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Test Facility Simulation Results for Aerospace Loss-of-Lubrication of Spur Gears

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Abstract

Prior to receiving airworthiness certification, extensive testing is required during the development of rotary wing aircraft drive systems. Many of these tests are conducted to demonstrate the drive system's ability to operate at extreme conditions, beyond that called for in the normal to maximum power operating range. One of the most extreme tests is referred to as the loss-of-lubrication or run dry test. During this test, the drive system is expected to last at least 30 min without failure while the primary lubrication system is disabled for predetermined, scripted flight conditions. Failure of this test can lead to a partial redesign of the drive system or the addition of an emergency lubrication system. Either of these solutions can greatly increase the aircraft drive system cost and weight and extend the schedule for obtaining airworthiness certification.

Recent work at NASA Glenn Research Center focused on performing tests, in a relevant aerospace environment, to simulate the behavior of spur gears under loss-of-lubrication conditions. Tests were conducted using a test facility that was used in the past for spur gear contact fatigue testing. A loss-of-lubrication test is initiated by shutting off the single into mesh lubricating jet. The test proceeds until the gears fail and can no longer deliver the applied torque. The observed failures are typically plastically deformed gear teeth, due to the high tooth temperatures, that are no longer in mesh. The effect of several different variables to gear tooth condition during loss-of-lubrication have been tested such as gear pitch, materials, shrouding, lubrication condition, and emergency supplied mist lubrication in earlier testing at NASA.

Recent testing has focused on newer aerospace gear steels and imbedding thermocouples in the shrouding to measure the air—oil temperatures flung off the gear teeth. Along with the instrumented shrouding, an instrumented spur gear was also tested. The instrumented spur gear had five thermocouples installed at different locations on the gear tooth and web. The data from these two types of measurements provided important information as to the thermal environment during the loss-of-lubrication event. This data is necessary to validate on-going modeling efforts.

Background and Introduction

The drive system used in rotorcraft applications is required to pass a 30-min loss-of-lubrication test prior to aircraft certification. This means that the drive system must continue to operate for 30 min with the primary lubrication system inoperative (Ref. 1). To achieve this capability, gears are extremely susceptible to failure due to a starved lubrication condition. High load, high pitch line velocity, or the combination of both can cause the gears, due to the meshing process, to heat to the point of failing.

Failure mechanisms of gear contacts can be summarized by Figure 1 (Ref. 2). In Figure 1, two of the mechanisms are of most importance for loss-of-lubrication. The first is the wear region where extreme loading at slower sliding speeds under starved lubrication conditions generates sufficient heat to expedite wear. The other region is the scoring region where high relative sliding of the teeth influences the heat being generated. In either case, the friction coefficient increases due to the loss of the full elastohydrodynamic fluid film, thus increasing the heat generation rate.

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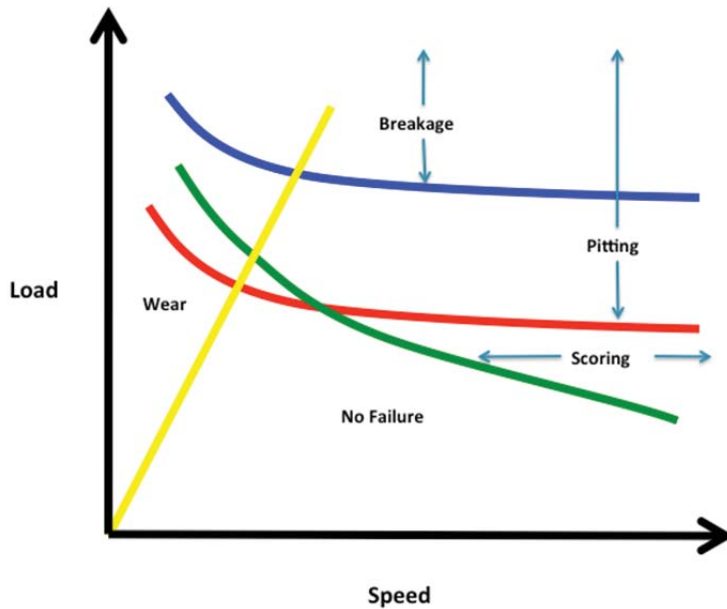


Figure 1.—Effects of speed and load on gear wear mechanisms.

Recent studies (Refs. 3 to 5) made initial attempts at evaluating the loss-of-lubrication behavior of tested components typically used at NASA Glenn for contact fatigue studies. In prior and current NASA testing, all tests were run in a dry sump manor, where all lubrication is jet fed and gravity drained. This type of lubrication system results in efficient operation of the drive system and is the lubrication mode typical in all rotorcraft main transmissions.

In these prior tests, many aspects were considered including run-dry conditions, vapor-mist lubrication, grease lubrication, test gearbox drainage, and shrouding. These test results indicated that testing in a relevant environment was essential for the generation of useful test results. Therefore, the current test arrangement evolved to represent an aerospace environment. Gear shrouding was used in all tests conducted in this paper.

The test results described in this paper document the on-going research assessment of aerospace quality components subjected to loss-of-lubrication conditions. Static instrumentation located in the gear shrouding was used on all tests. Also, one test gear was instrumented with thermocouples to provide temperature data on the gear. This gear was subjected to normal and loss-of-lubrication conditions. Results from these tests are described in this report.

