SAND2016-10796R

The State of stress in the Sanford Underground Research Facility (SURF) in Lead, South Dakota

by Moo Y. Lee,
Sandia National Laboratories, Geomechanics Department

Introduction

As a part of the U.S. Department of Energy (DOE) SubTER (Subsurface Technology and Engineering Research, Development and Demonstration) initiative, University of Wisconsin-Madison, Sandia National Laboratories, and Lawrence Berkeley National Laboratory conducted the Permeability (**k**) and **I**nduced **S**eismicity **M**anagement for **E**nergy **T**echnologies (kISMET) project. The objectives of the project are to define the in situ status of stress in the Sanford Underground Research Facility (SURF) in Lead, South Dakota and to establish the relations between in situ stress and induced fracture through hydraulically stimulating the fracture. (SURF) in Lead, South Dakota. In situ tests are conducted in a 7.6 cm diameter and 100 long vertical borehole located in the 4850 Level West Access Drift near Davies Campus of SURF (Figure 1). The borehole is located in the zone of Precambrian Metamorphic Schist.

Wireline Hydraulic Fracturing System

We used a fast and continuous tool-tripping wireline hydraulic fracturing system for in situ stress measurements and a fracture stimulation at SURF. The wireline hydraulic fracturing system consists of two major downhole tool assemblies: a straddle packer assembly for fracture initiation and extension within the selected test interval, and an impression packer orienting tool assembly for fracture delineation (Figure 2).

Straddle Packer

The wireline straddle packer assembly consists of three major components: two inflatable packer elements straddled by a hydraulic fracturing interval spacer, and a top adaptor for connecting a wireline and hydraulic lines. The packer element consists of a high pressure inner tube and braided or ribbed steel reinforced outer rubber cover. The straddle packer incorporates two

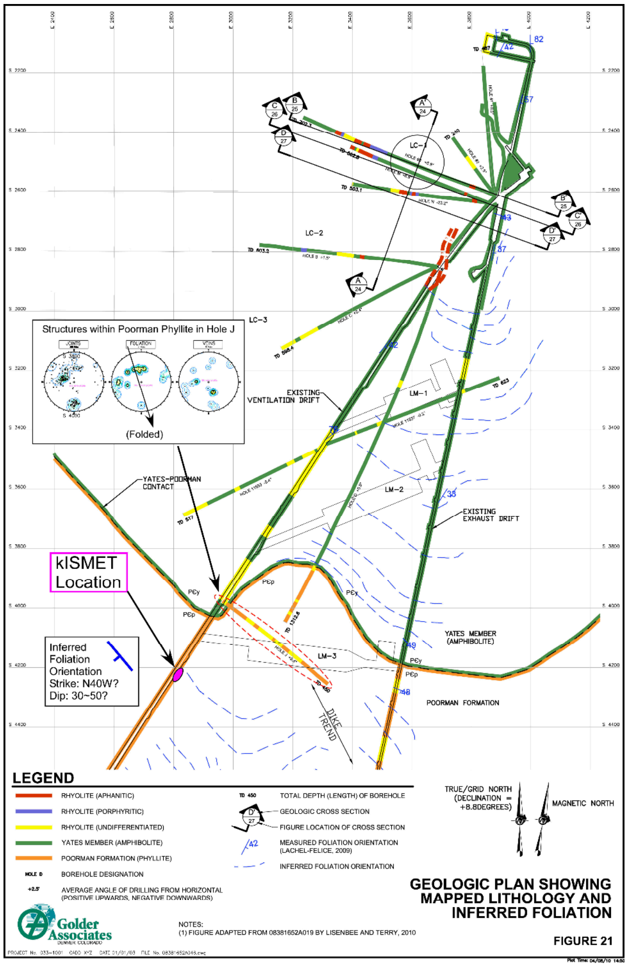

Figure 1. Location of kISMET test site at SURF.

separate mandrils with a rigid interval spacer. This arrangement enables the interval spacer to be flush with the packer elements, and preventing tensile failure by splitting of the interval spacer when very high pressures are required to fracture the test interval. The assembly is tripped in the borehole on a wireline operated by a hoist.

