NASA/TM—2011-217106

Gear Mesh Loss-of-Lubrication Experiments and Analytical Simulation

Robert F. Handschuh, Joseph Polly, and Wilfredo Morales
Glenn Research Center, Cleveland, Ohio

November 2011

NASA STI Program . . . in Profile

Since its founding, NASA has been dedicated to the advancement of aeronautics and space science. The NASA Scientific and Technical Information (STI) program plays a key part in helping NASA maintain this important role.

The NASA STI Program operates under the auspices of the Agency Chief Information Officer. It collects, organizes, provides for archiving, and disseminates NASA's STI. The NASA STI program provides access to the NASA Aeronautics and Space Database and its public interface, the NASA Technical Reports Server, thus providing one of the largest collections of aeronautical and space science STI in the world. Results are published in both non-NASA channels and by NASA in the NASA STI Report Series, which includes the following report types:

- TECHNICAL PUBLICATION. Reports of completed research or a major significant phase of research that present the results of NASA programs and include extensive data or theoretical analysis. Includes compilations of significant scientific and technical data and information deemed to be of continuing reference value. NASA counterpart of peer-reviewed formal professional papers but has less stringent limitations on manuscript length and extent of graphic presentations.

- TECHNICAL MEMORANDUM. Scientific and technical findings that are preliminary or of specialized interest, e.g., quick release reports, working papers, and bibliographies that contain minimal annotation. Does not contain extensive analysis.

- CONTRACTOR REPORT. Scientific and technical findings by NASA-sponsored contractors and grantees.

- CONFERENCE PUBLICATION. Collected papers from scientific and technical conferences, symposia, seminars, or other meetings sponsored or cosponsored by NASA.

- SPECIAL PUBLICATION. Scientific, technical, or historical information from NASA programs, projects, and missions, often concerned with subjects having substantial public interest.

- TECHNICAL TRANSLATION. English-language translations of foreign scientific and technical material pertinent to NASA's mission.

Specialized services also include creating custom thesauri, building customized databases, organizing and publishing research results.

For more information about the NASA STI program, see the following:

- Access the NASA STI program home page at *http://www.sti.nasa.gov*

- E-mail your question via the Internet to *help@sti.nasa.gov*

- Fax your question to the NASA STI Help Desk at 443–757–5803

- Telephone the NASA STI Help Desk at 443–757–5802

- Write to:
  NASA Center for AeroSpace Information (CASI)
  7115 Standard Drive
  Hanover, MD 21076–1320

NASA/TM—2011-217106

Gear Mesh Loss-of-Lubrication Experiments and Analytical Simulation

Robert F. Handschuh, Joseph Polly, and Wilfredo Morales
Glenn Research Center, Cleveland, Ohio

Prepared for the
67th Annual Forum and Technology Display (Forum 67)
sponsored by the American Helicopter Society (AHS)
Virginia Beach, Virginia, May 3–5, 2011

National Aeronautics and
Space Administration

Glenn Research Center
Cleveland, Ohio 44135

November 2011

Level of Review: This material has been technically reviewed by technical management.

Available from

NASA Center for Aerospace Information
7115 Standard Drive
Hanover, MD 21076–1320

National Technical Information Service
5301 Shawnee Road
Alexandria, VA 22312

Available electronically at http://www.sti.nasa.gov

Gear Mesh Loss-of-Lubrication Experiments and Analytical Simulation

Robert F. Handschuh, Joseph Polly,* and Wilfredo Morales
National Aeronautics and Space Administration
Glenn Research Center
Cleveland, Ohio 44135

Abstract

An experimental program to determine the loss-of-lubrication characteristics of spur gears in an aerospace simulation test facility has been completed. Tests were conducted using two different emergency lubricant types: (1) an oil mist system (two different misted lubricants) and (2) a grease injection system (two different grease types). Tests were conducted using a NASA Glenn test facility normally used for conducting contact fatigue. Tests were run at rotational speeds up to 10000 rpm using two different gear designs and two different gear materials. For the tests conducted using an air-oil misting system, a minimum lubricant injection rate was determined to permit the gear mesh to operate without failure for at least 1 hr. The tests allowed an elevated steady state temperature to be established. A basic 2–D heat transfer simulation has been developed to investigate temperatures of a simulated gear as a function of frictional behavior. The friction (heat generation source) between the meshing surfaces is related to the position in the meshing cycle, the load applied, and the amount of lubricant in the contact. Experimental conditions will be compared to those from the 2–D simulation.

Introduction

The drive system used in rotorcraft applications has to pass a 30-minute loss-of-lubrication test prior to aircraft certification. This means that the drive system must continue to operate for 30 minute with the primary lubrication system inoperative (Ref. 1). When a new drive system is being qualified, this test is typically the last of an exhausted list of tests that need to be successfully passed during the certification process. This one test can drastically alter a drive system's lubrication system configuration if a separate emergency lubrication system is necessary.

Gears are typically 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 to heat to the point of failing, when the teeth bend back and fail to provide power transfer. Failure at the contact of gears can be summarized by Figure 1 (Ref. 2).

Preliminary studies conducted recently (Refs. 3 and 4) have made some initial attempts at evaluating the loss-of-lubrication behavior of test hardware typically used at NASA Glenn for contact fatigue studies. There has been some minimal progress made in these studies, however, duplicating the aerospace environment required modification of our contact fatigue test facilities to better mimic a rotorcraft drive system. These modifications will be mentioned later in this study.

All tests were run in a dry sump manner, where all lubrication is jet fed and gravity drained. This type of lubrication system results in efficient operation of the drive system. If the gears were to dip into the lubricant, the power loss would become quite large which is not representative of aerospace drive systems.

As can be seen in Figure 1, many combinations of rotational speed (sliding velocity) or load can push a design to failure even if the lubrication system is working correctly. Therefore, if conditions are borderline with respect to full fluid-film lubrication development, failure in a starved lubrication condition becomes even more of an issue.

The work discussed here describes the evolution of our test configuration from basic contact fatigue tests to tests representative of an aerospace drive system. The current system consists of a shrouded spur gear pair with a lubricating jet and provisions for emergency lubrication systems. The front cover of the shroud is made from high temperature glass to permit operation to extremely high temperatures while providing visual access to the gears. Several design parameters were varied during testing. The lubricant, delivery method, gear design, and gear material were all parameters altered during testing. All of these effects will be discussed in this study.

