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STRADDLE-PACKER DETERMINATION OF THE VERTICAL DISTRIBUTION OF HYDRAULIC PROPERTIES IN THE SNAKE RIVER PLAIN AQUIFER AT WELL USGS-44, IDAHO CHEMICAL PROCESSING PLANT, INEL

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MASTER

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ABSTRACT

Many of the monitor wells that penetrate the upper portion of the Snake River Plain aquifer at the Idaho National Engineering Laboratory (INEL) are open over large intervals that include multiple water-bearing zones. Most of these wells are equipped with dedicated submersible pumps. The completion characteristics of these wells pose problems with respect to monitoring water quality and determining the hydraulic properties of the upper parts of the Snake River Plain aquifer. Water of varying quality from different water-bearing zones is mixed within the wells. The hydrologic properties of individual water bearing zones are difficult to determine.

Water quality and water-level data have been collected, reported, and interpreted from these monitor wells for more than forty years. Data from these monitor wells have been used to demonstrate the presence or absence of organic, heavy metal, and radioactive contaminants throughout the INEL site. The problems associated with well completions over large intervals through multiple water-bearing zones raise significant questions about the meaning of the data collected.

A straddle-packer system was developed and applied at the INEL site to investigate the monitor well network. The straddle-packer system was purchased by the INEL Oversight Program of the Idaho Department of Health and Welfare and was used in well USGS-44 near the Idaho Chemical Processing Plant (ICPP). Depth specific water samples and hydraulic data were collected from packed off intervals in the well. The straddle-packer system, hydraulic testing methods, data analysis procedures, and testing results are described in this report.

Hydraulic testing revealed that hydraulic head variations with depth in well USGS-44 are less than 0.27 feet over the entire 200 foot open interval. Variations in hydraulic conductivity with depth in the Snake River Plain aquifer at well USGS-44 are large, ranging over five orders of magnitude. The total hole transmissivity of well USGS-44 measured with the straddle packer is approximately 1/2 that estimated by Ackerman (1991, personal communication). Flowmeter estimates of hydraulic conductivity (Morin et al., 1992) are up to two orders of magnitude larger than those measured using the straddle packer.

The straddle-packer system and the straddle-packer testing and data evaluation procedures can be improved for future testing at the INEL site. Recommended improvements to the straddle-packer system are: 1) improved transducer pressure sensing systems, 2) faster opening riser valve, and 3) an in-line flowmeter in the riser pipe. Testing and data evaluation recommended improvements are: 1) simultaneous valve opening during slug tests, 2) analysis of the ratio of the times for head change and recovery to occur, 3) constant-drawdown tests of high transmissivity intervals, 4) multiple-well aquifer tests, and 5) long term head monitoring.

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CHAPTER 1:

INTRODUCTION

Statement of Problem

The Idaho National Engineering Laboratory (INEL) covers 894 square miles of the Eastern Snake River Plain in southeastern Idaho (figure 1). The INEL was established in 1949 for the construction, operation, and testing of various types of nuclear reactors by the Atomic Energy Commission. Originally known as the National Reactor Testing Station, the INEL has the world's largest and most varied collection of reactors (Robertson et al., 1974).

The Idaho Chemical Processing Plant (ICPP) was constructed at the INEL (figure 2) from 1950 to 1953 for the purpose of recovering unused fissionable materials from spent nuclear fuel elements for reuse in new materials. Re-processing of nuclear fuel and nuclear wastes at the ICPP began in 1952 and continued until 1992, when the U.S. Department of Energy (D.O.E.) indefinitely suspended the processing of nuclear fuel at the ICPP. Operation of the ICPP requires approximately 1 million gallons of water per day, pumped from wells CPP-1 and CPP-2 at the north end of the ICPP (figure 3). From 1952 to February 1984, waste water from the plant was injected directly to the Snake River Plain aquifer through well CPP-3, located 1850 feet south of the production wells. Since that time, waste water has been discharged to a pair of unlined infiltration ponds located 2,400 feet south of the injection well (Bobo, 1993). Waste water from re-processing spent nuclear fuel is contaminated with fission and activation products originating from the spent fuel elements, and chloride ions from water treatment. Disposal of waste water from the plant has resulted in the formation of a contaminant plume that is migrating southward from the

Figure 1. Relief map of Idaho showing the location of the INEL, Eastern Snake River Plain, and generalized groundwater flow lines of the Snake River Plain aquifer (from Barraclough et al., 1981).

Figure 2. Location of the Idaho Chemical Processing Plant and selected features at and near the Idaho National Engineering Laboratory (after Anderson, 1991).

Figure 3. Location of well USGS-44 and other monitoring wells penetrating the upper portion of the Snake River Plain aquifer in the vicinity of the ICPP, INEL (after Anderson, 1991).

ICPP via groundwater flow (Orr, 1991).

Between 1951 and 1990, thirty-two monitor wells were constructed in basalt in the upper portion of the Snake River Plain aquifer in the vicinity of the ICPP (D.O.E., 1990). Of these, thirty-one are currently in use. Cable tool methods were used to construct twenty-three wells from 1951 to 1962; air drilling methods have been used to construct the nine wells completed since 1962 (Prahl, 1992). Dedicated sampling pumps are installed in the upper portion of the open interval of each monitor well (Prahl, 1992). Water quality and water level data are collected from these wells on a monthly, quarterly, semi-annual, or annual basis by the U.S. Geological Survey.

Most of the monitor wells at the ICPP constructed prior to 1990 are completed over intervals of basalt ranging from 27 feet to 255 feet. Many of these wells are open to multiple water-bearing zones. Wells open over large intervals through multiple water-bearing zones pose problems for monitoring depth discrete water quality and determining hydrologic characteristics of the ground water system. Current (1993) monitor well construction standards call for short open intervals at the tops of aquifers or construction of monitor well clusters for thick aquifers (NWWA, 1986). In a complex hydrogeological setting such as at the ICPP, current monitor well construction standards require well clusters with each well open to a discrete water-bearing zone.

Water samples collected from a specific location in a well open over a large interval represent a mixture of water from numerous individual zones. This makes comparison of water quality between wells difficult. The three dimensional characteristics of water quality, especially as related to contamination, are poorly documented by these wells completed in this manner.

Water-level measurements taken in wells open over large or multiple intervals represent weighted averages of hydraulic heads from individual producing intervals. The weighted average heads are commonly different from heads that would be measured in any discrete portion of the aquifer.

Measurements of transmissivity obtained from wells open over large intervals through multiple water-bearing zones represent the sum of the transmissivities of the individual zones penetrated by the well. The transmissivity of individual zones in the upper portion of the Snake River Plain aquifer may vary over several orders of magnitude. Knowledge of the hydraulic characteristics of the individual zones is important in understanding contaminant transport.

The monitor-well network at the ICPP and the data collected and interpreted from it over the past 40 years represent a significant investment. Water-level and water-quality data have been and continue to be collected, reported, and interpreted from many wells as if the data are comparable without qualification. Water-quality data have also been used to demonstrate the presence or absence of organic, heavy metal, and radioactive contaminants throughout the INEL site. However, significant questions about the interpretation of these data have been raised because of the monitor well construction methods used from 1950 through the 1980's at the INEL.

The INEL Oversight Program was established by the legislature of the State of Idaho in 1989 to provide an unbiased and independent source of information regarding the INEL's impact on public health and the environment. The INEL Oversight Program is administered through the Idaho Department of Health and Welfare. One of the activities of the Oversight

Program is to conduct independent health and environmental studies, including an evaluation of the ground-water monitoring network of the Snake River Plain aquifer.

The INEL Oversight Program in cooperation with the three Idaho universities, the Idaho Geological Survey, and the U.S. Geological Survey started a study of monitor wells open through large intervals in 1991. The centerpiece of this study is the application of a straddle-packer system capable of collecting water-quality samples from and measuring hydraulic head in discrete intervals. Water-quality sampling and hydraulic testing of the Snake River Plain aquifer using the packer system was conducted in well USGS-44 in July and August of 1992. This report presents the results of hydraulic testing within well USGS-44 as part of the overall study project.

Purpose and Objectives

The purpose of this report is to describe the application of the straddle-packer system for hydraulic testing of monitor wells completed with long open intervals in the Snake River Plain aquifer. The general objectives are: 1) to describe and evaluate the application of the straddle-packer system for hydraulic testing in well USGS-44; and 2) recommend improvements for hydraulic testing and data analysis procedures for straddle-packer testing of additional wells.

The specific project objectives are to:

1. Review literature describing the regional hydrogeology of the eastern Snake River Plain aquifer,
2. Describe the straddle-packer system, and provide a review of literature relative to packers,
3. Describe the characteristics of well USGS-44, and present a hydrogeologic conceptual model for Snake River Plain aquifer at well USGS-44,

4. Describe the vertical distribution of head in well USGS-44 measured with the straddle-packer,
5. Describe the vertical distribution of hydraulic conductivity in well USGS-44 measured with the straddle-packer,
6. Compare the hydraulic characteristics of the Snake River Plain aquifer in well USGS-44 as measured with the straddle-packer with hydraulic characteristics determined by previous investigations.
7. Recommend improvements in hydraulic testing and data analysis procedures for straddle-packer application.

CHAPTER 2:

REGIONAL HYDROGEOLOGY

General Geology

The INEL is located on the west-central part of the eastern Snake River Plain, a large, northeast-trending graben or downwarped structural basin approximately 12,000 square miles in area (see figure 1). The basin has been filled to its current level by 2,000 to 10,000 feet of relatively thin Quaternary and Tertiary age basaltic lava flows with cinders and ash deposits in the upper section, and rhyolitic tuff and ash deposits in the lower section (Doherty et al., 1979; Whitehead, 1986). The basalts of the Snake River Plain were intruded by remobilized rhyolitic domes, such as Big Southern, Middle, and East Buttes (figure 2), which are elevated by as much as 2000 feet above the surface of the plain to the south of the ICPP (Robertson et al., 1974). Interbedded deposits of clay, silt, sand and gravel of fluvial, lacustrine, and eolian origin are common in the upper 2000 feet of basaltic rocks that underlie the INEL. A thin layer of recent alluvium, deposited principally by the Big Lost River, forms the present land surface in the vicinity of the ICPP. A comprehensive discussion of the geologic evolution of the Snake River Plain was given by Robertson et al. (1974), Hackett et al. (1986), and Lindholm and Vaccaro (1988).

Stratigraphy

Anderson (1991) described the stratigraphy of the unsaturated zone and uppermost part of the Snake River Plain aquifer at the ICPP and Test Reactors Area (TRA). Wells drilled to a depth of 700 feet at the ICPP and TRA penetrate a sequence of 23 basalt-flow groups and 15 to 20 sedimentary interbeds ranging in age from 200,000 to 640,000 years.

The 23 flow groups consist of about 40 separate basalt flows and flow units. Basalt flow groups consist of one to three petrographically similar basalt flows that erupted from related source areas during periods of less than 200 years (Kuntz et al., 1980). Anderson (1991) used composite stratigraphic units consisting of multiple basalt-flow groups and related sedimentary interbeds of similar age and source to describe the sub-surface stratigraphy in the ICPP and TRA area. Seven composite stratigraphic units have been identified in the upper 700 feet at the ICPP.

Well USGS-44 penetrates all seven of the composite stratigraphic units described by Anderson (1991). The water table in well USGS-44 during the 1992 field season occurred at approximately 461 feet below land surface (4458 feet ASL), in a composite stratigraphic unit made up of basalt flow-groups E, EF, F, FG, G and H and related sediment. The bottom of the well is in flow group I and related sediment.

Flow groups E, EF, F, FG, G, and H and related sediments consist mainly of thin, discontinuous basalt flows that form a wedge-shaped composite stratigraphic unit underlain by a widespread sedimentary interbed. These flows lap against the south, west, and east-sloping surface of flow group I; parts of the unit pinch out north and east of the TRA and north of the ICPP (Anderson, 1991). Flow group I and related sediment consists mainly of thick basalt flows at the ICPP and TRA. The stratigraphy at well USGS-44 is shown in figure 4.

Hydrogeology

The Snake River Plain aquifer occurs in the Snake River Plain basalts and underlies nearly all of the eastern Snake River Plain (see figure 1). Ground-water flow is generally

Figure 4. Stratigraphy of the unsaturated zone and uppermost part of the Snake River Plain aquifer at well USGS-44 as described by Anderson (1991).

from northeast to southwest. Recharge to the Snake River Plain aquifer near the ICPP is from the Mud Lake basin to the northeast of the INEL, from the Big Lost River to the northwest, and from Little Lost River and Birch Creek to the north and northwest. Recharge to the aquifer at the ICPP also occurs from un-lined percolation ponds located at the south end of the ICPP. A small amount of recharge is derived from local precipitation. Discharge from the Snake River Plain aquifer occurs along the Snake River at the Thousand Springs area near Hagerman, Idaho. Discharge from the Snake River Plain aquifer at the ICPP is from wells CPP-1, CPP-2, and CPP-4. Wells CPP-1 and CPP-2 provide process water to the ICPP. These wells each discharge approximately 3000 gallons per minute (gpm) when in operation. Well CPP-4 provides drinking water to the ICPP.

