

# AIR-SLUG LOW-PRESSURE STRADDLE-PACKER SYSTEM TO FACILITATE CHARACTERIZATION OF FRACTURED BEDROCK

Erik. Svenson, T. Schweisinger L.C. Murdoch

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AUTHORS: Clemson University, Department of Geological Sciences, 340 Brackett Hall, Clemson, SC 29634-0919

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**Abstract.** Straddle-packer tests are used for determining aquifer properties in fractured rock, but packer tests are often avoided because they can be expensive. We have developed a simple, inexpensive, lightweight air-slug straddle packer system that can measure transmissivity as well as head variations along boreholes.

The air-slug packer system was used at a site in Clemson, South Carolina to evaluate the transmissivity and head distributions in a borehole. The results show that transmissivity in the aquifer range from  $10^{-7}$  to  $10^{-4}$  m<sup>2</sup>/s. Transmissivity distributions show three permeable intervals ( $T \approx 10^{-4}$  m<sup>2</sup>/s) at depths of 24, 34, and 50m separated by relatively low permeability material ( $T \approx 10^{-7}$  m/s). Upward vertical head gradients of 0.013 and 0.0016 were measured in the well. Similar results were obtained with standard, high-pressure packers.

## INTRODUCTION

Straddle-packers tests are used in a variety of geological media for determining aquifer properties and fluid compositions (Price et. al. 1993). They are particularly effective for investigating fractured bedrock because individual water-bearing fractures or fracture zones can be isolated. Tests are carried out by sealing discrete intervals along boreholes and inducing fluid flow either into or out of the test interval. Depending on the test method, the well bore pressure, flow rate, or volume of water are measured and analyzed to determine formation properties (Brassington and Walthall, 1985). Straddle packer tests, however, are often avoided because requirements related to personnel and support equipment can make them expensive.

We have developed and implemented a simple, relatively inexpensive, lightweight air-slug low-pressure (LP) straddle packer system that can be used to measure transmissivity and head distributions in boreholes. The system consists of a compressed air source, well-head manifold, and a PVC pipe string with two low-pressure inflatable packers attached. The packers are also well suited to sample discrete intervals in fractured rock.

Air-slug packer tests offer a means of obtaining estimates of formation transmissivity by rapidly

perturbing the total head in a localized region of a borehole and measuring the falling or rising head as a function of time (Shapiro and Greene, 1995). These tests are performed by applying a constant air pressure in the pipe string above the water. This changes the total head in the well and causes groundwater to flow into the formation, resembling a conventional slug-in test (Shapiro and Hsieh, 1998). The added air pressure depresses the air-water interface, and pressure measurements are collected with a submerged pressure transducer. Equilibrium is achieved when the combined water and air pressure return to initial conditions. A slug-out test is conducted by releasing the pressurized air from the pipe string and monitoring the rising water level.

Air-slug tests were preferred over other slug test methods because perturbing the head through the use of pressurized air, rather than a solid slug or bailer, allows for considerably larger slug volumes to be used. Larger slug volumes, in turn will affect larger volumes of fractured rock.

## FIELD EQUIPMENT

The air-slug LP straddle-packer assembly includes two 11.89-cm-diameter pipe plugs manufactured by Cherne Industries (Figure 1). This size packer is intended to be used in a 6-inch nominal well bore. Each packer comes with a 2-inch NPT center pass-through and inflation ports on both ends of the packer. They are rated at a maximum inflation pressure of 2.4bars above hydrostatic pressure and are rated to seal differential pressure heads of up to 9m (0.9bars).

The packers are separated by a 2-inch nominal perforated PVC pipe. A threaded rod (5/16-inch) between the packers is used to provide additional tensile strength to the system. The packers are fitted with an air line that attaches to a pressure source at the ground surface, and a 2-inch nominal PVC pipe string attaches to the upper packer and extends to the ground surface (Figure 1).

The well-head manifold for conducting air-slug tests is composed of 2-inch nominal PVC pipe, three ball valves, a precision pressure regulator, a pressure gauge, and an air-tight compression fitting (Figure 1). The compressed

air used for slug tests is regulated at the well-head and air flow into and out of the system is controlled by valves. A pressure transducer (we used a 30-psi, Mini-Troll, InSitu Corp. accuracy 0.01% FSO) is placed inside the 2-inch pipe string and the data cable extends through the pressure-tight seal in the manifold assembly to a computer, where data is monitored in real-time.

The cost of the straddle packer is approximately \$450, and the wellhead equipment is approximately \$150. The approximate weight of the packer system is 25lbs. The system can be easily assembled in the field and it can be deployed and operated without a winch.

### FIELD PROCEDURE

The straddle packer is lowered by hand with sections of PVC pipe string to the testing depth in a 6-inch nominal well. Hydrostatic pressure at the test depth is calculated, and the packers are inflated to 2.4bars (35-psi) above the hydrostatic pressure. Water is typically displaced during packer inflation, so the system is allowed to equilibrate before testing.