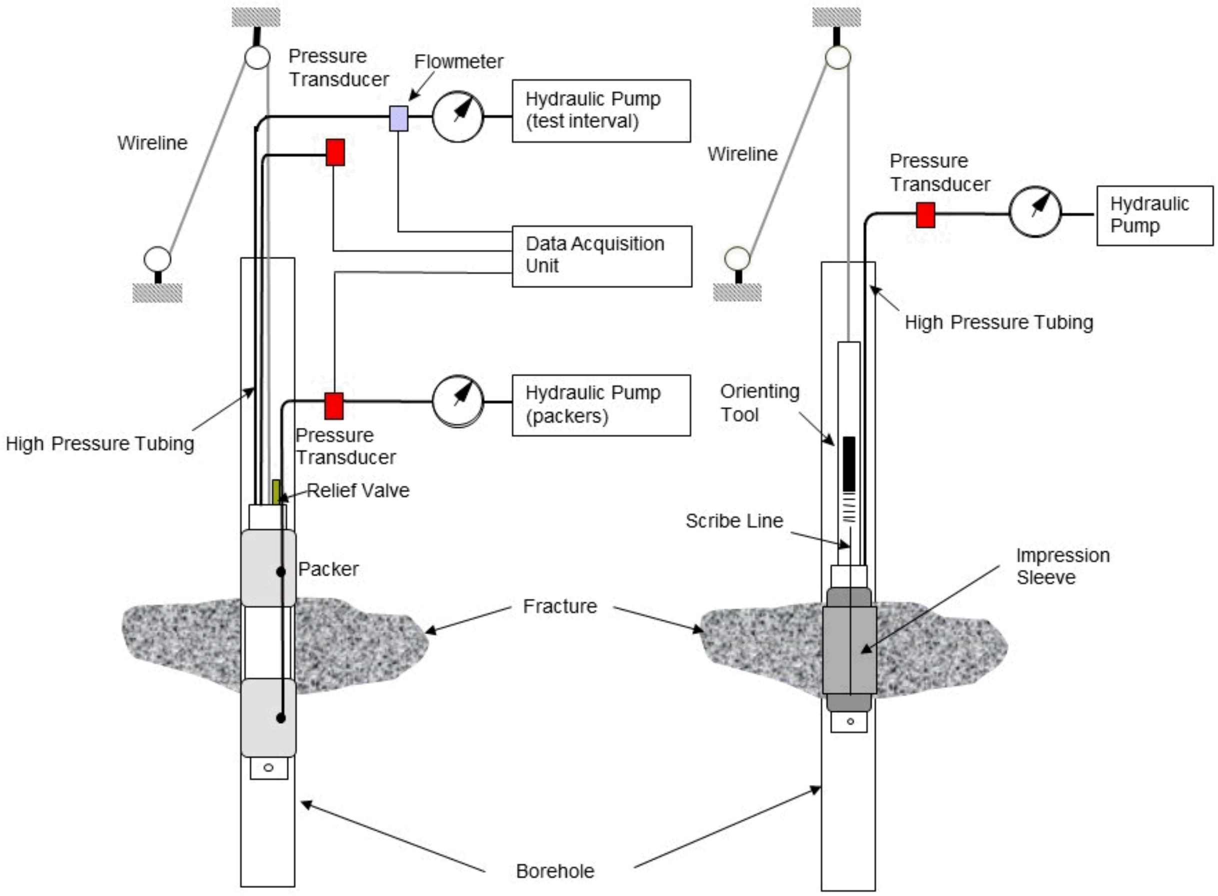

Figure 2. Wireline hydraulic fracturing system: Straddle packer for fracturing (left) and Impression packer for fracture delineation.

