“Development of a High-Pressure/High-Temperature Downhole Turbine Generator”

Phase I Final Report

Reporting Period Start Date: October 1, 2005
Reporting Period End Date: February 1, 2007

Prepared By:

Timothy F. Price
February 12, 2007

“Drilling, Completion and Stimulation Program”

Area of Interest 1: Deep Trek

Financial Assistance: DE-FC26-05NT42655

Dexter Magnetic Technologies Inc.

1050 Morse Avenue

Elk Grove Village, Illinois 60007

DISCLAIMER

"This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof."

ABSTRACT

The objective of this project as originally outlined has been to achieve a viable downhole direct current (DC) power source for extreme high pressure, high temperature (HPHT) environments of >25,000 psi and >250° C. The Phase I investigation posed and answered specific questions about the power requirements, mode of delivery and form factor the industry would like to see for HPHT downhole DC power. Phase I also investigated the viability of modifying a commercial downhole turbine generator tool for the HPHT environment, and noted specific components, materials and design features of that commercial system that will require upgrading to meet the HPHT project goals. During the course of Phase I investigation the scope of the project was expanded, without additional cost expected to the project, to include the addition of HT batteries to the power supply platform.

TABLE OF CONTENTS

EXECUTIVE SUMMARY

The objective of this project as originally outlined has been to achieve a viable downhole direct current (DC) power source for extreme high pressure, high temperature (HPHT) environments of >25,000 psi and >250° C.

The Phase I investigation posed and answered specific questions about the power requirements, mode of delivery and form factor the industry would like to see for HPHT downhole DC power. This was achieved through conversation and interviews with operators, major service companies and industry consultants. The end-user input and preferences were used to compile a list of specifications for the HPHT Downhole Generator.

Phase I also investigated the viability of using an existing and proven commercial downhole turbine generator platform, the UnderCurrent Downhole Turbine Generator, and modifying and upgrading it for the HPHT environment. During the course of the investigative Phase I, specific components, materials and design features of the commercial system were examined to determine specific items to be upgraded to meet the HPHT project goals.

It was determined through 3-D FEA modeling that the mechanical components, such as pressure housings and mud lubricated journal were good choices for the HPHT environment. Those items will require some redesign to withstand wellbore pressures of 25,000 psi and greater, but the base materials and general mechanical designs are sound.

One of the key features of the design that will allow the HPHT Downhole Turbine Generator system to operate in the HPHT environment is that there are no dynamic seals used in the tool. The basic operation of the tool will consist of scavenging a small percentage of the energy in the drilling fluid column, converting that energy to rotation through the use of turbine blades, and generating electric power via that rotary motion. In order to transfer the rotary energy from the turbines to the generator within the tool, a magnetic coupling was utilized in this design. The use of a synchronous magnetic coupling eliminates the need for a shaft from the prime mover to the generator. With no shaft, the need for a dynamic shaft seal is eliminated as well. This is particularly pertinent, as dynamic seals were identified in Phase 1 as one of the primary shortcomings in HPHT design. This information was obtained in report data from Triton Energy Services Company on "Drilling and Completion Gaps for HPHT Wells in Deep Water"[1]. The magnetic coupling technology and materials are already widely in use in downhole HPHT applications, so their functionality and applicability are~~is~~ already well documented.

The power generation for this project utilizes a 3-Phase generator with a wound copper stator and a rotating shaft with Samarium Cobalt (SmCo) permanent magnets mounted to it. The SmCo magnets are the same type used in the magnetic coupling, and again, are already field qualified for HPHT application. Wiring insulation on the wound stator coils is the only item in the generator that requires an upgrade. The existing insulation is rated for 200° C continuous operation, and will need to be upgraded to 250° C. The company that designed and built the existing generators assures us that this is not problem using commercially available potting and insulation materials. Ceramic insulators are another proven insulation technology that can be used if higher temperature ratings are desired or required.