Hydrostratigraphy

The hydrostratigraphy of the ICPP area originally was described by Jones (1961). Jones (1961) developed a localized, multiple aquifer, conceptual model for the upper 200 feet of saturated basalts and sediments based primarily on natural-gamma and hole diameter (caliper logs) from wells drilled prior to 1960. Jones (1961) identified aquifers as highly permeable interflow zones between dense, massive basalt flows. Five locally distinct aquifers were identified by Jones (1961) based on caliper logs, natural-gamma logs, and drillers' lithologic data. Highly productive aquifers were interpreted to exist where the borehole diameter exceeded the effective bit size by two inches with relatively low gamma-ray intensities. Borehole intervals with extensive enlargements and natural gamma intensities characteristic of sedimentary interbeds as well as borehole intervals with little or

no enlargement above the effective bit size were inferred to have relatively low hydraulic conductivity.

Prahl (1992) compared the lithostratigraphy of Anderson (1991) with the hydrostratigraphy of Jones (1961) and attempted to extrapolate Jones' (1961) methods of correlation to wells drilled since 1960. Prahl (1992) concluded that the hydrostratigraphic correlation methods of Jones (1961) cannot be used to define the spatial distribution of discrete water bearing intervals within or between post 1960 wells. Prahl (1992) also concluded that borehole enlargements shown on caliper logs cannot be strictly correlated with geologic contacts between the basalt flow groups identified by Anderson (1991).

Hydraulic Characteristics of Snake River Plain Basalts

The hydrologic characteristics of a lava flow are controlled by the chemical composition, the amount of volatiles in the magma, temperature of extrusion, flow thickness and degree of diagenesis, and regional tectonic setting (Wood and Fernandez, 1988). Chemical composition and temperature of extrusion affect the viscosity of basalt. The viscosity of a basalt flow in combination with the volume of basalt extruded determine the thickness, rate of flow, areal extent and physical characteristics of the basalt flow.

The physical characteristics of a basalt flow change as it moves away from its source vent, and the lava cools and degasses. Near the vent, temperature and gas content are highest, and the lava contains relatively few crystals. Lava with these characteristics typically forms pahoehoe. As the lava moves away from the vent source, it cools and degasses and gradually changes from pahoehoe to the generally more permeable aa basalt (MacDonald, 1953).

The amount of volatiles in the magma and the thickness of the flow controls the amount of vesicles in a basalt flow. Vesicles can lead to fairly high porosities. Wood and Fernandez (1988) reported total porosity ranges for basalt from a worldwide data base of zero to 75 percent, with most values between zero and 15 percent. Effective porosity in basalt is generally much less than total porosity due to the non-interconnected nature of vesicles.

The distribution of fractures and thus hydraulic conductivity of a basalt flow also is controlled by the cooling history of the flow. Cooling begins as soon as a lava flow reaches the surface. As a lava flow cools it shrinks, and the shrinkage results in fractures. Fractures that form at the upper and front surface of a flow form clinker and basalt blocks. As the flow advances, the rubbly flow top and flow front are buried, forming a permeable layer at the base of the flow. When extrusion ceases, the flow stops advancing and the rubbly flow tops and bases are preserved, forming permeable zones at the contact between two flows. The interior cools more slowly and tends to be less fractured. Interior joints form as the flow continues to cool.

Ground-water flow through the Snake River Plain aquifer is controlled by the structure of the basalt flows and the characteristics of the interbedded sediments. Intraflow structure and hydraulic conductivity vary considerably within the vertical extent of individual flows (Lindholm and Vacarro, 1988). Considerable horizontal variability may also exist in individual flows based on observations of recent lava flows in the INEL area. The rubbly and highly fractured top of an individual flow is typically very porous and has a high horizontal hydraulic conductivity. The more massive central part of the flow may have moderate porosity depending on vesicles and jointing, and typically has much lower

horizontal and vertical hydraulic conductivity than interflow zones. The base of a flow is typically scoriaceous and has high hydraulic conductivity (Lindholm and Vacarro, 1988). Intraflow structural controls on water movement in a discharge area of the Snake River Plain aquifer is illustrated in figure 5. Transmissivity of the Snake River Plain aquifer is reported to range from 1.1 to 7.6×10^5 feet squared per day (Ackerman, 1991).

Interbedded sediments may act as either a confining layer or an aquifer depending on the grain size and sorting of the sediments. Fine grained lacustrine and aeolian sediments reduce the hydraulic conductivity of an interflow zone and act as a confining layer whereas coarser grained fluvial sediments may increase the hydraulic conductivity of the interflow zone.

Kuntz et al. (1980) described three gradational structural and textural units in lava flows and flow units observed in drill cores from the Radioactive Waste Management Complex (RWMC), located approximately 8 miles southwest of the ICPP. The top of each flow or flow unit consists of fine grained, vertically and horizontally jointed, vesicular and locally clinkery basalt, typically less than two meters thick. The central portion of each flow or flow unit consists of a massive, coarser grained basalt with prominent vertical joints and vesicles arranged in vertical pipes and horizontal layers. Diktytaxitic texture is typical in the central portion of flows and flow units. The base of flows and flow units typically consist of a thin (less than one meter), typically oxidized bed of fine-grained scoriaceous basalt blocks.

Basalt flows and flow units of the Snake River Group were erupted from numerous eruptive centers. This has produced a complex overlapping and interfingering of flows (Nace et al., 1956). Individual lava flows are as much as 30 km in length and commonly cover 130 to 300 km². The thickness of individual lava flows ranges from three to 15 m and

POSITION IN FLOW	LITHOLOGY	HYDROGEOLOGY	HYDRAULIC CONDUCTIVITY
Center	See below		see below
Base	See below		see below
Interbed	Clay, silt		Very low, confining
Top	Basalt, vesicular, brecciated		High, may be very high
Center	Basalt, less vesicular than above, vesicularity decreases with depth; vertically jointed		Horizontal: low to moderate, depending on vesicularity and degree of fracture Vertical: depends on degree of fracture; commonly several orders of magnitude lower than horizontal conductivity
Base	Basalt, vesicular; platy		Base and interbed moderate to high; combined with top zone may be extremely high (interflow zone)
Interbed
Top	See above
Center	See above		see above

Figure 5. Generalized intraflow stratigraphy of the Snake River Basalts showing structural controls on ground water movement (after Lindholm and Vacarro, 1988).

averages six to seven m (Mundorff, 1964). A geologic cross section through the ICPP area appears in figure 6.

Figure 6. Geologic cross section through the ICPP area (after Anderson, 1991).

CHAPTER 3:

LITERATURE REVIEW OF PACKERS AND DESCRIPTION OF STRADDLE-PACKER TESTING EQUIPMENT

Packers in Hydraulic Testing and Ground-Water Monitoring

Packers are used in hydraulic testing to isolate discrete intervals in an uncased well or in a well with perforated casing. A packer is an expandable bladder that when inflated expands and forms a seal against the walls of a borehole or casing. A single packer isolates a well into two zones, one above the packer and one below. Two packers, separated by a finite distance, isolate an interval within a well.

A packer system used in hydraulic testing commonly consists of: 1) two or more packers, 2) a pump located between the packers, 3) valves to control the flow of water, and 4) pressure transducers to detect head changes in the packed-off interval and the portions of the well above and below it (figure 3). The packer is lowered into a well on riser pipes or by cable to the interval to be tested. The packers are expanded and the packed-off interval can then be sampled and hydraulically tested.

Fixed Casing Multi-Level Packers

Fixed casing, multi-level packers are ground-water monitoring systems where a casing is permanently installed in a well with packers located on the casing to separate individual water producing zones. Cherry and Johnson (1982) described a multi-level packer system designed to be permanently installed in an open borehole (figure 7). The device consists of a bundle of tubes contained within a PVC casing that is capped on the bottom. Each of the tubes extends to a different depth where a water producing zone has

Figure 7. Various packer configurations used for hydraulic testing and sampling. (A) depicts a ported casing with dedicated sampling tubes open to fractured zones similar to the system described in Cherry and Johnson (1982). (B) is a multi-level ported casing with movable inner packer similar to the system described by Bottomley et al. (1984). (C) is a straddle-packer system deployed in an open borehole similar to the straddle-packer used for hydraulic testing in Blankennagel (1968) and in this report.

been identified and is open to the water-producing zone through a 90° elbow that protrudes through the casing. Individual water-producing zones can then be sampled for water quality, hydraulic head can be measured, and tests can be performed to determine hydraulic conductivity.

Welch and Lee (1987) described a multiple-packer/standpipe system used for ground-water monitoring in consolidated media. The system described by Welch and Lee (1987) provides a known pressure seal between selected portions of a borehole, simultaneous access through several standpipes in each borehole, and can be removed from the borehole when desired.

Bottomley et al. (1984) described borehole techniques for investigating fractured rocks that utilizes a geochemical probe mounted between two packers that is lowered on an umbilical cable system into a multi-level ported casing. The multi-level ported casing is permanently installed in the borehole with casing packers between the ported casing sections to hydrologically isolate fracture zones.

Packers in Open Boreholes

Packer systems are also used in uncased portions of wells to isolate intervals for sampling or hydraulic testing, particularly in fractured rock environments. Numerous examples exist in the literature describing the application of straddle packers to hydrologic testing in open boreholes and remediation of contaminated aquifers. Straddle-packer systems have been used extensively at Department of Energy sites for hydrologic investigations of low permeability rock units as potential waste storage sites.

Jones (1961) used a straddle-packer system at the INEL to hydrologically test four wells near the ICPP. A total of 16 tests were conducted in wells USGS-42, 43, 44, and 49. Hydraulic testing consisted of injection tests and measurement of static heads. Injection test results were used to qualitatively assess the transmissivity of the straddled intervals.

A straddle-packer system was utilized at the Nevada Test Site (NTS) to conduct hydrologic tests in deep exploratory boreholes at Pahute Mesa ranging from 4,500 to 8,000 feet deep (Blankennagel, 1968). Hydraulic testing consisted of measuring relative specific capacity and static head.

Straddle packers also have been used at the Hanford site in Washington State where extensive hydrologic testing was conducted as part of the Basalt Waste Isolation Project. Strait et al. (1982) report on hydrologic testing methods and results from deep basalt boreholes. Strait and Mercer (1986) provide hydraulic property data from selected test zones on the Hanford site. Science Applications, Inc. (1978) report on testing methodology and results from hydrologic testing in borehole DC-2.

Straddle-Packer Design and Description

Introduction

A straddle-packer system was designed and acquired to meet the INEL Oversight Program objective of evaluating the ground-water monitoring network at the INEL. The straddle-packer system also allows for direct testing of the hydrostratigraphic conceptual model of Jones (1961) and for improvement of the hydrostratigraphic conceptual model for Snake River Plain aquifer near the ICPP. INEL Oversight Program objectives for the straddle-packer project are to:

1. Characterize and quantify changes in ambient natural and or contaminant chemistry with depth.
2. Characterize and quantify head and in-hole ground water flow profiles, under non-pumping conditions.
3. Characterize and quantify changes in hydraulic conductivity with depth.
4. Recognize the effective base of the Snake River Plain aquifer and place profiles from objectives 1, 2 and 3 into a hydrostratigraphic context.
5. Determine comparability of water chemistry profiles results with historic sampling results in the tested wells.
6. Use test results to make recommendations, as needed, for changes in sampling practices, reconstruction of existing wells, and/or location and construction of additional wells to improve the regional aquifer monitoring system.

Straddle-Packer Design

Design of the straddle-packer system was a joint effort by personnel from the Idaho Department of Health and Welfare, INEL Oversight Program; the Idaho Geological Survey; Idaho Water Resources Research Institute, Boise State University, University of Idaho, and Idaho State University. The design specifications called for a modular system consisting of three assemblies. The three modules were necessary to facilitate transport of the straddle-packer and assembly of the straddle-packer under drill rigs with mast heights less than the total length of the straddle-packer. The modules consist of:

1. Upper Packer Assembly containing the upper packer, upper transducer and protective shroud, and the riser valve;
2. Pump Assembly containing the pump, middle transducer and protective shroud, and the circulation valve;
3. Lower Packer Assembly containing the lower packer, lower transducer and protective shroud, and pup joints.

To be able to accomplish the aquifer testing objectives of the INEL Oversight Program, the straddle-packer system had to meet the following design criteria:

1. be made of chemically inert components,
2. be capable of operating to 1000 feet in depth,
3. be capable of hydrologic testing and water quality sampling, including purging prior to sampling,
4. be capable of adjustable straddle interval lengths,
5. be capable of passing through a 6 inch diameter casing.

Straddle-Packer Component Descriptions

The straddle-packer utilized in this testing program was built by Baski, Inc. of Denver, Colorado. The current minimum straddled interval length is 12.5 feet. From top to bottom the packer consists of (see figure 8): riser valve, upper transducer, upper packer, circulation valve, pump, middle transducer, lower packer and lower transducer.

The riser valve controls the flow of water through the riser pipe. The riser valve consists of an inflatable bladder contained within a stainless steel housing and the necessary fittings for inflation. When uninflated, water can flow between the bladder and the outer housing. When inflated, the bladder expands and shuts off flow.

The circulation valve is attached to the discharge end of the pump and allows the discharge from the pump either to circulate within the packed-off interval or to be discharged to the surface. The circulation valve is controlled by gas pressure. When open, the circulation valve directs the pump discharge into the packed-off interval for circulation. Water is pumped to the surface when the valve is closed.

