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HIGH-TEMPERATURE SEALS AND LUBRICANTS
FOR GEOTHERMAL ROCK BITS; FINAL REPORT

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TERRA TEK, INC.

Sandia National Laboratories

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Printed in the United States of America

Available from:

National Technical Information Service

U. S. Department of Commerce

5285 Port Royal Road

Springfield, VA 22161

Price: Printed Copy \$4.50; Microfiche \$3.00

SAND81-7076
Unlimited Release
Printed April 1981

Category UC-66c

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*Work performed under Sandia National Laboratories Contract No. 13-8783 for the U.S. Department of Energy, Division of Geothermal Energy

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ACKNOWLEDGMENTS

The authors wish to express their appreciation to Clifton Carwile of the Department of Energy, Division of Geothermal Energy, and Samuel Varnado of Sandia Laboratories for their support. Bob Reeber, Department of Energy, Division of Geothermal Energy, Washington, D.C., encouraged participation in his program on Geothermal Elastomer Materials (GEM), thereby deepening our understanding of the physical and chemical capabilities and limitations of elastomeric materials. Fran Asti of DuPont, Inc., Alan Hirasuna of L'Garde, Inc., Don Twomey of Pacer Lubricants, Inc., Charles Arnold of Sandia Laboratories, and Fred Pippert of Utex Industries, Inc. provided developmental seals and lubricants to the program on a no-cost basis.

Alan Black, Gordon Tibbitts, and Peter DeLaFosse of Terra Tek shared information on seals and lubricants in conjunction with the DOE/Division of Geothermal Energy "Program for the Improvement of Downhole Drilling Motor Bearings and Seals", Sandia Contract No. 46-3053.

ABSTRACT

High temperature seals (elastomeric and mechanical) and lubricants were developed specifically for journal-type rock bits to be used in geothermal well drilling. Results at simulated downhole conditions indicate that five selected elastomeric seals (L'Garde No. 267, Utex Nos. 227, 231 and HTCR, and Sandia Glow Discharge Coated Viton) are capable of 288°C (500°F) service. Two prototype mechanical seals did not achieve the life determined for the elastomeric seals. Six lubricants (Pacer PLX-024 oil, PLX-043 oil, PLX-045 oil, Geobond Oil, and Geobond Grease) demonstrated 316°C (600°F) capability. Recommendation is made for full-scale simulated geothermal drilling tests utilizing the improved elastomeric seals and lubricants. The following EXECUTIVE SUMMARY describes current results in the context of the overall program.

The research was sponsored by Sandia Laboratories and the U.S. Department of Energy (Contract No. 13-8783) to facilitate the upgrading of conventional sealed roller-cone bits for geothermal service. The reporting interval is July 10, 1979 to May 10, 1980.

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EXECUTIVE SUMMARY

Geothermal wells are drilled almost entirely with conventional roller-cone rock bits and related equipment developed for oil and gas drilling. The hostile downhole conditions (high temperatures, strong abrasive rock, and/or the use of air as the circulating fluid) frequently result in a drastic reduction in drill bit life. Time wasted in replacing worn bits greatly increases the well cost over that of a similar non-geothermal well.

Sandia Laboratories, Inc., under Department of Energy sponsorship, has initiated a long-range program to upgrade conventional roller-cone rock bits for geothermal service. These efforts included research on high-temperature bearings, as well as geothermal laboratory and field testing of eight unsealed 222 mm (8-3/4 inch) roller-bearing bits. Extensive testing and development of high-temperature seals and lubricants was conducted more recently. This report covers the last ten months of the seal and lubricant effort: July 1, 1979 to May 10, 1980. The reader is referred to Sandia/Terra Tek reports "Field Drilling Tests on Improved Geothermal Unsealed Roller-Cone Bits", TR 79-57, December, 1979, and "Materials and Seal Systems for the Improvement of Unsealed and Sealed Geothermal Rock Bits", TR 79-84, December, 1979, for extensive background information for this report.

The goal of the sealed bit program was to develop seals and lubricants having improved temperature capability for use in geothermal drilling. Previous efforts included construction of two unique test machines, and extensive screening of commercially available elastomeric seals and lubricants. The seal tester and lubricant tester are described in Appendices A and C. This report presents test results on two types of mechanical seals, twelve grades of elastomeric seals, and twelve grades of high-temperature lubricant. Five

of the elastomeric seals (L'Garde No. 267, Utex Nos. 227, 231, and HTCR, and Sandia Glow Discharge Coated Viton) demonstrated soak-temperature capabilities of 288°C (550°F), and six lubricants (Pacer PLX-024 oil, PLX-043 oil, PLX-045 oil, Geobond Oil and Geobond Grease) demonstrated adequate load-carrying capacity at 316°C (600°F). A plastic-bodied radial lip seal with metal expander spring was determined to be inferior to elastomeric types due to a soak temperature limitation of 250°C (487°F). A metal bellows face seal exhibited promising results, but requires further development of the seal ring materials to reduce wear and leakage. Full-scale drilling tests are now warranted to further evaluate these new lubricants and elastomeric seals.

INTRODUCTION

In oil, gas, and geothermal drilling the overall well cost can be substantially reduced by using bits with longer life, primarily due to the saving of rig time otherwise wasted in tripping to replace the bit. This is particularly true where per diem costs are high. Two of the most significant advances in life expectancy for roller-cone bits were (a) the introduction of sealed, lubricated roller bearings in 1959¹, and (b) the development of journal bearings in 1967¹.

In non-geothermal drilling, conventional sealed journal-type rock bits (Figure 1) are restricted almost exclusively to fluid-drilled wells, because of temperature limitations for the seals and lubricants, and the limited cooling provided when air, mist, or light foams are used as the circulating fluid.

Figure 1. Roller-Cone Rock Bit

Sealed bits cannot be used in many geothermal reservoirs due to the high bottom-hole temperatures. Drilling must be done with the much older, unsealed bit technology. The limited life of unsealed bits significantly increases drilling costs. The Department of Energy (DOE), Division of Geothermal Energy therefore initiated a program to improve the temperature capabilities of seals and lubricants for roller-cone bits.

In the following section, entitled TEST EQUIPMENT AND PROCEDURES, the seal test machine and lubricant test machine used in this development program, and their respective operating procedures, are briefly reviewed. The PERFORMANCE GOALS AND DESIGN CRITERIA section provides a brief review of the requirements for the seals and lubricants. Current test results are presented in RESULTS AND DISCUSSION.

TEST EQUIPMENT AND PROCEDURES

I. SEALS

I.A. Seal Test Machine

A geothermal seal test machine was constructed to simulate downhole conditions in geothermal wells. Detailed descriptions of this machine and test conditions are provided in Appendix A. Seal tests are run with a mixture of sand, Geysers abrasives, and water in a small reservoir directly over the seal; the lower side of the seal is exposed to lubricant. The radial eccentricities present in drilling are duplicated. Seal failure is detected by application of 0.7 to 1.4 MPa (100-200 psi) of differential pressure for fifteen minutes each hour. Loss of more than 1.0 ml of grease during the 15 minute interval indicates failure and the test is terminated. At all other times the differential is zero.

