Oil & Natural Gas Technology

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Final Report

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Development of a High Pressure/High Temperature Down-hole Turbine Generator

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ABSTRACT

As oil & natural gas deposits become more difficult to obtain by conventional means, wells must extend to deeper more heat-intensive environments. The technology of the drilling equipment required to reach these depths has exceeded the availability of electrical power sources needed to operate these tools. Historically, logging while drilling (LWD) and measure while drilling (MWD) devices utilized a wireline to supply power and communication from the operator to the tool. Lithium ion batteries were used in scenarios where a wireline was not an option, as it complicated operations.

In current downhole applications, lithium ion battery (LIB) packs are the primary source for electrical power. LIB technology has been proven to supply reliable downhole power at temperatures up to 175 ℃. Many of the deeper well s reach ambient temperatures above 200 ℃, creating an environment too harsh for current LIB technology. Other downfalls of LIB technology are cost, limitations on charge cycles, disposal issues and possible safety hazards including explosions and fires.

Downhole power generation can also be achieved by utilizing drilling fluid flow and converting it to rotational motion. This rotational motion can be harnessed to spin magnets around a series of windings to produce power proportional to the rpm experienced by the driven assembly. These generators are, in most instances, driven by turbine blades or moyno-based drilling fluid pumps. To date, no commercially available downhole power generators are capable of operating at ambient temperatures of 250 ℃. A downhole power g enerator capable of operation in a 250 ℃ and 20,000 psi ambient environment will be an absolute necessity in the future.

Dexter Magnetic Technologies' High-Pressure High-Temperature (HPHT) Downhole Turbine Generator is capable of operating at 250 ℃ and 20, 000 psi, but has not been tested in an actual drilling application. The technology exists, but to date no company has been willing to test the tool.

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Historical Background

Development of a High Pressure / High Temperature Downhole Turbine Generator
Contract Number: DE-PS26-05NT42655-1
Financial Assistance Awarded: September 29, 2005
Principal Investigator: Tim Price
Engineering Staff: Boris Bass

The National Energy Technology Laboratory (NETL) in association with the Department of Energy (DOE) had granted Dexter Magnetic Technologies a financial award in the amount of $494,610 with an obligation for Dexter to supply $354,262 for a total project budget of $848,872. This budget would be contingent on the approval of each of the three phases the project had been broken down into.

As the project began in late 2005, a design for a High Pressure / High Temperature Downhole Turbine Generator had been introduced with the help of existing data from Dexter's previous line of turbine-driven downhole power generation tools known as UnderCurrent. Several prototypes had been made and tested in the flow loop located in Rockwall, Texas prior to receiving the DOE grant. These prototypes had not been tested in high pressure or high temperature environments but, it was thought that the platform could serve as a starting point.

The original proposal to the DOE included a subcontract by Noble Wellbore Technology (NBT / Maurer Technology, Inc.) to perform several tasks including downhole testing. This partnership was a major selling point for initiating the project.

Phase I of the project was to conduct a feasibility study and define the concept of how power was to be generated under the harsh downhole conditions of 20,000 psi and 250 ℃. With the help of Boris Bass, Tim Price was able to clearly illustrate that not only was the concept feasible but, an initial design had been created with the intention of prototyping. The Phase I Final Report was released on February 1, 2007.

After the completion of Phase I, NBT had decided to withdraw from the project. The main reason for terminating the project was a decrease in significance of their measure while drilling (MWD) tools. Prior to their withdrawal NBT had supplied some information that helped the feasibility study in Phase I.

A Continuation Application for Phase II was drafted by Tim Price on December 11, 2007. This application was reviewed and revised by Ben Plamp and released on February 21, 2008 as he assumed the role of Principal Investigator. A revised Statement of Project Objectives (SOPO) and project timeline were also included with the application. These documents included a request for a six month extension from the original grant.

Principal Investigator: Ben Plamp
Engineering Staff: Yakov Kanevskiy, Severin Chayka, Chris Ras

Phase II of the project was to supply two (2) fully functional HPHT Turbine Generators with a supplemental battery supply. The prototype was broken down to three major sections; the mechanical portion of the tool, the rectification and regulation circuit, and the supplemental battery supply.

The starting point for the mechanical design was to modify existing technology being used in the UnderCurrent power generation platform. The UnderCurrent was not designed for 20,000 psi and had to be rotated by a magnetic coupling. The ability to remove heat from the system was necessary to operate at 250 ℃. With drilling flui d constantly flowing, a medium for heat removal was available. After speaking with Muirhead, a custom generator manufacturer, a cost effective solution could not be agreed on. To assist in the design of a custom generator Chuck Syverson was hired as an outside consultant on May 16, 2008. With the help of Mr. Syverson a hybrid generator design was chosen as the best solution.

An outside consultant was also hired to do much of the electrical design work for the rectification and regulation circuit needed to supply a constant 24 VDC during operation. The electronics consultant and the generator consultant were to work together. There were two stages in the prototyping of the rectification and regulation circuit. The first stage was to design a circuit that would operate at temperatures up to 175 ℃ and have 250 ℃ components identified for each.

After finalizing the 175 ℃ version of the rectification and regulation circuit, and running some preliminary tests, the components were ordered for the 250 ℃ prototype. The lead times for several of the components were in the 16 week range. This pushed the project out further than anticipated. Modifications to the UnderCurrent platform also helped to identify some areas of the tool that were not robust enough to endure a 200 hour "bit trip" resulting in another design review.

On March 6, 2009 a six month no cost time extension was requested by Ben Plamp to continue the project without an increase in the project budget. The extension was accepted and progress towards the completion of Phase II was continued.

Once all preliminary testing was complete, a new design for the HPHT Turbine Generator was initiated by Yakov Kanevskiy. The new design incorporated solutions to many of the issues that plagued the UnderCurrent platform. Some of the issues were excessive wear on the turbine blades, failure of the generator to self start, and inadequacy of then-current carbide bearings.

Some problems still hindered the development of the HPHT Turbine Generator. Some of the high temperature components did not arrive when scheduled, pushing back testing for the rectification and regulation circuit. Blade angle for the turbine blades had not been fully established due to wear issues as well as rpm control. The manufacturing department was late on numerous components pushing back testing dates. The NETL typically requests an application for Phase III one month prior to the start of the phase. The project was not going to be completed on time. John Terneus, the current project manager for the NETL asked for a presentation illustrating the progress of the project and the time management plan for the tasks that were not complete.

An update of the project was presented to the NETL and other DOE officials on August 31, 2009. A decision had to be made on whether to continue with the development of a HPHT Downhole Turbine Generator or drop the project and allocate money to incoming projects, as this is the time of year when applications for new projects are reviewed. After the presentation, the committee agreed that the project was still relevant and granted Dexter Magnetic Technologies to continue with Phase II by "borrowing" time from the future Phase III. It was also agreed during this presentation that the supplemental battery supply would be excluded from the project.

The following details the activity and accomplishment in Phases 1 & 2.

Phase I Detailed Summary

The objective of this project as originally outlined has been to achieve a viable downhole power source for extreme HPHT environments of >25,000 psi and >250 °C. During the course of Phase I investigation the scope of the project has been expanded, without additional cost expected to the project, to include the addition of HT batteries to the power supply platform.

As an addendum to the marketing efforts Dexter has been involved in for the UnderCurrent Downhole Turbine Generator product line, a notation was made on the UnderCurrent literature noting the DOE/NETL aided development of a HPHT version of the tool. This literature was distributed at industry trade shows, specifically the SPE sponsored Offshore Technology Conference 2006 and SPE's Annual Technical Conference 2006, as well as on Dexter's website. Persons who responded to this literature with a specific interest and application for downhole power in an HPHT environment 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.

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

Over seventy percent of potential users were interested in either a 6-3/4" or 4-3/4" platforms, 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.

Using Dexter's 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 affected thread interfaces and wall thicknesses were redesigned to accept the design pressure of >25,000 psi. O-rings for the pressure seals between sealed compartments were replaced with perflouroelastomer o-rings which are rated for the design temperatures and pressures, and are less prone to explosive decompression. A compromise was necessary on the 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 was a luxury, but not a necessity. Therefore more robust connectors typically used in the industry were incorporated into the design methodology.
Other mechanical components were noted during Task 5 analysis (Fig. 1) 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, flow diverters and turbine blade erosion tolerance, **shown in Figure 2**, will be addressed in a redesign scheduled for Task 7, **shown in Figure 3.**

Figure 1: UnderCurrent Downhole Turbine Generator in Flow Test Collar

Figure 2: Turbine Boss Erosion

Figure 3: Flow Diverter Port Erosion

The generator module itself, **shown in 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 through a thick Inconel housing from the wellbore pressure. The vendor who winds the generator modules assured us that insulation and potting materials suitable for winding this generator for 250 ℃ environmental temperatures are readily available. Early in Task 8 of Phase II the 250 ℃ version of the generator module will be wound and tested.

Figure 4: 200 Watt, 200°C Generator Module

One of the greatest challenges of Phase I was to identify the circuitry necessary to perform the required voltage regulation from the generator. A component-by-component review of the existing regulation circuit was undertaken. One of the first stumbling blocks was locating capacitors rated for >250 ℃ that were commercially available, and of a size and form factor compatible with the tool diameters. No such capacitors were located.

A brief investigation during the course of Task 4 was performed to determine whether providing active cooling could be applied to the voltage regulation electronics so 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 you must move the heat out. In a wellbore environment of potentially >250 ℃, 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 HPHT downhole generator tool would be of little use to the industry. A change in direction and another method for regulating the generator output voltage was required. An electromechanical voltage regulator of the type used in automobiles in the 1930's through the 1970's was considered, **see Figure 5**. The concept was tested at room temperature purely for functional applicability in the lab by running the 3-phase output (from a generator module used on the existing UnderCurrent tools) through a bridge rectifier to convert the AC to DC, across the electromechanical regulator to regulate the DC voltage, then into a resistor to simulate a load. A multi-meter confirmed the 3-phase generator output was being successfully rectified and successfully regulated to 12 VDC without the use of field effect transmitters (FET's) or capacitors. As there are no electronic components in this circuit other than the rectifier, which is commercially available for the rated temperatures, there is reason to believe the circuit 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.

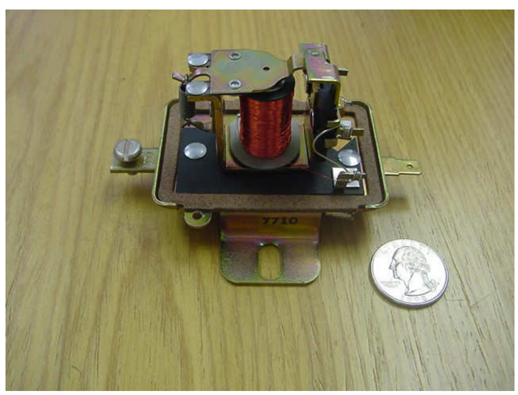

Figure 5: Automotive Type Electromechanical 12 VDC Voltage Regulator

A second voltage regulation methodology has since been discovered and is under consideration for inclusion in the project. A HT regulator was designed and tested by Sandia National Laboratories for a similar downhole application. This regulator is constructed using the latest Silicon Carbide (SiC) and other state-of-the-art components. It is an expensive option, one which was designed for much lower power density than is required for this application, but it appears to be a viable option as a contingency as it has already been designed and tested at Sandia National Laboratories successfully at >200℃.

Another item that has been added to the Statement of Project Objectives since the initial tool specifications were drafted is the addition of rechargeable downhole batteries to the HPHT Downhole Turbine Generator 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. We have noted from the beginning of this project that a downhole generator and downhole batteries are not mutually exclusive.

As an enhancement, as well as a critical component, research and discussions were initiated to see if a viable battery technology existed that could aid and compliment the downhole turbine generator. 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.

As it turned out there were two families of rechargeable batteries that showed some promise for downhole. One being Sodium Nickelchloride, and the other being Sodium Sulphur. Both of these battery chemistries require the batteries to be at elevated temperature to operate. At temperatures below 125 ℃, by their nature, materia ls within these batteries solidify. Until the temperature is raised above 125 ℃ no power can be drawn from these batteries. That in itself was intriguing, as, unlike the problems that wellbore heat posed in our active cooling investigation, the wellbore heat actually works to the advantage of either 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 we have elected to consider building 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. Our downhole turbine generator 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. Our 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 ℃ environment, the batteries will continue to deliver their stored electric power.

We 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.

Phase I of this project has been successful in meeting the stated tasks of:

- Assessing the state of the technology
- Developing the specifications for the device(s)

- Identifying temperature limits of the voltage regulator & components; identifying optional methods
- Identifying areas of the UnderCurrent tool platform that require modification for HPHT service

Phase II Detailed Summary

As the need for oil continues to grow, greater well depths need to be achieved. At greater depths, the environment's temperatures and pressures increase dramatically. The tools and equipment needed to drill deeper wells require power. Historically, disposable lithium batteries have been used to power strings of tools, but are limited in their life and ability to operate at extreme temperatures. The HPHT Turbine Generator we have prototyped will operate on motion caused by a drilling fluid traveling through a series of turbine blades. This product will help eliminate some of the dangers associated with lithium batteries, such as explosions and environmental contamination, and allow power to be produced whenever fluid is flowing.