One of the most challenging tasks of this project is to take the 3-Phase power and rectify it to DC and regulate it. Analysis of the commercial regulator system components determined that every component on the regulation circuit board would require a significant upgrade to meet the 250° C rating requirement. An investigation into the applicability and viability of adding an active cooling system to the existing conventional temperature electronics was undertaken. Three types of active cooling systems were examined, and each had the same problem. In a HPHT downhole environment the cooled electronics bay is always cooler than the infinite heat source of the hot wellbore. The heat transfer is always in the direction of the electronics. It was therefore determined that devising another voltage regulation circuit better suited for the HT environment would be a far easier task than trying to cool room temperature electronics for use in the HPHT environment.

The answer to the voltage regulation was determined to be a proven commodity from the automotive industry. An electromechanical voltage regulator of the type used on all domestic automobiles from the 1930's through the 1970's was mated with the 3-Phase generator and successfully tested on the bench top. The electromechanical regulator holds much promise due to its rugged construction and small number of components, none of which are sensitive to the 250° C operating temperature specification.

During the course of Phase I investigation the scope of the project was expanded, without additional cost expected to the project, to include HT rechargeable batteries in the power supply platform. Sodium Sulphur battery chemistries were found to be applicable for operation at temperatures above 125° C. Below 125° C the sodium material solidifies and no current transfer takes place, so a minimum temperature of at least 125° C must be maintained for the batteries to deliver current. In shallower and cooler areas of the wellbore, the HPHT Downhole Turbine Generator will provide electric current to a heating element to bring the battery cells up to (and maintain) an operating temperature of >125° C. A portion of the regulated DC current from the generator will also be directed to a recharge circuit to ensure the battery cells maintain the necessary charge. The batteries will filter the regulated DC from the electromechanical voltage regulator providing steady, clean DC power. The rechargeable battery cells will provide power when there is no drilling fluid flow, an option not available with only turbine generator power.

Once the rechargeable batteries reach their minimum operating temperature of 125° C they will deliver current even when there is no drilling fluid flow to power the turbine generator. The current delivery from the rechargeable batteries will continue on demand in wellbore temperatures above 125° C, with or without flow. In a wellbore environmental temperature cooler than 125° C and without drilling fluid flow to power the turbine generator, the rechargeable batteries will deliver current on demand until the battery cells cool to a temperature below 125° C.

The unified power source, comprised of a HPHT Downhole Turbine Generator and rechargeable HT batteries, that will result from the continued development, prototyping and testing in the follow-on phases of this project will offer the HPHT drilling market spud to total depth power supply that is currently not available.

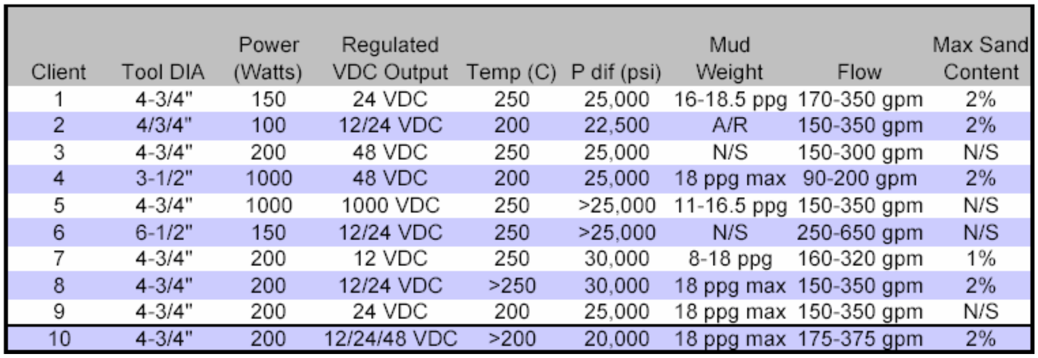
REPORT DETAILS

The Task 1 Research Management Plan and Task 2 Technology Status Assessment were prepared and filed in accordance with the project schedule.
Task 3 was outlined to develop the specifications for the high temperature turbine generator (HTTG). In preparation for this task, Dexter made a notation on the literature for the UnderCurrent Downhole Turbine Generator product line, noting the DOE/NETL aided development of a HPHT version of the tool. This literature was distributed at industry trade shows (SPE sponsored Offshore Technology Conference 2006 and SPE's Annual Technical Conference 2006) and to inquiries sent to Dexter's website regarding downhole power sources. Respondents to this literature were contacted by telephone and e-mail to determine if they had a specific interest and application for downhole power in an HPHT environment. Those that met the HPHT interest and application criteria were considered a qualified database from which to conduct the interviews called for in Task 3.

