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Program for the Improvement of Downhole Drilling Motor Bearings and Seals

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PHASE V - FINAL REPORT
PROGRAM FOR THE IMPROVEMENT OF
DOWNHOLE DRILLING MOTOR BEARINGS AND SEALS

SAND83-7102

by

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Submitted to:

U.S. Department of Energy
Division of Geothermal Energy
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ABSTRACT

This report describes the work done during the fifth and final phase of a program to improve downhole drilling motor bearings and seals. The principal activities in this phase were:

- (a) testing seals with abrasive-laden mud on the low-pressure side;
- (b) testing second- and third-generation designs of both elastomeric chevron seals and Teflon U-seals; and
- (c) testing a full-scale bearing/seal package.

Several operating parameters which have a radical effect on seal life were identified, and some promising designs and materials were tested.

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I. INTRODUCTION

This report summarizes the work completed during Phase V of the DOE/DGE "Program for the Improvement of Downhole Drilling Motor Bearings and Seals," Sandia National Laboratories Contract 74-6607.

Downhole motors require a bearing system to transfer the applied drilling weight from the non-rotating drill string to the bit. The bearing system must be lubricated with an oil having very good anti-wear properties. Seals are required to retain the oil and prevent drilling fluid from contaminating the lubricant. The seal must also resist the bit pressure drop; high bit pressure drops are desirable because they greatly increase the rate of penetration. In geothermal operation, the seals, bearings, and lubricant must also withstand higher bottomhole temperatures. The specific objectives of this program were therefore established as follows:

1. Develop a lubricated bearing pack with a life in excess of 200 hours;
2. Develop an improved rotary seal which allows bit pressure drops in excess of 1000 psi; and
3. Develop a bearing seal package to operate at 250°F circulating bottomhole temperature.

In the previous four phases of the program, the test facilities were designed and constructed, and extensive testing and development were accomplished. These efforts are summarized in Appendix C; additional information is available in prior annual reports, listed in the Bibliography.

The Phase V efforts were as follows:

1. The seal test machine was modified to allow testing with mud.
2. A mud pumping system was added to the Bearing Seal Pack Test Facility to enable long-term testing.

3. Tests were run on second and third generation elastomeric seals, second and third generation spring-loaded U-section teflon seals, and two types of face seals.
4. High-temperature load-capacity tests were run on a second generation lubricating oil with reduced viscosity.
5. New floating pistons were designed and fabricated, and tested in conjunction with Bearing-Seal package tests.
6. Shaft materials and finishes for radial seals were evaluated.

The report contains four major sections: Seal Testing and Evaluation, Bearing-Seal Package Testing and Evaluation, Lubricant Testing and Evaluation, and Bibliography.

II. SEAL TESTING AND EVALUATION

II.1 Seal Test Machine

A schematic of the Seal Test Machine is shown in Figure 1. Details of the design and operation of the machine will be found in prior Terra Tek reports listed in the Bibliography.

During this reporting period a mud injection system for the Seal Test Machine was fabricated and tested. A schematic of the mud injection system will be found in Figure 2. The system operated as follows. A cylinder was used for a mud reservoir. Inside the cylinder was a floating piston with mud on one side and hydraulic oil on the other side. A Haskel pump was used to pressurize the hydraulic oil which, in turn, pressurized the mud and injected it into the Seal Test Machine. A valve downstream of the Seal Test Machine was used to create a back-pressure on the mud and pressurize the system. A photograph of the mud injection system is shown in Figure 3.

The configuration and pressures in the Seal Test Machine were modified to use the mud injection system. In the seal tests with oil, the two test seal packs are installed in the machine in a "face-to-face" configuration. High pressure lubricant is injected between the seal packs at a pressure of 2500 psi. Low pressure lubricant is injected between the test seal packs and the vessel seals at a pressure of 1000 psi. This results in a net differential pressure of 1500 psi across each test seal pack. When using the mud injection system the two test seal packs are installed in the machine in a "back-to-back" configuration. Low pressure mud is injected between the two test seal packs at a pressure of 500 psi. High pressure lubricant is injected between the test seal packs and the vessel seals at a pressure of 1500 psi. This results in a net differential pressure of 1000 psi across each test seal pack. With the mud injection system the test pressures were reduced to prolong the life of the vessel seals.

Figure 1
Seal Test Machine Schematic

Figure 2
Mud Injection System Schematic

Figure 3
Mud Injection System

II.2 Seal Test Results

Table I shows the test conditions for the seal tests and Table II shows the seal test results. These tables show the test conditions and results for all phases of the Downhole Motor Program. During this reporting period tests DMT-54 through DMT-62 were completed. The graphs from these tests will be found in Appendix A.

Two seal types were tested during this reporting period: HTCR and Vari-seal®. The HTCR (High Temperature Corrosion Resistant) elastomer seal is manufactured by Utex Industries, Inc. Figure 4 shows a schematic of the HTCR seal. HTCR uses an Aflas® base. Aflas® is a copolymer of tetrafluoroethylene and propylene. The seal is reinforced with alternating plugs of synthetic arimid and glass fabric. Two versions of the HTCR seal were tested: HTCR-SF Design and HTCR-SSF Design. The two versions of the seal have the same geometry. The difference between the two versions is that the SSF Design contains twice as much material as the SF Design.

The second seal type tested was the second generation Variseal® (Variseal®-II), manufactured by American Variseal Corp. The Variseal®-II, a schematic of which is shown in Figure 5, incorporated design improvements based on the testing of the Variseal®-I in the previous phase of this program. These improvements are discussed in detail in Failure Analysis Associates Report No. FAA 81-7-6 (Bibliography Item No. 24). The Variseal®-II is composed of a TFE body filled with a proprietary material. The seal is loaded from the inside by an alloy spring.