Test Facility

The test facility used for conducting all loss-of-lubrication simulation tests was the NASA Glenn Contact Fatigue Test Facility (Refs. 5 to 7). The facility is shown in the sketch contained 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 the same number of teeth on the driving and driven gears. Facility speed and torque can be varied if needed during a test. Two different test gear designs were utilized during the tests: the NASA contact fatigue test specimen (28 teeth) and a design version that had 42 teeth. The basic gear design information is contained in Table 1. The majority of the tests were conducted using the 42-tooth gear design.

*LERCIP Summer Intern

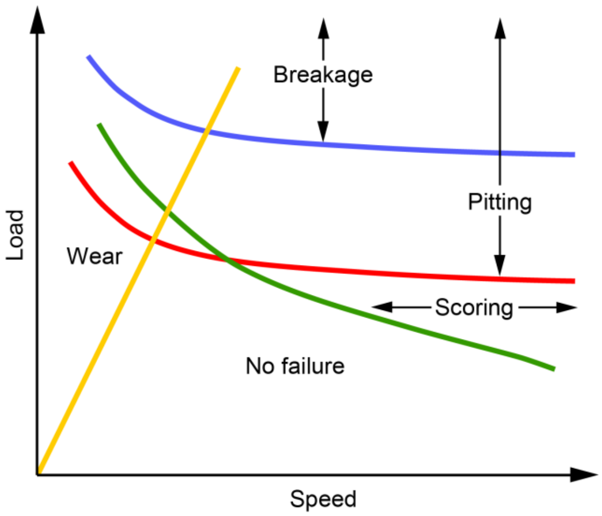

Figure 1.—Effects of speed and load on gear wear mechanisms.

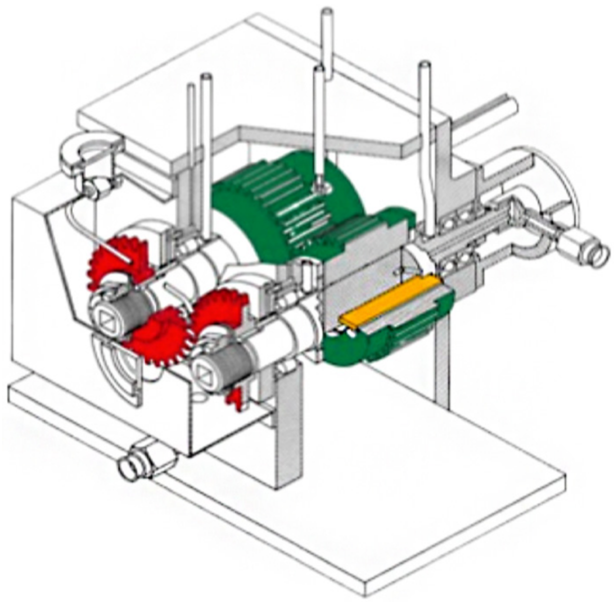

Figure 2.—Cross-sectional sketch of the test gearbox used for loss of lubrication testing.

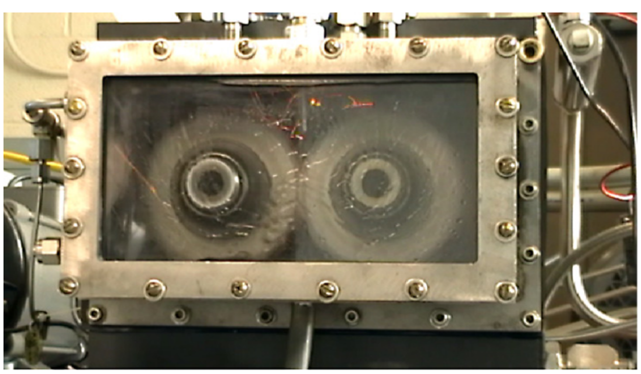

Figure 3.—Initial test gearbox arrangement during loss of lubricant testing.

TABLE 1.—BASIC GEAR DESIGN INFORMATION

	28 tooth gear	42 tooth gear
Diametral pitch (1/in.)	8	12
Pressure angle (deg.)	20	25
Pitch diameter (in.)	3.5	3.5
Addendum (in.)	0.125	0.083
Whole depth (in.)	0.281	0.196
Chordal tooth thickness (in.)	0.191	0.128
Face width (in.)	0.25	0.25

Over the period of time the tests were conducted a number of changes to the gear cover, drainage, and shrouding were made to make the test arrangement emulate an aerospace (rotorcraft) transmission. These modifications could affect the outcome of the type of testing conducted in this study. A number of cover and shroud combinations were tested at the nominal 10,000 rpm speed that the facility is operated at during the loss-of-lubrication tests. The initial test facility arrangement is shown in Figure 3.

Initially there was no shrouding, and drainage from the gearbox was not optimal. A deepened sump and shrouds of different configurations were assessed experimentally. The current arrangement used for conducting the tests is shown in Figure 4. A thin, high-temperature glass cover enabled visual inspection of the test section during normal and loss of lubrication testing.

A schematic of the emergency oil mist lubrication system tested is shown in Figure 5. The system used shop air to pick-up the lubricant supplied and formed an air-oil mist. The mist was then injected radially inward toward the gear axis of rotation at two locations. These two locations were located approximately 30° at the out-of-mesh location.

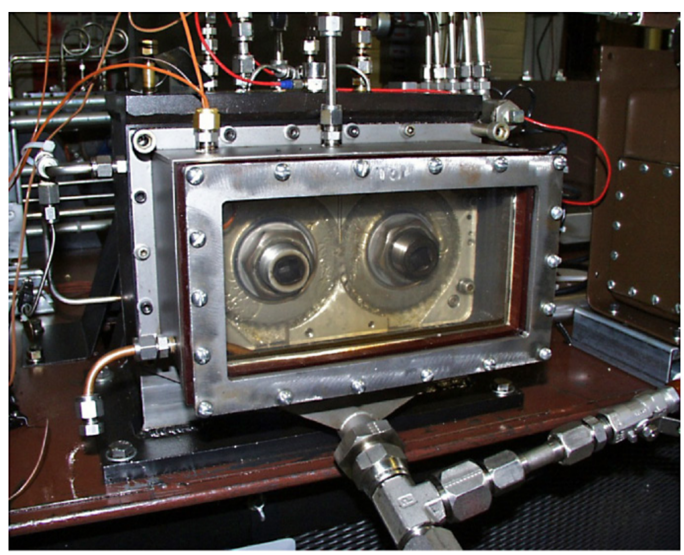

Figure 4.—Current test gearbox arrangement utilizing shrouds and improved lubricant drainage.

