HIGH-TEMPERATURE GEAR LUBRICATION

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ABSTRACT

The design features and operating characteristics of a gear-lubricant test machine for high-temperature, high-speed service are described. Results on the load-carrying capacity (or scuff-limited load) of ten lubricants in combination with four types of test gears, at 165°F and 400°F lubricant supply temperatures, are presented. The load-carrying capacity was found to be strongly influenced by the lubricant type and the gear material. Depending upon lubricant type and gear material, it was found that the load-carrying capacity could decrease, either markedly or but slightly, with an increase in the lubricant supply temperature.

INTRODUCTION

The Institute has been engaged, for several years, in a study of gear lubrication for various applications.[1, 2, 3, 4] During the past three years, under USAF Contracts AF 33(616)-6232 and AF 33(616)-7223, the emphasis has been placed on high-temperature service, such as those to be found in the power plant of the high-speed aircraft.

In order to cope with the long-range objectives of the Air Force, a gear-lubricant test machine capable of extreme operating conditions has been developed. However, because of the immediate need for information at 400°F bulk lubricant temperature, most of the experiments have been conducted in this temperature range. This paper will present some of the results on load-carrying capacity (or scuff-limited load) that have been obtained. It is planned that other aspects of the work will be published separately.

TEST EQUIPMENT

WADD High-Temperature Gear Machine

Until approximately three years ago, all of the gear lubrication work at SwRI was carried out with the well-known Ryder gear machine.[5] In late 1956, anticipating the need for a basic tool for obtaining data at temperatures and speeds beyond the capabilities of the standard machine, development work on an improved test device was initiated.

The WADD high-temperature gear machine is shown in cross section in Figure 1, and in an "exploded view" in Figure 2. As will be readily recognized, the high-temperature machine is similar to the standard machine in basic operating principle. However, in contrast to the standard machine, the high-temperature machine uses a case made of tool steel to insure structural stability at elevated temperatures (up to about 800°F). Further, there are important differences in design details: First, the high-temperature machine uses two double-row roller bearings to support each of the two shafts, instead of three journal bearings. The load chamber is located on the end of the driven shaft rather than in the middle of both shafts; and the oil pressure in the load chamber is maintained by means of an annular-groove nonrubbing seal instead of piston rings. Finally, screw-thread type nonrubbing seals, rather than elastomer seals, are used to separate the test oil and support oil chambers.

It was originally planned to design and construct a special drive system for the high-temperature machine. Subsequently, two drive systems for the standard machine became available. Estimates showed that the reduced friction in the bearings and seals should permit the machine to operate at a speed of about 30,000 rpm with the standard drive motor. Accordingly, the standard

