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SITING AND CONSTRUCTING VERY DEEP MONITORING WELLS ON THE U.S. DEPARTMENT OF ENERGY'S NEVADA TEST SITE

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ABSTRACT

Many aspects of the Nevada Test Site's (NTS) hydrogeologic setting restrict the use of traditional methods for the siting and construction of ground-water characterization and monitoring wells. The size of the NTS precludes establishing high-density networks of characterization wells, as are typically used at smaller sites. The geologic complexity and variability of the NTS requires that the wells be critically situated. The hydrogeologic complexity requires that each well provide access to many aquifers. Depths to ground water on the NTS require the construction of wells averaging approximately 1000 meters in depth. Wells meeting these criteria are uncommon in the ground-water industry, therefore techniques used by petroleum engineers are being employed to solve certain siting-, design- and installation-related problems. To date, one focus has been on developing completion strings that facilitate routine and efficient ground-water sampling from multiple intervals in a single well. The method currently advocated employs a new design of sliding side door sleeve that is actuated by an electrically operated hydraulic shifting tool.

Stemming of the wells is being accomplished with standard materials (cement based grouts and sands); however, new stemming methods are being developed, to accommodate the greater depths, to minimize pH-related problems caused by the use of cements, to enhance the integrity of the inter-zone seals, and to improve the representativeness of radionuclide analyses performed on ground-water samples. Bench-scale experiments have been used to investigate the properties of more than a dozen epoxy-aggregate grout mixtures -- materials that are commonly used in underwater sealing applications. Additional experiments are being planned to determine optimal methods for mixing and using the materials in the field. One material appears to have met the stringent set of requirements that were developed for use in deep monitoring wells.

Obtaining ground-water samples from multiple completions in a single well will require the construction of a special geophysical tool that employs packers to isolate the wellbore fluid in the vicinity of the sleeves from the fluid in the remainder of the well, to minimize purging volumes. A pumping system incorporating a custom slim hole pump is being designed to lower the water levels in the wells prior to sleeve actuation, to eliminate cross-contamination of water samples.

INTRODUCTION

Established methods for the siting and construction of ground-water monitoring wells are not always appropriate on the U.S. Department of Energy's (DOE) Nevada Test Site (NTS), because several unique hydrogeologic conditions exist. While some of these conditions occur naturally, others have been created as a result of the underground detonation of nuclear devices. The depth to water on the NTS ranges from 250 meters to as much as 650 meters below ground surface. Such depths require that drilling programs and monitoring wells be engineered with techniques and precisions used in the construction of petroleum production wells. To complicate matters, all drilling, construction, and stemming practices must minimize the introduction of foreign materials into the ground water and must not employ materials that would affect the chemical representativeness of the ground-water samples -- a problem not usually inherent in the design of petroleum exploration and production wells. For these reasons, characterization wells on the NTS exhibit an interesting crossbreeding of ground-water and petroleum exploration technologies.

Geohydrologic Setting

The NTS encompasses in excess of 3500 square kilometers of mountainous, semi-arid steppe. The geology underlying the NTS consists of Precambrian carbonates and clastics, Tertiary rhyolitic volcanics, and alluvial and colluvial sediments deposited in intermountain basins (1,2). Tertiary volcanism has created several caldera complexes near one of the principal testing areas (3) and the entire NTS has been deformed by Mesozoic thrusting and Cenozoic basin-and-range extensional faulting.

The most thorough conceptual model of the NTS's hydrogeology was presented by Winograd and Thordarson (4), whose study was based on virtually all of the available, but admittedly sparse, data. The authors identified ten hydrogeologic units underlying the NTS. Of these, three units -- the lower clastic aquitard, the lower carbonate aquifer, and the tuff aquitard -- were though to control the movement of ground water on a regional basis. Precipitation on the NTS is extremely variable, ranging from 5 cm/yr in the basins to in excess of 50 cm/yr on the mesas. Infiltration is thought to be very low -- perhaps as low as 2 mm/yr in some areas, and potentiometric gradients range from steep (coming off the mesas) to immeasurably flat in the basins. As a result, some of the ground water is thought to be very old. Several regional-scale ground-water flow and transport models have been constructed for the NTS (5,6,7,8), primarily in response to DOE's Yucca Mountain Project. Most of the models are based on data sets that are only slightly expanded over those used by Winograd and Thordarson.

