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PNNL-33581

Real-Time Seismic System for Monitoring, Imaging, and Characterization (RT-SEISMIC)

September 2022

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U.S. DEPARTMENT OF ENERGY

Prepared for the U.S. Department of Energy
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Richland, Washington 99354

Abstract

The goal of this Laboratory Directed Research and Development (LDRD) project was to develop a borehole seismic source and sensor array to enable real-time seismic imaging at scales and conditions relevant to the energy industry including both fossil-energy and geothermal.

In FY21 and FY22, we designed, built, and tested both a prototype impulse source module for generating seismic energy and a sensing module for recording ground motions generated by the source module array. A pneumatically driven vibratory source was also designed. The source modules were fabricated with all high temperature components and the team has worked to incorporate the current RT-SEISMIC electronics design into a commercially available, high temperature silicon-on-insulator chip integrated circuit.

Several issues were identified during fabrication and lab testing that led to redesign of several system components and subsequent retesting. The final round of testing showed that while metal/graphite-based seals worked quite well for static seals, they were unable to provide an adequate gas seal for dynamic, reciprocating part movements which necessitated a final redesign using Kalrez. This change will result in a continuous temperature rating of approximately 275 degrees C for the system.

While a field test of the RT-SEISMIC system was targeted in FY22, due to the extended lab testing and redesign efforts, field testing was not achieved. As a result of this LDRD investment, several sponsors have expressed interest in RT-SEISMIC and we expect to continue towards a field demonstration of the full system in the future.

Acknowledgments

This research was supported by the Energy and Environment Directorate (EED) Mission Seed, under the Laboratory Directed Research and Development (LDRD) Program at Pacific Northwest National Laboratory (PNNL). PNNL is a multi-program national laboratory operated for the U.S. Department of Energy (DOE) by Battelle Memorial Institute under Contract No. DE-AC05-76RL01830.

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1.0 Introduction

Most the world's energy resources are derived from the subsurface. Improvements in our understanding of subsurface processes would undoubtedly lead to advances in energy production and/or utilization. Real-time seismic imaging can enhance our understanding of subsurface processes.

We define real-time imaging as the ability to collect a complete set of seismic survey data more rapidly than the times scales at which subsurface processes of interest are occurring. Length scales up to 1 km, time scales on the order of an hour, and environmental conditions with temperatures up to 500 degrees C and pressures to 10 kpsi.

Real-time, high-resolution imaging requires that many energy sources be simultaneously deployed within an array of boreholes. Currently, borehole based seismic imaging is nearly always performed using a single energy source that is lowered into the borehole, energized, moved up/down to another location and the processed repeated. An array of sensors for detecting the seismic energy is deployed in either the same or an adjacent borehole. Data collected in this way can be used to produce an image of the seismic properties around/between the borehole(s). This process is time consuming and unable to adequately measure processes that rapidly alter the subsurface.

Several types of seismic sources have been designed and exist for the geotechnical or oil and gas markets but have not yet been incorporated into an array capable of real-time imaging at scales relevant to the energy industry (Barger & Hamblen 1980; Buogo & Cannelli 1999). To our knowledge, the only existing real-time seismic data acquisition system is the Continuous Active Source Seismic Monitoring (CASSM) designed and built by LBNL (Daily et. al 2007). CASSM has been used for several research applications. The fundamental limitation with this system is that the sources are piezoelectric based, and the strength is relatively week, unable to generate measurable seismic signals in most geologic settings beyond a few tens of meters. This limits the utility for most real-world applications. Existing sources are also not presently capable of continuous operation at temperatures relevant to many geothermal applications (>200 degrees C). RT-SEISMIC was designed to overcome these existing limitations.

In FY21 and FY22, we have designed, built, tested prototype RT-SEISMIC impulse source and sensing and control modules. A pneumatically driven vibratory source was also designed. Source modules were fabricated with all high temperature components. The current RT-SEISMIC sensing module electronics has been designed to make use of an existing high temperature silicon-on-carbide chip design to enable operation at up to 500 degrees C. Since the sensing-control module requires no moving parts, design of a high temperature housing was much simpler than for the source module.

2.0 RT-SEISMIC Design

RT-SEISMIC is composed of three major modules: 1) impulse source, 2) sensing and control, and 3) vibratory source extension. Each module required the design of several custom components. The overall design details are captured below.