Test Facility

The test facility used for conducting all loss-of-lubrication simulation tests is the NASA Glenn Contact Fatigue Test Facility (Refs. 6 to 8). The facility is shown in the sketch illustrated in Figure 2. The facility is a torque regenerative test rig that locks torque in the loop via a rotating torque applier. The test gears have a 1:1 ratio. Facility speed and torque can be varied as needed during a test. The basic gear design information of the tested gears is listed in Table 1.

As previously mentioned, the facility went through an evolutionary period (Ref. 5) where shrouding, visual access, gearbox lubricant removal, and instrumentation were added to the test section. A photograph of the current test gearbox arrangement is shown in Figure 3.

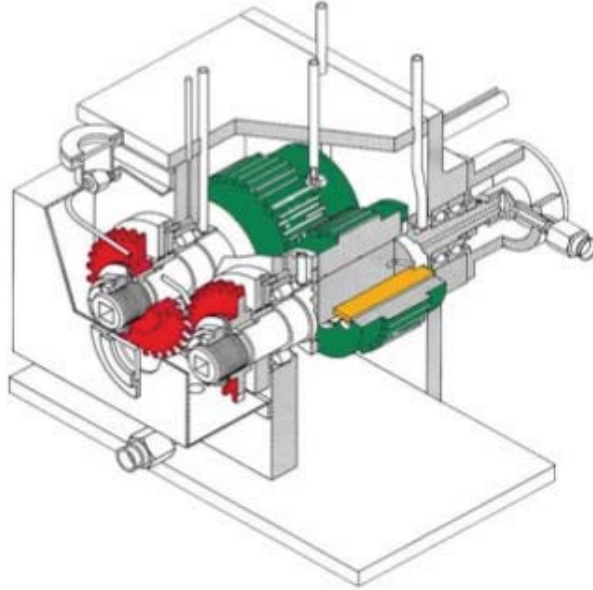


Figure 2.—Cross-sectional sketch of the test gearbox used for loss of lubrication testing.

TABLE 1.—BASIC GEAR DESIGN INFORMATION

	28 tooth gear
Module, mm [diametral pitch (1/in.)]	3.175 (8)
Pressure angle (deg.)	20
Pitch diameter, mm (in.)	88.9 (3.5)
Addendum, mm (in.)	3.175 (0.125)
Whole depth, mm (in.)	7.14 (0.281)
Chordal tooth thickness, mm (in.)	4.85(0.191)
Face width, mm (in.)	6.35 (0.25)

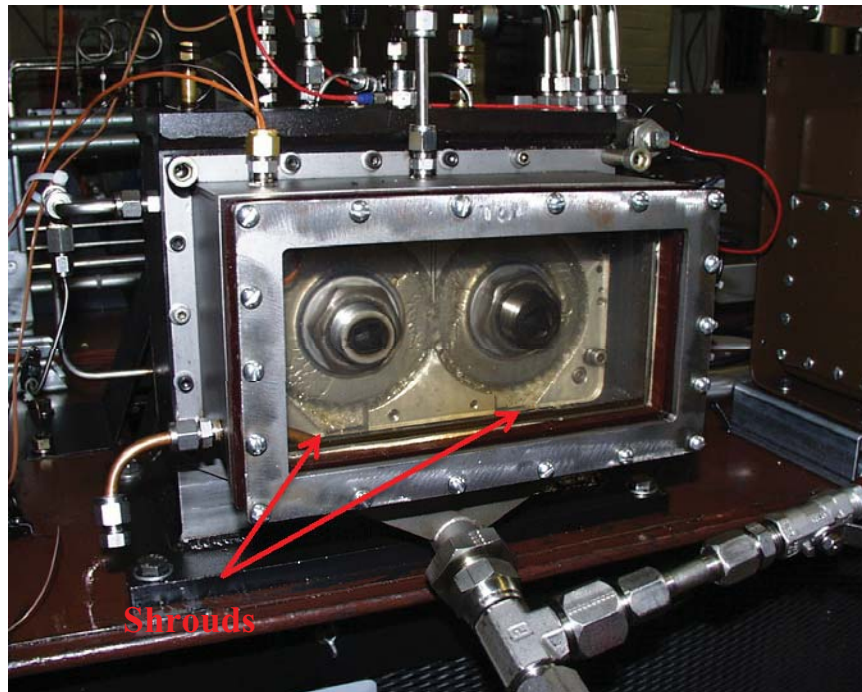


Figure 3.—Current test gearbox arrangement utilizing shrouds (bottom exit shown).