The HPHT Turbine Generator was designed to operate in a harsh environment for use in downhole drilling projects. The operating conditions are 250 ℃ and 20,000 psi ambient.

During Phase I: Feasibility Concept Definition of the project, the following tasks were completed:

- Task 1: Create a Research Management Plan
- Task 2: Conduct a Technology Status Assessment
- Task 3: Develop Specifications for the HPHT Turbine Generator
- Task 4: Identify Temperature Limits of Rectifier / Regulator Circuit and Conduct Literature Search for High Temperature Electronics Components
- Task 5: Evaluate Existing Platform to Identify Areas Needing Upgrade for HPHT Environment
- Task 6: Prepare Phase I Final Report
- Task 7: Initial Design of Mechanical Components

RESULTS OF WORK DURING PERIOD

Once the tasks were completed in Phase I, an application for Phase II was released and accepted by the N.E.T.L. During Phase II (Development of an HPHT Turbine Generator Prototype) the following tasks were completed:

- Task 8: Turbine Blade Testing
- Task 9: Bearing Design (Journal and Axial)
- Task 10: Electronics and Electronics Housing
- Task 11: Electrical Connections
- Task 12: Generator Design
- Task 13: Diverter Design
- Task 14: General Mechanical Design Overview
- Task 15: Supplemental Battery Charge and Heat Circuit Design

- Task 16: Prepare Phase II Final Report

The objective of Phase II in the "Development of a High Pressure / High Temperature Downhole Turbine Generator" was to manufacture two (2) functional prototypes for laboratory and field testing. The prototypes would then be used during Phase III to verify the design in both laboratory and field conditions.

Task 8: Turbine Blade Testing

The motion of the turbine blades can be explained using the diagram in **Figure 1 below**. Turbine blades operate on the principle that one of the blades remains stationary to direct fluid flow while the other is rotated from the impact of the fluid.

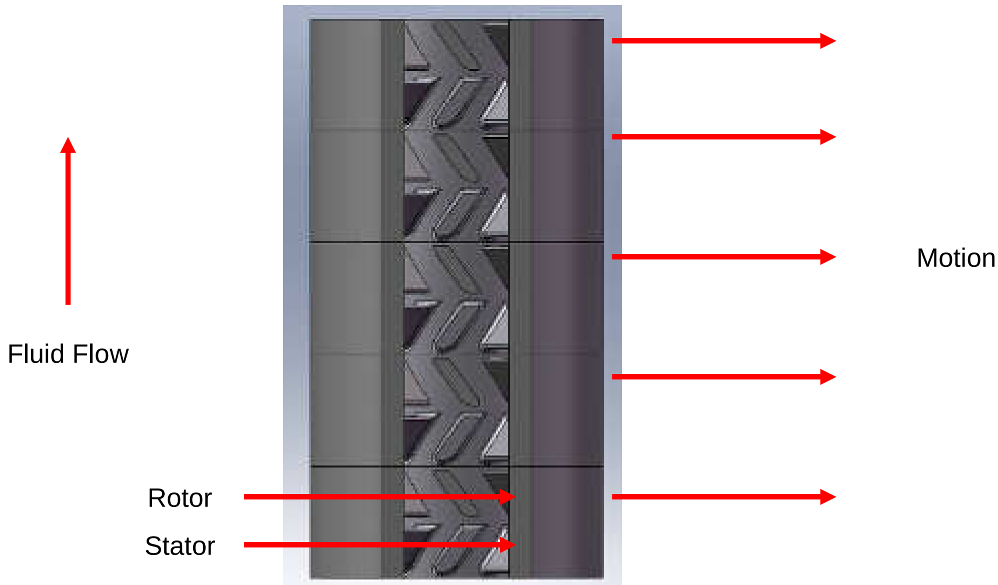

Figure 1: Schematic of Turbine Blade Motion

The first task in Phase II was to evaluate different turbine blade designs and coating operations to assure that a set of blades will last a minimum of one "bit trip." A bit trip is considered to be 200 hours of operation for our application. The turbine blades must be able to efficiently operate in 200-hour increments. For example, if it is known that the turbine blades will require replacement after 350 hours, they must be replaced after the first bit trip, as the tool will only be unearthed after 200-hour increments.

The criteria affecting blade wear consists of the following:

- Substrate Material
- Blade Angle
- Overall Geometry
- Fluid Velocity
- Fluid Density
- Sand Content of Fluid

Blade angle was found to be a driving variable that needed to be identified before any prototypes could be manufactured. More than one blade angle may be required to span the entire RPM range. To know if this condition will occur, the operator would need to know the flow conditions prior to assembling the turbine blades into the tool.

The torque produced by the turbine blades was approximated using the equation below:

$$\textbf{Torque (LB/FT)} = \rho QR[U_t - V_a(\cot(\alpha_1)+\cot(\beta_2))]$$

ρ = Fluid Density
Q = Flow Rate
R = Radial Distance From Center
U_t = Tangential Velocity (Rotor)
V_a = Fluid Velocity
A_1 = Flow Angle Of Stator
B_2 = Flow Angle Of Rotor

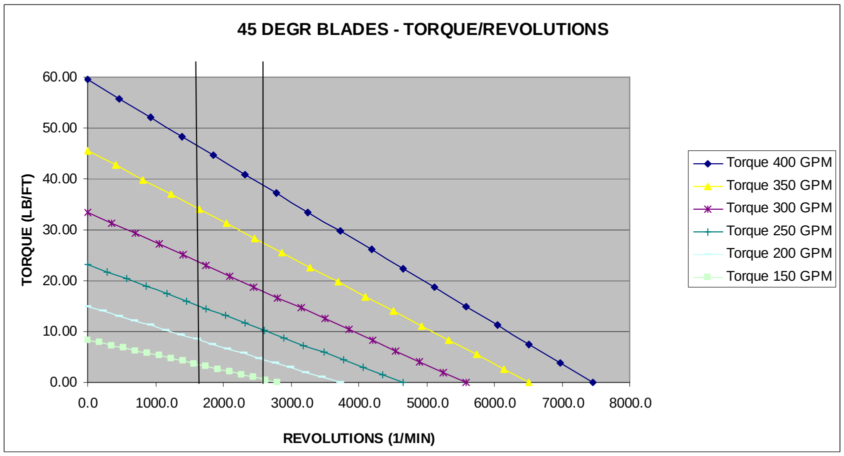

Figure 2: Torque vs. RPM

The power curve was generated using the equation below:

$$\textbf{Power (HP)} = (\text{Torque} * \text{RPM}) / 5252$$

Figure 3: Power vs. RPM

Ideally, the peak power should occur within the tool's nominal RPM range, which is specified between 1700 and 2200 rpm as **shown in Figure 3**. The curve changes with the blade angle, creating a dynamic system and allowing for multiple configurations to accommodate a wider range of fluid flow conditions. To date, a 55-degree turbine blade configuration will generate enough power to satisfy the specification for flow rate originally determined.

The UnderCurrent tool, used to derive an initial design for the HPHT Turbine Generator, utilized metal substrate blades to generate power. In early tests of the UnderCurrent tool, the turbine blades had experienced considerable amounts of wear and failure under short durations of operation.

Figure 4: Brittle Stator Blade

Each material tested had a unique set of wear characteristics; however, none of them were suitable for 200 hours of continuous use. With the metal substrate wearing excessively, the next step in the turbine bearing design was to apply different coatings and treatments to give the outer layer of the blade greater hardness or greater energy absorption. Epoxy coatings, annodization, and boronization were all attempted.

Figure 5: Epoxy Coated Rotor Blade

Figure 6: Boronized Rotor Blade

The initial blade coatings did not last more than 20 hours before they were completely removed by abrasion. It appeared that the epoxy coating had lasted longer than the boronized and anodized blades. Assuming that energy absorption was an important theory for extending turbine blade life, a set of blades were manufactured completely out of Rulon® for testing. The blades, shown below, displayed extreme amounts of wear after only five hours, rendering the solution useless.

Figure 7: Rulon® Stator Blade Post Test

The theory of energy absorption had proven ineffective during the prototyping phase. Reviewing the failure mode of the anodized and boronized blades revealed that the layer of hardened area was being removed via abrasion from sharp sand particulate in the drilling fluid.

Figure 8: 17-4 PH Stator Blade Post Test

The two processes, boronizing and anodizing, only apply a thin layer to the substrate. In the case of boronizing, the outer layer of the substrate itself is hardened. A thicker protective coating would add life to the turbine blades. According to the majority of literature, hexavalent chrome plating is a cost effective solution to applying thick layers (0.020" to 0.060" or greater). A complete set of five stators and five rotors, which were previously run in the tool for 75 hours, were hexavalent chrome plated.

The blades were used for approximately 50 hours in the HPHT Turbine Generator, which was tested within a flow loop containing drilling fluid and 1.5% sharp sand by weight. Sand content was checked periodically using a sand content test kit. If sand content was determined to be less than 1.5% more sand was added. The turbine blades and bearings "crush" the sand over time, reducing the content.

Figure 9: Uncoated 17-4 PH Stainless Steel Rotor Blade

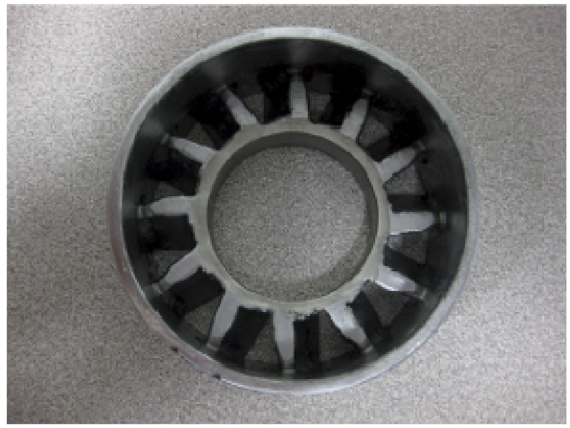

Figure 10: Hexavalent Chrome Plated Rotor Blade

After 50 hours of use, the blades still retained the majority of the hexavalent chrome plating as **shown in Figure 10**. The areas with the least amount of plating were areas identified as experiencing higher turbulence. The geometry of the blades became the focus of the design criteria. As drilling fluid enters the power section of the tool, it must pass through several diameter changes on the blades.

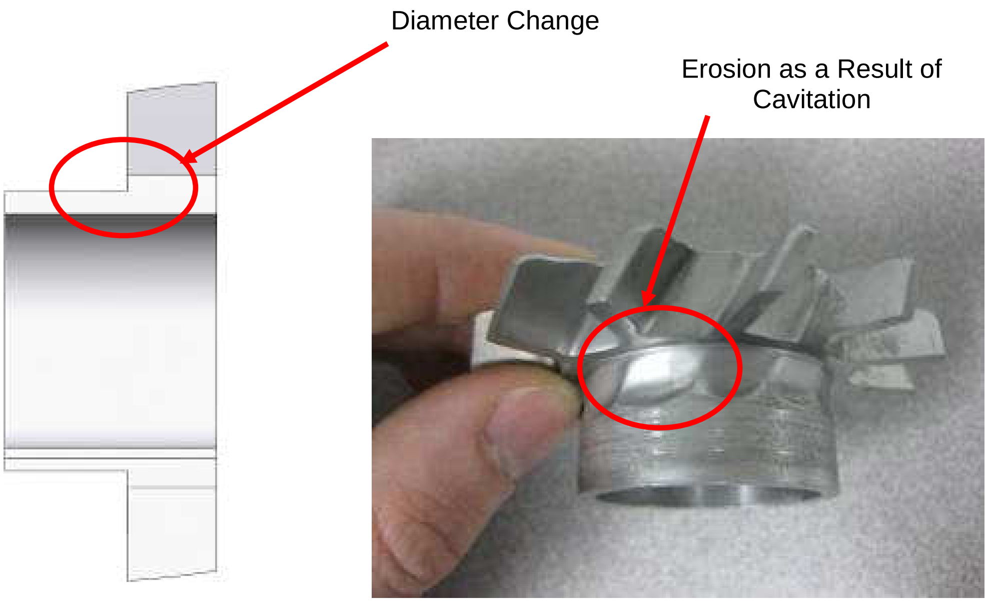

Figure 11: Cavitation Due to Diameter Change

Eliminating the diameter changes reduces the "swirling" effect, which causes cavitations in select areas of the blades. **Figure 11** illustrates the damage of a rotor blade caused by a change in diameter and resulting in the wear pattern highlighted. An investment cast was manufactured to produce a small quantity of the blades shown in the figure below.

