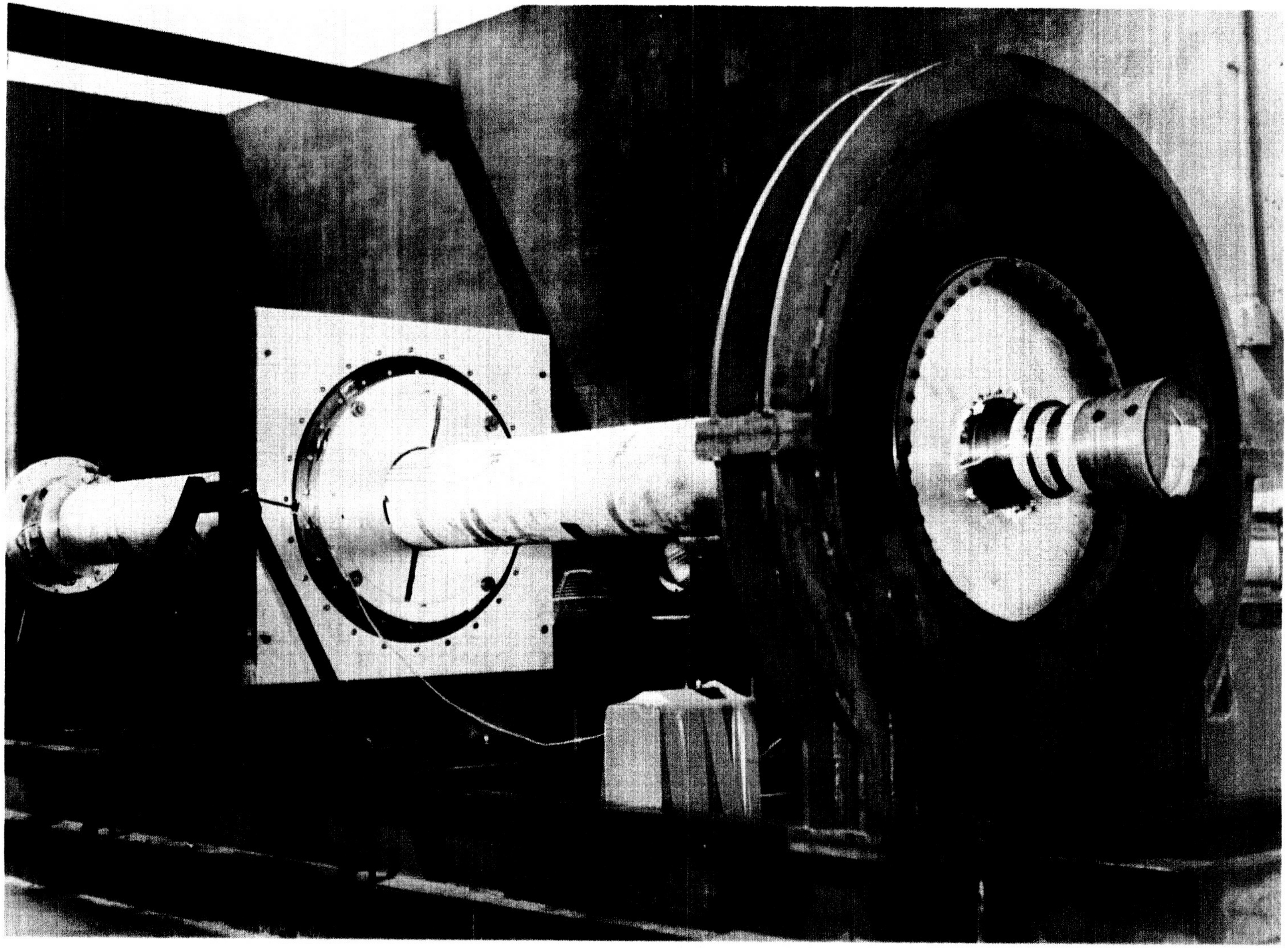

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Figure 5.- Detail of aft ball bearing - spin test apparatus.

