

## Development of a HT Seismic Downhole Tool

J.A. Henfling, Jeff Greving, Frank Maldonado, David Chavira, Yarom Polsky, Jim Uhl

Sandia National Laboratory, Albuquerque, New Mexico 87185-1033

Email – jahenfl@sandia.gov

**Keywords:** HT, SOI, EGS, seismic, microseismic, downhole

### ABSTRACT

Enhanced Geothermal Systems (EGS) require the stimulation of the drilled well, likely through hydraulic fracturing. Whether fracturing of the rock occurs by shear destabilization of natural fractures or by extensional failure of weaker zones, control of the fracture process will be required to create the flow paths necessary for effective heat mining. As such, microseismic monitoring provides one method for real-time mapping of the fractures created during the hydraulic fracturing process. This monitoring is necessary to help assess stimulation effectiveness and provide the information necessary to properly create the reservoir. In addition, reservoir monitoring of the microseismic activity can provide information on reservoir performance and evolution over time. To our knowledge, no seismic tool exists that will operate above 125°C for the long monitoring durations that may be necessary. Replacing failed tools is costly and introduces potential errors such as depth variance, etc. Sandia has designed a high temperature seismic tool for long-term deployment in geothermal applications. It is capable of detecting microseismic events and operating continuously at temperatures up to 240°C.

This project includes the design and fabrication of two High Temperature (HT) seismic tools that will have the capability to operate in both temporary and long-term monitoring modes. To ensure the developed tool meets industry requirements for high sampling rates (>2ksps) and high resolution (24-bit Analog-to-Digital Converter) two electronic designs will be implemented. One electronic design will utilize newly developed 200°C electronic components. The other design will use qualified Silicon-on-Insulator (SOI) devices and will have a continuous operating temperature of 240°C.

### 1. INTRODUCTION

Many geothermal sites in this country have not reached full economic potential because they lack adequate fluid production. DOE has a renewed interest in developing geothermal energy by utilizing Enhanced or Engineered Geothermal Systems (EGS). EGS technology enables geothermal energy to be extracted from the earth's crust in areas with higher than average heat flow but where the natural permeability or fluid content is limited. One of the key factors in the development of EGS is successfully creating adequate fractures between the injections and production wells to enable commercially viable power to be generated. Induced fractures can result in many undesirable scenarios (such as loss of fluid, etc.) that can severely impact the performance of the well. Real-time mapping of fractures during stimulation will enable insight into the direction of the propagating fractures and will help guide the stimulation procedure. This initial mapping also provides a reference that can be used to help maintain optimal performance over the life of the well. By comparing the initial fracture map

with data from periodic or continuous downhole monitoring, the well's "health" can be determined and corrective actions can be taken to help extend the life of the well. Clearly, real-time mapping during stimulation and microseismic monitoring are critical components in developing and maintaining geothermal power plants utilizing EGS technology. Geothermal wells often exceed the temperature limits of commercially available seismic tools. As such, a high temperature seismic tool is needed to help the advancement of EGS technology.

### 1.1 Program Objective

The program objective is to design, fabricate and field test two HT seismic tools in an EGS application. The developed tools will leverage our previously developed and field tested SOI-based well monitoring tool suite. Also, it is imperative to partner with an American-based company early in the development of the tool. This helps to ensure it will meet industry needs and establishes a clear path to commercialization. We have teamed with Pinnacle Technologies and the initial field test will be at their test facility.

### 1.2 Scope of Work

This project includes the design and fabrication of two HT seismic tools that will have the capability to operate in both temporary and long-term monitoring modes. To ensure the developed tool meets industry requirements for high data rates (>2ksps) and high resolution (24-bit Analog-to-Digital Converter) two electronic designs will be implemented. One electronic design will utilize newly developed 200°C electronic components. These components will meet the high data rate and high resolution requirement set forth by industry. The other electronic design will use qualified SOI devices and will have a continuous operating temperature of 240°C. The SOI based electronics should operate for years at 240°C but will have a considerably lower data rate (100 sps) and lower resolution (18-bit Analog-to-Digital Converter); this tool will be based on our long-term monitoring tool and the 240°C electronics package will utilize some of the HT SOI components that were developed for the Deep Trek JIP (Joint Industry Partnership).