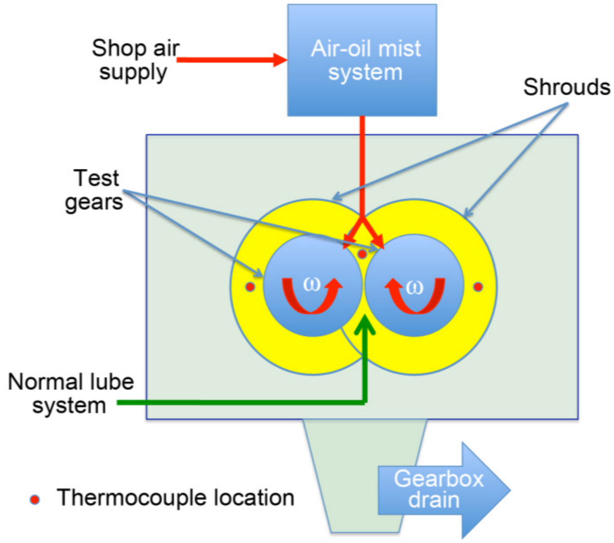

Figure 5.—Sketch of current air-mist lubrication system.


Figure 6.—Photograph of post-test gear that failed during testing.

Testing Methodology

The majority of the loss-of-lubrication tests were performed for the shroud, oil mist system, and modified gearbox cover configurations as follows. After all system parameters were at steady state (including oil inlet/outlet temperatures, lubricant flow rate, and facility parameters), the test was initiated. To initiate the test the normal lubricating jet flow was terminated. At this point the emergency lubrication system became operational. Testing was continued until failure to transmit torque or impending failure was reached. An example of a test that was operated until impending failure is shown in Figure 6.

When operating in the loss of lubrication mode, several parameters, including temperature within the test gearbox were monitored. For the mist system, the air-flow rate and air supply pressures were monitored. For the test gears, the temperatures measured within the gearbox were from the fling off directly out of mesh location and at sites 180° from the meshing location. No instrumentation of the gears were used during operation.

Test Results

The test results from all loss of lubrication tests conducted with an emergency lubricant will now be discussed. Tables 2 and 3 document the evolution of not only the test operation, but also includes changes to the shrouding, drainage, misting system, lubricant, and delivery method. Three series of tests were conducted with a total of 52 tests. The first series shown in Table 2(a) are tests conducted in a lubrication-starved mode. No additional lubricant was used other than what was applied via syringe prior to testing. The next series, Table 2(b), was mainly vapor-mist lubrication during the loss of primary lubrication event. The third series (Table 3) was an investigation of injected grease as a possible solution for increasing loss-of-lubrication performance.

Vapor-Mist Test Results

A total of 46 tests (Table 2(a) and (b)) were conducted using just a small amount of lubricant (no normal lubricant delivery system) or variations of the mist-lubricant delivery. During these tests, many parameters were changed such as the gearbox cover, shrouding, mist delivery system, gear size, gear material, and the mist lubricant. Many of these test conditions were only run once. Some general observations are provided below.

Gear Material and Backlash

Two gear materials were tested: AISI 9310 and M50. M50 was only used in five tests. The M50 and 9310 gears (8 diametral pitch) had excessive backlash from their final grinding step in manufacturing. Increased backlash is important for reducing the chance that the gears could jam during loss of lubrication events due to thermal expansion. For the limited number of tests, M50 appeared to last longer during loss-of-lubrication than the AISI 9310 for similar conditions.

TABLE 2.—(a) LOSS OF LUBRICATION TEST RESULTS SUMMARY FOR LUBRICANT STARVED CONDITIONS

Test no.	Diametral pitch, 1/in	Material, type	Serial no. left	Serial no. right	Shroud, Y/N	Backlash, in.	Gearbox cover	Emergency lubricant type	Total emer. lube used during test, ml	Flow rate, ml/min	Speed, rpm	Load pressure, psi	Test time to failure and comments
1	12	9310	EG-20	EG-21	N	0.004	Original	1	0.8	0	10000	250	Failed at 2.1 min, applied 1 drop / tooth with syringe
2	12	9310	EG-52	EG-62	N	0.004	Original	1	5	0	10000	250	Failed at 2.8 min, 5 ml syringed onto teeth
3	12	9310	EG-44	EG-40	N	0.0035	Original	1	0.5	0	10000	250	Failed at 2.18 min, 0.5 ml syringed onto teeth
4	8	9310	#0060	#0024	N	0.018	Original	1	5	0	10000	250	5 ml syringed on teeth, ran 61 min without failure
5	8	9310	#0024	#0060	N	0.018	Original	1	0.5	0	10000	250	Failed at 9 min, 0.5 ml syringed on teeth
6	8	M-50	1-8-1F	1-7-7K	N	0.009	Original	1	0.5	0	10000	250	Failed at 10.3 min, many teeth melted, 0.009 to 0.010 BL post test