In tests DMT-54 through DMT-54C the HTCR seals were tested with the Pacer PLX-014 lubricant (formulated under the commercial number of DHT-185M). This lubricant was used in the seal test machine for the first time in DMT-54. From the post-test examination of the seals and shafts it was concluded that

the premature failure of the seals was caused by inadequate lubrication. The DHT-185M lubricant is more viscous than the Texaco EP 85-90 lubricant used in prior tests. Also, starting with DMT-54 a carburized steel sleeve was used in place of the chrome sleeve used in tests DMT-01 through DMT-53. The carburized sleeve provided a much harder surface for the seal to ride against.

Based on the test results from DMT-54 through DMT54C, the Pacer PLX-014 lubricant was remixed to have the same viscosity as the Texaco EP 85-90 lubricant. The remixed lubricant was given the commercial number of DHT-90G. Test DMT-55 tested the HTRC seal with the DHT-90G. The test was terminated at 200 hours without a seal failure. The upper seal pack had leaked approximately 0.5 gallons of lubricant, while the lower seal pack had leaked approximately 0.15 gallons of lubricant. Post-test examination showed very little material degradation of the seals and almost no wear of the shaft.

In DMT-56 through DMT-58 the HTRC seals were tested using the mud injection system. The arrangement of the seals and the operation of the seal test machine using the mud injection system is described in Section II.1. Premature failure of the seals was observed in all of these tests. Post-test analysis of DMT-56 through DMT-58 indicated that the seal failure may have been caused by an unbalanced loading of the seals due to the "back-to-back" arrangement of the seals. DMT-59 and DMT-60 were run with the seals in the "back-to-back" configuration but with oil used on the low pressure side instead of mud. Premature failure of the seals in these tests was also observed, supporting the analysis that the "back-to-back" arrangement of the seals can cause an unbalanced loading resulting in premature seal failure.

The Variseal®-II was tested in DMT-61 and DMT-62. In these two tests a sleeve coated with Union Carbide Coating No. LWIN30 (87% WC/13% Co) was used in place of the chrome sleeve used in DMT-01 through DMT-53. The Union Car-

bide coated sleeve provided a much harder surface for the seal to ride against. DMT-062 was terminated at 100 hours without a seal failure. Post-test inspection of the shaft showed virtually no wear. Inspection of the seals showed very little wear on the Variseal® seal ring and significant wear on the anti-extrusion ring. There was also evidence of the anti-extrusion ring spinning against the bronze back-up ring. In future tests with the Variseal® it was concluded to eliminate the anti-extrusion ring and use the Variseal® seal ring only.

Table I
Test Conditions for Seal Tests

Rotary Speed: 412 rpm

Shaft Diameter: 5.000 + 0.000 - 0.002 in.

Shaft Surface Material: DMT-01 thru DMT-53: Chrome Plated
DMT-54 thru DMT-60: Carburized Steel
DMT-61 thru DMT-62: Union Carbide Coating #UCAR LW1N30

Shaft Surface Finish: Noted on Seal Test Results Table

Differential Pressure: 1500 psi

Lubricant: DMT-01: Steam Cylinder Oil
DMT-02 thru DMT-53: Texaco EP 85-90
DMT-54 thru DMT-54C: Pacer DHT-185M
DMT-55 thru DMT-62: Pacer DHT-90G