STRADDLE PACKER SCHEMATIC

Figure 8. Schematic diagram of the straddle-packer system showing the main components (not to scale).

The transducers are non-vented (absolute) Paroscientific DIGIQUARTZ® intelligent depth sensors with an operating range of 0 to 400 psia. The upper and lower transducers are housed in five-inch diameter stainless steel housings and sense pressures above and below the packed-off interval. The middle transducer is housed in the lower end of the pump shroud and senses pressure within the packed-off interval.

The packers are sliding end packers, with the lower end of each packer free to slide up the mandrel as the packer inflates and increases in diameter. This allows the packer to expand to a greater diameter than a fixed end packer. The total length of each packer is 4.18 feet. The lower 1.41 feet of the upper packer and the upper 1.41 feet of the lower packer are covered with chemically inert Viton; the remaining 2.77 feet of each packer is made of rubber. Separate inflation lines allow independent inflation and deflation of the packers.

The pump is a five horsepower stainless steel Grundfos pump, housed within a protective stainless steel pump shroud between the packers. The pump intakes are located at the top of the lower packer, which is connected to the pump shroud by two-inch stainless steel pipes of varying length to control the length of the packed off interval. The lower end of the two-inch pipe is connected to the upper end of the lower packer.

Packer Support Equipment

The straddle-packer is operated by eight, 1100-foot control lines that are housed on spools in the support bus. Five of the lines are stainless steel tubing: two 1/4-inch diameter stainless steel inflation lines to inflate the packers, a 3/16-inch diameter stainless steel inflation line to operate the riser valve, two 3/16-inch diameter stainless steel lines to operate the circulation valve. The other three lines are a teflon coated pump power cable, a teflon

coated transducer cable, and a 1/2 inch diameter teflon injection line for emplacement of tracer.

The straddle-packer was lowered into the well and moved from interval to interval in 1992 using a drill rig provided under contract by the U.S. Geological Survey. Power for operation of the straddle-packer pump as well as computers, analytical chemical equipment, and air conditioning equipment in the support bus and geochemistry van was provided by portable generators.

Data Acquisition Equipment

Transducer data were collected on a portable computer. A laptop computer using BASIC programs was used to collect the majority of the data. Two BASIC programs were used to record data from the transducers. The program used during the portions of hydraulic tests that required closely spaced readings recorded pressure at a rate of approximately three readings per second. A second program with a user programmable read rate was used for static head monitoring.

An IN-SITU HERMIT 2000 data logger was used to monitor barometric pressure and to monitor head changes in the riser pipe during various aquifer tests. The data logger also was used to monitor water levels in wells USGS-44, USGS-45, and USGS-46 before the start of straddle-packer testing. An electrical measuring tape was used to measure static water levels in the well and to measure the head changes during slug tests.

Water flow at the surface was controlled by the surface valve assembly. The surface valve assembly consists of stainless steel tubing and valves that direct the water flow to sampling ports, the geochemistry van and flow cell, or to a 2000 gallon discharge storage

tank used to store the discharge from the well. Discharge from the well was stored until samples from the tank had been analyzed for radioactive contamination. The discharge storage tank was drained onto the surface after analysis of samples from the tank showed no contamination.

An in-line flow meter located in the discharge line between the surface valve assembly and the storage tank was used to measure the flow rate in gallons per minute and flow volume in gallons. The flow meter was located in the discharge flow path after the sampling lines and thus did not include the flow through the sampling lines. Total discharge rate was calculated by adding the flow meter discharge rate to the discharge rate through the sample lines, measured using a graduated cylinder and stopwatch.

CHAPTER 4:

CHARACTERISTICS OF WELL USGS-44

Well Construction and Completion

Well USGS-44 was constructed in 1957. The construction information provided in the Comprehensive Well Survey (D.O.E., 1990) suggests well USGS-44 was drilled by cable tool methods. The well is located along the west side of the ICPP and is south of the Big Lost River channel. The total depth of well USGS-44 is 650 feet. The well is cased from 2 feet above land surface to 461 feet below land surface (bls) with 6.25-inch carbon steel casing. The well is open for 189 feet from 461 feet bls to 650 feet bls. From the surface to 35 feet bls the borehole was drilled with a diameter greater than 12 inches. From 35 feet bls to 385 feet bls the bit size was reduced and a 10-inch diameter hole was drilled. At 385 feet bls, the bit size was reduced again to 8 inches, and an 8 inch hole was drilled to 461 feet bls. Six inch diameter hole was drilled from 461 feet bls to the bottom of the hole at 650 feet bls (D.O.E., 1990). These reductions in bit size are typical of a cable tool drilled borehole. The annular space between the casing and the borehole was filled with sand, cement and grout from 454 feet bls to 461 feet bls below land surface and with drill cuttings from 454 feet bls below land surface to land surface.

Hydrologic Conditions

Transmissivity

Ackerman (1991) estimated transmissivities of the Snake River Plain aquifer at the INEL using aquifer test data from 183 aquifer tests at 94 wells. The transmissivity of the

Snake River Plain aquifer at well USGS-44 was estimated by Ackerman (personal communication) at 410,000 ft²/day. A comparison of Ackerman's (personal communication) transmissivity for well USGS-44 and straddle-packer measured transmissivities is presented in chapter 7.

Geophysical Logs of Well USGS-44

Caliper Logs

A caliper log represents variations in the diameter of an open borehole as well as the inside diameter of the casing. The caliper tools used in well USGS-44 contain three extendible feeler arms that are mechanically coupled to trace the wall of the borehole. The accuracy of the log produced by these tools is a function of the geometry of the borehole. The diameter measured by the caliper tool is that measured by the arm that extends the smallest distance. Caliper logs are used to locate fractures and cavernous zones, and to aid in the interpretation of diameter-dependent nuclear logs.

Caliper logs are available for well USGS-44 as logged by Morin et al. (1992), Wood and Bennecke on September 25, 1991 (personal communication), and the U.S. Geological Survey on May 5, 1960 (Bartholomay, 1990). The caliper log by Morin et al., (1992) appears in figure 9.

Caliper logs reveal a breakout that occurs just below the bottom of the casing at 461 feet that extends to approximately 475 feet bls. From approximately 475 feet bls to 495 feet bls the borehole is relatively smooth with minor variations in diameter. The interval from approximately 500 feet bls to 575 feet bls includes large breakouts separated by relatively thin intervals of smaller diameter from: 516 to 519 feet bls, 524 to 527 feet bls, 533 to 537

Figure 9. Selected borehole geophysical logs for well USGS-44. Elevations given as depth below ground surface and elevation above sea level. (After Morin et al., 1992).

feet bls, 552 to 558 feet bls, 563 to 565 feet bls, and 569 to 572 feet bls. The borehole below approximately 575 feet bls is relatively smooth.

Neutron-Porosity Log

A neutron-porosity log from the open interval of well USGS-44 conducted by the Morin et al., (1992) appears in figure 9. Neutron logs provide an indicator of total porosity under saturated conditions or the moisture content of unsaturated materials. The neutron-porosity log and caliper logs are similar. Low porosity intervals tend to coincide with intervals with little enlargement beyond the bit size, while high porosity intervals coincide with large diameter portions of the well.

Natural Gamma

A natural gamma log for the open interval of well USGS-44 conducted by (Morin et al., 1992) appears in figure 9. Natural gamma logging at the INEL is used primarily for identification of sedimentary interbeds that contain greater concentrations of naturally occurring radioisotopes, especially potassium-40 (Anderson, 1990).

The natural gamma log is noisy and shows relatively minor variation throughout the open interval. A 10-read moving average of the gamma log (figure 9) shows lows occurring at approximately 500, 540 and 570 feet bls and highs occurring at 520, 550 and 620 feet bls. The sedimentary interbed that occurs just above the "I" flow in most wells (Anderson, 1991) did not produce a gamma spike and may not be present in well USGS-44.

Flowmeter Logging

Flowmeter logging was conducted in well USGS-44 by the U.S. Geological Survey in cooperation with the Idaho Department of Health and Welfare INEL Oversight Program

in 1990 to assess hydrologic conditions in the well prior to straddle-packer testing (Morin et al., 1992).

Vertical movement of water is common in most wells open to more than one aquifer or where a substantial vertical hydraulic gradient exists. In layered basalt aquifers where head differences may exist between individual basalt flows, vertical flows are of particular importance. Naturally occurring vertical head differences caused by aquifer heterogeneities can be used to evaluate potential contaminant dispersal pathways.

Natural Flow Conditions

Thermal flowmeter measurements were made at nine depths in well USGS-44 under natural flow conditions and while pumping. Information on the nine measurement sites under natural flow conditions and pumping flow conditions is summarized in table 1.

Table 1. Thermal flow-meter measurements in well USGS-44 (after Morin et al., 1992).

depth (feet bls)	elevation (feet amsl)	flow without pumping (gpm)	flow while pumping (~22 gpm)
480	4,439	0.2 upflow	11.7 upflow
495	4,424	0.1 upflow	11.7 upflow
515	4,404	3.2 upflow	8.3 upflow
523	4,396	3.8 upflow	8.3 upflow
556	4,363	0.1 upflow	0.8 upflow
568	4,351	0.1 upflow	0.3 upflow
578	4,341	0	0
610	4,309	0	0
632	4,287	0	

Morin et al. (1992) reported that two separate upward circulation cells are present in well USGS-44 under natural flow conditions. A very weak cell occurs in the uppermost part of the aquifer just below the casing. A broader, more vigorous cell occupies the central

portion of the well. No flow is detectable below 579 feet bls, within flow group I (Morin et al., 1992). Flowmeter measurements taken while pumping imply that nearly half of the flow during pumping (approximately 10.3 gpm) comes from above 480 feet bls.

Flowmeter Hydraulic Conductivity Measurements

Morin et al., (1992) estimated the vertical distribution of hydraulic conductivity in well USGS-44 using a technique developed by Hufschmied (1984) that utilizes pumping at constant rates and concurrent flowmeter and pressure measurements. The hydraulic conductivity of seven individual layers in well USGS-44 from Morin et al. (1992) are shown in table 3. The hydraulic conductivity values span approximately 2 orders of magnitude. The cumulative transmissivity is 890,000 ft²/day for that portion of the Snake River Plain aquifer penetrated by well USGS-44. Morin et al. (1992) found that flow top zones identified by large diameter zones on caliper logs control the distribution of hydraulic conductivity in well USGS-44. The hydraulic conductivity estimates from Morin et al. (1992) are compared to hydraulic conductivity estimates from straddle-packer testing in chapter 7.

Table 2. Hydraulic conductivity of tested intervals as determined by flowmeter measurements in well USGS-44 (after Morin et al., 1992).

tested interval (feet bls)	Hydraulic Conductivity (ft/day)
461-480	>10,000
480-495	200
495-515	10,000
515-523	1,000
523-556	4,500
556-568	1,000
568-578	750

Hydrogeological Conceptual Model for the Snake River Plain Aquifer at Well USGS-44

The hydrogeological conceptual model presented in this section is based on: 1) the eight flows identified in the open interval of well USGS-44 by Morin et al. (1992), and 2) on the typical structural and textural units of flows and flow units described by Kuntz et al. (1980). The hydrogeological conceptual model consists of a layered sequence of alternating zones with high and low horizontal hydraulic conductivity values. Zones with low hydraulic conductivity may have higher vertical hydraulic conductivity values if vertical fractures extend through the interval. The hydrogeological conceptual model for well USGS-44 is illustrated in figure 10.

Selection of Tested Intervals

Ten intervals were tested in well USGS-44, covering all but eleven feet of the open borehole (shown on figure 10). The ten intervals were selected in order to characterize vertical variations in hydraulic head, hydraulic conductivity, background water chemistry and contaminant water chemistry. Each of the selected intervals tested portions of the borehole that represent either: 1) producing zones identified by Morin et al., (1992), 2) portions of the borehole characterized by either large breakouts on caliper logs (potential producing zones) or 3) portions of the borehole characterized by relatively uniform diameter on caliper logs (potential confining layers). The tested intervals were also selected to minimize the number of times the packer system had to be removed from the well to change the length of the interval straddled. Two straddle lengths, 20 feet and 15 feet, were used during the 1992 field season.

Figure 10. Hydrogeological conceptual model for the portion of the Snake River Plain Aquifer penetrated by well USGS-44 with hydraulic testing intervals.

Each tested interval required relatively smooth portions of borehole above and below for good packer seats. Packer seats were selected based on caliper logs done by Morin et al. (1992) and a borehole television log by Roger Jensen of the U.S. Geological Survey.

CHAPTER 5:

HEAD MONITORING DATA AND HEAD PROFILE DETERMINATION

Introduction

Heads were monitored overnight in seven straddled intervals to determine the static head profile in well USGS-44. Overnight head monitoring was completed on the 467-482, 480-495, 495-515, 500-515, 519-534, 580-600, and 600-620 feet bls straddled intervals. Head data from the 461-467 and 620-650 feet bls intervals were recorded with the upper and lower transducers, respectively, during testing of the 467-482 and 600-620 feet bls straddled intervals. Data from these tests were used to estimate the static head profile in well USGS-44 and the barometric efficiency of the tested intervals. The 535-555 and 557-577 feet bls intervals were not monitored overnight and barometric efficiency estimates were not made on these intervals.