The top straddle packer adaptor accommodates one hydraulic line to packers; two parallel hydraulic lines to interval; and a port to a downhole release valve (Figures 2 and 3). The separate hydraulic connections to packers and an interval allow controlling and monitoring the pressure in the packers and in the fracturing interval independently. We used two parallel hydraulic lines for interval pressurization and monitoring. One line is connected to the pressure generator to supply fracturing fluid and pressure to the fracturing interval. The parallel line is connected to the surface pressure transducer for monitoring the interval pressure. The parallel line will transfer the downhole pressure, less the hydraulic head, to the surface pressure transducer without friction loss due to the effect of the fluid's viscosity in the tube. After each test, the packers are deflated by releasing the packer pressure. The pressure relief valve is a normally-open valve consisting of a conically shaped piston and a spring acting against the piston. During tool tripping to the test depth, normally-open relief valve allows the packers and all hydraulic lines to be filled with the ground water in the borehole. During packer inflation, fluid is partially blocked by the small venting holes drilled inside the piston, and pressure accumulates on the inlet side. The pressure differential thus created eventually closes the relief valve. When the pressure is dropped, at the conclusion of a test, by venting the pressure line on the surface, the spring will push the piston to its normally-open position and the pressure will be released to a level equal to the water head. This facilitates the deflation of packer elements. The fracturing tool can be reset at a different depth in the hole without retrieval.

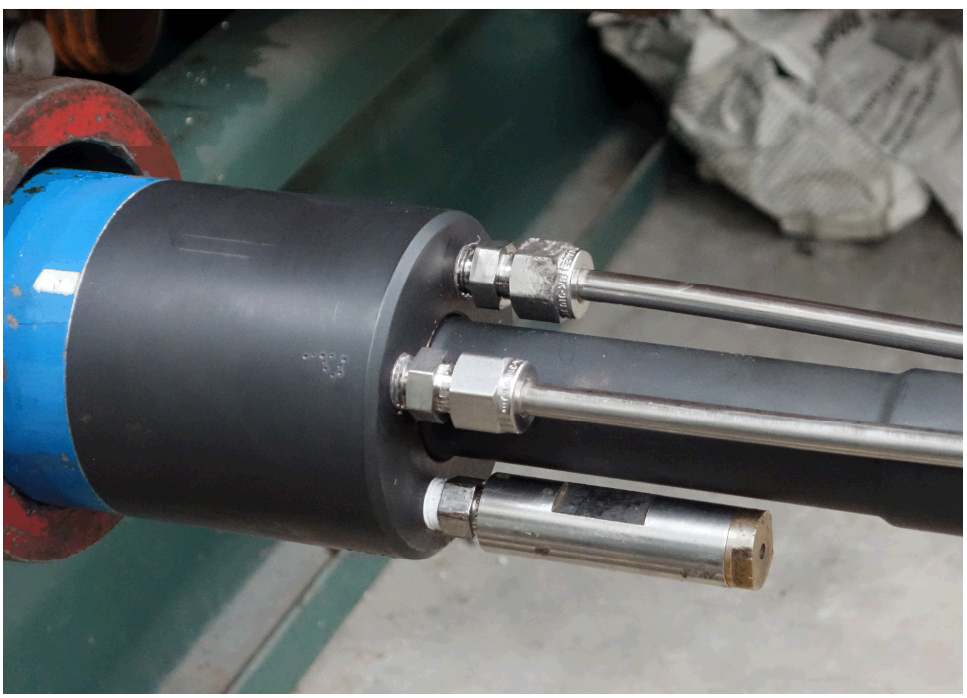

Figure 3. Top adapter on the straddle packer assembly shows the interval and the packer pressure lines and the normally-open relief valve. The parallel interval pressure line connected to the surface pressure transducer is hidden behind the stem connected to a wireline.

Impression Packer

The wireline impression packer-orienting tool assembly is a downhole probe employed to delineate the hydraulic fracture on the borehole wall. It consists of an orienting tool which is lowered to the test interval attached to the impression packer. The simultaneous and continuous tripping of the tool assembly significantly reduces the time required for fracture delineation, as compared with the conventional drill-rod procedure.

Once the impression packer-orienting tool was set at the precise depth of a previously fractured interval, the impression packer was pressurized ~15 MPa. The packer pressure was maintained for about 30 minutes to allow the soft impression sleeve to protrude into the opened hydraulic fracture. The orienting tool consists of a pitch/roll compensated compass/magnetometer which send the orientation of the reference line on the impression packer to the surface monitor in real time (Figure 4). While the packer is inflated the compass/magnetometer sends the orientation data through the RS485 serial interface up to 1200 m distance.

