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ASSURANCE OF LUBRICANT SUPPLY IN WET-LUBRICATED SPACE BEARINGS

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ABSTRACT

Recent research and development have made available two significantly new and different techniques for providing greater assurance of ample lubricant supply for bearings in despin assemblies and momentum wheels. Conventional lubrication techniques appear to be satisfactory, but rigorous proof of meeting a ten-year life requirement is lacking. One new approach provides additional lubricant only when commanded from ground control, while the other passively augments lubrication at all times. Each technique has specific advantages, and selection should be related to the application to obtain optimum performance.

INTRODUCTION

Early satellites were spin-stabilized and contained no moving parts, but advancing technology soon dispelled this state of simplistic bliss. Now we find that virtually all satellites contain critical applications of wet or dry lubricated ball bearings that are essential to meeting basic mission requirements. A modern satellite, by actual count, has as many as 52 ball bearings, many of which are in single-string failure locations with regard to mission performance. Some of the most important applications involve oil-lubricated ball bearings in the despin assemblies of dual-spin satellites or oil and grease lubricated bearings in momentum wheels of body-stabilized satellites. Unlike some ball bearing applications, despin and wheel bearings must rotate continuously for the life of the satellite, which is commonly expected to be as much as 10 years. In spite of relatively outstanding success in space, stringent life and performance requirements have aroused cause for concern and a desire for greater assurance of lubricant supply for these critical ball bearings.

Two techniques have been developed by the Hughes Aircraft Company for providing greater assurance of lubricant supply. Each technique, one active and one passive, is being applied to a flight program and has undergone extensive trade studies, qualification testing and life testing.

CONVENTIONAL LUBRICATION TECHNIQUES

Despin Bearings

Ball bearings employed in despin assemblies generally have bore sizes ranging from 60 to 150 millimeters and operate in the range of 5 to 100 rpm. They are usually lubricated with a hydrocarbon oil impregnated into porous cotton-phenolic ball retainers. Oil is fed by capillary action from the retainers as required by the ball bearings to maintain an equilibrium thin film of oil on the balls and races. Oil may also be contained in reservoirs of impregnated porous material located adjacent to the ball bearings (Ref. 1). Tests and measurements indicate that the value of reservoirs is dubious, and they are usually regarded as sources of oil which may escape through labyrinth seals of the assembly rather than a source of lubricant replenishment for the bearings. Since bearings are usually warmer than adjacent reservoirs, vapor and surface transport of oil tend to be away from the bearings.

Since despin bearings run at low speeds, a rather viscous oil and light preloads are preferred to ensure lubrication in the elastohydrodynamic regime. Lubricant life and life of the bearings are expended in three stages (initial film, equilibrium film, and boundary), the duration of which is determined as indicated in Table 1. Accordingly, the life profile of oil film thickness in Intelsat IV or IVA bearings is depicted graphically in Figure 1. This analysis indicates that there is ample margin to achieve the design life of 10 years in orbit.

Life of despin bearings in orbit is demonstrated by Intelsat IV satellites, the first of which has operated successfully for over five years. Three more vehicles of this series have demonstrated nearly four years each of continuous operation at approximately 50 rpm (Ref. 3). Hughes also has a complete despin assembly with 150 millimeter bore bearings that has operated in a chamber at high vacuum for five and one-half years.

Table 1. Lubricant/ bearing life determination for Intelsat IVA despin bearings

STAGE	DESCRIPTION	BASIS FOR TIME DURATION	TIME YEAR.
1	Reduction of initial oil film to equilibrium oil film.	Intelsat IV historical data.	2-4
2	Gradual reduction of oil film from initiation of equilibrium film.	o Loss of oil through evaporation/migration due to temperature differential. o TACSAT historical data. o Bearing and lubricant characteristics.	10
3	Progression of metallic wear in boundary lubrication regime after loss of EHD film (Ref.2).	o Composite roughness of balls and races. o Lubricant characteristics. o Calculation based on empirical data.	0.5

Wheel Bearings

Sizes of ball bearings used in momentum wheels vary according to the angular momentum of the wheel, but a large range of momentum is achieved by several wheel manufacturers with 12 millimeter bore bearings supporting the wheel. A typical bearing arrangement consists of two pairs of angular contact bearings mounted in face to face configurations within individual labyrinth sealed cartridges. The cartridges are spaced on a common shaft to provide a wheel base (Ref. 4). Another arrangement employs a single pair of angular contact bearings with precision spacers between the clamped races in a back to back configuration, thereby providing the wheel base.