Pursuant to Task 3.1 and 3.3 of the Statement of Project Objectives (SOPO), personal contacts were made to qualified operators and service companies. The respondents that were interviewed included four major operators, five major service companies, as well as, several smaller service companies, engineering companies and industry consultants. These interviewees were polled as to their preference on power required, preferred regulated voltage, operating current, physical size, and interface between the generator tool and the customers tools. Pursuant to Task 3.4, many of these respondents were able to provide specifics relating to mud weight, solids content, pressure, flow, and temperature on high temperature wells.

There were three predominate platform sizes of interest to the dozens of potential users who were interviewed: 6-1/2", 4-3/4" and 3-1/2".

The overwhelming majority were interested in a 4-3/4" platform, with the balance interested in slim--hole applications that would accommodate a 3-1/2" generator tool. The indicated preferences of output voltage from the regulated power supply were 48 VDC, 24 VDC or 12 VDC. There was no clear consensus of an industry preferred regulated voltage, as each potential user had a different end use or device in mind. All agreed they could adapt to any regulated DC voltage between 12 VDC and 48 VDC. Two respondents requested output voltages of 1000 V or greater. While some specialty applications were looking for power in excess of 1KW, and one requested 450 W, the vast majority indicated that 200 W would be ample power for their potential application. There was no definable industry preference in the type of electrical connector output from the tool used to interface with the end users devices. A summary of the results from these industry participants is noted in *Figure 1, HPHT Downhole Generator Survey Matrix.*



Client	Tool DIA	Power (Watts)	Regulated VDC Output	Temp (C)	P dif (psi)	Mud Weight	Flow	Max Sand Content
1	4-3/4"	150	24 VDC	250	25,000	16-18.5 ppg	170-350 gpm	2%
2	4/3/4"	100	12/24 VDC	200	22,500	A/R	150-350 gpm	2%
3	4-3/4"	200	48 VDC	250	25,000	N/S	150-300 gpm	N/S
4	3-1/2"	1000	48 VDC	200	25,000	18 ppg max	90-200 gpm	2%
5	4-3/4"	1000	1000 VDC	250	>25,000	11-16.5 ppg	150-350 gpm	N/S
6	6-1/2"	150	12/24 VDC	250	>25,000	N/S	250-650 gpm	N/S
7	4-3/4"	200	12 VDC	250	30,000	8-18 ppg	160-320 gpm	1%
8	4-3/4"	200	12/24 VDC	>250	30,000	18 ppg max	150-350 gpm	2%
9	4-3/4"	200	24 VDC	200	25,000	18 ppg max	150-350 gpm	N/S
10	4-3/4"	200	12/24/48 VDC	>200	20,000	18 ppg max	175-375 gpm	2%

Figure 1 - HPHT Downhole Generator Survey Matrix

A specification sheet was established based on this criteria and is noted below as *Figure 2, HPHT Downhole Generator Specifications.*

HPHT Turbine Generator Specifications

Tool Platform Size:	4-3/4"
Operating Temperature:	-40 to +250 degrees C
Max. Operating Pressure:	>25,000 psi
Output Voltage:	12 VDC - 24 VDC
Mud Flow Range:	≤19 ppg
Max. Sand Content:	2%
Lost Circulation Material:	40 lbs/bbl Medium Nut Plug

Figure 2 - Specification Table for HPHT Downhole Generator

Task 3.2 called for an examination of the data compiled in a report titled “Drilling and Completion Gaps for HPHT Wells in Deep Water"[1]. The stated criteria for HPHT classification in this report was *"...wells drilled 27,000 feet below mud line with reservoir temperatures in excess of 350°F and reservoir pressures of 24,500 psi."* While the qualifying temperature is some 75° C below the qualifying temperature for the HTTG, the report does acknowledge that reservoir temperatures up to 250° C are possible.

In the report’s conclusion, specific to Logging-While-Drilling (LWD)/Measurement-While-Drilling (MWD) applications in HPHT environments, it is stated that seals, telemetry and downhole power are currently the primary limiting factors to exploiting HPHT opportunities. The design methodology for the HTTG addresses two of these three limitations (seals and power). It is to be noted that the HTTG design does not include the use of dynamic seals.