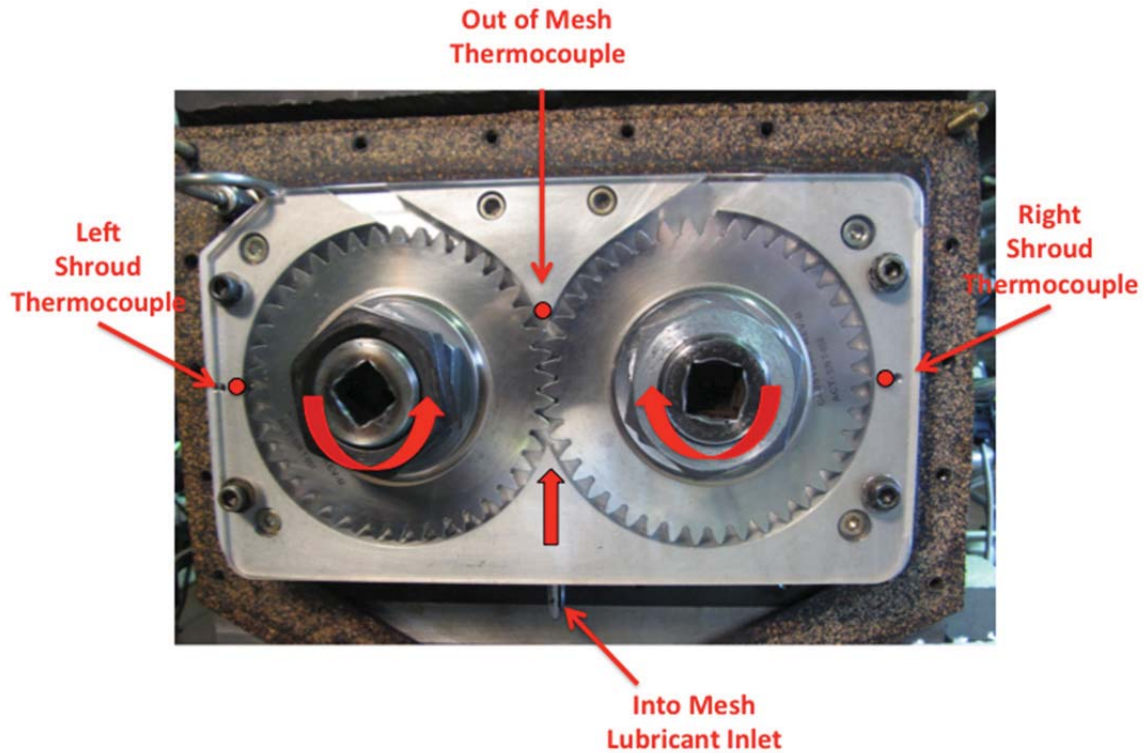


Figure 4.—Example of test gear arrangement with outer gearbox cover removed, top exit shrouds shown.

Static shroud thermocouples were utilized during all tests. High temperature glass was also utilized as the outside shroud to encase the gears. Ballistic plastic and another layer of high temperature glass provided visual (and video) access to the gears during operation. Lubricant for normal operation was fed at the into-mesh location through part of the shroud (Fig. 4). The normal operational flow rate was approximately 0.42 l/min (0.11 gpm) at 207 kPa (30 psig) jet pressure with the lubricant inlet temperature of ~110 °C (230 °F). Instrumentation and normal lubricant jet locations are shown in Figure 4. A turbine engine—drive system lubricant, MIL-L-85734, was used during the testing to be described in this report.

Testing Methodology

Prior to loss-of-lubrication testing discussed in this paper, the gears were broken-in to allow normal run-in wear to occur. The gears were operated for at least 1 hr at ~50 percent of maximum torque and at full facility speed (10000 rpm). After this period, the load was then increased to the maximum load and run for at least several more hours prior to conducting a loss-of-lubrication test. Most tests were run until the teeth failed to continue to carry torque (plastically deformed) or stopped just prior to this condition.

During all tests, the static instrumentation and live video were carefully monitored. Data from all sensors were collected at 1 Hz and stored for post-processing.

Testing and Discussion of Results

The test results to be described in this report were from the same lot of gears manufactured to the basic gear design information as shown in Table 1. The gear material was an aerospace gear steel (Ref. 9), that was carburized and final ground. The surface roughness was 0.41 micro-meters (16 micro-inch) or better. The gears have some tip relief starting at the highest point of single tooth contact and a small amount of crowning across the face width that is symmetric.

Five test results will be described in this report. The tests in the loss-of-lubrication condition were conducted at one of two load levels as documented in Table 2. The gear basic design information along with the load level produced maximum level of bending and contact stress found via the analysis technique of Reference 10.

An example of each of the two load levels will now be described. At the lower level of the two loads, two tests were conducted with the loss-of-lubrication time of 40.8 and 43.1 min in length. The data from the static thermocouples imbedded in the shrouds along with other facility temperatures is shown in Figure 5.

The gears in the post-test condition are shown in Figure 6. Note that the test was conducted until the gear tooth meshing heat generation and resultant temperature was high enough to plastically deform the gear teeth. This type of post-test condition occurred whenever the test was permitted to continue until total loss of torque delivery was achieved. A typical loss of lubrication failure at this condition is shown in Figure 7.

Two other tests were conducted at an elevated level of load (~83.6 N*m (740 in*lb)). These two tests, in the loss-of-lubrication mode, produced failures in 7.9 and 9.2 min. The test temperature data from the 7.9 min loss-of-lubrication test is shown in Figure 8. As can be seen from this data, the temperature did not reach an increased steady-state condition prior to increasing to failure as it did in the test shown in Figure 5. After the primary lubrication system was disconnected the temperature just continued to rise. The post-test condition of the test gears is shown in Figure 9 with the gearbox cover removed.