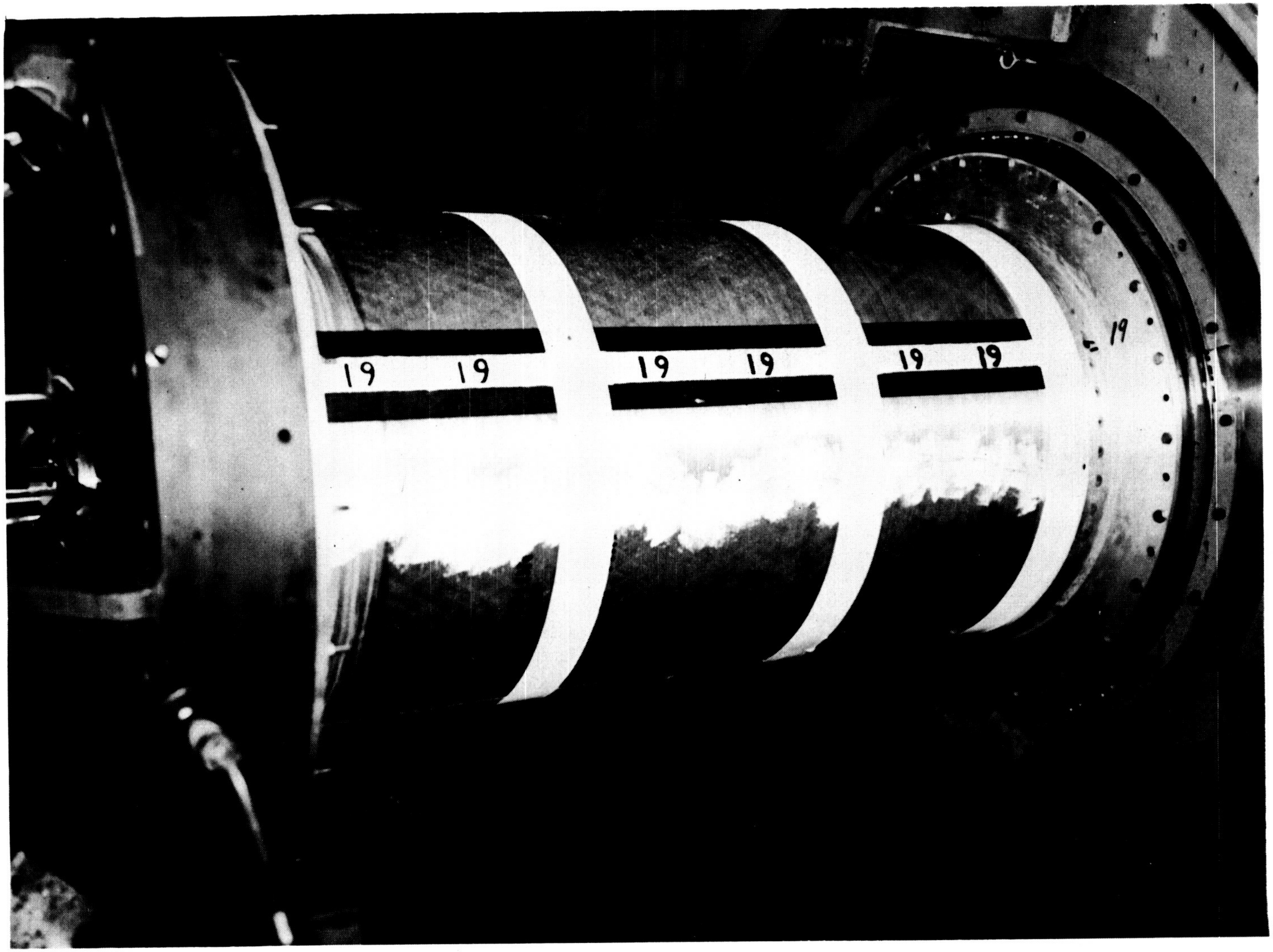

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Figure 6.- Thrust preload arrangement - spin test apparatus.

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Figure 7.- Control console - spin test apparatus.

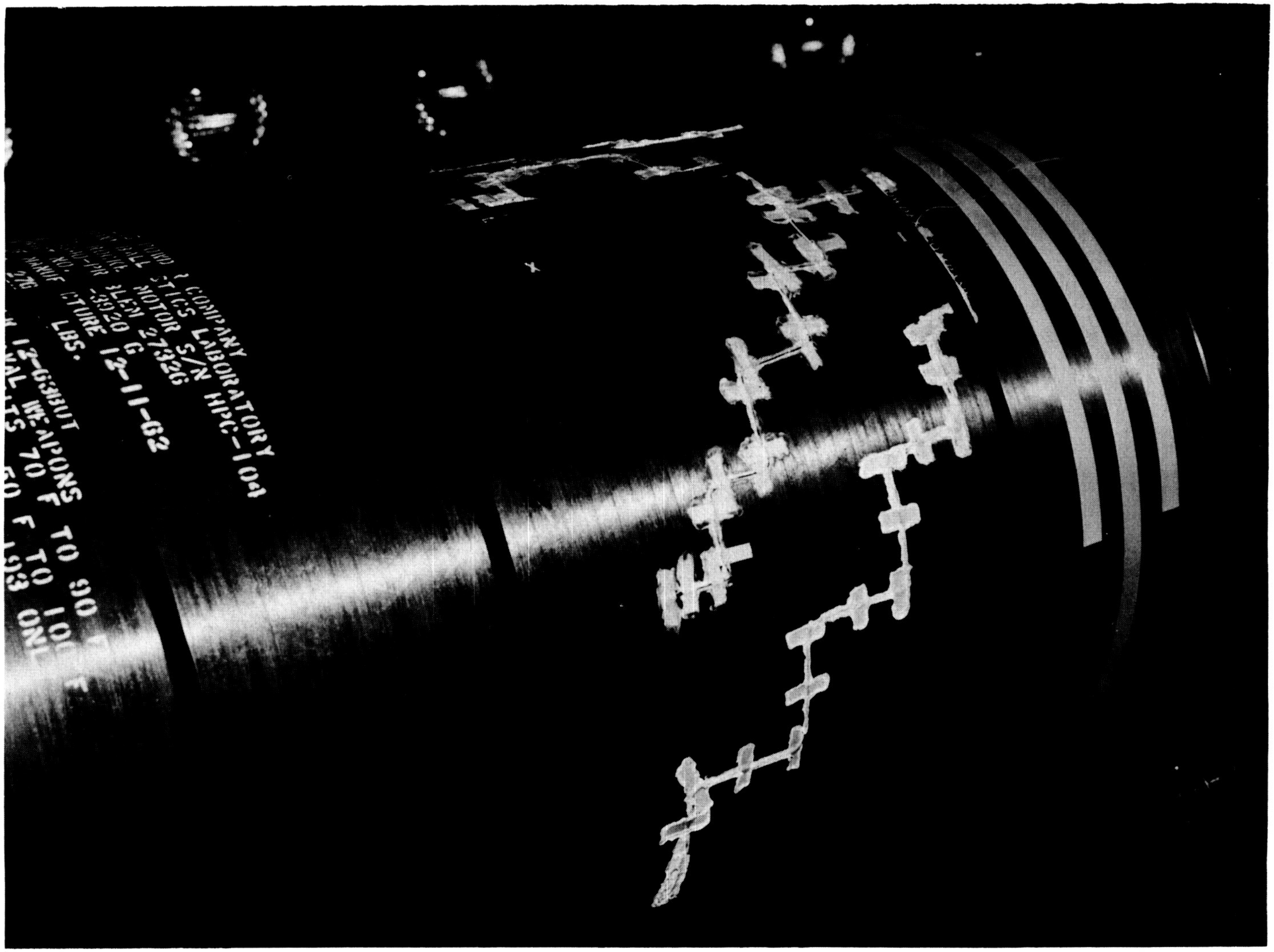

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Figure 8.- Typical thermocouple installation - spin test apparatus.