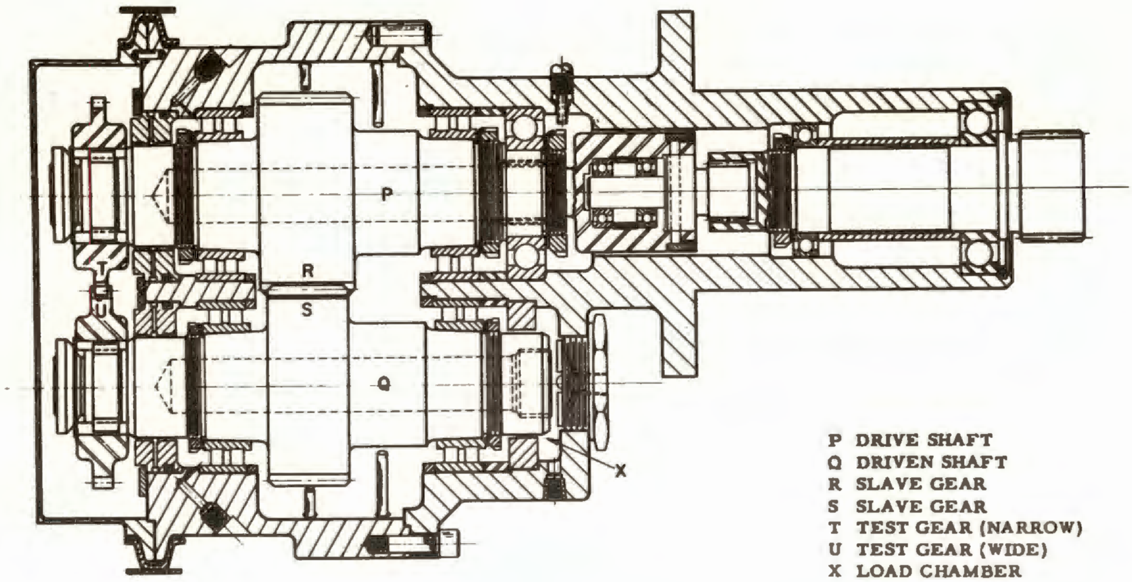

FIGURE 1. CROSS SECTION OF WADD HIGH-TEMPERATURE GEAR MACHINE

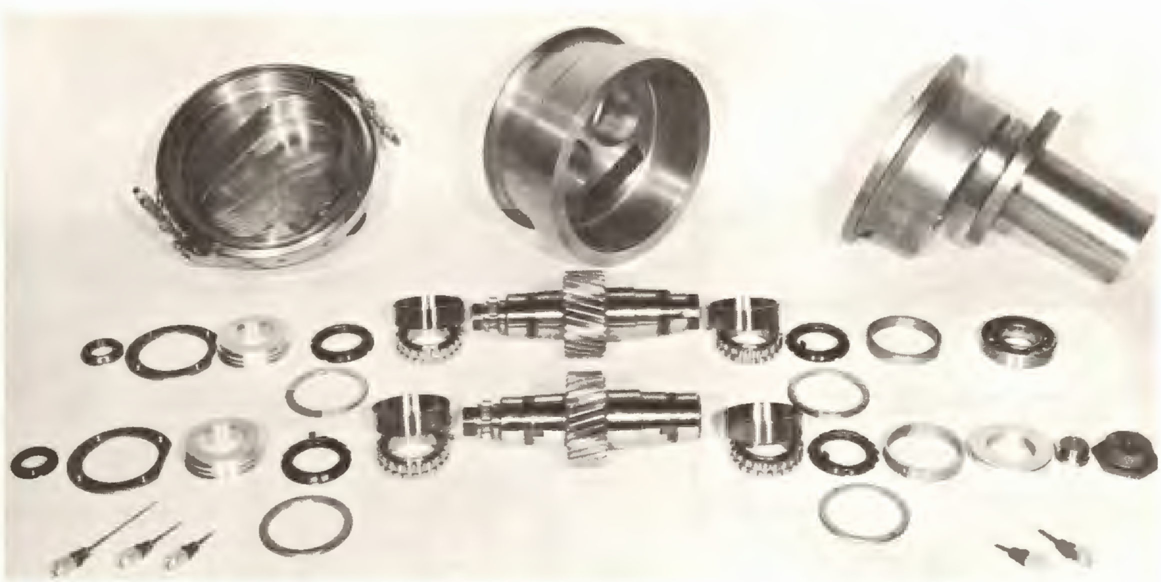

FIGURE 2. EXPLODED VIEW OF WADD HIGH-TEMPERATURE GEAR MACHINE

drive systems were modified by changing the step-up gear ratio from 4.53:1 to 9.25:1, and the support oil was changed from a MIL-L-6082B, Grade 1100, mineral oil to a MIL-L-7808C oil. With these changes, the maximum speed of the high-temperature machine was found to be 30,500 rpm, which was limited only by the capacity of the drive motor.

Two high-temperature machines were constructed and have been in operation at SwRI for nearly three years, and three others have been employed in other laboratories for periods up to about two years. The two machines at SwRI have since accumulated a total of about 2500 hours of operation over a wide range of temperatures and speeds (mostly at 400°F and 10,000 rpm). The operating experience has been most gratifying; and the reliability of these machines has proven to be superior to that of the standard machines.

Test Oil System. Figure 3 presents a schematic diagram of the test oil system used in this work. An "exploded view" of this system is given in Figure 4. It will be noted that the test oil is heated by means of a heat exchanger placed inside an insulated test oil sump. By this means of