TABLE 2.—TEST CONDITION STRESS ANALYSIS RESULTS (REF. 10)

Torque	Maximum contact stress	Maximum bending stress
N*m (in*lb)	GPa (ksi)	GPa (ksi)
59.3 (525)	1.67 (242)	0.214 (30.9)
83.6 (740)	1.88 (272)	0.296 (43)

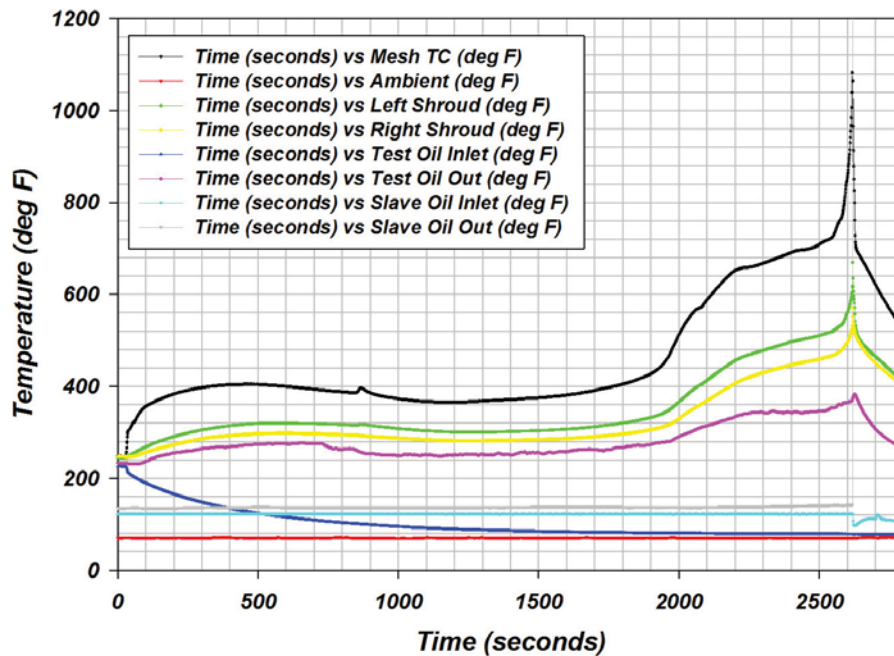


Figure 5.—LOL data for 1.72 kPa (250 psi) load pressure ~59.3 N*m (540 in*lb) torque tested at 10000 rpm.

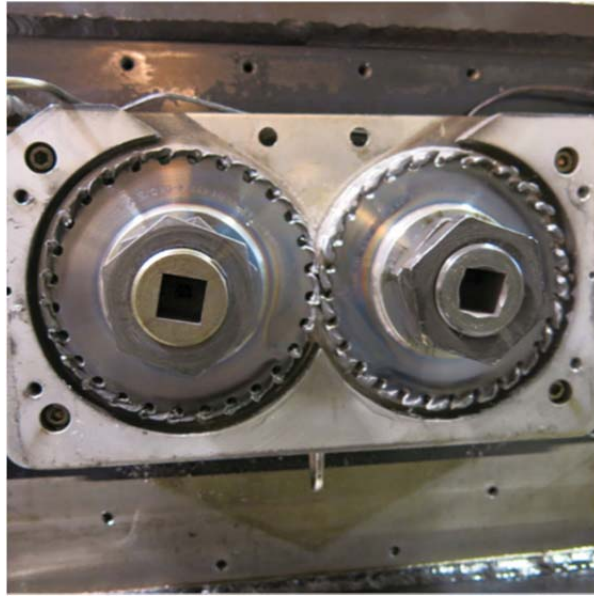


Figure 6.—Post-test condition of the gears (gearbox cover and outer high temperature glass removed).

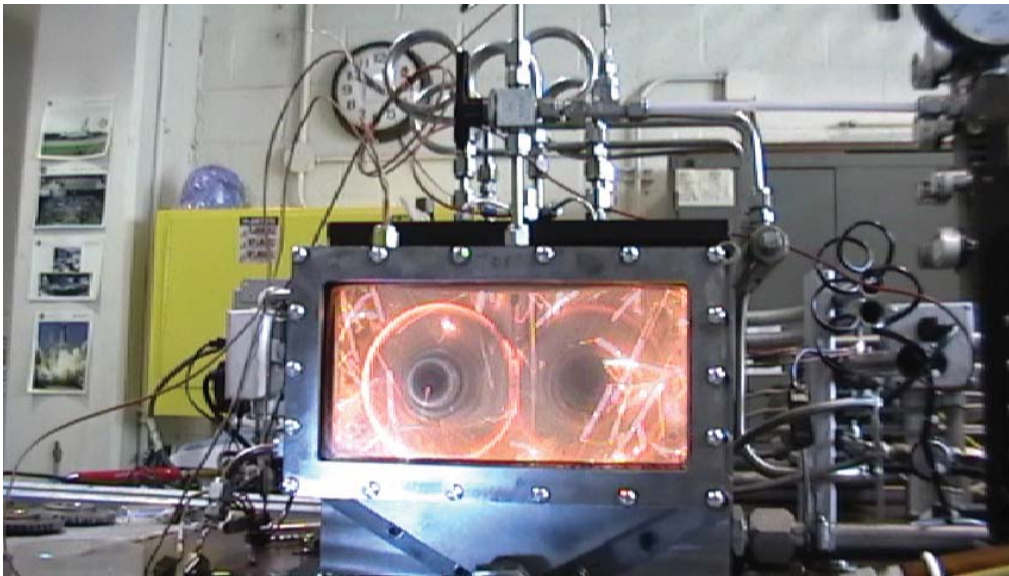


Figure 7.—Example of loss-of-lubrication test during final seconds of operation.