Packer deflation is achieved by pressure venting and activating the downhole relief valve as in the straddle packer (Figure. 2). After the retrieval of the impression packer, the impression packer was examined for any traces of fractures. These were marked with an indelible marker, and traced with respect to the scribe line on a transparent plastic sheet wrapped around the packer for later detailed analysis.

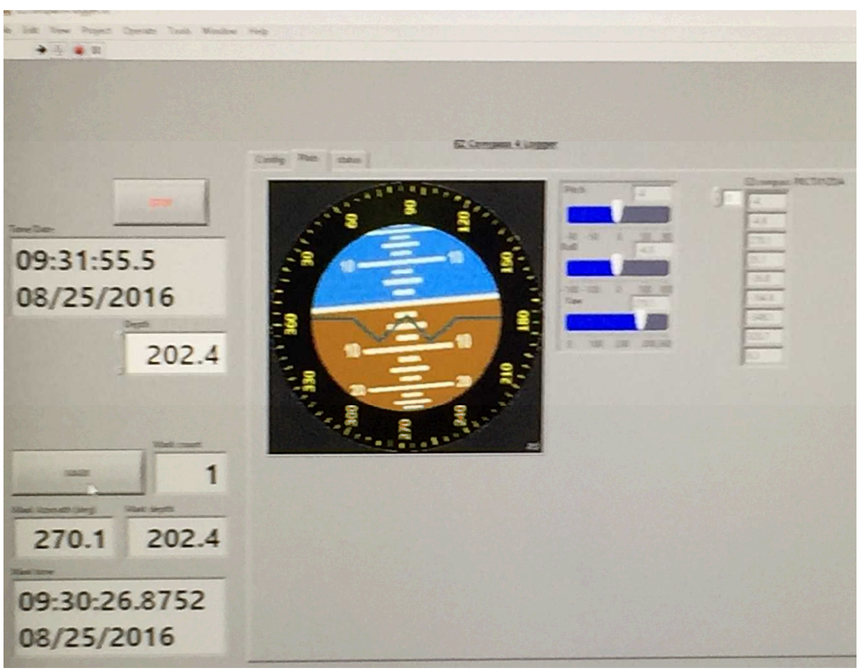

Figure 4. Real time transmission of compass/magnetometer information for the orientation of the impression packer

Pressure Generator

In order to run hydraulic fracturing tests hydraulic fluid pressure is generated by two pneumatic pumps (one for the packers and the other for testing intervals between the packers). This pumping system will have two pressure transducers and pressure gages to monitor pressures in the packers and the interval, respectively. A flow meter is also employed to monitor the flow of water into the test interval. Figure 5 shows the schematic of the pressure generator system. The system is designed to be intrinsically safe by using components with a pressure rating higher than the maximum pressure the pumps can generate.

