Los Alamos National Laboratory is operated by the University of California for the United States Department of Energy under contract W-7405-ENG-36.

RECEIVED**MAY 31 1996****OSTI**

TITLE: Cost Effectiveness of Sonic Drilling

AUTHOR(S): Dave Masten
Steven R. Booth

SUBMITTED TO: General Distribution, March 1996

MASTER

By acceptance of this article, the publisher recognized that the U S Government retains a nonexclusive, royalty-free license to publish or reproduce the published form of this contribution or to allow others to do so for U S Government purposes.

The Los Alamos National Laboratory requests that the publisher identify this article as work performed under the auspices of the U S Department of Energy.

Los Alamos

Los Alamos National Laboratory
Los Alamos, New Mexico 87545

ABRAM

Los Alamos

LA-UR-96-1328
March 1996

Cost Effectiveness of Sonic Drilling

Prepared by

*LANL Environmental Technology Costs-Savings Analysis Project (ETCAP)
under sponsorship of the Department of Energy -
Office of Science and Technology (EM-50)*

243A

LA-UR-96-????
March 1996

Cost Effectiveness of Sonic Drilling

Dave Masten, Ph.D.
Steven R. Booth, Ph.D.

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

Energy and Environmental Analysis (TSA-4)

Los Alamos National Laboratory
Los Alamos, NM 87545

By acceptance of this article, the publisher recognizes that the U. S. Government retains a nonexclusive, royalty-free license to publish or reproduce the published form of this contribution or to allow others to do so for U. S. Government purposes.

The Los Alamos National Laboratory requests that the publisher identify this article as work performed under the auspices of the U. S. Department of Energy.

MASTER

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

Contents

Abstract	1
1. Introduction	1
2. Background	2
3. Methodology	3
4. Description of Sonic Drilling System	4
4.1 Drilling	4
4.2 Geological Sampling	7
4.3 Well Completion	8
4.4 Crew Size and Experience	8
4.5 Rig Maintenance	8
5. Description of Baseline Technologies	9
5.1 Cable-Tool Drilling	9
5.1.1 Drilling	9
5.1.2 Geological Sampling	10
5.1.3 Well Completion	10
5.1.4 Crew Size and Experience	10
5.1.5 Rig Maintenance	10
5.1.6 Rig Cost	10
5.2 Mud Rotary Drilling	11
5.2.1 Drilling	11
5.2.2 Drilling Fluid	12
5.2.3 Geological Sampling	12
5.2.4 Well Completion	12
5.2.5 Crew Size and Experience	12
6. Performance Comparison	12
6.1 Site Characteristics	13
6.2 Waste Generation	13
6.3 Sample Quality	13
6.4 Scenarios	14
6.4.1 Scenario One	14
6.4.2 Scenario Two	16
6.3.3 Scenario Three	16
7. Economic Comparison	16
7.1 Scenario One	21
7.2 Scenario Two	21
7.3 Scenario Three	22
8. Ongoing and Future Developments	24
9. Health and Environmental Risk	24
10. Regulatory Approval	25
11. Summary	25
Acknowledgments	26
References	26
Bibliography	27
Appendix	28

Figures

Figure 1. Sonic drill rig.	4
Figure 2. Sonic drill oscillator.	5
Figure 3. Sonic drill head.	5
Figure 4. Core barrel.	5
Figure 5. Split-spoon sampler.	7
Figure 6. Cable-tool rig.	9
Figure 7. Drill string.	10
Figure 8. Mud rotary rig.	11
Figure 9. Scenario 1 -- Cost comparison of sonic vs. cable-tool at Hanford.	21
Figure 10. Scenario 2 -- Cost comparison of sonic vs. mud rotary at Sandia.	22
Figure 11. Scenario 2 -- Sensitivity to percent hazardous waste.	22
Figure 12. Scenario 3 -- Cost comparison of sonic vs. cable-tool and mud rotary.	23

Tables

Table 1. Specifications of different sonic drill rigs.	6
Table 2. Scenarios and cost comparisons.	15
Table 3a. Cost of drilling technologies -- borehole (clean site)	17
Table 3b. Cost of drilling technologies -- borehole (hazardous site).	18
Table 3c. Cost of drilling technologies -- borehole (mixed waste site).	19
Table 4. Cost of drilling technologies -- completion.	20

Abstract

Sonic drilling is an innovative environmental technology being developed in cooperation with the DOE-sponsored Arid-Site Volatile Organic Compounds (VOCs) Integrated Demonstration at Hanford and the Mixed Waste Landfill Integrated Demonstration (MWLID) at Sandia National Laboratory. The principal developer of the technology is Water Development Corporation (WDC) of Woodland, California under the service mark ResonantSonic™. This report studies the cost effectiveness of sonic drilling based on performance data from the above mentioned demonstrations and estimates of expected performance. The baseline technologies are cable-tool (the primary drilling technology used at Hanford hazardous sites) and mud rotary (popular for fast drilling and used at Sandia). The primary benefit of sonic, as compared to the baseline technologies, is its ability to drill in all types of formations without introducing a circulating medium; as a result, little secondary waste is generated at hazardous sites.

Early demonstrations of sonic drilling were plagued by downtime due to drill string and drill head failures. Later tests indicate that the drill head problems have, for the most part, been solved. Some improvements have been made to increase drill-string life. However, additional research and technology developments are necessary to mitigate this problem. Even so, based on the scenario results in this report, sonic appears to be a superior, cost-effective technology when compared to cable-tool for drilling in both hazardous and "clean" sites. It is also superior to mud rotary in hazardous sites. For the scenario based on ideal estimates of sonic drill rates, it appears that sonic also may be able to effectively compete with mud rotary in clean sites.

1. Introduction

Sonic drilling is an innovative environmental technology that has been tested at the Arid-Site VOCs Integrated Demonstration at Hanford, the Mixed Waste Landfill Integrated Demonstration (MWLID) at Sandia National Laboratory, and the Cooperative Research and Development Agreement (CRADA) between Water Development Corporation (WDC), Westinghouse Hanford Company (WHC), Pacific Northwest Laboratory (PNL), and the Department of Energy (DOE).¹ This report is a

study of sonic drilling based on data from four separate demonstrations conducted at these sites. These include three separate demonstrations of sonic drilling at the Hanford site and one at the Sandia site. Data from these demonstrations are integrated in this report to illustrate the variance in performance and cost effectiveness of sonic drilling with geological setting, equipment size and condition, and the implementation of new technology. This report will also demonstrate the most recent and ongoing technological advances in sonic drilling.

Sonic drilling is being tested as a viable alternative to more conventional technologies for drilling and sam-

pling at hazardous and radioactive waste sites. The following review is intended to demonstrate the principal performance and cost differences between the new and conventional, or "baseline," technologies at the Hanford and Sandia demonstrations. This comparison will provide basic background information and cost effectiveness of sonic drilling to managers of environmental restoration projects.

2. Background

The idea of penetrating the earth using vibrational energy is not new. The tendency of wood or steel to vibrate when struck has been utilized to drive piles into the ground since Roman times. Not until this century, however, have high frequency, vibrational machines been successfully utilized to penetrate the earth. In the early 1960s, Albert G. Bodine, Jr. developed the first successful resonant pile driver. Previous attempts to develop such a machine had failed because the high forces involved tended to destroy the machine itself. Several large companies subsequently used Bodine's sonic driver, called the Bodine Resonant Driver (BRD), to drive thousands of feet of piling in many areas of the world. Despite its initial use and acceptance, the equipment and method were plagued with problems. In the thirty years since Bodine's original work, sonic drilling has experienced a somewhat "on again, off again" trend of development. During this time, various companies and individuals have invested time and money to improve the reliability of resonant sonic drilling. While finding some application in driving piles, it has remained a secondary technology and has received limited exposure and use in the field [1].