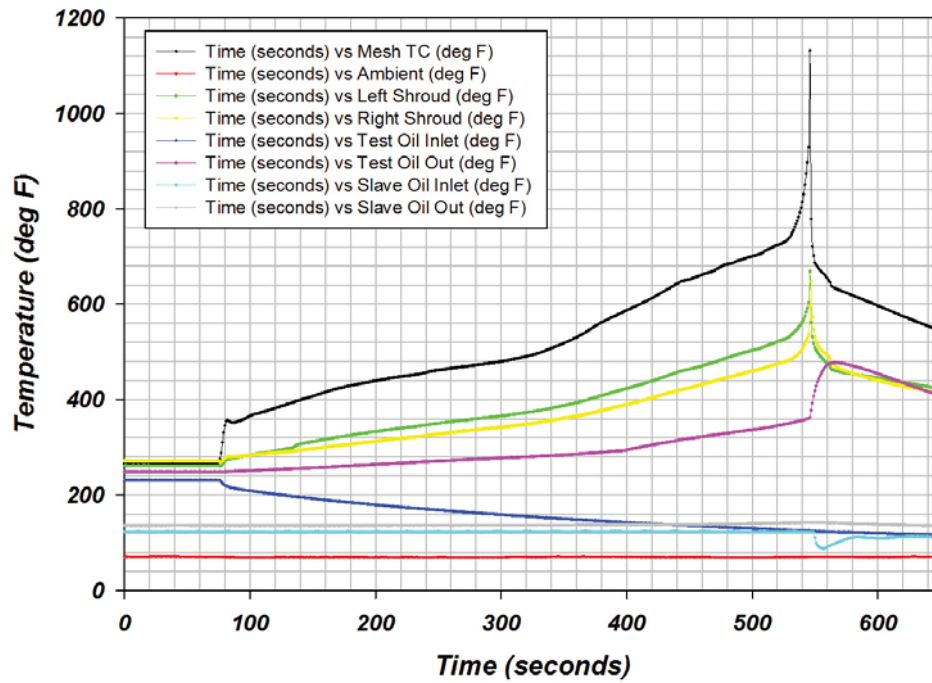


Figure 8.—Loss-of-lubrication data from higher load test 83.6 N*m (740 in*lb).

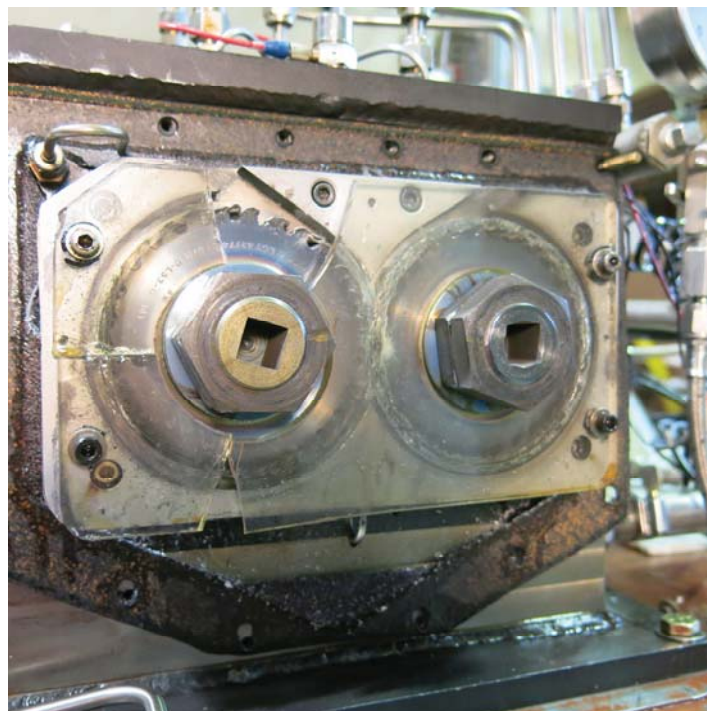


Figure 9.—Post-test photograph of increased load test gears with outer shroud high temperature glass fractured.

Instrumented Gear Test

The most desired test for loss-of-lubrication behavior is to have on-component information. While it would be of great benefit to have instrumentation at the gear-meshing surface, this has been shown to be very difficult to accomplish. Even with full elasto-hydrodynamic film the lubricant viscosity of turbine engine lubricants, as used in rotorcraft drive systems, is insufficient to develop films thick enough to keep the on-surface instrumentation from wearing away. Therefore, thermocouples were installed at locations in areas of the gear where contact does not occur were used.

The gear used in these tests is shown in Figure 10. It was the gear installed in the left side of the gearbox. The left side gear acts as the driving gear of the test section of the facility. A total of five thermocouples were attached to the gear at the tooth tip mid-face width, root mid-face width, and on the side of the gear at the pitch radius, root radius and mid-web locations. As shown in Figure 10, the thermocouple wires were covered by a thin metal foil that was spot welded to the side of the gear to protect the instrumentation during operation. The rest of the required hardware is shown in Figure 11 prior to installation in the test rig. The assembly in the test rig is shown in Figure 12.