2.1 Impulse Source Module

Major components of the impulse source module are shown in Figure 1: top cap, air piloted actuator, air shuttle, and firing chamber. In all of the following figures, colored arrows illustrate direction of motion for mechanical components that work to actuate the source: green indicates firing state and red indicates stable/non-firing state.

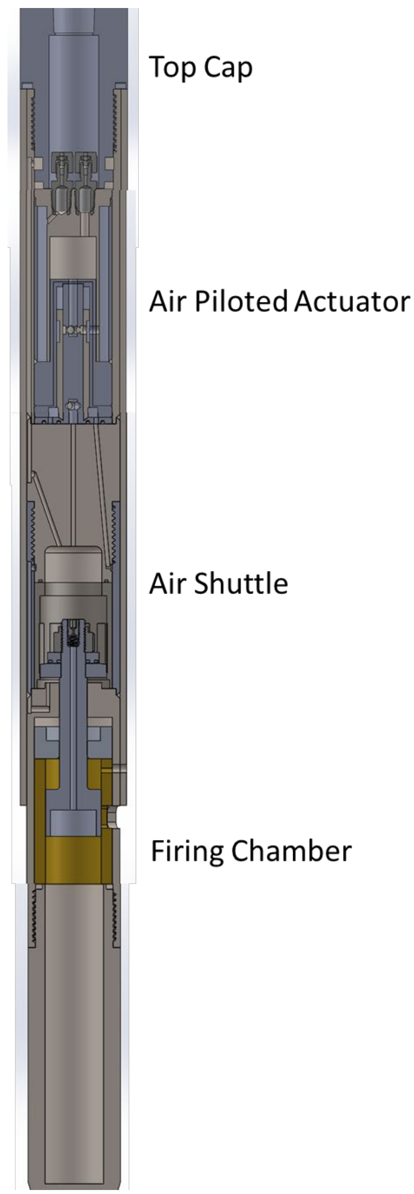

Figure 1. Overall schematic of the RT-SEISMIC impulse source module

2.1.1 Top Cap

The top cap assembly is used connect the process lines to the RT-SEISMIC source. Three process lines are: 1) firing chamber charge, 2) vent, and 3) air actuator control. High pressure air is routed from the top cap to the firing chamber via a port in the top cap and a channel machined between outer interference fit sleeve and the inner housing as shown in Figure 2. Air is designed to leak from the assembly and be exhausted at the surface through the vent line. Actuator line is used to apply air pressure (greater than the firing chamber pressure) to maintain the air piloted actuator in a closed position.

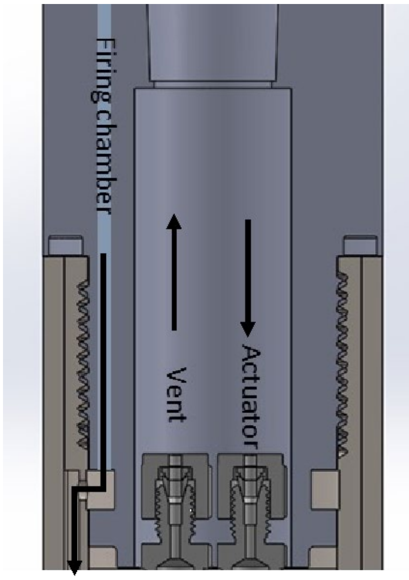

Figure 2. Top cap (blue-grey assembly) of the RT-SEISMIC module. Arrows illustrate the process connections and air flow paths

2.1.2 Air Piloted Actuator

An air piloted actuator valve is used to switch between stable and firing operations (Figure 3). The valve is normally closed by applying pressure higher than the firing chamber pressure to the actuator line. Actuator pressure forces the cylindrical piston downwards, sealing the central port at the bottom of the actuator from the vent line. To actuate and fire the source, the actuator pressure is simply reduced to less than the firing chamber pressure.