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Figure 9.- ALCOR IA firing (prefire) - spin test apparatus.

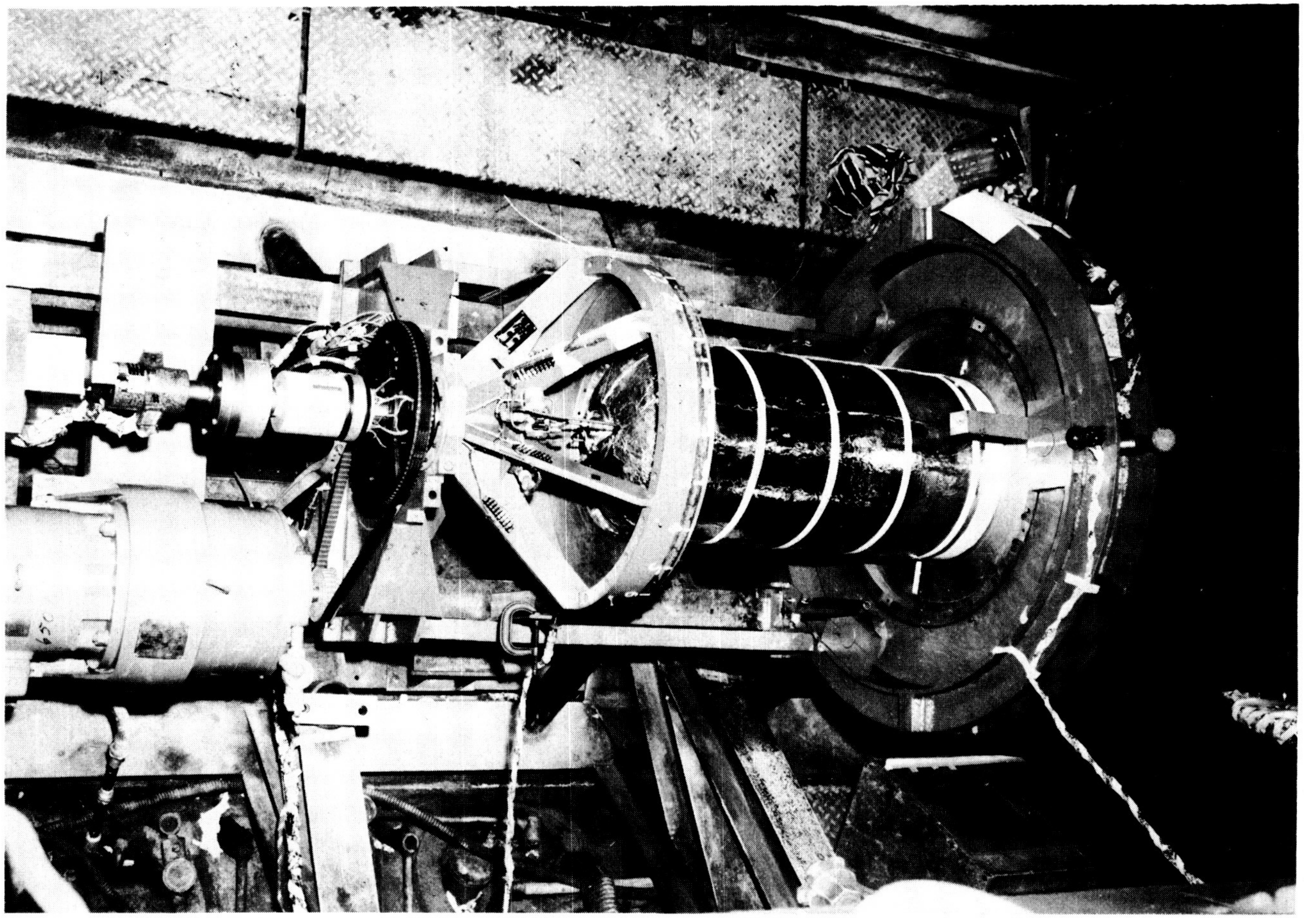

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Figure 10.- ABL X-258-B1(s/n RH 47) firing (prefire) - spin test apparatus.