Thermocouple Locations on Test Gear

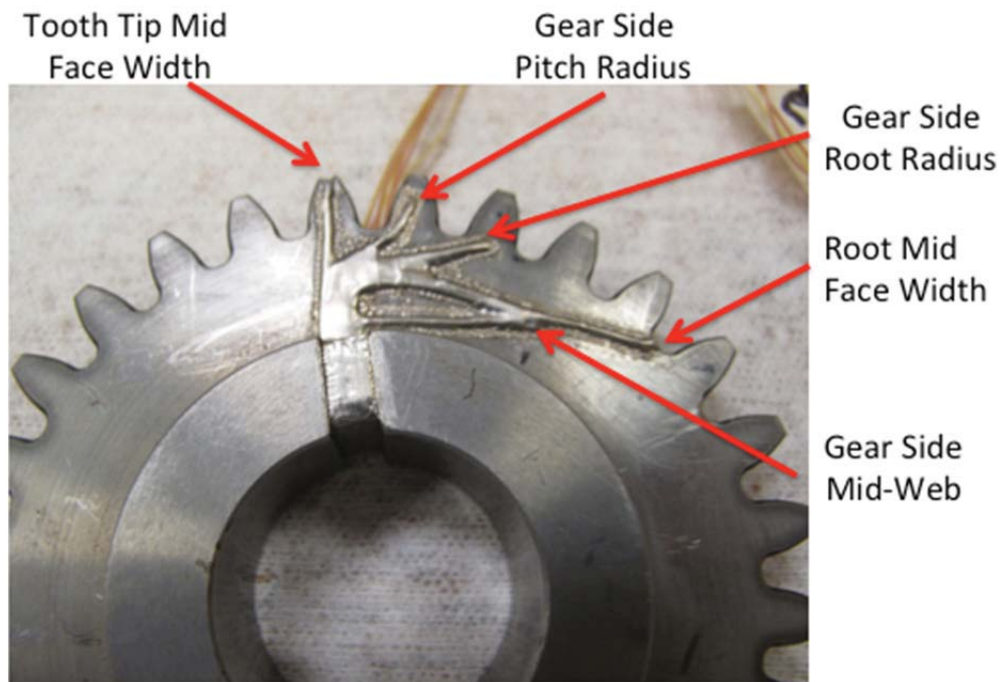


Figure 10.—Instrumented LOL test specimen before testing.

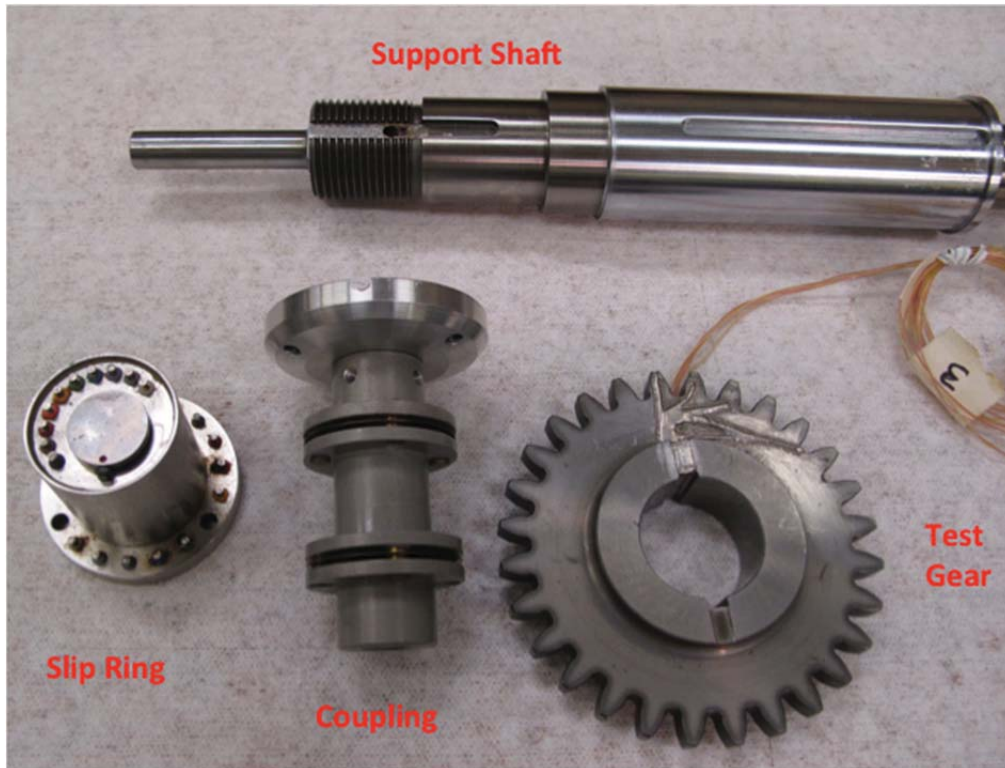


Figure 11.—Loss-of-lubrication test specimen and related components.