### 2. PROJECT DETAIL

Work pertaining to the HT seismic tool project can be divided into the following subtopic areas: hardware, electronics and testing. The following subsections will discuss each of these areas in detail.

#### 2.1 Hardware

The hardware design consists of the clamping mechanism and the pressure housing to protect the electronics and sensors from the wellbore environment. The clamping mechanism is critical to the success of the tool. Without an adequate clamping mechanism, the data will not truly represent the seismic events. If the tool is not solidly coupled to the formation, it may have a structural resonance

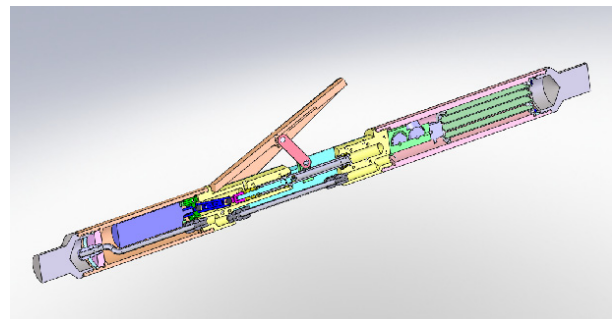
that could act as a “tuning fork”. When the tool is excited with seismic energy, these resonance modes can potentially cause spurious vibrations within the tool. These modes are detected by the sensor and cause narrow-band signals to occur at the natural frequencies of the modes. Consideration of these issues has been addressed in the design. The high temperature seismic tool is based on the low temperature seismic tool that was developed many years ago by Sandia. This tool used a piston type clamp actuator as shown in figure 1. The developed tool was fielded and a modified version was commercialized with OYO Geospace and is shown in figure 2. It is the basis for the tool presently used by Pinnacle Technologies. Many of the software algorithms that Pinnacle uses today are based on the field data from these tools. While the hardware design from the previously developed seismic tool served as a beneficial starting point, modifications were required to account for high temperature operation and accommodate industry needs. Two significant changes from the original design are: 1) Swing arm clamp instead of the piston actuator. This change enables the design to include a safety releasing feature to ensure the tool can be safely removed from the well in the event the power to the tool is compromised. In high temperature applications cablehead issues often result in the loss of power to the tool. Thus, the safety releasing feature is highly desirable by industry. 2) Metal face seals and welded electrical feedthroughs in the electronic/sensor section of the tool. This enhancement will eliminate elastomer seals as the primary sealing mechanism. While elastomer-only sealing systems are utilized successfully in short-term, low-temperature tools, this type of design is not adequate for high temperature applications. The Solid Works drawing in figures 3 and 4 shows the swing arm clamp. The arm can also utilize a “shoe” to increase the contact area with the wellbore. The estimated maximum clamping force is > 1000 lbs based on the design of the clamping mechanism and the selection of the motor, gearhead and jack screw. It is believed (based on previous lab and field tests) a clamping force of approximately 5 times the weight of the tool is required to adequately couple the tool (seismic sensors) to the wellbore wall. The estimated tool weight is 40 lbs and as such a minimum force of 200 lbs is required. The next step is to fabricate hardware to verify the clamping forces and to evaluate its performance at temperature. Drawings are finalized and we expect to have hardware fabricated by July. In parallel with this effort is a feasibility study to determine if strain gages can be integrated into each arm. While this is not imperative to the design, it would provide a means to confirm the tool is properly clamped.



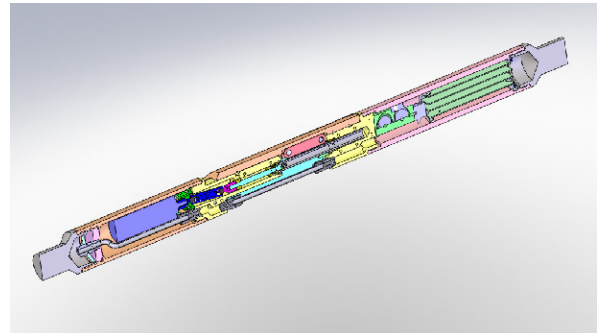
**Figure 1: Sandia-designed prototype seismic tool.**