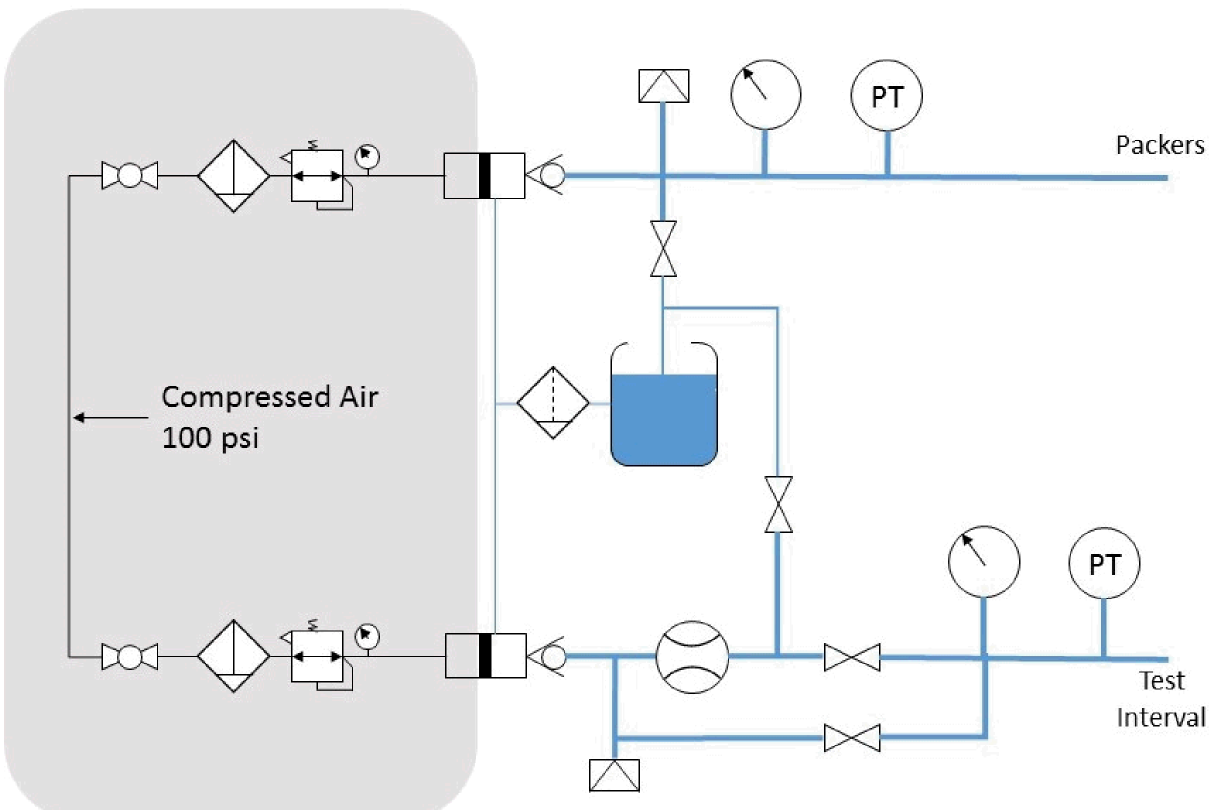

Figure 5. Schematic diagram of the pressure generator used for kISMET hydraulic fracturing and fracture stimulation.

Hydraulic Fracturing Digital Data Recording

The flowrate of the injection fluid into the fracturing test interval is monitored by a turbine flowmeter connected between the surface pump and the high pressure tubing leading to the test interval. The packer and test-interval pressures as well as the flowrate are recorded simultaneously digitally in a portable computer using an analog-to-digital (A/D) converter and also in the integrated digital data logger at 10 samples/s for each channel. Digital recording data recording allows for statistical discrete data analysis for analyzing shut-in and fracture reopening pressures. A schematic diagram for the digital data recording system is shown in Figures 2 and 6.

Figure 6. Pressure generators and digital data recorders used for hydraulic fracturing and fracture stimulation at SURF.

Hydraulic Fracturing Procedures

To perform a HF, a section of a borehole is sealed off by use of two inflatable rubber packers sufficiently pressurized so that they adhere to the borehole wall. Hydraulic fluid (water) is pumped under constant flow rate into the section, gradually raising the pressure on the borehole wall until a fracture is initiated in the rock.   Pumping is stopped by closing the valves in compressed air side in Figure 2, allowing the interval pressure to decay. Several minutes into the shut-in phase, the pressure is released and allowed to return to ambient conditions. The pressure cycle is repeated several times maintaining the similar flowrate. Key pressure values used in the computation of the in situ stresses are picked from the pressure–time record. The repeated cycles provide redundant readings of the key pressures. The interval pressure is released and the flowback from the interval is coming back to the surface. Figure 7 shows a typical pressure-flowrate-time plot from hydraulic fracturing test in SURF.