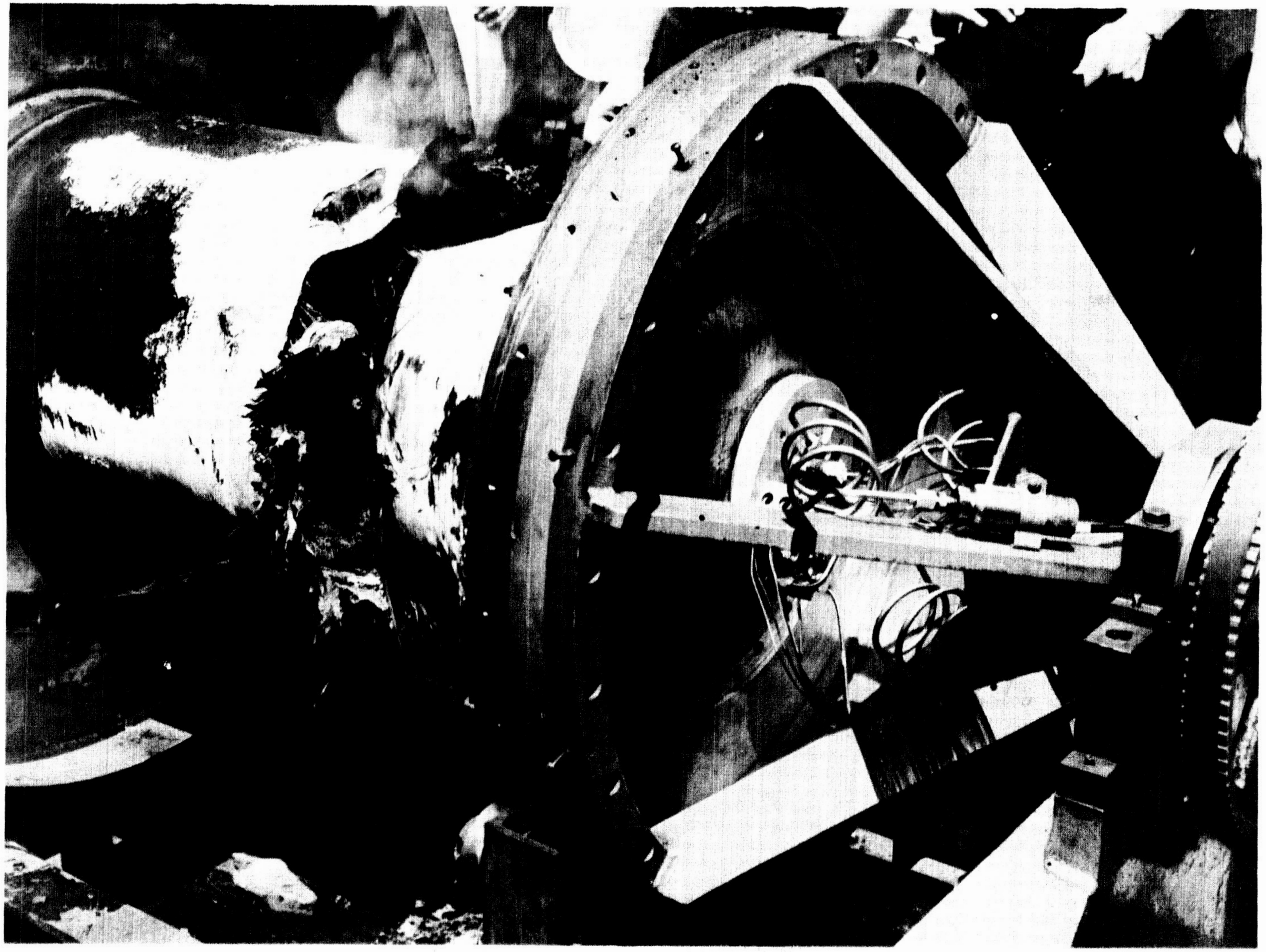

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Figure 11.- Post-fire condition X-258 - spin test apparatus.

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Figure 12.- Post-fire condition X-258 - spin test apparatus.

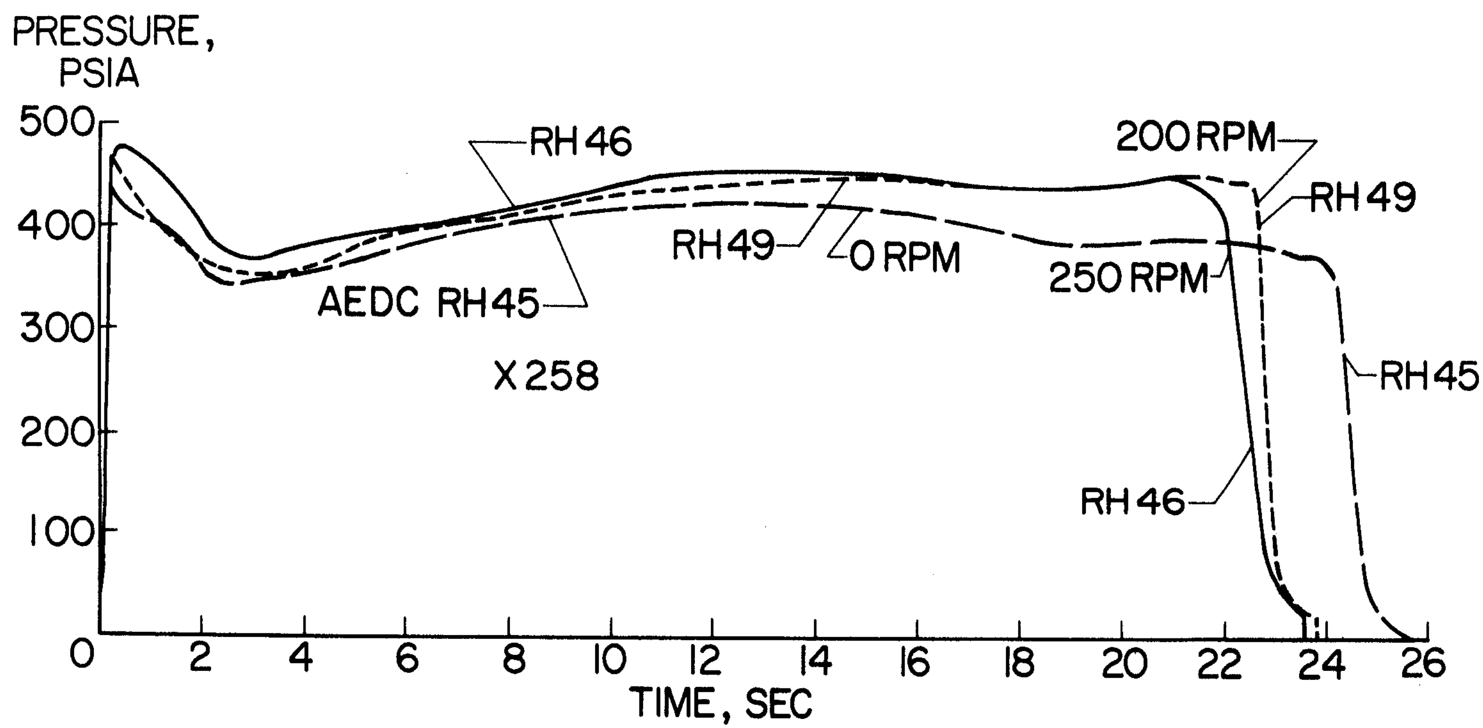

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Figure 13.- Pressure - time history of X-258 rocket motor in spin and nonspin environment.