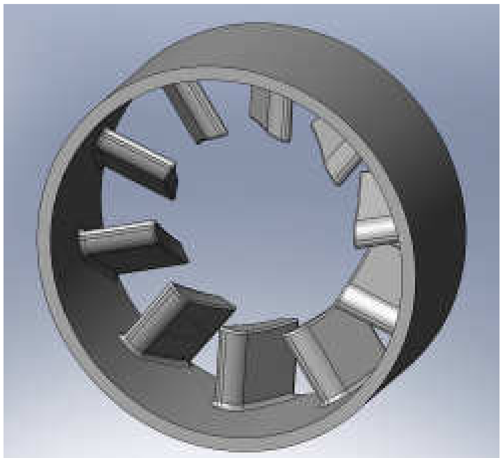

Figure 12: Current Design of Rotor Blade

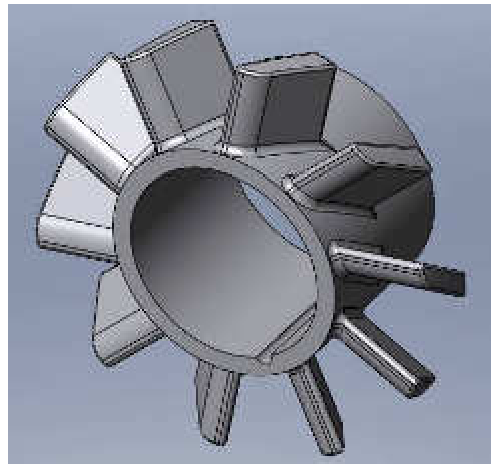

Figure 13: Current Design of Stator Blade

The rotor blade previously incorporated an inner ring connecting the “teeth” that cause a point of turbulence as the drilling fluid flowed.

The new blades were cast out of 17-4 PH condition A. The new blades were placed in the tool and tested for over 100 hours, after which they showed no cavities and very little overall wear. The teeth of the blades had experienced a reduction in thickness, changing from 0.150” to 0.140”. This wear occurred during an operational flow rate of 350 GPM and 1.5% sharp sand by weight. The nominal operational flow range for the generator is 150 GPM to 275 GPM.

Figure 14: Used Rotor Blade

Figure 15: Used Stator Blade

The uncoated blades have been deemed acceptable with no additional coating; however, if cost effective, the blades will be hexavalent chrome plated to extend the maintenance cycle. Further testing of a complete set of plated blades will have to be conducted to verify the life of the component. Multiples of 200 hours has yet to be achieved to use the blades for multiple bit trips.

It is unknown at this point how, if at all, temperature will affect the wear of the turbine blades, as well as other mechanical components in the system. It has been noted that some metals experience a change in properties that govern erosion as temperature changes. The effects are typically negligible and testing in laboratory conditions is extremely dangerous and expensive. With an ambient temperature of 250 °C, the drilling fluid would become steam unless high pressure was applied.

Task 9: Bearing Design (Journal and Axial)

The bearing design for the HPHT Turbine Generator was broken down into two different areas: journal bearings and axial bearings. Journal bearings are used to accommodate radial loads and axial bearings are used for loads transmitted along the axis of the tool. The bearings, much like the turbine blades, must last a minimum of 200 hours. Ideally, bearings should not need to be replaced during every excursion downhole.

The criteria affecting bearing wear consists of the following:

- Substrate Material
- Load
- Shock and Vibration
- Overall Geometry
- Fluid Velocity
- Sand Content of Fluid
- Distance Between Bearings

The UnderCurrent tool had incorporated a fully-dense carbide outer race reacting on spray-coated carbide inner race for the radial bearings. The axial bearings consisted of an Inconel substrate with polycrystalline diamond compact (PDC) inserts. The spray-coated carbide shaft had completely worn after brief testing, exposing the Inconel shaft as **shown in Figure 16**.

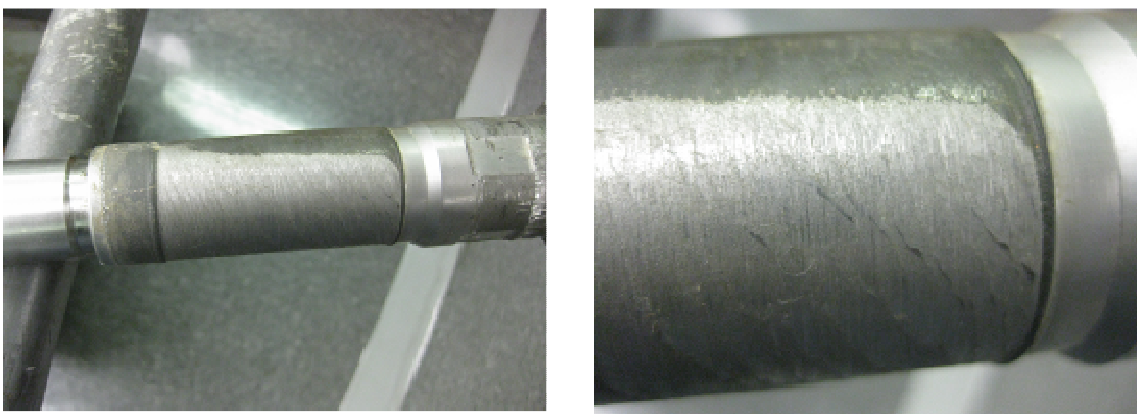

Figure 16: Spray-On Carbide Wear

The fully-dense carbide outer race did not show signs of significant wear. The axial bearings had been able to withstand the thrust load applied to the PDC inserts. The substrate that houses the PDC inserts has exhibited signs of severe damage.

Figure 17: Worn Axial Bearing

Figure 18: Worn Shaft

The most common assembly procedure for the PDC bearing required a hole drilled through Inconel substrate to allow out-gassing during the brazing operation, which bonds the inserts to the substrate. These holes allowed drilling fluid to enter and erode the metal body. The inserts themselves showed only minor indication that the bearing had been used.

Another factor adding to the erosion around the through hole was the diameter change at the bearing junction. The drilling fluid flow path was interrupted with this diameter change, which ultimately caused a more turbulent flow in this area. The damage to the shaft is shown in **Figure 18**.

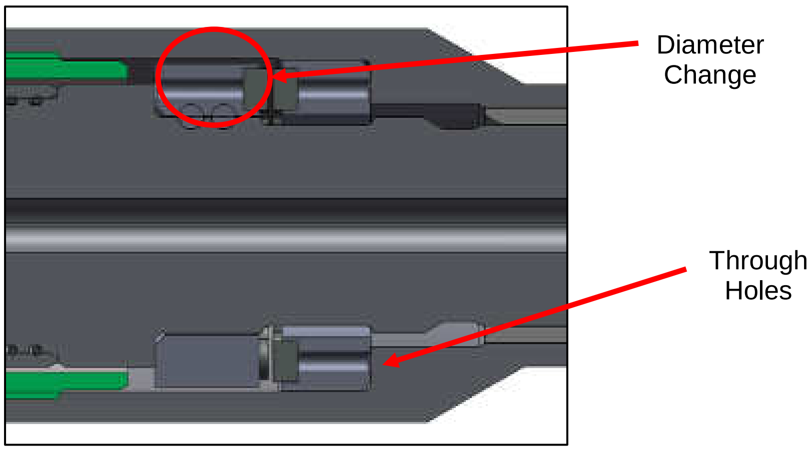

Figure 19: Axial Bearing Diameter Transition (Previous)

After gathering information on PDC bearing manufacturers, a company was located that does not require through holes to braze the PDC inserts to the substrate. This eliminated a path for drilling fluid to flow, reducing the erosion of the bearing. The transition of the diameters had also been removed to assist in the control of the flow path. The changes are illustrated in **Figure 20**.

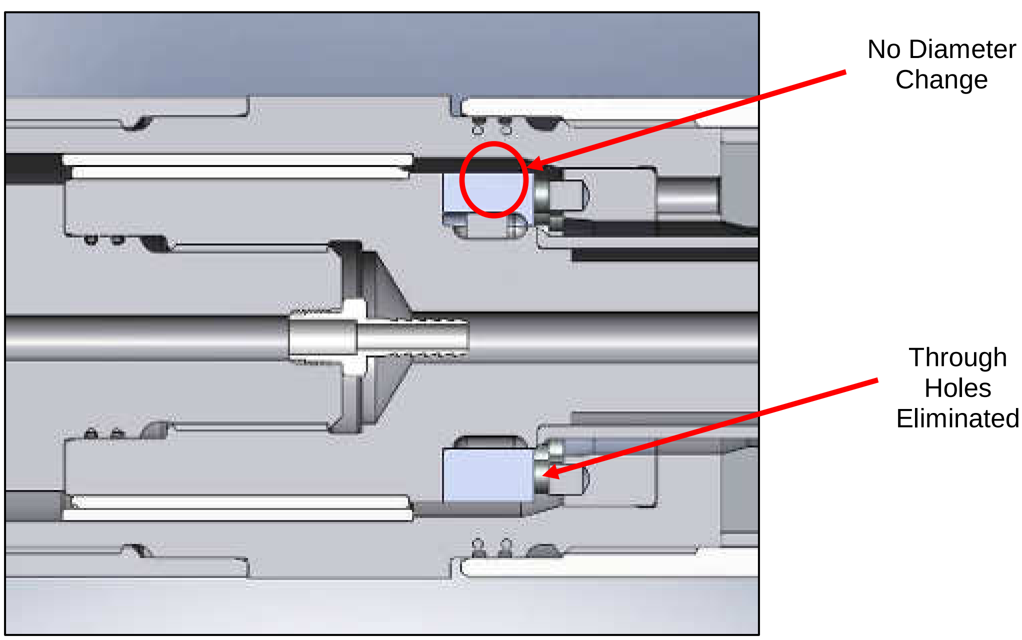

Figure 20: Axial Bearing Diameter Transition (Current)

The axial bearing showed no signs of wear after 100 hours. The generator was operated at 350 GPM with 1.5% sharp sand by weight. The tool was tested in a horizontal position.

To address the radial bearing issue, two designs were initially investigated. The first design was to replace the fully-dense carbide outer race with a marine bearing. Marine bearings incorporate a metallic outer shell with a polymer core. A shaft reacts against the polymer with less wear than a conventional bearing and also allows foreign object debris (F.O.D.) to pass through without damage. Upon investigation, nearly all marine bearing are rated for temperatures much lower than 250 ℃.

The modes of failure for the fully-dense carbide on spray-coated carbide are primarily a result of sharp sand, friction, shock and vibration. A marine bearing utilizes a metal outer shell with an injection molded polymer interior. The molded interior is "lobed" to allow F.O.D. to pass through the bearing. F.O.D. that is not allowed to pass can cause damage to the bearing. The lobes also reduce the amount of contact area between the two races, creating less friction. Another desirable feature of the marine bearing is the soft material used to damp shock and vibration. Fully dense carbide can be brittle and crack under certain conditions.

Prototypes were ordered and tested. The results yielded problems as temperatures elevated. The thermal expansion coefficient for polymers is typically higher than for metals. This resulted in excess friction at higher temperatures. Another problem with the marine bearing at higher temperatures was the ability to remain adhered to the housing. It is possible a custom design would be functional; however, the FMEA determined that the risk of failure is too high.

The second design was to make an inner and outer race out of Inconel and have them brazed with tungsten carbide cladding. Conforma Clad, a division of Kennametal, supplied the prototypes of the inner and outer races. There was some uncertainty as to the effectiveness of the cladding under the RPM range of the HPHT Turbine Generator as Kennametal does not specify their tungsten carbide cladding for RPM ranges over 800. (The operating range for the generator is between 1700 and 2700 RPMs).

Figure 21: Unused Conforma Clad Bearing

The prototype bearings were installed and tested in drilling fluid with 1.5% sand content by weight. After 25 hours of operation, the bearings had lost all of the cladding and much of the substrate material had also been removed. The bearings were no longer functional.

The two initial designs had proven to be ineffective. The tested theories had been reassessed and examined in an attempt to indicate a potential solution to the radial bearing issue. The only material showing few signs of wear was the fully-dense carbide used on the UnderCurrent platform. The next prototype would consist of a magnetic bearing with an integrated sacrificial wear component.