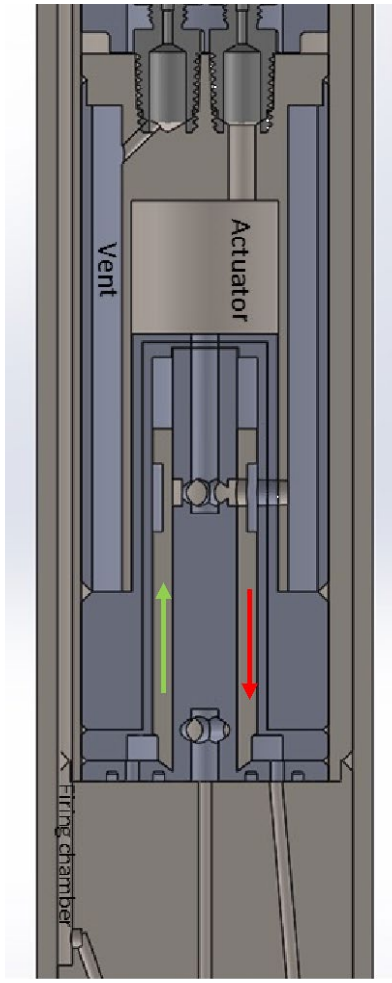

Figure 3. Air piloted actuator (blue-grey) within the upper source housing (grey). Arrows shown on the slide valve illustrate the direction of movement when the system in non-operating (red) and operating/firing (green)

2.1.3 Air Shuttle

The air shuttle is a rapidly acting, high flow, air release valve. Air enters the upper volume above the shuttle and more slowly enters the lower volume below the shuttle in the firing chamber by flowing through an orifice in the center of the shuttle. When the air piloted actuator opens, the upper section of the firing chamber is connected to the vent line which quickly reduces the pressure above the shuttle mechanism and due to the orifice, changes the pressure in the lower section more slowly. This causes pressure to be higher in the firing chamber relative to the pressure above the shuttle and forces the shuttle assembly upwards, firing the source (Figure 4).

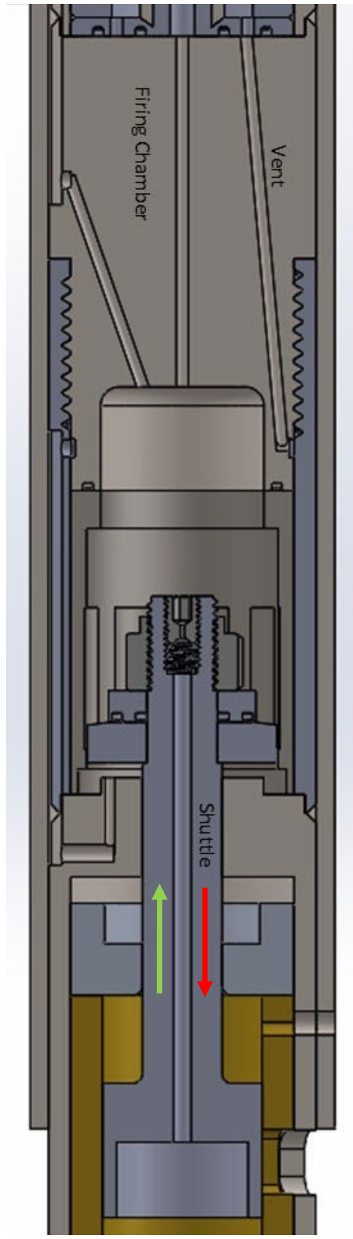

Figure 4. Air shuttle assembly (grey-blue) within the lower and upper source housing (grey). Arrows shown on the slide valve illustrate the direction of movement when the system in non-operating (red) and operating/firing (green)

2.1.4 Firing Chamber

Operation of the impulse source occurs when the shuttle moves upward exposing the large area, outer ports (Figure 5). High pressure air stored in the firing chamber is released through the ports. When operated as an air gun source, the high energy air bubble enters the wellbore and generates impulsive mechanical energy to the surrounding soil/rock.

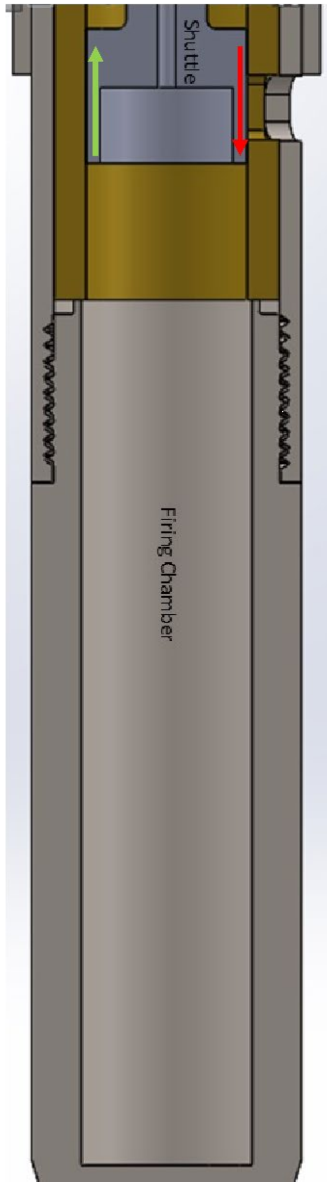

Figure 5. Firing chamber for the RT-SEISMIC source module. Volume is charged with high pressure nitrogen gas and rapidly released through side exhaust ports