I.B. Trip-In Simulation Test Procedure

After initial screening (see references 16 and 21), selected seals were evaluated at simulated service conditions, i.e. selected soak temperature for two hours, followed by rotation at 150°C (300°F)(see Figure 2). A new seal was tested at successively higher soak temperatures to determine the ultimate soak temperature. The lubricant used for the seal tests is a successful candidate high-temperature elastomer-compatible journal grease developed under the program (to be discussed).

II. LUBRICANTS

II.A. Test Machine

The high temperature lubricant test machine was constructed to facilitate screening tests on candidate lubricants for geothermal rock bits. The test is based on the widely used "ring-and-block" method described in ASTM Specifica-

tion D 2714-68, and illustrated in Figure 3. Boundary-layer and bulk film (solids) lubrication can be evaluated at temperatures to 427°C (800°F) in a nitrogen environment at 0.70 MPa (100 psi). The pressure capability permits evaluation of many lubricants which would otherwise boil off and/or oxidize during the test. The ASTM procedure calls for the ring to be rotated at 72 RPM for 5000 revolutions (69 minutes), which causes wear on the block. The load-bearing ability is determined by dividing the static load by the area of the wear scar; uniform stress is assumed. A detailed description of the lubricant tester and test procedure are provided in Appendix C.

Figure 2. Trip-In Simulation Seal Test

Figure 3. Terra Tek Ring and Block Lubricant Tester Schematic

PERFORMANCE GOALS AND DESIGN CRITERIA

I. SEALS

I.A. Seal Performance Goals

The primary objective is to develop components for a sealed rock bit which will provide 100 hour life for fluid-drilling formations with resident temperatures of 350°C (662°F).²¹ Foam or air drilling of 300°C (572°F) reservoirs is also required. Two important considerations can be made at this point:

- 1) Seals that do not require changes to bit design have the best chance of commercialization. Elastomers are for this reason, in addition to having significant potential for improved temperature capability, prime candidate materials.
- 2) Total satisfaction of the design goals requires mechanical seals since elastomers cannot withstand 350°C (662°F).

Fortunately, in fluid-drilled wells, bits are exposed to the full formation temperature only when circulation is absent, such as when "tripping". The cooling provided by the drilling fluid was characterized in a previous study⁷; a typical time-temperature relationship is shown in Figure 4. The highest steady-state circulating bottom-hole temperature noted in this study was 175°C (348°F), for a 400°C (750°F) reservoir.

I.B. Design Requirements for Geothermal Rock Bit Cutter Seals

The first four design requirements listed below are common to geothermal and conventional bits, while the additional considerations for geothermal applications are covered in Item 5.

- 1) Restricted space - The most common seal gland cross-section for rock bits is approximately 4.7 mm (0.19 inches) square.

Figure 4. Temperature Model for a Hydrothermal Well

- 2) Eccentricities - Radial runout is caused by the shifting loads on the drilling inserts and is on the order of ± 0.13 mm (± 0.005 inches). The eccentric motion tends to fatigue the seal and also causes pressure pulsations within the lubricant which induce leakage.
- 3) Abrasive particles - The seal must resist wear by the abrasive particles generated by drilling.
- 4) Lubricant compatibility - The seal must resist degradation by constituents in the lubricant such as anti-wear additives.
- 5) Geothermal drilling conditions - Elevated temperature is the single most important aspect of the geothermal environment, regardless of the drilling fluid used. Problems generally associated with geothermal brines, such as corrosion and hydrogen embrittlement (stress corrosion cracking) are mitigated by the drilling fluid.

II. LUBRICANTS

II.A. Lubricant Performance Criteria

Journal-type rock bits intended for geothermal service require a grease which can provide elevated-temperature lubrication similar to that provided by conventional journal bit lubricants at normal operating temperatures. Although the requirement for high load carrying ability is difficult to meet, the pressurized, oxygen-free atmosphere is beneficial.

II.A.1. Load Capacity Criterion Tests¹

The performance criterion used to evaluate the candidate geothermal lubricants was established by conducting a series of "ring and block" lubricant tests on a conventional rock bit grease at ambient temperature, using the Terra Tek tester. A rock bit manufacturer, who wishes to remain anonymous, supplied a quantity of lubricant used in their journal-type rock bits. A total of four consecutive tests (Table I) gave an average load capacity of

Table I

Criterion Tests at Ambient Temperature on a
Lubricant for Conventional Journal-Type Rock Bits

TEST NUMBER	INITIAL TEMPERATURE °C (°F)	FINAL TEMPERATURE °C (°F)	LOAD CAPACITY MPa (KSI)
36	18 (64)	43 (109)	28 (4.1)
37	20 (68)	41 (106)	33 (4.8)
38	24 (75)	48 (118)	22 (3.2)
39	21 (70)	36 (97)	36 (5.2)
AVERAGE			30 (4.3)

¹The Load Capacity and the Repeatability tests were previously reported in Sandia/Terra Tek Report "Materials and Seal Systems for the Improvement of Sealed and Unsealed Geothermal Rock Bits", TR 79-84, and is repeated here for continuity of the report.

30 MPa (4.3 KSI) for the conventional lubricant. Note that the lubricant temperature increased about 20°C during the test, due to heat generated by friction.

II.A.2. Repeatability Tests

The repeatability of the lubricant test machine was established with a series of seven load capacity tests on a pharmaceutical mineral oil.* The test procedure was the same as for the test lubricants, with the exceptions that tests were run at room temperature, without nitrogen pressure. Test results, presented in Table II, indicate load capacities for all seven tests were within ± 8 percent of the mean. The standard deviation was 0.0031.

Table II
Repeatability Test Results for the Lubricant Test Machine

TEST NUMBER	LOAD CAPACITY MPa (Ksi)	NORMALIZED DEVIATION FROM THE MEAN
84-A	28 (4.1)	0.007
84-B	26 (3.8)	-0.067
84-C	26 (3.8)	-0.067
100-	30 (4.4)	+0.0807
101	30 (4.3)	0.0561
108	29 (4.2)	0.0316
109	27 (3.9)	-0.0421
MEAN LOAD CAPACITY	28 MPa (4.1 Ksi)	---
STANDARD DEVIATION	--	0.0031

*The calibration fluid specified in ASTM D2714-68 is "white mineral oil conforming to U.S. Pharmacopeia Vol. XVII, p. 399." Faville-LaVally, Inc., the principle manufacturer of testers for ASTM D2714-68, was contacted, but could not supply the calibration fluid. Squibb pharmaceutical mineral oil was used.

The measured mean load capacity for these tests was significantly lower than the range of 36-62 MPa specified in ASTM D2714-68, due possibly to the non-certified mineral oil used. The reader is cautioned against making direct comparisons between the following test results and data generated on Alpha LFW-1 or Falex Model No. 1 machines.