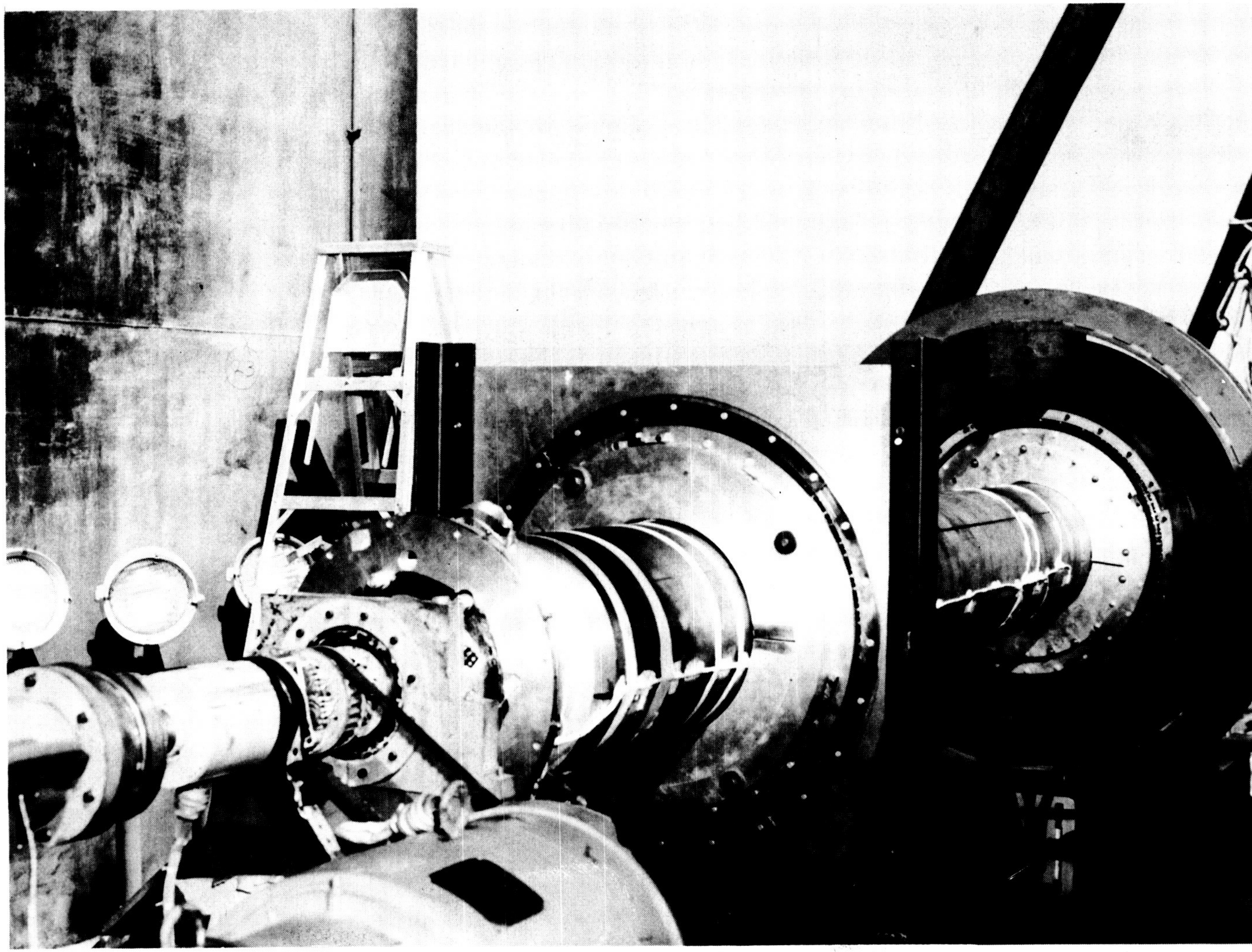

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Figure 14.- Prefire condition of NOTS 551 - spin test apparatus.