Project Objectives

On the NTS, the principal objective of the Groundwater Characterization Project (GCP) is to refine the knowledge of

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the flow and transport systems so that any real risks (if such risks exist) from past and ongoing underground nuclear tests can be understood, quantified, and reduced to an acceptable level. In order to accomplish this objective, approximately 100 wells are to be drilled over a six to seven year period across the NTS. Twenty one existing wells are currently sampled, both by the DOE and by the U.S. Environmental Protection Agency (EPA), for a variety of constituents including radionuclides. However, all of these wells would have to be classified as 'target of opportunity' wells; they were not specifically designed as monitoring wells but, rather, were drilled for purposes of geologic exploration or water production. The wells were not situated properly for use in a ground-water monitoring network. Some were never cased or were screened in multiple aquifers, such that potentiometric levels and ground-water samples exhibit composite values. Even if sampling is continued in these wells, the density of data available at the end of the GCP will be sparse in comparison to most hazardous waste sites. For this reason, it is crucial that the wells be situated and designed so as to provide the maximum amount of useful hydrogeologic data.

Site-Specific Problems

The size of the NTS may make the traditional 'plume chasing' approach, employed at many hazardous waste sites, inappropriate -- especially if each test location is viewed as a potential source area. A better approach might be to cluster the test locations into groups and treat each group as a source. On a larger scale, each of the five major testing areas (Pahute Mesa, Rainier Mesa, Frenchman Flat, Yucca Flat and Shoshone Mountain) could be viewed as an areal source. The number of monitoring wells might be considerably reduced if hydrogeologic studies indicate that regional-scale features have created preferential flow paths. However, making such determinations would require a relatively detailed knowledge of the hydrostratigraphy and subsurface geologic structure.

Among the difficulties of defining the geologic structure on the NTS are, again, its size, the large distances between wells, the expense of constructing deep wells, and the limited areal information that can be determined from borehole geophysical methods. While many geologic characterization holes have been drilled in the areas used for underground nuclear testing, these wells explore less than 20% of the total facility. Thus, the majority of the new hydrogeologic characterization holes will be drilled in previously unexamined areas. Detailed hydrogeologic studies, combined with surface geophysical studies and numerical simulations involving uncertainty analysis and quantitative risk assessment are currently the approaches being advocated to deal with the size-related problem.

Difficulties also exist in attempting to characterize the hydraulic and transport properties of the aquifers underlying the NTS. For example, certain units of hydrogeologic interest either deform plastically or fracture when subjected to small overpressures. These attributes make it especially difficult to quantify in-situ hydraulic parameters, such as transmissivity and storativity, through the use of conventional hydraulic testing techniques. The large depths to water also complicate the designs of equipment used for aquifer testing and sampling. On the mesas, sequences of ash-fall and ash-flow tuffs influence transport rates and directions. These deposits are limited in areal extent and the depositional sequence is not precisely known.

A large number of underground tests have been conducted on the NTS; of these, at least 100 are thought to have directly impacted on the ground-water system. Nuclear testing creates unique features such as cavities, chimney structures, and craters. In addition, nuclear testing has been observed to cause long-term aberrations in the elevations of water tables, especially in Yucca Flat. Potential pathways for radionuclide migration from test cavities have only been partially defined. Initial studies have shown that most radionuclides remain either near the cavities as a result of vitrification and injection or, through thermal convection, remain near the tops of the aquifers; it is not known if other processes carry certain radionuclides downward. The active depth of circulation in the various testing areas has not been determined. All of these specialized hydrogeologic environments influence near- and far-scale patterns of contaminant migration.