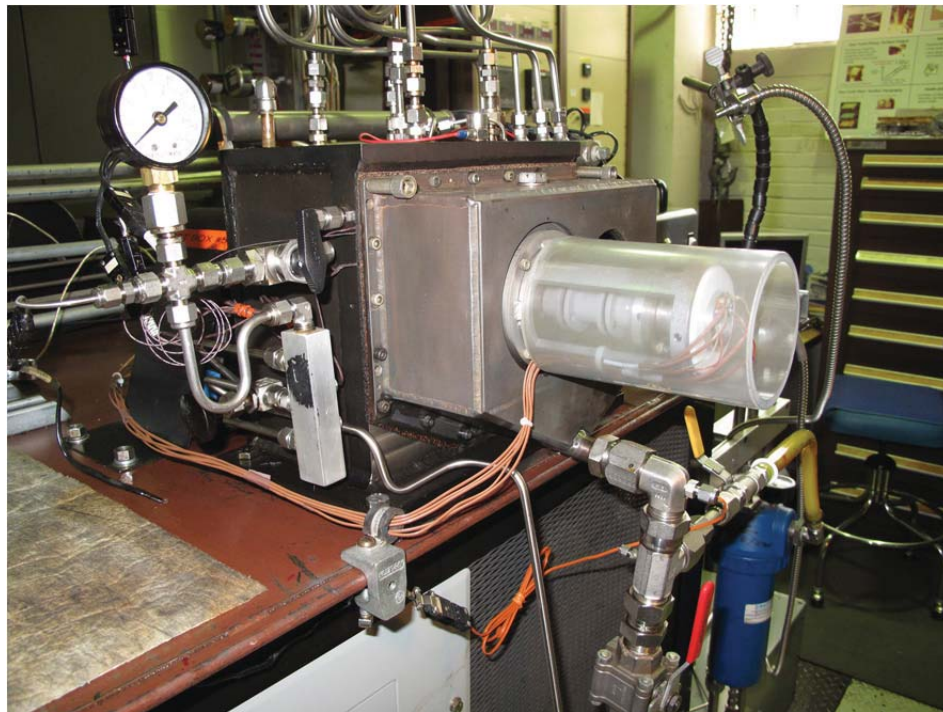


Figure 12.—Test setup for instrumented test gear.

The initial data for warm-up and operation of the facility in the normal to loss-of-lubrication mode is shown in Figure 13. During this same test the lubricant was shut off and the test run until failure. The data from loss-of-lubrication initiation to failure for the shroud (static) and other facility thermocouples is shown in Figure 14.

The data in Figures 13 and 14 indicate that the bulk temperatures of the gear were exceeding the temperature that was found from the static shroud thermocouples. In the normal lubrication condition this value was 20 to 40 °F depending on the location. In the loss-of-lubrication mode, this amount was as high as 500 °F higher on the gear than that of the static shroud thermocouples. In Figure 13, the data beyond 8200 sec is believed to be invalid due to post-test inspection of the thermocouple wiring that was melted together at the common locations through the shaft. The thermocouple wiring coating was exposed to bulk temperatures in the gear beyond the melting point of the wire coating.

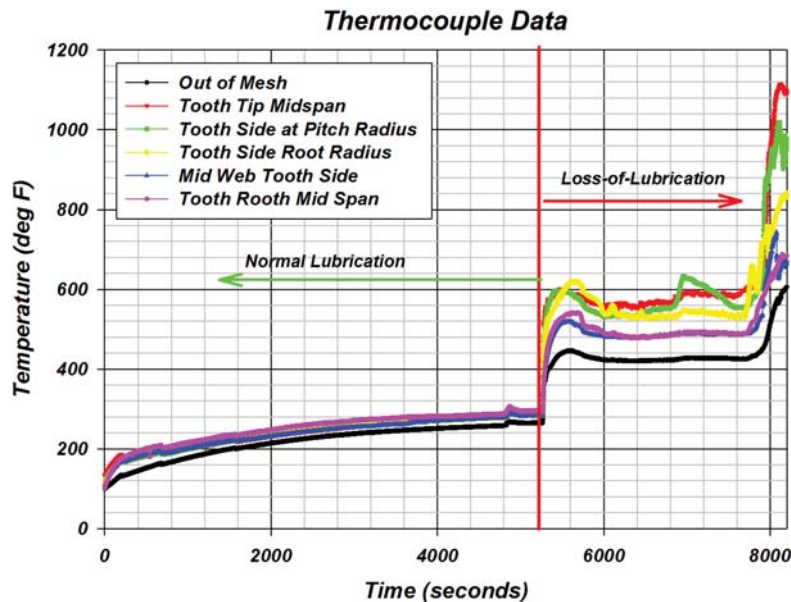


Figure 13.—On-gear and out-of-mesh thermocouple data from star-up to instrumentation failure during loss-of-lubrication.

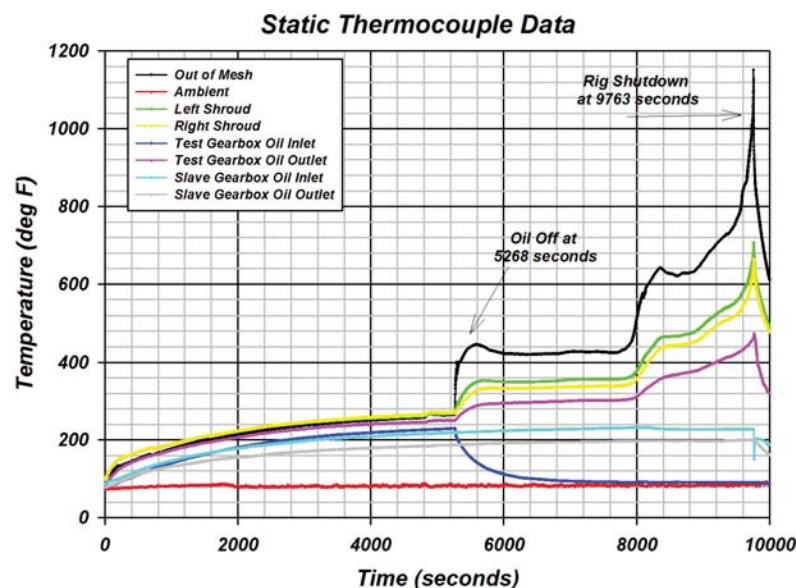


Figure 14.—Data from shroud and facility (static) thermocouples.