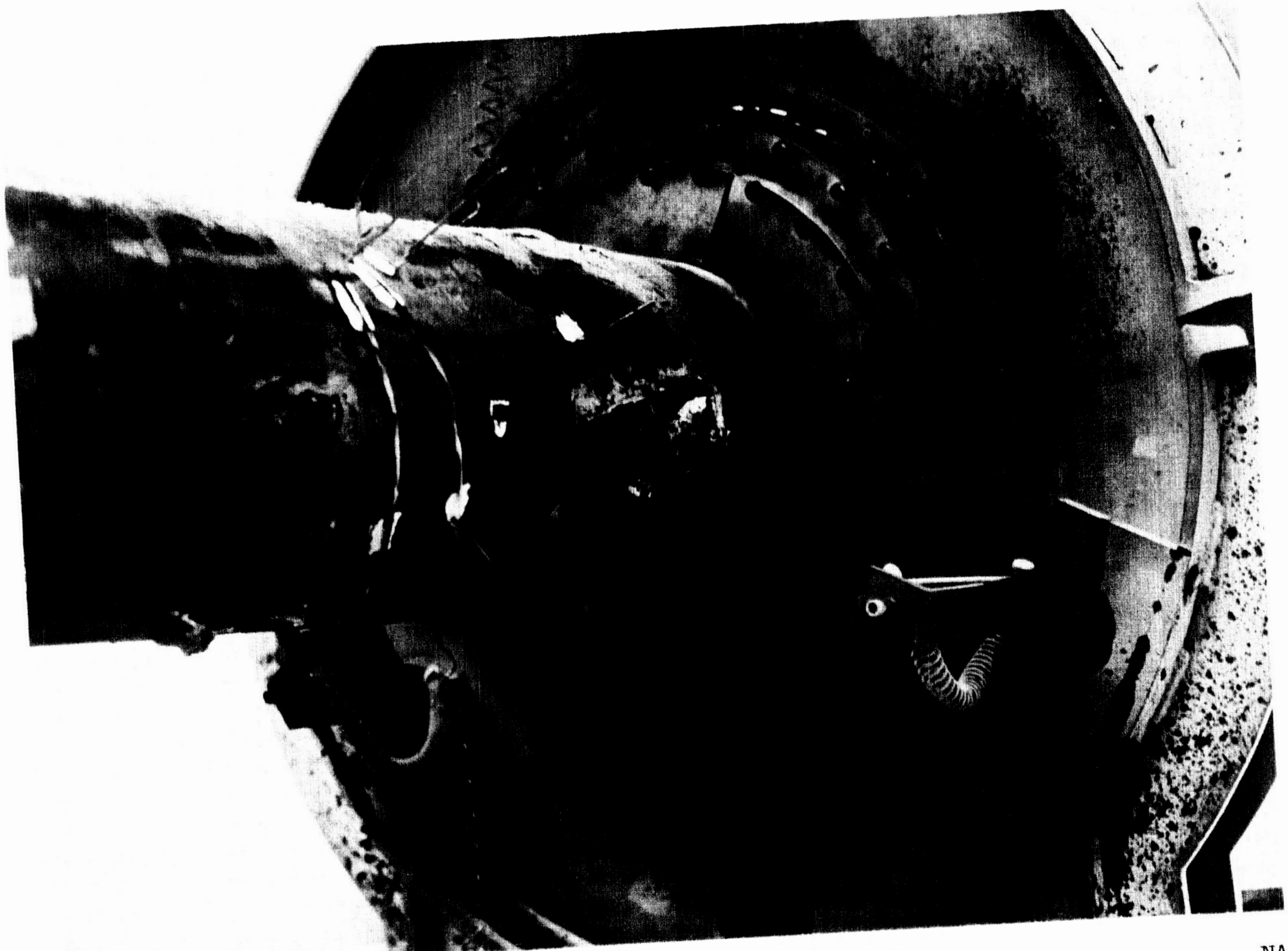

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Figure 15.- Postfire condition of NOTS 551 - spin test apparatus.

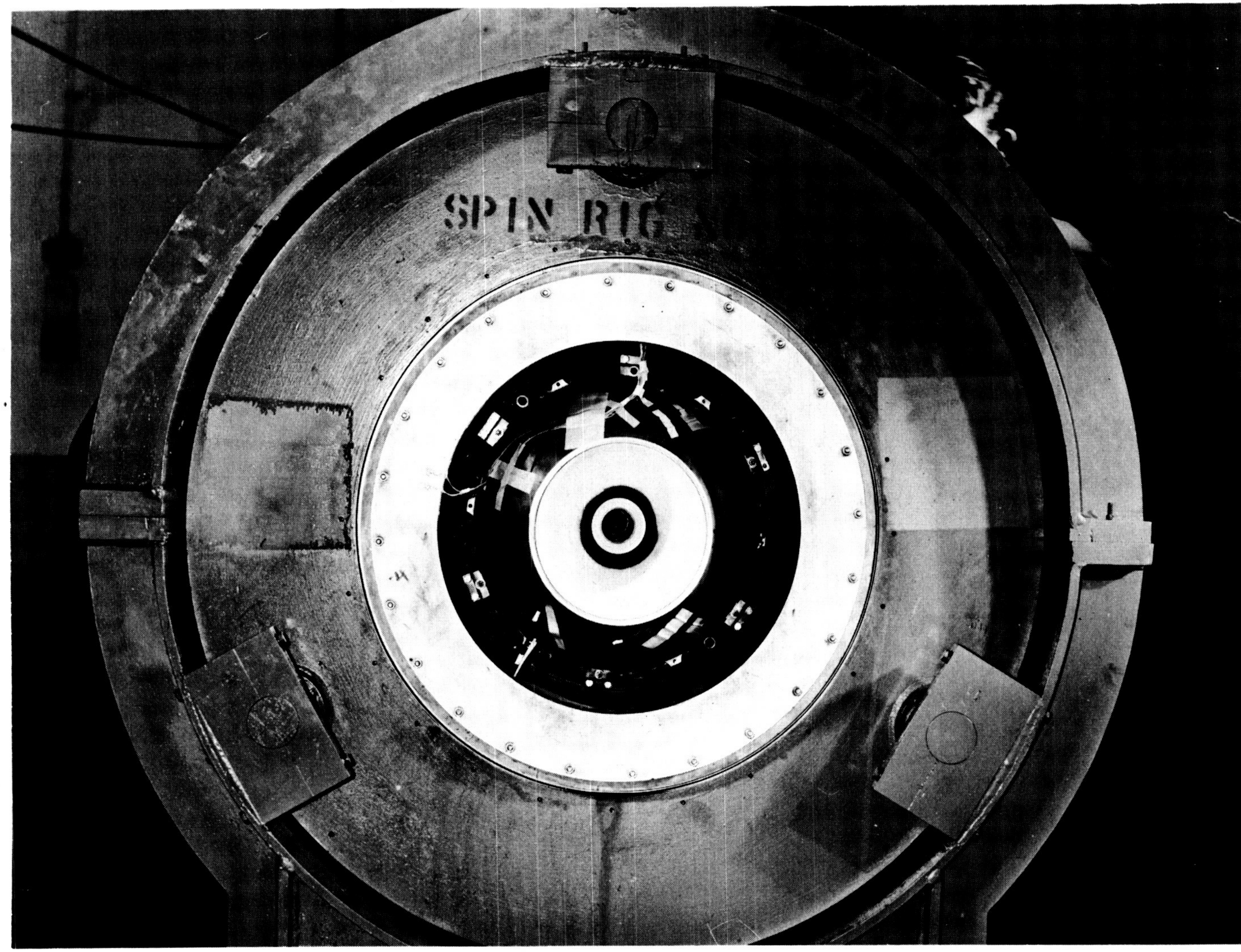

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Figure 16.- Prefire condition of AGC CYGNUS 15 - spin test apparatus.