(b) LOSS OF LUBRICATION TEST RESULTS FOR MISTED LUBRICATION

Test no.	Diametral pitch, 1/in	Material, type	Serial no. left	Serial no. right	Shroud, Y/N	Backlash, in.	Gearbox cover	Air flow rate, SCFM	Mister used	Mister air pressure, psi	Emergency lubricant type	Total emer. lube used during test, ml	Flow rate, ml/min	Speed, rpm	Load pressure, psi	Test time to failure and comments
1	8	M-50	1-8-2K	1-7-1K	N	0.014	Original	0.38	1	30	None	0	0	10000	250	No failure, ran greater than 60 min, temps as high as 640 °F
2	8	M-50	1-8-2K	1-7-1K	N	0.014	Original	0.38	1	30	None	0	0	10000	250	No failure after 88 min
3	8	9310	#0058	#0075	N	0.009	Original	0.42	1	38	1	NR	NR	10000	250	No failure, test ran greater than 180 min including mister air pressure lowered to 38 psi - 2 mister orifices out of mesh, T_{max}=376 °F
4	12	9310	T-067	T-034	N	0.004	Original	0.43	1	40	1	NR	NR	10000	250	Failed at 9 min, Mister at 40 psi, T_{max}=330 °F
5	12	9310	T-061	T-035	N	0.004	Original	0.38, 0.33	1	30, 20	1	NR	NR	10000	250	Failed at 48 min, changed mister pressure twice (30 and 20 psi), T_{max}=460 °F
6	8	9310	23	66	Y	0.015	Modified	NR	1	NR	1	41	0.342	10000	250	No failure after 120 min of operation, T_{max}=527 °F
7	8	9310	23	66	Y	0.015	Modified	NR	1	NR	None	0	0	10000	250	Failed at 20 min, T_{max} > 600 °F
8	8	9310	N0070	N0047	Y	0.0155	Modified	NR	1	30	None	0	0	10000	250	Failed at 23.3 min, T_{max} > 700 °F
9	12	9310	EG57	EG58	Y	0.005	Modified	NR	1	50	None	0	0	10000	250	Failed at 8 min, T_{max}=387 °F
10	12	9310	EG50	EG56	Y	0.005	Modified	0	1	0	None	0	0	10000	250	Failed at 4.7 min, T_{max} =427 °F
11	12	9310	EG48	EG43	Y	0.005	Modified	0.5	1	50	2	143	0.397	10000	250	No failure after 360+ min, T_{max} > 402 °F, 0.005 in backlash to start, 0.006 in. finish
12	12	9310	EG60	EG68	Y	0.005	Modified	0.5	1	50	1	259	0.682	10000	250	No failure after 380 min, no change to backlash, T_{max}=281 °F
13	12	9310	EG53	EG04	Y	0.003 to 0.0045	Modified	0.5	1	50	1	17	0.92	10000	250	Failed at 18.5 min, T_{max} =426 °F
14	12	9310	EG65	EG63	Y	0.005	Modified	0.5	1	50	2	61	2.65	10000	250	Failed at 23 min, T_{max} >580 °F
15	12	9310	EG65	EG63	Y	0.005	Modified	0.5	1	50	2	18	3	10000	250	Failed at 6 min, T_{max} > 500 °F
16	12	9310	EG48	EG43	Y	0.006	Modified	0.5	1	50	2	118	0.319	10000	250	No failure after 370 min of operation, T_{max}=620 °F
17	12	9310	EG29	EG22	Y	0.005	Modified	0.5	1	50	1	88	0.978	10000	150	No failure after 92 min of operation, T_{max}=270 °F
18	12	9310	EG29	EG22	Y	0.005	Modified	0.5	1	50	1	110	0.458	10000	150	No failure after 240 min of operation, T_{max}=278 °F
19	12	9310	EG47	EG46	Y	0.005	Modified	0.5	1	50	1	150	0.568	5000	250	No failure after 265 min of operation
20	12	9310	EG47	EG46	Y	0.005	Modified	0.5	1	50	1	13	0.159	10000	150	Failed at 18 min, T_{max} =750 °F

Test no.	Diametral pitch, 1/in	Material, type	Serial no. left	Serial no. right	Shroud, Y/N	Backlash, in.	Gearbox cover	Air flow rate, SCFM	Mister used	Mister air pressure, psi	Emergency lubricant type	Total emer. lube used during test, ml	Flow rate, ml/min	Speed, rpm	Load pressure, psi	Test time to failure and comments
21	12	9310	EG01	EG28	Y	0.005	Modified	0.5	1	50	None	0	0	5000	150	Failed at 7.75 min, T_{max} =350 °F
22	12	9310	EG13	EG15	Y	0.005	Modified	0.5	1	50	1	103	0.621	5000	250	No failure after 166 min of operation
23	12	9310	EG13	EG15	Y	0.005	Modified	0.5	1	50	1	200	0.563	7500, 10000	250	No failure after 355 min of operation, T_{max}=245 °F
24	12	9310	EG13	EG15	Y	0.005	Modified	2.4	2	23	1	18	0.3	10000	250	No failure after 62 min of operation, T_{max}=189 °F
25	12	9310	EG13	EG15	Y	0.005	Modified	2.4	2	23	1	13	0.217	10000	250	No failure after 58 min of operation, T_{max}=188 °F
26	12	9310	EG13	EG15	Y	0.005	Modified	2.4	2	23	1	20	0.333	10000	250	No failure after 60 min of operation, T_{max}=195 °F
27	12	9310	EG13	EG15	Y	0.005	Modified	1.75	2	10	1	4	0.138	10000	250	Failed at 29 min, T_{max} =324 F
28	12	9310	EG12	EG10	Y	0.005	Modified	2.4	2	23	1	15	0.092	10000	250	No failure after 163 min, T_{max}=286 °F
29	12	9310	EG19	EG17	Y	0.005	Modified	3.3	1	50	1	1.06	0.133	10000	250	Failed at 8 min, T_{max} >1000 °F
30	8	M-50	1-10-2F	1-7-4K	Y	0.01	Modified	2	1	50	1	31.5	0.525	10000	250	No Failure after 60 min, T_{max} =786 °F
31	8	M-50	1-10-2F	1-7-4K	Y	0.0125	Modified	3.3	1	50	1	8.52	0.142	10000	250	No failure after 60 min, T_{max}=741 °F
32	8	9310	33	32	Y	0.013	Modified	3.3	1	50	1	3.3	0.167	10000	250	Failed at 20 min. T_{max}=885 °F, post test backlash 0.025 in.
33	12	9310	EDG14	EDG11	Y	0.005	Modified	2.2	1	50	2	16.5	0.275	10000	250	No failure after 60 min, T_{max}=383 °F
34	12	9310	EDG-14	EDG-11	Y	0.005	Modified	3.3	1	50	2	1.5	0.166	10000	250	Failed at 9 min
35	12	9310	EAG-23	EAG-24	Y	0.005	Modified	3.3	1	50	2	0.444	0.0833	10000	150	Failed at 5.3 min
36	12	9310	EDG-006	EDG-016	Y	0.005	Modified	3.2	1	50	2	12	0.1	10000	150	No failure after 120 min of operation
37	12	9310	EG-76	EG-42	Y	0.005	Modified	1.1	3	45	1	40	0.666	10000	150	No failure after 60 min of operation
38	12	9310	EG-76	EG -42	Y	0.005	Modified	1.1	3	45	1	1	0.17	10000	150	Failed after 6 min
39	12	9310	EG-64	EG-69	Y	0.005	Modified	1.1	3	45	1	36.5	0.61	10000	250	No failure after 60 min of operation
40	12	9310	EG-54	EG-55	Y	0.005	Modified	1.2	3	45	None	0	0	10000	150	Failure after 3 min

Notes: Emergency lubricant 1, Reference 8, emergency lubricant 2, Reference 9.
NR, not recorded.
Gray shaded cells denote flow rate and amount not verified.