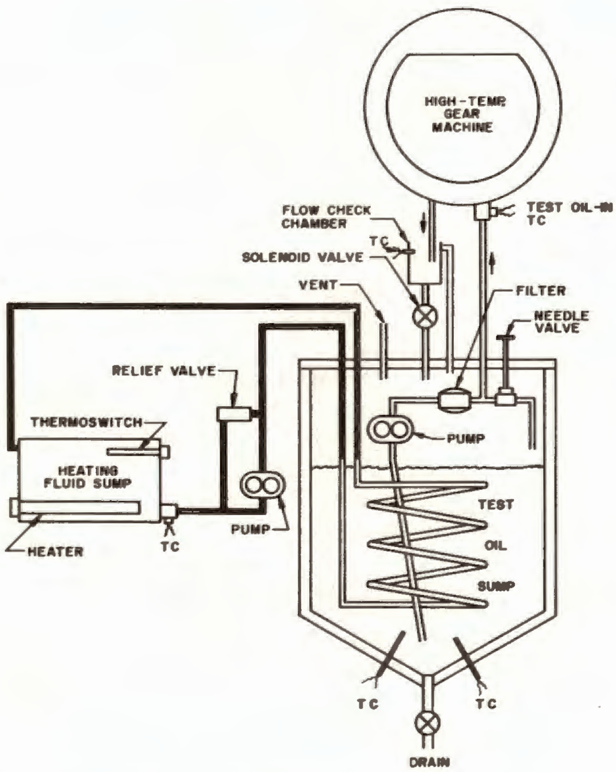

FIGURE 3. SCHEMATIC DIAGRAM OF TEST OIL SYSTEM

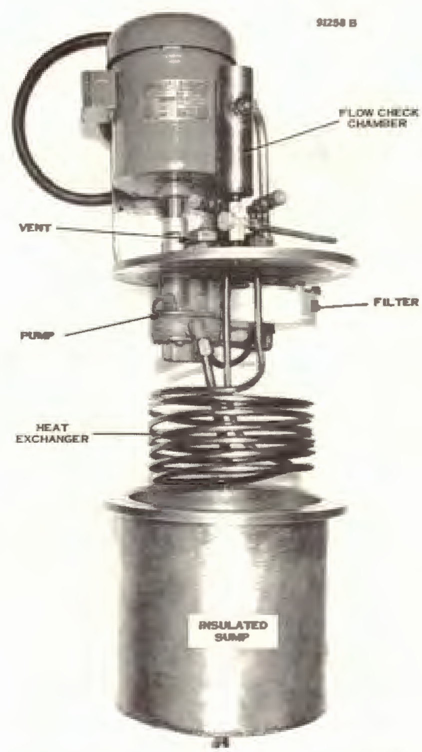

FIGURE 4. EXPLODED VIEW OF TEST OIL SYSTEM

heating, the test oil is subjected only to the temperature of the heating fluid being circulated in the heating coils, which need only be a few degrees higher than the temperature of the test oil. All of the accessories, such as the filter, pressure pump and bypass valve, are placed inside the sump, thereby eliminating considerable heat loss to the ambient. The lines leading to and from the gear machine are made very short, again in an effort to minimize heat loss. With these precautions, the temperature of the test oil in the sump need only be a few degrees higher than that entering the machine; and a minimum of deterioration for the test oil is obtained during a test.

The test oil flow rate may be checked at any time during test without entering the test cell. This is done by actuating a solenoid valve installed in the drain line from the gear machine, and noting the time required to fill the flow check chamber to the level of a bare-wire thermocouple shown. An instant increase in temperature will be noted when the hot oil rises to touch the tip of the thermocouple.

Support Oil System. A dual-temperature support oil system, which represents a compromise between an experimental requirement and a maintenance requirement, was used in this work. The experimental requirement was that the gear machine must be maintained at the temperature of the test oil, so that there would be a minimum of heat loss from the test gears under equilibrium operating conditions. This would insure that the temperature of the test gears would not be affected by ambient conditions. The maintenance requirement was that the drive system should operate at a lower temperature, in order to increase its operating reliability.

Figure 5 shows a schematic diagram of the complete support oil system. The low-temperature section services the step-up gearbox and the bearings in the adaptor block. The high-temperature section, shown also in photograph in Figure 6, provides pressure in the load chamber and lubrication for all points forward of the jack shaft. The pressure pump and scavenge pump are located in the high-temperature sump. The entire high-temperature section is enclosed except for short lines leading to and from the gear machine, thereby minimizing heat loss.

Load Control System. Until recently, the load oil pressure was controlled by manual adjustment. In an effort to obtain better load control, a controller-recorder system has recently been installed. The use of this system has afforded automatic setting and control of the load oil pressure to within ±0.25 psi over a range of 0 to 120 psig. This corresponds to a sensitivity of about ±10 lb/in. for tooth loads ranging from 0 to 5500 lb/in. with the WADD high-temperature gear machine. The simplicity of operation is such that the operator is required only to set the control to the pressure desired; after a few seconds of delay, the load is automatically changed to the preset value and recorded, requiring no further attention from the operator until the end of the run period. The rate of load application is constant for any one load setting and is independent of the operator.