The transducer is submerged below the air-water interface and sealed at the top of the well-head manifold (Figure 1). Valves 2 and 3 on the manifold are closed and valve 1 is open so the air pressure used in the slug test can be set at the regulator. The initial static water pressure is recorded by the transducer before testing.

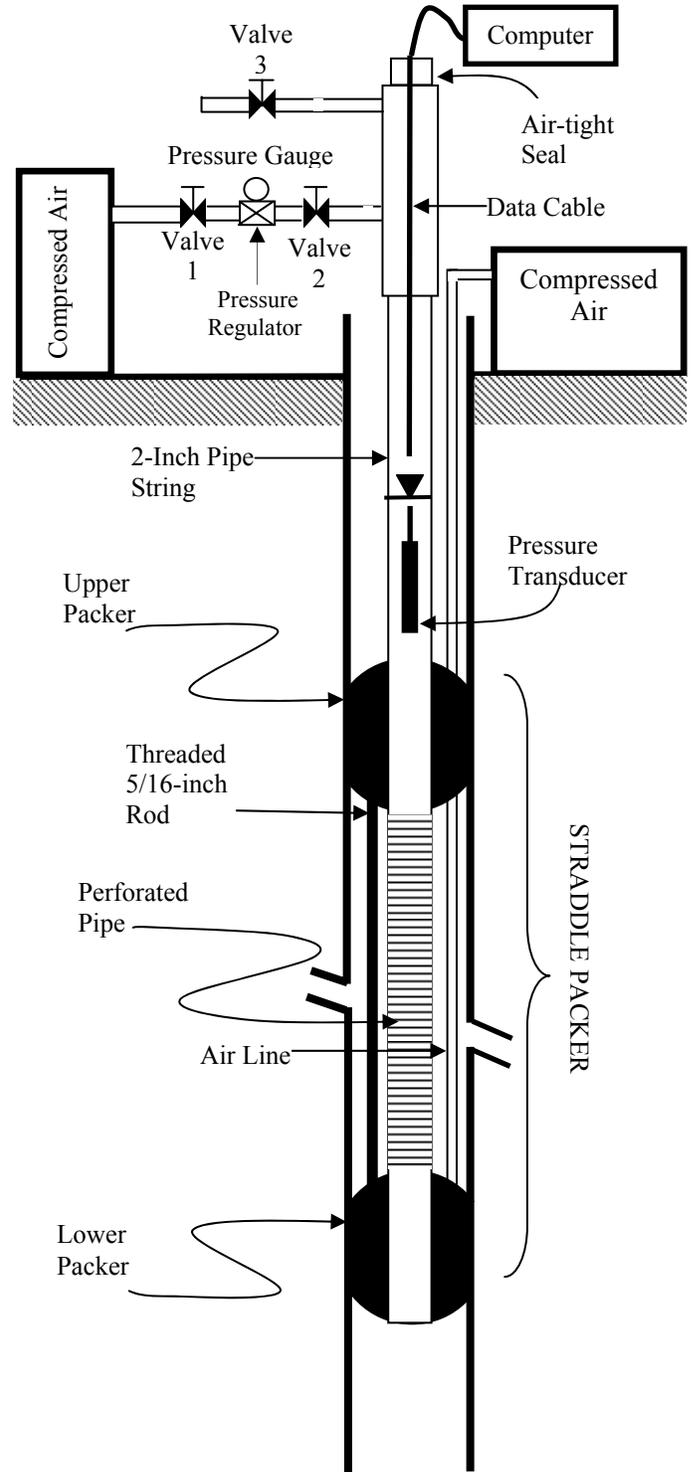
A slug-in test is initiated by opening valve 2, which allows the compressed air to flow into the pipe string. The applied air pressure abruptly increases in the pipe string, changing the total head in the well. The air pressure depresses the air-water interface, lowering the total head, and eventually, the water level drops by an amount equal to the applied air pressure as the system equilibrates.

A slug-out test is initiated by simultaneously closing valve 2 and opening valve 3. This allows the pressurized air in the pipe string to vent to the atmosphere, rapidly dropping the head in the well, and inducing fluid flow into the wellbore. The water level rises and the transducer records the measurements as a function of time. The slug-out test is completed when the water level returns to the initial elevation.