TABLE 3.—LOSS OF LUBRICATION TEST RESULTS SUMMARY USING GREASE (AISI 9310 MATERIAL).

Test no.	Diametral pitch, 1/in	Material, type	Shroud, Y/N	Backlash, in.	Gearbox cover	Emergency lube, type	Initial lube on gears, g	Grease injection rate, g/pulse	Speed, rpm	Load pressure, psi	Time to failure or test stopped, min
1	12	9310	Y	0.005	None	1	3.11	-----	2500 and 5000	150	None
2	12	9310	Y	0.005	None	1	3.99	-----	7500	150	9
3	12	9310	Y	0.005	Modified	1	3.16	0.16	7518	150	None
4	12	9310	Y	0.005	Modified	1	3.89	0.16	10000	150	~4
5	12	9310	Y	0.005	Modified	1	0	0.16	10000	150	30
6	12	9310	Y	0.005	Modified	2	0	0.35	10000	150	46

Note: Lubricant 1, Reference 10, and lubricant 2, Reference 11

Gearbox Cover Modifications, Shrouds, and Mist Delivery

The original gearbox cover did not drain as well as needed for conducting this type of test. The flat-bottomed, gravity drained test gear cover allowed extra lubricant to stay within the vicinity of the rotating gears. The cover was changed and the residual lubricant in the testing zone was reduced.

Another modification to the test facility included the addition of shrouds. Several designs were fabricated and tested until the present system evolved. The final arrangement is shown in Figure 4. This shrouding arrangement, with a high temperature glass cover, permitted test observation.

Mist Delivery System

Three different commercially available mist systems were used during testing. All three provided an acceptable mist during operation. The control over the amount of lubricant per cubic foot of air was an issue as the need to adjust this amount was important to our test program. The minimum flow rate to achieve long-term operation in the loss of primary lubrication mode was dependent on the amount of lubricant being utilized. For this test system, the minimum level for the gears operating at 10000 rpm and approximately 70 N*m (630 in.*lb) torque was approximately 0.3 ml/min (see Table 2(b)). Flow rates less than this amount often resulted in failure of the components prior to 30 minute.

Speed, Load, and Liquid Lubricants

For most tests the speed was set to the maximum for the facility (10000 rpm). However, several tests were run at 5000 rpm and different load levels. Tests ran with speed and load variation also experienced failure if emergency lubricant flow was too low or non-existent. Also, two different lubricants were used as vapor mist lubricants. Most of the tests used MIL-L-87354 (Ref. 8). Several tests were run using another high temperature lubricant (Ref. 9). No clear advantage was seen between the two lubricants tested.

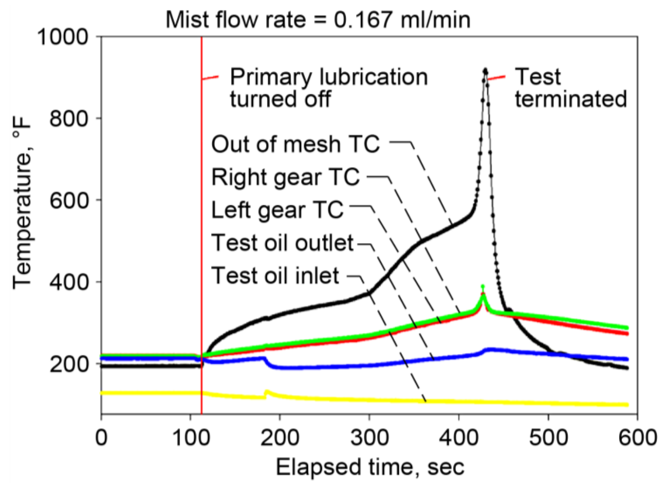

Figure 7—Loss of lubrication data from test that failed after 6 minute.

Example of Loss of Lubricant, Air-Oil Mist Tests

As an example of using a mist system, two tests will now be described. In one test the system failed after 6 minute of operation. The test data is shown in Figure 7. The flow rate of lubricant misted was 0.167 ml/min (Test no. 38, Table 2(b)). This test was halted as the temperature started to exponentially increase and the gears ended up operating such that a large amount of metal-to-metal contact was apparent. A photograph taken from a video of the test is shown in Figure 8.

In the second test (Test no. 37, Table 2(b)) the mist lubricant rate was increased to 0.67 ml/min. In this test no failure resulted and the temperature reached a new steady state after the initial increase at the time when the primary lubrication system was shut down. The test results are shown in Figure 9. The test was ended after 1 hr of operation in this mode of lubrication and it is assumed that it would continue operation in this mode for some time, as evidenced by the temperature plots.

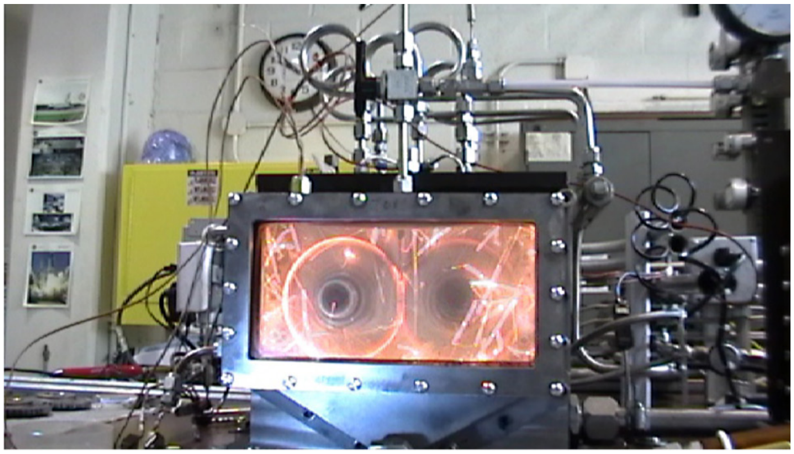

Figure 8.—Photograph of gears in action during final seconds of operation.