Seal Failure Criteria: Leakage of one gallon of lubricant past the seal

Table II
Seal Test Results

Test I.D.	Seal Assembly	No. of Rings	Shaft Finish	Back Up Ring Material	Diametrical Clearance Shaft to Back Up Ring	Test Duration	Failure Analysis	Notes
DMT-01	701 - Elastomer	3	16 μ in	Buna-N	As Manufactured	53.0 hrs	Slow, constant leak by upper seal	1
DMT-02	701 - Elastomer	3	16 μ in	Buna-N	As Manufactured	27.3 hrs	Constant leak by upper seal during second half of test	1,2
DMT-03	42D - Elastomer	3	16 μ in	Buna-N	As Manufactured	20.4 hrs	Catastrophic failure - upper seal	1
DMT-04	42D - Elastomer	3	16 μ in	Buna-N	As Manufactured	12.4 hrs	Catastrophic failure - upper seal	1
DMT-05	42D - Elastomer	3	16 μ in	Buna-N	As Manufactured	5.5 hrs	Catastrophic failure - upper seal	1
DMT-06	42D - Elastomer	3	16 μ in	Buna-N	As Manufactured	24.2 hrs	Catastrophic failure - upper seal	1
DMT-07	42D - Elastomer	3	16 μ in	Buna-N	As Manufactured	3.1 hrs	Catastrophic failure - upper seal	
DMT-08	701 - Elastomer	2	17 μ in	Brass	0.010 in	18.2 hrs	Catastrophic failure - lower seal	
DMT-09	701 - Elastomer	2	16 μ in	Brass	0.010 in	3.5 hrs	Catastrophic failure - upper seal	
DMT-10	701 - Elastomer	2	16 μ in	Brass	0.010 in	10.3 hrs	Catastrophic failure - upper seal	
DMT-11							Aborted	
DMT-12							Aborted	
DMT-13	RD181 - Elastomer	2	12 μ in	Brass	0.010 in	11.3 hrs	Catastrophic failure - upper seal	
DMT-14	RD181 - Elastomer	2	12 μ in	Brass	0.010 in	8.6 hrs	Catastrophic failure - upper seal	
DMT-15	701 - Elastomer	1	12 μ in	Brass	0.010 in	5.5 hrs	Catastrophic failure - upper seal	
DMT-16	Grafoil® - BeCu	5	12 μ in	Brass	0.010 in	17.5 hrs	Catastrophic failure - upper seal	
DMT-17	Grafoil® - BeCu	5	11 μ in	Brass	0.010 in	9.9 hrs	Catastrophic failure - upper seal	
DMT-18	701 - Elastomer	3	16 μ in	Brass	0.010 in	1.2 hrs	Catastrophic failure - upper seal	
DMT-19	Graphite - Metal Matrix (RD-170)	3	16 μ in	Aluminum Bronze	0.010 in	4.6 hrs	Continuous leakage by upper seal from beginning of test	
DMT-20	Graphite - Metal Matrix (RD-170)	1	13 μ in	Aluminum Bronze	0.010 in	13.1 hrs	Continuous leakage by upper seal from beginning of test	
DMT-21	Grafoil® - BeCu	3	17-18 μ in	Aluminum Bronze	0.002 in	5.9 hrs	Catastrophic failure - upper seal	
DMT-22	Uneepac®	3	17-18 μ in	Aluminum Bronze	0.003 in	10.6 hrs	Catastrophic failure - upper seal	
DMT-23	Uneepac®	3	17 μ in	Aluminum Bronze	0.015 in	26.6 hrs	Catastrophic failure - upper seal	
DMT-24	Grafoil® - BeCu	3	4 μ in	SAE 660 Bronze	Zero clearance Back up I	40.9 hrs	Catastrophic failure - upper seal	
DMT-25	Graphite - Metal Matrix (RD-171)	3	4-8 μ in	Teflon and SAE 660 Bronze	Zero clearance Back up II	2.0 hrs	Catastrophic failure - upper seal	
DMT-26	Graphite - Metal Matrix (RD-171)	3	4-8 μ in	Teflon and SAE 660 Bronze	Zero clearance Back up II	2.0 hrs	Catastrophic failure - upper seal	
DMT-27	Graphite - Metal Matrix (RD-194)	3	4-8 μ in	SAE 660 Bronze	Zero clearance Back up I	23.5 hrs	Catastrophic failure - upper seal	
DMT-28	Grafoil® - Brass	3	4-8 μ in	SAE 660 Bronze	Zero clearance Back up I	2.9 hrs	Seal tester disassembled and assembled several times - possible damage to seals	
DMT-29	Grafoil® - Brass	3	4-8 μ in	SAE 660 Bronze	Zero clearance Back up I	3.2 hrs	Test aborted - spline at bottom of seal tester shaft was damaged	
DMT-30	Canted (31A)	2	4-8 μ in	9C Aluminum Bronze	0.008 in	0 hrs	Seals would not hold ΔP	
DMT-31	Canted (42DR)	2	4-8 μ in	9C Aluminum Bronze	0.008 in	0 hrs	Seals would not hold ΔP	
DMT-32	Graphite - Metal	3	4-8 μ in	SAE 660 Bronze	Zero clearance Back up I	8.6 hrs	Catastrophic failure - upper seal	
DMT-33	Canted (42DR)	2	4-8 μ in	9C Aluminum Bronze	0.008 in	0.7 hrs	Seal would not hold ΔP after 45 minutes	
DMT-34	Grafoil® - Phosphor Bronze	3	4-8 μ in	SAE 660 Bronze	Zero clearance Back up III	3.5 hrs	Constant leakage during test; leakage rate reduced during 1750 psi ΔP	3,6
DMT-35	Grafoil® - Phosphor Bronze	3	4-8 μ in	SAE 660 Bronze	Zero clearance	32.3 hrs	Upper seal leaked gradually during test	7

Table II (continued)