Task 4.1 consisted of identifying the voltage rectification and regulation circuit components of the existing **UnderCurrent™** that require upgrading to meet the HPHT performance requirements. This task was performed by consulting the Bill of Materials from the existing circuit and checking the temperature specifications. No particular attention was given to the pressure ratings of any of the electrical components, as they are designed to operate at atmospheric pressure, which will be provided by a pressure housing suitable for the environment. Every component on the circuit board, including the printed circuit board material itself was rated below 250° C, therefore, every component in the circuit required a temperature upgrade.

Task 4.2 entailed compiling and researching literature to determine which of the voltage rectification and regulation circuit components could be replaced with a HT component. Some components such as the printed circuit board itself, diodes and FET's did have HT variants that could possibly be used. However, one of the biggest stumbling blocks was locating commercially available capacitors rated for >250° C and of a size and form factor compatible with the tool diameters. No such capacitors were located. The existing board design requires no fewer than four such capacitors. Toward the end of Phase 1, some capacitor projects that are underway were identified, but will not be commercially available at a time that fits within the HTTG's project schedule.

As part of Task 4.2, a power rectification and regulation circuit based on Silicon Carbide components was identified at Sandia National Laboratory. The system had been tested for functionality at temperatures similar to our project requirements. However, due to the low power requirement of that particular design, it could not be used as-is. While this device demonstrates the viability of building a HT regulator using the SiC component technology, the relative cost or form factor requirements to upgrade such a device to the 200 W @ 250° C power and temperature requirements has not been investigated. At this time, this device provides an optional methodology should the primary regulation method prove not to be dependable.

An investigation during the course of Task 4.3 was performed to determine whether providing active cooling to the voltage regulation electronics was a viable option so that lower temperature, more readily available electronic components could be used. Three types of active cooling were considered: Peltier Coolers, Sterling Coolers and Magnetic Refrigeration. Any of the three could provide sufficient heat transfer to cool the required electronics, if not for the wellbore environment itself. To cool the electronics, the heat must be moved out. In a wellbore environment of potentially >250° C, moving the heat out becomes a monumental task. It became apparent early that active cooling was not a viable option.

This was a serious juncture in the project, as even with a generator module capable of producing power at the required temperatures, without a reliable method to regulate that voltage, the HTTG tool would be of little use to the industry. A no-cost extension was requested and granted to allow for continued study on the methodology for voltage regulation. Without a suitable voltage regulator, there was no chance of successfully completing the project. Therefore, a change in direction and another method for regulating the generator output voltage were required. An electromechanical voltage regulator of the type used in automobiles in the 1930's through the 1970's was considered (Figure 3). The concept was tested in the lab at room temperature purely for functional applicability. An automotive type electromechanical voltage regulator was purchased. A generator module used on the existing UnderCurrent tools was connected to a bridge rectifier to convert the AC to DC, fed across the electromechanical regulator to regulate the DC voltage, then into a resistor to simulate a load. The generator was connected to a variable speed motor to provide rotation (simulating the turbine prime mover). A multimeter confirmed the 3-phase generator output was being successfully rectified and regulated to 12 VDC without the use of field effect transistors (FET) or capacitors. As there are no electronic components in this circuit other than the rectifier, which is commercially available for the rated temperatures, the circuit as described and tested will operate successfully at the temperatures required for the finished device. Manufacture and comprehensive testing of a built-for-purpose electromechanical regulator of the type tested here will be conducted as the first task of Phase II.

