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BLIND SHAFT DRILLING - THE STATE OF THE ART

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1.0 BRIEF HISTORY OF UNITED STATES NUCLEAR EXPLOSIVE FIELD TESTING

- 1.1 Nuclear explosive testing is fundamental to weapons development. The world's first nuclear weapons test on July 16, 1945, was conducted under the pressure of wartime conditions at Trinity Site in southern New Mexico on what was then the Alamogordo Bombing Range and is now the White Sands Missile Range. This event, followed by nuclear explosions over Japan three weeks later, hastened the end of World War II and began the era of nuclear weapons development and testing.
- 1.2 United States nuclear tests were conducted on an intermittent basis from 1946 to October 1958. During this period 193 field tests were conducted in the Pacific and the Nevada Proving Ground, forerunner to the Nevada Test Site (NTS). Pacific test locations included the Johnson Island Area, Enewetak, Bikini, and Christmas Island Area. On November 1, 1958, the United States, under President Eisenhower, entered into a unilateral testing moratorium with the Soviet Union. On August 31, 1961, the Soviet Union announced its decision to resume nuclear weapons testing and the moratorium ended in September 1961 with the Soviet Union conducting a series 45 tests within 65 days. President Kennedy ended United States compliance to the testing moratorium with his announcement of an underground nuclear test conducted on September 15, 1961, but the United States did not resume atmospheric testing until April 25, 1962, seven months later.
- 1.3 After the moratorium, the United States conducted sixteen atmospheric field tests. Between July 1945 and September 23, 1992, the United States conducted a total of 849 announced nuclear tests. After the moratorium, the United States conducted most high-yield atmospheric tests in the Pacific, while lower-yield atmospheric and underground tests were conducted in Nevada.
- 1.4 The Limited Test Ban Treaty (LTBT), ratified by the United States, the United Kingdom, and the Soviet Union, and signed in Moscow on August 5, 1963, prohibited testing in outer space, under water, or in the atmosphere.
- 1.5 Since July 1962, all nuclear tests conducted in the United States have been underground and most of them have been at the NTS. Tests conducted off the NTS include: the Nellis Air Force Base Bombing Range, in central and northwestern Nevada, in Colorado, New Mexico, Mississippi, and on Amchitka Island, one of the Aleutian Islands off the coast of Alaska. The first underground nuclear test was as a safety experiment conducted on July 26, 1957, in an unstemmed vertical shaft, code name Pascal-A. This test was followed one month later by the first tunnel test, code name Saturn, which was also a safety experiment. Pascal-A initiated

a new direction in field testing of United States nuclear devices. Scientists improved methods of testing nuclear explosives underground, encouraged by the effective containment of radioactive debris this technique makes possible. They developed new diagnostics experiments for measuring fission and fusion reactions, shifting their focus from primary air blast phenomena, to the measurement of radiation propagation, particle emissions, and shock interaction.

- 1.6 The Threshold Test Ban Treaty (TTBT), was signed on March 31, 1976, by the United States and the Soviet Union, which limits the maximum yield of underground tests to 150 kilotons (KT). This treaty was never ratified by the United States because of uncertainty and limitations in verification.
- 1.7 The United States entered into a nine month test moratorium on October 1, 1992, in accordance with Senate Amendment 3043, commonly referred to as the Hatfield Amendment.
- 1.8 The history of blind shaft or big hole drilling is linked to the nuclear test programs of Los Alamos and Lawrence Livermore National Laboratories. Larger shafts and tunnels became desirable as new diagnostics techniques were developed and ever more complicated diagnostic instrument and device canisters were designed.