Despite its infrequent application, the resonant sonic drilling method has once again attracted attention, this time from the environmental restoration community. The

most important factors contributing to the appeal of sonic drilling for environmental applications are that little or no circulation medium is required even under the most difficult conditions, and a minimal amount of waste is generated. These are not only important economic considerations but, in certain geological and/or contamination situations, may be requirements. These advantages may make sonic drilling an attractive new "tool" in the "toolbox" of environmental restoration technologies.

The demonstrations described in this report have played important roles in the development of sonic drilling. From September 1991 to May 1992, a 15-year-old sonic drilling rig (Hawker Siddeley drill owned by Harrison-Western Drilling, Inc.) was tested at the Hanford site under the Drilling Technology Development Technical Task Plan (TTP) and the Environmental Restoration Program. The former was administered by DOE's Office of Technology Development. Results of this test were burdened by high downtime due mostly to head and drill-string failures. This test proved to be very useful by demonstrating the potential of sonic drilling to become a viable method if improvements in the system components can be made.

In 1993, three different sonic drilling rigs were demonstrated at the Sandia site. These were all newer rigs with many improvements over the rig previously demonstrated at the Hanford site. Technological advances in both the drill head and drill string resulted in much less downtime at Sandia than was observed at Hanford. This test demonstrated that sonic drilling has advanced sufficiently to be a viable drilling method and showed promise that further improvements in system components are possible.

Newer sonic drilling rigs were evaluated at the Hanford site as part of the joint CRADA under the TTP.

These rigs performed well, with reduced downtime and increased drill rates [2].

The Sandia and Hanford rigs are all owned by drilling contractor Water Development Corporation (WDC) of Woodland, California, which has become the leading advocate and developer of the sonic drilling method in the United States. WDC acquired much of the Albert Bodine estate as well as the sonic drilling equipment of Harrison Western. Current WDC sonic systems use the service mark ResonantSonic™.

3. Methodology

The methodology used to evaluate a new environmental technology is composed of two parts; a performance evaluation and an economic evaluation [3]. In evaluating a new environmental technology, it is necessary to have some conventional or baseline technology with which to compare it. This immediately raises questions about how to compare two technologies that may be seemingly incomparable. The method chosen is to construct some reasonable basis for comparison known as a "performance scenario." The general performance scenario creates a level playing field in the context of several realistic geological settings. Each specific case is referred to simply as a "scenario."

Emphasis is given to the performance evaluation, as performance issues are critical to establishing a balanced comparison from which economic cost savings can be calculated. The challenge is to present often diverse technologies in a fashion that will lead to a fair and reasonable assessment of the cost effectiveness of the new technology. The purpose of the performance scenario is therefore to equate the results of the competing technologies so that the cost-effectiveness analysis is reduced to a direct comparison of costs. With this goal in mind, the major

components of the methodology are:

- **Identify major performance characteristics of the new environmental technology.**
- **Identify appropriate conventional technologies to serve as the baseline for performance comparisons with the new technology.**
- **Compare performance between the new technology and the conventional alternatives.**
- **Use scenarios to provide a realistic context for the performance comparison.** (Where possible, scenarios represent actual field experiments that have been performed.)
- **Perform an economic comparison of the new technology and the conventional alternatives.**
- **Assess uncertainty in performance, cost, and regulatory permitting.**
- **Consider all other relevant aspects and/or effects involved in the use of the new environmental technology.** (When it is not possible to quantify these influences in scenarios due to lack of detailed information, provide a qualitative discussion. Important issues to cover are: future developments expected in both technologies, applicable geological settings for both technologies, health and environmental risk reduction, regulatory status, and perceived public acceptance.)

A fundamental issue in the evaluation of a new environmental technology is the choice of the baseline technology (e.g., cable-tool, mud rotary, or auger drilling). The large number of similarities in the purpose and performance of sonic and many other drilling technologies (e.g., installing monitoring wells, or taking continuous core in similar geological settings) make their application practically equivalent. As a result, the performance scenarios in this report serve only to provide a realistic context for comparison of the technologies.

To add realism to the analysis, we include in the cost comparison all relevant costs for drilling activities. Consequently, a cost difference between the technologies can be divided by the total baseline cost to show a percentage savings.

This report is intended to provide background information and the cost effectiveness of sonic drilling to managers of environmental restoration projects, both in gov-

ernment agencies and private industry. The reader should pay careful attention to caveats discussed in this report to determine how this technology can best be utilized at a particular environmental restoration site. This report is not intended to be a detailed analysis of all possible scenarios, but is presented in a descriptive approach to be of general use to the DOE community.

4. Description of Sonic Drilling System

The sonic drilling system was designed to penetrate a wide range of forma-

tions including the sandy, gravely soils which are common at the Hanford and Sandia sites. For environmental applications, the benefits of the system include: (1) minimal or no circulation medium is required; (2) continuous core is usually the only soil "waste" generated; and (3) contamination control is maintained at the wellbore. A total of five different sonic drilling rigs have been demonstrated at the Hanford and Sandia sites; two at Hanford and three at Sandia. Different rig specifications (e.g., forces that can be generated, size and weight, etc.) and the implementation of new technology as it

has been developed make each of these rigs unique. The basic mechanics of all five rigs, however, are essentially

the same. A description of the sonic drilling method, substantially taken from reference 4 is presented in the following 4.1 section.

4.1 Drilling

The sonic drilling rig (Figure 1) uses a combination of mechanically generated vibrations and rotary power to penetrate the soil. The oscillator or drill head (Figures 2

Features:
No circulation media
No secondary waste
Continuous core sampling

Figure 1

Sonic drill rig.

& 3) consists of two counter-rotating rollers that cause the drill pipe to vibrate. The rollers are synchronized to

Figure 2 Sonic drill oscillator.

ensure that the vertical force component is transmitted downward along the drill pipe or core barrel. The vibrations are isolated from the rig structure by the use of an air spring. Resonance is the term used to describe the

Figure 3 Sonic drill head.

condition when the frequency of the vibrations is equal to the natural frequency of the drill pipe. When the drill pipe is in resonance, the maximum displacements of the pipe are occurring. When in resonance, forces generated by the oscillator head range from 50,000 to 280,000 pounds. The resonance of the drill pipe, with the weight of the drill pipe and the downward thrust of the drill head, allows penetration of the formation. Concurrent with the resonant energy, the drill head can be rotated to help penetrate the formation and ensure that new formation is always adjacent to the cutting surfaces of the bit. With the rotational and vibrational energy being generated, the drill pipe is advanced into the ground by weight applied hydraulically at the surface. The magnitude of the hydraulically applied force depends on the type of formation being drilled, but it can range from small forces around 1,000 pounds up to large forces of 90,000 pounds.

As the hole is advanced, additional sections of drill pipe (typically 5 or 10-foot lengths) are added and drilling continues. The soil enters the drill string through an open-face (core type) drill bit and is contained in an inner core tube that rests on the inside shoulder of the bit (Figure 4). In the wireline method of coring, a heavy weight or a latch assembly keeps the core barrel in contact with the drill bit. When the core barrel is filled with soil, as revealed by the position indicator, it is removed via a wireline retrieval system. As a result, a continuous core of the formation is obtained. A slightly different method of coring called the dual-rod

Figure 4 Core barrel.

method incorporates an inner steel rod and spring mechanism to keep the core barrel in contact with the drill bit.

The borehole integrity is maintained by the threaded carbon steel drill pipe, which remains in the ground while the core barrel is removed. To keep the joints from unscrewing, the drill rig's hydraulic rotation system is used to apply torque to the drill pipe threads.

The basic mechanics of the sonic rigs demonstrated at the Hanford and Sandia sites are the same. Variations in the size, design, and intended application of these rigs should be noted. A summary of specifications for the five rigs already demonstrated is shown in Table 1.

hole, often taking a continuous core. It was then used as a cable-tool rig to ream the 4-inch borehole to a larger diameter and drive casing to install a monitoring well. Air rotary was used to clean the hole. This combination allows easier attainment of greater depths as friction on the sonic drill string is reduced. Borehole depths as great as 550 feet have been achieved. This rig was also used at Hanford for the CRADA Phase II work on the bioremediation and Redox projects.