Interpretation of Transducer Readings

The Paroscientific transducers used in the straddle-packer system are non-vented transducers. The transducers measure absolute pressure, and are not compensated for changes in atmospheric pressure. As a result, pressure readings from the transducers are a measure of both atmospheric pressure and fluid pressure.

Since the transducers measure total pressure, changes in atmospheric pressure may result in changes in the pressure measured by the transducers, depending on the nature of the aquifer system being monitored. The equation describing the pressure measured at the transducer (Tr) in a confined aquifer open to the atmosphere during periods when the atmospheric pressure is changing is given by:

$$Tr = \bar{P}a + \bar{P}w + \Delta Pa(1 - B.E.) \quad \text{eq. 5-1}$$

where $\bar{P}a$ is an average atmospheric pressure, ΔPa is the change in barometric pressure, $\bar{P}w$ is pore water pressure under average atmospheric pressure ($\bar{P}a$), and $B.E.$ is barometric efficiency. The average atmospheric pressure used in head calculations in this report is the average of all atmospheric pressures measured during the field season (28.59 feet H_2O). A discussion of the method used to develop equation 5-1 appears in Appendix 1.

Head Monitoring Field Procedures

Head monitoring tests were conducted by continuously monitoring heads during an overnight period of at least 10 hours. Concurrent surface barometric pressure readings were recorded using a transducer and data logger. Head monitoring tests included times when the ICPP production wells were off and also when the ICPP production wells were pumping. Plots of barometric pressure and head versus time for each overnight monitored interval appear in figures 11-17. The test dates and ICPP production well in use during each overnight test are summarized in table 3. Head was determined as the sum of pressure head and the elevation of the point of observation, in feet above mean sea level (asl).

Head Monitoring Data Evaluation Methods

Data from the overnight head monitoring tests were evaluated in two stages. Barometric efficiency and static head estimates for each interval and an estimated static head profile for well USGS-44 were developed in the first stage. In the second stage, the validity of the static head profile was evaluated by comparing head differences between transducers.

Figure 11. Plot of head and barometric pressure versus time from overnight head monitoring of the 467 to 482 feet bls interval.

Figure 12. Plot of head and barometric pressure versus time from overnight head monitoring of the 480 to 495 feet bls interval.

Figure 13. Plot of head and barometric pressure versus time from overnight head monitoring of the 495 to 515 feet bls interval.

Figure 14. Plot of head and barometric pressure versus time from overnight head monitoring of the 500 to 515 feet bls interval.

Figure 15. Plot of head and barometric pressure versus time from overnight head monitoring of the 519 to 534 feet bls interval.

Figure 16. Plot of head and barometric pressure versus time from overnight head monitoring of the 580 to 600 feet bls interval.

Figure 17. Plot of head and barometric pressure versus time from overnight head monitoring in the 600 to 620 feet bls interval.

Table 3. Test dates and ICPP production well in use during overnight head monitoring tests.

Tested Interval:	Dates tested (1992):	ICPP Well:
467-482	8/13-8/14	CPP-1
480-495	8/14-8/15	CPP-1
495-515	8/6-8/7	CPP-1
500-515	11/5-11/12	CPP-1
519-534	8/17-8/18	CPP-1
580-600	7/29-7/30	CPP-2
600-620	8/3-8/4	CPP-2
600-620	8/4-8/5	CPP-1

Static Head Profile and Barometric Efficiency Estimation

Static head and barometric efficiency at each overnight monitored interval were estimated by performing a linear regression on the head and barometric pressure data with barometric pressure as the independent variable and head as the dependent variable. The regression provides an estimate of the barometric efficiency ($-X$ coefficient) and a qualitative measure of the reliability of the estimate (R^2).

Static head under average barometric pressure at each interval was calculated using:

$$H = (X \times \bar{P}a) + C \quad \text{eq. 5-2}$$

where:

H = static head,

X = X coefficient from regression,

$\bar{P}a$ = average barometric pressure,

C = constant from regression.

In intervals that were not continuously monitored, static head was estimated by subtracting the average barometric pressure from the average transducer pressure measured in the interval under non-pumping conditions, plus the elevation of the point of observation. This may result in static head errors as large as 0.5 feet in these intervals.

Analysis of Results

A plot of head versus barometric pressure for all overnight monitored intervals appears in figure 18. Static head data and the results of the head versus barometric pressure regression appears in table 4. Calculated head values range from 4457.92 feet asl in the 461-467 feet bls interval to 4457.33 feet bls in the 620-650 feet bls interval. Barometric

Figure 18. Plot of head versus barometric pressure for all overnight monitored intervals.

Table 4. Static head regression, barometric efficiency and storativity data for tested intervals in well USGS-44.

Interval (feet bls)	Transducer elev. (ft amsl):	Constant (ft amsl)	X Coefficient (-B.E.)	R Squared	average head (ft amsl)	error band (feet)	barometric pressure change (ft H ₂ O)
461-467	4457.87	4475.63	-0.62	0.75	4457.92	0.74	0.17
467-482	4441.72	4482.93	-0.88	0.87	4457.72	0.70	0.17
480-495	4428.60	4482.82	-0.88	0.66	4457.78	1.24	0.14
495-515	4412.92	4496.69	-1.36	0.57	4457.78	2.43	0.13
500-515	4409.10	4469.56	-0.42	0.86	4457.51	0.19	0.76
519-534	4389.70	4476.11	-0.64	0.40	4457.74	1.63	0.14
535-555*	4372.99	N.A.	N.A.	N.A.	4457.88	N.A.	N.A.
557-577*	4351.69	N.A.	N.A.	N.A.	4457.90	N.A.	N.A.
580-600	4328.69	4482.01	-0.85	0.60	4457.65	2.59	0.14
600-620	4308.68	4484.15	-0.93	0.54	4457.65	1.27	0.16
620-650	4290.96	4482.35	-0.88	0.41	4457.33	1.55	0.16

* intervals not monitored overnight

efficiency estimates vary from 42% in the 500-515 feet bls interval to greater than 100% in the 495-515 feet bls interval.

The calculated static heads in table 4 are dependent on the barometric efficiency calculated from the regressions. Small barometric pressure changes (~ 0.15 ft) result in barometric efficiency estimates with a high degree of uncertainty. This uncertainty is expressed as the error band in table 4. The error band was calculated by multiplying the standard error of the X-coefficient by $\bar{P}\alpha$. The 500-515 feet bls test, a seven day test with a barometric pressure change of 0.76 feet, has the most reliable barometric efficiency and therefore the most reliable estimate of static head. Head monitoring tests where the barometric pressure change is less than about 0.3 feet are not adequate for estimating static head using the regression method.

The estimated barometric efficiency of greater than 100% in the 495-515 feet bls interval is not theoretically possible. The continually decreasing head after 18:00 hours in the test cannot be explained by increasing barometric pressure alone. The cause of the continually decreasing head is unknown.

Comparison of Transducer Head Differences

Head differences between the upper, middle and lower transducers are apparent from figures 11-17. The validity of the static head profile can be evaluated by comparing head differences between transducers. Table 5 summarizes transducer head differences measured with packers inflated and uninflated at each overnight monitored interval, and head differences with the transducers under atmospheric conditions in the casing. A correction of 0.001 ft H₂O per foot of elevation difference between transducers was made on measurements made under atmospheric conditions.

Table 5. Head differences between the middle and upper and lower transducers while under atmospheric conditions, at the USGS dedicated pump location and with packers inflated and uninflated at each overnight monitored interval.

location:	mid-lower		mid-upper	
	average	standard dev.	average	standard dev.
top of casing (8/7/92)	0.37	0.015	0.54	0.016
5 pipes down (8/12/92)	0.21	0.012	0.00	0.011
bottom of casing (8/12/92)	0.21	0.013	0.14	0.011
467-482 feet bls uninflated	0.42	0.018	-0.12	0.040
467-482 feet bls inflated	0.29	0.019	-0.21	0.022
480-495 feet bls uninflated	0.41	0.013	0.12	0.019
480-495 feet bls inflated	0.40	0.016	0.12	0.015
495-515 feet bls uninflated	0.23	0.014	0.27	0.012
495-515 feet bls inflated	0.38	0.044	0.25	0.031
500-515 feet bls uninflated	0.43	0.010	0.05	0.004
500-515 feet bls inflated	0.43	0.027	0.00	0.029
USGS pump (8/12/92)	0.34	0.013	0.06	0.010
USGS pump (8/13/92)	0.47	0.011	0.19	0.011
519-534 feet bls uninflated	0.54	0.015	0.28	0.017
519-534 feet bls inflated	0.34	0.020	0.20	0.035
580-600 feet bls uninflated	0.24	0.011	0.37	0.013
580-600 feet bls inflated	0.26	0.012	0.29	0.016
600-620 feet bls uninflated	0.21	0.012	0.18	0.014
600-620 feet bls inflated	0.33	0.024	0.29	0.027

The data in table 5 indicate that the head measured by the middle transducer is always greater than the head measured at the lower transducer. This head difference could be due to consistently decreasing head with depth in the borehole, errors in the transducer separation measurements, or calibration errors in the lower, middle or both transducers. Similarly, head measured by the middle transducer is greater than the head measured at the upper transducer in all intervals except 467-482 and 500-515 feet bls. In the 467-482 feet bls interval under inflated and uninflated conditions, head measured by the middle transducer is less than head

measured by the upper transducer. In the 500-515 feet bls interval heads measured by the middle and upper transducers are nearly equal. The data in table 5 also indicates that the head differences between the middle and upper or lower transducers are similar whether the packers are inflated or uninflated. This suggests that flow constrictions in the borehole due to the uninflated packers do not allow for total-hole head measurements.

Head differences between transducers also existed when the transducers were under atmospheric conditions. Head differences between transducers under atmospheric conditions indicate that the transducers were not calibrated correctly or that transducer separation distances were not measured accurately.

Head differences between the middle and upper transducers under atmospheric conditions changed with time during lowering of the packer through the casing on 8/12/92. Head differences changing with time also occurred during the 500-515 and 600-620 feet bls overnight head monitoring tests. Head differences changing with time may indicate that air bubbles had formed in the transducer pressure sensing tubes.

The static head values at the 461-467 feet bls and 620-650 feet bls measurement points were measured by the upper and lower transducers respectively. The head differences between the middle and upper or lower transducers make these head values suspect. Head measured by the upper transducer averages 0.15 feet greater than head measured at the middle transducer. The head estimated at 461-467 feet bls is 0.21 feet less than the head measured at the middle transducer. After a 0.15 foot head correction in the 461-467 feet bls interval, head is nearly equal in the two intervals. Head measured by the lower transducer averages 0.34 feet less than the head measured at the middle transducer. A 0.34 foot

correction applied to the 620-650 feet bls head value results in a head value nearly equal to the 600-620 feet bls head value.

Barometric Efficiency and Static Head Summary

Static head observations from each monitored interval showed distinct response to changes in barometric pressure and varying response to pumping from the ICPP production wells. ICPP on-off pumping effects are apparent below 515 feet bls with a period of about 6 hours, and an amplitude of about 0.05 feet. Total drawdown in all the intervals is similar, ranging from 0.04 to 0.09 feet. Drawdown was estimated by subtracting a five read average centered on the bottom of a drawdown cycle from a five-read average at the peak of a recovery cycle. Early response seems greatest in middle to lower intervals in the well. The rapid response and nearly uniform drawdown suggest confined conditions.

Barometric pressure is transmitted to aquifer water pressure with an estimated efficiency of 42 percent in the 500-515 feet bls interval. None of the other intervals provided sufficient data for estimation of barometric efficiency. The maximum barometric change recorded during the 1992 field season was 0.42 feet of H_2O . Head changes resulting from barometric pressure variations are expected to be less than 0.4 feet, and variation due to the ICPP pumping is typically less than 0.04 feet.

Project objectives included determination of static head profiles in the borehole. The interpretation of static head data, however, is complicated by four conditions:

1. Hydraulic head is continually changing in response to changes in barometric pressure.
2. Hydraulic head is continually changing in response to pumping of the ICPP production wells.
3. Air bubbles may have been introduced into the transducer sensing system.

4. Small vertical hydraulic head gradients exist relative to variations induced by other factors listed above.

The combined effects of these four conditions result in a vertical head profile containing a relatively high degree of uncertainty. The maximum head difference measured by the middle transducer between intervals monitored overnight was 0.27 feet. The possible errors in corrections for changes in barometric pressure and for changes in ICPP pumping may be larger than the 0.27 feet of variation observed.

CHAPTER 6:

HYDRAULIC TESTING DATA AND RESULTS

Hydraulic Testing Procedures

The typical hydraulic testing procedure at each interval consisted of measuring static head in the interval with electrical tape and transducers before and after inflating the packers, conducting pumping tests during purging and sampling of the interval, and slug testing after sampling was completed. A slug test was performed prior to any pumping if the hydraulic conductivity of the tested interval was anticipated to be low. Some of the straddled intervals span varying lithologies that may have highly variable hydraulic properties. Hydraulic testing results for all straddled intervals are reported as average hydraulic conductivity over the length of the interval. Detailed descriptions of the hydraulic testing procedures are presented in the following sections.