Test Gears. In the majority of the work, special test gears made of M-50 steel and Nitralloy N steel were used. These gears, to be designated as "Design S," have the same principal dimensions as the standard Ryder test gears except for the face width of the wide gears. In addition, Nitralloy N steel test gears of another design, which will be referred to as "Design X," (having same face width for the wide gear as Design S), were used. Further, for comparative purposes, tests were also made using the standard Ryder test gears, which are made of AMS-6260 steel.

The basic characteristics of the high-temperature test gears are shown in comparison with those of the standard Ryder test gears in Table 1. The use of a narrower face width for the wide high-temperature test gear was prompted by the desire to place an induction coil close to the shoulders of both the narrow and wide gears. This method enables both gears to be heated to the desired test temperature, thereby insuring that the oil film in the contact zone is subjected to a known temperature. However, induction heating was not employed in the experiments reported herein.

Closed-Circuit Television for Gear Inspection

To insure safety of the operating personnel from exposure to high-temperature parts and toxic lubricant fumes, it is now standard practice at SwRI to locate all high-temperature test rigs in individual test cells that are well-ventilated, and to perform all controlling and inspection operations from outside the test cells. For the purpose of assessing gear damage, a closed-circuit television technique has been developed to replace the visual inspection method commonly employed. The accuracy of the television inspection method has been carefully checked; and the results are found to be identical to those from the visual inspection method.

TEST PROCEDURES

A comparison of the several test methods used to determine load-carrying capacity is given in Table 2. In Federal Test Method 6508, standard Ryder gear machine and standard Ryder test gears are called for. The tests with the WADD high-temperature gear machine followed closely Federal Test Method 6508. Note that although the same load-pressure increment of 5 psi was used in all tests, the corresponding tooth-load increment was 230 lb/in. with the high-temperature machine, as compared with 370 lb/in. with the standard machine.