The post-test condition of the gears used in this test is shown in Figure 15. What can be noted is that a bending failure occurred before the loss-of-lubrication test, as the failed tooth has no evidence of running in this post-test condition. A hypothesis is that the failed tooth was initiated by a spot weld in the root-fillet region from the thin metal protection strap that was used to cover the thermocouple wiring.

In Figure 16, the tooth that failed in bending shows no apparent damage due to loss-of-lubrication since it occurred before this lubrication condition was initiated. Upon closer examination, the thin metal strapping used to overcoat the wiring and spot-welded to the tooth, was found to be the initiation site of the bending failure. Future test hardware for this purpose will not have this as a hold-down feature for the tooth root-fillet area.

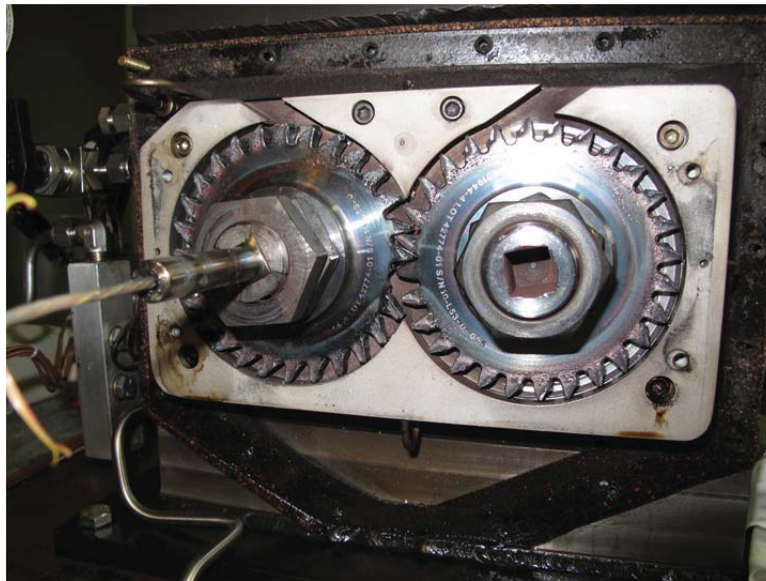


Figure 15.—Post-test condition after loss-of-lubrication test was completed. Gearbox housing, slip ring and outer high temperature glass removed.

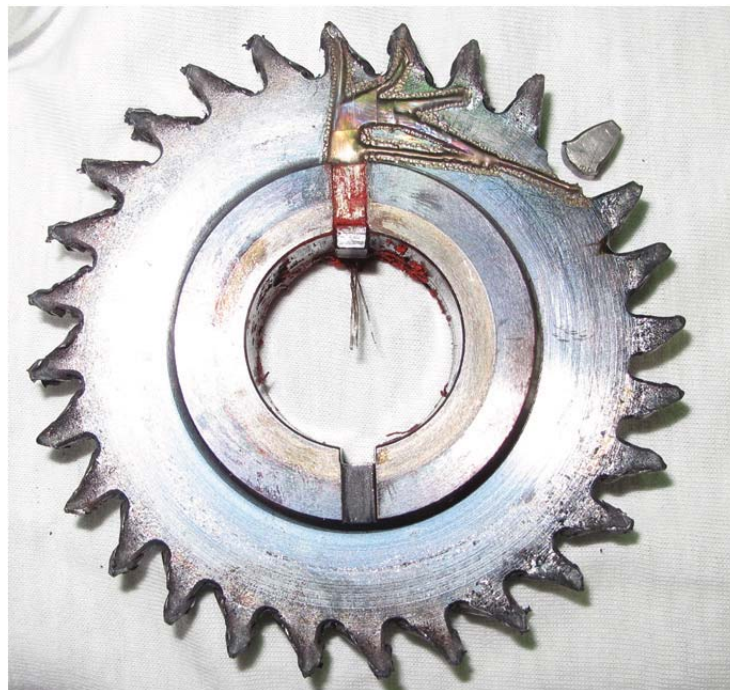


Figure 16.—Instrumented spur gear post-loss-of-lubrication test condition.

Conclusions

A series of five loss-of-lubrication tests were conducted in an aerospace simulated environment using consistent sets of test hardware. The following is a summary of the test results:

1. Applied torque can have a drastic effect on loss-of-lubrication time. An increase of torque by 40 percent, 59.3 to 83.6 N*m (525 to 740 in.-lbs) resulted in a decrease in loss-of-lubrication operation time by 75 percent (42 to 8 min).
2. Operation in loss-of-lubrication mode at lower torque produced an elevated steady state temperature condition. The higher torque level did not have this operating time at an elevated steady state temperature condition. During the higher torque tests, the temperature continued to increase until failure of the teeth.
3. On-component thermocouple data revealed that the gear under normal conditions have bulk temperatures that are 20 to 40 °F higher than the fling-off temperatures measured by the static shroud thermocouples.
4. On-component thermocouple data indicated that during loss-of-lubrication, conditions bulk temperatures on the gear are from 150 to 500 °F higher at certain times during this test mode when compared to the static shroud temperatures.

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