Slug Tests

Field Procedures

Slug tests were carried out on five low hydraulic conductivity intervals: 480-495 feet bls, 580-600 feet bls, 580-650 feet bls, 600-620 feet bls, and 620-650 feet bls. Both positive head slug tests (where the head was raised), and negative head slug tests (where the head was depressed) were conducted.

Positive head slug tests were performed by deflating the packers and pumping a slug of water into the riser pipe from the open borehole. After shutting off the pump, the riser valve was closed, trapping the slug within the riser pipe. The packers were then inflated.

The depth to water was measured with an electrical tape and the change in head recorded when the pressure in the packed off interval had stabilized. The circulation valve was then opened to allow water to flow into the packed off interval, and the slug was released by opening the riser valve. Head changes on all three transducers were monitored and recorded.

The procedures for a negative head slug test were similar to those for a positive head slug test. The packers were deflated, circulation and riser valves opened, and nitrogen gas introduced into the riser pipe to depress the head. When the head was depressed sufficiently, the riser valve was closed and the packers re-inflated. The depth to water was measured with an electrical tape and the change in head recorded. The test was then begun by opening the riser valve and allowing the head in the packed off interval to return to static while recording heads on all three transducers.

The riser valve did not open instantaneously. The time delay between when the pressure was released on the riser valve and when the riser valve began to open led to uncertainty in when the slug test started. While partially open, water leaked slowly past the riser valve, causing differences between the head change measured by the electrical tape and that measured by the middle transducer.

Data from the five slug tests conducted are summarized in table 6. The times for the maximum head change to occur were estimated by comparing the difference between successive transducer readings. No head change occurred during the first approximately 80 seconds after the riser valve pressure was released, and any difference between successive readings was due to "background noise" in the transducers. The head changes between successive transducer readings began to increase steadily as the valve opened completely.

Table 6. Summary of slug test data from slug tests on low permeability zones.

Interval tested (ft bls)	E-tape measured head change (ft)	Transducer measured head change (ft)	Percent of head lost during riser opening	Delay between release of riser valve and maximum head change (sec)	Time for max. head change to occur (sec)	Time for head to recover (sec)	Percent of time for maximum head change to occur
480-495	39.24	38.70	1.38	108.00	6.00	4215.00	0.14
580-600	17.35	13.37	23.00	102.00	20.00	191.00	10.40
580-650	32.40	25.79	20.00	97.00	20.00	714.00	2.80
600-620	14.18	13.61	4.00	not recorded	14.00	925.00	1.50
600-650	16.25	15.37	5.00	not recorded	17.00	545.00	3.00

Data Evaluation Methods

Slug tests were analyzed using the method of Cooper et al., (1967). This method allows calculation of transmissivity for the area immediately surrounding the packed off portion of the borehole. In order for the Cooper et al., (1967) method to be applied to the slug test data from straddle packer testing, the data files were converted from their raw format (clock time, lower, middle, upper transducer readings in psi) to heads in feet of water and time since the injection or removal of the slug. The change in head (H_0) was calculated by subtracting the average head before the test from the maximum head measured during a positive head slug test or the minimum head measured during a negative head slug test. The time of maximum head change was assumed to represent the beginning of the test. Data files consisting of time since the test began and H/H_0 were analyzed using AQTESOLV (Duffield and Rumbaugh, 1989).

The method of Cooper et al. (1967) contains the following assumptions:

1. The aquifer is homogeneous, isotropic, of uniform thickness, and of sufficient areal extent that aquifer boundaries do not impact test results;

2. head change in the well occurs instantaneously;
3. well is fully penetrating;
4. aquifer is confined;
5. flow to or from the well is horizontal;
6. diameter of well is very small so that storage in the well can be neglected.

The extent to which the tested intervals meet the assumption of being isotropic, extensive and homogeneous depends on the nature of the fractures in the tested interval. Slug tests were performed on portions of the borehole that were relatively uniform in diameter with no large fractures visible. The slug tested intervals can therefore be assumed to be isotropic and homogeneous, as well as having uniform thickness over the area tested. The slug tested intervals are fully penetrated, but the aquifer is not. Vertical flow is likely and may result in a more rapid H/H_0 change than predicted. Head changes in the well did not occur instantaneously.

Effect of varying H_0 and Time of Slug Test Start

Slow opening of the riser valve resulted in uncertainty concerning when the slug test started and the magnitude of the total head change in the interval. The effects of varying H_0 and the time when a slug test begins were analyzed by manipulating H_0 and the time when the slug test begins (t_0) using data for the 580-600 feet bls interval slug test. The 580-600 feet bls interval slug test was chosen for analysis because this slug test deviated significantly from the type curves of Cooper et al. (1967) and because the test conditions are exceptionally well documented in the field notes.

The 580-600 feet bls slug test was conducted on July 29, 1992. The depth to water measured with an electrical tape before the slug test was 461.38 feet bls. Following depression of the head, depth to water measured with an electrical tape was 478.73 feet bls. H_0 measured with the electrical tape is 17.35 feet. The maximum head change of 13.38 feet occurred within the straddled interval one hundred and two seconds after the riser valve was released (figure 19).

The theoretical time when the test begins (t_0) can range from the time the riser valve is opened to the time when the maximum head change occurs. Data files with t_0 lagged in 20 second intervals from the time the riser valve pressure is released were created to evaluate the effects of varying t_0 . The data were analyzed using AQTESOLV, an aquifer test solving program by Duffield & Rumbaugh, (1989). One additional file with t_0 occurring 10 seconds after the maximum head change occurred was also created and analyzed. Selected examples showing the effects of varying t_0 are shown in figures 21-23.

Figure 20 shows a plot of H/H_0 versus time using an H_0 of 13.37 feet and a start time (t_0) coinciding with the time of maximum head change. A type curve matched to the middle portion of the data curve indicates an average hydraulic conductivity of 1 ft²/day. The data plot using this H_0 and t_0 appears "compressed"; the middle portion of the data curve is steeper than the type curve and the early portion of the data curve is flatter than the type curve. The data curve would match the type curve more closely if the data curve were to be pulled from both ends, so that the data points represented a longer time. Figure 21 shows a plot of H_0 versus time with t_0 lagged to 10 seconds after the maximum head change occurs. This results in a flattening of the middle portion of the data curve and a better fit with the type

Figure 19. Plot of head change versus time since release of riser valve pressure in the 580-600 feet bls interval.

Figure 20. Plot of H_o versus time for for slug test on the 580-600 feet bls interval. H_o equals 13.37 feet and t_o is set at the time of maximum head change.

Figure 21. Plot of H_o versus time for slug test on 580-600 feet bls interval. H_o equals 10.72 feet and t_o is set at 10 seconds after maximum head change occurs.

Figure 22. Plot of H_o versus time for slug test on 580-600 feet bls interval. H_o equals 7.58 feet and t_o is set at 20 seconds after maximum head change.

curve. The calculated average hydraulic conductivity from a type curve match to the middle portion of the data curve is 3 ft/day, more than twice the average hydraulic conductivity calculated using t_0 equal to the time of maximum head change. Figure 22 shows the results of setting t_0 to 20 seconds after the maximum head change. The data points begin to deviate from the type curve during the early portion of the data curve but match at later times.

The effects of varying H_0 are illustrated in figures 23-26. Increasing H_0 while keeping t_0 fixed at the time of maximum head change results in decreasing the slope of the data curve. With H_0 equal to 17.35 feet, average hydraulic conductivity is calculated to be 3 ft/day. As H_0 is reduced, the data curve gets steeper and the calculated average hydraulic conductivity decreases. When H_0 is equal to 14.35 feet, calculated average hydraulic conductivity equals 2 ft/day. The results of lagging t_0 and varying H_0 on the calculated average hydraulic conductivity of the 580-600 feet bls interval are summarized in table 7.

Table 7. Summary of effects of lagging t_0 and H_0 on the average hydraulic conductivity calculated from the slug test on the 580-600 feet bls interval. Lagged t_0 is time in seconds since release of riser valve pressure. Maximum head change of 13.37 feet occurred 102 seconds after riser valve pressure release.

H_0 (feet)	Lagged t_0	Average hydraulic conductivity
13.37	102.00	1.30
13.37	112.00	3.00
13.37	20.00	0.01
17.35	102.00	3.00
16.35	102.00	2.00
15.35	102.00	2.00
14.35	102.00	2.00

The degree to which a slug test approaches the ideal situation of an instantaneous head change can be evaluated by determining the time necessary for the head change to

Figure 23. Plot of H_o versus time for slug test on 580-600 feet bls interval with H_o equal to 17.35 feet and t_o set to time of maximum head change.

Figure 24. Plot of H_o versus time for slug test on 580-600 feet bls interval with H_o equal to 16.35 feet and t_o set to time of maximum head change.

Figure 25. Plot of H_o versus time for slug test on 580-600 feet bls interval with H_o equal to 15.35 feet and t_o set to time of maximum head change.

Figure 26. Plot of H_o versus time for slug test on 580-600 feet bls interval with H_o equal to 14.35 feet and t_o set to time of maximum head change.

occur relative to the time it takes for the head to return to near pre-slug test levels following the slug test. The percentage of time the head change took to occur relative to the time for the head to recover for each slug test is shown in table 6. The percentage ranges from less than one percent for the 480-495 feet bls interval to greater than 10 percent for the 580-600 feet bls interval. The percentage of time the head change took to occur relative to the time for the head to recover appears to be a good measure of how close a slug test approaches ideal conditions. The 480-495 feet bls slug test data plot matches the type curves quite well, while the 580-600 feet bls slug test data plot deviates from the type curve significantly.

Evaluation of the effects of varying H_0 and t_0 during slug test analysis indicates that uncertainty in H_0 and t_0 can result in underestimating the average hydraulic conductivity of the tested interval by as much as 50%. This is particularly the case in slug tests where the time for the head change to occur is 10 percent or more of the time for the head to recover, and H_0 and t_0 are taken as the maximum transducer measured head change and the time of maximum head change respectively.

Analysis of Intervals

480-495 feet bls

Transducer readings from the middle transducer were erratic prior to the slug test on the 480-495 feet bls interval. A 1.49 foot decrease in head from 29.31 feet to 27.82 feet occurred during a two second span approximately one minute before release of the riser valve pressure. Head then began to slowly rise in the straddled interval until it had recovered to 29.26 feet before the riser valve opened. No activities associated with operating the straddle packer were taking place at the time of the head change. The pump had run for 15

seconds with the packers uninflated at 12:41 to place a slug in the riser pipe, the packers were inflated at 12:42, and the unexplained head change occurred at 13:00.

The sudden and unexplained head change raises questions concerning the validity of the 480-495 feet bls interval slug test. However, the test is considered valid because the head had recovered to within five one hundredths of a foot of the head before the jump, and the head difference due to the jump is small relative to the head change from the slug test. The sudden and unexplained head change may have been due to the presence of an air bubble in the transducer or in the transducer sensing port. Similar unexplained head changes were observed during long term static head monitoring at the end of the field season.

The data plot from the slug test on the 480-495 feet bls interval (figure 27) provides the best match to the type curves. The amount of time over which the head change occurred was less than one percent of the time required for the head to recover. Average hydraulic conductivity for the 480-495 feet bls interval is calculated to be 0.07 ft/day using a storativity of 1×10^{-4} .

580-600 feet bls

The slug test on the 580-600 feet bls interval (figure 28) deviates the most from ideal slug testing conditions. The time for the head change to take place was greater than 10 percent of the time for the head to recover. Using a storativity of 2.6×10^{-4} , average hydraulic conductivity is calculated at 1.2 ft/day.

580-650 feet bls

The 580-650 feet bls interval was slug tested (figure 29) after the 580-600 feet bls interval by deflating the packers then re-inflating the upper packer only, packing off the

Figure 27. Graphical curve matching of 480-495 feet bls slug test data with type curve from Cooper et al. (1967). Type curve represents an average hydraulic conductivity of 0.07 feet²/day and a storativity of 1×10^{-4} .

Figure 28. Graphical curve matching of 580-600 feet bls slug test data with type curve from Cooper et al. (1967). Type curve represents an average hydraulic conductivity of 1.2 feet/day and a storativity of 1×10^{-4} .

Figure 29. Graphical curve matching of 580-650 feet bls slug test data with type curve from Cooper et al. (1967). Type curve represents an average hydraulic conductivity of 0.3 feet/day and a storativity of 1×10^{-4} .

Figure 30. Graphical curve matching of 600-620 feet bls slug test data with type curve from Cooper et al. (1967). Type curve represents an average hydraulic conductivity of 0.3 feet/day and a storativity of 1×10^{-4} .

borehole from 580 feet to the bottom of the hole at 650 feet. The head was depressed 32.4 feet, and a maximum head change of 25.8 feet occurred in the interval. The time necessary for the head change to occur represents approximately 3 percent of the time for the head to recover.

The data plot for the 580-650 feet bls slug test is very similar to the 580-600 feet bls data plot. Using a storativity of 1×10^{-4} , average hydraulic conductivity is calculated at 0.3 ft/day.