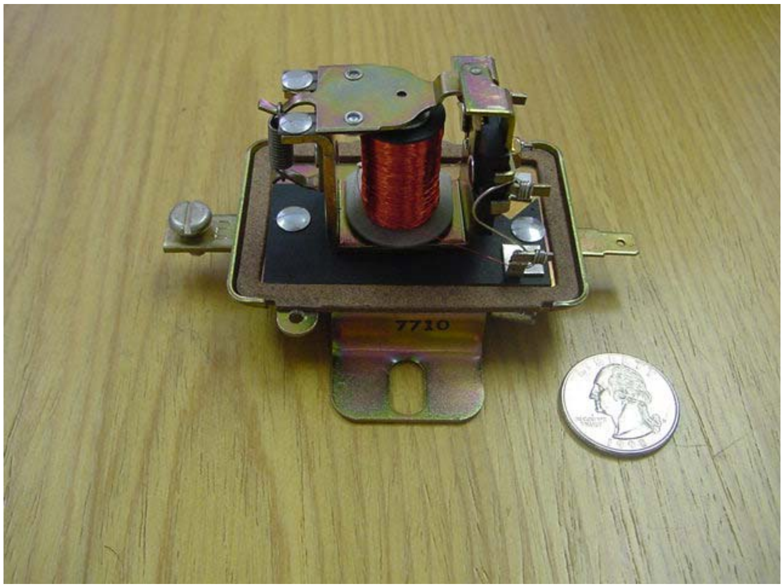


Figure 3 - Automotive Type Electromechanical 12 VDC Voltage Regulator

The generator module itself (Figure 4) proved to be one of the least challenging items to elevate to the demanding operating temperature range. The generator is located within a dedicated housing within the tool, isolated from the wellbore pressure via a thick Inconel housing. The vendor who winds the generator modules is confident that the insulation and potting materials suitable for winding this generator for a 250° C environmental temperature~~s~~ are readily available. Early in Task 8 of Phase II the 250° C version of the generator module will be wound and tested.

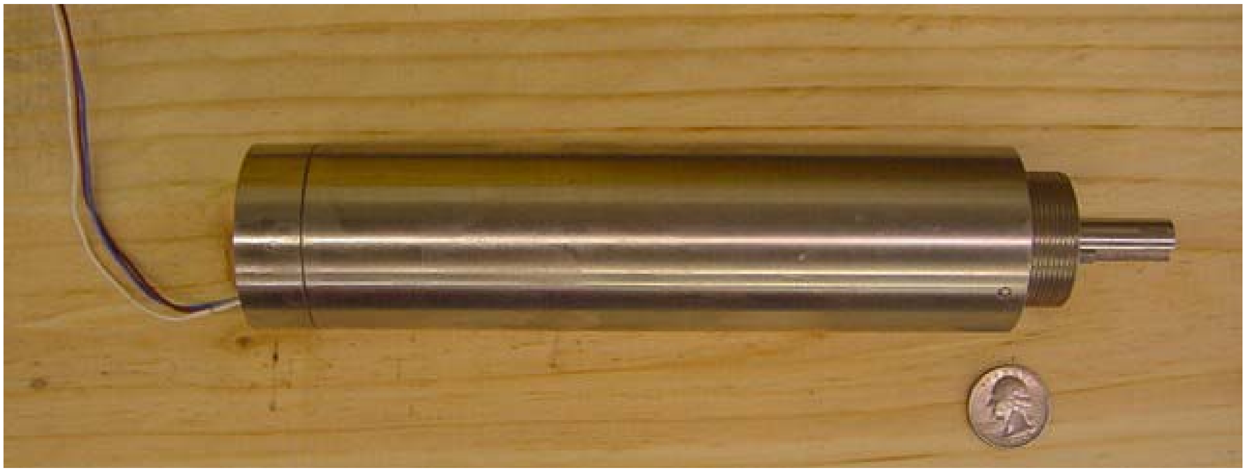


Figure 4 - 200 Watt, 200°C Generator Module

Using the UnderCurrent Downhole Turbine Generator as a starting platform for design, individual components, subassemblies and systems of the UnderCurrent Downhole Generator were modeled and subjected to mechanical analysis in COSMOS and ANSYS to determine design suitability for the HPHT environment during Task 5. Items, including the generator housing wall thickness, regulator housing wall thickness, threaded interface between housings, o-ring material and electrical bulkhead connectors, were found to be deficient for either temperature, pressure or both.

The generator pressure housing was modeled in SolidWorks. This model was used in COSMOS to provide a mechanical finite element analysis (FEA) of the pressure that the housing could safely operate in without becoming compromised. A differential pressure was applied to the outside wall of the barrier, and gradually increased until the housing wall failed in the model. An operating temperature of 250° C was also factored into the model. The existing pressure housing yielded at just above 15,000 psi differential pressure. While acceptable for some drilling applications, this result is almost 10,000 psi short of the requirement for the projected tool. For future reference the designer performing the FEA modeling increased the outer wall thickness of the pressure barrier until the barrier would withstand 25,000 psi differential. This was performed purely as insurance that there will be sufficient diametrical space to accommodate the additional pressure barrier wall thickness when the mechanical elements are redesigned in Phase II, Task 7.4.