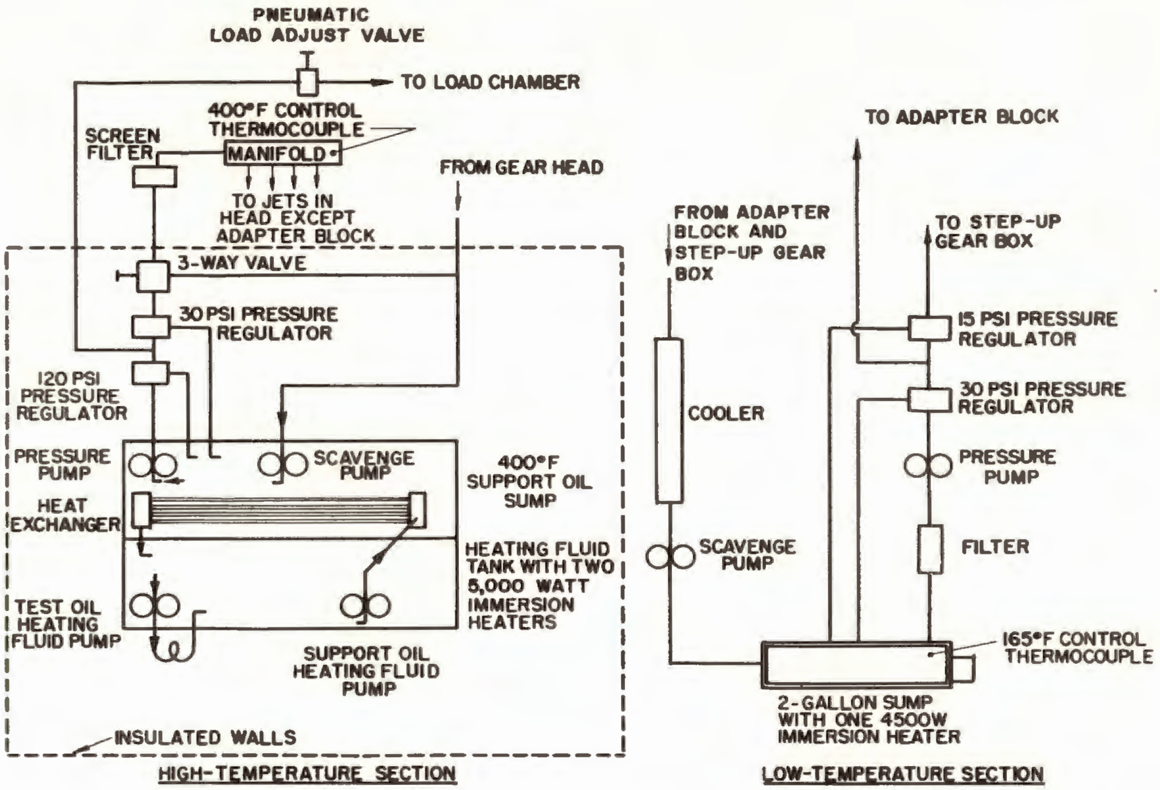

FIGURE 5. SCHEMATIC DIAGRAM OF DUAL-TEMPERATURE SUPPORT OIL SYSTEM

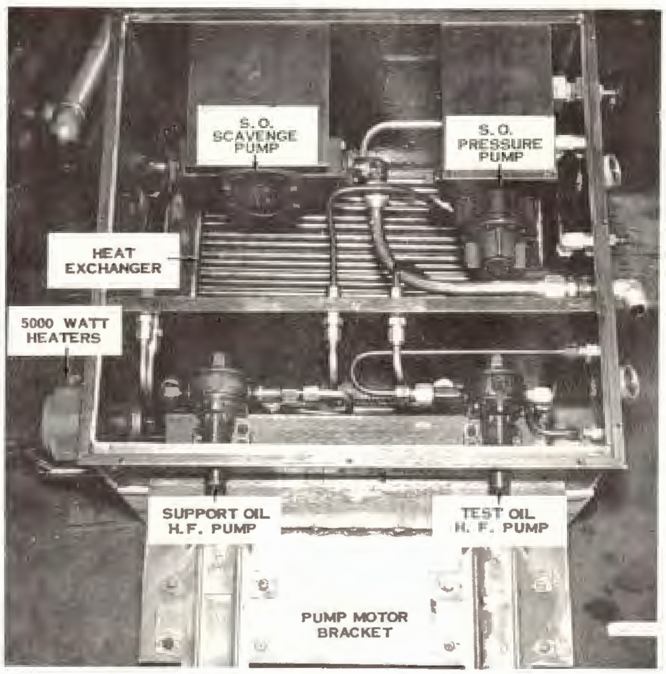

FIGURE 6. HIGH-TEMPERATURE SECTION OF DUAL-TEMPERATURE SUPPORT OIL SYSTEM

TABLE 1. COMPARISON OF BASIC CHARACTERISTICS OF STANDARD RYDER TEST GEARS WITH HIGH-TEMPERATURE TEST GEARS

	Standard Ryder Test Gears	High-Temperature Test Gears		
		M-50 Steel, Design S	Nitralloy N Steel, Design S	Nitralloy N Steel, Design X
Pitch Diameter, in.	3.500	3.500	3.500	3.500
Face Width, Narrow Gear, in.	0.250	0.250	0.250	0.250
Face Width, Wide Gear, in.	0.937	0.375	0.375	0.375
Number of Teeth	28	28	28	35
Diametral Pitch	8	8	8	10
Pressure Angle, degree	22.5	22.5	22.5	20
Tip Relief	None	None	None	None
Material	AMS-6260	M-50	Nitralloy N	Nitralloy N
Case Hardness, Rockwell 15N	90-92	90-92	90-92	92-94
Case Thickness, in.	0.025-0.040	Through-hardened	0.018-0.024	0.018-0.024
Core Hardness, Rockwell C	30-40	Through-hardened	30-40	38-44
Surface Finish, rms, in.	$20\text{-}35 \times 10^{-6}$	$20\text{-}35 \times 10^{-6}$	$20\text{-}35 \times 10^{-6}$	20×10^{-6} (Max.)

TABLE 2. COMPARISON OF LOAD-CARRYING CAPACITY TEST METHODS

	Federal Test Method 6508	Methods Used in Present Program	
		165°F Test	400°F Test
Test Machine	Ryder gear machine	WADD high-temperature gear machine	WADD high-temperature gear machine
Test Gears	Ryder test gears	As required	As required
Operating Conditions			
Test gear speed, rpm	10,000 ± 100	10,000 ± 100	10,000 ± 100
Test oil flow rate, ml/min (exit lubrication)	270 ± 5	270 ± 5	270 ± 5
Test oil-in temperature, °F	165 ± 5	165 ± 5	400 ± 5
Support oil-in temperature:			
High-temperature section, °F	165 ± 5	165 ± 5	490 ± 10
Low-temperature section, °F	---	165 ± 5	165 ± 10
Method of Loading			
Increment steps in tooth load (corresponding to 5-psi steps in load oil pressure), lb/in.	370	230	230
Duration of load-increment steps, min	10	10	10
Criterion of Lubricant Rating	Tooth load at which 22.5% of working tooth area is scuffed	Tooth load at which 22.5% of working tooth area is scuffed	Tooth load at which 22.5% of working tooth area is scuffe

TEST LUBRICANTS

A brief description of the lubricants used in the work reported herein is presented in Table 3. Virtually all of the lubricants are of proprietary makes. It is not possible to furnish further information on these lubricants, because of the proprietary interests involved.