RESULTS AND DISCUSSION

I. SEALS

I.A. Radial Lip Seal

This seal system consists of a plastic seal body and integral spring which expands the seal radially, causing it to seal between the lug and gland in the cone (Figure 5). The expander spring accommodates the radial eccentrici-

Figure 5. Cross Section of the Fluorocarbon, Inc. Radial Lip Seal. The seal lies in the horizontal plane.

cities, thus minimizing stress levels in the plastic. The prototypes were fabricated by Fluorocarbon, Inc. specifically for the program; similar seals, known as style "RP", are commercially available for high-temperature rotary and reciprocating applications. Seal bodies were supplied in two grades of polytetrafluoroethylene (PTFE - "Teflon") based composites: 15% glass, 5% MoS₂, 80% PTFE, and a proprietary material known as "Fluoroloy-K". Expander springs were of 301 stainless steel; the seal cross section was approximately 7.1 mm (0.28 inches) square.

The results of eleven seal life tests were previously reported. These tests led to the following observations and recommendations:

1. Wearing of the seal lips was minimal: examination at 50x revealed some scoring, but very little embedded sand. The Fluoroloy-K was recommended over the glass/moly/PTFE since it experienced less wear.
2. The seals were unable to resist more than 0.20 MPa (30 psi) reverse pressure without leaking, when rotation and eccentricities were present. The seals were, however, able to seal against at least 3.5 MPa (500 psi) in the forward (self-activating) direction. A more powerful expander spring was recommended to increase the reverse pressure capability.
3. The seal bodies tended to shrink when exposed to temperatures of 200°C (392°F) or greater; the inner diameters tended to increase, while the outer diameters tended to decrease. It was recommended that seals be rough-machined and then stress-relieved by cycling from room temperature to 200°C (392°F) in an air oven. After several cycles, the seals were to be machined to their final dimensions. The stronger expander spring recommended above was also expected to reduce the effects of shrinking.

Fluorocarbon, Inc. supplied the program with a batch of Fluoroloy-K seals which had been stress-relieved prior to final machining. Although Fluorocarbon, Inc. originally agreed to supply seals with stiffer expander springs, the seals actually supplied utilized the same spring type as the seals previously tested. The new batch of seals were therefore identical to the previously tested Fluoroloy-K seals except for the thermal stress relieving.

Trip-in simulation tests were run using soak temperatures of 250°-288°C (482°-550°F). In all tests, the seals held pressure at ambient temperature,

but not at elevated temperature. Upon examination, the two seals which soaked at 288°C had lost nearly all the initial compression; the one seal soaked at 250°C retained 70% of its original compression. Since the dimensional stability of the plastic seal body limits the maximum soak temperature to less than 250°C, no further development is recommended for this seal. The seal test data are presented in Appendix B.

I.B. Metal Bellows Face Seal

Shaft seals for high temperatures and severe environments, such as jet engines, pumps, turbines, and submersible motors generally are of the face-seal type. This is because the face-seal concept can utilize wear-resistant materials for both primary sealing surfaces. A spring system is required to activate the primary seal. A secondary (static) seal is required to prevent leakage past the primary seal; this can consist of a metal bellows, elastomeric O-ring, radial lip seal, or packing. Extensive development and testing of a face seal with an elastomeric O-ring secondary seal was reported previously.²¹

A similar seal, utilizing a metal bellows secondary seal was evaluated during the current reporting interval (Figure 6).

The principal problem associated with putting a face-seal in a rock bit cone is obtaining adequate spring force and compliance in the limited available space. The seal must also be adequately protected from exposure to the hole wall as the cones wear. One method of providing the required spring force is to recess coil compression springs in holes in the cone body as shown in Figure 6. The coil spring system permits rapid experimental alterations of the closing force. It may or may not be possible to design a one-piece spring system such as a disc spring (belleville washer) or wave spring for this application; force-deflection properties for the coil spring system and a

suitable disc spring are compared in Figure 7. Note that the coil spring system provides higher compliance and closing force. A previous study²¹ of available high-temperature alloys indicated that springs of 17-7 Ph steel would operate at 316°C (600°F) over the life of the bit, with no more than 5% relaxation. A more expensive alloy, NS-A286, can be used for temperature in the 316°-538°C (600-1000°F) range. The construction details for the metal bellows seal are provided in Table III.

Table III

Construction Details for Terra Tek Metal Bellows Face Seal

Mating Ring	Timken CBS-600 steel, case-carburized to .070", Rc62 at surface. Surface dressed to 8 microinch on horizontal grinder.
Primary Seal Ring	316 Stainless steel with chromium-oxide ceramic coating #PTI-25, applied by Plasma Technology, Inc., Torrance, California. Chrome-oxide surface lapped to within 2 light-bands. 48.4 mm (1.095 inches) O.D.
Guard Ring	316 Stainless steel, 68.7 mm (2.705 inches) O.D.
Bellows	321 Stainless steel, 0.13 mm (0.005 inches) thick (hydroformed), TIG welded to seal ring and then to guard ring. Manufactured by Bel-Flex Products, Inc., Orange, California.
Springs	17-7 Ph Stainless steel, 3.1 mm (0.12 inches) O.D., 22 mm (0.85 inches) free length, 8.8 KN/m (50 #/inch), 18 mm (0.69 inches) solid height, 0.71 mm (0.028 inch) diameter wire. Manufactured by Associated Spring Corp., Plymouth, Michigan.

A total of nine seal life tests of the trip-in simulation type were run in the current reporting interval; the detailed test data are reported in Appendix B. The following observations were made:

1. Leakage at the primary seal increased with temperature and was generally unacceptable above 100°C. The suspected cause of this leakage is warping of the primary seal ring due to residual stresses induced during welding of the metal bellows.

Figure 6. The Metal Bellows Face Seal.

Figure 7. Force-Deflection Characteristics of Two Spring Systems for the Metal Bellows Face Seal.

2. The metal bellows was crushed when the lubricant pressure exceeded the wellbore pressure by 1.0 MPa (150 psi). The bellows was undamaged when wellbore pressure exceeded lubricant pressure by 2.0 MPa (300 psi).
3. The compression springs, metal bellows and other seal components were undamaged by a two-hour soak at 350°C (660°F).
4. Wearing of the carburized steel (CBS-600) mating ring was excessive in tests with Geysers abrasives. Tests of 82 hours at 200°C (392°F) and 99 hours at 250°C (482°F) produced grooves of 0.80 mm (0.03 in.) and 1.0 mm (0.04 in.) in the mating ring. The chrome oxide surfaces on the primary seal rings experienced no measurable wear.

The following conclusions can be made:

1. The springs and bellows provided adequate performance.
2. The primary seal and mating ring need to be redesigned to reduce wear and warpage. When the metal bellows face seal is installed in a rock bit, it will be necessary to supply a mating ring rather than running the primary seal directly on the lug (leg) of the bit as was originally planned.

I.C. Parker, Inc. 4205 Viton

Extensive testing on this commercially available compound has been reported in references 11, 14, 15, 16, 21, 24 and 25. Results indicated that Viton based compounds were superior to other commercially available base polymers.* Trip-in simulation tests were therefore required to complete the evaluation of 4205 Viton. These results are representative of the best com-

*Kalrez (DuPont) is a possible exception: not enough testing and development were done to categorically eliminate it. Data indicated that performance was roughly equivalent to Viton. The high cost of Kalrez could not be justified; see reference 21.

mercially available elastomer for the application. The data on 4205 Viton can therefore be used as a basis of comparison when evaluating elastomers and coatings developed specifically for the application.