At the same time the thread interfaces identified in Task 5.2 were reviewed to ensure sufficient area and material to allow the use of standard stub Acme threads in conjunction with the previously noted increase in wall thickness. O-rings for the pressure seals between sealed compartments were specified as Viton material on the conventional temperature generator platform, however, Viton is not rated for 250° C. A suitable o-ring material called perflouroelastomer was located and will be used as o-rings in all static seal locations on the tool. Perflouroelastomer o-rings are not only appropriately temperature rated, they have the required chemical resistance and are much better suited for purpose as it relates to explosive decompression. The manufacturer claims the o-rings are used widely in HPHT downhole applications.

Task 5.2 also identified the electrical bulkhead connectors to be deficient for the application. The Arlon connector body is only rated for 204° C, and the pressure rating is only 20,000 psi. A compromise was necessary on these electrical bulkhead connectors, as no suitable bulkhead connectors rated for bidirectional pressure of >25,000 psi at >250° C were located. The bidirectional pressure rated connectors provided a redundant pressure seal, with the primary pressure seal created using multiple o-rings at each thread interface between tool sections. Having a redundant pressure seal at the electrical connector is a luxury, but not a necessity. A more robust connector with an Inconel body, which is rated by the manufacturer at 260° C but only handles pressure in one direction (25,000 psi) was located and will be incorporated into the design methodology. These LWD connectors will be fitted into a new style bulkhead when the mechanical redesign transpires in Task 7.4.

Other mechanical components were noted during the Task 5 analysis (Figure 5), not due to functionality, but due to long term reliability. Due to the increased reliability required for deep HPHT wells, where tripping out of and back into a well are extremely costly, other areas of upgrade such as the mud lubricated journal bearings, turbine blade erosion and flow diverter design will be addressed in a redesign scheduled for Task 7.4. The scalloped erosion shown on the turbine blade boss in Figure 6 shows the effects of non-optimized blade stage spacing and tolerances. The eroded holes between the exit ports on the lower flow diverter in Figure 7 are evidence that the flow path could benefit from some optimization. Minimizing erosion requires optimizing the flow path design with a 3-D FEA tool. Dexter purchased a license for CFX, which is integrated into the ANSYS Multiphysics platform currently used for mechanical analysis. Only after receipt and unsuccessful modeling attempts using the CFX FEA flow modeling software, it became evident that multiple other modules were required to perform the multi-component dynamic flow analysis that is required for the type of analysis described. This made it cost prohibitive to continue pursuing CFX as a flow analysis tool. Another 3-D FEA software tool was evaluated and proven capable of the flow analysis and optimization that would significantly benefit the design effort of this project. No software purchases were requested in the project budget. However, should Dexter elect to purchase what would be their second 3-D FEA flow analysis software package, we will request that the project be allowed to lease sufficient analysis time on that software to optimize the flow in these targeted areas. The benefit to the project will be a nontrivial increase in tool life netting higher reliability and more hours between maintenance for the HTTG.

Figure 5 - UnderCurrent Downhole Turbine Generator in Flow Test Collar for Task 5.2