2.2 Vibratory Source Extension Module

The vibratory source is designed as an extension module to the impulse source (Figure 6). The extension is pressed onto the firing chamber as an interference fit. Rather than allowing the pressurized air volume from the firing chamber to escape into the wellbore, the vibratory source extension captures the air and directs it towards an air motor with an attached eccentric mass. The rapidly rotating mass imparts vibratory motion to the ground when mechanically coupled to the wellbore.

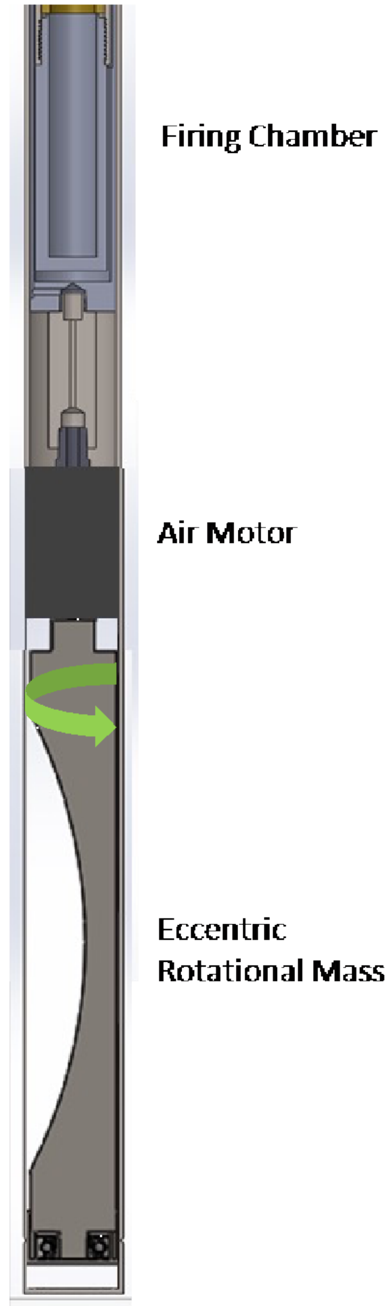

Figure 6. RT-SEISMIC vibratory source extension module. Rotating eccentric mass is driven by the high energy air from the impulse source firing chamber and imparts vibrations to the rock/soil surrounding the wellbore

2.3 High Temperature & Pressure Seals

All the static seals used in the RT-SEISMIC source modules are rated for continuous operation at temperatures up to 500 degrees C and pressures up to 10 kpsi. Static seals are Inconel 718 alloy metallic O-rings and C-rings (Figure 7). Graphite-aluminum composite dynamic seals (Figure 8) were custom designed for this project and, as will be discussed in the testing section of this document, ultimately required a final redesign using Kalrez O-rings. This modification will derate the continuous operating temperature of the system to approximately 275 degrees C.

Figure 7. Inconel C-rings used for RT-SEISMIC static seals

Figure 8. Composite graphite-aluminum seals used for dynamic reciprocating motion of the shuttle assembly