Seal Test Results

Test I.D.	Seal Assembly	No. of Rings	Shaft Finish	Back Up Ring Material	Diametrical Clearance Shaft to Back Up Ring	Test Duration	Failure Analysis	Notes
DMT-36	Canted (Buna-N)	2	4-8 μ in	9C Aluminum Bronze	0.008 in	0 hrs	Seal would not hold ΔP	
DMT-37	Grafoil® - Phosphor Bronze	3	4-8 μ in	SAE 660 Bronze	Zero clearance Back up I	0 hrs	Test attempted twice. Torques too high.	
DMT-38	Hybrid Assembly SF Design	3	8-12 μ in	SAE 660 Bronze	0.016 in	8 hrs	Both seals leaked gradually during test; leakage rate increased at end of test	
DMT-39	Hybrid Assembly V Design	3	4-8 μ in	SAE 660 Bronze	Zero clearance Back up III	3.8 hrs	Upper seal leaked during test.	7
DMT-40	HTCR - SF Design	3	8-12 μ in	SAE 660 Bronze	0.016 in	53.3 hrs	Leakage due to excessive shaft wear	
DMT-41	Variseal® - I	1	8-12 μ in	SAE 660 Bronze	0.063 in	5.3 hrs	Catastrophic failure - upper seal	
DMT-42	Variseal® - I	1	8-12 μ in	SAE 660 Bronze	0.063 in	4.3 hrs	Catastrophic failure - lower seal	
DMT-43	Mesh Matrix Copper Wire	3	4-8 μ in	Sintered Graphite	0.008 in	0.8 hrs	Catastrophic failure - sintered graphite adapters fractured.	
DMT-44	Mesh Matrix Glass Fiber	3	4-8 μ in	Sintered Graphite	0.008 in	0 hrs	Seals would not hold ΔP . Sintered graphite adapters fractured.	
DMT-45	Variseal® - I	1	8-12 μ in	SAE 660 Bronze	0.005 in	164.8 hrs	Catastrophic failure - lower seal. Excessive wear of shaft.	
DMT-46	HTCR - SF Design	3	8-12 μ in	SAE 660 Bronze	0.016 in	71.8 hrs	Lower seal leaked gradually. Excessive wear of shaft.	
DMT-47	Variseal® - I	1	8-12 μ in	SAE 660 Bronze	0.005 in	10.3 hrs	Catastrophic failure - upper seal. Crack in heel	
DMT-48	Hybrid Assembly SF Design (Modified)	2	8-12 μ in	SAE 660 Bronze	0.016 in	6.7 hrs	Upper seal leaked continuously.	
DMT-49	Mesh Matrix Copper Wire	3	4-8 μ in	SAE 660 Bronze	0.016 in	0 hrs	Seals would not hold ΔP	
DMT-50	Mesh Matrix Glass Fiber	3	4-8 μ in	SAE 660 Bronze	0.016 in	2.0 hrs	Upper seal leaked continuously.	
DMT-51	Canted (Buna-N)	2	8-12 μ in	9C Aluminum Bronze	0.008 in	0 hrs	Seals would not hold ΔP .	
DMT-52	Grafoil® - Phosphor Bronze (Horizontal Laminates)	3	4-8 μ in	SAE 660 Bronze	Zero clearance Back up III	3.7 hrs	Catastrophic failure - lower seal	7
DMT-53	Variseal® - I	1	8-12 μ in	SAE 660 Bronze	0.005 in	0.9 hrs	Catastrophic failure - lower seal. Crack in heel.	
DMT-54	HTCR - SF Design	2	8-12 μ in	SAE 660 Bronze	0.005 in	16.7 hrs	Lower seal leaked during test. Back up rings had spun.	
DMT-54A	HTCR - SF Design	2	8-12 μ in	SAE 660 Bronze	0.005 in	9.2 hrs	Lower seal leaked - catastrophic failure - lower seal - seals had spun during test.	
DMT-54B	HTCR - SF Design	3	8-12 μ in	SAE 660 Bronze	0.005 in	1.0 hrs	Aborted because of excessive torque and seal temperature.	
DMT-54C	HTCR - SF Design	1	8-12 μ in	SAE 660 Bronze	0.005 in	7.8 hrs	Catastrophic failure - lower seal. Conclusion: DMT-54 to DMT-54C; inadequate lubrication; viscosity of lubricant lowered.	
DMT-55	HTCR - SF Design	2	8-12 μ in	SAE 660 Bronze	0.005 in	200 hrs	Test terminated at 200 hours without a seal failure.	
DMT-56	HTCR - SF Design	2	8-12 μ in	SAE 660 Bronze	0.005 in	8.3 hrs	Lower seal leaked gradually. Seals spun during test.	4,5
DMT-57	HTCR - SF Design	2	8-12 μ in	SAE 660 Bronze	0.005 in	41.8 hrs	Lower seal leaked gradually.	4,5
DMT-58	HTCR - SSF Design	1	8-12 μ in	SAE 660 Bronze	0.005 in	19.0 hrs	Lower seal leaked gradually.	4,5
DMT-59	HTCR - SSF Design	1	8-12 μ in	SAE 660 Bronze	0.005 in	16.0 hrs	Lower seal leaked gradually.	4
DMT-60	HTCR - SSF Design	1	8-12 μ in	SAE 660 Bronze	0.005 in	74.0 hrs	Terminated because of increasing leakage of both seals. Conclusion from DMT-56 to DMT-60: Back-to-back arrangement can cause unbalanced loading on seals.	4
DMT-61	Variseal® - II	1	8-12 μ in	AISI 4140 Steel	0.005 in	1.8 hrs	Back up rings caused galling on shaft.	
DMT-62	Variseal® - II	1	8-12 μ in	SAE 660 Bronze	0.005 in	100 hrs	Terminated at 100 hrs without seal failure.	

Notes:

1. Test run at 211 rpm.
2. Test run at 1400 psi.
3. ΔP increased to 1750 psi in middle of test.
4. Test run at 1000 psi ΔP ; seals back-to-back.

5. Mud injection system used: lubricant high pressure side; mud low pressure side.
6. Back up III with 3 each - 0.031 in leaves.
7. Back up III with 4 each - 0.016 in leaves.

SF DESIGN $A = 0.281''$
SSF DESIGN $A = 0.562''$

Figure 4
HTCR Seal Schematic

Figure 5

Variseal® - II Schematic

II.3 Conclusions

The following summarizes the conclusions from the Seal Testing and Evaluation portion of the Downhole Motor Program:

1. The best candidate seals tested were the HTCR-SSF Design seal manufactured by Utex Industries, and the Variseal® manufactured by American Variseal Corporation.
2. The shaft/seal combination must be considered together in solving the sealing problem. A hard shaft surface is necessary to prevent the seal from wearing a groove in the shaft. The best shaft materials tested were a carburized steel shaft and a shaft coated with Union Carbide coating LWIN30. Both of these materials performed better than a chrome surface. In the long duration seal tests, excessive wear of the chrome surface was observed.
3. In using a lip seal, the optimum design is one sealing lip. By stacking more than one lip seal ring in a seal pack, improper lubrication of the inner seal rings occurs.

III. BEARING-SEAL PACKAGE TESTING AND EVALUATION

III.1 Bearing-Seal Package Test Facility

The Bearing-Seal Package is tested under simulated downhole conditions in the Bearing-Seal Package Test Facility. A schematic of the test facility is shown in Figure 6. Details of the design and operation of the Bearing-Seal Package and Bearing-Seal Package Test Facility will be found in prior Terra Tek reports listed in the Bibliography.

During this reporting period the Bearing-Seal Package was modified to accept installation of face seals. Bearing-Seal Package parts were designed and fabricated for face seals manufactured by Gits Brothers Manufacturing Co. and Stein Seal Company.

Also during this reporting period a small mud pumping system was installed in the Drilling Research Laboratory. This separate mud system allowed operation of the Bearing-Seal Package Test Facility on a 24 hour per day basis independent of any other testing in the Drilling Research Laboratory.

Figure 6

Bearing-Seal Package Test Facility Schematic

III.2 Bearing-Seal Package Test Results

Table III shows the test conditions and Table IV shows the test results for all phases of the program. BSP-04 through BSP-15 were completed during this reporting period. The graphs from these tests will be found in Appendix B.

The HTCR seal, Gits Brothers Manufacturing Co. face seal, Stein Seal Company face seal, and Variseal®-III were tested during this reporting period. The HTCR seal was discussed in Section II.2. The Variseal®-III seal is similar to the Variseal®-II seal discussed in Section II.2, with the elimination of the anti-extrusion ring.