600-620 feet bls

The 600-620 feet bls slug test was a rising head slug test (figure 30). The head was depressed 14.18 feet and a maximum head change of 13.61 feet occurred in the interval. The time for the head change to occur was approximately 1.5 percent of the time for the head to recover. Using a storativity of 1×10^{-4} , the calculated average hydraulic conductivity of the tested interval is calculated at 0.3 ft/day.

600-650 feet bls

The 600-650 feet bls slug test was also a rising head slug test (figure 31). The head was depressed 16.25 feet and the maximum head change in the interval was 15.37 feet. The time for the head change to occur is approximately 3 percent of the time for the head to recover. Using a storativity of 1×10^{-4} , the calculated average hydraulic conductivity of the tested interval is 0.1 ft/day.

Slug Test Summary

Averaged hydraulic conductivity values calculated using a range of storativity values for each slug test appear in table 8. Slug testing results indicate that portions of the borehole

Figure 31. Graphical curve matching of 600-650 feet bls slug test data with type curve from Cooper et al. (1967). Type curve represents an average hydraulic conductivity of 0.1 feet²/day and a storativity of 1×10^{-4} .

Table 8. Summary of average hydraulic conductivity values for slug tests calculated using storativity values of 1×10^{-3} , 1×10^{-4} , and 1×10^{-5} .

Tested Interval	Average Hydraulic Conductivity (ft/day)		
	$S = 0.001$	$S = 0.0001$	$S = 0.00001$
480-495	0.04	0.07	0.09
580-600	0.70	1.20	1.60
580-650	0.20	0.30	0.40
600-620	0.20	0.30	0.50
600-650	0.08	0.10	0.20

identified by caliper logs with relatively minor diameter increases over drill bit size have low average hydraulic conductivities. The 480-495 feet bls interval has the lowest average hydraulic conductivity, consistent with the low porosity and small diameter increase over bit size shown on geophysical logs. The 580-600 feet bls interval has the highest average hydraulic conductivity, again consistent with porosity and caliper logs. Below 600 feet average hydraulic conductivity apparently decreases with depth.

Most of the head recovery curves from slug tests deviate significantly from the type curves. During the mid-time portion of the tests, the data curves are steeper than the type curves, indicating rapid head recovery. The steepening of the head recovery curves during the middle portion of the tests could be due to rapid head recovery from vertical leakage from above or below the straddled interval, leakage past the packers, or to the non-ideal testing conditions discussed previously.

Constant-Rate Discharge Tests

Field Procedures

Constant-rate discharge tests were conducted during sampling and lithium bromide tracer recovery tests of packed off intervals. Lithium bromide tracer recovery tests were performed to ensure complete purging of the tested interval prior to sampling. The lithium bromide test consisted of: 1) emplacement of lithium bromide into the packed off interval, 2) circulation of the lithium bromide in the packed off interval by pumping with the circulation valve open, 3) stopping the pump, 4) closing the circulation valve, 5) starting the pump and 6) discharging to the surface. The constant-rate discharge test began during the final step, when discharge was routed to the surface. Static heads were monitored prior to beginning

pumping to determine antecedent trends. An attempt was made to conduct all sampling during the off cycle at the ICPP production wells; the status of the ICPP production wells was determined prior to sampling.

Constant-rate discharge tests conducted during sampling typically occurred after the lithium bromide recovery test. The pump was shut off and heads were allowed to return to static conditions once it had been determined that the interval was purged. The pump was then turned on and drawdown monitored and recorded. Discharge was measured using the flow meter supplemented by use of a bucket and stop watch.

Data Evaluation Methods

Static head was determined by monitoring the packed-off interval prior to the constant-rate discharge test. Drawdown was calculated by subtracting the pumping head values from the static head value. Flow rates from the flow meter were converted from gallons per minute to cubic feet per day.

Analysis of Intervals

Semi-log plots of drawdown versus time from constant-rate discharge tests appear in figure 32. Analysis of constant-rate discharge test data was complicated by several factors:

1. extremely rapid aquifer response,
2. very small drawdowns,
3. small discharge rate,
4. non-constant discharge rate,
5. Possible vertical aquifer leakage from zones above or below the packers.

Figure 32. Semi-log plots of drawdown versus time for constant-rate discharge tests.

Most of the drawdown occurred in the first second of the pumping test. The drawdown was one foot or less in all constant-rate discharge test with the exception of the 580-600 feet bls and 580-650 feet bls tests. The discharge was too small to produce measurable drawdown in high transmissivity intervals. Non-constant discharge resulted from adjusting the discharge during sampling, startup of the pump, and changing head in the riser pipe.

Test complications prohibit the application of graphical techniques for estimation of average hydraulic conductivity for constant-rate discharge tests. Specific capacity, however, may be estimated with a relatively high level of confidence due to the horizontal nature of the time-drawdown graphs (figure 32). The specific capacity of the tested intervals is shown in table 9. The specific capacities listed in table 9 provide a relative relation of the average hydraulic conductivity of the tested intervals.

Table 9. Specific capacity of constant-rate discharge tested intervals.

Tested Interval	Specific Capacity (gpm/foot)
467-482	22.00
495-515	2200.00
519-534	20.00
535-555	2200.00
557-577	100.00
580-600	0.10
580-650	0.20

Summary of Constant-Rate Discharge Tests

Drawdown curves from constant-rate discharge test show an almost immediate flattening of the drawdown curve. This kind of response suggests either: 1) a high degree of vertical leakage, 2) decreasing discharge, 3) well loss with almost no aquifer loss, or 4) the presence of a nearby positive head boundary. No hydrogeological evidence exists that would suggest a positive boundary nearby, and discharge during the constant-rate discharge test was nearly constant. The rapid flattening of constant-rate discharge test curves therefore suggests well loss or vertical leakage. The rapid flattening of the drawdown curves could also result from leakage past the packers. If high hydraulic conductivity intervals exist above or below the tested interval, leakage past the packers would not result in detectable pressure changes at the upper or lower transducers. In any event, data from the constant-rate discharge tests cannot be analyzed using graphical techniques.

Constant Rate Injection Tests

Field Methods

Constant rate injection tests were completed on three low hydraulic conductivity intervals: 600-620 feet bls, 600-650 feet bls, and 480-495 feet bls. Injection tests were conducted on these low hydraulic conductivity intervals to determine if they were suitable hydraulic tests and for comparison with slug test results. De-ionized water was used in order to avoid contamination of the aquifer. The procedures for injection tests were as follows:

1. Inflate packers and monitor static head in packed interval.
2. When head in packed interval has stabilized, pump five gallons of de-ionized water down the injection line at approximately 0.7 gallons per minute while monitoring head changes in the packed-off interval.

3. Continue to monitor and record head changes after pumping stops to gather recovery data.

Data Evaluation Methods

Data evaluation methods for constant rate injection tests were similar to those for constant-rate discharge tests. Injection rates were determined by measuring the amount of time necessary to inject a known volume of de-ionized water. Static head in the interval was determined by monitoring head prior to injection. Drawdown was determined by subtracting the static head from the head values measured during injection and recovery. Time and drawdown data were imported into AQTESOLV (Duffield And Rumbaugh, 1989) for evaluation. The drawdown and recovery phase of each injection test was analyzed using the semi-log methods of Cooper and Jacob (1946) and the recovery method of Theis (1935) respectively. The following assumptions are necessary for solutions using these two methods:

1. aquifer has infinite areal extent,
2. aquifer is isotropic, homogenous, and of uniform thickness,
3. pumping rate is constant,
4. flow to or from pumping well is horizontal,
5. aquifer is confined,
6. water is released or taken into or out of storage instantaneously with decline or increase of hydraulic head,
7. diameter of pumping well is very small so that storage in the well can be neglected,
8. values of u are small,

9. specific storage is the same during pumping and recovery periods (recovery analysis).

The extent to which the injection tests meet these assumptions determines the validity of the solutions. The short duration of the injection tests assures that the cone of depression does not reach any boundaries. The presence of fractures in the affected area of the tested intervals may introduce anisotropy and heterogeneity to the interval. A single fracture intersecting the tested interval would introduce a high degree of anisotropy and heterogeneity. A tested interval may behave as an isotropic and homogenous porous medium if it contains numerous inter-connected fractures. The injection tested intervals appear from television logs to be dense flow interiors with no large fractures, and therefore can be treated as homogenous and isotropic media. The dense flow interiors can be assumed to be homogenous and isotropic and of uniform thickness over the area affected by the test.

The pumping rate during injection tests was not constant. The head difference between the tested interval and the injection reservoir at the surface caused the water in the injection line to convert to vapor prior to injection. When pumping began, the vapor in the injection line was converted back to water and any unfilled portions of the injection line were filled before a constant discharge was achieved. Water vapor in the injection line and unfilled portions of the injection line resulted in increasing discharge as the vapor was converted to water and the line was filled.

Figures 33 and 34 show the relationship between head changes in the packed-off interval and the time since injection began in the 480-495 feet bls and 600-620 feet bls intervals. In both cases, there is a time lag between when injection begins and the head in the interval begins to change. The maximum drawdown occurs 37 seconds after injection ends in the 480-495 feet bls injection test. The head continues to increase after the pump was

Figure 33. Head changes during injection and recovery during the de-ionized-water injection test on the 480-495 feet bls interval.

Figure 34. Head changes during injection and recovery during the de-ionized-water injection test on the 600-620 feet bls interval.

shut off because of gravity drainage through the injection line. This resulted in discharge decreasing to zero at the end of the test, rather than ending instantaneously.

Head changes during the recovery portion of an injection test tend to average the effects of variable discharge rates. Analysis of recovery data shows that transmissivities calculated from recovery data are in close agreement with transmissivities calculated from injection data. All the remaining assumptions are adequately met for application of the methods.

Analysis of Constant Rate Injection Tests

480-495 feet bls

Plots of the drawdown and recovery from the injection test on the 480-495 feet bls interval appear in figures 35 and 36. The long "tail" at high values of t/t' is due to accumulation of water in the injection line. This slow decline in the injection rate makes it difficult to decide when injection actually ends. Similar "tails" occur in the data from 600-620 feet bls and 600-650 feet bls injection tests.

Comparison of the drawdown and recovery curves from the injection test on the 480-495 feet bls interval with a theoretical curve calculated using the Theis (1935) equation indicates that the injection test conditions deviate significantly from the assumed ideal conditions. The injection test curve does not flatten with increasing time, suggesting that the discharge was increasing throughout the injection portion of the test.

Average hydraulic conductivity calculated from the recovery and injection portions of the test are 0.01 ft/day. These values have questionable validity because of the operational problems with the tests noted above.

Figure 35. Injection portion of the injection test on the 480-495 feet bls interval.
Calculated average hydraulic conductivity is 0.01 ft/day.

Figure 36. Recovery portion of the injection test on the 480-495 feet bls interval.
Calculated average hydraulic conductivity is 0.01 ft/day.

600-620 feet bls

Plots of drawdown and recovery from the injection test on the 600-620 feet bls interval appear in figures 37 and 38. Figure 34 indicates that leakage occurred around the lower packer as evidenced by a head increase in the lower portion of the borehole. Leakage may have occurred because of a poor seat for the lower packer, or the leakage may have been through fractures past the lower packer. The maximum head change in the interval of approximately 12.5 feet occurred before injection had ceased. Continued injection resulted in no increase in head in the packed interval as leakage occurred.

Average hydraulic conductivity calculated from both the recovery and injection portions of the test is 0.1 ft/day. The leakage, whether around the packers or through fractures in the tested interval, violates the assumption of vertical flow necessary for application of the analytical methods and casts doubt on the average hydraulic conductivity calculated from this test.

600-650 feet bls

Plots of the injection and recovery portions of the 600-650 feet bls interval injection test appear in figures 39 and 40. The data plot of the injection portion of the 600-650 feet bls constant-rate injection test has two distinct slopes. The injection data plot has a steep slope at first and then flattens. The flattening of the data plot could be due to leakage past the upper packer. Leakage may have occurred because of a poor seat for the upper packer, or the leakage may have been through fractures past the upper packer.

Calculated average hydraulic conductivity is 0.1 ft/day for both the early portion of the drawdown plot and the recovery portion of the test. The leakage, whether around the

Figure 37. Injection portion of the injection test on the 600-620 feet bls interval.
Calculated average hydraulic conductivity is 0.1 ft/day.

Figure 38. Recovery portion of the injection test on the 600-620 feet bls interval.
Calculated average hydraulic conductivity is 0.1 ft/day.

Figure 39. Injection portion of the injection test on the 600-650 feet bls interval.
Calculated average hydraulic conductivity is 0.1 ft/day.

Figure 40. Recovery portion of the injection test on the 600-650 feet bls interval.
Calculated average hydraulic conductivity is 0.1 ft/day.

packer or through fractures in the tested interval, violates the assumption of horizontal flow necessary for application of analytical methods and casts doubt on the average hydraulic conductivity calculated from this test.

The calculated average hydraulic conductivity of the 600-650 feet bls interval is only slightly larger than the calculated average hydraulic conductivity of the 600-620 feet bls interval. The average hydraulic conductivity of the portion of the borehole from 620-650 feet bls should be the difference between the average hydraulic conductivity of the 600-650 feet bls interval and the 600-620 feet bls interval. Accordingly, the average hydraulic conductivity of the borehole below 620 feet is probably less than 0.1 ft/day.