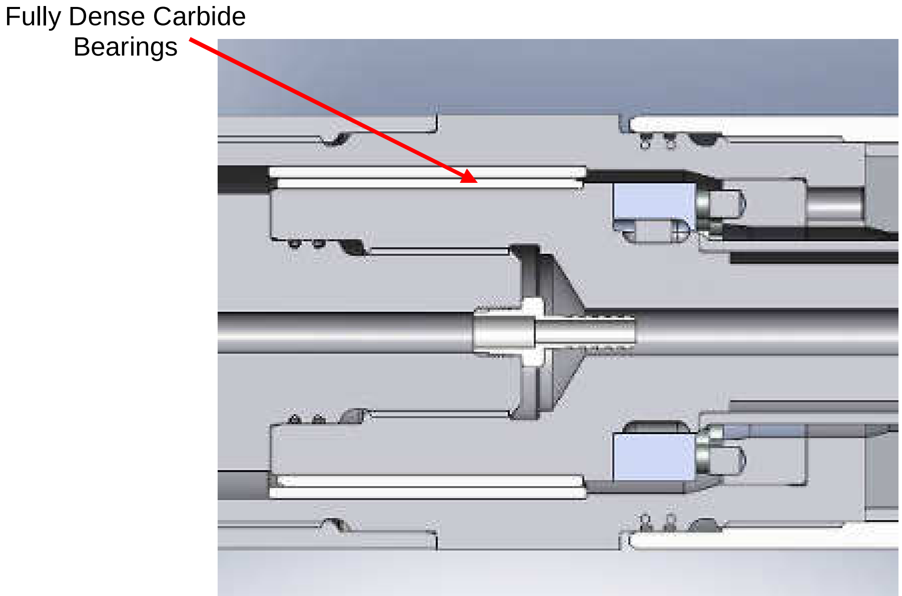

Figure 22: Radial Fully-Dense Carbide Bearings

A magnetic bearing prototype was manufactured and tested at Dexter Magnetic Technologies' Elk Grove Village, Illinois facility, **shown in Figure 23**. Magnetic bearings use opposing forces on the inner and outer races to create a non-contact bearing during operation. Magnetic bearings are commonly used in high speed applications. **Figure 24** demonstrates the magnetic bearing operating at 3500 rpms, a speed much higher than the required speed of the tool. As the tool speed is decreased, the races of the bearing come into contact. At low RPMs, the bearing could be damaged without the addition of a mechanical bearing. This mechanical bearing would be replaceable. The cost of a magnetic bearing is much higher than a conventional bearing; however, the maintenance cycle is much longer. Shock and vibration could not be quantified with the equipment available, which could play a significant role in the reliability of the system. The complexity of designing a magnetic bearing and the additional length associated with this style of bearing make it an option, but not an ideal solution. Based on the information gathered from the radial bearing prototypes, fully-dense carbide reacting on fully-dense carbide would be tested as an alternative to the costly magnetic bearing.

Figure 23: Cross-Section of Magnetic Bearing

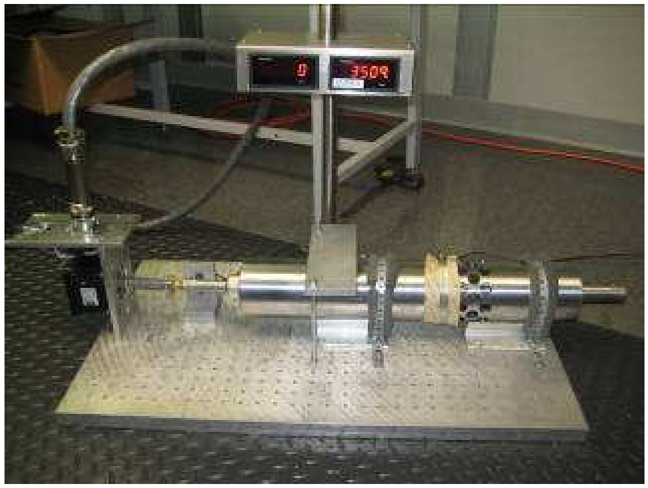

Figure 24: Magnetic Bearing in Operation

After 100 hours of use, the carbide inner and outer races had worn approximately 0.005” on the upper diverter. The inner and outer race in the shaft area had worn much more, approximately 0.020” in some areas. The inner race on the shaft, which does not rotate, had a distinct erosion pattern that indicated sharp sand particles were not being “flushed” through the bearing as intended. The damage is indicated in **Figure 25**.

Figure 25: Shaft Bearing Erosion

To increase the flow through the bearing an adjustment had to be made in the “outlet” following the prime mover as **shown in Figure 26**. The outlet area was reduced thus forcing more drilling fluid through the bearing rather outside of the tool. While increasing the flow through the bearing did not eliminate F.O.D., it did greatly reduce the measureable wear.

Figure 26: Adjustable Outlet in 3 Configurations

After reviewing the data from the tests conducted, fully-dense carbide reacting on fully-dense carbide will last longer than any other material combination prototyped. Bearing replacement is another area that needs to be addressed to ease customer maintenance issues. Currently, the bearings must be shrink-fitted onto or into the component they are aligning. This involves the use of liquid nitrogen and an oven capable of heating components to over 400 ℃. With this method, on drilling sites is nearly impossible. To assist in maintenance procedures, replaceable bearing cartridges will be incorporated into the design wherever possible. The replaceable shaft bearing **shown in Figure 27** below is one example.

Figure 27: Removable Fully-Dense Carbide Bearing Cartridge

Task 10: Electronics and Electronics Housing

The electronics portion of the HPHT Turbine Generator consists of a rectification and regulation circuit. The rectification portion of the circuit is needed to change the AC voltage produced by the generator to a DC voltage, which could then be used by other equipment in the "drill string." The regulation portion of the circuit would maintain and constant DC voltage output. The output is currently regulated to 24 VDC but could be easily changed to any DC voltage value by replacing a single resistor.

The criteria affecting rectification and regulation circuit performance consists of the following:

- Temperature
- Pressure
- Shock and Vibration
- Heat Transfer

The UnderCurrent platform was used to initiate a dialogue for the design of the HPHT rectification and regulation circuit. The electrical components on the UnderCurrent circuit have a temperature rating of 175℃ and a pressure rating of 20,000 psi (compared to the HPHT's temperature rating of 250 ℃ and pressure rating of 20,000 psi).

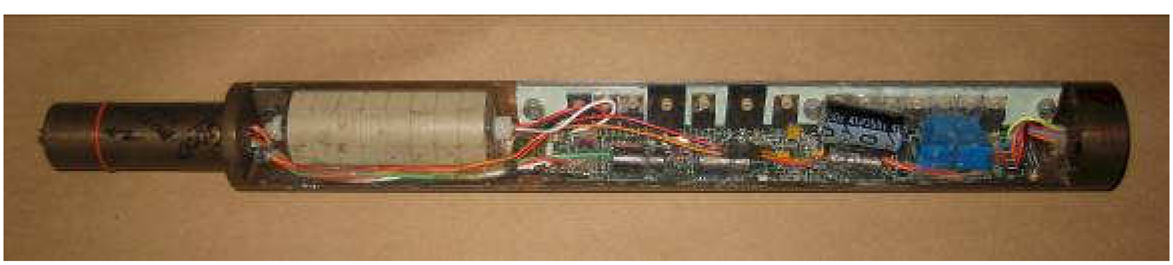

Figure 28: UnderCurrent Electronics

An extensive search for a high temperature electronics design company had resulted in very few leads. No company was willing to agree that a functional prototype could be created, only that services would be rendered in an attempt to meet design criteria. The high-temperature component industry (+200 ℃) has made large strides in producing a wider array of components. During the beginning of the project, each component of the UnderCurrent electronics circuit was identified and a high-temperature counterpart was pursued. High-temperature versions of the components used to regulate the system are especially hard to find with a temperature rating of (+200 ℃). The UnderCurrent used a series of torroids to perform regulation. High-temperature torroids are not readily available for replacement.

Figure 29: Torroid Stack in UnderCurrent Electronics

In April of 2008 a consultant by the name of Gary Box had been acquired for high-temperature electronics design by Dexter Magnetic Technologies. Mr. Box has had experience working with high-temperature circuitry as well as power rectification and regulation devices. Mr. Box, in conjunction with the generator consultant, Chuck Syverson, began working on a concept to use a "saturable core" to assist in the regulation of the voltage. This rough regulatory device is needed to eliminate components that may not be available or are too costly with a 200 ℃+ temperature rating. The concept of a saturable core will be described in detail under **Task 12: Generator Design.**

The scope of the electronics design was broken down into three phases. The first phase of the project was to create a schematic of the circuit, identify necessary component types and produce a topical report explaining the success rate in attempting to manufacture a high temperature prototype. Phase II of the project was to assemble a "low-temperature" 175 ℃+ prototype with a bill of materials listing each high-temperature counterpart needed for the high temperature (250 ℃ maximum) prototype. The last phase of the project was to manufacture a fully functional rectification and regulation circuit capable of operating at 250 ℃.

A schematic for the low temperature prototype had been produced and a prototype assembled.

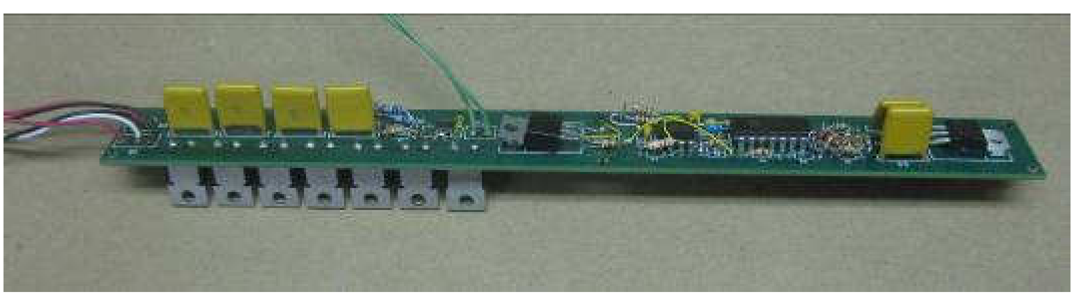

Figure 30: Low Temperature Rectification / Regulation Prototype

The low-temperature circuit, **shown in Figure 30**, had been tested with a copper wound laminate stack. The test results verified that the circuit was able to rectify the generator's AC output to DC. The circuit was also able to reduce the output, when compared to the absence of a regulation device, but could not maintain a constant voltage of 24 VDC. The electronics board was returned to Gary Box to evaluate the regulation issues.

The circuit was tested at Mr. Box's facility and the electrical current output of the "control windings" was recorded. The control windings are the driving mechanism for core saturation. Without enough current traveling through the control windings, the regulation ability will be limited.

Once all troubleshooting was complete, the bill of materials for the high temperature counterparts was reviewed and an order was placed. The lead times for some of the more exotic components were in the 16 week range. This added a sizeable delay to the continuation of the electronics design.

Once all of the parts were received, they were sent to Houston Sigma Technology L.P., the PCB manufacturing company, to be assembled. The board itself had to be made out of a high-temperature polyimide material. The assembled boards were mounted on the electronics chassis with a high-temperature polymer gasket underneath and tested with the power generation portion of the tool. Each of the two circuits was capable of rectifying the AC output to DC. The regulation was still unachievable in the high temperature prototypes based on oscilloscope readings. The circuit was supplying current to the control windings in the generator, but it was not enough to regulate the output voltage to 24 VDC. Further analysis proved that the theory was incorrect rather than the electrical design.

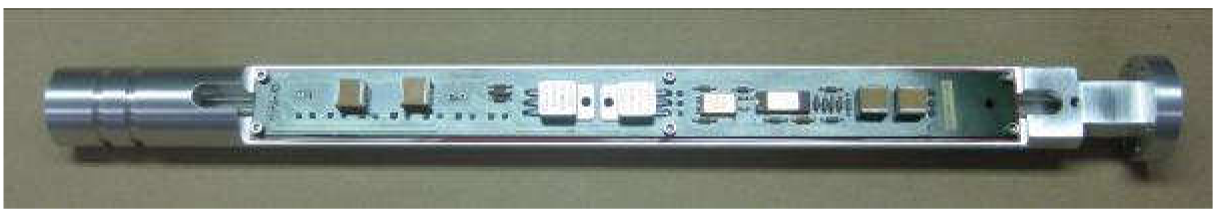

Figure 31: High Temperature Electronics Top View

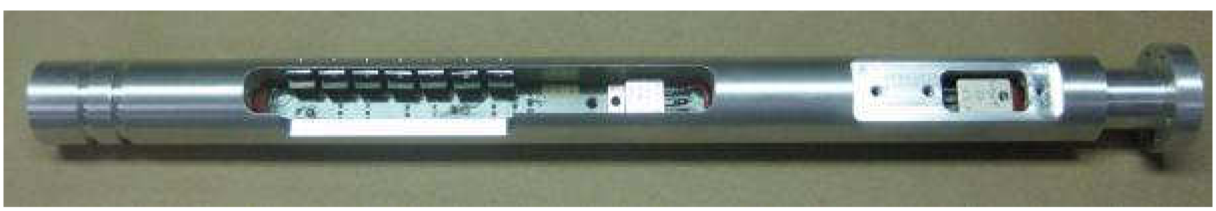

Figure 32: High Temperature Electronics Bottom View

After the prototype HT electronics was returned to Mr. Box for review, it was discovered that the saturable core concept was not an efficient method for regulating voltage. The saturable core design lacked the ability to "convert" the voltage to another form, limiting the power output of the device. To solve this problem, the HT electronics had to incorporate what is commonly referred to as a "buck converter." A buck converter is a step-down DC voltage to DC voltage converter that utilizes an inductor or series of inductors to store the power until it is needed.