**Figure 2: Sandia-designed seismic tool commercialized with OYO.**



**Figure 3: Pressure housing; shown with clamping arm open.**

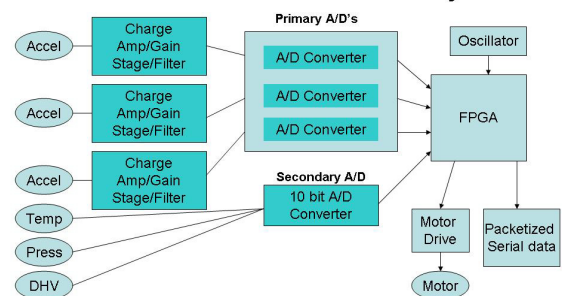


**Figure 4: Pressure housing; shown with clamping arm closed.**

## 2.2 Electronics

The electronic package consists of sensors, signal conditioning and filter circuits, analog-to-digital converters, motor control circuits, power conditioning circuits, data transmit circuit and a Field Programmable Gate Array (FPGA). The FPGA is the “heart” of the tool and it controls the data collection, data transmission and motor functions. A block diagram of the electronics package is shown in Figure 5. Details of the electronic package are highlighted in the following subsections.

### Seismic Tool General Layout



**Figure 5: Block diagram of the electronic package.**

### 2.2.1 Seismic Sensor Background

The seismic sensor, along with the associated signal conditioning circuits and the analog-to-digital converters (discussed later) are the important elements of the electronics design. By definition, seismic sensors require extreme sensitivity and must be appropriately rugged to survive the rigors of tool deployment. As one might imagine as a device is made to respond to microseismic activity, compromises are necessary and the end result is a reduction of shock survivability. In other tool applications, shock

sensitive sensors or components can be protected by shock-mounting the sensor or component in such a way as to isolate it from being in direct contact with the tool housing. In this application however, the sensor must be coupled to the wellbore wall and as such, the sensor is hard-mounted to the housing. In other words, the sensor will be subjected to the same shock loading as the housing. During deployment this shock loading could be quite high. The sensor must not only meet the shock survivability and sensitivity criteria, it must also have acceptable performance over a wide temperature range. While there are low temperature seismic sensors available that have built-in signal conditioning circuits, no high temperature counterpart exists. As such, all signal conditioning circuits must be designed using high temperature components and should be physically co-located with the sensors. The following specification highlights the properties of an ideal seismic sensor:

- Resonant frequency > 3 KHz
- Operational frequency range - DC to 2 KHz
- Maximum operating temperature range > 240°C
- Sensitivity > 50ug
- Low cross-axis sensitivity
- Shock survivability > 5000 g

Unfortunately, no commercially available seismic sensor can meet the specifications listed above. The funding for this project is not adequate to design and fabricate a custom sensor that might meet the above specifications. For this project we will be using a commercially available sensor with acceptable performance characteristics. Currently there are two choices for high temperature seismic sensors. They are: 1) geophone (OYO Geospace SMC1850) and 2) HT accelerometer (Endevco 7201-100 and 7703A-1000 accelerometers). Note: In the previously developed seismic tool, the Wilcoxon 731-20A accelerometer was utilized. This accelerometer is no longer available.

The SMC1850 geophone is best suited for detecting low frequency events (<100 Hz) and is prone to cross-axis sensitivity issues. It is rated to 200°C with limited life. The manufacturer does not have lifetime data at 200°C, but many years ago it was successfully tested to 600 hours. The manufacturer has provided a test unit and as part of the test plan for this year, Sandia will be performing a life test with this unit. The data and the test unit will be returned to the manufacturer to help improve the reliability and life of the sensor. The geophone also does not have a shock survivability rating. The manufacturer believes the shock rating is approximately 250 to 500 g, depending on the orientation.

The Endevco 7201-100 and the 7703A-1000 piezoelectric accelerometers have an operational frequency of 1 to 8 kHz and 1 to 3 kHz respectively. By design, accelerometers are considerably less prone to cross-axis sensitivity (provided a good mechanical alignment is maintained within the housing). Both are rated to operate up to 260°C. The manufacturer does not have lifetime data but Sandia has tested the 7201-100 for 1000 hours. Both of these sensors will be included in the life tests stated above and the data will be provided to Endevco.