Table 1 Specifications of different sonic drill rigs.

Sonic Drill Rig (Site)	"Harrison-Western" (Hanford)	"Barber" (Sandia)	"Dresser" (Sandia & Hanford)	"Angle" (Sandia)	"Simco" (Hanford)
Resonant Frequency	0 to 150 hertz	0 to 150 hertz	0 to 150 hertz	0 to 150 hertz	0 to 150 hertz
Rig Power	250 hp	250 hp	250 hp	250 hp	300 hp
Maximum Force Generated by the Drill Head	50,000 lbs.	50,000 lbs.	50,000 lbs.	50,000 lbs.	100,000 lbs.
Maximum Force Transmitted Due to Hydraulic Thrust Alone	10,000 lbs.	15,000 lbs.	15,000 lbs.	15,000 lbs.	30,000 lbs.
Maximum Hole Diameter	up to 7 in.	up to 6 5/8 in.	up to 6 5/8 in.	up to 6 5/8 in.	up to 10 3/4 in.

Several notes should be made concerning the five drilling rigs described in Table 1. While the Barber, Dresser, and Angle rigs appear to be the same, there are some important differences.

1) The Dresser drilling rig is not solely a sonic rig. It was designed to combine the strengths of both sonic, cable-tool, and air rotary drilling in a single rig and is capable of performing all types of drilling. Typically at Sandia, the Dresser rig was used first as a sonic rig to drill a 4-inch bore-

2) The Angle rig is designed specifically for drilling shallow slant wells down to 10 degrees from the horizontal. It is therefore designed to be lighter than either the Barber or Dresser rigs and is built almost entirely of aluminum. With this rig, 180-foot angled holes have been drilled.

3) The Barber rig is very similar to the first rig tested at the Hanford site. There were, however, several improvements made in the Barber rig over the Harrison-Western rig. The most sig-

nificant were to the air spring and the sonic drill head which resulted in much less downtime at Sandia than was previously observed at Hanford. These improvements, as well as the changes previously mentioned, were also made on the Dresser and Angle rigs.

Also note that the hole diameters listed in Table 1 are the largest diameters that the respective rigs can be expected to drill quickly and reliably. While all of the rigs are capable of drilling larger diameters than those listed, these diameters represent the largest sizes that each rig was designed to drill. Employing any rig to drill beyond its design expectations will undoubtedly result in slower penetration rates and higher downtime. This may be an important factor contributing to the high downtime observed with the 15-year-old Harrison-Western rig. The size of this rig (horsepower, forces generated, etc.) indicates that it was designed to drill holes up to 6 or 7 inches in diameter.

There are other factors that should also be noted as possibly contributing to the high downtime of the Harrison-Western rig. The age of the rig itself is of some concern. Older equipment normally requires more maintenance and can be expected to break down more often and for longer periods. A second concern is the casing used. Although N-80 casing with a yield strength of 80,000 psi and tensile strength of 100,000 psi was specified for the job, A-105 casing with a yield strength of 30,000 psi and tensile strength of 48,000 psi was mistakenly ordered and used. As a result, failure of the casing was responsible for 18 days of downtime at a single well.

The Simco incorporates the latest technology in drill head design, drill string, etc. The Simco rig is approximately twice the size (horsepower, forces generated, etc.)

of the three rigs demonstrated at Sandia. It was used at the Hanford site with remarkable success. During the CRADA Phase I test at Hanford, the Simco rig experienced less than 10% downtime [2]. Similar downtime figures have been reported for the Angle and Barber sonic rigs at Sandia [5].

4.2 Geological Sampling

Sampling occurs during drilling as required by the applicable work plans. Physical properties and/or chemical sampling may be required. Geological samples are easily obtained from the continuous core via a plastic sleeve attached to a cyclone separator. The plastic sleeve is used during sonic rotary drilling using a tri-cone bit to cut the formation. This technique is applied when continuous core samples are not required. At the Sandia demonstration, the core samples were heated to temperatures which are unacceptable for chemical sampling. When sampling for volatile compounds, this can be a problem because the rate of volatilization is temperature dependent. This problem was addressed through the use of a split-spoon sampler driven ahead of the drill string. In this way, samples can be recovered before they are heated by the drill string. If split-spoon sampling is required, the core barrel is removed from the drill pipe and a conventional split-spoon sampler (Figure 5) is screwed onto

Figure 5 Split-spoon sampler.

a 4 1/2-inch OD steel drill rod and lowered inside the drill pipe to the bottom of the borehole. The split-spoon sam-

pler is normally a 5-inch OD by 4-inch ID, 2-foot-long, stainless-steel assembly. Extended length samplers have since been designed to further address the temperature concerns. The sampler is vibrated into the ground using the same energy transfer mechanisms used for drilling. The drill pipe remains stationary while the sample is being obtained. Other methods are being utilized to improve sample temperature and quality, including reduction of drilling frequencies and rotation rate. Using these techniques, Hanford reports "soil disturbance comparable to samples taken using cable-tool methods [2]." However, they note, "further study of factors such as lithology, penetration rates, amount of vibration, rotation, should be studied in detail to improve the quality of the core runs [2]."

4.3 Well Completion

A standard Hanford ground water monitoring well has a permanent stainless-steel casing installed prior to the removal of the drill pipe. With sonic drilling, the drill pipe is the temporary casing which is used to temporarily stabilize the hole. The permanent stainless-steel casing is lowered inside the drill pipe/temporary casing. As the drill pipe/casing is removed, an annular seal (such as bentonite clay) is placed between the permanent casing and the formation to prevent downward migration of contaminants along the annulus of the well.

During back-pull with the sonic system the drill pipe is vibrated and can be rotated. The vibration tends to fluidize (sustain continual movement) the soil particles adjacent to the drill pipe and allow the pipe to be easily withdrawn from the ground. The combination of vertical hydraulic thrust with resonant vibration and rotation allows rapid back-pulling of the drill pipe. Drill pipe is removed from the well and each section is hydraulically

unscrewed until all of the pipe is extracted. The completion of a 168-foot deep well at Hanford, in a single day, is indicative of the potential of sonic for expeditious turnaround.

4.4 Crew Size and Experience

Sonic drilling normally requires one driller and one or two helpers depending on the rig size. As with other drilling systems, such as core drills and cable-tool drills, the driller must have extensive operational experience on the rig. The crew for a typical hazardous waste site investigation using the sonic drill system also includes: a field team leader, a geologist, a site safety officer, a sampling scientist, a health physics technician, and two sampling technicians. The extra sampling technician, needed due to the rapid penetration rate of the sonic drill, makes the crew size one person larger than is typical of a cable-tool drilling crew. For the cost analyses of this report, rates are based on 8-hour work days at Hanford and 10-hour work days at Sandia. Salaries for both Hanford and Sandia are based on Hanford burdened salary rates. Therefore, Scenario 1 (Hanford) and Scenario 2 (Sandia) results are not directly comparable. Scenario 3 assumes 10-hour days so that all technologies can be compared.

4.5 Rig Maintenance

At the first Hanford demonstration in 1992 the sonic drill required approximately 2.5 hours per week of preventive maintenance. The majority of non-preventive maintenance was required on components directly related to the sonic drill head. The air spring and multi-circuit hydraulic system were the two systems that required the most maintenance. The following factors heavily influenced the reliability of these components: (1) drilling conditions and the required depth of the well; (2) minimal

preventative maintenance program by a drilling contractor; (3) when a failure occurred, contractor repairs were made by memory, because no rig manual, drawings, or spare parts lists were ever provided to field personnel; and (4) due to the contractors job load, personnel who were intimately familiar with the configuration of the sonic head were not available, therefore, the wrong parts were sent to the job for repairs.