Momentum wheels supported on ball bearings usually operate in a speed range of 3,000 to 4,000 rpm, but speeds within the range of 1,000 to 6,000 rpm have been used. This range of speeds, combined with commonly used lubricants, preloads, and ball and race finishes, ensures elastohydrodynamic lubrication provided the oil film is adequately maintained by the lubrication system.

In a manner similar to that used for despin bearings, cotton-phenolic ball retainers are impregnated with oil to supply part of the lubrication. Since the amount of this oil is only one to three milligrams per bearing retainer, it is not regarded as the primary lubricant source. Additional oil may enter the ball-race interface region by bleeding out of grease adhering to the bearing rings, or it may migrate from porous oil-impregnated reservoirs or grease-filled reservoirs suitably located within the bearing enclosure.

Since the ball retainer provides a minor contribution to the lubrication life in wheel bearings and the mechanism by which oil is resupplied to the balls and races is varied and ill-defined, life expectancy is based largely on performance history. Successful operation in orbit is known to have occurred for five to six years, and similar continuous operating periods have been achieved with wheels operating in vacuum life tests.

NEW TECHNIQUES FOR ASSURANCE OF LUBRICANT SUPPLY

Life demonstrations for both despin and wheel bearings are impressive and, when coupled with analytical techniques, provide high confidence of satisfying a 10-year requirement. Analytical methods for predicting life of despin bearings are probably somewhat more established than those applicable to wheel bearings because of the availability of fairly extensive data on torque, temperatures and performance from satellites in orbit. These data, derived especially from TACSAT and Intelsat IV satellites, build confidence that the despin lubricant systems can last for more than ten years. Nevertheless, the desire always exists to increase the margin or to back up the system with an alternate. Toward this end, Hughes has developed two lubrication techniques that provide basically different approaches to augmenting the lubricant supply for greater assurance of long bearing life.

Relubrication by Command

The specifications for the Intelsat IVA and Comstar I satellites required that the despin bearing assembly include a feature that would permit adding oil to the bearings on command from ground control. Prior to contract award Hughes had applied research to this subject, had developed a working engineering model of a commandable oiler and had confirmed its performance. The oiler was applied directly to the Intelsat IVA and Comstar I satellites following optimization of size, weight and power consumption.

Before selecting the relubrication approach, numerous ideas were collected, evaluated and finally narrowed to three models for experimental demonstration. One approach had no moving parts, consisting of an annular metal cartridge which contained porous material impregnated with oil and a heater to cause the oil to evaporate. This device was mounted immediately adjacent to a bearing and was found to transfer oil by evaporative means. The approach was dropped because of high power consumption and poor efficiency; i.e., only about 35 percent of the oil given up by the cartridge reached the bearing. The method also suffered from indefinite control of quantity of oil transferred. The other two methods were both positive displacement types which delivered incremental quantities of oil with each stroke of a solenoid. Both of these approaches incorporated features to cope with cavitation or vapor lock, which occurred on an earlier feasibility model. This problem was solved in one version by employing a sealed bellows, the only outlet of which was a port normally closed by a check valve. The bellows was completely filled with degassed oil. Operation of the solenoid would cause a ratcheting mechanism to compress the bellows an incremental amount causing the check valve to open momentarily, allowing oil to pass through a duct to the bearing. This version of a solenoid-actuated oiler was abandoned for the following reasons:

- The bellows absorbed some of the impulse of the solenoid stroke, resulting in a low pressure for injecting oil into the bearing.
- The ratchet mechanism had wearing surfaces which required dry lubrication.
- The increment of oil ejected per stroke of the sc   ioid was larger than desired.

The selected oiler approach has a reservoir of oil contained in a chamber which includes a small cylinder. A piston, integral with the solenoid plunger, engages the cylinder when the solenoid is stroked. Since the moving plunger of the solenoid is contained within the oil chamber, the single moving part of the oiler is well lubricated. A quantity of oil equal to the volume of the cylinder (less leakage) is ejected from the oiler through a ball check valve at each stroke of the solenoid, thereby transferring oil in small known amounts. The oilers are oriented on the spinning bearing housing so that centrifugal force feeds oil from the chamber into the cylinder at all times. A breathing port on the oiler allows the escape of air from the interior of the oiler as the satellite enters the vacuum of space, but the port incorporates a series of fine-mesh screens which prevent the loss of oil during adverse orientation in earth's gravity. The oiler appears in cross-section in Figure 2, which illustrates the features described above. Table 2 provides design parameters of the oiler.