WELL DESIGN

A number of alternative well designs were considered for use on the Groundwater Characterization Project (9), the principal criterion being that the selected design had to permit both characterization and monitoring of multiple hydrostratigraphic units over the long term in a cost-effective manner. The designs included (1) drilling several wells at each site to different depths; (2) installing multiple piezometers in a single large-diameter well; (3) using external casing packers on a completion string, to isolate zones of interest; (4) installing a commercial multi-port sampling system, such as the Westbay system; and (5) installing multiple sliding side door sleeves in a single completion string. Each design was weighed against several factors, such as the availability of materials, whether or not the design had a proven history of long-term reliability, the likelihood of being able to install the hardware in a successful manner, the representativeness of ground-water samples that would be obtained with the design, the ability to conduct aquifer tests in the completed intervals, and cost. The method currently advocated employs a modified design of a standard oil-field sliding side-door sleeve. The modifications consists of changes in the designs of the latch-in profile and seals, to improve cycle life.

Wells being constructed on the Groundwater Characterization Project follow a generic design. A 75-cm-diameter surface hole is drilled to a competent casing point, in order to set surface casing. The surface holes generally range from 25 to 35 meters in depth, with preference being given to deeper holes as an aid in establishing hole verticality for subsequent drilling. Once drilled, a 51-cm surface casing is hung in the hole and grouted in place.

Drilling continues through the surface casing with a 45-cm rock bit. Two drilling methods have been employed, depending on the properties of the rocks being penetrated: (1) air hammering (a percussion type of bit, not unlike a jack hammer) using direct circulation (compressed air and foam circulates down through the drill pipe and up through the wellbore annulus), and (2) button bit drilling using dual-wall reverse rotary circulation with any of the following drilling fluids: air, air foam, water, or mud. (In dual-wall reverse rotary circulation, the drill string consists of a pipe within a pipe -- hence 'dual wall.' Drilling fluids circulate down the pipe annulus and return through the inner pipe. The method minimizes the intrusion of drilling fluids into the borehole wall and carries drill cuttings to the surface faster, minimizing the mixing of cuttings from different depths). All drilling fluids are tagged with a 20 ppm tracer of lithium bromide. When the depth of drilling nears the predicted elevation of the water table, drilling is suspended for 30 to 60 minutes to allow hydrostatic pressures to equalize in the borehole. The hole is then blown clear and samples of the drilling fluid are collected and examined with a bromide electrode. Dilution of the bromide tracer by a factor of two is considered diagnostic for confirmation of having encountered water.

Drilling is continued in increments of one field joint (roughly 10 meters) until positive confirmation of the position of the water table has been established. Two additional joints are drilled to provide sufficient depth for a subsequent series of geophysical tests; presently, the tests include fluid density, caliper, spectral gamma ray, dual induction, compensated density, epithermal neutron, magnetometer, and color video camera.

After the geophysical logs have been completed, a fine sand is used to backfill the hole to a point 15 meters above the static water level. A 5-cm tremmie line (a small-diameter line that is used to place stemming materials in the well annulus) and 34-cm carbon steel intermediate casing are hung in the hole approximately 1.5 meters above the sand layer. The purpose of the intermediate string is to maintain hole integrity during subsequent drilling operations; in competent rocks, the intermediate string may be omitted. The purpose of the sand pack is to keep grout from invading the rock in the vicinity of the static water level. Once positioned, the intermediate casing is grouted in place with conventional materials. The lower portion of the casing is grouted from the bottom up with the aid of a stab-in shoe welded to the bottom of the intermediate string. Subsequent lifts are placed with the tremmie line.

After the grout has cured, the hole is re-entered with a 31-cm bit and drilled to total depth. Current plans call for the wells to range in depth from 915 to 1220 meters; however, certain wells may be as deep as 1830 meters. Drilling may be interrupted any number of times for the purpose of obtaining core samples. Once total depth has been reached, the hole is conditioned (cleaned of drilling fluids) and a second suite of geophysical logs is run; the current plan includes fluid density, caliper, spectral gamma, dual laterolog, epithermal neutron, formation microscanner, acoustic, magnetometer, borehole deviation (gyroscopic or multi-shot, run after the completion string has been installed), compensated density, and video (run after completion of the aquifer tests).