The Endevco 7201-100 has a sensitivity of 100 pC/g and a maximum shock limit of 5000 g. The Endevco 7703A-1000 has a sensitivity of 1000 pC/g and a maximum shock limit of

1000 g. In general, it is desirable to utilize sensors with the greatest sensitivity. This reduces the requirements on the signal conditioning circuits. In high temperature applications where component selection is limited, a wide operating temperature range is required, and signal conditioning circuits may be separated from the sensor, high output sensors are extremely desirable.

Shock sensitivity can be an issue with piezoelectric accelerometers. Piezoelectric material has a tendency to fracture or completely break when the sensor mechanical shock limits have been exceeded. The acceleration levels and frequency may also excite the sensors resonance frequency, thus possibly resulting in damage to the sensor material. When shock frequencies excite the mechanical resonance of the sensor, approximately 1/100<sup>th</sup> of the “rated” shock load could damage the sensor.

From previous experience, shock survivability is an important parameter to consider in selecting a seismic sensor. For example, the previously designed low temperature seismic tool utilized the Wilcoxon 731-20A piezoelectric accelerometers. They have a maximum shock limit of 200 g peak, and were critically damaged when pulling out of a cased hole at a rate greater than 50ft/min. (This deployment rate would also apply during the insertion of the sonde downhole).

While the Wilcoxon 731-20A will not be used in this tool due to its availability and shock sensitivity, it will be included in the lab tests for comparison purposes. During the development of the Sandia seismic tool several years ago, this sensor had adequate sensitivity and was successfully tested at 200°C but no life tests were performed.

### 2.2.2 Sensor Selection

Based on preliminary evaluations of the available sensors, the prototype seismic tool will use the Endevco 7703A-1000. While this will be the “sensor of choice”, the critical signal conditioning circuits are designed to interface to either the Endevco 7702-100 or the Endevco 7703A-1000. As new sensors become available and are proven to have acceptable performance (adequate sensitivity, frequency response, ruggedness, and low cross-axis sensitivity) over the desired temperature range, they will be incorporated into the developed HT seismic tool.

### 2.2.3 Electronic Boards

As stated earlier, two electronic packages are being developed. One electronic design will utilize newly developed 200°C electronic components. The other electronic design will use qualified SOI devices and will have a continuous operating temperature of 240°C. The 200°C electronic package will utilize 200°C components from Texas Instruments and/or Texas Components. While these components are not SOI and will have a limited life (<1000 hours at 200°C) they will enable us to design an electronics package that will better meet current industry needs. The design will utilize high resolution, fast (>2 kHz), 24 bit analog-to-digital converters (ADC) and will aid in resolving ug seismic data. The second electronic design will use qualified SOI devices capable of operating continuously at temperatures up to 240°C. The SOI based electronics should operate for years at 240°C, but will have a considerably lower data rate (100 Hz) and lower resolution (18-bit ADC). The SOI electronic package will be based on our long-term monitoring tool, but will utilize some of the HT SOI components that were developed for the Deep Trek JIP. The additional components include a vastly improved

operational amplifier, 18-bit ADC, EEPROM (Electrically Erasable Read-Only Memory), and a Field Programmable Gate Array (FPGA). Unfortunately, issues were discovered regarding several (but not all) of the components developed for the Deep Trek JIP. The 18 bit A/D converter and the precision OP amp will perform adequately for this application and are being used in the electronics design. The FPGA and EEPROM have issues and will not be available as packaged parts in the near future. Fortunately a MultiChip Module (MCM) was developed for the National Energy Technology Laboratory (NETL). It is referred to as the Reconfigurable Processor for Data Acquisition (RPDA) and contains the HT FPGA, HT EEPROM memory and HT SRAM (Static Random Access Memory). Once delivered to NETL, a joint program to evaluate this module will be initiated (late June). If this module performs satisfactory and time permits, it will be integrated into the electronics design. This module is one of the workaround options for the FPGA/EEPROM (see below for details). It is worth noting that the improved op amp's performance is excellent and it is now available as a packaged device from Honeywell. All of our tests to date indicate the op amp performs well up to 260°C and is still functional up to 350°C.