TEST PRECISION

Test Repeatability

Based on the experience at SwRI[6], the repeatability standard deviation of Federal Test Method 6508 (which uses standard Ryder gear machine and standard Ryder test gears, at 165°F lubricant supply temperature) is very nearly 9 percent of the average scuff-limited load; and this "fractional repeatability standard deviation" has been found to be essentially independent of the lubricant type, or of the specific magnitude of the average scuff-limited load.

Table 4 presents the data currently available on the repeatability of several load-carrying capacity test methods using the WADD high-temperature gear machine, with four different types of test gears at two lubricant supply temperatures. It will be noted that the fractional repeatability standard deviation of all 165°F tests using the high-temperature machine fell within the same range as that of the standard load-carrying capacity test. The repeatability of the 400°F load-carrying capacity tests using the high-temperature machine was, on the whole, considerably inferior to that of the 165°F tests. It is not known at present as to whether this poor repeatability was inherent in a high-temperature test, or whether it was a function of the test equipment. No information is available on the repeatability of a 400°F test using the standard Ryder gear machine, because it has not been possible to operate the latter reliably at 400°F.

Test Reproducibility

Data on the reproducibility of the load-carrying capacity tests using the WADD high-temperature gear machine are not sufficient to provide a reliable quantitative analysis at this time. However, from the data now available (see Tables 4 and 5), it appears that the reproducibility has been quite satisfactory.

RESULTS AND DISCUSSION

Effect of Equipment Variables

Test Machine. Tests were made at 165°F lubricant supply temperature to determine the effect of test machine type on scuff-limited load, using standard Ryder test gears throughout. This work included three standard Ryder gear machines, two WADD high-temperature gear machines, and four lubricants of widely different types. The results obtained are presented in Table 5. Note that the two types of machines gave almost identical scuff-limited loads at 165°F for each of four lubricants tested. No comparative data at 400°F lubricant supply temperature are available, because it has not been possible to operate the standard Ryder gear machine reliably at this temperature.

Test Gear Material. The test results on ten lubricant types, determined in the WADD high-temperature gear machines at two lubricant supply temperatures, using four test gear types, are summarized in Table 6. It is proposed to examine the effect of the different variables separately.

As shown in Table 1, the standard Ryder test gears and the two Design S test gears have the same principal design features, differing only in the materials used. Referring to Table 6, it will be noted that test gear material had a powerful influence on the scuff-limited load of all lubricants tested, at both lubricant supply temperatures. However, depending upon lubricant type and gear material, the effect of lubricant supply temperature was not uniform. Considering only the gross effect of gear material for the moment, it will be noted that M-50 steel gave, on the whole, markedly higher scuff-limited load than AMS-6260 steel at both lubricant supply temperatures. On the other hand, Nitralloy N steel was decidedly superior to AMS-6260 steel only at the higher lubricant supply

TABLE 3. DESCRIPTION OF TEST LUBRICANTS

Oil Code	Viscosity, cs 100°F	Viscosity, cs 210°F	Description
Reference B	237.8	20.3	Mineral oil, MIL-L-6082B, Grade 1100
GTO-313	17.1	4.6	Synthetic oil, MIL-L-7808C
GTO-770	64.6	10.9	Synthetic oil
GTO-790	27.3	5.2	Synthetic oil, medium ester base
GTO-794, 803	34.5	7.3	Synthetic oil, medium ester base (different batches)
GTO-855	28.1	5.3	Synthetic oil, medium ester base
GTO-861, 885, 915	15.5	3.6	Synthetic oil, MIL-L-9236B (different batches)
GTO-882, 939	15.1	3.4	Synthetic oil, MIL-L-9236B (different batches)
LRO-8, 11	70.9	6.3	Synthetic oil, polyphenol ether base
LRO-13	368.1	13.2	Synthetic oil, polyphenol ether base