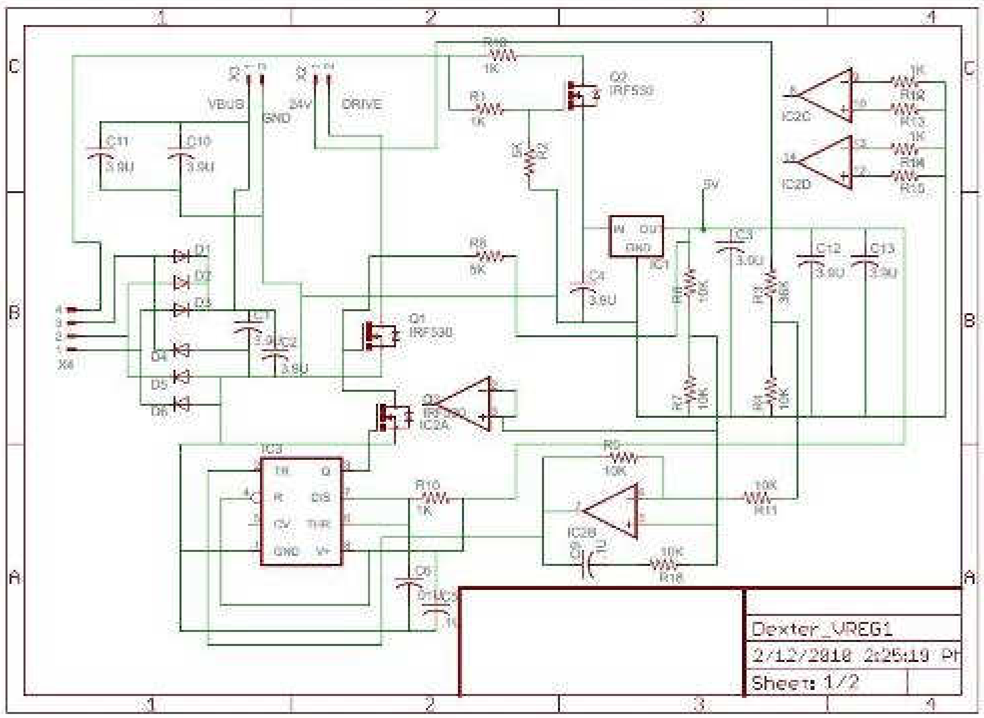

Figure 33: High Temperature Electronics Schematic

Using a buck converter for power regulation is not a novel idea. They are commonly used in "low-temperature" applications, ambient environments under 200 ℃. In an environment such as the one specified for this particular project, finding a high-temperature inductor with a rating to 250 ℃ is very difficult. To resolve this issue, a custom inductor had to be manufactured from steel laminations rather than a powder ferrite and epoxy combination.

The buck converter design has been prototyped and tested at Mr. Box's facility in Golden Valley, MN. The prototype was able to rectify AC voltage to DC voltage, and able to regulate an input voltage to 24 VDC. The prototype is approximately 14 inches longer than the first HT prototype. This change now requires an increase in length to the HPHT electronics housing. The modifications will be completed after the arrival of a high-temperature MOSFET from Cissoid.

The HPHT electronics housing design was not dissimilar to the original UnderCurrent electronics housing design. Both systems had a design constraint of 20,000 psi. The pressure housing was analyzed using ANSYS® finite element software to ensure it is capable of enduring 20,000 psi without permanent deformation. The deformation of the pressure housing is **shown in Figure 34**.

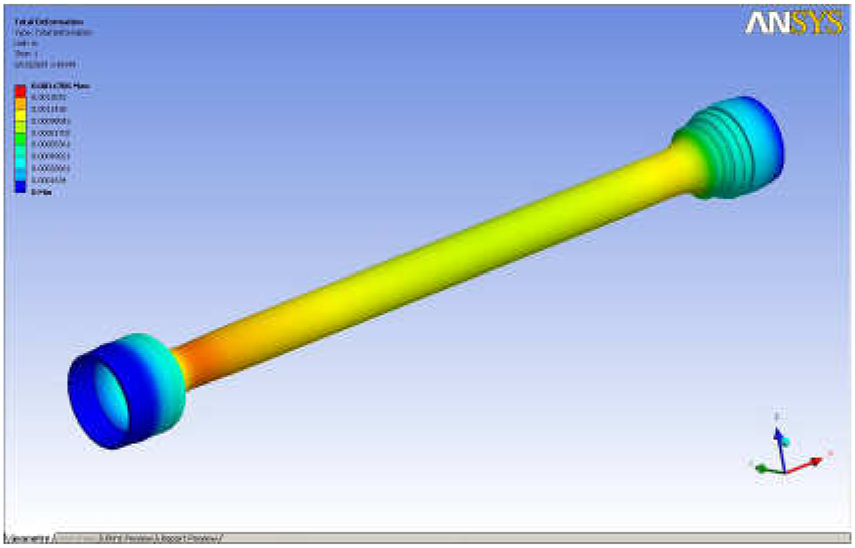

Figure 34: ANSYS Analysis of Electronics Pressure Housing

Task 11: Electrical Connections

The criteria affecting the electrical connections consist of the following:

- Electrical Current
- Size / Geometry
- Temperature
- Pressure
- Durability
- Ease of Maintenance

The UnderCurrent platform used a six-conductor connector from Greene Tweed that was pressure rated to 20,000 psi. The temperature rating of the connector was 175 °C. The steel removal pin on the connector, which also acted as an alignment key, was continuously bent and in some cases removed. Overall, the connector was not suitable for extreme temperatures and had several failure modes associated with the design.

Figure 35: Green Tweed 6 Conductor Connector

The first stage of the design process for the connector was to establish how many conductors are required and how much current each conductor would have to pass. If 200 watts of power are to be supplied from a 24 VDC source, the current required is over eight amps. This current would only need to be passed through two of the conductors. A total of four conductors will be needed; one for power, one for ground and two through lines to transmit data.

The simplest approach to electrical connector selection is to purchase a product that already exists. Greene Tweed and Kemlon Products, Inc. are among the most recognized companies for electrical connectors in the oil & gas industry. Neither of the companies had a standard solution for the package size constraints of the system. Several other companies were contacted with the design constraints of the connector and none of them had a suitable “off the shelf” solution. After exhausting research efforts for a standard connector, a custom design was created and submitted for manufacture. Several companies had supplied schematics and pricing for custom designs and Kemlon’s electrical connector was chosen for prototyping.

Figure 36: Kemlon High Temperature High Pressure Connector

The electrical connectors would be used on both ends of the tool to allow information to be passed through the drill string as well as to supply power to the attached equipment.

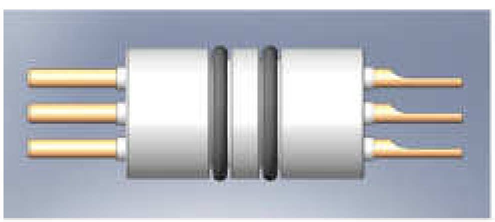

Figure 37: Connector Locations

The connector has undergone pressure and temperature tests to verify that the connectors will not fail under the 250 ℃ and 20,000 psi conditions. The tests were conducted by Kemlon Products, Inc. prior to shipping. The design includes a backup support ring to reduce chances of extrusion under high pressure.

Task 12: Generator Design

The criteria affecting the permanent magnet generator consist of the following:

- 200 Watt Power Output
- 20,000 psi Pressure Rating
- Performance At Maximum Temperature (250 ℃)

- 4000 Hour Operational Life
- Shock and Vibration
- Heat Transfer

Historically, the UnderCurrent platform utilized a magnetic coupling to drive a permanent magnet generator as **shown in Figure 38**.

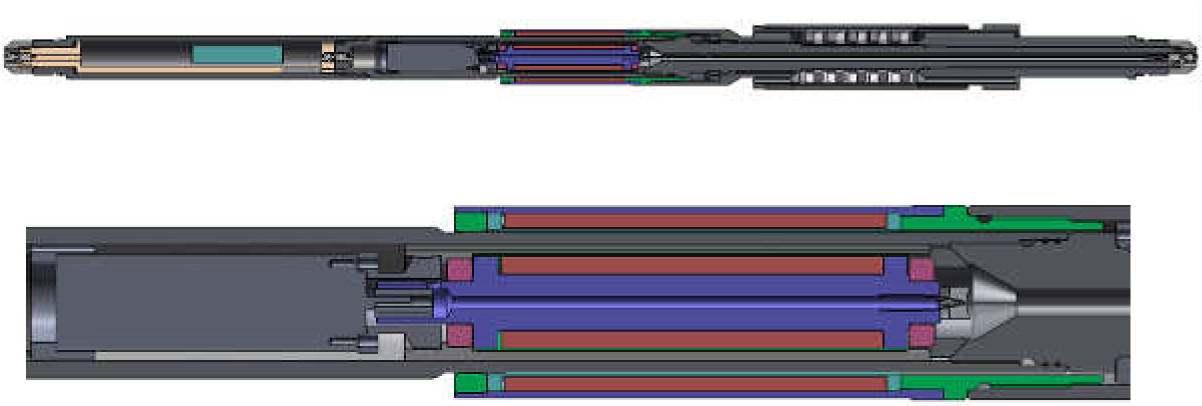

Figure 38 (Cross-Section of Magnetic Coupling)

Few extended operation tests had been conducted with the UnderCurrent tool. With a maximum operating temperature of 175 ℃, overheating was not a significant threat. At an operating temperature of 250 ℃, the HPHT Turbine Generator could very easily become too hot and degrade performance or permanently damage the generator if improperly designed. To extract heat from the tool, drilling fluid would have to pass between the rotor and stator portions of the generator. Excess heat can be generated from eddy currents. An eddy current is the magnetic equivalent to friction and can generate heat when a conductor is exposed to a changing magnetic field. Since the rotor assembly of the generator contains numerous high energy magnets, large amounts of heat are generated in the copper windings as well as the structural components of the stator assembly during operation. The rotor contains Samarium-Cobalt magnets, which undergo changes with temperature as plotted on the figure below.

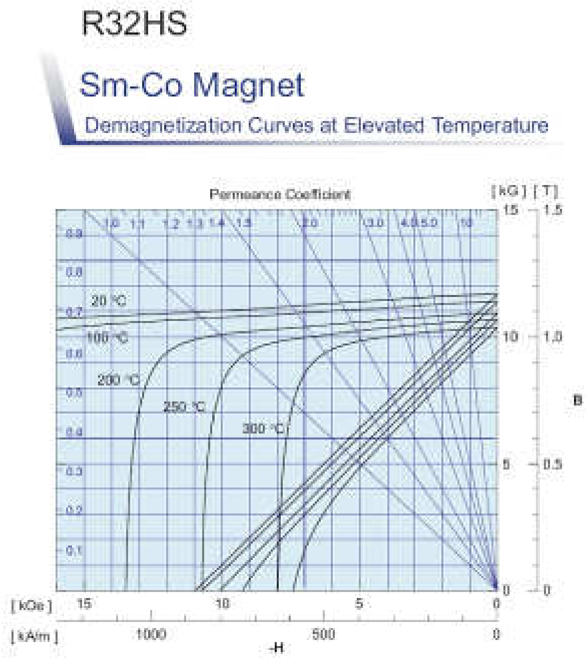

Figure 39: Demagnetization Curve of Samarium-Cobalt

Dexter Magnetic Technologies approached a company specializing in motor and generator design. A schematic was supplied to Dexter illustrating a design that would meet our design criteria. The company could not guarantee that the generator would supply 200 watts at 250 ℃. The cost exceeded the generator portion of the budget. Syverson Consulting was ultimately contracted to design the HPHT permanent magnet generator. Mr. Syverson has designed generators for many companies including aerospace and oil & gas industries.

Syverson was supplied a Statement of Work and began running simulations on what the laminations for the stator should look like. A series of laminations is used as a base for the copper windings to assist in eddy current reduction. The generator type was to be a three-phase with a wye configuration.

Syverson suggested that we contract GBOX for electronics consultant work, being that the electronics and generator consultants will have to work together to supply a functional product. Syverson and GBOX have worked on several projects together in the past. To accomplish voltage regulation efficiently, a “control winding” was incorporated to force current into the stator and saturate the core. By saturating the core, magnetic flux influencing the phase windings is reduced and results in a lower voltage output.