Since the first Hanford demonstration, Water Development Corporation has performed all remaining sonic drilling described in this report. Technological advances in the drill head, drill string, air spring, etc. made by WDC and regular preventive maintenance have reduced downtime. Regular preventive maintenance is still a significant cost. For this report, an estimated cost of \$20,000 per year (or \$121 per operational day) is used [6].

5. Description of Baseline Technologies

5.1 Cable-Tool Drilling

The cable-tool drilling method, also called the percussion, drive-barrel, or churn drill method, has been used to drill wells for more than 2,000 years. Prior to the development of mud rotary, it was the standard technology used for most forms of drilling [7]. It has been used at the Hanford site for 45 years due to its ability to contain contamination, minimize waste, and obtain samples and therefore is used as the baseline technology for the Hanford demonstrations. Cable-tool is a versatile method which can be used in the hardest and softest formations, for almost any depth and diameter. Conversely, it is slow which results in higher overall costs for drilling, sampling, and well-installation activities. A description of cable-tool drilling from reference 4 follows next.

5.1.1 Drilling

The cable-tool rig (Figure 6) drills by driving a core barrel, which is 3 to 5 feet in length, into the sediments.

The core barrel is suspended from the drill cable and additional weight (e.g., stem, jars) is used to drive the core barrel into the ground. The core barrel is driven ahead of the casing, and a soil plug is retrieved. The steel casing is then driven ahead to the point where the soil was removed. Drilling continues until the borehole reaches

Figure 6

Cable-tool rig.

total depth (TD). With the core barrel method, addition of water is not normally required. If the formation cannot be penetrated in this fashion (e.g., hard rock formations), the core barrel is replaced with a drill bit as shown in Figure 7. In a process known as "hard-tool" drilling, the bit is continuously lifted and dropped into the well.

Figure 7 Drill string.

The weight and rotation of the drill bit (and gravity) cause the bit to continuously break up the formation below. The drill bit is dropped at a rate of 0.5 to 1.0 hertz. Water is added to the wellbore to create a mud slurry; the material is then bailed from the hole using a bailing apparatus. As the hole is deepened, a temporary steel casing is driven into the borehole to keep the formation from collapsing.

5.1.2 Geological Sampling

Geologic samples can be taken from the material removed from the core barrel or from the soil slurry if hard-tool drilling is used. Split-spoon samples can be obtained by removing the drill bit or core barrel and attaching a split-spoon sampler. The sampler is driven into the ground by the repeated dropping of the drill tools on the sampler. The drilling jars (Figure 7) allow the drill string to be raised and dropped repeatedly until the sampler has been driven the required distance. As with the sonic drilling system, the drill pipe remains stationary while the sample is being retrieved.

5.1.3 Well Completion

Completion techniques for the cable-tool method are similar to those used for the sonic system; however, instead of using the cable-tool drill to back-pull the temporary casing, hydraulic jacks are frequently used to extract the casing from the ground. By completing the well with the hydraulic jacks, the drill rig is available to drill other wells.

5.1.4 Crew Size and Experience

The cable-tool system requires one driller and one helper to operate the rig. In addition, the crew for the typical hazardous waste site location would include: a field team leader, a geologist, a site safety officer, a sampling scientist, a health physics technician, and one sampling technician. In total, this is usually one less person than for sonic and mud rotary.

5.1.5 Rig Maintenance

The cable-tool drill rig requires about two hours per week of preventive maintenance [4]. Repairs to the cable-tool rig are seldom necessary and, if required, are usually completed rapidly in the field. In addition, the hydraulic jacks used for back-pulling cable-tool drilled wells are reliable and require limited maintenance.

5.1.6 Rig Cost

A cable-tool rig, similar in capacity to the sonic rigs tested could be purchased for approximately \$200K. The rental rate charged by Kaiser Engineers Hanford Co. for a cable-tool rig was \$101 per day. However, this covers only the maintenance and fuel costs of the rig. No rental cost of cable-tool rigs is incurred because they are owned by DOE. For the report, a more internally consistent approach, based on estimated capital cost, use, and amorti-

zation rates, was used to amortize the costs of the various rig types. For cable-tool, this results in a capital cost of \$117 per day.

5.2 Mud Rotary Drilling

Rotary drilling, like the cable-tool method, has been used for thousands of years. The early Egyptians used rotary drills to quarry stone for the pyramids. It isn't until 1844, however, that the first reference to lubrication of rotary drills with a circulating fluid can be found. Today, mud rotary drilling is one of the most effective, rapid, reliable, and widely used drilling methods available [8].

It is used as a conventional drilling technology at several DOE waste sites, including the Sandia site, and therefore we will use it as the baseline technology for the Sandia scenario.

Due to mixed waste conditions at the Hanford site, mud rotary drilling or any fluid-based drilling system is not commonly used due to potential cross-contamination and secondary waste generation issues.

5.2.1 Drilling

The direct rotary drilling method uses a rotating bit to penetrate the earth. The bit is attached to the end of a string of hollow drill pipe which transmits the rotating action from the drill rig (Figure 8) to the bit. Cuttings are removed by a continuous circulation of drill-

ing mud that carries them from the bit to the surface. The mud also acts as an essential lubricant for the cutting bit. Further, it serves to stabilize the borehole wall and prevent the inflow of formation fluids [7]. The rotation of the bit combined with the weight of the drill string allow high penetration rates. The driller can vary the speed of rotation according to the resistance of the formation being drilled and the rate of penetration. Depending on the depth being drilled and resistance of the formation, a "pull-down"

Figure 8

Mud rotary rig.

pressure can also be applied to the drill string to help speed penetration rates. This pull-down force is derived from the weight of the rig itself through the use of chain assemblies that allow a portion of the rig's weight to be carried by the drill string. Direct mud rotary drilling is fast and versatile. It can be used for deep wells and for both consolidated and unconsolidated formations. However, the use of drilling fluid is problematic for hazardous site characterization because it introduces a large fluid volume which may require subsequent treatment as hazardous waste.

5.2.2 Drilling Fluid

The mud lubricant is pumped down the inside of the drill string and out through ports in the drill bit to provide lubrication. The mud then flows up the annular space between the drill pipe and the borehole, carrying cuttings to the surface. Once at the surface, the mud is pumped through a series of settling pits where the cuttings are settled out before the mud is recirculated back down to the drill bit. The volume of mud that may be circulated during drilling operations normally ranges from 150 to 200 gallons per minute [9]. To allow adequate settling time, thousands of gallons of mud must be circulated during drilling. For application in known contamination sites this is a significant problem as the mud may then require treatment as hazardous or radioactive waste. Drilling fluid also increases the possibility of spreading the extent of an underground waste plume. Thus, the application of this method is normally limited to clean sites. Further, the mud can influence the quality of ground water samples, make identification of aquifers more difficult, and increase the well development period.

5.2.3 Geological Sampling

Samples can be obtained directly from the stream of circulated fluid from the discharge flow before the settling pit. However, the quality of the samples obtained from the circulated fluid is generally not satisfactory for formation characterization. Drilling fluid also masks hazardous waste constituents making chemical analysis difficult. Split-spoon, thin-wall or wireline samples can be obtained in unconsolidated material by using a bit with an opening through which sampling tools can be inserted. Drilling fluid circulation must be broken to collect samples. The rotary drill stem acts as casing as the sample tools are inserted through the drill stem and bit and a sample is collected. Typical practice at Sandia was to collect three 10-foot core samples per well, adding approximately a full day to the drilling schedule.

5.2.4 Well Completion

Completion techniques are similar to those used for the sonic system. As with sonic, temporary casing is not normally required unless overburden or multiple aquifers are encountered.

5.2.5 Crew Size and Experience

The mud rotary system requires one driller and two helpers to operate the rig. Otherwise, the crew is the same as for the cable-tool. Thus the entire crew is the same size as for sonic, substituting a drill helper for the extra sampling technician.