A schematic of a face seal installed in the Bearing-Seal Package is shown in Figure 7. The face seal comprises two parts. In the first part, a seal carrier is fixed to the Bearing-Seal Package case, which remains stationary. This carrier contains the stationary seal face. In the second part, a seal carrier is fixed to the Bearing-Seal Package shaft, which is rotating. This carrier contains the rotating seal face. The schematic shows the rotating face spring-loaded against the stationary face. The stationary face may also be spring-loaded (not shown in the schematic).

Three generations of the Gits Brothers Manufacturing Co. face seal were tested. A photograph of the Gits Brothers seal is shown in Figure 8. The Gits Brothers-I face seal consisted of a tungsten carbide coated face vs. a solid silicon carbon face. The Gits Brothers-II face seal consisted of a tungsten carbide coated face vs. a tungsten carbide coated face. The Gits Brothers-III face seal consisted of a solid tungsten carbide face vs. a solid tungsten carbide face.

Figure 9 shows a photograph of the Stein Seal Co. face seal. This seal consisted of a graphite face vs. a tungsten carbide coated face.

Two types of floating pistons were used in these tests (the HTCR and the Variseal®). The HTCR floating pistons are a one piece molded part, manufactured from the same material as the HTCR seal. The HTCR floating pistons, however, did not contain any reinforcing fibers; the material was homogeneous. A schematic of the HTCR-I floating piston is shown in Figure 10. This floating piston has a double lip on both the OD and ID. A schematic of the HTCR-II floating piston is shown in Figure 11 and a photograph of the piston is shown in Figure 12. This piston has a double lip on the OD and a single lip on the ID. The HTCR-III floating piston is similar to the HTCR-II floating piston except that there is a fabric reinforcement on the ID lip. The HTCR-IV floating piston is similar to the HTCR-II floating piston except that there is a teflon reinforcement on the ID lip.

Figure 13 shows a schematic of the Variseal®-I floating piston. This piston consists of a bronze carrier with O-ring seals on the OD and Variseal® seals on the ID. Figure 14 shows a schematic of the Variseal®-II floating piston. This piston consists of a bronze carrier with Variseal® seals on both the OD and ID.

The HTCR-SF design seal was tested in BSP-04 and BSP-06 and the HTCR-SSF design seal was tested in BSP-07, BSP-09, BSP-11, and BSP-12. In BSP-06 the test was terminated at six hours due to seizure of the Bearing-Seal Package. Post-test inspection showed that one of the dowel pins in the seal pack had sheared, allowing the back-up rings to spin. In the remainder of the tests with the HTCR seal post-test analysis showed excessive wear of the floating piston, allowing mud to enter the Bearing-Seal Package. In all of these tests, except BSP-11, the HTCR seals were in good condition.

The Gits Brothers-I face seal was tested in BSP-05. The seal failed before rotation due to cracking of the silicon carbide face.

The Gits Brothers-II face seal was tested in BSP-08. The test was terminated at ten hours because of an inability to maintain the differential pressure across the seal due to seal failure. Post-test inspection showed that the tungsten carbide coating had worn away.

The Gits Brothers-III face seal was tested in BSP-15. The test was run for 24 hours and terminated so that examination of the seal and floating piston could be made. Post-test analysis showed that the floating piston had failed, allowing mud to enter the Bearing-Seal Package. The seal was in good condition.

The Stein face seal was tested in BSP-10. The test was terminated at ten hours. Post-test inspection showed that the carbon graphite face had been worn away during the test; no parts of the seal were found.

The Variseal®-III seal was tested in BSP-13 and BSP-14. BSP-13 was terminated at 46 hours and post-test inspection showed the floating piston had failed, allowing mud to enter the Bearing-Seal Package. BSP-14 was terminated at 24 hours so that examination of the seal and floating piston could be made. Post-test analysis showed the floating piston had failed, allowing mud to enter the Bearing-Seal Package. In both tests the Variseal® seals were in good condition.

In most of the Bearing-Seal Package tests, the life of the Bearing-Seal Package was limited by the failure of the floating piston.

Table III

Test Conditions for
Bearing-Seal Package Tests

Rotary Speed: 450 rpm

Rotary Shaft Diameter: 5.000 + 0.000 - 0.002 in.

Nominal Floating Piston Size: 4 in. I.D. x 6.5 in. O.D.

Differential Pressure: 1000 psi

Axial Load: 10,000 lb

Lubricant: BSP-01 thru BSP-03: Pacer PLX-014
BSP-04 thru BSP-15: Pacer DHT-90G

Floating Piston Sleeves: BSP-01 thru BSP-11: Chrome Plated
BSP-12 thru BSP-15: Carburized Steel

Mud Properties: 9 lb/gal Water-Based Mud
2-3% Abrasive Content (#3 Blasting Sand)
pH: 7-9