2.0 BLIND SHAFT OR BIG HOLE DRILLING

2.1 INTRODUCTION TO BLIND SHAFT DRILLING

- 2.1.1 The "Art" of blind shaft drilling has been in a continual state of evolution at the NTS since the start of underground testing in 1957. Emplacement holes for nuclear devices are still being drilled by the rotary drilling process, but almost all the hardware and systems have undergone many changes during the intervening years. Blind shaft drilling and tunnel construction technologies received increased emphasis with the signing of the LTBT in 1963.
- 2.1.2 The current design of bits, cutters, and other big hole drilling hardware results from contributions of manufacturers and NTS personnel. The dual string, air lift, reverse circulation system was developed at the NTS and is now being used throughout the world within mining and general construction applications. Necessity was really the mother of this invention, but this circulation system can be utilized under almost any condition.
- 2.1.3 Drill rigs for Big Hole drilling are usually adaptations of large oil well drill rigs with modifications to handle the big bits and drilling assemblies. However, current trends on the NTS and elsewhere are toward the

utilization of rigs designed specifically for blind shaft drilling in a quest to: drill larger holes; decrease the resulting attrition to rigs as a result of high torques and heavy bottom-hole assemblies; and increase the efficiency of drilling operations thereby reducing operational cost. Steel remains the favorite shaft lining material, but a lot of thought is being given to concrete linings, especially precast concrete.

2.2 BLIND SHAFT DRILLING

- 2.2.1 The "Art" of blind shaft drilling has been developed at the NTS as a part of the nation's nuclear testing program. Design of diagnostic canisters is inexplicitly linked to the hole size. Agreements with the Soviet Union specify that the radioactive products of a detonation shall not pass the national boundaries. Therefore, nuclear experiments are conducted underground mostly in drilled shafts. There have been more than 550 shafts, with a total footage in excess of 1,050,000 feet, drilled at the NTS for this purpose. These big holes range in size from 48 inches to 144 inches in diameter, with some shafts opened or reamed to 252 inches, and range in depth from 500 feet to over 5,000 feet.
- 2.2.2 These holes were drilled at a rate in excess of 100 feet per day and with a bottom offset of only slightly over one foot per 1,000 feet of depth. This drilling rate of 100 feet per day includes the actual drilling time, the time required for trips and connections, as well as time spent surveying the hole. The bottom offset was determined by optical surveys of the completed hole, whereby the bottom of the hole is located by surveying the surface with a theodolite. Laser logging tools are now being used to provide detailed information on hole conditions.
- 2.2.3 This directional control was achieved by using the "plumb bob" effect with the drilling assembly whereby only 40 percent of the weight of the drilling assembly is used to drill the hole; the other 60 percent of the weight is used to keep the hole vertical.
- 2.2.4 The geology of the NTS is almost entirely of volcanic origin. There may be some sedimentary material included in the alluvium, but the underlying formations are volcanic tuff. Compressive strength of the hardest densely welded tuffs may run as high as 25,000 psi but the average compressive strength of the material drilled is less than 4,000 psi.
- 2.2.5 Attachment 1 is a one-page history of the evolution of big hole drilling tools and techniques at the NTS. This presentation does not begin to indicate the difficulties that were encountered using various techniques and undersized equipment before the current equipment and techniques were developed.