#### 2.2.4 Workaround for Honeywell FPGA/EEPROM

Since we do not have a packaged solution for the Honeywell FPGA and EEPROM, workarounds have been defined and are based on the intended operating temperature of the tool. As stated previously, two electronic packages will be designed. The 200°C electronics package will use the Actel FPGA. This device will operate at 200°C for 1000 hours. The 240°C SOI based electronics package will use: 1) RPDA module developed for NETL or 2) HT chipset which includes the Sandia-developed SOI ASIC (Application Specific Integrated Circuit). If the HT chipset option is utilized, the tool program will be stored in volatile memory and as such, the program will require reloading upon power failure.

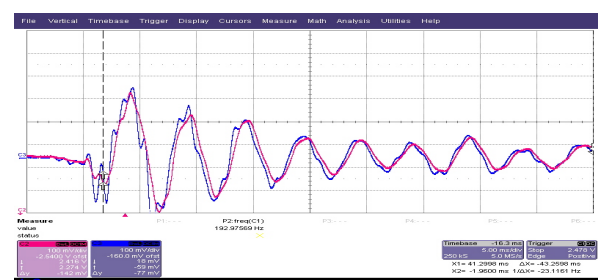
Along with the seismic sensor and the signal conditioning circuits, a high resolution A/D converter is required to adequately convey the seismic data. In the 240°C SOI based electronic package we only have one option for an A/D converter. Obviously, the design will use this device. On the other hand, we have two A/D converters available that are rated to operate at 200°C. One is newly available from Texas Instruments and the other is available from Texas Components. The specifications for both appear to be adequate for this application. A noise floor study is currently underway and will include all three A/D converters. This study will provide insight as to the maximum achievable resolution of the system and will help determine the final design for the signal conditioning circuits. Also, it will help to define the requirements of the seismic sensor, both present and future. The ADCs will be tested in 10 degree increments from 20 to 250°C. The measurements will include the signal to noise ratio (SNR) and the harmonic free noise floor for each temperature and each converter. Table 1 compares and summarizes the common characteristics of the three ADCs. For those ADCs with more than one differential input, only one input will be used. Only the SPI port(s) of the ADCs will be used for communication and programming. All power and reference voltages will be derived from battery systems to eliminate noise and ripple. Each ADC will be operated at the sampling rate shown in Table 1. High temperature polyimide printed circuit boards (PCB) have been designed and fabricated. Each PCB will provide EMI/RFI shielding around the ADC in an effort to reduce external noise. At the completion of the series of tests outlined above, a plot will be generated of the output noise

spectrum. Also, the SNR and the harmonic free noise floor for each ADC at each temperature will be calculated. As stated earlier, the results of this study will determine the final design for the electronic packages.

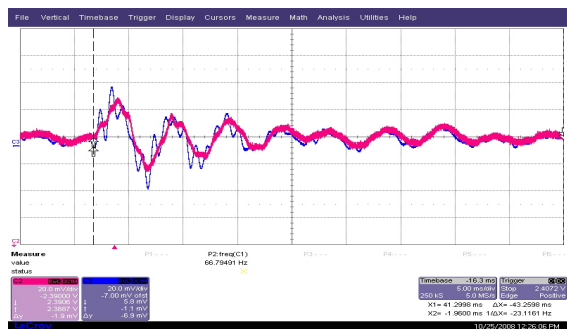
**Table 1: Comparison of HT analog-to-digital converters**

ADC	Analog Inputs	Outputs	Voltages	SNR
<b>HTADCSD1 8 18 Bit ADC</b>	<b>1</b>	1 SPI Port	+5V Digital, +5 V Analog; using internal Voltage Ref.	Target 108 dB at 100 Samples per second
<b>ADS1278 24 Bit ADC</b>	<b>8</b>	1 SPI Port & 1 JTAG Port & 9 Control Lines	+1.8V Digital, +5V Analog, 3.3V I/O; using external 2.5 Voltage Ref.	111 dB at 52,000 samples per second
<b>TX424 24 Bit ADC</b>	<b>4</b>	2 SPI Ports & 3 Control Lines	+5V digital, +5V Analog, -5V Analog; using internal Voltage Ref.	127 dB at 4000 samples per second