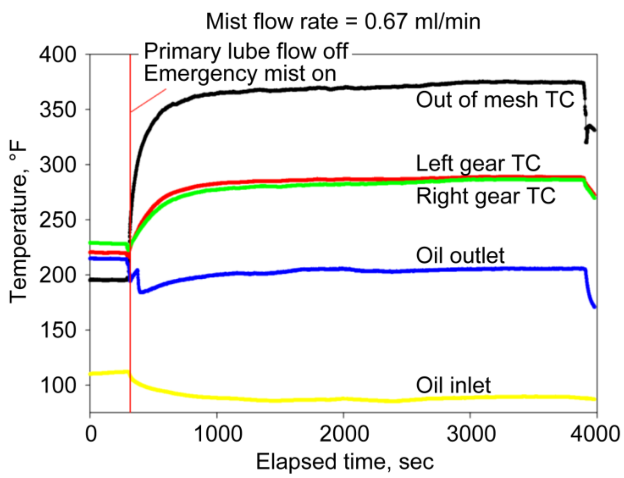

Figure 9.—Loss of lubrication data from a test that was terminated after 1 hr of successful operation.

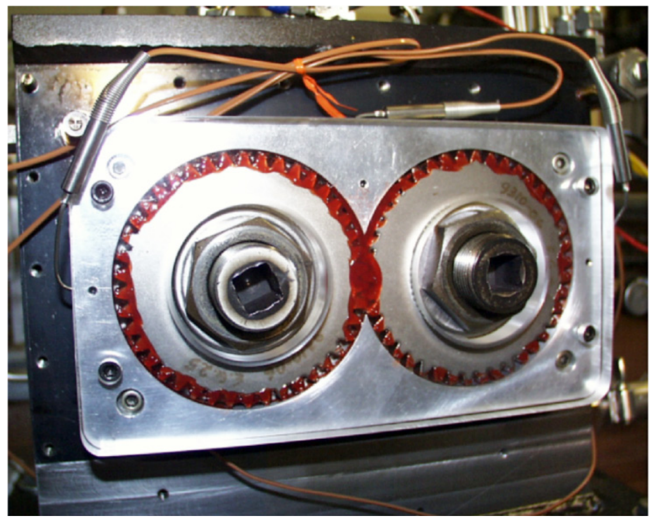

Figure 10.—Grease test—fully shrouded test before operation.

Grease Tests

As an alternative approach to improve gear performance, several tests were conducted to determine if a grease system might be better than using mist. It was thought that if the grease was injected in the correct location, operation in these extremely difficult situations might be better. A limited number of tests were run (six in total). The results are shown in Table 3. At first a completely closed gear shroud arrangement was tested as shown in Figures 10 and 11 (before and during the test respectfully). Test no. 1 from Table 3 was conducted to determine how well the gear would operate at high speed and at approximate 60 percent torque in a closed system. Test no. 2 indicated that higher speed and only a given amount of grease was not sufficient as the test failed at 9 minute. The grease used in Tests 1 to 5 was hydrocarbon-based grease (Ref. 10). Test 6 used high-temperature, perfluoropolyether- (PFPE) based grease (Ref. 11). For tests 3 and 4 grease was injected into a closed system after an initial amount was used prior to starting the test.

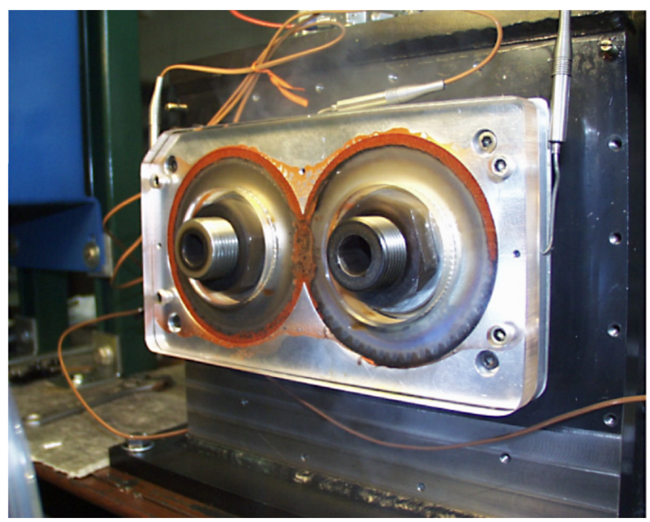

Figure 11.—Fully shrouded grease test just prior to shutdown (strobed photo).

Tests 5 and 6 were conducted in a similar fashion as the vapor mist tests described earlier (see Fig. 12). Both of these tests were conducted at 10000 rpm, but the load was ~60 percent of the full load that the facility could develop.

For the grease tests conducted to date, the injection system provided a predetermined amount of grease in 1 minute intervals after loss of the primary lubrication system occurred. Both grease types were run at the same operational conditions. The hydro-carbon based grease operated for 27 minute after the primary lubrication system was shut down. The teflon-based grease lasted for 46 minute. The post-test gears are shown in Figure 13 for the teflon-based grease.

Analytical Simulation and Results

A two-dimensional heat transfer simulation, as described in Reference 2, was used to model the loss-of-lubrication condition. In this prior work, a 2–D finite difference mesh was used to develop a modeling method for spiral bevel gears. Elements of this simple model are used in this paper to describe how an emergency lubrication condition can be modeled.

The model used is shown in Figure 14. Here, a 2–D rectangular region is used to simulate the actual spur gear tooth. The basic gear dimensions and number of teeth, speed, and load conditions were applied. The tooth whole depth was used as the height and the chordal thickness was used as the simulated tooth width. The finite difference mesh is shown in Figure 15. Several points within the finite difference mesh will be used for monitoring the temperature reached during normal and emergency lubrication conditions.

In Figure 14, the gear tooth is shown with a position varying heat flux applied. The heat flux was found from an analysis of the sliding and rolling losses as a function of meshing position (Refs. 12 and 13). The heat transfer coefficients were found from flat plates in forced convection conditions as described in References 2 and 14. In Figure 15, five locations of the model were followed for the results to be presented.

The model was run to a steady state condition at which time conditions were modified to reflect the loss-of-lubrication condition. It was assumed that the load, speed, and ambient conditions remained the same during the loss-of-lubrication period. In the model, at a predetermined number of “revolutions” the heat flux imposed at the surface was increased by a set amount. In the real event, the friction coefficient is changing from the fully-flooded contact to a mixed elastohydrodynamic condition to one of a starved, metal-to-metal condition.