Table 2. Oiler functional parameters

Solenoid:	
Stroke	.317 inch
Coil Resistance	17.3 ohms
Excitation	30.5 volts
Current	1.76 amps
Power	54 watts
Time to Stroke	90 milliseconds
Oil System:	
Oil Supply	6.0 grams
Oil Pumped Per Stroke	45 milligrams
Strokes to Empty	130
Check Valve Opens	15 - 20 psig
General:	
Weight	0.85 pound
Diameter	2.25 inches
Length	2.78 inches

In the Intelsat IVA satellite, the coils of the two oilers are connected to simple pulsing circuits identical to the type used for commanding attitude control jets. When the despin bearing assembly is built, ducts made of 1/16 inch stainless steel tubing are installed into the housing to carry oil from the mounting surfaces of the oilers to the forward and aft bearings, respectively. Oil leaves the formed end of either duct with a velocity and direction which cause it to deposit directly onto the outer raceways of the bearings. Since the bearing is rotating at about 50 rpm, the balls immediately pick up the new oil and distribute it throughout the bearing. Figure 3 illustrates the mounting of oilers on the Intelsat IVA despin assembly. Each oiler is separately commandable so that either bearing may be reoiled independently.

Since Intelsat IVA satellites are in geosynchronous orbit, every six months an eclipse season is encountered. During several days at the height of each season, the temperature at the despin bearings changes about 15°F within a 24-hour period. Telemetry data on despin torque and bearing temperatures provide the inputs needed to calculate the oil film thickness in the bearings, and this result provides operators with an input for determining use of the oilers. (Ref. 3) Figure 4 is the torque-temperature profile of the F-4 satellite of the Intelsat IV series on 19 March 1972. These data indicated an oil film thickness of 500 microinches (early stage 1), which is sufficient to preclude use of oilers had they existed on the Intelsat IV. By March of 1975 the change in torque due to eclipse had reduced to much smaller values, indicating the initiation of stage 2. Similar conditions have occurred on other Intelsat IV satellites, indicating that they are following the classical lubrication profile.

Passive Relubrication

The cotton-phenolic ball retainer impregnated with oil has been a standard feature in wet-lubricated space bearings for many years. One of its shortcomings is the relatively small amount of retained oil ranging from about one to five percent by weight, a small fraction of which will actually feed to the bearing. This situation prompted Hughes to develop a ball retainer with much greater oil retention over the period 1971 to 1974. The result was the foam (nitrile acrylic copolymer) retainer illustrated in Figure 5 (Ref. 5). Retainers are illustrated with bearings having bore sizes of 60 and 12 millimeters, typical for despin bearings and momentum wheels, respectively. Foam retainers contain from 10 to 100 times more oil than cotton-phenolic retainers, and because of the small size of the capillaries which connect the numerous reservoirs within the foam cellular structure, the oil is metered to the bearing at a controlled rate to maintain the oil film. Thus, the foam retainer constitutes a passive oil replenishment technique with far greater capacity than the conventional approach.

The foam retainer has been applied to bearings having bore sizes of 150, 90, 80, 60, 12 and 6 millimeters. Vacuum life tests are presently running on four each of 60 and 12 millimeter bearings. The former, typical despin bearings, have been operating at 100 rpm for three and one-half years, and the latter, typical momentum wheel bearings, have been operating at 5,000 rpm for one year.

Because the capillaries in foam retainers average about 10 microns in diameter, they maintain a calculated 90 microinch thick film of oil on balls and races versus 20 microinches for cotton-phenolic retainers. This thicker film insures ample oil for elastohydrodynamic lubrication, but it also produces a higher oil churning torque. Consequently, despin bearings with foam retainers run at about a 20 percent higher torque than with cotton-phenolic retainers after equilibrium film has been established. The duration of stage 1 for despin bearings with foam retainers is comparable to that for bearings with cotton-phenolic retainers, but duration of stage 2 is calculated to be 122 years.