The results of six tests are presented in Appendix B. A seal life of 107 hours was obtained at 260°C (500°F); the seals failed in additional tests at 265°C (509°F) and 270°C (518°F). The trip-in temperature limit is therefore 260°C (500°F).

I.D. Coated Elastomeric Seals

The addition of a coating of PTFE ("Teflon") to an elastomeric seal can be expected to reduce frictional heating at the sealing surface. In addition, resistance to chemical and mechanical degradation, such as tearing, cracking, and pitting, may also be improved. Previous tests on seals coated with paraffin-C indicated that the coating tended to detach from the elastomer.¹⁶

Two types of PTFE coatings were evaluated under the current program (Table IV). Both coatings were evaluated on Parker, Inc. 4205 Viton seals from

TABLE IV
Teflon-Coated Elastomeric Seals

Seal Name	Coating Thickness	Base Elastomer(s)	Process Details
Sandia Capacitive Discharge Coated	0.03 mm (0.001 inches)	Parker 4205 Viton ¹	Plasma-polymerized film is deposited on the elastomer in a vacuum (40 Pa or 0.3 torr) at ambient temperature over a two hour period. Applied field was 200 Vpp at 13.6 MHz.
Sandia Glow Discharge Coated	0.002 mm (80 micro-inches)	Parker 4205 Viton ¹ Parker EPDM ²	Seal is prepared by exposure to ultraviolet radiation to create free radicals on the surface. Proprietary * process propels ionic CF ₃ monomer to surface where it forms a highly branched and cross-linked molecular polymer which is linked to the elastomer at numerous sites.

*The Glow Discharge Process is also used for military purposes.

the same batch as those reported previously. The Glow Discharge coating was also evaluated on Parker, Inc. EPDM seals; an uncoated EPDM seal was tested to provide a basis of comparison.

Preliminary results on the Capacitive Discharge coated seals were not encouraging, as reported in Appendix B. Tearing and loss of material was observed in a 250°C (482°F) test.

A total of eight tests were run to evaluate the Glow Discharge coating. Results indicate a significant improvement in soak temperature capability is provided by the coating. The 4205 Viton survived a 288°C (550°F) soak, with a seal life of 53 hours. Previous results on uncoated 4205 Viton indicated a maximum soak temperature capability of 260°C (500°F), and 107 hour life. Further testing on coated 4205 seals would most likely indicate that 100 hour life can be obtained (as opposed to 53 hours) at a temperature slightly below 288°C (550°F).

The observed benefit of the Glow Discharge coating to the Parker EPDM seals was more pronounced. Both a coated and an uncoated seal were subjected to 288°C (550°F) trip-in simulation tests. The coated seal survived 34 hours, while the uncoated seal lasted only 9½ hours.

The Glow Discharge method was to have been further evaluated on three each of the two leading candidate developmental elastomers: HTCR and Z-267 (to be discussed). Unfortunately, scheduling problems at the coating facility delayed evaluation on the seal test machine.

I.E. Developmental Elastomeric Seals

Seal manufacturers formulate elastomeric compounds for specific applications, using available base polymers.* The geothermal rock bit seal applica-

*The majority of base polymer stock is obtained from DuPont, Inc. or 3M, Inc. The evaluation of representative base polymers is covered in Reference 21.

tion is large enough to warrant the formulation of new compounds. Two candidate seals were provided by L'Garde, Inc. of Newport Beach, California in cooperation with a related DOE program for the development of elastomers for geothermal packers. Utex Industries, Inc. of Houston, Texas has supplied a total of ten grades to the program, five of which were evaluated during the current reporting interval.

Four of the seven developmental grades were successful: 288°C (550°F) soak capability and 100 hour life were obtained (Table V). Detailed test results for 14 seal life tests are presented in Appendix B. When compared

Table V
Summary of Trip-In Simulation Tests¹ on
Four Developmental Elastomeric Seals

Designation	Manufacturer	Base Polymer(s)	Maximum Soak Temp. °C(°F)	Seal Life Hours ²
267-II-3S ³	L'Garde, Inc.	EPDM/Viton ⁴	288(550)	104
RD-227	Utex Industries, Inc.	Proprietary	" "	94+
RD-231	" " "	"	" "	92+
HTCR	" " "	"	" "	120+

1. All tests run at 90 rpm with abrasives present, 0.13 mm (0.005 inches) wobble and stroke. Run temperature was 150°C (302°F).
2. Life tests were frequently terminated for scheduling reasons. These are denoted by a plus sign.
3. L'Garde, Inc. 257-II-3S was formulated for static seal applications.
4. Ethylene-propylene-diene monomer terpolymer/fluorocarbon elastomer.

with the commercially available Parker, Inc. 4205 Viton, the new compounds provide a 28°C (50°F) higher soak temperature capability. All four of the developmental grades experienced minimal degradation: durometer shifts were 5 points or less, and surfaces were free of cracks, pitting or discoloration.

L'Garde, Inc. stressed that 267-II-3S was developed for static seals, and that performance could possibly be improved by modifying the compound for dynamic seal applications. Utex Industries' compounds were developed on a reiterative basis, and HPCR was the final compound. HPCR has subsequently been made available commercially.

II. LUBRICANTS

II.A. Background

Previous testing of 31 commercially available high-temperature lubricants¹⁶ indicated that only 8 could provide adequate load carrying capacity at 316°C (600°F) and of these, only two were claimed to be compatible with elastomers at temperature. Pacer Lubricants, Inc. of Houston, Texas supplied 17 developmental grades to the program in order to improve load capacity, while meeting the elastomer compatibility requirement. Of these, five were successful, and results were presented in the last report.²¹ These data are presented again for continuity (Table VI).

TABLE VI
Load Carrying Capacity of Five Lubricants
Developed for Geothermal Bits

DESIGNATION	TYPE	VISCOSITY ² SUS (CST) OR WEIGHT	ELASTOMER COMPATIBILITY	TEST TEMPERATURE °C (°F)	LOAD CAPACITY MPa (KSI)	NUMBER OF TESTS
PLX - 014	OIL	190 (40.4)	YES	316 (600)	73 (10.6)	15
PLX - 014	OIL	190 (40.4)	YES	204 (400)	52 (7.6)	4
PLX - 014	GREASE ¹	NLGI No. 2	YES	316 (600)	62 (9.0)	10
PLX - 022	OIL	180 (38.3)	NO	316 (600)	81 (11.7)	12
PLX - 023	OIL	254 (54.5)	NO	316 (600)	67 (9.7)	5
PLX - 024	OIL	286 (61.4)	YES	316 (600)	69 (10.0)	3

1. Available commercially as Geoband Grease.

2. Saybolt Universal Seconds at 210°F, or Centistokes at 100°C.

II.B. Current Test Results

II.B.1. Screening Test Results

One additional commercially available high-temperature lubricant, known as Mystic "High Temp" was evaluated, but its load capacity was below the required 30 MPa (4.3 ksi) criterion. The test data are presented in Appendix D, Table D2, tests 154 and 155.