After completion of the second geophysical suite, a two-month period has been devoted to hydrogeologic testing and aquifer sampling. Initially, a standard multiple rate (step drawdown type) test is conducted to determine the overall efficiency and specific capacity of the well, as a function of pumping rate; these data are used to select proper pumping rates for subsequent testing. Next, the well is subjected to a standard long term (24-72 hours) radially converging test to determine the gross transmissivity of the aquifer system. A Schlumberger oxygen activation log is run third, to locate specific zones of major transmissivity that might act as pathways for radionuclide migration; this test is similar to an iodine-131 tracejector survey, but it does not introduce radioisotopic solutions into the wellbore. Finally, a series of drill stem tests is used to quantify the transmissivity of the permeable zones identified with the oxygen activation log. The tests are conducted with double packers (primary and guard) above and below the zone of interest, to enhance the chance of obtaining successful packer seals. The physics of the drill stem tests resembles what hydrogeologists might call a variable rate bailer test. Before the test begins, all drilling fluids are removed from the drill stem, so that only air fills the stem. At a specified time, a valve in the drill stem is opened by rotating the drill stem with the drilling rig. This permits the formation water between the packers to flow into the drill stem, in response to its own hydrostatic pressure. The rise in fluid level is measured in the drill stem with a pressure transducer. As the inner diameter of the drill stem is known, both pressure (head) and flow rate can be determined, as functions of time, from the transducer response. Transmissivity is calculated from the temporal changes in the flow rate and pressure. Present plans do not call for the construction of additional wells, that might be used as observation wells, at any of the sites. For this reason, aquifer storativities will not be able to be measured.

At the conclusion of the hydrogeologic tests, a long string (completion string) is installed in the well. The long string is assembled from an engineered 14-cm internal flush stainless steel pipe that has been modified by heat treating to increase its yield strength. Interspersed at field-selected intervals is a set of sliding side-door sleeves that have been modified for use on the GCP. Sliding side door sleeves are commonly employed in the petroleum industry as a means of gaining and restricting access to different producing units; their principal function is to permit production from formations that exhibit different pressures, in multiply completed wells, without crossflow -- i.e., so that one formation cannot abstract fluid (thief) from another. While the sleeves have proven to be extremely rugged, standard designs do not permit more than a few openings and closings. Sleeves used on the GCP will be operated for ground-water sampling on at least an annual basis and perhaps as frequently as four times per year. For this reason, the GCP sleeves have had seal and profile modifications that permit a demonstrated 400 openings and closings, with a 10^7 Pa pressure differential (both overbalanced -- the greater pressure is on the inside of the sleeve -- and underbalanced -- the greater pressure is on the outside of the sleeve), without significant seal or profile wear. A profile is a series of radial grooves that has been machined into the inner diameter of an element in a long string so that the positioning of a tool into the element can be precisely controlled. Profiles are also used as bearing surfaces, for tools that must exert a force against the long string to operate properly. In this case, profiles are used to permit the latching in of a tool that is used to open and close the sleeves. The sleeves are protected from sand intrusion with an external slotted casing. The system offers mechanical simplicity (as compared to designs employing external casing packers) and is simpler to install than are multiple piezometers. The cost of the units is relatively low -- in the $7,000 to $10,000 range. The design also maintains a relatively large wellbore (12 cm at the narrowest point, within the sleeves), permitting the installation of moderately-sized pumps for testing and sampling of the individual hydrostratigraphic units. The only known disadvantage of the design is the unproven long-term integrity of the seals. However, the large internal diameter of the units would permit the setting of internal packers, should the seals fail.

SLEEVE OPERATION

In the oil field, sliding side door sleeves are opened and closed with a wireline tool called a shifter. The tool is positioned in the hole below the sleeve and is then pulled up until a set of extendable locks or 'dogs' on the tool latch into the sleeve's profile. The tool is jarred upward 20 to 30 times until the sleeve is opened. Once opened, the dogs are forced back into the tool by the sleeve's profile and the tool passes upward through the sleeve. Closing is accomplished in a reverse fashion, with the tool inverted and with a set of sinker bars hung off the tool to provide the jarring force. While such a procedure is adequate for a limited number of openings and closings, profile and seal wear would limit the life of the sleeve to a few cycles.