Figure 6 illustrates two momentum wheel fixtures, each containing four 12 millimeter bearings. One employs the baseline lubrication approach with cotton-phenolic retainers, while the other has foam retainers. As with despin bearings, the foam retainers maintain a higher equilibrium film of oil on the bearing metal than is the case with cotton-phenolic retainers. This causes a more severe running torque penalty, 1.1 ounce-inches versus 0.5 ounce-inch, because of the much higher operating speed. Continuation of life testing is required to provide data leading to possible application of foam retainers to wheel bearings.

The extensive life testing and excellent performance of foam retainers in despin bearings has resulted in their adoption for the despin assembly of the Pioneer Venus satellite.

CONCLUSION

The two lubricant augmentation approaches provide totally different solutions to satisfy the desire for greater lubrication assurance of wet-lubricated space bearings. Each has been adopted for flight, one already in orbit and one scheduled on a flight program. Table 3 shows an attempt to compare the relative advantages and disadvantages of the two techniques. This evaluation reveals that a clear-cut overall advantage does not exist for either approach, but rather that the choice should be made with relation to specific requirements of each application.

Table 3. Comparison of Oil Augmentation Techniques

ACTIVE REPLENISHMENT COMMANDABLE OILER	PASSIVE REPLENISHMENT FOAM RETAINER
ADVANTAGES	
1. Preserves flight-proven ball retainer.	1. No added weight or volume.
2. Augmented oil supply reserved for emergency.	2. Oil replenishment is automatic.
3. Replenishment by conscious command allows thinner oil films, less torque.	3. Failure modes are virtually non-existent.
DISADVANTAGES	
1. Weight and volume penalty.	1. Departure from flight-proven ball retainer.
2. Command channel(s) required.	2. Viscous friction torque is higher.
3. Failure modes exist.	3. Thick oil films can cause more torque variation.

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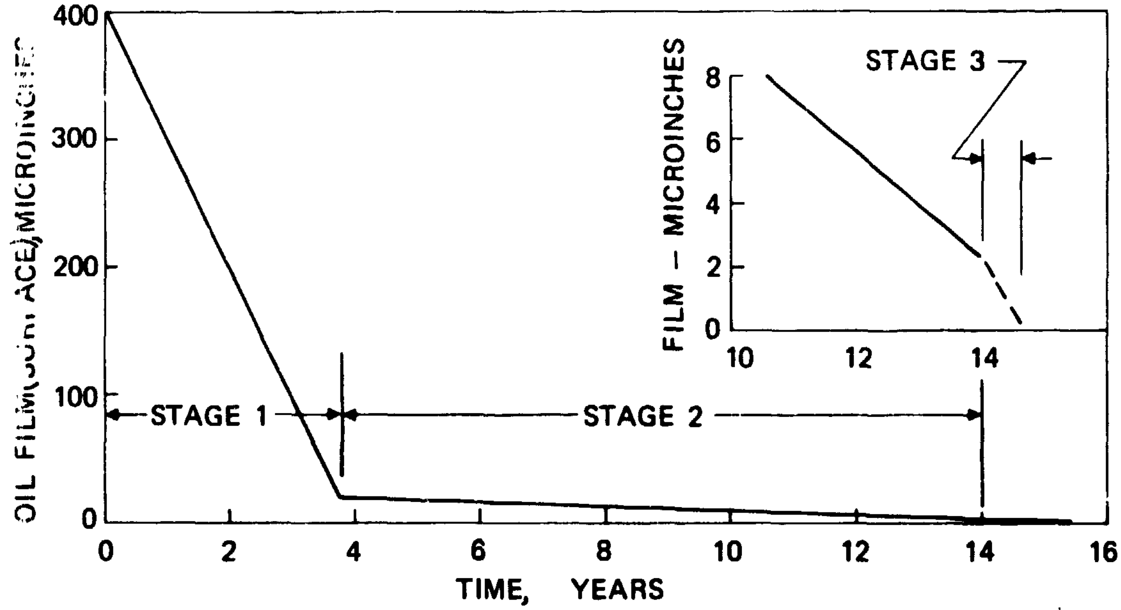