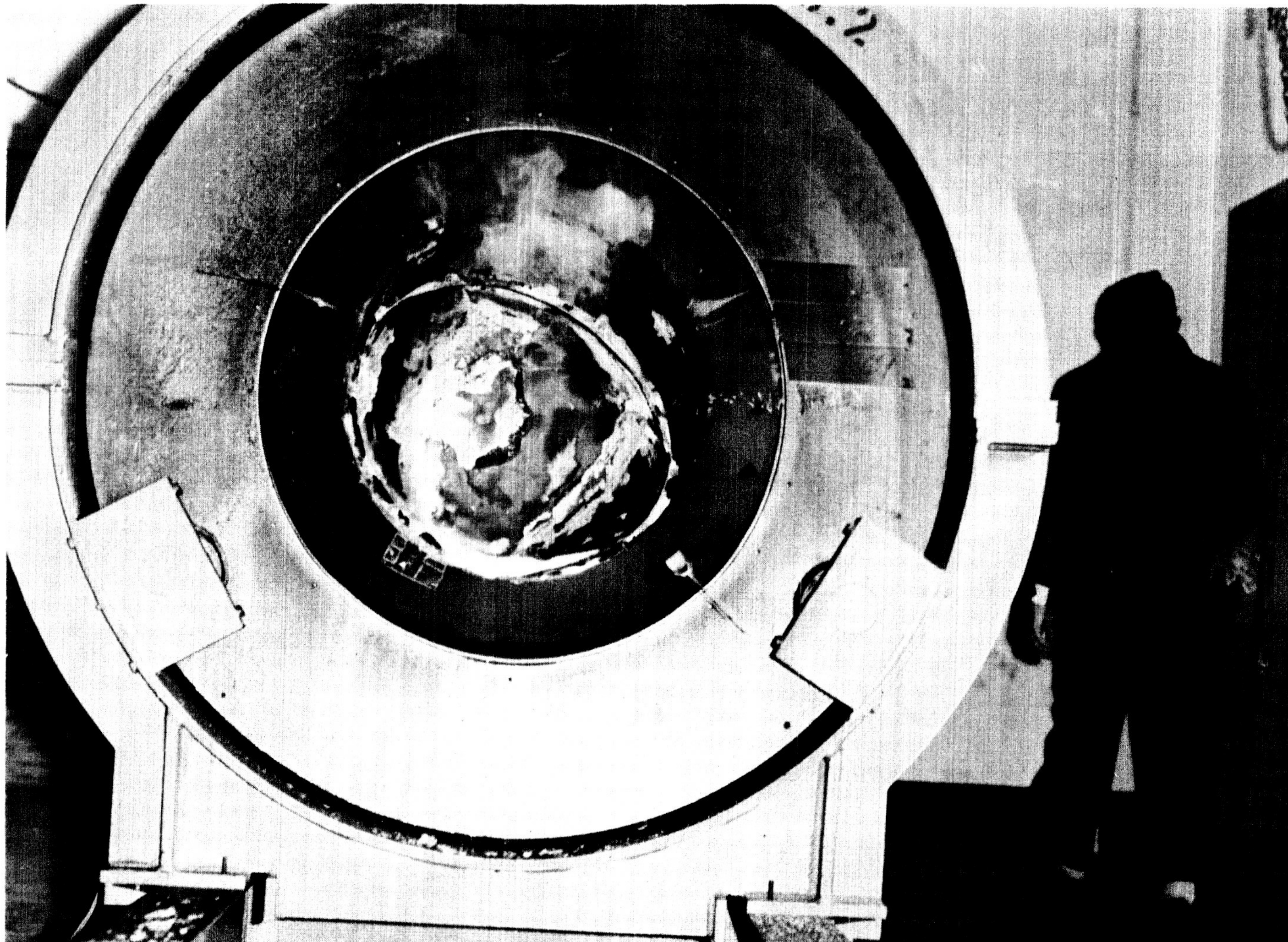

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Figure 17.- Postfire condition of AGC CYGNUS 15 - spin test apparatus.