2.3 CIRCULATION SYSTEM

- 2.3.1 The rate of penetration relates to the efficiency of cleaning the bottom of the hole, which, in turn, is a function of the circulation system. Direct circulation is normally used in oil well drilling. This system has been used for big hole drilling, but its use is limited because of the huge volumes of air or liquid required to produce an acceptable annular velocity. Reverse circulation, in which the flow is reversed from that used in direct circulation, has been used to a limited extent with air pressure or air vacuum. Air pressure reverse circulation results in a pressure in the annulus and in the formation which can destabilize incompetent formations resulting in debris cascading into the hole. In addition, this pressure must be bled off each time a joint of pipe is added to the string. Air vacuum limits the circulation rate because of the small amount of pressure drop available to the circulation system. Air vacuum is susceptible to formation fluids and requires extensive filtration equipment to protect the blowers that provide the vacuum, but vacuum drilling does not disturb the formations being drilled.
- 2.3.2 Most big hole drilling is done with a reverse circulation air lift system or with a dual-string circulation system shown in Figure 1. Both systems use an air lift system, to lift the drilling fluid and formation cuttings up the drill pipe. In the air lift system the hole is kept full of fluid and air is injected through tubing suspended inside the drill pipe. This system requires a fluid circulation rate in excess of 4,000 gpm to efficiently remove cuttings. The capacity of a fluid to carry a cutting is to the third power of the velocity. Large volumes of fluid are required to achieve a velocity capable of carrying a cutting in the large drill pipe.
- 2.3.3 The dual string circulation system was developed at the NTS because formations would not support a hole full of fluid. This system requires a special drill pipe which consists of a large diameter drill pipe with an integral inner string. Air and drilling fluids are introduced into the drill pipe annulus and travel together to the bit where they are essentially separated by gravity and centrifugal force. The drilling fluid goes out the bit jets to clean out the bottom of the hole. Air goes through the air jets and provides the air lift. Circulation rates are much lower, in the order of 300 to 600 gpm.
- 2.3.4 Air lift pumping operates when the pressure, due to the submergence, exceeds the pressure created by the aerated column of fluid inside the casing. The mechanics of air lift pumping are similar to those in oil and water production. Theoretical and experimentation activities are ongoing at the NTS to correlate data and develop an efficient drilling system.
- 2.3.5 The dual string system requires more power than the conventional air lift system. Operating pressures of the compressors and pumps are much

Figure 1 Dual String Circulation System

more than required on the air lift system. We feel that the dual string system does a better job of cleaning the bottom of the hole due to the effect of the high-velocity water jets and the resulting turbulence they create.

2.4 SURFACE EQUIPMENT

- 2.4.1 Blind shafts are drilled in two phases; the first phase is the surface hole which is drilled with an auger rig from 0 to approximately 120 feet; and the second phase is drilled utilizing a large oil field type drill rig. The auger rig requires only limited amount of water, primarily for dust control, since cuttings are removed by mechanical means. The surface hole is require to support circulation during phase two drilling operations which utilize the circulation system described earlier.
- 2.4.2 Most big holes are drilled with large oil field type drill rigs, usually with only minor modifications. These rigs must be equipped with large heavy duty type rotary tables to supply the necessary drill pipe torque. Rotary table failures were a part of the early history of big hole drilling. Rotary table supporting structure modifications are indicated since the table and

supporting structure must be removed whenever the drilling assembly is pulled to change the bit. Special equipment is required to make and break the drill pipe tool joints. Thirteen and three-eighths-inch drill pipe requires make-up torque of 100,000 foot pounds. Drill pipe required to drill 16-foot and larger diameter holes, such as 20-inch drill pipe, will require at least 500,000 foot pounds of torque.

- 2.4.3 Making and breaking the drill pipe tool joints presents a problem in rotary table type rigs because of the high torque involved. Oil field practice is to spin the joint up with a chain and torque it with drill pipe tongs. Thirteen and three-eighths-inch drill pipe cannot be spun with a chain. It can be spun with a rope, but rope costs are high because of frequent breakage. Spinning is best accomplished with casing tongs. Only recently have drill pipe tongs been offered which were designed for the torque required for 13 3/8-inch drill pipe. Self-contained, hydraulically operated torque wrenches are available which make and break tool joints more safely than with drill pipe tongs. Drill pipe tongs are not suitable for 20-inch drill pipe; a self contained torque wrench must be used.
- 2.4.4 Current and expected future trends in blind shaft drill rigs is for rigs specifically designed for this type of drilling. This rig has a top drive, instead of a rotary table, to rotate the drill pipe and bit. The top drive also makes and breaks the tool joints, replacing the spinning and torquing device(s) required on rotary type rigs. Unfortunately, this machine pulls 30-foot joints which must be laid down, whereas an oil well type rig usually pulls 90-foot stands which are racked in the derrick.