FIGURE 1. LIFE PROFILE OF OIL FILM THICKNESS IN DESPIN BEARINGS

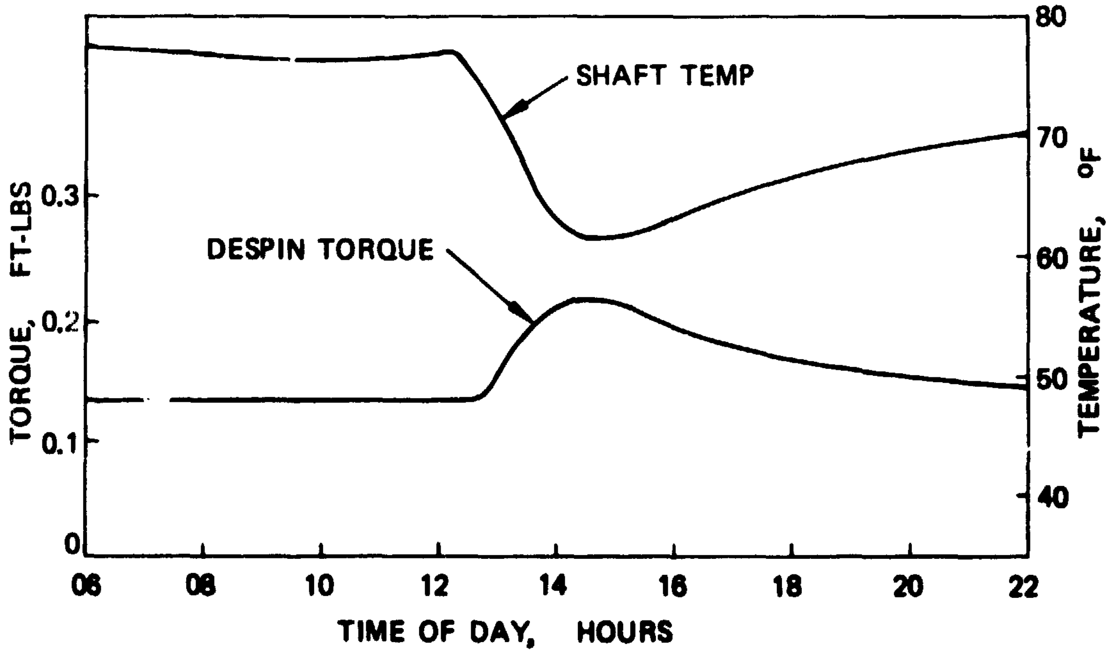

FIGURE 4. TORQUE/TEMPERATURE PROFILE OF INTELSAT IV, F-4, ON 19 MARCH 1972 DURING ECLIPSE