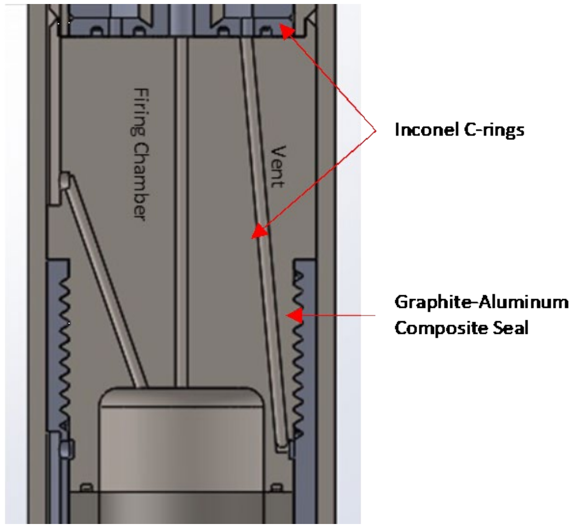

Figure 9. Seal locations in the air shuttle assembly

2.4 Sensing and Control Module

The array of RT-SEISMIC sources requires the mechanical connection to the three process lines. The firing chamber and vent lines are relatively simple and need only a manifold connection at each of the source (no downhole control). Separate actuation control; however, is required to operate each source independently. To minimize the number of control lines, the sensing and control module is needed to apply/remove actuation pressure to each RT-SEISMIC source. In addition, measurement of ground motions signals that are generated by each source when actuated is also essential. A prototype sensing and control module that incorporates a mechanical actuator and three geophone ground motion velocity sensors mounted in a triaxial configuration was designed and tested (Figure 7 and Figure 8). The prototype used 3D printed PVA material but since no moving external components are present, adaptation to high temperature housing materials should be straightforward relative to the source design. The RT-SEISMIC team also worked with a high temperature integrated circuit manufacturer (Ozark IC Inc.) to adapt the current prototype electronics design into a commercially available silicon-on-carbide package for continuous operation at high temperature (~500 degrees C).

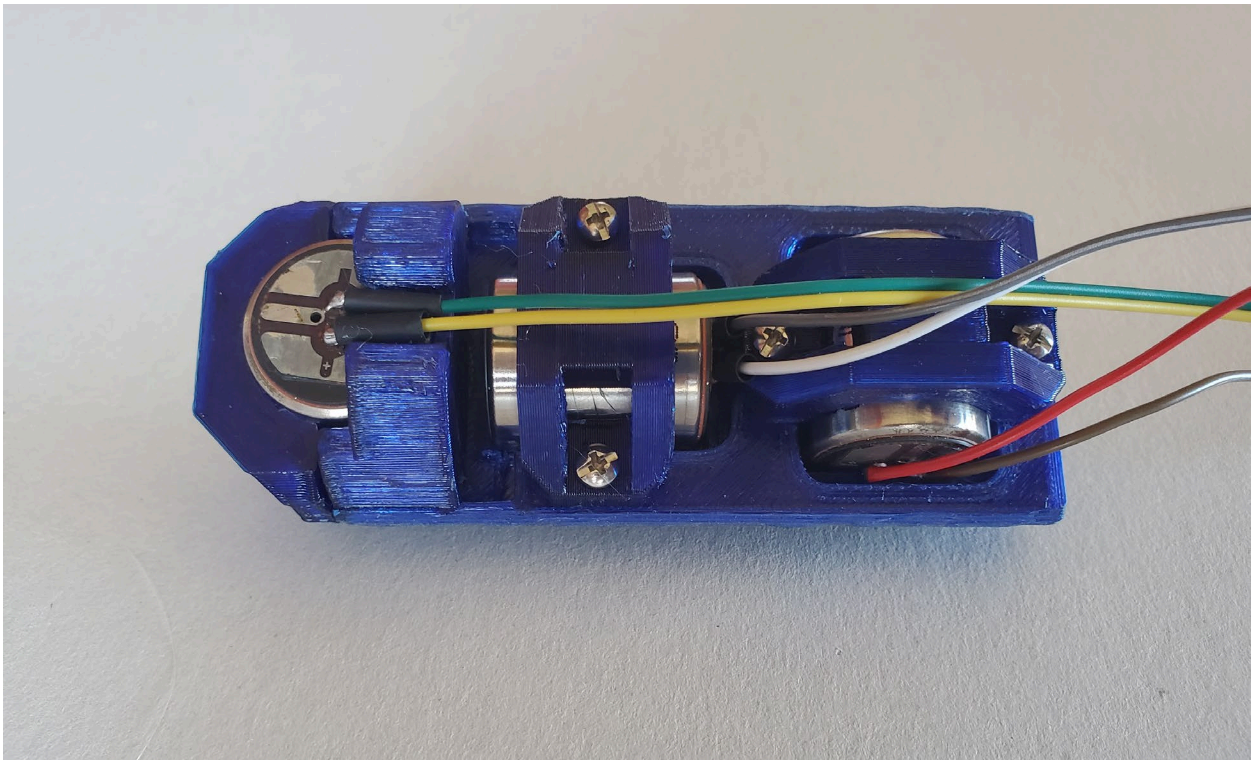

Figure 10. RT-SEISMIC prototype sensing and control electronics and triaxial geophones