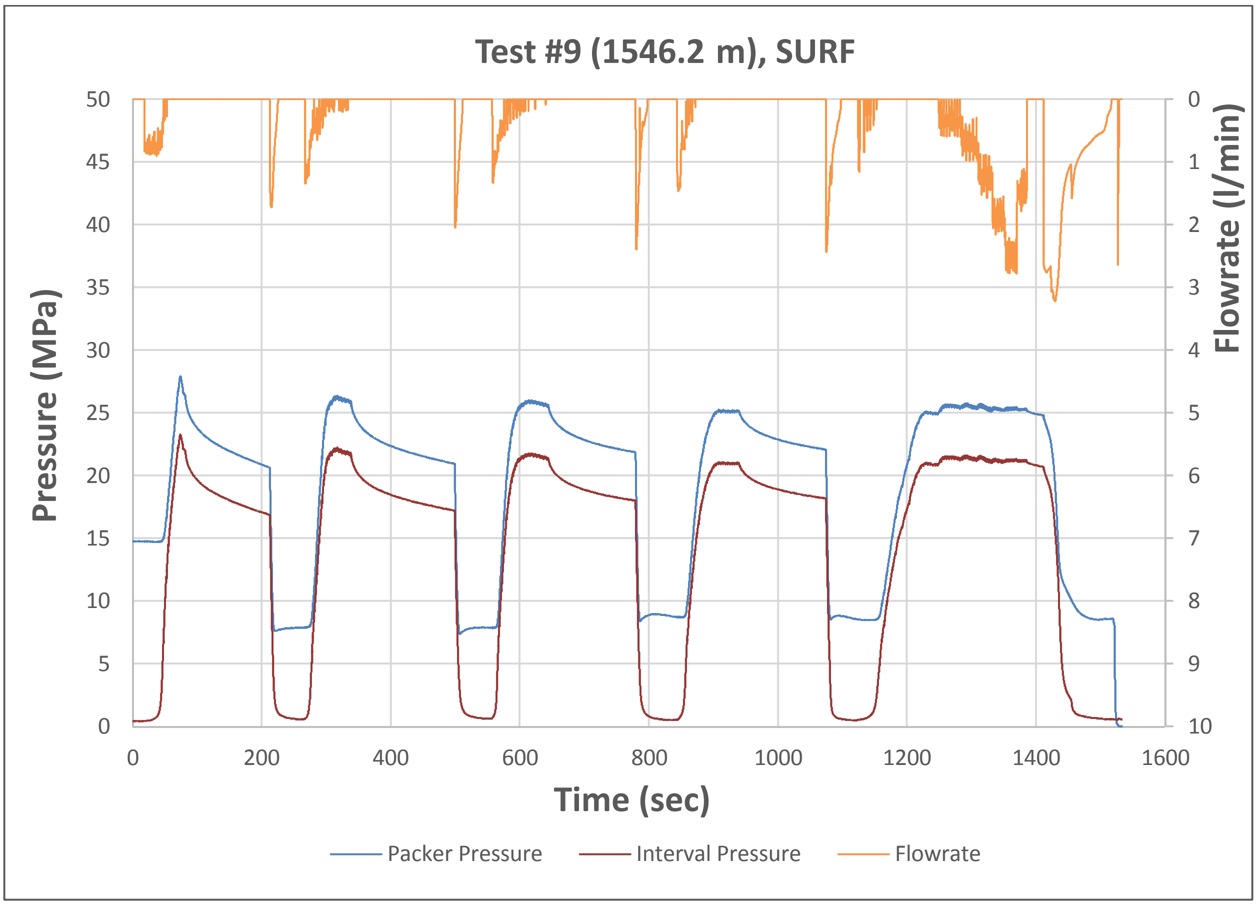

Figure 7. Pressures-Tim and Flowrate-Time plot obtained in Test #9 at SURF.