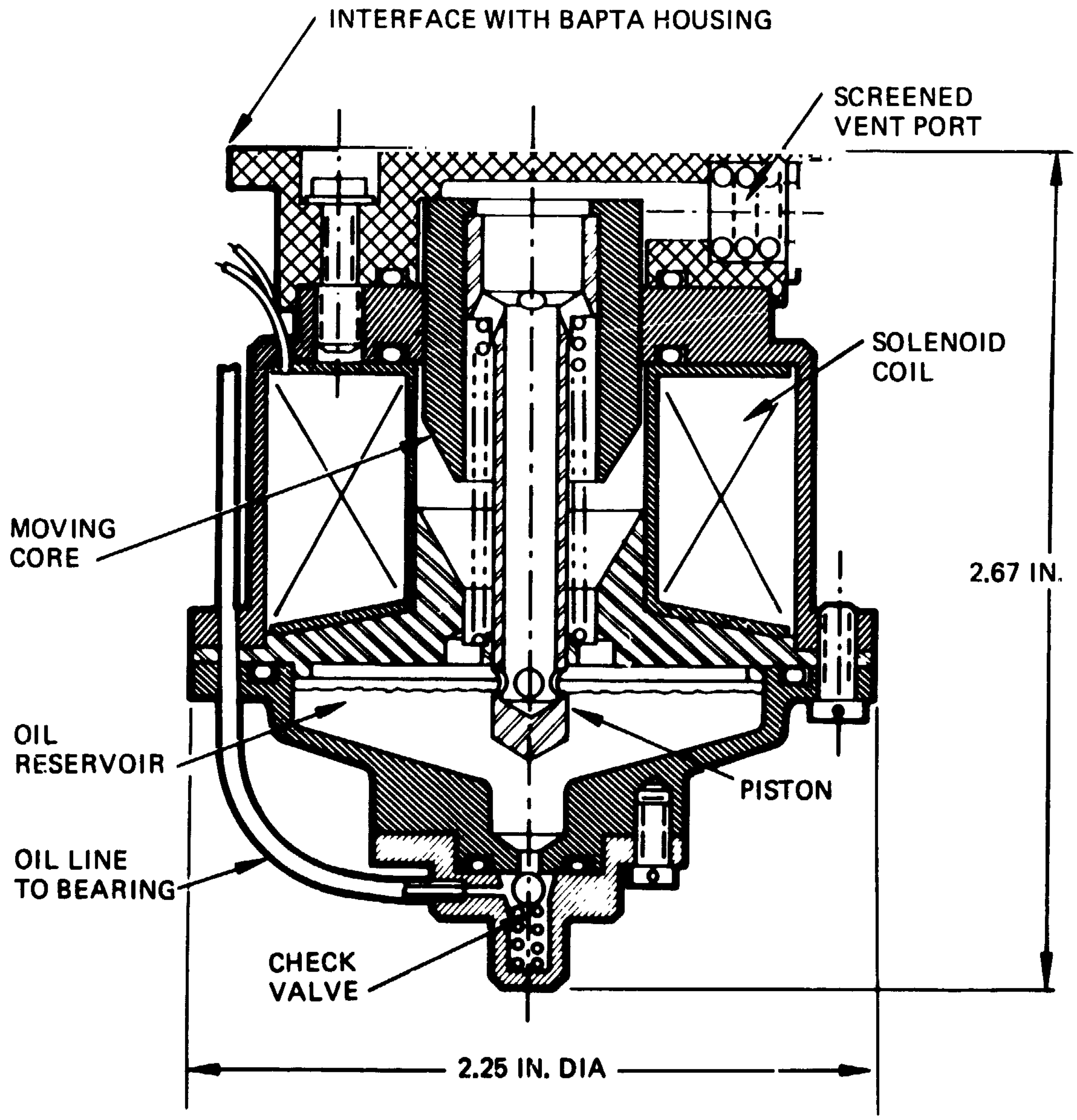

FIGURE 2. CROSS-SECTION OF SOLENOID-ACTIVATED OILER

Figure 3. Oiler Installation on Intelsat IVA Despin Assembly