TABLE 4. COMPARISON OF FRACTIONAL REPEATABILITY STANDARD DEVIATIONS OF SEVERAL LOAD-CARRYING CAPACITY TEST METHODS

	Fractional Repeatability Standard Deviation							
	Standard Ryder Test Gears (AMS 6260 Steel)		Design S H. T. Test Gears				Design X H. T. Test Gears (Nitralloy N Steel)	
			M-50 Steel		Nitralloy N Steel			
Oil Code	165°F	400°F	165°F	400°F	165°F	400°F	165°F	400°F
Reference B	0.109(14)	0.143(4)	-	-	-	-	-	-
GTO-313	0.136(8)	0.092(4)	-	-	-	0.403(8)	-	0.091(5)
GTO-770	-	0.285(6)	-	-	-	0.082(6)	-	-
GTO-790	-	-	-	0.094(6)	-	-	-	-
GTO-794, 803	0.093(11)	0.520(10)	-	0.094(4)	-	0.255(6)	-	0.162(6)
GTO-855	0.077(6)	-	-	0.101(4)	-	0.165(8)	-	0.063(6)
GTO-861, 885, 915	0.082(12)	0.054(4)	0.042(4)	-	0.126(6)	0.277(8)	0.044(6)	0.069(6)
GTO-882, 939	-	-	-	-	-	0.212(8)	-	0.081(6)
LRO-8, 11	-	-	-	-	-	0.158(8)	-	0.078(6)
LRO-13	-	-	-	-	-	0.091(8)	-	0.043(4)

The values identified with solid underlines were obtained with WADD high-temperature gear machine No. 1. Those without underline were obtained with machine No. 2. Those with dashed underlines were obtained with both machines. The number of determinations made in each case is shown in parenthesis. Test conditions are as defined in Table 2.

TABLE 5. COMPARISON OF SCUFF-LIMITED LOADS OBTAINED AT 165°F WITH STANDARD RYDER GEAR MACHINES AND WADD HIGH-TEMPERATURE GEAR MACHINES, USING STANDARD RYDER TEST GEARS

Test Machines	Scuff-Limited Load, lb/in			
	Ref. B	GTO-313	GTO-770	GTO-790
Standard Ryder Gear Machines:				
Machine No. 4	2630(36)	2220(8)	---	---
Machine No. 5	2640(110)	2070(10)	---	2650(4)
Machine No. 6	2600(8)	---	4250(8)	---
WADD High-Temperature Gear Machines:				
Machine No. 1	2720(14)	2250(8)	4400(2)	2480(4)
Machine No. 2	2640(8)	---	---	---

The scuff-limited load given is the average of the number of determinations shown in parenthesis. Test conditions are as defined in Table 2.

TABLE 6. COMPARISON OF SCUFF-LIMITED LOADS OBTAINED BY SEVERAL LOAD-CARRYING CAPACITY TEST METHODS

Oil Code	Scuff-Limited Load, lb/in							
	Standard Ryder Test Gears (AMS 6260 Steel)		Design S H. T. Test Gears				Design X H. T. Test Gears (Nitralloy N Steel)	
			M-50 Steel		Nitralloy N Steel			
	165°F	400°F	165°F	400°F	165°F	400°F	165°F	400°F
Reference B	2720(14)	2080(4)	>5090(2)	>5300(2)	-	>5600(4)	-	4600(3)
GTO-313	2250(8)	1690(4)	4200(3)	4360(2)	-	2360(8)	-	2780(5)
GTO-770	4400(2)	2330(6)	>4800(3)	>5120(2)	-	4320(6)	-	3950(3)
GTO-790	2480(4)	750(8)	>4100(2)	4160(6)	-	-	-	-
GTO-794, 803	2990(11)	1140(10)	4950(3)	4540(4)	-	1310(6)	-	3400(6)
GTO-855	2280(6)	670(2)	3910(2)	4200(4)	-	1190(8)	-	2430(6)
GTO-861, 885, 915	1890(12)	390(4)	4270(4)	2200(2)	1980(6)	1110(8)	2280(6)	2260(6)
GTO-882, 939	1900(2)	1210(2)	4590(2)	3750(2)	-	1240(8)	2390(2)	1890(6)
LRO-8, 11	-	-	2510(2)	2750(2)	-	1330(8)	-	2380(6)
LRO-13	-	-	-	-	-	1650(8)	-	3130(4)

The scuff-limited load given is the average of the number of determinations shown in parenthesis. All tests performed using WADD high-temperature gear machines under test conditions defined in Table 2.

temperature. The importance of gear material with regard to scuff-limited load is well supported by experiments on other materials.[3, 7]

Test Gear Design. The effect of gear design on scuff-limited load can be judged by comparing the data in Table 6 for the two Nitralloy N steel test gears, which are designated as Design S and Design X, respectively. It will be noted that six of the lubricants gave markedly higher scuff-limited load at 400°F with Design X test gears than with Design S test gears. However, this was not true with three other lubricants. The reason for this behavior is not clear at present. In an earlier investigation[3], a significant variation in gear design showed little effect on the scuff-limited load of several lubricants of other types.