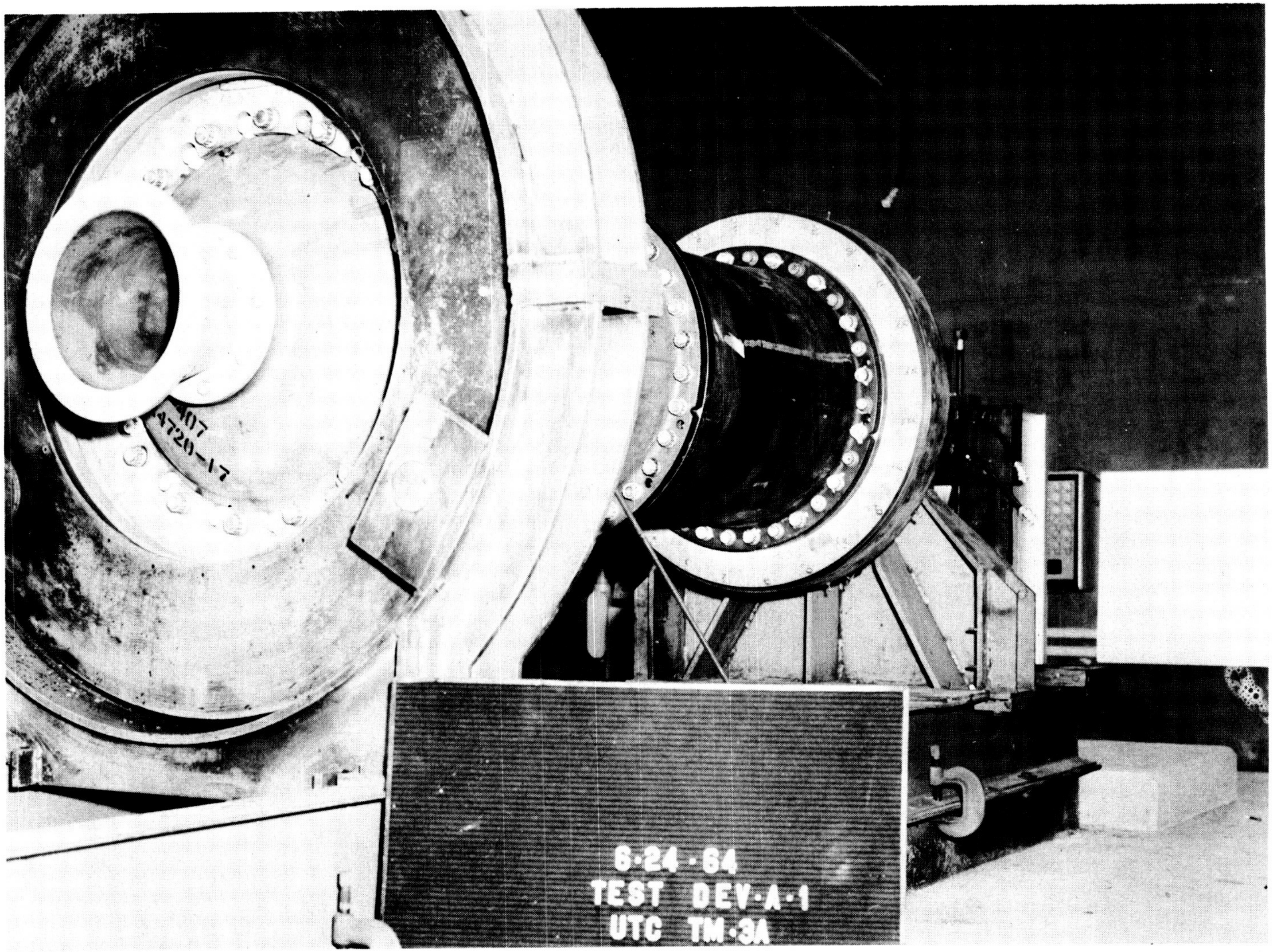

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Figure 18.- Prefire view of UTC TM-3A - spin test apparatus.

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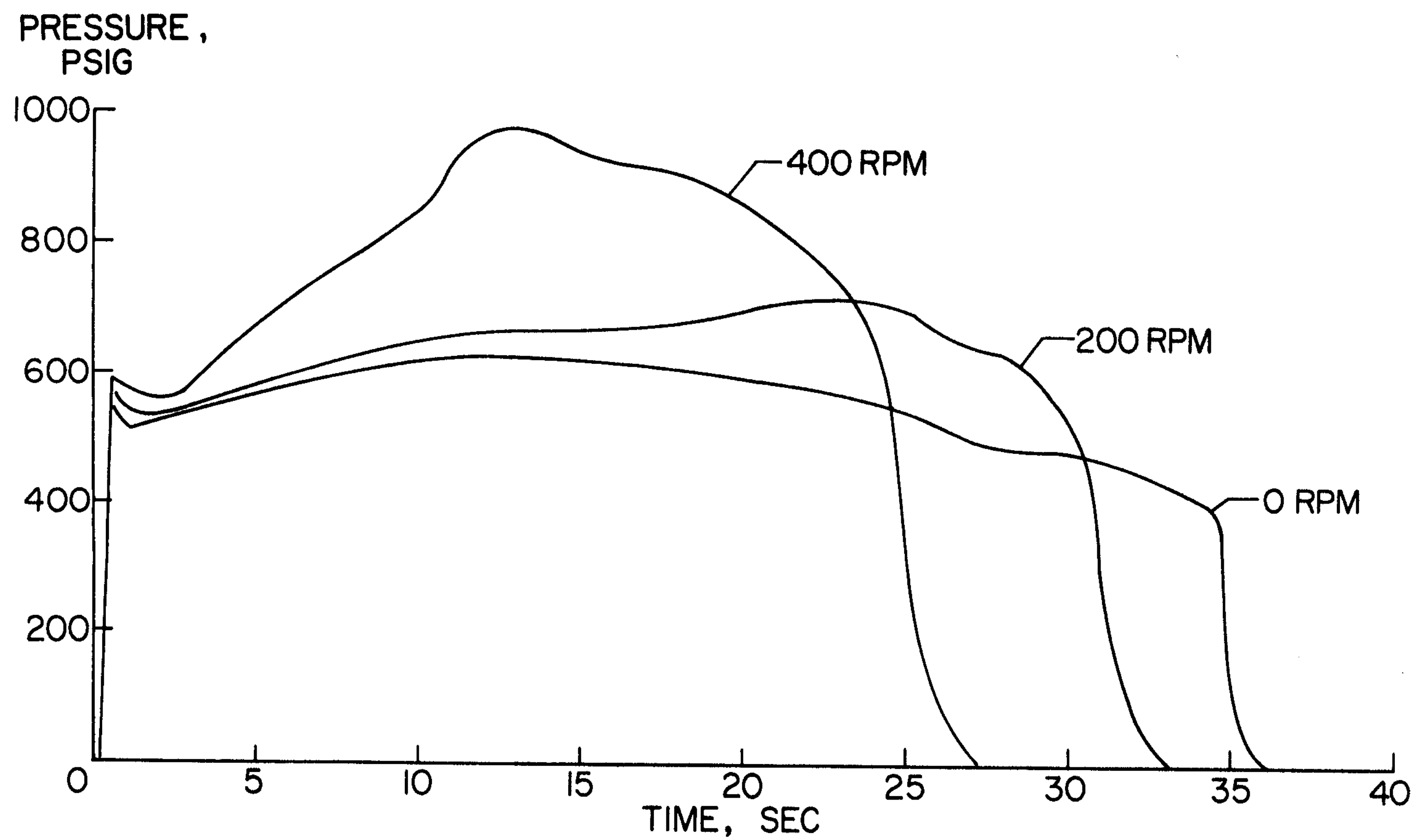

Figure 19.- Pressure history of TM-3 motors in spin and nonspin environment.