Preliminary signal conditioning, voltage regulator, and voltage reference designs are complete for both the 200°C and the 240°C electronic packages and HT test boards have been fabricated. Since Spice models for the HT components do not exist, boards must be fabricated to properly evaluate a design. In the future, Spice models should become available for HT components and will aid in verifying circuit design prior to the fabrication of printed circuit boards. The fabricated HT test boards have several circuit design options, and at the completion of the tests, the best performing circuits will be integrated into the final electronics design. The evaluated subsystems include: three charge amp circuits, three post amplifiers, three low pass filters, voltage regulation and reference circuits, Actel FPGA and 24 bit Analog-to-Digital converters. The graphs in figures 6 and 7 compare the response of an Endevco 87-1 COTS seismic sensor (unfiltered, with a 10X amplifier; 10V/g sensitivity) and the HT signal conditioning circuit with the Endevco 7703A-1000 sensor (filtered; charge amp with an additional 10X amplification stage; 10V/g sensitivity). The blue trace is the COTS seismic sensor response and the red trace is the HT sensor/signal conditioner. The results are encouraging. Even in an open (unshielded) setup, it is evident that an acceleration level of less than 2mg can easily be detected. In a shielded setup, one would expect a factor of approximately 50 – 100 improvement in sensitivity.



**Figure 6: A graph comparing the output of a low temp seismic sensor to the HT seismic sensor with the HT signal conditioning circuits with a 50 mg vibration test.**



**Figure 7: A graph comparing the output of a low temp seismic sensor to the HT seismic sensor with the HT signal conditioning circuits with a 4mg vibration test.**

## 2.3 Testing

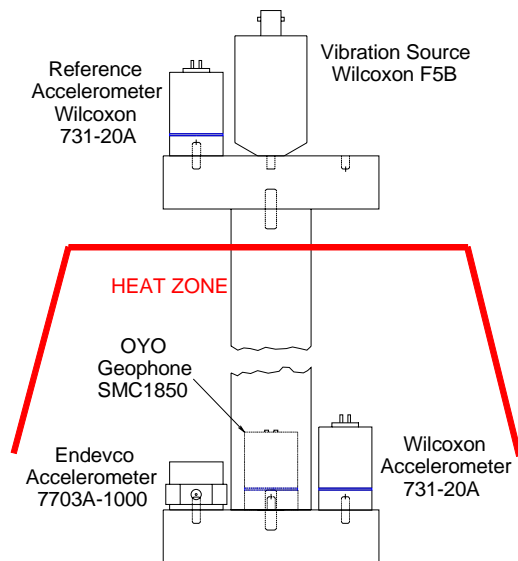
### 2.3.1 Subsystem Lab Evaluations

In parallel with the hardware design, A/D converter noise floor study, signal conditioning and sensor work, a low level vibratory system has been fabricated. This system enables us to provide a low level, variable frequency vibratory source to the seismic sensors at temperature. The signal conditioning circuits and the sensors are heated. The vibration source and the reference accelerometer are located outside the oven. A sketch of the system is shown in figure 8. Several tests were conducted to evaluate the performance of the accelerometers, charge amplifiers, filters and other critical subsystems at temperatures up to 240°C. Figures 9 and 10 show the results of two of the tests at 200°C using a 45 Hz and 1kHz vibration source.