Effect of Operating Variables

Lubricant Supply Temperature. Table 6 shows that increasing lubricant supply temperature resulted, in general, in a decrease in scuff-limited load. However, depending upon lubricant type and gear material, the scuff-limited load could decrease either markedly, or rather slightly, with an increase in lubricant supply temperature. This general pattern of behavior has also been reported by several investigators.[3, 7, 8, 9]

It was shown in an earlier work[3] that, with nonadditive type mineral oils, the decrease in scuff-limited load with increasing lubricant supply temperature was determined solely by lubricant viscosity. This reflects the hydrodynamic load-carrying action of gear operation. In the present case, any possible hydrodynamic effect with the synthetic oils was apparently drastically modified by the boundary lubrication action between the gear teeth. As is well known, boundary lubrication is influenced, among other factors, by the lubricant-material combination.

Rate of Lubricant Supply. The effect of the rate of lubricant supply is shown in Table 7 for lubricant GTO-915 at 400°F supply temperature, using two designs of Nitralloy N steel test gears in the WADD high-temperature gear machine. From these results, it appears that an increase in the lubricant supply rate from 270 to 1000 ml/min had little effect on the scuff-limited load. These data confirm the results obtained earlier[3] on two other lubricants at 165°F supply temperature, using a standard Ryder gear machine and standard Ryder test gears. It should be remarked

TABLE 7. EFFECT OF RATE OF LUBRICANT SUPPLY ON SCUFF-LIMITED LOAD

Rate of Lubricant Supply, ml/min	Scuff-Limited Load, lb/in	
	DesignS N. N. Test Gears	DesignX N. N. Test Gears
270	1100(8)	2260(6)
1000	1030(6)	2300(6)

Tests were made in WADD high-temperature gear machine No. 1. GTO-915 at 400°F supply temperature was used. The scuff-limited load given is the average of the number of determinations shown in parenthesis.

that, in all these experiments, the lubricant was introduced on the exit side of the gear mesh. Since the lubricant tends to be thrown out, due to gear rotation, when the gears come into mesh, the effect of supply rate would not be expected to be large.

Effect on Lubricant Type

The nature of the present program has not been such as to permit a systematic investigation of the effect of lubricant type or composition on scuff-limited load. Apart from yielding experimental information on fluids of specific interest to the Air Force, the data presented in Table 6 show no more than what is generally known[3, 7, 8, 9], that both hydrodynamic lubrication and boundary lubrication enter in the make-up of gear load-carrying capacity. All that can be emphasized here is that the scuff-limited load is influenced, among other factors, by both the lubricant type and the gear material, and that the combined effect of these cannot be predicted on the basis of the present work.

CONCLUSIONS

The WADD high-temperature gear machine has demonstrated a high degree of operating reliability. Load-carrying capacity tests conducted with this machine with several types of test gears, at a lubricant supply temperature of 165°F, gave essentially the same test precision as the standard load carrying capacity test (Federal Test Method 6508). The precision of tests with this machine was considerably inferior when the lubricant supply temperature was raised to 400°F. However, no comparative data are available for the standard Ryder gear machine at 400°F lubricant supply temperature, because it has not been possible to operate the standard machine reliably at this temperature.

The rating level of the WADD high-temperature gear machine was essentially the same as that of the standard Ryder gear machine, at 165°F lubricant supply temperature. No comparison for the rating level of the two machine types at 400°F lubricant supply temperature can be made, because it has not been possible to operate the standard machine reliably at this temperature.

The scuff-limited load was found to be strongly influenced by the lubricant type and the gear material. Depending upon lubricant type and gear material, the scuff-limited load could decrease, either markedly or but slightly, with an increase in lubricant supply temperature.

Because of the above considerations, it does not appear that tests conducted on a lubricant with one gear material at one lubricant supply temperature could provide a realistic measure of the load-carrying capacity of the same lubricant when used with a different gear material at a different lubricant supply temperature.

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