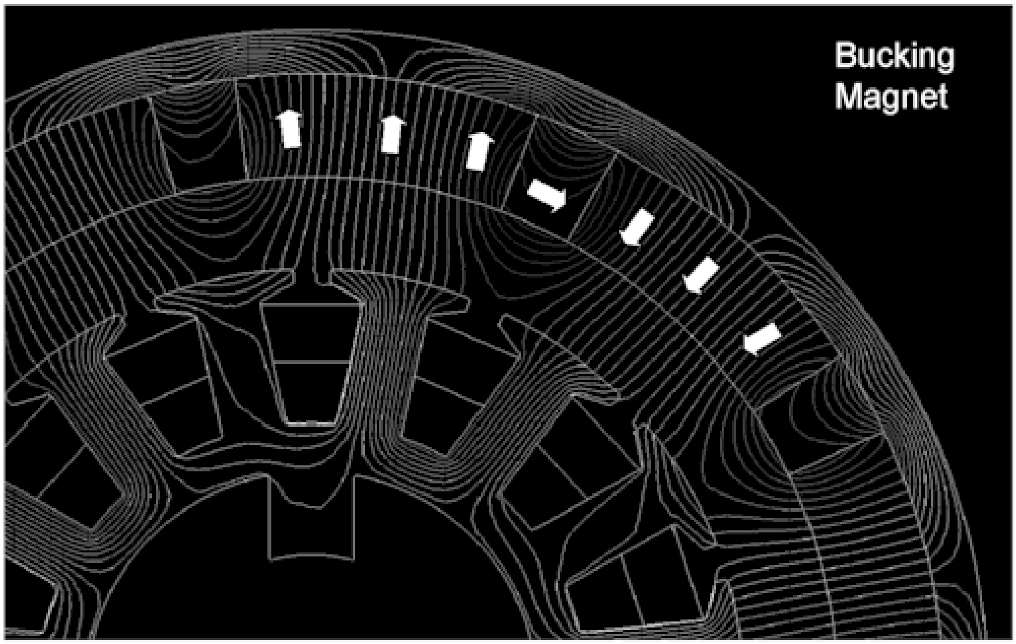

Figure 40: Magnetic Flux Lines Passing Through Laminate

The rectification and regulation circuit would receive the three-phase AC voltage and route part of the voltage back to the control windings. This would reduce the amount of electricity generated by the three phases to an output that can be regulated without the use of a toroid or other sophisticated electrical components. Toroid design is not simple for applications in the 250 ℃ temperature range.

The rotor portion of the permanent magnet generator contains magnets with alternating poles. The poles are arranged in a "quadrature" configuration to increase the penetration depth of the magnetic field. This configuration is **displayed in Figure 40**. By increasing the penetration depth, a larger "air gap" can exist between the rotor and stator. A larger gap between the rotor and stator will allow more drilling fluid to pass through the generator, removing more of the heat generated by eddy currents.

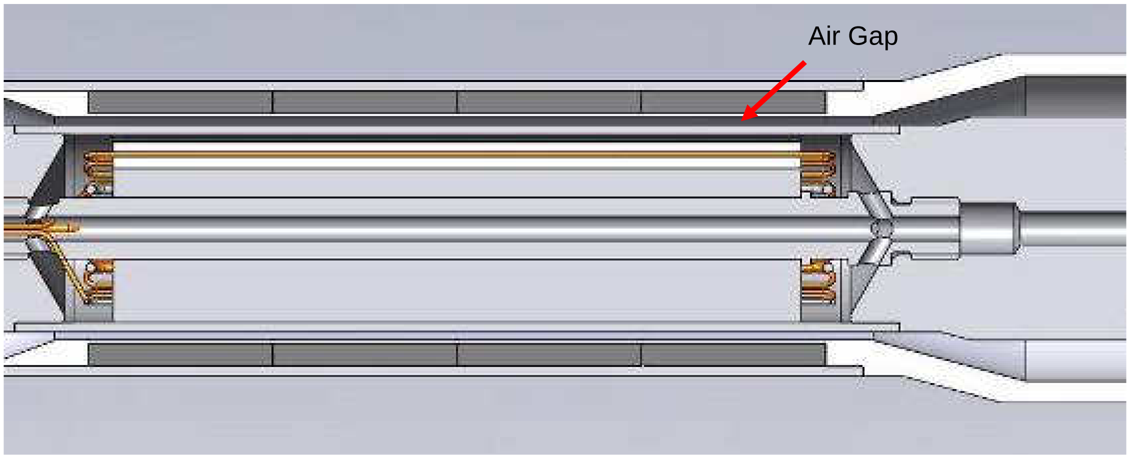

Figure 41: Air Gap / Heat Removal Path

With the drilling fluid running parallel to the rotor and stator and the flow remaining mostly laminar, the permanent magnet generator experiences little wear during operation. Improper maintenance of the fully dense carbide radial bearings could allow the rotor to come into contact with the stator.

Upon testing the first prototype of the generator, it was discovered that the power output was not enough to meet the 200 watt specification. Several other prototypes were manufactured with different combinations of increased length and higher density copper fill. The latest version of the generator was powerful enough to produce 200 watts of power through the entire rpm range of the tool. The prototype was tested on a lathe to correlate the rpm and voltage output.

RPM	Voltage (DC)	Load (Ω)	Power (Watts)
1740	57.9	9.8	342.1
1800	59.7	9.8	363.7
2000	65.6	9.8	439.1
2200	71.7	9.8	524.6
2400	77.6	9.8	614.5
2700	87.0	9.8	772.3

Table 1: RPM and Voltage Correlation (9.8 Ω Load)

RPM	Voltage (DC)	Load (Ω)	Power (Watts)
1740	64.4	16.5	251.4
1800	66.8	16.5	270.4
2000	73.6	16.5	328.3
2200	80.6	16.5	393.7
2400	87.2	16.5	460.8
2700	97.9	16.5	580.9

Table 2: RPM and Voltage Correlation (16.5 Ω Load)

After creating the correlation between rpm and voltage, a correlation could be made between flow rate and rpm. The data **shown in Tables 3 and 4** was taken from the most current generator design.

Hz	VDC	GPM	Load (Ω)	RPM	Power (W)
25	25.1	159	10	658	63
30	34.1	190	10	956	116
35	43.8	227	10	1277	192
40	52.6	257	10	1569	277
45	61.5	286	10	1863	378
50	68.3	316	10	2088	466
55	71.8	341	10	2204	516

Table 3: RPM and Flow Rate Correlation (10.0 Ω Load)

Hz	VDC	GPM	Load (Ω)	RPM	Power (W)
25	30.7	161	16	763	59
30	41.4	194	16	1073	107
35	51.7	228	16	1370	167
40	61.8	258	16	1662	239
45	71.5	288	16	1943	320
50	79.0	317	16	2159	390
55	82.4	340	16	2258	424

Table 4: RPM and Flow Rate Correlation (16.0 Ω Load)

The maximum flow rate specification of 350 gpm was verified inside of the flow loop. At 350 gpm the rpm range remained at the upper end of the band making it acceptable to operate at this flow rate for intermittent periods of time.

Task 13: Diverter Design

The criteria affecting the diverters consist of the following:

- Substrate Material
- Overall Geometry
- Fluid Velocity
- Fluid Density
- Fluid Flow Path
- Sand Content of Fluid

The lower diverter within the UnderCurrent tool consisted of many small paths for fluid to enter the prime mover. The fluid velocity for each path was considerably high for a fluid containing 1.5% sharp sand by weight. The angle of impact is also very blunt causing most of the energy of F.O.D. to transfer directly into the face of the upper diverter. The image **depicted in Figure 42** illustrates the severe wear pattern of the lower diverter.

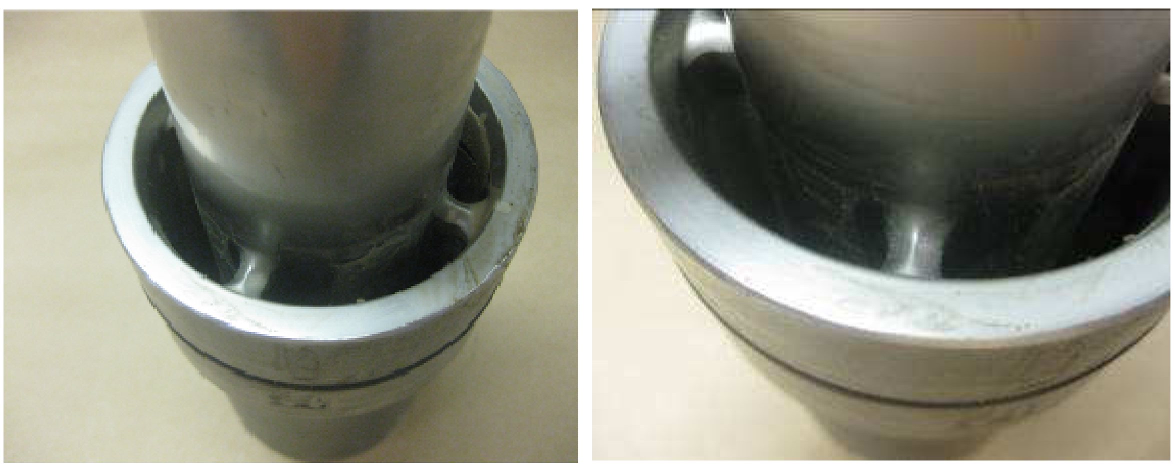

Figure 42: Upper Diverter Wear Pattern

The upper diverter of the UnderCurrent tool consisted of four large openings to allow drilling fluid access to the prime mover. The large openings greatly reduce the velocity of the drilling fluid when compared to the lower diverter. The entrance to the upper diverter is also very blunt, containing no transition for the drilling fluid to enter smoothly. The “webs” between the openings of the diverter are the primary features to experience wear.

Figure 43: Unused Lower Diverter

Figure 44: Post Operation Lower Diverter

As the upper and lower diverters wear, they reach a point of critical damage. If one of the diverters fails the tool will essentially stop working and cause damage to itself and possibly other equipment that it is connected to. The pictures shown above demonstrate the wear accumulated after less than 100 hours of use. Ideally, the diverters are core components of the HPHT Turbine Generator and should last for several bit trips. After 100 hours, the UnderCurrent tool has experienced enough wear to cast doubt on the tools performance and structural integrity after a single bit trip.

The duration of the diverters must be increased for the HPHT Turbine Generator to be a cost effective alternative solution to lithium ion batteries. Geometry and sharp changes in fluid flow direction are the principal elements reducing the life of the diverters. Each issue was addressed to reach the current diverter designs in the HPHT Turbine Generator.

The lower diverter utilizes a “sacrificial” tapered component, **shown in Figure 45**, to assist in gradually directing the flow of the drilling fluid out of the tool. The numerous small paths used on the UnderCurrent had been replaced by four larger openings running along the axis of the tool. The cross-sectional area has been increased at the outlet resulting in a decrease in velocity of the drilling fluid. After 100 hours of operation, the diverter itself experienced little wear. The sacrificial components were also fully intact and would last several bit trips before replacement would be required.

Figure 45: Lower Diverter Post Operation

The upper diverter was modified to guide the drilling fluid into the prime mover through three large slots. The gradual incline along with an increase in cross-sectional area make the redesigned upper diverter far more robust than the original. After 100 hours of use the diverter shows no discernable signs of wear as a result of sharp sand particle impact. See figure below.

Figure 46: Upper Diverter Current Design

Only one area of the diverter required addressing; the o-ring groove that restricts flow from traveling around the tool and forces the drilling fluid to progress through the prime mover. The o-ring groove was much wider than suggested by any design guide. The initial reasoning for this was to allow more room for the o-ring, as it is only restricting flow and not sealing. The increased clearance allowed mud to erode the feature. Continued erosion would generate a path for drilling fluid to flow, reducing the restriction and degrading performance. **Figures 47 & 48** below, demonstrate the damage that can occur.

Figure 47: Upper Diverter Post-Operation

Figure 48: O-Ring Seal Wear

Future tools will have an increased o-ring cross-section or a reduced o-ring groove width. This will maintain an appropriate flow restriction without damaging the upper diverter. The upper diverter in the two prototypes prepared for downhole use will utilize the larger o-ring. If erosion remains present, another flow restrictor will be used until the appropriate changes to the upper diverter can be made.

Task 14: General Mechanical Design Overview

The criteria affecting the total mechanical portion of the tool consist of the following:

- Ability to Operate at 250 ℃
- Ability to Operate at 20,000 psi
- Ability to Generate 200 Watts
- Ability to Operate Continuously for 200 Hours

Extensive fixturing and tooling were required to test the entire HPHT Turbine Generator. To simulate drilling operations, a flow loop has been designed to pump drilling fluid, with 1.5% sharp sand by weight, in a closed loop system. The flow loop has various instrumentation to monitor pressure, temperature, flow rate and voltage output. The entire tool fits inside of a “drill collar,” which allows drilling fluid to pass over and through the tool to replicate erosion. The drill collar is **shown in Figure 52**. **Figures 49 thru 53** show the major components of the flow loop.