Table IV
Bearing-Seal Package Test Results

Test I.D.	Seal Assembly	Shaft Coating	Shaft Finish	Back Up Ring Material	Diametrical Clearance Shaft to Back Up Rings	Floating Piston	Test Duration	Failure Analysis	Notes
BSP-01	Style 701 3 Pressure Rings						Debugging Test		
BSP-02	Style 701 3 Pressure Rings						Debugging Test		
BSP-03	Style 701 3 Pressure Rings	Chrome	8-12 μ in	SAE 660 Bronze	0.010 in	Oil Seals - OD Uneepac $\emptyset$ - ID	5.0 hrs		1,2
BSP-04	HTCR - SF Design 2 Pressure Rings	Carburized Steel	8-12 μ in	SAE 660 Bronze	0.005 in	HTCR - I (Double lip on ID)	30.9 hrs	Floating piston failed - Allowed mud into the bearing pack	
BSP-05	Gits Brothers - I (Tungsten carbide coated face vs. solid silicon carbide face)	n/a	n/a	n/a	n/a	HTCR-I	0 hrs	Seal failed before rotation-pressure caused silicon carbide face to crack.	
BSP-06	HTCR - SF Design 2 Pressure Rings	Carburized Steel	8-12 μ in	SAE 660 Bronze	0.005 in	HTCR - I	6 hrs	Test terminated because of seizure of bearing pack. Dowel pin sheared allowing back up rings to spin, causing seizure.	
BSP-07	HTCR - SSF Design 1 Pressure Ring	Carburized Steel	8-12 μ in	SAE 660 Bronze	0.005 in	Variseal $\emptyset$ - I (Variseal $\emptyset$ - ID O-ring - OD)	51.3 hrs	Test terminated because of excessive bearing temperatures. Floating piston failed, allowing mud to enter the bearing pack.	
BSP-08	Gits Brothers - II (Tungsten carbide coated face vs. Tungsten carbide coated face)	n/a	n/a	n/a	n/a	HTCR-II (Single lip on ID)	10.0 hrs	Lost ΔP across seal. Seal failed.	
BSP-09	HTCR-SSF Design 1 pressure ring	Carburized Steel	8-12 μ in	SAE 660 Bronze	0.005 in	HTCR-II	3.5 hrs	Floating piston failed. Mud in bearing pack.	
BSP-10	Stein (carbon graphite face vs. Tungsten carbide coated face)	n/a	n/a	n/a	n/a	HTCR-II	10.8 hrs	Seal failed - carbon graphite face destroyed - no parts found.	
BSP-11	HTCR - SSF Design 1 Pressure Ring	Carburized Steel	8-12 μ in	SAE 660 Bronze	0.005 in	HTCR-III (Same as II but with fabric reinforcement on ID)	48.0 hrs	Terminated because of not being able to hold P. Mud in bearing pack. Floating piston and main seals both worn.	
BSP-12	HTCR - SSF Design 1 Pressure Ring	Carburized Steel	8-12 μ in	SAE 660 Bronze	0.005 in	HTCR-III	46.0 hrs	Mud in bearing pack. Floating piston ID worn.	
BSP-13	Variseal $\emptyset$ - III 1 Pressure Ring	Carburized Steel	8-12 μ in	SAE 660 Bronze	0.005 in	Variseal $\emptyset$ - II (Variseal $\emptyset$ ID and OD)	46.0 hrs	Mud in bearing pack. Floating seals and main seals slightly worn.	3
BSP-14	Variseal $\emptyset$ - III 1 Pressure Ring	Carburized Steel	8-12 μ in	SAE 660 Bronze	0.005 in	Variseal $\emptyset$ - II	24.0 hrs	Mud in bearing pack. Floating piston failure.	
BSP-15	Gits Brothers - III (solid tungsten carbide face vs solid tungsten carbide face)	n/a	n/a	n/a	n/a	HTCR-IV (Same as II but with Teflon reinforcement on ID)	24.0 hrs	Mud in bearing pack. Floating piston failure.	

Notes:

1. Test run at 900 psi ΔP .
2. Test run at 400 rpm.
3. Test run at 500 psi ΔP .

**BEARING PACK BIT BOX
(ROTATING)**

**BEARING PACK CASE
(STATIONARY)**

MUD

**STATIONARY SEAL CARRIER
LUBRICANT**

STATIONARY FACE

ROTATING FACE

ROTATING SEAL CARRIER

3

Figure 7

Face Seal Schematic

Figure 8
Gits Brothers Face Seal

Figure 9

Stein Face Seal

Figure 10
HTCR-I Floating Piston Schematic

Figure 11

HTCR-II Floating Piston Schematic

Figure 12
HTCR-II Floating Piston

FLOATING PISTON SEAL CARRIER

MUD

VARISEAL

O-RING

LUBRICANT

Q

Figure 13

Variseal® - I Floating Piston Schematic

Figure 14
Variseal® - II Floating Piston Schematic

III.3 Conclusions

The following summarizes the conclusions from the Bearing-Seal Package Testing and Evaluation portion of the Downhole Motor Program:

1. The life of the bearing pack was limited by the failure of the floating piston.
2. It is recommended that a bellows arrangement be used in place of the floating piston. The floating piston requires an ID and OD seal. The bellows requires an ID seal only that seals against a replaceable surface.

IV. LUBRICANT TESTING AND EVALUATION

IV.1 Lubricant Test Results

A schematic of the lubricant test machine is shown in Figure 15. Details of the lubricant test machine and test procedures will be found in prior Terra Tek reports listed in the Bibliography. The test conditions are shown in Table V and the lubricant test results are shown in Table VI for all phases of the program. Three lubricant tests were run during this reporting period: 185, 186 and 187.

Based on seal test results discussed in Section II.2, the Pacer PLX-014 was remixed to have the same viscosity as the Texaco EP 85-90 lubricant. The remixed lubricant was assigned the commercial number DHT-90G. Three lubricant tests were performed on DHT-90G to compare the results with the tests on the original PLX-014 lubricant. One test each was performed at 200°F, 400°F and 660°F. The DHT-90G test results are comparable to the PLX-014 test results.

Table V

Test Conditions for Lubricant Tests

<u>Test Ring</u>	Diameter:	1.3775 + 0.0001, -0.0005 in.
	Width:	0.321 ± 0.005 in
	Material:	SAE 4620 Steel
	Hardness:	R _C 58 to 63
	Surface Finish:	5 to 15 μ in. rms
<u>Test Block</u>	Width:	0.250 + 0.005, -0.000 in.
	Length:	0.620 ± 0.005 in.
	Material:	SAE 01 Steel
	Hardness:	R _C 27 to 33
	Surface Finish:	4 to 8 μ in. rms
<u>Test Load</u>		142.5 lbs
<u>Rotary Speed</u>		72 ± 1 rpm
<u>Surface Velocity</u>		26 ± 0.52 fpm
<u>Confining Pressure</u>		100 psi (Nitrogen)
<u>Test Duration</u>		5,000 revolutions
<u>Temperature</u>		200°F: Test 185
		400°F: Test 32 to 104, 162, 163, 186
		550°F: Test 105
		660°F: Tests 106, 107, 187