6. Performance Comparison

Sonic, cable-tool, and mud rotary drilling can all obtain the required results of drilling a borehole, continuous coring, and well installation. Because they are all used to complete essentially the same tasks, comparison

of these technologies is rather simple. The basic performance scenario becomes a head-to-head comparison of the technologies performing the same task.

However, a complete performance comparison of any technologies must be more than simply a quantitative comparison to determine the fastest, most cost-effective technology. It must also take into account the quality of work being done. With this consideration in mind, each drilling technology has certain strengths and purposes for which it is better suited. A few of the variables that affect the performance of these technologies include: site characteristics, drilling purpose, and quality of results.

6.1 Site Characteristics

Of primary importance are the geology of the proposed drilling site and expected presence, location, type, and extent of contamination. This section emphasizes the geological setting where the sonic drilling method may be used and where it is advantageous. Essentially, sonic drilling can be used in any site, including the open-frame-work gravel incorporating cobbles, silts, and interbedded silts and clays typical at the Hanford site. Wells were also drilled into cemented formations. Sonic has been used effectively in river alluvium, caliche, rock, cobble, and boulder formations typical at Sandia. It can be used in both consolidated and unconsolidated formations, saturated and unsaturated. If a ground water well is intended, the depth to the water table may become a consideration. While the combined sonic/cable-tool Dresser rig has been used to depths exceeding 550 feet, present demonstrations have shown sonic to be most effective at depths less than 350 feet [5].

Two sonic rigs have also demonstrated angle drilling capability. The Angle rig demonstrated at Sandia was used to drill holes greater than 150 feet at 15 degrees from

the horizontal. The Simco rig has been used at Hanford to drill and complete a 168-foot vapor extraction well angled at 45 degrees.

6.2 Waste Generation

Hanford policy is to drum waste if it is from the water table or material from the vadose zone that is wet [4]. The primary advantage of the sonic technique is that no circulating fluid is needed to drill in any formation, so waste generation from above the water table is minimized. For example, a 168-foot angle well in a carbon tetrachloride site generated only a single 55-gallon drum of waste. Another estimate places the generated waste at as little as five gallons for a 150-foot borehole [5]. In fact, the amount of waste generated from rig decontamination may be greater than that generated from the drilling of the borehole. Five drums of rinsate waste were generated from the above angle well. However, it was noted that waste volume reduction can be attained with alternative cleaning methods [2]. The initial Hanford study reported an average of one drum per rig (three drums estimated for mixed waste). Waste containment is also excellent because the cuttings are confined to the core barrel.

6.3 Sample Quality

Sonic may provide performance benefits in core quality compared to the baseline technologies. A continuous core is obtained without the use of a circulation media (fluid or air), thus dry, uncrushed samples can be collected. Because the sonic drill provides a continuous core of the formation, identification of thin layers is possible. Also, root casts were recovered from the Hanford gravels. These are fragile structures rarely logged with cable-tool. Clay lenses and chemical precipitates were also observed. The slurries resulting from hard-tool, cable-tool drilling or mud

introduction make identification of such features less probable. Hanford reports: "compared to cable-tool drilling, ResonantSonic™ drilling produced a much better quality of lithologic characterization soil cores [2]." Mud rotary may leave drilling mud and wall cake on the outer perimeter of the filter pack and borehole wall making well development more difficult and time consuming. Also, introduction of a drilling fluid makes identification of aquifers more difficult and can enlarge subsurface waste plumes [7].

Conversely, lack of a cooling circulating media may potentially result in higher core temperatures, and thus inaccurate quantitative sampling of volatile compounds. This potential problem is believed to have been adequately addressed with resultant soil samples collected "at temperatures comparable to cable-tool [11]."

These and other issues must be addressed when choosing the most effective drilling technology for any application. A single variable may determine whether a particular technology is or is not feasible or cost effective. For example, in situations where waste minimization is important, mud rotary drilling would be a poor choice, due to the large volume of mud that must be circulated. However, if waste minimization and continuous coring are not required, the speed and reliability of mud rotary in most geological settings make it an attractive possibility. With these variables in mind, separate performance scenarios for each demonstration are developed to give the most accurate comparison possible.

6.4 Scenarios

Three scenarios were chosen for this report. All are broken down into separate borehole drilling and well completion costs. Because the emphasis is on DOE sites, sampling is included as a high priority. The scenarios are

subdivided into sites that are clean and those that are expected to contain hazardous (chemical), and mixed (combined chemical and radioactive) wastes. Where differences are significant, they are further characterized for lithology type as either "regular" or "difficult." Regular refers to the somewhat easier drilling of unconsolidated formations. Difficult drilling generally refers to cobble/boulder/consolidated and clay layers where greater resistance to drill advance is encountered. For the cable-tool rig, difficult drilling is accomplished with the hard-tool drilling technique and water addition.

Where applicable, actual drilling rates from the demonstrations are used. However, for a more consistent cost comparison, labor rates, disposal rates, and most other costs are based on assumed industry averages. Equipment capital costs are amortized over an assumed 15-year useful life. A summary of all scenarios, and their calculated resultant costs, is shown in Table 2.

6.4.1 Scenario One

The first scenario compares sonic to cable-tool, and assumes a 100-foot well is desired at the Hanford site. A typical 3-inch completed well and 7-inch borehole is assumed. The Integrated Demonstration data are not extensive enough to yield accurate breakdowns by drill diameter. The sonic scenario uses results from the CRADA tests for the Redox Manipulation Experiment at Hanford including downtime [12]. In that experiment, one injection well and fifteen monitoring wells were completed. This is compared to the average for 10 cable-tool wells and boreholes drilled at Hanford in 1992. Table 3 lists the actual sonic and cable performance for this scenario in rows A, B, and G through K. The sonic performance (including downtime) differs among the three tests. The 1992 demonstration resulted in an average drilling rate of

Table 2

Scenarios and cost comparisons.

Scenario 1

Hanford, Sonic vs. Cable-tool, real drill rates (downtime included), 8-hour days
100-foot well, sampling, \$ per foot

CLEAN SITE							HAZARDOUS SITE		MIXED WASTE SITE	
DRILLING	regular	difficult	regular	difficult	regular	difficult				
Sonic	\$244	\$244	\$253	\$255	\$269	\$275				
Cable-tool	\$655	\$655	\$669	\$716	\$693	\$820				
Sonic Drilling Savings	\$411 (63%)	\$411 (63%)	\$416 (62%)	\$461 (64%)	\$424 (61%)	\$545 (66%)				
COMPLETION										
Sonic							\$75			
Cable-tool							\$248			
TOTAL										
Sonic	\$319	\$319	\$328	\$330	\$344	\$350				
Cable-tool	\$903	\$903	\$917	\$964	\$941	\$1,068				
Sonic Total Savings	\$584 (65%)	\$584 (65%)	\$589 (64%)	\$634 (66%)	\$597 (63%)	\$718 (67%)				

Scenario 2

Sandia, Sonic vs. Mud Rotary, real drill rates (downtime included), 10-hour days
300-foot well, sampling, mixture of easy and difficult drilling, \$ per foot

CLEAN SITE				HAZARDOUS SITE		MIXED WASTE SITE	
DRILLING							
Sonic		\$210		\$226		\$253	
Mud Rotary		\$118		\$365		\$792	
Sonic Drilling Savings		-\$92 (-78%)		\$139 (38%)		\$539 (68%)	
COMPLETION							
Sonic				\$93			
Mud Rotary				\$64			
TOTAL							
Sonic		\$303		\$319		\$346	
Mud Rotary		\$182		\$429		\$856	
Sonic Total Savings		-\$121 (-66%)		\$110 (26%)		\$510 (60%)	

Scenario 3

Sonic vs. Cable-tool vs. Mud Rotary, estimated drill rates (downtime excluded), 10-hour days
150-foot well, sampling, \$ per foot