Fracture Stimulation Procedures

After all planned hydraulic fracturing in situ stress measurements were completed, the straddle packer was moved to the 1518.6 m level for the stimulation test in conjunction with geophysical monitoring of the induced fracture. Continuous Active Source Seismic Monitoring (CASSM) was setup to run continuously, and Electric Resistivity Tomography (ERT) was triggered to capture the steady state of constant Pressure-Flowrate (P-Q) following initiation of a hydraulic fracture, where a relatively stable state with an open fracture was maintained. Low flowrates were used in order to maintain an open fracture indicated by constant pressure. Following initiation of a hydraulic fracture indicated by breakdown pressure at 22.7 MPa, five stimulation cycles were conducted (Figure 8). The first two cycles were conducted with relatively low flowrate of 0.48 lpm; and the next three cycles with relatively high flowrate of 0.63 lpm. For each cycle, the steady state pressures were achieved at 20.1-20.3 MPa. The steady state of P-Q was maintained for approximately 15 minutes in order to finish one round of ERT data acquisition (CASSM run takes ~ 20 sec). The amount of fluid injected for each cycle was 7.2, 7.7, 6.0, 9.0, and 11.7 liter from 1st to 5th stimulation cycles, respectively. The fracture stimulation tests were successfully conducted with continuous CASSM data and four sets of ERT data with open fractures.

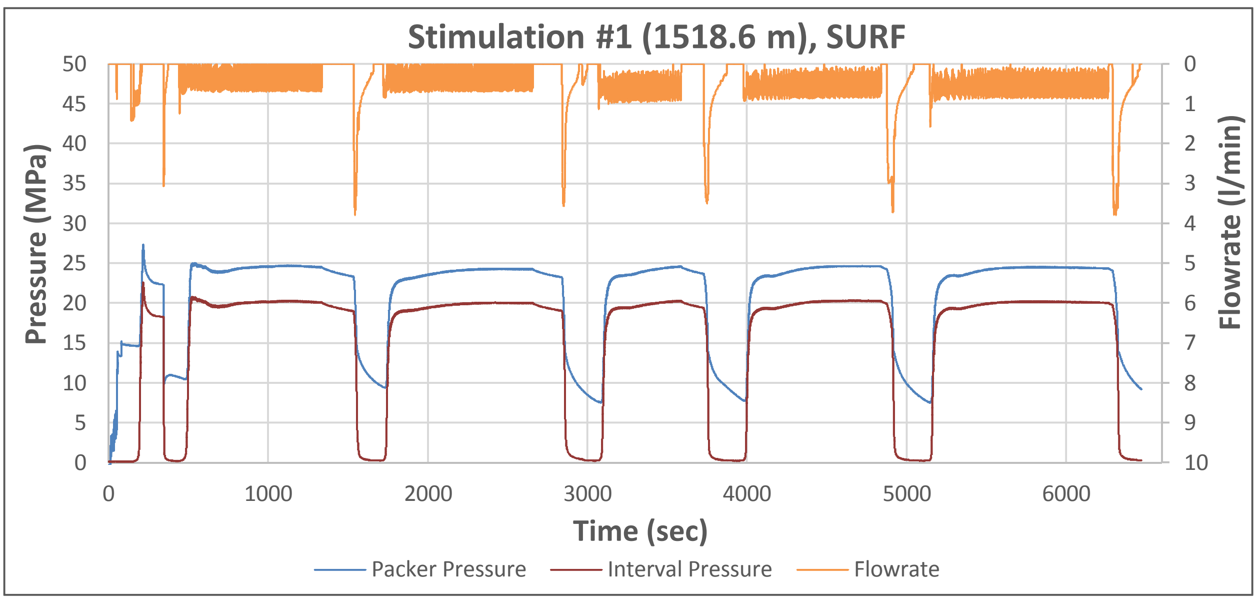

Figure 8. Pressure-Flowrate-Time plot obtained during stimulation of a fracture at SURF.

Fracture Delineation and Orientation

After completion of seven hydraulic fracturing tests, we attempted to obtain oriented fracture impressions using the wireline impression packer with compass/magnetometer. The impression packer was lowered to the shallowest test depth (Test #7 at 1540 m). The impression sleeve produced only short traces of a fracture. The traces were about 2 inches long and they were not mirrored on the other side of the packer. The incomplete trace was thought to be an effect of inflating the packer to only 15 MPa while the shut in pressure of that test appeared to be around 20 MPa. For the second impression test (Test #5 at 1551.6 m), the packer inflation pressure was raised to 20 MPa to get clear impression of the fracture. The pressure was declining slightly, and an attempt to bring the pressure back to 20 MPa level resulted in a failure of the packer element. On retrieving the packer back to the surface it became stuck in the hole after coming up only about 30 cm. It appeared the impression packer element was ruptured and resulted in inflating the impression sleeve excessively. Many attempts to retrieved the impression packer failed. Finally, we decided to retrieve the compass/magnetometer probe and hydraulic lines leaving the impression packer in the borehole by shearing the safety pin located between the packer element and the downhole orienting probe.