An alternate means of operating the sleeves has been developed by TAM International (10). Originally conceived as a means of operating sleeves in horizontal wells (where wireline tools cannot be used and where the jarring action of a shifting tool cannot be generated), TAM has developed an electrically operated hydraulic shifting tool. The tool is positioned beneath the sleeve and an electrical signal is sent to the tool to open two pairs of dogs. The tool is then pulled uphole slowly, allowing one pair of dogs to latch into a stationary profile in the sleeve's outer casing. The second pair latches into the moving element of the sleeve. The operator sends a second signal to turn on a hydraulic pump. Hydraulic fluid shifts the second pair of dogs longitudinally, exerting a bearing force against the first set and opening the sleeve. Confirmation of sleeve position is obtained by watching pressure buildups on the pump's discharge side. Once the position of the sleeve has been confirmed, the dogs are retracted, the pump is shut off, and the tool is repositioned for the next operation. A sleeve can be closed without reversing the tool. Sleeve operation is smooth; no jarring actions are required.

GROUTS

The final step in completing the well consists of grouting the long string in place. One problem inherent in the design of any monitoring well with multiple completions involves the mechanical and chemical properties of the stemming materials. It is well known (11) that neat cement raises the pH of well water within which it is in equilibrium to between 11 and 12. This high pH range can affect the chemistry of ground-water samples drawn from the wells. The problem becomes acute with radionuclides, many of which behave chemically in a fashion similar to their non-radioactive metallic counterparts. Awareness of this problem is one reason why hydrogeologists use bentonite to isolate sampling zones.

However, the use of bentonite does not solve the problem entirely. Bentonite can raise the pH of water to between 8 and 10. In wells with a single completion interval, this may be the only problem that bentonite causes and it may be an acceptable trade-off when dealing with cements. In wells with multiple completion intervals -- where layers of bentonite, sand and cement are alternated -- the water in the wellbore can take on a high pH value during the stemming process as a result of contact with the cement. The problem is exacerbated in deep wells where standard stemming practice is to flush out the tremmie line with water after the cement has been pumped into place; this is done to keep the cement from setting up in the tremmie line. The waste cement does not form a plug at the current stemming level. Rather, it is blown throughout the water column in the form of a fine- to coarse-particulate suspension that eventually settles out in the wellbore annulus. The cement crumbs do not develop mechanical strength but, because of their high surface area and buffering capacity, do raise the pH of the well water. When bentonite is subsequently tremmied into position through the high pH water, it deflocculates, forming a fluffy suspension, losing its ability to form a good expanding seal, and losing its compressive strength. If sand or cement is tremmied in on top of the bentonite, it displaces or mixes with the bentonite layer.

An attempt is being made to overcome problems inherent in the use of cement-based grouts by investigating the potential use of geotechnical grouts and epoxies -- materials that are used for sealing cracks in dams, foundations, and underwater structures. To be compatible with the objectives of the wells, we tasked ourselves with finding one or more materials that would meet the following rather stringent set of requirements:

- When placed in contact with water, the grout could not lower the water's pH beyond 6.5 nor raise it above 7.5.
- The concentration of organic chemicals introduced by the grout into the well water must be minimal. Small concentrations of organic chemicals were thought not to be detrimental to project objectives, because the principal species being investigated were radionuclides, not organic solvents.
- The grout had to exhibit a working time of at least 1 hour. Working times as long as 12 hours could be permitted.
- The grout had to be workable at temperatures ranging from 10 to 50 degrees Celsius, to be compatible with ambient and expected down-hole temperatures.
- The grout had to be able to be mixed with conventional mixing equipment.
- It was desirable that the grout not react with quartz pea gravel, so that gravel could be mixed with the grout to decrease the volume of epoxy that was required.
- The grout had to be able to be pumped downhole with conventional pumping and tremming equipment.
- The grout had to develop a mechanical strength similar to that developed by cement-based grouts when placed under water.
- The grout had to exhibit a water permeability, when cured, equal to or less than that exhibited by cement.
- The grout had to maintain a specific gravity in excess of 1.5 during all phases of placement and curing.
- The grout was not permitted to outgas significantly.
- Health hazards posed to workers during emplacement of the grout had to be minimal.
- The grout could not be a source of environmental problems.