CLEAN SITE							HAZARDOUS SITE		MIXED WASTE SITE	
DRILLING	regular	difficult	regular	difficult	regular	difficult				
Sonic	\$147	\$166	\$163	\$182	\$190	\$209				
Cable-tool	\$420	\$420	\$432	\$479	\$454	\$580				
Mud Rotary	\$133	\$188	\$381	\$436	\$807	\$863				
Sonic Drilling Savings (Sonic vs. Cable-tool)	\$273 (65%)	\$254 (60%)	\$269 (62%)	\$297 (62%)	\$264 (58%)	\$371 (64%)				
Sonic Drilling Savings (Sonic vs. Mud Rotary)	-\$14 (-11%)	\$22 (12%)	\$218 (57%)	\$254 (58%)	\$617 (76%)	\$654 (76%)				
COMPLETION										
Sonic	\$61									
Cable-tool	\$172									
Mud Rotary	\$88									
TOTAL										
Sonic	\$208	\$227	\$224	\$243	\$251	\$270				
Cable-tool	\$592	\$592	\$604	\$651	\$626	\$752				
Mud Rotary	\$221	\$276	\$469	\$524	\$895	\$951				
Sonic Total Savings (Sonic vs. Cable-tool)	\$384 (65%)	\$365 (62%)	\$380 (63%)	\$408 (63%)	\$375 (60%)	\$482 (64%)				
Sonic Total Savings (Sonic vs. Mud Rotary)	\$13 (6%)	\$49 (18%)	\$245 (52%)	\$281 (54%)	\$644 (72%)	\$681 (72%)				

8.9 feet/day using the old Harrison-Western rig. The 1994 Bioremediation test using the CRADA machine drilled much faster (30.5 feet/day) and created boreholes > 300 feet with 11-inch diameters. The 1995 Redox test drilled a total of 822 feet with an average rate of 39.8 feet/day.

6.4.2 Scenario Two

The second scenario assumes a 300-foot well drilled at the Sandia site with comparison of sonic to mud rotary. The drilling data are based on the Mixed Waste Landfill Integrated Demonstration. This depth is typical of the three sonic (Barber) wells and four mud rotary wells drilled in the 1992-1993 period. Sonic-drilled well depths varied from 168 to 510 feet. Drill rates included downtime. Sonic downtime was typically in the 5-10% range, which is presumed to be more indicative of expected performance. The Sandia formations consist of a river alluvial assortment of silts, pebbles, caliche, rocks, cobbles, and boulders. Drilling has been characterized as "tough" and causes problems for drilling techniques such as hollow-stem augering. Mud rotary has been the technology of choice at Sandia for use in non-hazardous sites. Due to the limited amount of data and number of wells, this scenario is not further subdivided into regular and difficult formations.

6.3.3 Scenario Three

The third scenario assumes a 150-foot well. This scenario primarily differs from the other two in using *estimated* drilling and completion rates for sonic. These estimates are based on performance seen in the field at both Sandia and Hanford. To maintain an "apples to apples" comparison, estimated rates are also used for mud rotary. Cable-tool rates are actual rates from Hanford because that technology is sufficiently mature there.

However, because the numbers for sonic are estimates, one should be cautious about placing undue weight on the scenario outcomes.

7. Economic Comparison

The three scenarios outlined in Table 2 are analyzed for net-present-value life-cycle costs. These scenarios are comprehensive cost estimations for borehole drilling and/or well completion. Some caveats must be mentioned. The cost of the sonic rigs is estimated [6]. Even so, it is only a secondary contributor to the overall drilling cost (for example, it accounts for about 5% of the cost per foot calculated in Scenario 2). The biggest cost driver is the drilling rate, which impacts costs through the daily charges (most significantly, personnel costs). This highlights the need for the most accurate drill rate information that can be gathered. The current numbers are considered to be preliminary, thus the final cost estimates must be considered in kind. Mobilization and demobilization costs are assumed to be equivalent across technologies. This may not be the case at particular sites because these costs depend substantially on the local availability of the drill rig in question. Mud rotary is widely available, as is cable-tool in the Hanford area. Sonic, being a new technology, is at a disadvantage here. However, for a more consistent comparison, we extrapolate to a future period where sonic rigs may be more readily available. As cable-tool often uses hydraulic jacks, rather than the rig itself, to back-pull the temporary casing (i.e., to complete the well), a second mob/demob cost may be incurred. However, this is assumed to be offset by the availability of the original rig for use on other sites while completion occurs.

Tables 3 and 4 describe the borehole and completion costs, respectively, for each of the scenarios and for the

Table 3a. Cost of drilling technologies--borehole (clean site).

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
	Depth (feet)	Formation	Drilling Rate Information	Rig Cost (\$ per day)	Repair/ Maintenance of Rig (\$ per day)	Fuel Cost (\$ per day)	Personnel Cost (\$ per day)	Drilling Days (number)	Average Drilling Rate (feet per day)	Waste Generated (drum)	Waste Disposal Cost (\$ per borehole)	Mobilization/ Demobilization Cost (\$ per borehole)	Site Preparation/ Fencing Cost (\$ per borehole)	"Clean" Borehole Cost Before Permitting and Taxes (\$)	"Clean" Permitting Cost (\$ per borehole)	"Clean" Taxes (\$ per borehole)	"Clean" Total Cost (\$ per foot)
Cable-Tool																	
A. TOTAL Hanford (1992)	1073	mix	data (downtime inc)	\$117	\$101	inc. in col 5	\$3,520	132.9	8.1	61.0							*
B. TOTAL Hanford (1992)	1073	mix	data (downtime exc)	\$117	\$101	inc. in col 5	\$3,520	84.9	12.6	61.0							*
C. Scenario 1	100	regular	row A (downtime inc)	\$117	\$101	inc. in col 5	\$3,520	12.3	8.1	2.7	\$0	\$4,500	\$6,320	\$56,968	\$1,139	\$7,385	\$655
D. Scenario 1	100	difficult	row A (downtime inc)	\$117	\$101	inc. in col 5	\$3,520	12.3	8.1	11.4	\$0	\$4,500	\$6,320	\$56,968	\$1,139	\$7,385	\$655
E. Scenario 3 (10 hr/day)	150	regular	row B (downtime exc)	\$117	\$101	inc. in col 5	\$4,400	9.5	15.8	3.5	\$0	\$4,500	\$6,320	\$54,801	\$1,096	\$7,113	\$420
F. Scenario 3 (10 hr/day)	150	difficult	row B (downtime exc)	\$117	\$101	inc. in col 5	\$4,400	9.5	15.8	16.6	\$0	\$4,500	\$6,320	\$54,801	\$1,096	\$7,113	\$420
Sonic, Harrison-Western and CRADA**																	
G. TOTAL Hanford (1992)	938	mix	data (downtime inc)	\$234	\$121	\$72	\$3,904	105.7	8.9	18.0							*
H. TOTAL Hanford (1992)	938	mix	data (downtime exc)	\$234	\$121	\$72	\$3,904	39.2	23.9	18.0							*
I. TOTAL Hanford (1994)	610	deep	data (downtime inc)	\$263	\$121	\$54	\$3,904	20.0	30.5	Not avail.							*
J. TOTAL Hanford (1995)	822	shallow	data (downtime inc)	\$263	\$121	\$54	\$3,904	20.7	39.8	13.0							*
K. TOTAL Hanford (1995)	822	shallow	data (downtime exc)	\$263	\$121	\$54	\$3,904	14.4	57.1	13.0							*
L. Scenario 1	100	regular	row J (downtime inc)	\$263	\$121	\$54	\$3,904	2.5	39.8	1.7	\$0	\$4,500	\$6,320	\$21,730	\$435	\$2,216	\$244
M. Scenario 1	100	difficult	row J (downtime inc)	\$263	\$121	\$54	\$3,904	2.5	39.8	2.2	\$0	\$4,500	\$6,320	\$21,730	\$435	\$2,216	\$244
Mud Rotary																	
N. TOTAL Sandia (1993)	2954	mix	data (downtime inc)	\$263	\$152	\$120	\$4,220	42.0	70.3	Not avail.							*
O. Scenario 2	300	mix	row N (downtime inc)	\$263	\$152	\$120	\$4,220	4.3	70.3	139.8	\$0	\$4,500	\$6,320	\$31,110	\$622	\$3,524	\$118
P. Scenario 3 (10 hr/day)	150	regular	estimate	\$263	\$152	\$120	\$4,220	1.5	100.0	69.9	\$0	\$4,500	\$6,320	\$17,952	\$359	\$1,673	\$133
Q. Scenario 3 (10 hr/day)	150	difficult	estimate	\$263	\$152	\$120	\$4,220	3.0	50.0	69.9	\$0	\$4,500	\$6,320	\$25,084	\$502	\$2,676	\$188
Sonic, Barber/Simco																	
R. TOTAL Sandia (1993)	941	mix	data (downtime inc)	\$263	\$121	\$54	\$4,880	26.0	36.2	Not avail.							*
S. Scenario 2	300	mix	row R (downtime inc)	\$263	\$121	\$54	\$4,880	8.3	36.2	8.9	\$0	\$4,500	\$6,320	\$54,894	\$1,098	\$6,989	\$210
T. Scenario 3 (10 hr/day)	150	regular	estimate	\$263	\$121	\$54	\$4,880	1.7	90.0	4.5	\$0	\$4,500	\$6,320	\$19,684	\$394	\$1,940	\$147
U. Scenario 3 (10 hr/day)	150	difficult	estimate	\$263	\$121	\$54	\$4,880	2.1	70.0	4.5	\$0	\$4,500	\$6,320	\$22,216	\$444	\$2,303	\$166