II.B.2. Water Contamination Tests

The susceptibility of Pacer Lubricants, Inc. PLX-014 oil to degradation due to water contamination was investigated in conjunction with a related program on lubricants for downhole drilling motors.²⁷ These three tests were run at 204°C (400°F), whereas all other lubricant tests were run at 316°C (600°F). 1.5 ml of water was added to the standard test volume of 85 ml of PLX-014 oil. The load capacity for the contaminated PLX-014 was determined to be 27.1 MPa (3.9 ksi). This represents a reduction of 48 percent in load capacity as compared to uncontaminated PLX-014 oil at 204°C (Table VI). Although this loss in performance is significant, the load capacity comes close to meeting the performance criterion of 30 MPa (4.3 ksi). The test data are presented in Appendix D, Table D2, tests 161-163.

II.B.3. Developmental Lubricants

Pacer Lubricants, Inc. supplied an additional nine lubricants for evaluation. These included "Geobond" oil, which is the commercial designation for PLX-014, developed previously under the program. These additional grades were designed to determine how various components of the lubricants affect overall performance. Oil viscosity, suspended solids, and extreme pressure additives were evaluated. Test variables and test results are presented in Table VII; detailed lubricant test results are presented in Appendix D. The coefficient

Table VII

**Test Results for Nine High-Temperature Lubricating
Oils from Pacer Lubricants, Inc. at 316°C(600°F)**

Destination	Description	Viscosity SUS(CST) ¹	Suspended Solids	Elastomer Compatibility at Temperature	Load Capacity MPa(KSI)	Number of Tests
PLX-025	PLX-014 with teflon swelling agent ²	190(40.4)	Yes	Yes	13.0(1.9)	2
PLX-030	PLX-022 with additives to improve performance below 135°C	180(38.3)	Yes	No	See note 3	2
PLX-031	" " " " " "	" "	"	"	" " "	1
PLX-042	PLX-014 with high temp E.P. additive	180(38.3)	"	less than PLX-014	64(9.3)	2
PLX-043	High viscosity base oil mixed with base oil of PLX-014	290(62.1)	No	Yes	63(9.1)	2
PLX-044	High viscosity base oil	280(60.0)	"	"	66(9.5)	2
PLX-045	High viscosity base oil	313(67.5)	"	"	69(10.0)	2
PLX-046	Very high viscosity base oil	455(100)	"	"	21(3.0) ⁴	3
Geobond	Commercial version based on PLX-014	190(40.4)	"	"	55(8.0)	7

1. Saybolt Universal Seconds at 210°F, or Centistokes at 100°C.
2. PLX-025 was intended to counter the shrinking problem encountered with the Fluorocarbon seals.
3. Tests were terminated due to seizing of the journal bearing in the lubricant tester, very early in the test. Wear rates were very high, indicating unacceptable load capacity.
4. Two of the three tests had to be terminated due to seizing of the journal bearing in the lubricant tester.

of friction was calculated in each lubricant test. Coefficient of friction values did not show significant correlation with performance. The data indicate that six of the candidates (including three reported on previously, from Table III) can be recommended for evaluation in full scale geothermal drilling tests in conjunction with elastomeric seals:

PLX-014 oil ("Geobond Oil")

PLX-014 grease ("Geobond Grease")

PLX-024 oil

PLX-043 oil

PLX-045 oil

CONCLUSIONS

Seals and lubricants are needed for journal-type rock bits for geothermal applications. Extensive development and testing has produced materials suitable for drilling hydrothermal wells to 288°C (550°F).

Seals

- 1) Four elastomer compounds developed under the program demonstrated 288°C (550°F) soak temperature capability and 100 hour life at 150°C (302°F). The maximum soak temperature for a conventional Viton compound was established to be 260°C (500°F).
- 2) A teflon coating technique known as the Glow Discharge method significantly improved the soak temperature capability and overall life of two conventional elastomers. The Glow Discharge method needs to be evaluated on the four elastomer compounds developed under the program.
- 3) Extensive development was done on an all-metal seal designed specifically for roller-cone bits. Further development is needed to isolate improved wear surface materials. A plastic radial lip seal was found to be inferior to commercially available elastomeric seals in this application.

Lubricants

- 1) Six lubricants developed under the program demonstrated at 316°C (600°F) load-carrying capacity in excess of the requirement for journal-type rock bits. The lubricants' compatibility with the selected elastomers (mentioned above) has been established through extensive testing in the seal test machine.

Full-scale drilling tests under simulated geothermal drilling conditions are now required to qualify the candidate seals and lubricants for commercial use.

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Appendix A
Geothermal Seal Test Machine

Geothermal Seal Test Machine

General Description: The seal test machine (Figures A1 and A2) was constructed to duplicate the conditions experienced by the seals of a roller-cone rock bit drilling in a geothermal reservoir. In addition to temperature, pressure, rotational velocity, lubricant, and abrasives, the rotational eccentricities are also simulated.

The operation of the machine is detailed by the schematic diagram shown in Figure A3. The test is conducted within a pressure vessel, which is filled

Figure A1. Geothermal Seal Test Machine Shown with Test Assembly out of the Pressure Vessel.

Figure A2. Sectioned View of the Seal Test Machine

Figure A3. Schematic Diagram of a Typical Seal Test

with water. Internal heaters and insulation establish the test temperature, which can be as high as 427°C (800°F). Tests are run at 15.2 MPa (2,200 psi), which simulates a well depth of 1,550 meters (5,075 feet). The seal is held stationary in a carrier (gland), while an internal "lug simulator" is rotated by the main drive shaft. A reservoir immediately above the seal may be filled with abrasive particles, and is open to the water environment within the vessel. The volume below the seal is filled with a bit lubricant with known compatibility with the seal under test. Differential pressure across the seal is controlled and monitored by the system shown in Figure A3.

The seal carrier and the wear surface on the "lug simulator" are readily replaceable. A large number of seal carriers are available for the number 2-329 O-ring, and the Reed Rock Bit Company oval seal, to provide installed compressions from 7 to 14%. Test adapters have also been built for the face seals and radial lip seals discussed in the report.

The axial "stroke" is caused by an external cam located at the top of the main drive shaft. This motion is approximately sinusoidal, and occurs once per revolution, with an amplitude of ± 0.13 mm (± 0.005 inches). The radial eccentricities are created by the mechanism shown in Figure A4. The two rollers on the bottom of the "lug simulator" strike the nine pins in the stationary cup, resulting in a regular motion with an amplitude of ± 0.13 mm (± 0.005 inches). These mechanical eccentricities test the ability of the seal to resist entry of abrasive particles. The entire experiment, including all rotating components, is built on the top plug assembly, as shown in Figure A5.

Figure A4. Lug Simulator with replaceable sealing surface and jogger mechanism. Seal carrier and spacers removed for clarity.

Figure A5. Top plug assembly.

Appendix B
Detailed Seal Test Data

DETAILED SEAL TEST DATA

Test Conditions: The test parameters for the seal life tests on the radial lip seal, metal bellows face seal, Parker Viton seal, coated elastomeric seals, and the developmental elastomeric seals are presented in Table B1. The maximum capabilities for the seal tester are also given. The only exceptions to these conditions were in the testing of the metal bellows seals: different run temperatures were used, and abrasives were used in only two of the tests.