2.5 DRILLING TOOLS

- 2.5.1 The drilling tools for a dual string circulation system are shown in Figure 2. The swivel must be of adequate capacity and have a large bore. Swivels designed to be used with 13 3/8-inch drill pipe have a 12 1/2-inch diameter bore and are available to a working capacity up to 700 tons. This swivel must be adapted to the dual-string circulation. This requires the addition of the inner string wash pipe, packing, and gooseneck. The return flow of fluid, air, and cuttings is quite abrasive, particularly where the fluid is forced to change direction. A one-inch replaceable rubber pad under the gooseneck cover absorbs the impact of the returning fluid and cuttings with less wear than steel.
- 2.5.2 The inner string wash pipe is screwed into the swivel saver sub. This connection has been designed so that the inner string can float and seek the center of the packing. Torque is transmitted from the rotary table to the drilling assembly through the square kelly and the drill pipe, all units of which are equipped with an inner string. Details of this inner string installation are shown in Figure 1. Also shown are the details of the circulation system.

Figure 2 Cutters and Drill Bits

2.6 BITS AND CUTTERS

- 2.6.1 Three different types of bit cutters have been used on the NTS: milltooth cutters which consist of approximately one-inch high teeth covered with powered tungsten carbide and are used in soft rock formations; button cutters which consist of varying height tungsten carbide inserts distributed across the cutter periphery and used in hard rock formations; and kerf cutters which consist of discs and utilizes a plowing action to break rock. Kerf cutters have been used on a limited basis on the NTS with operational results slightly below or comparable to the other types of cutters but have a higher equipment cost. Bottom-hole assembly stabilization is a key concern with kerf cutter drill bits due to the increased torque requirements. Each type of cutter is equipped with ball and roller bearings to take the radial and thrust loads imposed during normal drilling operations. The seals are critical components of any cutter. Bearing life is dictated by these seals in that the bearing failure usually results from seal failure which allows contamination of the lubricant with drilling fluid and cuttings.
- 2.6.2 A large amount of work has been devoted to the placement of cutters on the drill bit. Ten-fold improvements in penetration have been realized over the last ten years from advanced designs in cutter placement. Cutters must be placed so there is at least one cutter for each radial portion of the hole; that is, there must be full coverage. Cutter locations should be balanced with respect to one another and extra gauge cutters are required to ensure that the hole is kept at full diameter. Cutters should not be placed at equal angles; this will contribute to bit bounce.
- 2.6.3 The location and sizing of the fluid jets are carefully designed to assure efficient transport of cuttings toward the pickup point located at the center of the drill bit cutting surface. Current practice is to have one jet per cutter and to have a total fluid jet area of approximately 2.75 square inch, with the ratio of fluid jet area to air jet area equal approximately 4:1.

Experience has shown that as the hole gets deeper, the jet ratio should decrease.

2.7 CASING AND CEMENTING

- 2.7.1 Steel is used as the primary liner material for big holes although concrete has been used to a limited extent through precast concrete sections or shotcrete. The cost of these steel liners has made an adverse contribution to the economics of drilled shafts, since the cost of a steel liner, installed and cemented in place, can be as much as two-thirds the total cost of the shaft. As each section was added, the steel shell is welded to the previous sections. Liners that are set below the water table will float, and lowering is accomplished by pumping fluid into the liner sections.
- 2.7.2 Cementing of liners has, historically, been done by oil well cementing companies utilizing modified oil field techniques. Tremmie lines (small diameter tubing) is positioned on the outside of the liner and the annulus area of the liner is cemented in place from the bottom up with the cement displacing water as it rises.