As an example, the actual gears (12-pitch 42 teeth) used in the tests were modeled using this analysis. The gear design parameters are shown in Table 1. The analytical results are shown for the following conditions: 10000 rpm, 70 N*m (630 in*lb) torque. The analysis was assumed to be at a steady state condition by 50000 revolutions of the pinion (approximately 300 sec). At this point the friction coefficient was increased by a factor of 10.

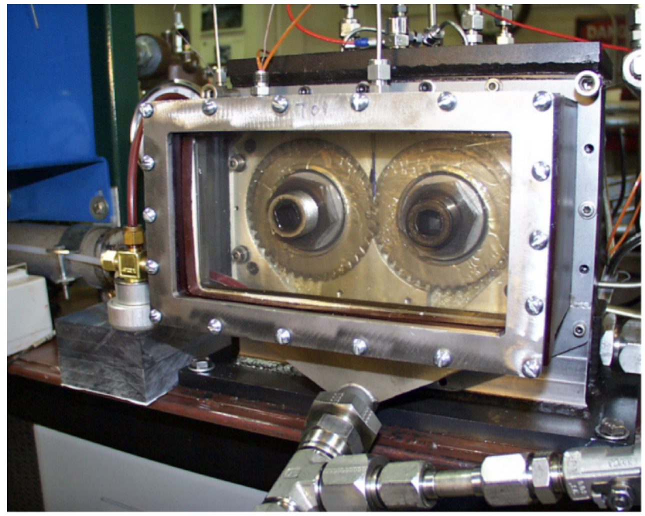

Figure 12.—Photograph of test configuration with grease injection system.

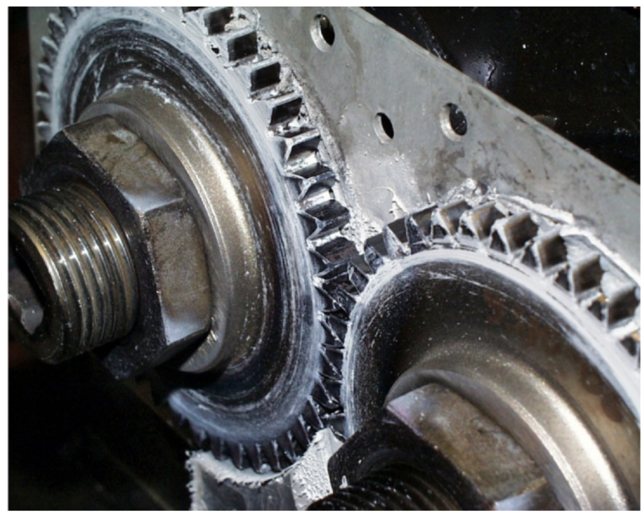

Figure 13.—High temperature grease test, post-test condition with shrouding removed.

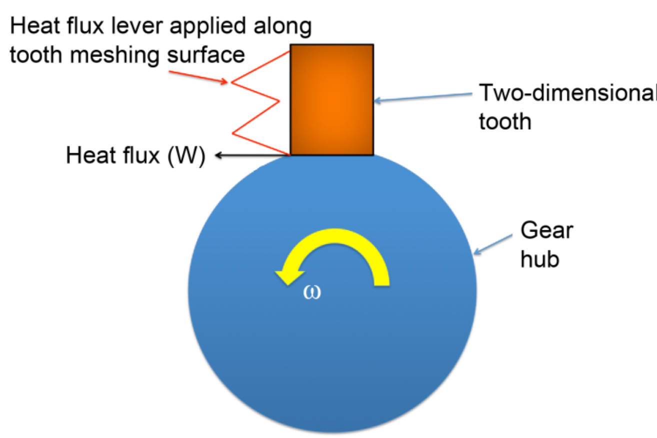

Figure 14.—Two-dimensional simulation model.

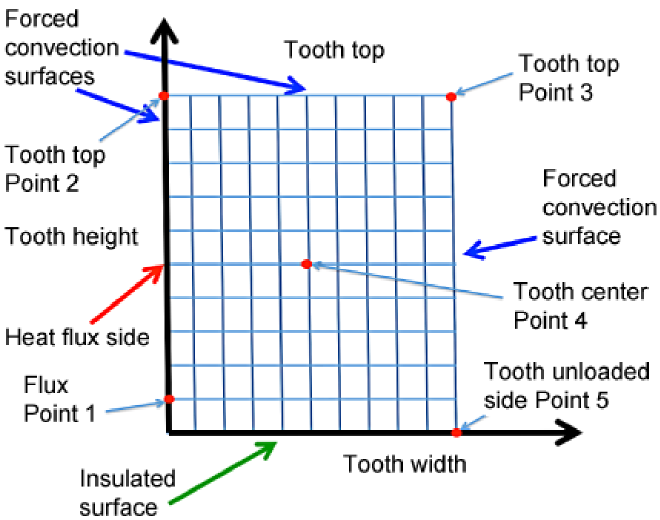

Figure 15.—Simulated spur gear tooth finite difference mesh.

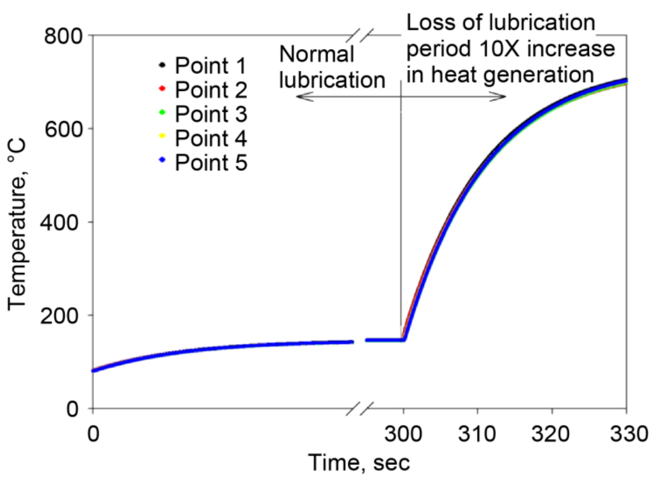

Figure 16.—Steady state temperatures until the heat flux was increased 10X at 300 sec.