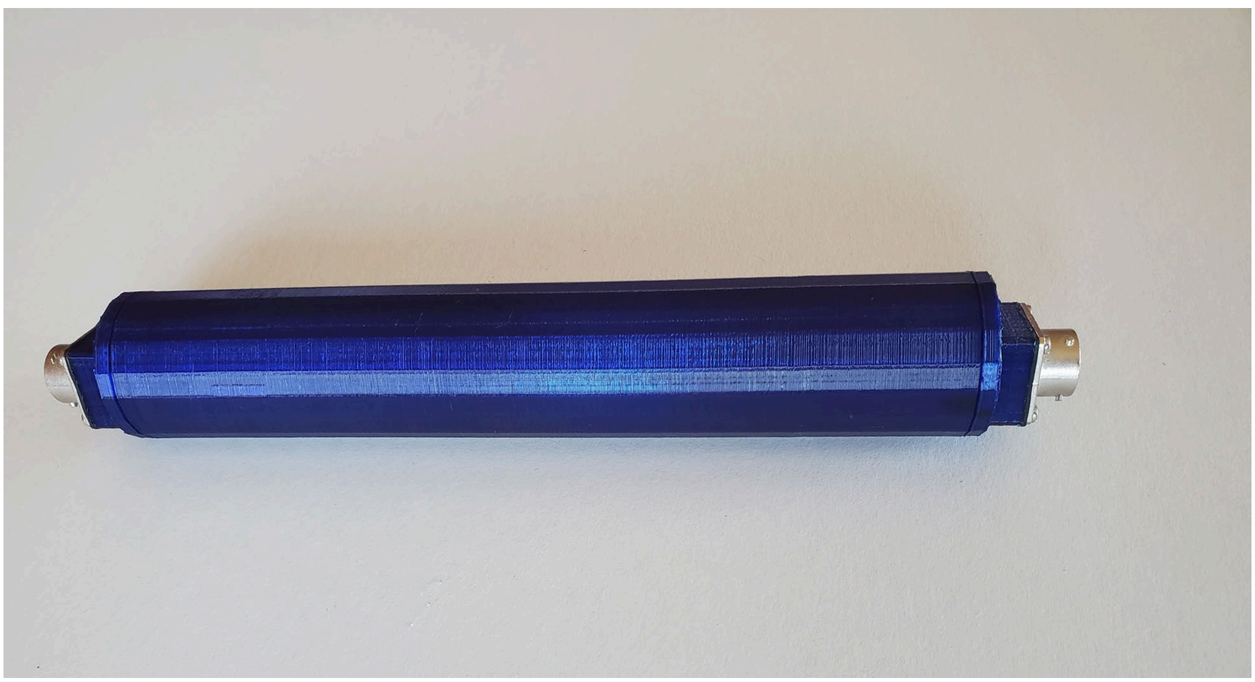

Figure 11. Outer sensing and control module housing

3.0 Fabrication and Lab Testing

3.1 Actuator Design

The initial RT-SEISMIC design utilized an electromagnetic solenoid as the actuator mechanism (Figure 12. The solenoid was wound with high temperature rated ceramic coated nickel wire. Ferrite was to be used as the solenoid core, but machining proved to be difficult. Ferrite power was then mixed with high temperature epoxy and the resulting composite material was much easier to machine. Laboratory testing revealed two issues. First, the nickel wire ceramic coating was brittle and cracked when wound around the relatively small diameter solenoid housing (Figure 13. This led to electrical shorting. Second, the reduced magnetic permeability of the composite ferrite-epoxy material also reduced the actuation force capacity of the solenoid. For these reasons, an air piloted actuator (Figure 14) was designed to replace the electromagnetic solenoid.

Figure 12. Electromagnetic solenoid actuator that was initially designed for use in the RT-SEISMIC source module

Figure 13. Electromagnetic solenoid winding

The first air piloted actuator design was machined and welded. Subsequent laboratory testing revealed that the slide valve was seized within the housing. After a destructive evaluation, the team determined that during welding, excessive thermal warpage was causing the inner slide mechanism to move relative to the outer housing. Ultimately, an interlocking recess was incorporated into the design which eliminated the issue.