2.8 OPERATING PROCEDURES AND PARAMETERS

- 2.8.1 Surface holes are drilled with an auger rig as indicated earlier. Normal procedure is to auger a 104-inch or a 120-inch diameter hole and ream the hole to the desired finished diameter. Surface casing is set by a crane and cemented in place with batch plant cement.
- 2.8.2 The 100 feet-per-day penetration rate at the NTS is achieved with drilling parameters somewhat different from the cutter manufacturer's recommendations. A 96-inch bit with 18 cutters will seldom be loaded to more than 120,000 pounds and can be rotated as high as 30 rpm, although 15 to 18 rpm are typical. This equates to less than 7,000 pounds per cutter, whereas cutter manufacturers recommend cutter loading at 20,000 to 30,000 pounds. This lower cutter loading is acceptable because of the relatively soft formations. The 30 rpm rotating speed is much higher than normal recommendations. This speed has not adversely affected cutter life; it does directly affect the penetration rate.
- 2.8.3 Bits are run for approximately 100 hours and then pulled and changed. This is done to prolong cutter life and to guard against the possibility of leaving a cutter in the hole. Milltooth cutters that removed from the bit are retipped, and seals replaced. Tungsten Carbide Insert (TCI) cutters are relubricated after the first run and reused. After the second run, the TCI cutters are disassembled and repaired. Normal life for a milltooth cutter is 6 runs or 600 hours, for TCI cutters 4 runs or 400 hours.

- 2.8.4 Penetration rates as high as 35 feet per hour have been achieved with a 96-inch bit, although 8 to 12 is more typical for prolonged periods of time. This equates to an excavation rate of 600 cubic feet or 22.2 cubic yards per hour. This is accomplished through a 7-inch inner string with 2,000 to 4,000 scfm of air, depending on depth, and 400 gpm of water.

2.9 PROBLEMS AND SOLUTIONS

- 2.9.1 Two principal problems affect drilling operations at the NTS. The first problem, lost circulation formations, led to the development of the dual-string circulation system. Even so, it is sometimes difficult to maintain the desired submergence to get dual-string circulation. This can usually be cured by use of lost circulation materials, but sometimes it is necessary to drill without proper circulation.
- 2.9.2 The second and potentially serious problem involves hole sloughing. A considerable portion of the drilled hole is unsupported by hydrostatic pressure, since drilling is accomplished with 200/300 feet of water in the hole. Portions of this unsupported hole have been known to collapse over the bit. The most successful procedure to recover the drilling assembly has been to pump fluid into the hole to the top of the fill and fluidize the fill over the bit. If sloughing is not too severe, drill operations can proceed without further remedial action. In cases of severe sloughing, it has been found necessary to plug the hole back with concrete to fill the cavity and then redrill the hole.

3.0 CONCLUSIONS

- 3.1 Big hole drilling represents a "state of the art" method of blind shaft construction. Holes to 180-inch diameter can be drilled, in most places, with the current 13 3/8-inch drill pipe and associated drilling assemblies. Larger holes will require larger drilling tools. Twenty-inch drill pipe and compatible drilling assemblies should be sufficient for 20 to 24-foot shafts.
- 3.2 Conventional mining shaft sinking is a hazardous occupation. The accident rate is high. Blind shaft drilling is much safer, since the work is done from the surface and no one goes into the shaft until it is completed. Shaft drilling is also much faster than conventional shaft sinking. Penetration rates of 100 feet-per-day may not be achieved, but drilling rates should always be ahead of the rates which result from drilling, blasting, and mucking.
- 3.3 Shaft drilling is most adaptable to some areas that offer severe problems to conventional shaft sinking methods. An area with severe water problems would cause major problems to conventional shaft sinking, but no

problems to shaft drilling. Water flows would be controlled by keeping the hole full of fluid.

- 3.4 These comments were not designed to serve as a text for big hole drilling. Rather, they were intended to define the "state of the art" for anyone who has a shaft to sink, and provide him with some basic information about the parameters for big hole drilling.

Attachment 1

EVOLUTION OF BIG HOLE DRILLING TOOLS & TECHNIQUES REYNOLDS ELECTRICAL & ENGINEERING CO INC

END

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