* Total cost per foot was calculated for the scenarios only.

** Harrison-Western rig was used in 1992; CRADA rig was used in 1994-95.

The word "deep" under Formation (Row I, Column 2) refers to 2 deep wells each at a 305-foot depth.

The word "shallow" under Formation (Row J&K, Column 2) refers to 16 shallow wells. Each well was from 45 feet to 55 feet deep.

Table 3a Cost of drilling technologies--borehole (clean site).

Table 3b Cost of drilling technologies—borehole (hazardous site).

Table 3b. Cost of drilling technologies--borehole (hazardous site).																	
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
	Depth (feet)	Formation	Drilling Rate Information	Rig Cost (\$ per day)	Repair/ Maintenance of Rig (\$ per day)	Fuel Cost (\$ per day)	Personnel Cost (\$ per day)	Drilling Days (number)	Average Drilling Rate (feet per day)	Waste Generated (drum)	Waste Disposal Cost (\$ per borehole)	Mobilization/ Demobilization Cost (\$ per borehole)	Site Preparation/ Fencing Cost (\$ per borehole)	"Hazardous" Borehole Cost Before Permitting and Taxes (\$)	"Hazardous" Permitting Cost (\$ per borehole)	"Hazardous" Taxes (\$ per borehole)	"Hazardous" Total Cost (\$ per borehole)
Cable-Tool																	
A. TOTAL Hartford (1992)	1073	mix	data (downline in)	\$117	\$101	inc. in col 5	\$3,520	132.9	8.1	61.0							*
B. TOTAL Hartford (1992)	1073	mix	data (downline in)	\$117	\$101	inc. in col 5	\$3,520	84.9	12.6	61.0							*
C. Scenario 1	100	regular	row A (downline in)	\$117	\$101	inc. in col 5	\$3,520	12.3	8.1	2.7	\$1,309	\$4,500	\$6,320	\$8,277	\$1,166	\$7,466	\$669
D. Scenario 1	100	difficult	row A (downline in)	\$117	\$101	inc. in col 5	\$3,520	12.3	8.1	11.4	\$5,606	\$4,500	\$6,320	\$8,274	\$1,251	\$7,152	\$716
E. Scenario 3 (10 b/day)	150	regular	row B (downline in)	\$117	\$101	inc. in col 5	\$4,400	9.5	15.8	3.5	\$1,719	\$4,500	\$6,320	\$8,519	\$1,130	\$7,219	\$452
F. Scenario 3 (10 b/day)	150	difficult	row B (downline in)	\$117	\$101	inc. in col 5	\$4,400	9.5	15.8	16.6	\$8,163	\$4,500	\$6,320	\$8,964	\$1,259	\$7,618	\$779
Sonic, Harrison-Western and CRADA**																	
G. TOTAL Hartford (1992)	938	mix	data (downline in)	\$234	\$121	\$72	\$3,904	105.7	8.9	18.0							*
H. TOTAL Hartford (1992)	938	mix	data (downline in)	\$234	\$121	\$72	\$3,904	39.2	23.9	18.0							*
I. TOTAL Hartford (1994)	610	deep	data (downline in)	\$263	\$121	\$54	\$3,904	20.0	30.5	Not avail.							*
J. TOTAL Hartford (1995)	822	shallow	data (downline in)	\$263	\$121	\$54	\$3,904	20.7	39.8	13.0							*
K. TOTAL Hartford (1995)	822	shallow	data (downline in)	\$263	\$121	\$54	\$3,904	14.4	57.1	13.0							*
L. Scenario 1	100	regular	row J (downline in)	\$263	\$121	\$54	\$3,904	2.5	39.8	1.7	\$848	\$4,500	\$6,320	\$22,578	\$452	\$2,268	\$253
M. Scenario 1	100	difficult	row J (downline in)	\$263	\$121	\$54	\$3,904	2.5	39.8	2.2	\$1,060	\$4,500	\$6,320	\$22,791	\$456	\$2,281	\$255
Mid Rotary																	
N. TOTAL Sandia (1993)	2954	mix	data (downline in)	\$263	\$152	\$120	\$4,220	42.0	70.3	Not avail.							*
O. Scenario 2	300	mix	row N (downline in)	\$263	\$152	\$120	\$4,220	4.3	70.3	139.8	\$58,660	\$4,500	\$6,320	\$99,770	\$1,995	\$7,770	\$365
P. Scenario 3 (10 b/day)	150	regular	estimate	\$263	\$152	\$120	\$4,220	1.5	100.0	69.9	\$34,330	\$4,500	\$6,320	\$52,282	\$1,046	\$3,796	\$381
Q. Scenario 3 (10 b/day)	150	difficult	estimate	\$263	\$152	\$120	\$4,220	3.0	50.0	69.9	\$34,330	\$4,500	\$6,320	\$59,414	\$1,188	\$4,799	\$456
Sonic, Barber/Sinco																	
R. TOTAL Sandia (1993)	941	mix	data (downline in)	\$263	\$121	\$54	\$4,880	26.0	36.2	Not avail.							*
S. Scenario 2	300	mix	row R (downline in)	\$263	\$121	\$54	\$4,880	8.3	36.2	8.9	\$4,384	\$4,500	\$6,320	\$59,278	\$1,186	\$7,260	\$226
T. Scenario 3 (10 b/day)	150	regular	estimate	\$263	\$121	\$54	\$4,880	1.7	90.0	4.5	\$2,192	\$4,500	\$6,320	\$21,876	\$438	\$2,076	\$163
U. Scenario 3 (10 b/day)	150	difficult	estimate	\$263	\$121	\$54	\$4,880	2.1	70.0	4.5	\$2,192	\$4,500	\$6,320	\$24,408	\$488	\$2,439	\$182
* Total cost per foot was calculated only for the sonotube. Harrison-Western rig was used in 1992. CRADA rig was used in 1994-95. The word "deep" under Formation (Row I, Column 2) refers to 2 deep wells each at a 305-foot depth.																	

* Total cost per foot was calculated only for the scenarios.

** Harrison-Western rig was used in 1992; CRADA rig was used in 1994-95.

The word "deep" under Formation (Row I, Column 2) refers to 2 deep wells each at a 304-foot depth.

The word "shallow" under Formation (Row J&K, Column 2) refers to 16 shallow wells. Each well was from 45 feet to 55 feet deep.