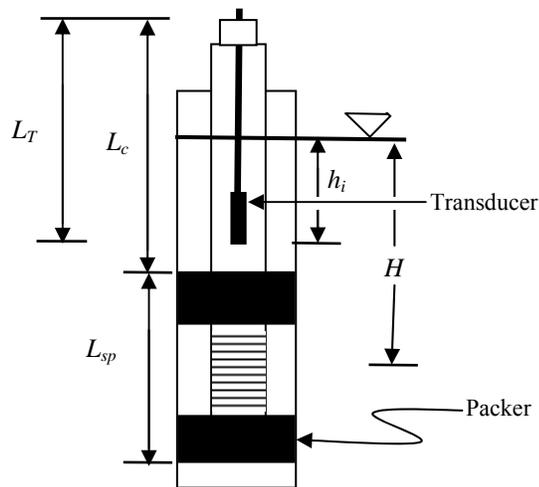
The LP packer system provides a means for obtaining the ambient head between the straddle packers using

$$H = \left[ \left( \frac{L_{sp}}{2} + L_c \right) - L_T \right] + \left( P_i * 0.704 \frac{m}{psi} \right) \quad (1)$$

where  $P_i$  is the initial static water pressure (*psi*),  $L_{sp}$  is the straddle packer length (*m*),  $L_c$  is the pipe string and manifold length (*m*), and  $L_T$  is the length of transducer and cable (*m*) (Figure 2.)



**Figure 1. Schematic of the air-slug straddle packer system**



**Figure 2. A schematic of the test system during static conditions.**

When packers are inflated in low permeability zones the head may not fully equilibrate before the slug test starts. Under these circumstances, the head between the packers exceeds the head in the formation so measurements are not used to calculate vertical head gradients.

#### SITE APPLICATION

A suite of air-slug LP packer tests was performed at a site in Clemson, South Carolina to evaluate the transmissivity and head distributions in a wellbore that penetrates fractured biotite gneiss. A total of 27 air-slug packer tests were carried out in 40-m-long sections of fractured rock (test interval ~1.4-m). A slug volume of  $0.07\text{m}^3$  and a differential head of approximately 2.5m were applied to each test interval, and subsequent head measurements were recorded every second. Test durations varied from a few minutes to an hour, depending on formation properties. The suite of 27 tests required 3 days to complete.

In addition, air-slug straddle-packer tests were performed in the same borehole using a Roctest LP-190 high pressure (HP) packer for comparison. The packers were inflated to 150-psi above hydrostatic pressure and a differential head of approximately 2.5m was applied to each test interval. HP packers were separated by 3.5m, which is 2.5 times longer than the separation of the LP packers.

The transient pressure head data were analyzed using a type curve similar to the one given by Cooper, Bredehoeft and Papadopolous (1967), so

$$T \approx \frac{d_c^2}{t_{0.37}}$$

where  $d_c$  is the diameter of the pipe string (m) and  $t_{0.37}$  is the time (s) at which a normalized head of 0.37 is obtained.

The results from both HP and LP packer measurements show transmissivity values that range from  $10^{-7}$  to  $10^{-4}\text{m}^2/\text{s}$  (Figure 3a). Transmissivity distributions from both packer tests indicate three permeable intervals ( $T \approx 10^{-4}\text{m}^2/\text{s}$ ) at depths of 24, 34, and 50m separated by lower permeability material ( $T \approx 10^{-7}\text{m}^2/\text{s}$ ). High permeability zones along the borehole coincide with fracture locations observed from camera and caliper surveys. Upward vertical head gradients of 0.013 and 0.0016 were calculated from the heads measured in the high permeability zones (Figure 3b).