Table B1
Seal Life Test Conditions and Tester Maximum Capabilities

Parameter	Maximum Capabilities	Life Test Conditions
Soak Temperature	427°C (800°F)	Variable
Run Temperature	427°C (800°F)	150°C (302°F)
Pressure	21MPa (3,000 psi)	14.5-15.2 MPa (2,100-2,200 psi)
Rotational Velocity	500 RPM	90 RPM
Radial Motion	±0.43 mm (±0.017 in.)	±0.13 mm (±0.005 in.)
Axial Motion	±0.64 mm (±0.025 in.)	±0.13 mm (±0.005 in.)
Abrasives	Any	Geysers Franciscan Graywacke and Feldspar Sand Mixture
Fluid	Non-corrosive	Water

Seal condition was checked each hour by pumping in a quantity of lubricant which was sufficient to establish a 1.0 MPa (150 psi) positive differential pressure, and observing the decay of the differential over a 15-minute interval. Loss of the 1.0 MPa differential, which corresponds to about 1 ml

of grease, was taken as an indication of seal failure, and the test was terminated. The differential pressure was removed after 15 minutes, if the seal was still functioning normally. The test pressure was reduced to 0.5 MPa (75 psi) for some of the metal bellows seal tests, to avoid crushing the bellows.

Seal Test Data: Detailed seal test results are presented in separate tables for each of the five categories: Table B2, radial lip seal; Table B3, metal bellows seal; Table B4, Parker No. 4205 Viton seal; Table B5, coated elastomeric seals; and, Table B6, developmental elastomeric seals.

Table B2
Radial Lip Seal

(FCRLS)

TEST NO.	SEAL DESCRIPTION	INSTALLED COMPRESSION, %	SOAK TEMP °C (°F)	SOAK TIME HOURS	LIFE AT 150°C (300°F), HOURS	DUROMETER, SHORE D BEFORE/AFTER	COMMENTS
223	glass/moly/PTFE ¹ FC00912	19.1	260(500)	2½	1	57/50	Minimal wear on sealing surface. Significant changes in I.D., O.D., thickness and height.
247	Fluoroloy-K ² FC00911	11.5	288(550)	2	0	55/N.A. ²	Seal shape was deformed, and significant changes in I.D., O.D., thickness and height were observed.
253	Fluoroloy-K ² FC00911	9.5	288(550)	2	0	53/49	" "
254	Fluoroloy-K ² FC00911	8.7	288(550)	2	0	53/49	" "
262	Fluoroloy-K ² FC00911	31.6	288(550)	2	7½	53/48	" "
264	Fluoroloy-K ² FC00911	26.8	250(482)	2	0	53/50	Less deformation than previous tests, but increased abrasive wear.
265	Fluoroloy-K ² FC00911	25.1	250(482)	2	0	53/49	Seal shape was deformed, and significant changes in I.D., O.D., thickness and height were observed.

1. Polytetrafluoroethylene polymer with glass fiber and molybdenum-disulfide fillers.

2. Proprietary plastic compound of Fluorocarbon, Inc.

Table B3
Metal Bellows Seal

TEST NO.	MATING DISC	CUTTINGS	SPRING FORCE POUNDS	TEMPERATURE SCHEDULE °C (°F)	MAXIMUM DIFFERENTIAL PRESSURE MPa (PSI)	TOTAL RUN TIME HOURS	COMMENTS
233	Chrome Oxide	No	150	1 hr @ ambient, 1/2 hr @ 200(392)	3.5(500)	1 1/2	Held pressure at ambient but not at temperature. Positive lubricant pressure of 3.5 MPa (500 psi) inadvertently applied, causing crushing of bellows. Seal held pressure upon cooling to ambient.
234	Chrome Oxide	No	150	1 hr @ ambient 13 hr @ 200(392)	1.0(150)	14	Seal held pressure at ambient, and at 200°C for 8 1/2 hours. Bellows crushed by 1.0 MPa (150 psi) differential pressure. Chrome oxide primary surface worn away by chrome oxide mating ring.
235	CBS-600	No	150	1 hr @ ambient 4 1/2 hr @ 200(392) cool to ambient 1/2 hr @ 200(392)	1.4(200)	6	Seal held pressure at ambient and at 200°C for 4 1/2 hours. Machine failure required shutdown. Attempt to restart test also failed. Sealing surfaces were unworn, bellows was crushed.
249	CBS-600	No	100	14 1/2 hr @ ambient	0.5(75)	14 1/2	Seal held pressure until failure occurred due to breakage of weld between bellows and guard ring. Bellows not crushed. Sealing surfaces showed negligible wear.
250	CBS-600	No	100	5 1/2 hr @ ambient 2 1/2 hr @ 75(167) 3 1/2 hr @ ambient	0.5(75)	11 1/2	Test terminated due to machine failure. No wear on chrome oxide primary surface; 0.05 mm (0.002 inch) groove worn in CBS-600 mating ring.
250	CBS-600	No	100	5 1/2 hr @ ambient 2 1/2 hr @ 75(167) 3 1/2 hr @ ambient	0.5(75)	11 1/2	Test terminated due to machine failure. No wear on chrome oxide primary surface; 0.05 mm (0.002 inch) groove worn in CBS-600 mating ring.
257	CBS-600	No	100	4 hr @ ambient 15 1/2 hr @ 100(212) 1 hr @ 150(302)	0.5(75)	20 1/2	Leakage rate became excessive at 150°C. Wear on sealing surfaces similar to test No. 250, above.
258	CBS-600	No	100	4 hr @ ambient 19 hr @ 150(302) 17 hr @ 200(392)	0.5(75)	40	Leakage rate became excessive at 200°C. Overall condition of bellows, springs, and sealing surfaces was excellent; cause of leakage could not be determined.
261	CBS-600	Yes	150	82 hr @ 200(392)	0.5(75)	82	Wear test only: leakage was not monitored. Chrome oxide primary seal was not worn, but primary seal wore a groove in the CBS-600 0.80 mm (0.03 inches) deep.
263	CBS-600	Yes	150	2 hr soak @ 350(662) 96 1/2 hr @ 200(392)	0.5(75)	98 1/2	Results similar to test 261 above. Groove worn in CBS-600 disc to a depth of 1.0 mm (0.04 inches).

1. A positive differential pressure is applied to the lubricant for leakage detection.

Table B4
Parker No. 4205 Viton Seal

TEST NO.	INSTALLED COMPRESSION, %	SOAK TEMP °C (°F)	SOAK TIME HOURS	LIFE AT 150°C (300°F), HOURS	DUROMETER, SHORE A BEFORE/AFTER	COMMENTS
216	9.7	250(482)	1	109+	75/75	Seal has only slight abrasive wear.
219	7.6	265(509)	2	1	74/73	Seal in good condition. Cause of failure could not be determined.
220	6.7	260(500)	2	107+	75/75	I.D. shows abrasion and small tears.
224	6.7	270(518)	2	1	73/71	I.D. shows abrasion and small tears.
225	6.6	270(518)	2	4	73/73	Smooth abrasion, slight tearing, some extrusion.
232	12.1	288(550)	2	32	77/61	Extensive durometer shift, severe cracks and tears on I.D., nearly all grease lost from jogger cup.