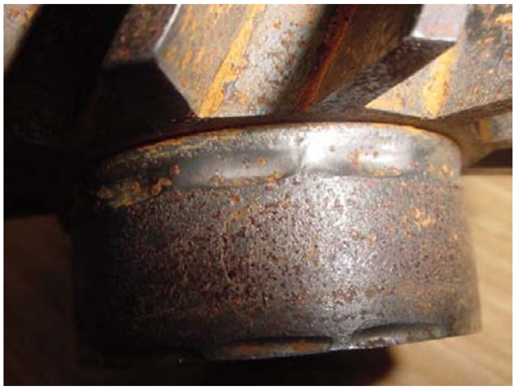


Figure 6 - Turbine Boss Erosion To Be Addressed In Task 7

Figure 7 - Flow Diverter Port Erosion From Task 5.2

Another item that has been added to the SOPO is the addition of rechargeable downhole batteries to the HTTG platform. In deep, hot HPHT drilling applications reliability is paramount. Tripping out of and back into a deep HPHT well offshore can run into hundreds of thousands of dollars. Therefore, redundancy on the downhole power delivery system is not only preferred, it most likely will be required before any operator or contractor will run a new tool in their HPHT well. It has been noted from the beginning of this project that a downhole generator and downhole batteries are not mutually exclusive. Not only does a unified power supply containing both a generator and batteries offer the redundancy mentioned earlier and power delivery while there is no mud flow, it becomes a critical component in the delivery of "clean" voltage. Without the availability of capacitors rated for temperatures of >250°C to smooth the regulated DC voltage, a rechargeable battery can function as a similar line filter and final fine regulation of voltage.

Research and discussions were initiated to see if a viable battery technology existed that could aid and compliment the downhole turbine generator.

Two families of rechargeable batteries that showed some promise for downhole HPHT application, one being Sodium Nickelchloride and the other Sodium Sulphur, were identified. Both of these battery chemistries require the batteries to be at elevated temperature to operate. At temperatures below 125° C, by their nature, materials within these battery cells solidify. Until the temperature is raised above 125° C no power can be drawn from these batteries. That in itself was intriguing, as, unlike the problems that wellbore heat posed in the active cooling investigation, the wellbore heat actually works to the advantage of these battery types. There is a fair amount of active research and development being done with rechargeable Sodium Sulphur battery chemistries specifically for application downhole, so this is the technology selected to build into a unified downhole power supply with our turbine powered downhole generator.

The reasoning behind a unified power supply, containing a turbine powered generator and rechargeable batteries is multifold. Neither a regulated turbine generator nor rechargeable batteries will work from surface to total depth on a HPHT well without the benefit of the other, so the result of combining the two into a unified power system is greater than the sum of the parts. The HTTG must have regulation to a specific voltage, and as part of the regulation it must have a method of smoothing the output voltage. Without the availability of capacitors, rechargeable batteries can perform this necessary function. Sodium Sulphur batteries require heat to operate. The turbine generator produces 3-Phase power from the time the mud pumps are turned on until the moment they are shut down. A portion of that raw 3-phase power can be immediately converted to heat by running it to a ceramic (or similar) band heater around the batteries. Upon initial insertion into the well, flow can be circulated through the turbine generator, which produces heat that brings the batteries to operating temperature. Generator heats batteries; regulator uses batteries to filter the voltage as well as providing recharge current to the batteries. The use of the turbine generator and battery systems together provides redundancy and therefore reliability necessary for HPHT wells. The generator works to keep the batteries operating until they reach wellbore temperatures that would sustain their operation. It then provides recharge current. Should the batteries at some point fail to hold a charge downhole, they will still aid in filtering the regulated voltage from the turbine generator thereby allowing it to deliver power for the remainder of the bit trip. Should the turbine generator catastrophically fail in a >125° C environment, the batteries will continue to deliver their stored electric power.

Dexter will work with one of the groups active in the development of these Sodium Sulphur rechargeable downhole batteries. Any testing we do on the unified system will benefit both devices.

CONCLUSION

The lack of a viable HPHT downhole power supply is still one of the primary issues facing the HPHT drilling and completions industries, as stated in Tom Proehl's report to MMS and the DeepStar consortium, “Drilling and Completion Gaps for HPHT Wells in Deep Water"[2]. Under the heading "Identify necessary gap closures prior to drilling DeepStar wells" Mr. Proehl makes the statement "*Major improvements in both turbine and battery technology will be required*." Temperature is the primary limiting factor that must be overcome to make downhole power systems viable for use in the HPHT environment.

Starting with a working turbine generator platform, and with the goal of modifying and adapting that tool for the HPHT market, we have developed and outlined a plan, assessed the state of the technology and developed specifications for the tool based on end-user input. We have analyzed and confirmed that the material selection is adequate, and power generation components and design methodology are in place to ensure manufacturability. We have identified two workable methods of regulating the output voltage and noted any and all modifications that will be required to bring the current platform up to the operational standards of this project.