Variable-Rate Injection Tests

Field Methods

Variable-rate injection tests are a variation of slug tests conducted on high hydraulic conductivity intervals. Slug tests were modified on high hydraulic conductivity intervals because the head loss resulting from flow through the packer system and riser pipe is large relative to the induced head change in the straddled interval. In slug tests on low hydraulic conductivity intervals flow rates are much smaller and consequently friction losses in the riser pipe and packer system can be neglected. Variable-rate injection tests were performed on the 467-482, 495-515, 519-534, 535-555 and 557-577 feet bls intervals.

The procedures for variable-rate injection tests are similar to those for a falling head slug test. The riser pipe was filled to the surface by pumping from the either the open borehole with packers un-inflated or from the packed off interval. If the riser pipe was filled from the packed off interval, heads within the packed off interval were allowed to return to

static conditions prior to the variable-rate injection test. The riser valve was opened with the circulation valve closed. The circulation valve was then opened to allow the slug of water to flow into the straddled interval. The timing of the opening of the riser valve and circulation valve was critical to a successful variable-rate injection test. Proper timing of valve openings was necessary to minimize pre-test leakage into the test interval from the filled riser pipe. The riser valve takes approximately one minute to open fully with 460 feet of head in the riser pipe. Pressure readings from the transducers were recorded beginning when the riser valve was released until the head in the straddled interval returned to pre-injection water level values. Flow rates in the riser pipe were monitored by placing a 200 psi transducer connected to a data logger in the riser pipe and by fixing electrical tapes in the riser pipe and recording the time required for a 100 foot head change.

Variable-rate injection tests were performed on the 535-555 feet bls and 557-577 feet bls intervals before coordinated valve opening was perfected. Data from these straddled intervals was not analyzed since the flow rates in the riser pipe during the 535-555 feet bls and 557-577 feet variable-rate injection tests are not comparable to flow rates using the circulation valve.

Data Evaluation Methods

Data from variable-rate injection tests were evaluated using a spreadsheet program developed by Gary Johnson (personal communication, 1993) that simulates aquifer response from a variable-rate injection test. The development of the evaluation method for variable-rate injection tests is described below.

Development of Methodology

Flow rates were estimated based on measured flow velocities in the riser pipe as the slug was released. Figure 41 shows the head changes that occurred in the riser pipe when the slug was released by opening the circulation valve. Leakage past the pump check valve appears as a slow rate of pressure change during the first four seconds of the test. Complete opening of the valve occurred by five seconds after the beginning of the record. The complete opening of the valve resulted in a dramatic decline in pressure within the riser pipe as the water accelerated from near zero velocity to over 20 feet per second. Transducer readings between four and 20 seconds shown in figure 41 were probably affected by venturi effects from high flow velocities and consequently do not represent actual pressure within the riser pipe. Electrical tape measurements from tests conducted on August 6 on the 467-482 feet interval and on August 13 on the 495-515 feet interval are plotted as X's on figure 41 along with the transducer measurements. The electrical tape measurements from the 467-482 feet bls interval and the 495-515 feet bls interval are comparable because the flow rate in the riser pipe is primarily a function of the friction loss in the packer system and is relatively unaffected by the small head change in the tested intervals. The width of the X symbol represents the approximate uncertainty in the timing of the measurements. All the electrical tape measurements fall approximately along a linear interpolation on the semi-log graph between observations at four seconds and at 20 seconds into the test. This linear interpolation suggests a relationship between pressure head on the circulation valve and the log of time. The empirical equation relating pressure head to time in the linear part of the curve in figure 41 is:

Figure 41. Head changes in the riser pipe during variable-rate injection test conducted on the 467-482 feet bls interval on 8-13-92. X's mark electrical tape measurements from this test and from a test on the 495-515 feet bls interval conducted on 8-6-92.

Figure 42. Calculated flow rates used in simulation of variable-rate injection tests.

$$H = 638 - (418 \times \log t) \quad \text{eq. 6-1}$$

where:

H = pressure head in feet of water;

t = time from start of observations, in seconds.

The logarithmic relation between time and pressure is not theoretically supported and requires additional research. Flow rate at any time greater than 4 seconds can be estimated from the derivative of the logarithmic relationship expressed above. Instantaneous discharge rate can be calculated from:

$$Q = \left(\frac{dh}{dt} \right) \times \text{area} = \left(\frac{181 \text{ ft}}{\text{time}} \right) \times 0.02 \text{ ft}^2 \quad \text{eq. 6-2}$$

Where:

Q = the estimated flow rate in $\text{ft}^3/\text{second}$,

dh/dt = the derivative of equation 6-1 and is equal to 181 ft/time,

area = the cross sectional area of the riser pipe (0.02 ft^2),

time = the time since the beginning of the record for the test on 8/13/92, in seconds.

Flow rates calculated from equation 6-2 for test times greater than four seconds, and from actual measured head changes during the first four seconds of the 8/13/92 test are shown in the graph in figure 42. These flow rates were used as input to the variable-rate injection test simulations. Maximum flow rates are estimated to be about 360 gpm. The equation relating time to head on the circulation valve was extrapolated to times where the water levels had dropped beneath the level of the pressure transducer in the riser pipe. Errors resulting from this extrapolation represent only a small percentage of the injected volume and should not appreciably affect the results of the multiple well injection test analysis.

The use of multiple theoretical constant discharge wells to simulate aquifer response to variable rates of pumping or injection is based on the concept of superposition of the

aquifer response from each of the theoretical wells. The Theis (1935) equation was used to calculate aquifer response to thirty theoretical wells, with each well turning on in succession injecting or pumping a discharge that varies with time according to equation 6-2. The injection or discharge rate from each well is given by:

$$Q_t = q_n - q_{n-1} \quad \text{eq. 6-3}$$

where: Q_t = discharge or injection rate at time t ,

q_n = flow rate in riser pipe at time t ,

q_{n-1} = flow rate in riser pipe at previous time.

As each successive well comes on, the discharge increases until the peak discharge is reached at $t = 5$ seconds. Flow rates in the riser pipe then begin to decrease as the head in the riser pipe falls; the discharge from each subsequent theoretical well is negative.

The drawdown from each well at each time step was calculated using the Theis equation, and the drawdowns from each theoretical well were summed and plotted against time. Actual drawdowns from the variable-rate injection test were plotted on the same graph, and transmissivity and storativity were adjusted by trial and error until the maximum head change in the modeled data equaled the maximum head change in the actual data.

The 200 psi transducer was only available during the 467-482 feet bls tests, therefore this is the only interval with detailed riser pipe discharge data. Discharge rates estimated from the 467-482 feet bls test were used to evaluate all three tests. Use of the 467-482 discharge rates may introduce some error into the test analysis on the 495-515 feet bls and 519-534 feet bls intervals. However, the discharge rates from the 467-482 feet bls test should be applicable to the other variable-rate injection tests if the average hydraulic

conductivity of the tested interval is high enough so that the primary control on the discharge rate from the riser pipe is friction loss in the riser pipe and packer.

Radius for each tested interval was determined by averaging the radius from caliper logs (Morin, personal communication) over the tested interval. Multiple values of transmissivity and storativity were used to establish a range of possible transmissivity values for the tested intervals. Average hydraulic conductivity for the tested intervals was calculated by dividing transmissivity by interval length.

Variable-rate Injection Test Results

467-482 feet bls

The variable-rate injection test on the 467-482 feet bls interval produced a maximum head change of 33.7 feet (figure 43). The best simulated match using a storativity of 3.8×10^{-5} and an effective well radius of 0.3 feet gives an average hydraulic conductivity of 110 ft/day. A storativity of 3.8×10^{-4} produces an average hydraulic conductivity of 80 ft/day and a storativity of 3.8×10^{-6} results in an average hydraulic conductivity of 130 ft/day.

The flattening of the drawdown curve from the 467-482 feet bls variable-rate injection test may indicate that vertical leakage occurred during the test. Deviations between simulated and measured response may also be a result of inaccurate estimation of flow rates.

495-515 feet bls

The variable-rate injection test on the 495-515 feet bls interval produced only 0.47 feet of head change (figure 44). Analysis using the spreadsheet program indicates an average

Figure 43. Plot of variable-rate injection test head changes in the 467-482 feet bls interval with simulated head changes.

Figure 44. Plot of variable-rate injection test head changes in the 495-515 feet bls interval with simulated head changes.

hydraulic conductivity of 6000 ft/day for this interval using an effective well radius of 0.35 feet and a storativity of 2.1×10^{-3} . Changing storativity to 2.1×10^{-2} results in an average hydraulic conductivity of 4300 ft/day. A storativity value of 2.1×10^{-4} produces an average hydraulic conductivity value of 7300 ft/day.

519-534 feet bls

A maximum head change of 44.24 feet occurred during the variable-rate injection test on the 519-534 feet bls interval (figure 45). Simulation of the aquifer response to this variable-rate injection test indicates average hydraulic conductivity values of 50 ft/day using a storativity of 7×10^{-4} and an effective well radius of 0.32 feet. Increasing storativity to 7×10^{-3} results in an average hydraulic conductivity of 30 ft/day, reducing storativity to 7×10^{-5} results in an average hydraulic conductivity of 75 ft/day.

Variable-rate Injection Tests Summary

Variable-rate injection tests provide estimates of average hydraulic conductivity in high hydraulic conductivity intervals that could not be analyzed using conventional slug tests or constant-rate discharge tests. Average hydraulic conductivity values obtained from variable-rate injection tests vary over three orders of magnitude, from approximately 75 ft/day in the 467-482 feet bls interval to 6,000 ft/day in the 495-515 feet bls interval.

Summary of Quantitative Treatment of Hydraulic Testing Data

Determination of average hydraulic conductivity values from packed intervals in well USGS-44 has not been highly successful. Constraints formed because of components of the packer system and the extreme range of hydraulic properties in the packed intervals

Figure 45. Plot of variable-rate injection test head changes in the 519-534 feet bls interval with simulated head changes.

combines to limit the data that can be analyzed. Averaged hydraulic conductivity results range from about 0.1 ft/day to more than 1,000 ft/day (figure 46). The error band on all of these values is large.

All analysis methods used rely on the critical assumption that no vertical flow is affecting the response of the tested interval. This assumption is not valid in most of the tested intervals, however. The degree to which this failure affects estimates is uncertain. Vertical flow into or out of the tested interval will result in over estimation of aquifer average hydraulic conductivity. The average hydraulic conductivity of the individual intervals is summarized for each test method in table 10.

Table 10. Summary of average hydraulic conductivities for individual intervals by test method.

Interval:	Average Hydraulic Conductivity Ranges (ft/day)			
	Slug Test:	Constant-rate Discharge:	Constant-rate Injection:	Variable-rate Injection:
467-482	N.A.	~20	N.A.	80 - 130
480-495	0.04 - 0.09	N.A.	0.01	N.A.
495-515	N.A.	~2,000	N.A.	6000 - 7000
519-534	N.A.	~20	N.A.	50 - 75
535-555	N.A.	~2,000	N.A.	N.A.
557-577	N.A.	~100	N.A.	N.A.
580-600	0.7 - 1.6	~0.1	N.A.	N.A.
580-650	0.2 - 0.4	~0.2	N.A.	N.A.
600-620	0.2 - 0.5	N.A.	0.10	N.A.
600-650	0.08 - 0.2	N.A.	0.10	N.A.

* specific capacity in gpm/foot

A qualitative comparison of results of different test methods is possible to a limited degree from the data presented in table 10. Slug test and constant-rate injection test results

Figure 46. Variations in average hydraulic conductivity with depth in well USGS-44.

are of similar magnitudes in the three intervals tested by both methods. The relative differences in average hydraulic conductivity between the three intervals are also similar. Constant-rate discharge and variable-rate injection test results can be compared in three intervals, though the comparison is made between specific capacity and average hydraulic conductivity. Average hydraulic conductivity is indicated to be two orders of magnitude greater in the 495-515 feet bls interval than the 467-482 feet bls or 519-534 feet bls intervals. In the constant-rate discharge tests on the same intervals the differences in specific capacity are also two orders of magnitude.

CHAPTER 7:
COMPARISON OF STRADDLE PACKER HYDRAULIC TESTING RESULTS
WITH PREVIOUS ESTIMATES OF HYDRAULIC PROPERTIES IN WELL
USGS-44

Ackerman (1991)

Ackerman (1991) estimated the transmissivity of the Snake River Plain aquifer at the INEL using aquifer test data from 183 single well tests at 94 wells. Ackerman (1991) developed a regression relation between specific capacity and transmissivity from the results of type-curve analysis of 37 tests at 26 wells. He used this relation to estimate transmissivity from specific capacity data for all other wells.

The transmissivity of the Snake River Plain aquifer at well USGS-44 was estimated by Ackerman (personal communication) at 410,000 ft²/day using the regression relation between specific-capacity and transmissivity. This estimate is based on drawdown of greater than 0.1 foot measured during a 100 minute test with a discharge of 24.1 gallons per minute. Uncertainty in the transmissivity value translates to a range from 163,000 ft²/day to 1,000,000 ft²/day.

Summing the transmissivities of the individual straddle-packer tested intervals produces a total-hole transmissivity of approximately 200,000 ft²/day. This value is approximately one-half that calculated by Ackerman (personal communication) but within his estimated range of values.