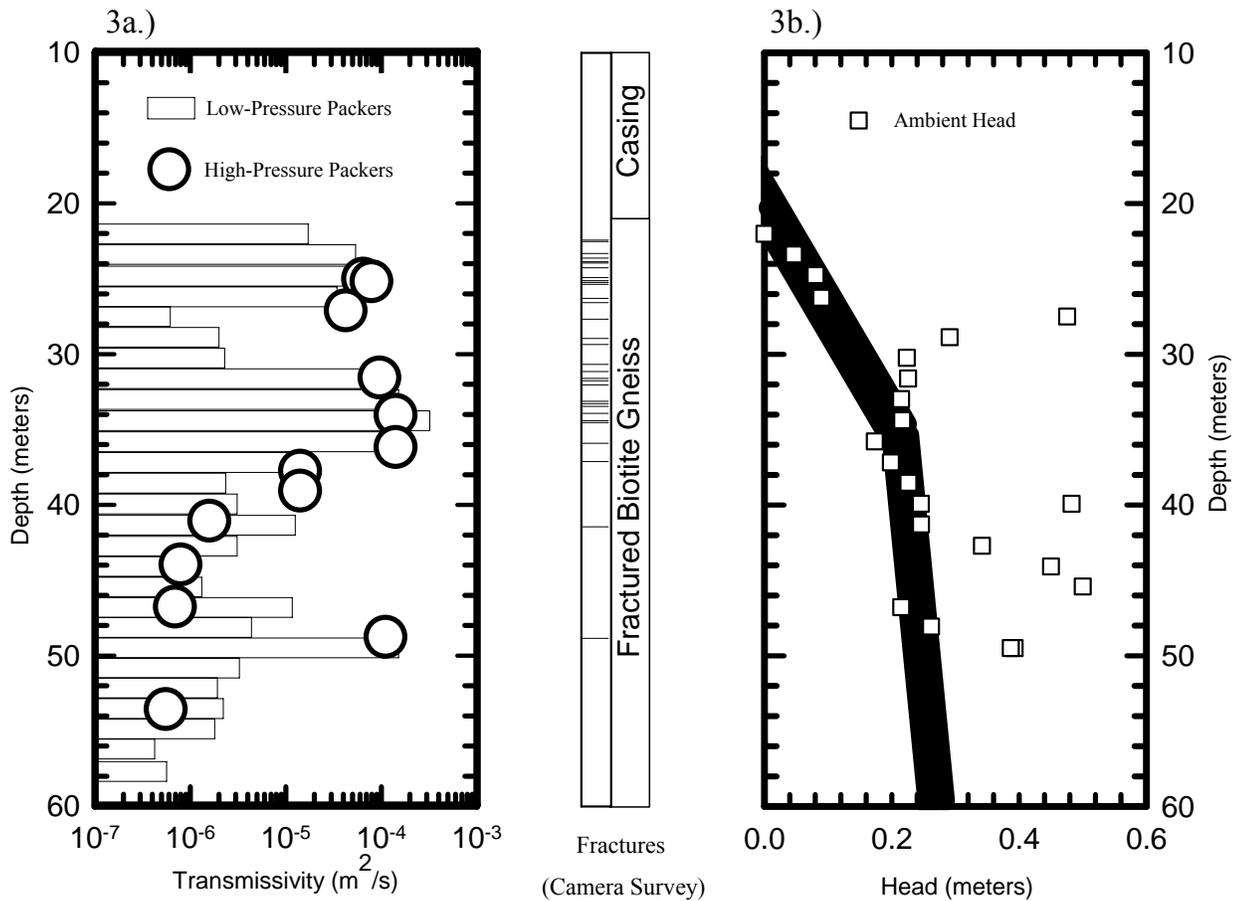
The HP and LP packer tests were compared by determining the effective  $T$  from the LP packer results that coincide with each HP packer interval (Figure 4). Transmissivity values from HP packer tests correlate well with most LP packer results. In high permeability zones the results are well within a factor 3.5 of each other. Transmissivity values in low permeability zones are between factors of 3.5 to 10 of each other.

#### CONCLUSIONS

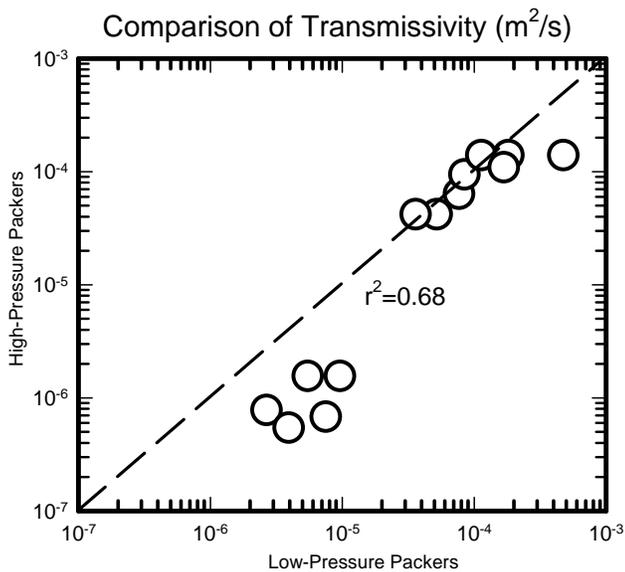
The HP packer tests are the industry standard for determining aquifer properties and fluid compositions. The HP packers we used cost approximately \$4,000. Moreover, the HP packers require using a winch, which makes them cumbersome to deploy and increases operational cost.

The LP straddle packers give results that are similar to those of the HP system, but they are considerably less expensive. Moreover, the LP system can be used without a winch, so it is easier to deploy than the HP packers.

The HP packers are nearly three times longer than the LP packers, and we expect that this will reduce the effectiveness of the seal produced by the LP system in some applications. This will be particularly important in low permeability intervals and may be why  $T$  measured with the LP system was greater than  $T$  measured with the HP packers in the tighter intervals during our tests. Nevertheless, the low cost and ease of use of the LP packers should make packer tests more accessible for characterizing fractured rock.



**Figure 3. a.) Transmissivity distributions from both HP and LP packer tests b.) Apparent equilibrated hydraulic head distribution using LP packers. Thick black line is the inferred ambient head—the points where heads are above the black line are in low T intervals and did not fully equilibrate.**



**Figure 4. Transmissivities calculated from LP and HP packer tests.**

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