Table VI
Lubricant Test Results

Test* I.D.	Lubricant Manufacturer	Lubricant Number	Avg. Wear Scar Width (inches)	Nominal Load Bearing Capacity (psi)
32	Pacer	PLX-013	0.077	7,435
33	Pacer	PLX-013	0.080	7,155
40	Pacer	PLX-015	0.108	5,277
41	Pacer	PLX-015	0.098	5,816
42	Pacer	PLX-011	0.102	5,588
43	Pacer	PLX-011	0.075	7,600
44	Pacer	PLX-011	0.083	6,895
45	Pacer	PLX-014	0.070	8,143
46	Pacer	PLX-014	0.064	8,860
47	Pacer	PLX-014	0.057	9,942
48	Pacer	PLX-010	0.092	6,218
49	Pacer	PLX-010	0.094	6,064
50	Schmierstoffe	Gleitmo 500	0.104	5,463
51	Schmierstoffe	Gleitmo 500	0.147	3,878
52	Schmierstoffe	Gleitmo 500	0.132	4,329
53	API	BUC 5A2	0.114	5,000
54	API	BUC 5A2	0.130	4,396
55	Mavom	B5K	0.142	4,014
56	Mavom	B5K	0.162	3,519
57	Optimol-Olwerke	Optimoly White T	0.307	1,857
58	Optimol-Olwerke	Optimoly White T	0.376	1,516
59	Texaco	EP 85-90	0.260	2,190
60	Texaco	EP 85-90	0.259	2,205
61	Wooley Booger	Teflon Grease	0.204	2,990
62	Wooley Booger	Teflon Grease	0.173	3,301
63	Mobil	600W	0.137	4,171
64	Mobil	600W	0.148	3,851
65	Jet-Lube	Kopper Kote	0.136	4,181
66	Jet-Lube	Kopper Kote	0.197	2,889
67	Jet-Lube	Kopper Kote	0.136	4,181
68	Watch	10:1	0.116	4,900
69	Watch	10:1	0.165	3,448
70	Tenneco	Anderol 456	0.167	3,406
71	Tenneco	Anderol 456	0.185	3,087
72	Watch	10:1	0.158	3,696
73	Dow-Corning	710	0.576	900
74	Dow-Corning	710	0.561	1,016
75	Dow-Corning	M-77	0.269	2,119
76	Amoco	31052	0.326	1,752
77	Amoco	M-125	0.164	3,476
78	Amoco	Rykon No. 2 EP	0.150	3,808
79	Amoco	Rykon No. 2	0.140	4,081
80	Amoco	Amdex No. 1 EP	0.242	2,360
81	Amoco	1157	0.125	4,560
103	Pacer	PLX-014	0.070	8,104
104	Pacer	PLX-014	0.087	6,577
105	Pacer	PLX-014	0.068	8,342
106	Pacer	PLX-014	0.043	13,256
107	Pacer	PLX-014	0.041	13,902
162	Pacer	PLX-014	0.174	3,276
163	Pacer	PLX-014	0.108	5,278
185	Pacer	DHT-90G	0.110	6,195
186	Pacer	DHT-90G	0.091	6,525
187	Pacer	DHT-90G	0.065	9,135

*Lubricant Test Machine was developed in conjunction with the "Program to Develop Improved Sealed-Geothermal Rock Bits." This program was funded by the Department of Energy/Division of Geothermal Energy with Terra Tek as the prime contractor. Lubricant tests for the Downhole Motor Program and the Geothermal Bit Program were numbered consecutively. The tests results listed in this table apply to the Downhole Motor Program.

Figure 15
Lubricant Test Machine Schematic

IV.2 Conclusions

The following summarizes the conclusions from the Lubricant Testing and Evaluation portion of the Downhole Motor Program:

1. Synthetic lubricants are necessary for the temperature requirements of this program. Hydrocarbon lubricants are thermally unstable at these temperatures.
2. The best candidate high temperature lubricant tested was PLX-014 manufactured by Pacer Lubricants. The commercial version of this lubricant is numbered DHT-90G.

PROGRAM SUMMARY

Conclusions about specific aspects of seals, lubricants, and test equipment are included in the preceding sections, but some attention must be given to the implications of the complete program.

First, it is clear that we did not achieve all the program goals listed on page 1; rather, the program was ended by budget constraints before reaching a satisfactory technical result.

Many useful tasks were accomplished, however, ranging from the development of unique test apparatus to the identification of promising materials and designs. The testing program with a wide variety of seal types led to an accumulation of experience that is relevant to other seal applications, and the specific knowledge concerning drilling motor seals in high temperature service is not available elsewhere.

It is not clear that industry has successfully designed a downhole seal system (either motors or pumps) for geothermal conditions. We hope that the results of this program will contribute to that effort and that some of the lessons learned so painfully here will not require repetition by other investigators.

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APPENDIX A
SEAL TEST RESULTS