The acoustic borehole televiewer (BHTV) is a logging device that provides an oriented acoustic reflectivity image of the borehole wall. A fracture intersecting the borehole appears as a dark signature on the images caused by its low acoustic reflectivity (Figure 9). Acoustic BHTV was used as the primary logging tool to delineate and orient the hydraulic fracture in SURF.

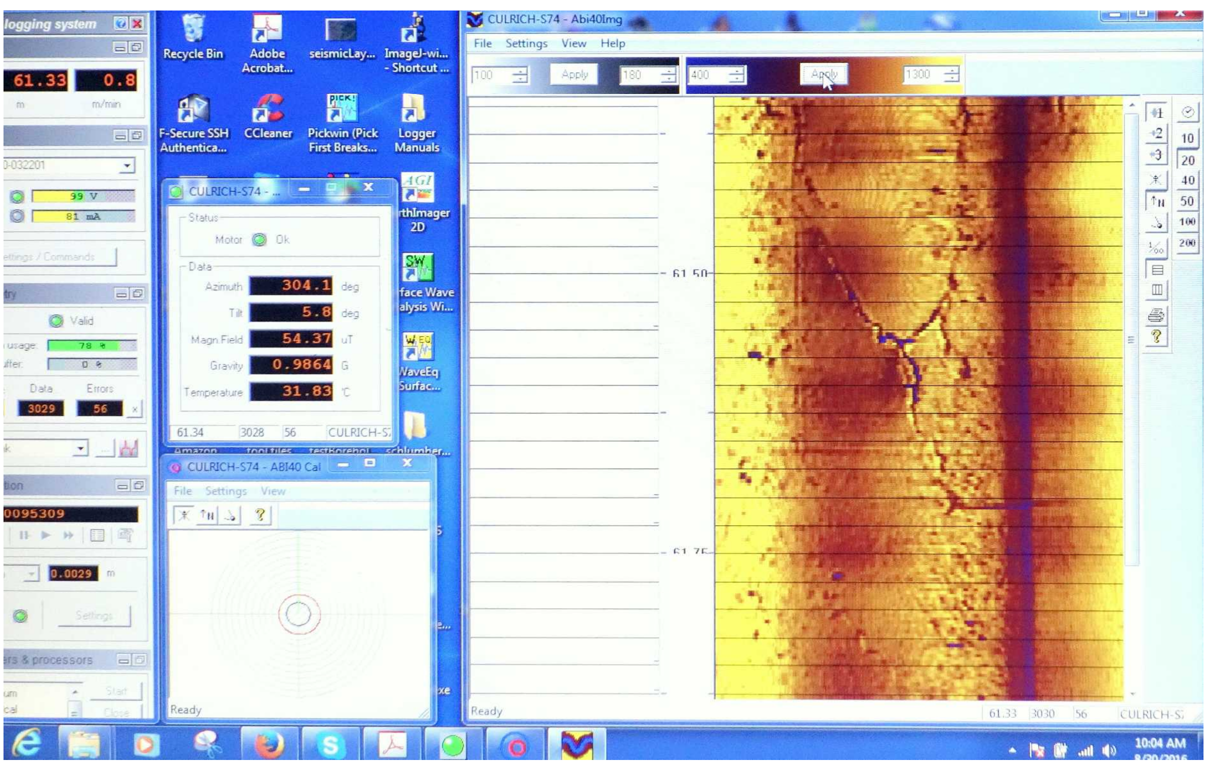

Figure 9. Screen shot of the acoustic BHTV pictures for hydraulic fracture at Test#7, 1540 m.

Sandia National Laboratories is a multi-mission laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.