In order to proceed to the Phase II manufacture and test phase of this project it is necessary for our Phase I efforts to have met four specific criteria:

a) the potential for successfully developing a device that meets the industry requirements determined from Task 3;

> The industry requirements referred to in criterion "a" was established in Task 3 through end-user input, the details of which were used to prepare the device specifications noted above in Figure 2. FEA analysis and manufacturers data was used to determine that the basic mechanical design and materials are available and applicable to the environment in which the HTTG will be designed to operate. The successful compilation of industry requirements into a list of specifications, and the results of the FEA analysis performed assure a high probability of successfully meeting criterion "a".

b) the probability of successfully building regulation circuitry either from available HTHP electronic components, or employing an active cooling system for the electronics;

Successful bench testing of an off-the-shelf automotive type electromechanical voltage regulator to condition the 3-Phase output from the UnderCurrent generator module yields a strong probability that a similar device with the benefit of high temperature insulation will perform as required to fulfill the necessary voltage regulation for the project. A second voltage regulation platform constructed primarily of HT SiC board level components assures that there is a proven alternative voltage regulation methodology if needed. The probability of successfully meeting criterion "b" is extremely high.

c) the probability of successfully overcoming the potential failure modes of the parts, subassemblies, assemblies, and systems with regard to the functions that the system requires to work properly;

The primary advantage of this development project is that the HTTG is based on an already operational and documented platform. FEA analysis demonstrates that sufficient real estate is available to increase pressure barrier wall thicknesses to a level sufficient to withstand the project requirement of >25,000 psi. Static elastomeric seals (o-rings) will be upgraded to a material already proven in use in the downhole HPHT industry. All metallic component specifications have been examined to assure their applicability. All of the required components and materials are available and specified for the device to be constructed in Phase II. Criterion "c" has already been met through the identification and specification of materials already proven and in use in HPHT operation.

d) the magnitude of improved, modified, or re-designs shall be limited to fit within the agreed upon budget.

The primary material used to construct the bulk of the HTTG is Inconel. Inconel prices have more than doubled since the original project budget was established. Offsetting that to some degree is the change in course from a fully electronic voltage regulator to an electromechanical voltage regulator. A HT electromechanical voltage regulator is considerably less expensive to design and produce than a fully electronic HT voltage regulation circuit. The electromechanical regulator system can be rebuilt after failure mode testing as opposed to the scrap-and-repurchase method necessary when testing an electronic regulator. It is highly probable that the HTTG device will be designed, built and tested within the current and agreed upon budget, therefore fulfilling criterion "d".

Having met all Go/No Go criteria established in the SOPO, and with a well defined plan in place, it is our recommendation that work proceed to the fabrication and testing of the HTTG as detailed in Phase II.

GRAPHICAL MATERIALS LIST

LIST OF ACRONYMS

3-D - Three Dimensional

A/R - As Required

AC - Alternating Current

C - Degrees Celsius

DC - Direct current

DIA - Diameter

DOE - United States Department of Energy

F - Degrees Fahrenheit

FEA - Finite Element Analysis

FET - Field Effect Transistor

gpm - Gallons per minute

HP - High Pressure

HPHT - High Pressure High Temperature

HT - High Temperature

HTTG - High Temperature Turbine Generator

KW - Kilowatt

lbs - Pounds

LWD - Logging While Drilling

Max - Maximum

MMS - Minerals Management Service of the United States Department of Interior

MWD - Measurement While Drilling

N/S - Not Specified

NETL - National Energy Technology Laboratory of the U.S. Department of Energy

OTC - Offshore Technology Conference

ppg - Pounds Per Gallon

LIST OF ACRONYMS (cont.)

psi - Pounds per Square Inch

SiC - Silicon Carbide

SmCo - Samarium Cobalt Magnet Material

SOPO - Statement of Project Objectives

SPE - Society of Petroleum Engineers

V - Volts

VDC - Volts Direct Current

W - Watts

REFERENCES

1. Proehl, Tom. "Drilling and Completion Gaps for HPHT Wells in Deep Water", Minerals Management Service project 519, June, 2006: p. 5

2. Proehl, Tom. "Drilling and Completion Gaps for HPHT Wells in Deep Water", Minerals Management Service project 519, June, 2006: p. 20