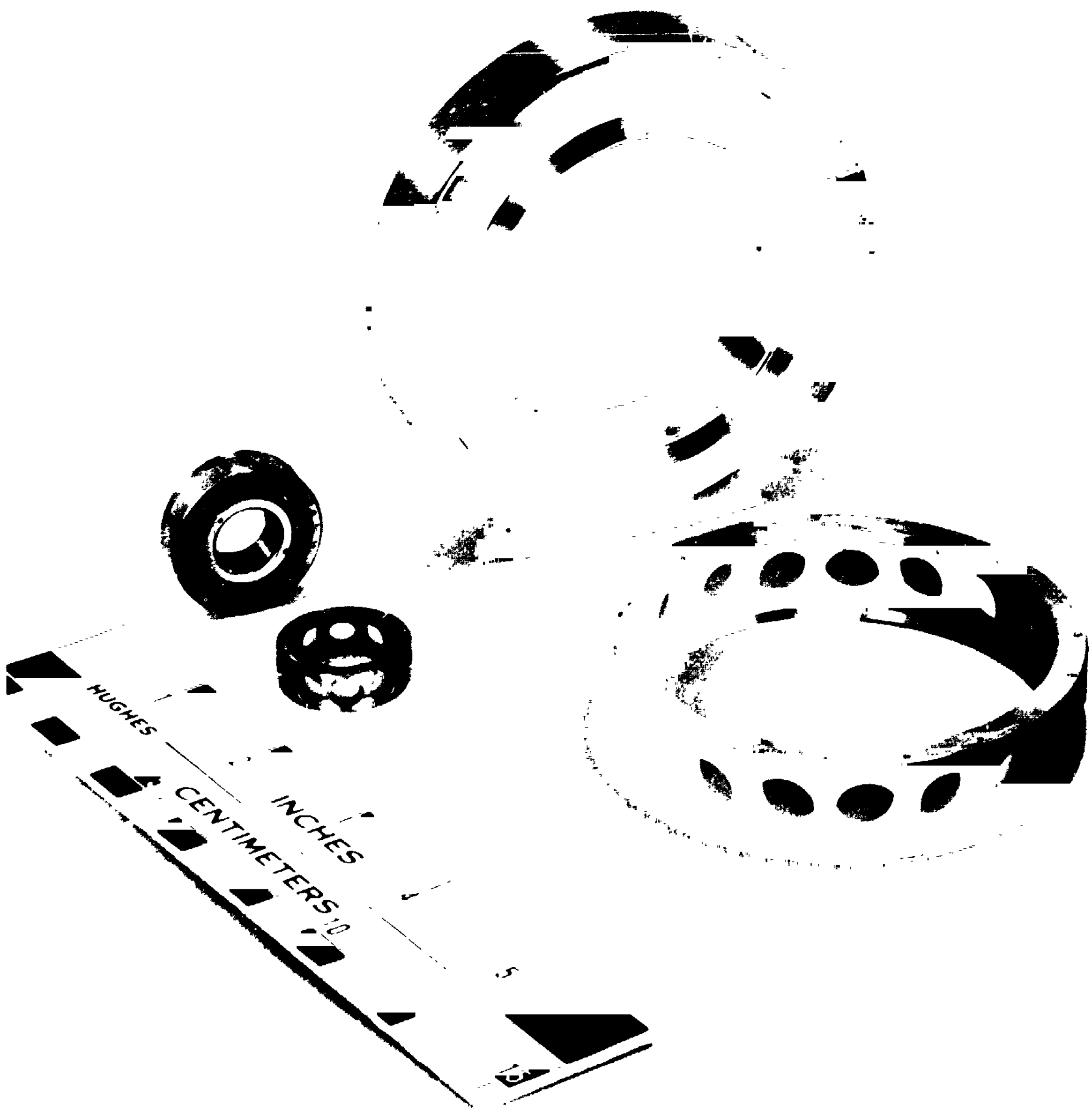

Figure 5. Foam Retainers with 60 and 12 mm Bearings

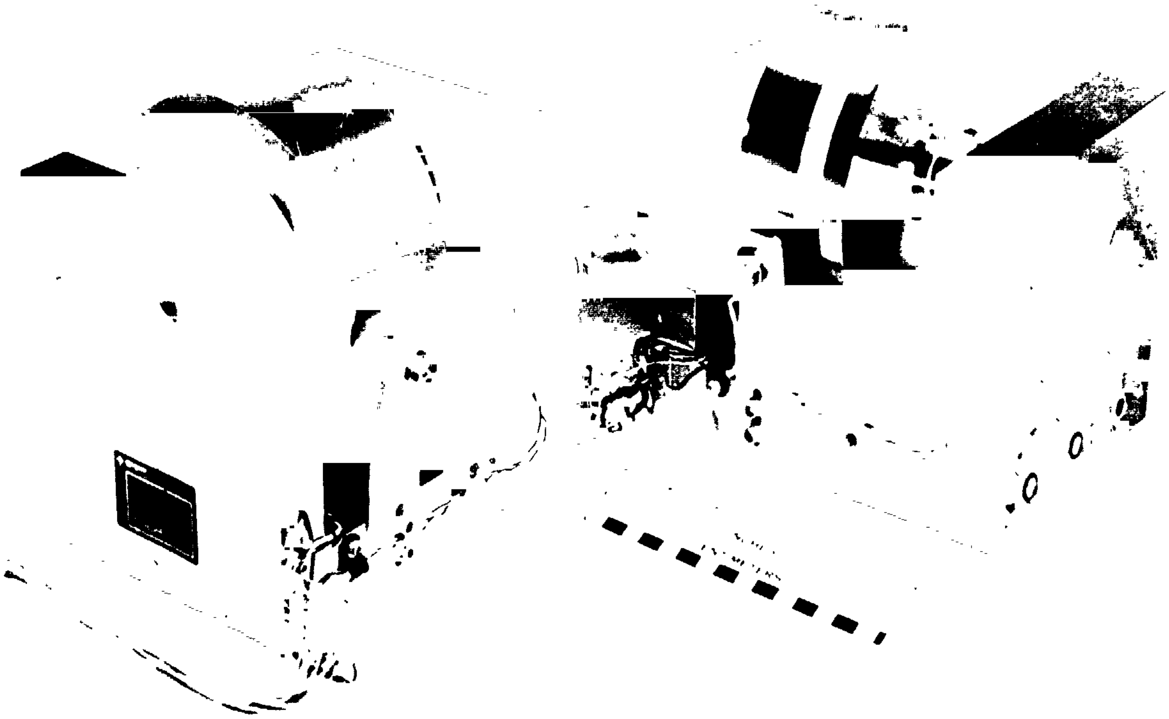

Figure 6. Momentum Wheel Fixtures in 5,000 RPM Life Test