1. Tests were sometimes terminated for scheduling reasons. These are denoted by a plus sign following the seal life.

Table B5
Coated Elastomeric Seals

TEST NO.	ELASTOMER	INSTALLED COMPRESSION %	SOAK TEMP °C (°F)	SOAK TIME HOURS	LIFE AT 150°C (300°F), HOURS	DUROMETER, SHORE A BEFORE/AFTER	COMMENTS
217	4205 Viton*	7.6	250	1½	107	75/76	Tearing along I.D. with pieces missing.
218	4205 Viton*	7.6	250	1	40+	75/73	Test terminated due to problems with tester.
241	4205 Viton	10.2	288(550)	2	18	79/78	Total grease loss. Large chunk of elastomer missing. Concave abrasive wear on sealing surface.
242	4205 Viton	10.2	288(550)	2	1½	79/78	Concave abrasive wear on sealing surface. Seal also seized to shaft and spun in carrier.
243	4205 Viton	10.2	288(550)	2	2	86/74	Severe tearing and abrasion. Molding seam on O.D. experienced 5mm (0.20 inch) separation.
245	4205 Viton	10.2	288(550)	2	6	79/74	Sealing surface worn to flat condition. Some tearing at lower edge.
246	4205 Viton	12.8	288(550)	2	53	86/77	I.D. torn and cracked, with embedded cuttings.
244	EPDM	9.6	288(550)	2	34	76/65	Chunks of material torn out of seal I.D.; coating bonded to seal carrier.
248	EPDM	10.2	288(550)	2	0	76/67	Seal took square compression set. Seal bonded to shaft and to carrier.
227	Uncoated EPDM	8.3	288(550)	2	9½	72/NA	Severe abrasion of I.D. with loss of small pieces of elastomer.

*The seals evaluated in tests 217 and 218 were coated using the Capacitive Discharge method. All others were coated using the Glow Discharge method, except test 227, which was uncoated.

Table B6
Developmental Elastomeric Seals

TEST NO.	SEAL DESCRIPTION	INSTALLED COMPRESSION %	SOAK TEMP °C (°F)	SOAK TIME, HOURS	LIFE AT 150°C (300°F), HOURS	DUROMETER, SHORE A BEFORE/AFTER	COMMENTS
226	EPDM/Viton No. 267-11-35 (L'Garde, Inc.)	11.9	288(550)	2	104	91/85	Very good grease retention. No tearing, cracks, or pitting were observed and overall surface condition was excellent. Sealing surface wore in tapered configuration with greatest wear on the abrasives side.
259	EPDM/Viton No. Z-267 (L'Garde, Inc.)	10.0	288(550)	2	33	95/91	Abrasive damage to sealing surface and top surface, but otherwise good surface condition. Wear on top indicates seal seized to shaft and spun in carrier.
228	RD-231 Utex Industries, Inc.	9.2	288(550)	2	1½	89/85	Seal was in good condition, cause of leakage could not be determined.
229	RD-231, Utex Industries, Inc.	8.8	288(550)	2	1½	89/85	Seal spun in carrier, embedding abrasives in seal surface, causing leakage.
238	RD-231 Utex Industries, Inc.	10.2	288(550)	2	92+	89/86	Smooth abrasive wear with some intrusion by sand and cuttings.
230	RD-217 Utex Industries, Inc.	7.5	288(550)	2	0	98/82	Complete loss of sealing surface to depth of 2.5 mm (0.10 inch) due to tearing.
231	RD-217 Utex Industries, Inc.	7.5	288(550)	2	1	98/82	Severe Tears in upper portion of the I.D.
236	RD-236, Utex Industries, Inc.	9.4	288(550)	3	0	95/94	Severe abrasion on I.D., with loss of small chunks of elastomer.
237	RD-236 Utex Industries, Inc.	8.9	288(550)	2	0	95/96	Compression - set and smooth abrasive wear on sealing surface.
239	RD-227 Utex Industries, Inc.	10.9	288(550)	2	51	93/85	Compression - set and smooth abrasive wear on sealing surface.
240	RD-227 Utex Industries, Inc.	10.7	288(550)	2	93+	93/84	Compression - set and smooth abrasive wear on sealing surface.
251	RD-239 Utex Industries, Inc.	10.2	288(550)	2	3	89/85	Tearing and pitting observed on upper and lower extremes of sealing surface; central portion was smoothly abraded.
252	RD-239 Utex Industries, Inc.	10.7	288(550)	2	120+	89/84	Slight abrasive wear on sealing surface, but overall condition was very good.
256	RD-239 Utex Industries, Inc.	10.0	302(576)	2	5	89/85	Abrasion on sealing surface with cracking and flaking of elastomer.
260	RD-239 Utex Industries, Inc.	12.0	288(550)	2	0	89/88	Large segment of the sealing surface tore out; possible molding defect.

1. Tests were sometimes terminated for scheduling reasons. These are denoted by a plus sign following the seal life.

Appendix C
High-Temperature Lubricant Test Machine

The Terra Tek High Temperature Lubricant Test Machine (Figure C1) was constructed to facilitate screening tests on candidate lubricants for geothermal rock bits. The test is based on the widely used "Ring and Block" method described in ASTM specification D 2714-68*, and illustrated in Figure C2. The machine evaluates boundary-layer and bulk film (solids) lubrication** at elevated temperatures in a pressurized nitrogen environment. The pressure capability permits evaluation of many lubricants which would otherwise boil off and/or oxidize during the test.

Rock bit manufacturers use the ASTM D2714-68 test, or the ASTM D2596 (or D 2783) "Four Ball" test to screen candidate lubricants for conventional rock bits. The lubricants exhibiting the highest load-carrying ability are then evaluated in a proprietary full-scale journal bearing simulator, prior to field drilling tests. The bit manufacturers consider the ASTM tests to be an effective means of reducing the number of the more expensive full-scale tests required. The "ring and block" method was selected over the "four-ball" method for screening of candidate geothermal lubricants, for two reasons:

1. The relatively long (69-minute) test interval used in the "ring and block" test can evaluate the settlement of particulate additives, and other time-related degradation of the lubricant.
2. The "ring and block" method was more readily adapted for pressurized high-temperature testing.

* ASTM specification D2714-68, "Calibration and Operation of the Alpha LFW-1 Friction and Wear Testing Machine," also applies to the successor to the Alpha tester, known as the "Falex Model No. 1 Ring and Block Test Machine" manufactured by Faville-LaVally Corporation, Downers Grove, Illinois.

** The low rotational speed of 72 RPM precludes significant hydrodynamic lubrication; the similar conditions in journal bearing bits likewise indicate that the hydrodynamic effect is not important to bit lubrication.