Figure 49: Electric Motor

Figure 50: Pump

Figure 51: Mixer

Figure 52: Drill Collar

Figure 53: Flow Loop in Operation

The flow loop is controlled by using the interface **displayed in Figure 54**.

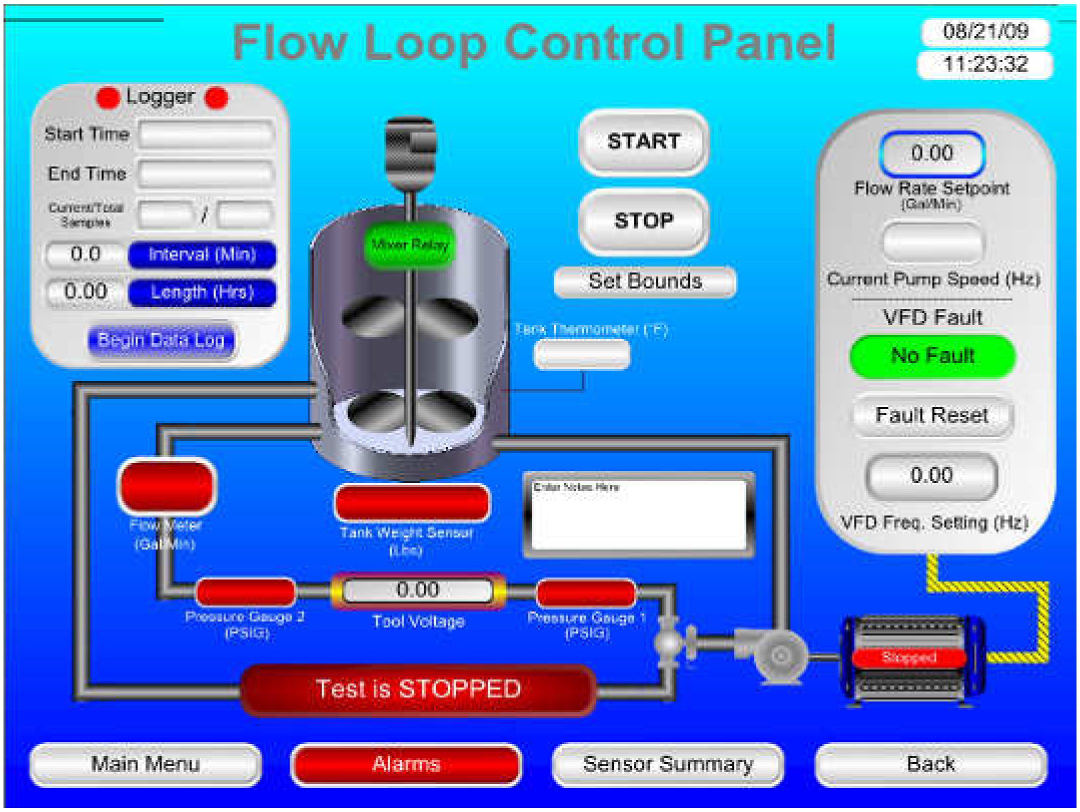

Figure 54: Flow Loop Control Panel

High temperature simulation was accomplished using a fixture manufactured internally that incorporated heat bands and high-temperature oil 250 ℃+ in conjunction with an air driven motor. The fixture was unable to flow the oil because of safety and cost constraints.

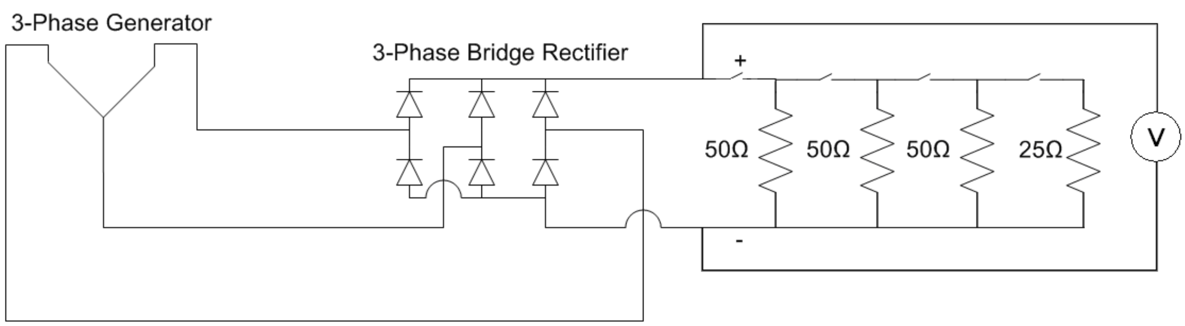

Figure 55: Electrical Schematic for Testing

Figure 56: High Temperature Test Fixture

High pressure tests were achieved using a pressure vessel designed and operated by Maxbar, Inc. The pressure vessel was capable of exerting external pressures up to 20,000 psi and either maintaining or cycling the pressure. Each test was certified and a test report was released upon completion of testing.

Figure 57: Pressure Vessel Seal

Figure 58: Pressure Vessel Disassembled

The HPHT Turbine Generator was tested throughout Phase II to validate areas of design that would be crucial for continuation. One of the tests conducted was a pressure test on the o-rings of the system to verify that the tolerances used could accept cyclic loading conditions. A test fixture was manufactured with two o-ring grooves. The two grooves had progressively tighter clearances between the shaft and the bore. The inner portion of the test fixture contained a moisture-activated dye that would indicate if the o-rings had remained sealed. The fully encapsulated test fixture was sent to Maxbar, Inc. and placed in the custom pressure vessel. The pressure vessel was steadily increased from 0 to 20,000 psi and cycled 50 times. The assembly was shipped back to Dexter Magnetic Technologies for evaluation. Upon inspection, the o-rings had not allowed any fluid inside the housing. Further inspection of the o-rings revealed that the seals had not been extruded, a common fear in the design of high-pressure systems.

Figure 59: O-Ring Pressure Test Fixture

The second pressure test conducted was for confirmation of the structural integrity of the stator assembly within the permanent magnet generator. The stator assembly is composed of a welded laminate stack and a vacuum-epoxy-filled Inconel housing. At 20,000 psi, the outer shell of the housing would deflect and make contact with the epoxy and laminates. It was theorized that without any voids in the epoxy, the assembly would stay intact and suffer no performance-degrading deformation. The assembly was sent to Maxbar, Inc. and placed in the custom pressure vessel. The pressure vessel was steadily increased from 0 to 20,000 psi and cycled 50 times. The assembly was shipped back to Dexter Magnetic Technologies for inspection. Upon inspection, there were two areas of deformation.

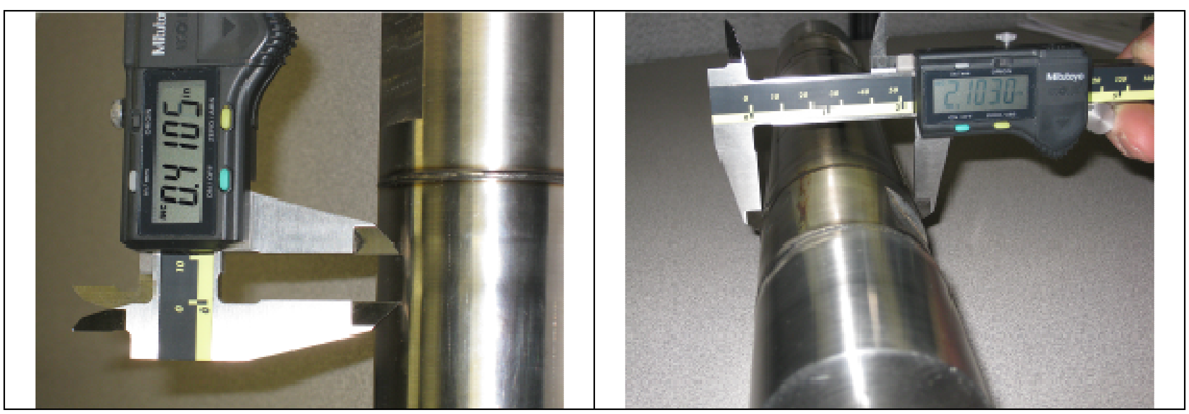

Figure 60: Stator Deformation

Figure 61: Cross-Section of Stator Assembly Post Pressure Test

The housing had yielded in the area that contains no laminates. The outer sleeve of the housing compressed in an area that contains strictly epoxy. The deformation was approximately 0.050" diametrically and did not cause any damage to the laser welds. Each of the three phases, two control windings, and the neutral lead were tested with a megaohmeter to verify that none of the wires had short circuited to the housing. The resistance of the wires remained the same as the pretested values. No short circuits were detected to the housing or line-to-line.

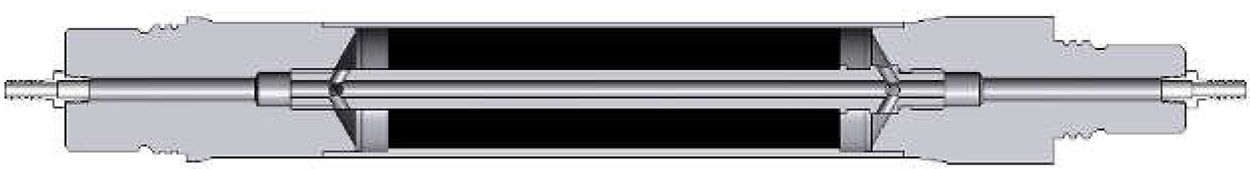

Figure 62: Stator Assembly Cross-Section

The deformation in the stator assembly can be reduced or eliminated by adding support to the area that contains only epoxy. This would be primarily for cosmetic purposes.

The HPHT Turbine Generator had to be placed inside of the high-temperature fixture to ensure that 200 watts of power could be produced at 250 ℃. The resistance of the copper windings increases with temperature. Concerns about the epoxy used to fill the stator assembly containing the lamination stack and windings also had to be nullified. Thermal expansion of the fully-dense carbide bearings was another area of design that needed to be verified. Each bearing was shrink-fitted into or onto a metal component. Thermal expansion coefficients for carbide vary depending on the elements from which it is composed.

The results of the high-temperature test are shown in Table 2 below. At room temperature, the system is able to produce approximately 340 watts at the low end of the RPM range. At the upper end of the RPM range, over 750 watts are produced. The amount of power produced at room temperature is extremely high when compared to the power requirement of 200 watts. When operating at 250 ℃, the power output is betwe en 200 and 475 watts. At the low end of the RPM spectrum the target power production is just reached.

RPM	Load (Ω)	VDC (23 °C)	Watts (23 °C)	VDC (250 °C)	Watts (250 °C)
667	9.8	25.4	65.7	16.5	27.8
983	9.8	34.9	124.4	24.6	61.8
1077	9.8	37.8	145.4	27.1	74.8
1227	9.8	42.3	182.4	30.9	97.2
1334	9.8	45.5	211.4	33.7	115.9
1459	9.8	49.3	247.9	36.7	137.7
1526	9.8	51.3	268.7	38.4	150.1
1660	9.8	55.4	312.7	41.8	178.3
1740	9.8	57.9	342.1	44.0	197.6
1800	9.8	59.7	363.7	45.5	211.3
2000	9.8	65.6	439.1	50.6	261.3
2200	9.8	71.7	524.6	55.7	316.6
2400	9.8	77.6	614.5	60.8	377.2
2700	9.8	87.0	772.3	68.4	477.4