Figure 14. Air piloted actuator assembly components

3.2 Full Assembly Testing

After testing of individual components, the full RT-SEISMIC assembly (Figure 15) underwent testing in the laboratory. First, where possible, static seals above the shuttle assembly were tested by plugging, pressurizing, and measuring the leak-off rates. The Inconel O-rings and C-rings worked as expected. The laboratory testing apparatus is shown in Figure 16.

Next, the actuator mechanism was tested within the full assembly. While the air piloted actuator valve did successfully operate, the leakage around the slide valve was substantial (up to 500 mLPM).

Finally, the shuttle mechanism and firing operation was tested with the result being that the custom designed composite graphite-aluminum seals were unable to provide an adequate gas tight seal. Leakage rates were over 10 LPM for all pressure setpoints from 50-150 psig. A redesign of the dynamic seals was needed (Figure 17). The final design incorporates Kalrez O-rings (white circles in Figure 17) in three locations which are expected to provide effective seals but will ultimately reduce the final operating temperature of the system to ~275 degrees C.

Figure 15. Final assembly of the RT-SEISMIC impulse source module

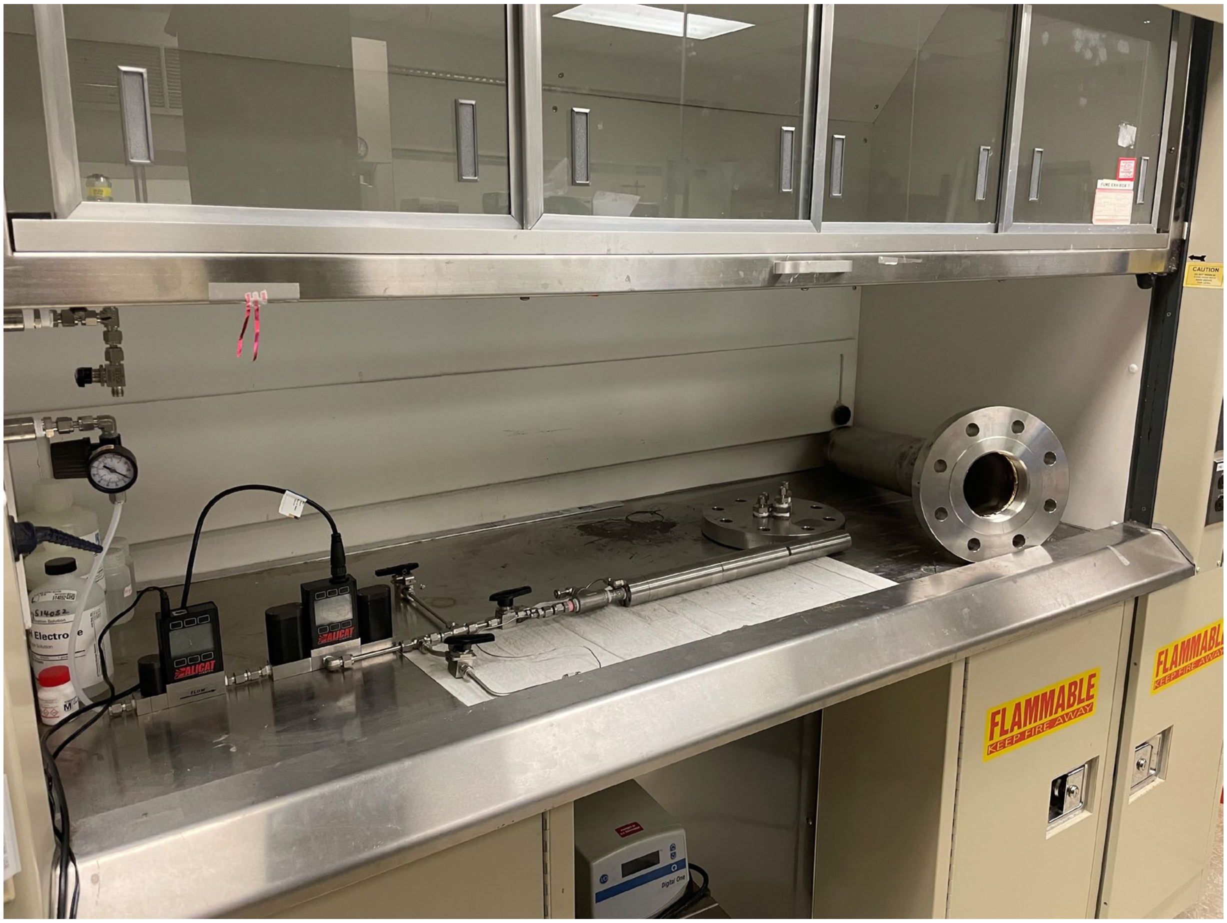

Figure 16. Laboratory testing apparatus: Pressure and mass flow controllers/meters (left), valving and RT-SEISMIC source (center), pressure containment vessel (right)

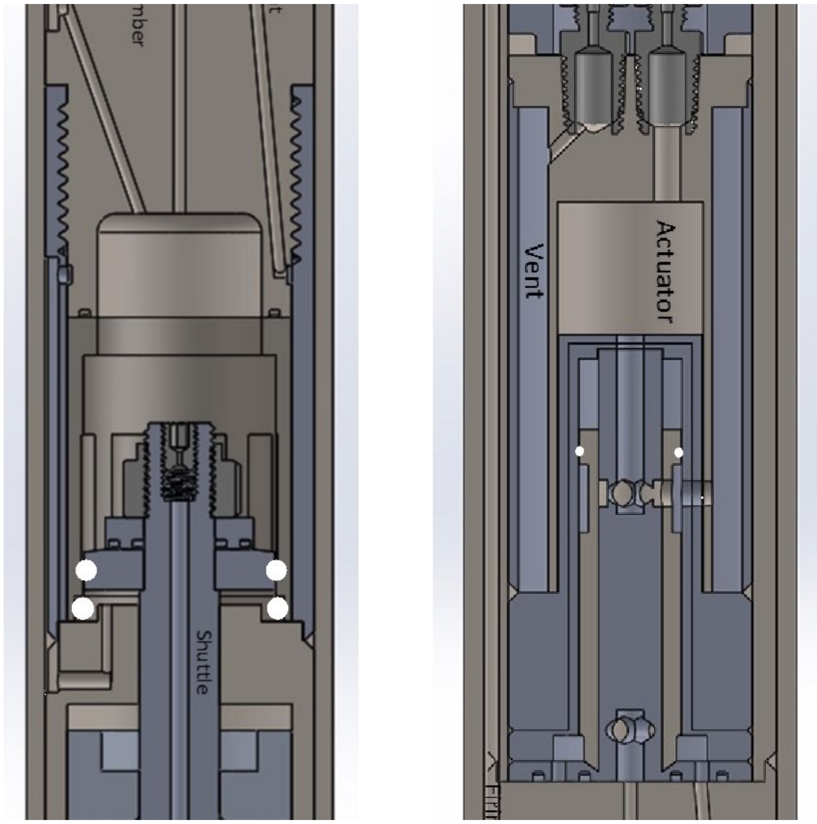

Figure 17. Final design utilizing Kalrez O-rings (white circles) for dynamic seals

4.0 Summary