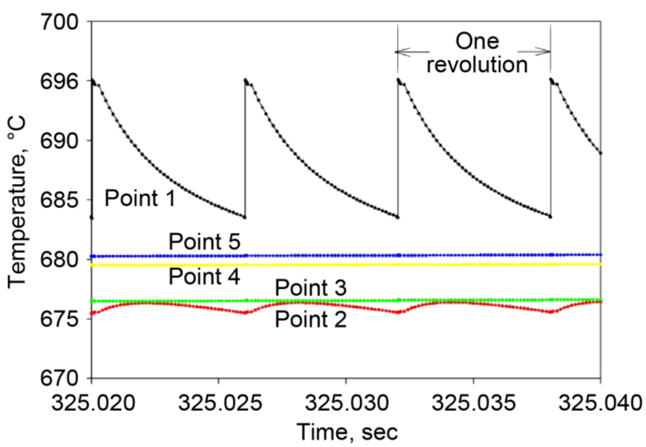

Figure 17.—Transient condition during simulated loss of lubrication conditions.

As shown in Figure 16, the temperature of the tooth increases rather quickly. Since the tooth pitch is rather fine, the difference in temperature at the five locations shown in Figure 15 is rather small during the loss-of-lubrication event or during normal operation. If during the loss-of-lubrication period the time scale is changed to show three revolutions, the output is shown in Figure 17. The temperature is at its maximum at the surface the instant that the heat flux is imposed at the surface node. The cool down is due to the forced convection conditions for the rest of the tooth revolution.

This modeling technique can help with scaling the requirements for actual aviation applications. Enhancements to the modeling technique to improve its accuracy would allow it to then be used on other systems during the design stage.

Conclusions

Based on the results of the testing and analytical simulation described in this paper the following conclusions can be drawn:

1. An air-oil mist system was implemented in a simulated aerospace configuration such that loss-of-lubrication due to primary lubrication system failure was extended beyond the current 30-minute aircraft requirement. Running tests without any emergency lubrication system in a shrouded gearbox led to failure within several minutes.
2. Gear material and gear backlash may have some benefit in increasing loss-of-lubrication behavior, but this would need further verification through additional testing.
3. Grease injection was demonstrated to be a viable emergency lubrication system for our test facility. However this type of emergency system will require greater evolution to determine if it can be utilized in an aerospace environment.
4. A model has been developed that can provide some insight into loss-of-lubrication behavior. An analysis methodology is necessary to be able to scale test data collected to a high-speed main transmission system as found in rotorcraft.

References

1. ADS-50-PRF, "Aeronautical Design Standard, Rotorcraft Propulsion Performance and Qualification Requirements and Guidelines," U.S. Army Aviation Troop Command, April 1996.
2. Handschuh, R., "Thermal Behavior of Spiral Bevel Gears," NASA TM–106518, ARL–TR–403, January 1995.
3. Morales, W. and Handschuh, R., "A Preliminary Study on the Vapor/Mist Phase Lubrication of a Spur Gearbox," NASA TM-1999-208833, February 1999.
4. Morales, W., Handschuh, R., and Krantz, T., "Feasibility Study of Vapor-Mist Phase Reaction Lubrication Using a Thioether Liquid," NASA/TM—2007-215035, December 2007.

5. Oswald, F., "Mechanical Components Branch Test Facilities and Capabilities," NASA/TM—2004-212722, January 2004
6. Krantz, T. and Kahraman, A., "An Experimental Investigation of the Influence of the Lubricant Viscosity and Additives on Gear Wear," NASA/TM—2005-213956, ARL–TR–3126, October 2005.
7. Krantz, T., "The Influence of Roughness on Gear Surface Fatigue," NASA/TM—2005-213958, October 2005.
8. Aeroshell Turbine Engine Oil 555, Product Data Sheet, Shell Oil Company, May 2008.
9. Santovac Fluids, LLC, MS-293 Advanced High Temperature Fluid Material Data Sheet.
10. Exxon Mobil, Material Data Sheet, Mobil Grease 28, March 2006.
11. Dupont Krytox High Temperature (XHT) Grease, Material Data Sheet.
12. Anderson, N., and Lowenthal, S., "Spur Gear System Efficiency at Part and Full Load," NASA TP–1622, TR–79-46, February, 1980.
13. Hamrock, B., "Lubrication of Machine Elements," NASA RP–1126, August 1984.
14. Holman, J.: Heat Transfer, Fourth Edition, McGraw-Hill Book Company, 1976.

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
01-11-2011

2. REPORT TYPE
Technical Memorandum

3. DATES COVERED *(From - To)*

4. TITLE AND SUBTITLE
Gear Mesh Loss-of-Lubrication Experiments and Analytical Simulation

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Handschuh, Robert, F.; Polly, Joseph; Morales, Wilfredo

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER
WBS 877868.02.07.03.01.01.01

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
John H. Glenn Research Center at Lewis Field
Cleveland, Ohio 44135-3191

8. PERFORMING ORGANIZATION REPORT NUMBER
E-17681-1

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
Washington, DC 20546-0001

10. SPONSORING/MONITOR'S ACRONYM(S)
NASA

11. SPONSORING/MONITORING REPORT NUMBER
NASA/TM-2011-217106

12. DISTRIBUTION/AVAILABILITY STATEMENT
Unclassified-Unlimited
Subject Category: 37
Available electronically at http://www.sti.nasa.gov
This publication is available from the NASA Center for AeroSpace Information, 443-757-5802

13. SUPPLEMENTARY NOTES

14. ABSTRACT
An experimental program to determine the loss-of-lubrication (LOL) characteristics of spur gears in an aerospace simulation test facility has been completed. Tests were conducted using two different emergency lubricant types: (1) an oil mist system (two different misted lubricants) and (2) a grease injection system (two different grease types). Tests were conducted using a NASA Glenn test facility normally used for conducting contact fatigue. Tests were run at rotational speeds up to 10000 rpm using two different gear designs and two different gear materials. For the tests conducted using an air-oil misting system, a minimum lubricant injection rate was determined to permit the gear mesh to operate without failure for at least 1 hr. The tests allowed an elevated steady state temperature to be established. A basic 2-D heat transfer simulation has been developed to investigate temperatures of a simulated gear as a function of frictional behavior. The friction (heat generation source) between the meshing surfaces is related to the position in the meshing cycle, the load applied, and the amount of lubricant in the contact. Experimental conditions will be compared to those from the 2-D simulation.

15. SUBJECT TERMS
Gears; Transmissions

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
U	U	U	UU	17	STI Help Desk (email:help@sti.nasa.gov)
					19b. TELEPHONE NUMBER *(include area code)* 443-757-5802

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. Z39-18