DMT-54

DMT-54A

DMT-54B

T/C #6 Out of
Position

No Leakage Observed
in Upper Seal Pack

No Leakage Observed
in Lower Seal Pack

DMT-54C

T/C #6 Out of
Position

No Leakage Observed
in Upper Seal Pack

DMT-55

DMT-56

DMT-57

DMT-58

DMT-59

SIGNAL FROM THERMOCOUPLE
NO. 6 WAS LOST DURING
THE TEST

LOWER SEAL DID
NOT LEAK DURING
THE TEST

DMT-60

TORQUE VS TIME

DMT-060

UPPER SEAL TEMP 6 VS TIME

DMT-060

UPPER SEAL LEAK VS TIME

DMT-

LOWER SEAL TEMP 7 VS TIME

DMT-060

LOWER SEAL LEAK VS TIME

DMT-060

DMT-62

APPENDIX B
BEARING-SEAL PACKAGE TEST RESULTS

BSP-4

BSP-6

BSP-7

BSP-8

BSP-9

BSP-10

BSP-11

BSP-12

BSP-13

BSP-14

APPENDIX C
SUMMARY OF PROGRAM RESULTS

SUMMARY OF PROGRAM RESULTS

Phase I - Major Accomplishments

- (1) Gathered background information to determine current needs of industry and establish a range of conditions needed to simulate geothermal conditions -
  - A meeting was conducted with downhole motor experts at Rice University.
  - Jeddy Nixon presented his experiences in downhole motor development at a review meeting at Terra Tek, Inc.
  - John Jeter was consulted on the Bearing-Seal Package design and the DHM Seal Test Machine.
  - Industry contacts and correspondence was established.
  - Information from the Geothermal Bit Program such as downhole geothermal temperatures, rock formations, and drilling problems was used to establish design limits of the seal and bearing test equipment.
- (2) Determine the state-of-the-art in motor development and the feasibility of new motor concepts -
  - Maurer Engineering conducted a patent search on downhole motors and reported the results in the Semi-Annual (TR76-59) and Final (TR77-29) reports.
  - Maurer Engineering presented a review of the economic incentives for geothermal downhole motor development.
- (3) Performed the preliminary design of the Bearing-Seal Package -
  - The Bearing-Seal Package design was described in the Semi-Annual (TR76-59) and Final (TR77-29) reports.
- (4) Candidate high temperature seals were identified -
  - A description of the candidate seals was presented in the Semi-Annual (TR76-59) and Final (TR77-29) reports.
  - Bearing application was presented in the Semi-Annual (TR76-59) and Final (TR77-29) reports.

- (5) Design and fabrication of the DHM Seal Test Machine was completed -
- Preliminary concepts and evolution of the final design were presented in the Semi-Annual (TR76-59) report.
  - John Jeter was consulted on the design of the DHM Seal Test Machine.
  - Detailed design and fabrication of the DHM Seal Test Machine was completed.
- (6) Conceptual design of the Bearing-Seal Package Test Facility was completed.

Phase II - Major Accomplishments

- (1) Seal Testing and Evaluation -
- Debugging tests on the DHM Seal Test Machine were completed.
  - The first evaluation tests on the baseline seals were completed.
  - Contacts were established with major seal manufacturers.
  - Candidate seals for future testing were obtained.
- (2) Bearing-Seal Package Testing and Evaluation -
- Preliminary design of the Bearing-Seal Package Test Facility was completed.
  - Fabrication of the Bearing-Seal Package was completed.
- (3) Lubricant Testing and Evaluation -
- The Terra Tek High Temperature Lubricant Tester was made operational.

Phase III - Part 1 - Major Accomplishments

- (1) Seal Testing and Evaluation -
- Baseline tests on a standard industry seal were completed.
  - Several of the new candidate seal types were tested.
  - Additional high temperature candidate seal types were tested.

- The DHM Seal Test Machine underwent several modifications to improve ease of handling and for more reliable operation.
- (2) Bearing-Seal Package Testing and Evaluation -
- A design to solve the fluid erosion problem was completed and successfully tested.
  - Final Design of the Bearing-Seal Package Test Facility was completed. Fabrication of parts was started.
  - Machining of the Grayloc connections in the pressure vessel tubes was completed.
  - Design and fabrication of the pressure vessel holding fixture was completed.
  - The Dynamic Actuator was received and modifications for the Bearing-Seal Package Test Facility were started.
  - The 100-HP hydraulic power supply to drive the dynamic actuator and Bearing-Seal Package was designed and purchased.
- (3) Lubricant Testing and Evaluation -
- Wear rings and blocks for the Terra Tek High Temperature Lubricant were obtained.
  - A survey of downhole motor manufacturers was made to obtain lubricant recommendations. The candidate lubricant matrix was revised.

Phase III - Part 2 - Major Accomplishments

- (1) Seal Testing and Evaluation -
- Second and third generation seals were obtained and some of these seal types tested.
  - New seal back up system designs were completed and tested.
- (2) Bearing-Seal Package Testing and Evaluation -
- Bearing-Seal Package Test Facility was completely assembled and debugging was started.
  - The hot water system was completed and operated. Three tests were performed.

- The electronics from the DHM Seal Test Machine system were interfaced with the Bearing-Seal Package Test Facility.

(3) Lubricant Testing and Evaluation -

- Initial screening of candidate high temperature lubricants was completed in the Terra Tek High Temperature Lubricant Tester.
- The candidate lubricant was selected for testing in the Bearing-Seal Package.

Phase IV - Major Accomplishments

(1) Seal Testing and Evaluation -

- Landmark tests were run with HTCR SF Design and Variseal® seals in which excessive shaft wear was observed.
- Flexing leaves back up system was tested.
- HTCR SF Design SEals, new generation Mesh Matrix Seals, Hybrid Assembly Seals and Grafoil® (Horizontal Laminate) Seals were tested for the first time.
- Design completed to introduce abrasive mud on the low pressure side of the Seal Test Machine.

(2) Bearing-Seal Package Testing and Evaluation -

- The dynamometer and mud cooling system were designed and fabricated.
- Tests were run with the Bearing-Seal Package to establish data for the self-generation of heat by the seals.

(3) Lubricant Testing and Evaluation -

- Several new lubricant samples were tested in the Terra Tek High Temperature Lubricant Tester.

Phase V - Major Accomplishments

(1) Seal Testing and Evaluation -

- Landmark test run with HTCR seal - test terminated at 200 hours without a seal failure.
- Shaft sleeve manufactured from carburized steel and shaft sleeve coated with Union Carbide UCAR-LWIN30 were tested.

- Seals tested with Pacer lubricant.

(2) Bearing-Seal Package Testing and Evaluation -

- Gits Brothers and Stein face seals were tested for the first time.
- HTCR and Variseal® floating pistons were tested.
- Seals tested with Pacer lubricant.

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