A high-temperature and high-pressure borehole seismic source and sensing system was designed, built, and tested to enable real-time seismic imaging for a wide range of applications that include environmental, geothermal, national security, and fossil energy. The system (RT-SEISMIC) consists of both impulse and vibratory source modules for generating seismic energy along with a sensing-control module for source actuation and recording of ground motions generated by the array of source modules. The source modules were fabricated with all high temperature components and the RT-SEISMIC electronics was designed to be incorporated into a commercially available high temperature rated silicon-on-insulator integrated circuit package.

Several issues were identified during fabrication and lab testing that led to redesign of several system components and subsequent retesting. The final round of testing showed that while metal-based seals worked quite well for static seals, the graphite-composite seals were unable to provide an adequate gas seal for dynamic, reciprocating motions. This necessitated a final redesign using Kalrez O-rings for the dynamic seals and results in a reduction of the continuous temperature rating to approximately 275 degrees C for the system.

Due to extended lab testing and redesign efforts, field testing was not performed; however, because of this LDRD investment, the project team was able to successfully complete the final design of the RT-SEISMIC system. Several sponsors have expressed interest in RT-SEISMIC and we anticipate future opportunities to continue progressing this technology up the TRL ladder.

5.0 References

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Pacific Northwest National Laboratory

902 Battelle Boulevard
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