Hydraulic Properties Estimated From Flow-meter

Morin et al., (1992) estimated the distribution of hydraulic conductivity in well USGS-44 using a technique developed by Hufschmied (1984). The Hufschmied (1984) technique includes pumping at constant rate with concurrent flowmeter and pressure measurements. Flowmeter and pressure measurements are obtained as a function of depth after constant rate pumping has continued for a long enough time to ensure that drawdown has reached a quasi-steady state.

Morin et al., (1992) made flowmeter measurements at specific depths under both static and pumping conditions. Pressure measurements were not made concurrent with the flow measurements. Data from flowmeter measurements (table 1) were used to calculate the vertical distribution of hydraulic conductivity.

The following assumptions were used in the analysis:

1. the formation under consideration is composed of numerous horizontal layers,
2. flow from each layer is horizontal,
3. drawdown is propagated uniformly throughout the well.

Hydraulic conductivity was computed using an equation derived by Cooper and Jacob (1946). The transmissivities of seven individual layers in well USGS-44 calculated by Morin et al. (1992) are shown in table 3. The transmissivities span approximately 2 orders of magnitude and sum to a cumulative transmissivity of 890,000 ft²/day for that portion of the Snake River Plain aquifer penetrated by well USGS-44. This is approximately twice the value estimated by Ackerman (1991).

A comparison of hydraulic conductivity measurements computed using the flowmeter and the straddle-packer is shown in table 11. High hydraulic conductivity zones in the

Snake River Plain aquifer are likely located at thin, rubbly flow contacts. Hydraulic conductivities measured using both the heat-pulse flowmeter and the straddle-packer could not be obtained at the scale of vertical resolution necessary to test these narrow contact zones. The values of hydraulic conductivity presented in table 11 are integrated over the thickness of the tested interval and encompass both high and low hydraulic conductivity lithologies.

Table 11. Comparison of hydraulic conductivities measured using the heat-pulse flowmeter and the straddle-packer system in well USGS-44.

Heat-pulse flowmeter		Straddle-packer	
Tested interval (ft bls)	Hydraulic conductivity (ft/day)	Tested interval (ft bls)	Hydraulic conductivity (ft/day)
461-480	20,000	467-482	80
480-495	200	480-495	0.01
495-515	12,000	495-515	6,000
515-523	2,000	519-534	50
523-556	4,000	535-555	5,000*
556-568	1,200	557-577	500*
568-578	800	* estimated value	

The data portrayed in table 11 indicate that the hydraulic conductivities measured using the heat pulse flowmeter are up to three orders of magnitude greater than those measured using the straddle packer. The large discrepancies between the heat-pulse flowmeter measurements and the straddle-packer measurements can be explained by uncertainty in the drawdowns used to calculate hydraulic conductivity using both the heat-pulse flowmeter and the straddle-packer. The drawdown used in the heat-pulse flowmeter calculations was measured by Ackerman (personnel communication) at a precision of plus or minus 0.01 foot. A measured drawdown of 0.01 foot therefore could be

0.02 foot or 0 foot. This uncertainty is expressed by both Ackerman (1991) and Morin et al., (1992) as ± 0.4 orders of magnitude.

Morin et al., (1992) report that while the absolute value of the hydraulic conductivities measured using the heat-pulse flowmeter may vary significantly due to the uncertainty in the drawdowns used to calculate hydraulic conductivity, their relative values should remain relatively unchanged. Figure 47 shows the vertical distribution of hydraulic conductivity measured with the heat-pulse flowmeter and the straddle-packer. The relative differences between hydraulic conductivity values measured using the two methods are not consistent, again reflecting the large potential error in the methods used.

Figure 47. Comparison of the vertical distribution of hydraulic conductivity measured by the straddle-packer and heat-pulse flowmeter.

CHAPTER 8:

CONCLUSIONS AND RECOMMENDATIONS

General Conclusions

Straddle-packer testing of monitor wells open over large intervals is an important aspect of understanding water quality and hydraulic properties of the Snake River Plain aquifer. Straddle-packer testing of well USGS-44 has demonstrated strengths and weaknesses of the straddle-packer system for hydraulic testing. The primary strength of the straddle-packer is the ability to isolate zones for head and hydraulic conductivity testing. Low to moderate hydraulic conductivity intervals can be tested more readily than high hydraulic conductivity intervals. Weaknesses include limited capabilities for testing high hydraulic conductivity intervals and the inability to differentiate between vertical leakage past the packers and vertical leakage through nearby fractures in the tested interval. Static head monitoring and determination of a static head profile are complicated by the presence of air bubbles in the transducers and extremely small vertical head gradients.

Specific Conclusions

Straddle-packer testing of the Snake River Plain aquifer at well USGS-44 leads to the following specific conclusions:

1. Vertical head gradients in well USGS-44 are very small,
2. Barometric efficiency of the 500-515 feet bls interval is about 42%,
3. Hydraulic conductivity values in well USGS-44 varies over six orders of magnitude, from about 0.01 ft/day to 1,000 ft/day,

4. The upper portion of the Snake River Plain aquifer is under confined conditions with respect to short term hydraulic testing,
5. Straddle-packer measurements of hydraulic conductivity are less than the flowmeter measurements of hydraulic conductivity by Morin et al. (1992) or the total-well transmissivity estimated by Ackerman (personal communication, 1992).

Recommendations

Improvements in the Straddle-Packer and Support Equipment

Several changes to the straddle-packer and to the straddle-packer testing program are recommended that would improve the quality of the data and the operation of the program. In its first field season, the straddle-packer system demonstrated the ability to gather depth-specific water samples and hydrologic data.

Air bubbles in the transducers and in the transducer sensing ports resulted in erratic pressure readings and a degree of precision much lower than reported for the transducers. A closed pressure sensing system would prevent air bubbles from entering the transducers. A closed system would be achieved by placing a device similar to a water-filled balloon over the end of the sensing tube. Pressure changes would then be transmitted through the balloon device to the transducers.

The quality of slug test data was compromised by the slow response of the riser valve. Replacing the current pneumatic control system with a faster acting control system would decrease the amount of time it takes for the riser valve to open.

The in-line flow meter needs to be moved to the pump side of the surface valve assembly so that the discharge is read before any sampling lines or ports are reached. Ideally, a digital, in-line flow meter capable of reading discharge in either direction that reads to a computer or

data logger at the surface should be placed directly above the riser valve. This would assist in interpretation of pumping tests and would be especially helpful in simulations of variable rate injection tests.

Barometric pressure data should be included as part of each data file. The transducers read absolute pressure, which includes barometric pressure; barometric pressure must be subtracted to convert absolute pressure to hydraulic head.

Improvements in the Straddle -Packer Hydraulic Testing Program

Analysis of slug test results was complicated by slow opening of the riser valve. In order to minimize the effects of slow valve opening, positive head slug tests should be conducted and the interval should be slugged by simultaneously opening the circulation valve and the riser valve. This would also decrease the head losses that occurred before the riser valve opened completely. The start of the slug test should be the time when the maximum transducer measured head change occurs in the tested interval.

Analysis of slug test results should begin with an analysis of the ratio of the time for the head change to occur versus the time for the head to recover. The larger this ratio is, the more uncertainty in the calculated transmissivity. There is more uncertainty in the calculated transmissivity for a large ratio.

Constant rate discharge testing of high hydraulic conductivity intervals is limited by the maximum discharge of the straddle-packer pump. Variable rate injection testing allows estimation of the hydraulic conductivity of a small area immediately adjacent to the borehole. A longer term test with a high discharge injection rate should be conducted in order to determine the characteristics of a larger area of the aquifer and to determine the

characteristics of confining beds. This test could be accomplished by re-injecting water pumped from an interval and stored in a tank back into the interval at a higher rate.

Multiple-well tests utilizing the straddle packer could also be performed at the INEL. The straddle packer should be used to monitor head changes in a packed off interval in an observation well while another well is pumped. One or more additional straddle-packer systems would be needed for this program.

Static head monitoring tests should have durations of several days in order to include larger barometric pressure changes.

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APPENDIX 1

DEVELOPMENT OF TRANSDUCER EQUATION

The Paroscientific transducers used in the straddle packer system are non-vented transducers. This means that the transducers measure absolute pressure, and do not compensate for changes in atmospheric pressure. As a result, pressure readings from the transducers are a measure of both atmospheric pressure and fluid pressure, in pounds per square inch (psi). These pressure readings were converted to pressure head readings in feet of water (ft) by multiplying the pressure head by 2.3067.

Since the transducers measure total pressure, changes in atmospheric pressure result in changes in the pressure measured by the transducers. The pressure changes measured at the transducers depend on the nature of the aquifer system being monitored. Four hypothetical situations ranging from simple to more complex are presented below in order to fully understand the pressure changes in a well due to changes in atmospheric pressure.

The first situation is the simplest and is depicted in figure A-1a. In this case, the transducer is submerged in a barrel of water with the sensing portion of the transducer located at a depth H from the surface of the water. In this case, the absolute transducer reading (Tr) is the sum of the atmospheric pressure (P_a) and the water pressure (P_w):

$$Tr = P_a + P_w \quad \text{eq. A-1.}$$

P_w is a function of H , the height of the column of water above the transducer. A change in atmospheric pressure (dP_a) acts directly on the water surface and results in a change in the transducer reading (Tr) so that in this case Tr is given by:

$$Tr = P_a + dP_a + P_w + dP_w \quad \text{eq. A-2.}$$

The change in atmospheric pressure is the same everywhere on the surface of the water. No

Figure A-1. Hypothetical situations used in development of transducer equations.

pressure gradients exist and there is no change in H . Since there is no change in H , there is no change in P_w ($dP_w = 0$) resulting from the change in atmospheric pressure.

The next situation is an unconfined aquifer penetrated by a piezometer, depicted in figure A-1b. This situation is conceptually similar to a barrel filled with water. The only differences are that the unconfined aquifer has a much larger areal extent and is filled with a porous media. Atmospheric pressure changes are transmitted equally to the water table and to the water surface in the piezometer. In an unconfined aquifer, a change in atmospheric pressure does not affect the water level in the well. Therefore there is no change in H and no change in P_w . However, the absolute transducer reading will change by an amount equal to the barometric pressure change. The equations describing the pressure recorded at the transducer in a well in an unconfined aquifer are the same as eq. A-1 and eq. A-2 shown above.

The third and fourth situations are confined aquifers with barometric efficiencies of 100% (figure A-1c) and 0% (figure A-1d). Transducer measurements in wells completed in confined aquifers are affected by barometric efficiency.

Barometric efficiency can be defined as:

$$B.E. = \frac{\gamma dH}{dPa} \quad \text{eq. A-3.}$$

where:

γ = weight density of water (lb/ft^3),

dH = change in water level in the well (ft),

dPa = change in atmospheric pressure (lb/ft^2).

In an aquifer with a barometric efficiency of 100%, $\gamma dH = -dPa$. In an aquifer with a barometric efficiency of 0%, $\gamma dH = 0$.

Changes in atmospheric pressure act on an aquifer as a blanket load, and are also transmitted down the borehole where they act directly on the water surface in the borehole. When the riser packer valves are open, atmospheric pressure works directly on the water column in the riser pipe. The changes in barometric pressure which work directly on the water surface in the well are added to or subtracted from the water pressure in the well. The changes in barometric pressure act on the confined aquifer and are supported by both the aquifer matrix and the water in the aquifer. As long as the atmospheric pressure is undergoing change, a pressure differential exists between the well and the aquifer (Domenico and Schwartz, 1990).

A 100% barometric efficient aquifer is represented in figure 11c. The change in atmospheric pressure is equal to and opposite in sign to the change in water pressure in the well ($dP_a = -dP_w$). As a result, the transducer does not show any response to changes in atmospheric pressure in a confined aquifer with a barometric efficiency of 100%.

The final situation is depicted in figure 11d. This is a confined aquifer with a barometric efficiency of 0%. No change in water level occurs in response to changes in atmospheric pressure ($dP_w = 0$). However, changes in atmospheric pressure result in equal changes at the transducer. A confined aquifer with a barometric efficiency of 0% responds in the same manner as an unconfined aquifer.

The response of the non-vented transducers to changes in atmospheric pressure is the opposite of that which is at first expected, which could easily lead to misinterpretation of static head data measured with non-vented transducers. Barometric efficiency has traditionally been defined in terms of the change in water level in a well as measured by a steel or electrical tape, not in terms of changes in pressure sensed by a non-vented transducer

in the monitored interval or well. In an interval or well with very high barometric efficiency, water levels measured in the well are changing nearly as much as atmospheric pressure, but the pressure sensed by the transducer in the straddled interval is not. In an interval or well with very low barometric efficiency, water levels are changing slightly while the pressure measured by the transducer is changing nearly as much as the atmospheric pressure. The equation describing the pressure head measured at the transducer during periods when the atmospheric pressure is changing and the straddled interval is open to the atmosphere is given by:

$$Tr = \bar{P}a + Pw + \delta Pa(1 - B.E.) \quad \text{eq. A-4}$$

where $\bar{P}a$ is an average atmospheric pressure and all other terms are as previously described .

The average atmospheric pressure used in head calculations in this report is the average of all atmospheric pressures measured during the course of the field season.