Figure C1. Terra Tek High-Temperature Lubricant Test Machine

Figure C2. Lubricant Tester Schematic Diagram

The test procedure is as follows: the wear block is loaded with a dead-weight and lever system, forcing it into contact with the test ring, which is immersed in the test lubricant. The initial peak Hertzian stress between the ring and block, 470 MPa (68,000 psi), is greater than the load-bearing ability of any lubricant. This induces wear in the block, which forms a journal and results in a continuing reduction in the peak stress. This process eventually reduces the contact pressure to the point where the lubricant enters the journal and reduces or eliminates metal-to-metal contact; this event also produces a marked decrease in the frictional force, which is monitored on a strip-chart recorder.

The load-bearing ability is determined by dividing the static load by the area of the wear scar; uniform stress is assumed. After each test the pressure vessel and all internal components are cleaned thoroughly, first with a cleaning solvent, then with chloroethane-NU; the ring and block are replaced. Further detail is provided in Figures C3 - C6.

Figure C3. Pressure Vessel Base Showing Replaceable Journal Bearing.

Figure C4. Rotating Parts (Counter-Clockwise from Center): Test Ring, Ring Holder, Support, and Parts Assembled for Test.

Figure C5: Test block holder (left), showing loading rod, crown bearing and tangential force rod. Also shown are the miniature bellows assemblies (with broad flange bases) used to transmit forces through the walls of the pressure vessel.

Figure C6: Detailed view of the test system showing the pressure vessel installed in the insulation chamber with drive shaft (right) and transducer (top). (Vessel top plate, upper insulation chamber, and dead-weight beam removed for clarity.)

Appendix D
Detailed Lubricant Test Data

DETAILED LUBRICANT TEST DATA

Test Conditions: The test parameters for the lubricant load capacity tests are presented in Table D1.

Table D1
Conditions for the Lubricant Load Capacity Tests

Parameter	Description
Temperature	316°C (600°F) ¹
Atmosphere	Dry Nitrogen
Pressure	0.7 MPa (100 psi)
Rotational Velocity	1.2 S ⁻¹ (72 rpm)
Block Load	634N (142.5 pounds)
Revolutions	5,000
Test Time	69 minutes
Lubricant Volume	85 ml
Ring	S-25, ² conforming to ASTM D2981-71. SAE 4620 steel, hardness of R _C 57-63, surface finish of 22-28 microinch RMS.
Block	H-30, ² conforming to ASTM D2714-68. SAE 01 tool steel, hardness of R _C 27-33, surface finish of 22-28 microinch RMS.

¹Tests 161-163 were run at 204°C (400°F).

²Purchased from Faville LeVally Corp., Inc., 2753 Curtiss St., Downers Grove, Illinois 60515.

Lubricant Test Data: The results of all 46 lubricant load capacity tests are presented in Table D2.

Table D2

**Load Capacity Test Data for Mystic "High Temp",
Pacer Lubricants, Inc. Developmental Lubricants, and Water
Contamination Tests on Pacer PLX-014 Oil.**

TEST	LUBRICANT	COEFFICIENT OF FRICTION			LOAD CAPACITY MPa(ksi)
		Start	400 REV	End	
136	PLX-023 oil	0.26	0.20	0.18	89.4(13.0)
137	PLX-023 oil	0.21	0.15	0.13	74.2(10.8)
138	PLX-023 oil	0.22	0.11	0.13	57.0(8.3)
139	PLX-023 oil	0.22	0.13	0.14	63.4(9.2)
140	PLX-023 oil	0.13	0.11	0.12	50.4(7.3)
141	PLX-024 oil	0.18	0.17	0.20	74.2(10.8)
142	PLX-024 oil	0.14	0.14	0.20	53.9(7.8)
143	PLX-024 oil	0.14	0.15	0.13	80.2(11.6)
144	PLX-022 oil	0.15	0.14	0.14	42.3(6.1)
145	PLX-022 oil	0.19	0.13	0.13	67.8(9.8)
146	PLX-022 oil	0.30	0.14	0.14	91.5(13.3)
147	PLX-022 oil	0.18	0.12	0.11	64.5(9.3)
148	PLX-022 oil	0.23	0.13	0.14	74.2(10.8)
149	PLX-022 oil	0.22	0.11	0.11	78.6(11.4)
150	PLX-014 grease	0.18	0.16	0.12	65.0(9.4)
151	PLX-014 grease	0.14	0.18	0.11	59.6(8.6)
152	PLX-025 oil	0.13	0.14	0.14	14.9(2.2)
153	PLX-025 oil	n.a.	n.a.	0.12	11.2(1.6)
154	Mystic JT-6 grease ¹	0.15	0.15	0.10	20 (2.9)
155	Mystic JT-6 grease	0.10	0.25	0.21	16.3(2.3)
156	Mystic JT-6 grease	0.10	0.36	0.37	33.6(4.8)
157	PLX-030 oil	0.28	0.34	n.a.	Journal seized at 900 rev.
158	PLX-030 oil	n.a.	n.a.	n.a.	Journal seized at 300 rev.
159	PLX-031 oil	n.a.	n.a.	n.a.	Journal seized at 100 rev.
160	PLX-014 grease	0.15	0.14	0.16	47.4(8.9)
161	PLX-014 oil, water ²	0.25	0.19	0.18	22.5(3.3)
162	PLX-014 oil, water ²	0.28	0.15	0.12	22.6(3.3)
163	PLX-014 oil, water ²	0.28	0.35	0.18	36.4(5.3)
164	Pacer Geobond oil	0.25	0.15	0.12	41.4(6.0)
165	Pacer Geobond oil	0.10	0.16	0.13	19.1(2.7)
166	Pacer Geobond oil	0.18	0.13	0.12	70.2(10.2)
167	Pacer Geobond oil	0.20	0.17	0.15	54.6(7.9)
168	Pacer Geobond oil	0.15	0.15	0.15	62.4(9.1)
169	Pacer Geobond oil	0.11	0.15	0.15	46.8(6.8)
170	Pacer Geobond oil ³	0.21	0.15	0.15	39.3(5.7)
171	PLX-042 oil	0.32	0.15	0.14	58.7(8.5)
172	PLX-042 oil	0.24	0.13	0.12	69.0(10.0)
173	PLX-043 oil	0.35	0.33	0.38	55.9(8.1)
174	PLX-043 oil	0.06	0.18	0.25	68.9(10.0)
175	PLX-044 oil	0.08	0.18	0.26	62.4(9.0)
176	PLX-045 oil	0.11	0.14	0.13	75.6(11.0)
177	PLX-044 oil	0.13	0.19	0.24	68.6(9.9)
178	PLX-045 oil	0.15	0.19	0.21	69.0(10.0)
179	PLX-046 oil	0.15	0.28	0.16	21.0(3.0)
180	PLX-046 oil	n.a.	n.a.	n.a.	Journal seized at 175 rev.
181	PLX-046 oil	0.12	0.41	n.a.	Journal seized at 4200 rev. 21.8(3.2)

1. Mystic "High Temp" grease, Cato Oil and Grease Manufacturing, Oklahoma City, Oklahoma.
2. 1.5 ml of water was added to, but not mixed in; the standard load of 85 ml of lubricant for tests 161-163; tests run at 204°C (400°F).
3. Test No. 170 was inadvertently run without nitrogen pressure.

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