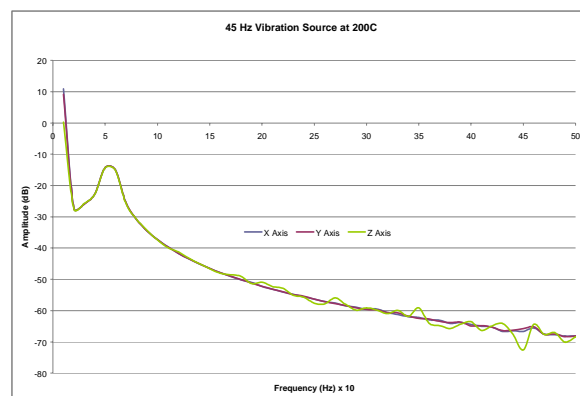
### 2.4 Field Testing Test Plan

Sandia is presently working with Pinnacle Technologies to outline the details of a joint field test at their facility. Pinnacle has a test well designed to evaluate and qualify seismic systems and a joint test will enable us to compare our developed tool with a commercial system. The results of this initial test will provide feedback to ensure the developed system meets the requirements of industry and helps ready us for fielding the system in a geothermal well. Pinnacle Technologies is supportive of this project and has provided us with hardware (Sandia-designed hardware that was commercialized with OYO) to use as a basis for the high temperature design. The existing test plan is to deploy the developed HT tool below their tool string and to run a series of calibration shots to learn if our tool is comparable to their existing system. Pinnacle's seismic system will provide our tool with power to operate the clamp and the electronics. It will also send a signal to indicate the start of a test, at which time our seismic tool will operate as a stand-alone system with the capability of storing data in the tool. Due to the high data rate requirement, a large memory capacity is needed. Although this is not possible in a HT environment, we have designed a low temperature 8GB memory data logger that will be adequate for this initial test. After the completion of this test, we will move forward to fielding the tool in a HT EGS well. The first step would be to develop a high speed data link using HT components. Ideally the data link would use a fiber optic driver. While currently a HT fiber optic driver does not exist, it is a topic being considered for development. A non fiber optic based high speed data link may initially be designed until a HT fiber optic driver is available. The high speed data link is currently being evaluated and options are being identified, but the bulk of the work will not begin until late in 2009.

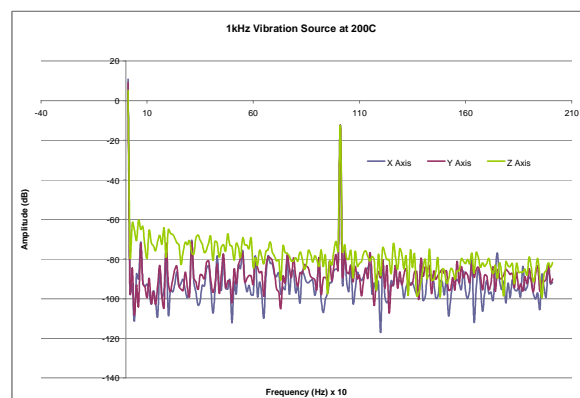
Once complete, the EGS field test will provide a real world opportunity to evaluate the developed system.



**Figure 8: This picture shows the lab subsystem evaluation setup.**



**Figure 9: Chart depicting the accelerometer response at 45 Hz and 200°C**



**Figure 10: Chart depicting the accelerometer response at 1kHz and 200°C**

In order to adequately field a HT seismic tool string, a minimum of three levels (three tools separated by 50 to 100 feet of cable) are normally utilized. If the developed tool is fielded successfully, a minimum of three additional tools will be required (two additional tools and one spare). If



funding is secured to fabricate the additional tools, the tool string will be fielded in 2010.

### 3. CONCLUSION

This project is well on its way to completion. Unfortunately, funding issues slowed progress and as such details of the A/D noise study, fabrication of hardware and final HT board set were not complete by the due date of this draft paper. It is the intent to include these details along with additional lab tests and the results of the initial field test in the final paper.

In summary, a High Temperature Seismic Tool has been design and will be fielded in September of 2009. The hardware design is finalized and will be fabricated by July 2009. The electronics designs are complete and subsystems have been tested at temperatures up to 240°C with satisfactory performance. It is expected that the completed tool will meet the goals of this project.

### ACKNOWLEDGEMENTS

Sandia National Laboratories is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy under Contract DE-AC04-94AL85000.

### REFERENCES

- Warpinski, N.R, Branagan, P.T., Peterson, R.E., Fix, J.E. Uhl, J.E., Engler, B.P., and Wilmer, R.: Microseismic and Deformation Imaging of Hydraulic Fracture Growth and Geometry in the C Sand Interval, GRI/DOE M-Site Project, SPE, (1997).
- Warpinski, N.R, Uhl, J.E., and Engler, B.P.: Review of Hydraulic Fracture Mapping Using Advanced Accelerometer-Based Receiver Systems, SAND Report (1997)).