A series of bench-scale experiments was performed on samples of cements and epoxy-resin grouts supplied by various vendors. The materials included barite, a weighting agent used in standard drilling muds; Pyrament, 'regulation set,' Lumnite, and Ciment Fondu, a series of grouts recommended by the U.S. Army Corps of Engineers' Waterways Experiment Station (WES); two soil stabilizing hydrophobic polyurethanes called Mountain Grout and Saudi Grout (and mixtures of these with barite) (12); Ceilcote 612 (and mixtures of Ceilcote with cement), GE-329 and GE-332 (13); and Hydromite (14). The results of these experiments will be detailed in a subsequent report, but some initial observations are worth mentioning.

Each material was subjected to a series of increasingly selective tests that included pH, set time (viscosity) as a function of temperature, permeability, and bond strength (a shear-strength test that gives an indication of the bond between the grout and the well casing). The materials were examined visually for qualitative factors such as outgassing, floating, settling through a water column, and miscibility with quartz pea gravel, by pouring the materials through columns of water into 8-cm lucite tubes. The WES cements were eliminated early in the testing program because of the high pH values that they generated. The Mountain Grout products formed hard plugs underwater but were eliminated because of outgassing problems and because of high permeabilities.

The Ceilcote products appear to be the most promising, with a field test of Ceilcote GE-329 (modified) to be performed in the Fall of 1991. The purpose of the field test is to verify that conventional mixing equipment can be used to tremmie the materials into place. In addition, mixing and tremming equipment are being coated with a polyethylene to prevent sticking; the efficacy of this concept needs to be tested. Finally, the quality of the grout plug itself needs to be examined. To accomplish these goals, the grout will be stemmed into a section of well casing that is lowered beneath the static water level in an existing NTS well. After the grout plug has cured, the pipe will be withdrawn, split, and the plug will be examined.

DEVELOPMENT, PURGING AND SAMPLING

Once the well has been completed, each zone of hydrogeologic interest will be developed, purged, and sampled. Development will maximize the ability of the screened interval to produce water by partially removing any of the remaining drilling fluids and cuttings that have invaded the formation, and by flushing and grading the filter pack surrounding the screens. Development of the filter packs will be accomplished either by swabbing or by pumping. The wells will be purged prior to sampling with a high capacity, high lift, slim-hole pump that is being developed. Purging operations will be deemed complete when the discharged water has stabilized with respect to temperature, pH, and electrical conductivity. Ground-water samples will be collected subsequent to purging operations for volatile and semivolatile organics; total petroleum hydrocarbons; standard cations (including metals such as lead); certain other metals of interest including arsenic, mercury and selenium; standard anions; alkalinity; TDS; pH; EC; and a suite of radionuclides including gross alpha, gross beta, gamma scan, ^{3}He, ^{4}He, ^{85}Kr, ^{86}Sr, ^{87}Sr, ^{234}U, ^{238}U, ^{137}Cs, ^{125}Sb, ^{60}Co, ^{90}Sr, ^{14}C, ^{99}Tc, ^{36}Cl, ^{2}H, ^{3}H, ^{16}O, ^{18}O, ^{12}C, ^{13}C and ^{14}C. The large initial suite is being used to establish baseline conditions. Subsequent sampling, for monitoring purposes, will, most likely, be reduced to a smaller suite of radionuclides that act as indicator parameters.

CONCLUSIONS

Established methods for the construction of ground-water monitoring wells are not always appropriate on the U.S. Department of Energy's (DOE) Nevada Test Site (NTS), because several unique hydrogeologic conditions exist that influence the designs of the wells. As a result, the GCP is employing a new design of characterization well, based on a crossbreeding of ground-water and petroleum production technologies. The new design employs a modified form of a sliding side door sleeve, to gain access to formations of hydrogeologic interest. A hydraulic shifting tool is used to operate the sleeves. Packers and sample bottles can be added above the shifter to minimize purge volumes and draw representative samples of ground water. An epoxy-resin grout has been identified that has permeabilities and working characteristics that are slightly better than conventional cement-based grouts. The new grout introduces small amounts of organic materials into the ground water but appears to minimize the pH-related problems caused by the use of cements.

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