Table 5: Power Output at 250 °C

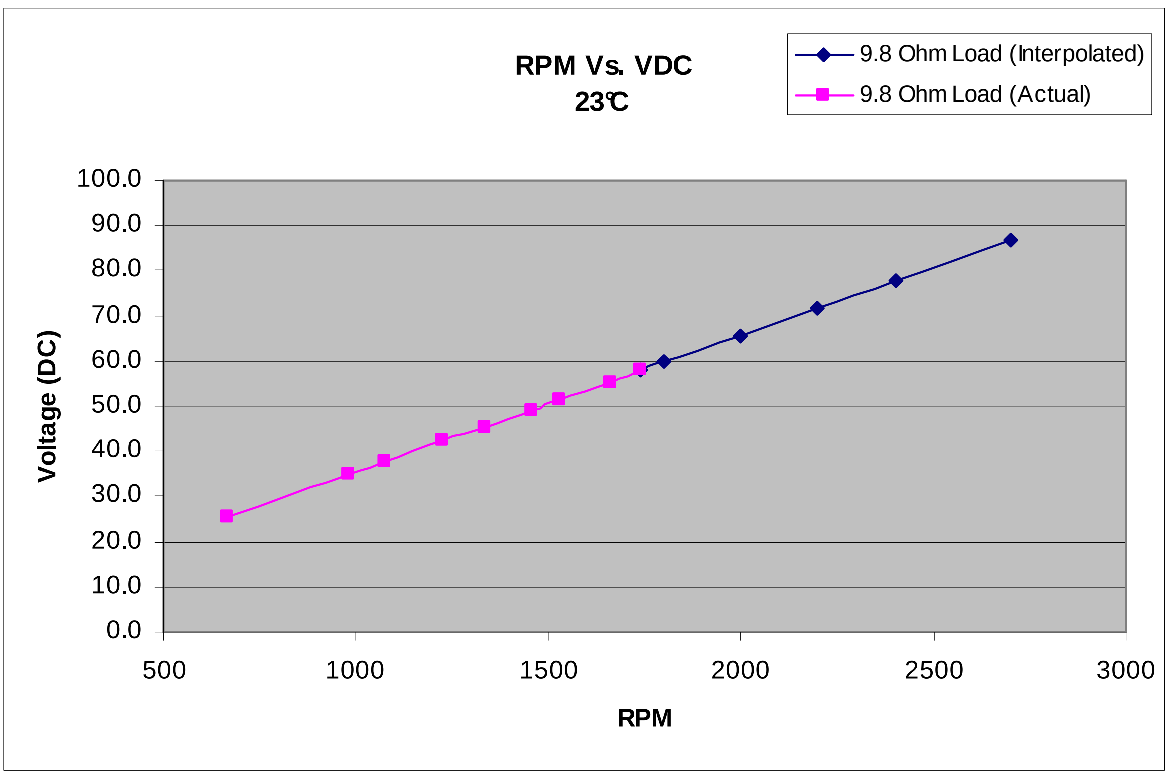

Figure 63: RPM vs. Voltage @ 23 °C

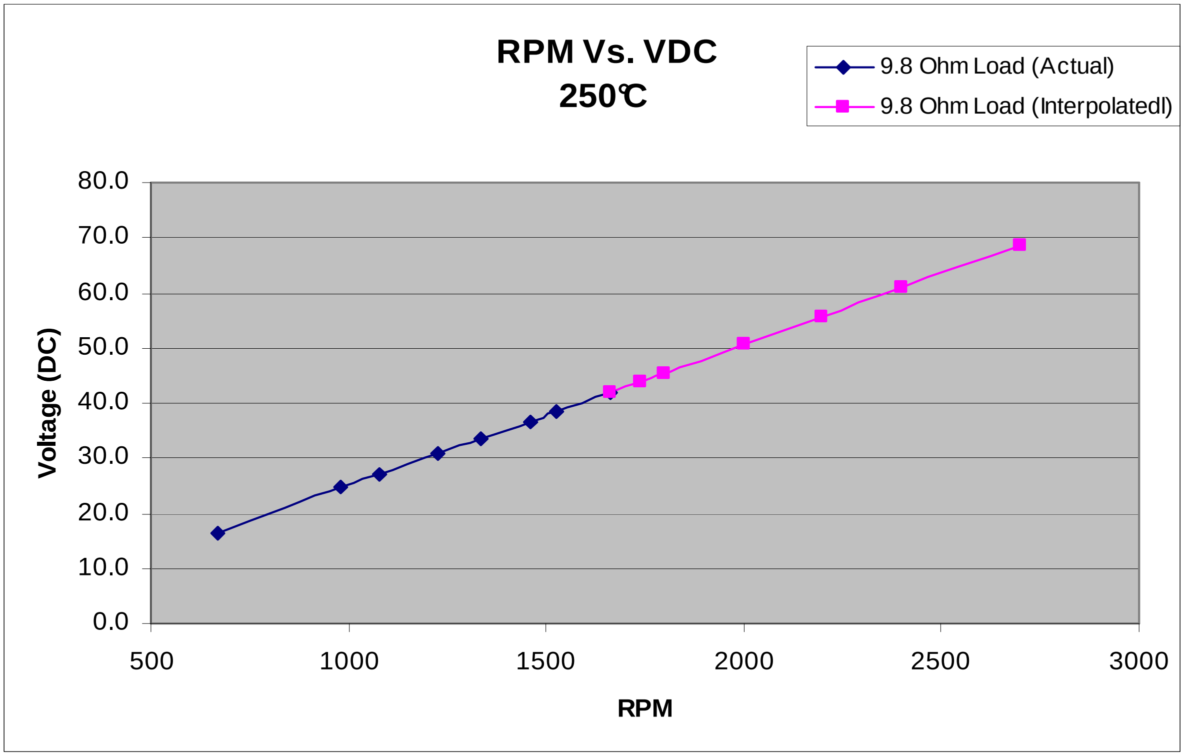

Figure 64: RPM vs. Voltage @ 250 ℃

Periodic inspection of the tool as the temperature was increased did not indicate that there were any problems with the interference of the shrink fit on any of the fully-dense carbide bearings. Once the test was completed the entire HPHT Turbine Generator was inspected for any signs of damage. The permanent magnet generator was probed to identify any short circuits that may lead to a system failure. There were no short circuits in the tool. The one minor failure identified was a cracked laser weld. Upon further inspection, the material beneath the welded housing was made manufactured from aluminum rather than a stainless steel. The other components in the assembly were made from different grades of steel and Inconel. The coefficient of thermal expansion is significantly higher for aluminum than steel or Inconel and thus, the force exerted from the varying degrees of expansion most likely caused the crack in the laser welded assembly **shown in Figure 67**.

Figure 65: Rotor Assembly

Figure 66: Crack in Laser Weld

The aluminum has been removed from the assembly and was replaced with Inconel. The problem has not since occurred.

After all preliminary mechanical design tests had been completed, areas of redesign were addressed and the final version of the prototype was created. This prototype was endurance tested in Dexter Magnetic Technologies' Elk Grove, Illinois drilling fluid flow loop. The HPHT Turbine Generator was tested for over 100 hours at 350 GPM in 1.5% sharp sand by weight.

The results of the endurance test proved that the tool was quite resilient under the conditions of the flow loop. The turbine generator experienced no failures and the wear on the disposable components was far less than expected. The turbine blades had lost minimal amounts of material ensuring that a 200-hour life would be achievable even without a hexavalent chrome plating operation. The diverters had maintained their respective forms and showed mild "pitting" around the components. The one exception was an unusual wear pattern found on the shaft bearing and an area of the permanent magnet stator **shown in Figures 67 & 68 below**.

Figure 67: Wear on Stator Assembly

Figure 68: Wear on Shaft Bearing

The fully dense-carbide bearings had shown approximately 0.004" on the upper diverter and 0.015" on the shaft bearing. The increased wear on the shaft bearing, as well as the stator, was due to operation in a horizontal position in unison with insufficient drilling fluid flow through the bearing. As previously stated under **Task 9: Bearing Design (Journal and Axial)**, the outlet opening had to be adjusted to increase the fluid flow. The increased fluid flow acted as a barrier between the two fully dense carbide races. After 25 more hours of operation, the increased fluid flow prevented further damage to the respective components.

As the last task of Phase II, the General Mechanical Overview has identified the areas of the tool that need improvement and areas that can be redesigned to be more cost effective. At this point in the prototyping phase, maintenance issues have been acknowledged and improved wherever possible.

Task 15: Supplemental Battery Charge / Heat Circuit

The criteria affecting the supplemental battery charge of the tool consist of the following:

- Ability to Operate at Temperatures of 0℃ to 250 ° C
- Ability to Operate at 20,000 psi
- Ability to Supply 200 Watts
- Ability to Fit Within a Pressure Housing

Dexter Magnetic Technologies has been working with Electrochemical Systems, Inc. on the feasibility of incorporating a lithium ion battery with the HPHT Turbine Generator. Josip Caja of Electrochemical Systems, Inc. has been the primary contact for Dexter Magnetic Technologies to obtain updates and information regarding the development of the lithium ion batteries.

The proposed battery module from Electrochemical Systems, Inc. would consist of 18 DD size cells stacked in series. The lithium ion cells would be approximately 90.00" long and would remain functional for 100 amp-hours. The pressure housing would be similar to the design of the electronics housing. Both must withstand an ambient environment of 20,000 psi. The operational temperature range for the cells is 150 °C to 220 °C . This poses a problem for battery use in lower-temperature environments.

As of March 3, 2010, all companies involved in the development of high temperature lithium ion batteries had not resolved issues allowing a field test. Until these issues are resolved, the batteries will not be tested in a downhole environment.

A number of other companies have been contacted, however, finding a lithium ion cell that is capable of operating at high temperatures and high pressures has proven to be very difficult.

Phase II of the project has been successful in meeting the stated tasks of:

- Designing a system capable of supplying 200 watts of power at 250 °C and 20,000 psi
- Designing a system capable of operating for a minimum of 200 hours without requiring maintenance
- Manufacturing two (2) HPHT Turbine Generator prototypes
- Manufacturing two (2) high temperature rectification / regulation circuits
- Preparing the prototypes for a supplemental module for power storage

Identifying Partners for Downhole Testing

Prior to initialing Phase III of the project, Dexter Magnetic Technologies had made a requirement to locate a company to collaborate with in downhole testing. If no partner could be found, the project must be terminated. The following leads had been established:

Halliburton

Christopher Golla
Electronics Excellence Manager
christopher.golla@halliburton.com

Initially Ron Dirkson, Global Reservoir Solutions Manager for Halliburton, was contacted with a request to test DMT's HPHT Turbine Generator. Mr. Dirkson referred DMT to the guidance of Christopher Golla, the Electronics Excellence Manager. Mr. Golla requested test results and data from the tool which have been promptly sent to him. Halliburton has developed internal hardware to address their HPHT power requirements; however, they are very interested in the reliability of DMT's high-temperature rectification and regulation circuitry.

In recent years Halliburton's Drilling and Evaluation Division has partnered with Total S.A. to design and manufacture ultra-high-temperature measurement-while-drilling (MWD) systems. The project, titled "Project Victoria," will take place in the Victoria field of the North Sea. The companies are claiming to utilize "industry-first" technology to extract hydrocarbons from environments with ambient temperatures of 450 °F. The project is scheduled to begin in the fourth quarter of 2010.

Schlumberger

Vladimir Vaynshteyn
Project Manager of DOE DE-PS26-03NT41835 Development of High-Pressure High-Temperature MWD Tool
vvaynshteyn@slb.com

Mr. Vaynshteyn was contacted on January 27th, 2010 and supplied with information about the HPHT Turbine Generator. Mr. Vaynshteyn has been placed on another project and our information has been supplied to his successor. DMT was advised that we would be contacted by the new manager of the high-temperature LWD and MWD division. To date, DMT is awaiting further contact.

Weatherford

Grant Affleck
Business Development Manager
Co-Author of "Innovating While Drilling"
grant.affleck@eu.weatherford.com

Mr. Affleck was contacted on January 27th, 2010 with information and specifications regarding the HPHT Turbine Generator. Throughout the correspondence several questions were answered regarding the lower end of the operating temperature. The technology is of interest at Weatherford and DMT is awaiting further contact.

In light of these communications, it is the belief of Dexter Magnetic Technologies and its associates that an Industry Partner will be established in the near future. The criteria for selection will need to include:

- Drill String Diameter

- Maximum Ambient Temperature
- Maximum Ambient Pressure
- Sand Content
- Equipment to Accept Power
- Duration of Operation
- Date of Access

Halliburton is a customer of Dexter Magnetic Technologies and currently appears to be the most qualified and most willing to participate in the field testing of the HPHT Turbine Generator.

The original Statement of Project Objectives had included an agreement between Noble Drilling and Dexter Magnetic Technologies to participate in downhole testing. Noble Drilling withdrew from the project prior to Phase II. Halliburton, Schlumberger and Weatherford have all been contacted, repeatedly, with requests to operate the tool downhole in exchange for data collected during operation. All of the companies were intrigued by the technology, but were unable to pair the HPHT Turbine Generator with an existing tool requiring power in “extreme” environments.

Dexter’s presence at the 2010 Offshore Technology Conference verified the conclusion that sensor design for harsh drilling conditions have not advanced to operating temperatures of 250 ℃. With sensors for Measure While Drilling (MWD) and Logging While Drilling (LWD) being the primary market for downhole power generation, the likelihood of testing the HPHT Turbine Generator within a realistic timeframe is improbable. Rather than continuing to invest more time and money from both Dexter Magnetic Technologies and the Department of Energy by initiating Phase III, the decision was made to terminate the project.

Project Conclusion

A number of technological advances have emerged as the result of the collaboration between Dexter Magnetic Technologies and the National Gas & Oil Program at the NETL. Feasibility of the project was met in Phase I. Prototypes of the High-Pressure High-Temperature (HPHT) Turbine Generator were manufactured and tested in laboratory conditions during Phase II of the project. As Phase III approached, an industry partner could not be identified to assist in testing the HPHT Turbine Generator in a true 20,000 psi environment with an ambient temperature of 250 ℃.

Dexter Magnetic Technologies appreciates the opportunity granted by the Department of Energy and, as discussed, will accredit the Natural Gas & Oil Program at the NETL for assisting in the development of the project.

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