Table 3c. Cost of drilling technologies—borehole (mixed waste site).

Table 3c. Cost of drilling technologies—borehole (mixed waste site).																	
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
	Depth (feet)	Formation	Drilling Rate Information	Rig Cost (\$ per day)	Repair/ Maintenance of Rig (\$ per day)	Fuel Cost (\$ per day)	Personnel Cost (\$ per day)	Drilling Days (number)	Average Drilling Rate (feet per day)	Waste Generated (drum)	Waste Disposal Cost (\$ per borehole)	Mobilization/ Demobilization Cost (\$ per borehole)	Site Preparation/ Fencing Cost (\$ per borehole)	"Mixed Waste" Borehole Cost Before Permitting and Taxes (\$)	"Mixed Waste" Permitting Cost (\$ per borehole)	"Mixed Waste" Taxes (\$ per borehole)	"Mixed Waste" Total Cost (\$ per foot)
Cable-Tool																	
A. TOTAL Hanford (1992)	1073	mix	data (downtime inc)	\$117	\$101	inc. in col 5	\$3,520	132.9	8.1	61.0							*
B. TOTAL Hanford (1992)	1073	mix	data (downtime exc)	\$117	\$101	inc. in col 5	\$3,520	84.9	12.6	61.0							*
C. Scenario 1	100	regular	row A (downtime inc)	\$117	\$101	inc. in col 5	\$3,520	12.3	8.1	2.7	\$3,565	\$4,500	\$6,320	\$60,533	\$1,211	\$7,605	\$693
D. Scenario 1	100	difficult	row A (downtime inc)	\$117	\$101	inc. in col 5	\$3,520	12.3	8.1	11.4	\$15,264	\$4,500	\$6,320	\$72,232	\$1,445	\$8,329	\$820
E. Scenario 3 (10 hr/day)	150	regular	row B (downtime exc)	\$117	\$101	inc. in col 5	\$4,400	9.5	15.8	3.5	\$4,680	\$4,500	\$6,320	\$59,480	\$1,190	\$7,402	\$454
F. Scenario 3 (10 hr/day)	150	difficult	row B (downtime exc)	\$117	\$101	inc. in col 5	\$4,400	9.5	15.8	16.6	\$22,228	\$4,500	\$6,320	\$77,029	\$1,541	\$8,488	\$580
Sonic, Harrison-Western and CRADA**																	
G. TOTAL Hanford (1992)	938	mix	data (downtime inc)	\$234	\$121	\$72	\$3,904	105.7	8.9	18.0							*
H. TOTAL Hanford (1992)	938	mix	data (downtime exc)	\$234	\$121	\$72	\$3,904	39.2	23.9	18.0							*
I. TOTAL Hanford (1994)	610	deep	data (downtime inc)	\$263	\$121	\$54	\$3,904	20.0	30.5	Not avail.							*
J. TOTAL Hanford (1995)	822	shallow	data (downtime inc)	\$263	\$121	\$54	\$3,904	20.7	39.8	13.0							*
K. TOTAL Hanford (1995)	822	shallow	data (downtime exc)	\$263	\$121	\$54	\$3,904	14.4	57.1	13.0							*
L. Scenario 1	100	regular	row J (downtime inc)	\$263	\$121	\$54	\$3,904	2.5	39.8	1.7	\$2,309	\$4,500	\$6,320	\$24,039	\$481	\$2,358	\$269
M. Scenario 1	100	difficult	row J (downtime inc)	\$263	\$121	\$54	\$3,904	2.5	39.8	2.2	\$2,888	\$4,500	\$6,320	\$24,618	\$492	\$2,394	\$275
Mod Rotary																	
N. TOTAL Sandia (1993)	2954	mix	data (downtime inc)	\$263	\$152	\$120	\$4,220	42.0	70.3	Not avail.							*
O. Scenario 2	300	mix	row N (downtime inc)	\$263	\$152	\$120	\$4,220	4.3	70.3	139.8	\$186,963	\$4,500	\$6,320	\$218,072	\$4,361	\$15,086	\$792
P. Scenario 3 (10 hr/day)	150	regular	estimate	\$263	\$152	\$120	\$4,220	1.5	100.0	69.9	\$93,481	\$4,500	\$6,320	\$111,433	\$2,229	\$7,453	\$807
Q. Scenario 3 (10 hr/day)	150	difficult	estimate	\$263	\$152	\$120	\$4,220	3.0	50.0	69.9	\$93,481	\$4,500	\$6,320	\$118,565	\$2,371	\$8,457	\$863
Sonic, Barber/Simco																	
R. TOTAL Sandia (1993)	941	mix	data (downtime inc)	\$263	\$121	\$54	\$4,880	26.0	36.2	Not avail.							*
S. Scenario 2	300	mix	row R (downtime inc)	\$263	\$121	\$54	\$4,880	8.3	36.2	8.9	\$11,938	\$4,500	\$6,320	\$66,831	\$1,337	\$7,727	\$253
T. Scenario 3 (10 hr/day)	150	regular	estimate	\$263	\$121	\$54	\$4,880	1.7	90.0	4.5	\$5,969	\$4,500	\$6,320	\$25,652	\$513	\$2,309	\$190
U. Scenario 3 (10 hr/day)	150	difficult	estimate	\$263	\$121	\$54	\$4,880	2.1	70.0	4.5	\$5,969	\$4,500	\$6,320	\$28,185	\$564	\$2,672	\$209

* Total cost per foot was calculated only for the scenarios.

** Harrison-Western rig was used in 1992; CRADA rig was used in 1994-95.

The word "deep" under Formation (Row I, Column 2) refers to 2 deep wells each at a 305-foot depth.

The word "shallow" under Formation (Row J&K, Column 2) refers to 16 shallow wells. Each well was from 45 feet to 55 feet deep.

* Total cost per foot was calculated only for the scenarios.

** Harrison-Western rig was used in 1992; CRADA rig was used in 1994-95.

The word "deep" under Formation (Row I, Column 2) refers to 2 deep wells each at a 305-foot depth.

The word "shallow" under Formation (Row J&K, Column 2) refers to 16 shallow wells. Each well was from 45 feet to 55 feet deep.

Table 4. Cost of drilling technologies--completion.

	18	19	20	21	22	23	24	25	26	27	28	29	30	31
	Depth (feet)	Completion Rate Information	Rig Cost (\$ per day)	Repair/ Maintenance of Rig (\$ per day)	Fuel Cost (\$ per day)	Personnel Cost (\$ per day)	Material Cost (\$ per well)	Completion Days (number)	Average Completion Rate (feet per day)	Mobilization/ Demobilization Cost (\$ per well)	Well Completion Cost Before Permitting and Taxes (\$)	Permitting Cost (\$ per well)	Taxes (\$ per well)	Completion Total Cost (\$ per foot)
Cable-Tool														
A. TOTAL Hanford (1992)	726	data (downtime inc)	\$117	\$101	inc. in col. 21	\$1,800		46.9	15.5					*
B. TOTAL Hanford (1992)	726	data (downtime exc)	\$117	\$101	inc. in col. 21	\$1,800		31.3	23.2					*
C. Scenario 1	100	row A (downtime inc)	\$117	\$101	inc. in col. 21	\$1,800	\$4,456	6.5	15.5	\$4,500	\$21,975	\$440	\$2,391	\$248
D. Scenario 3 (10 hr/day)	150	row B (downtime exc)	\$117	\$101	inc. in col. 21	\$2,250	\$5,606	5.2	29.0	\$4,500	\$22,872	\$457	\$2,449	\$172
Sonic, Harrison-Western and CRADA**														
E. TOTAL Hanford (1992)	796	data (downtime inc)	\$234	\$121	\$72	\$1,800		39.1	20.4					*
F. TOTAL Hanford (1992)	796	data (downtime exc)	\$234	\$121	\$72	\$1,800		26.5	30.0					*
G. TOTAL Hanford (1994)	610	data (downtime inc)	\$263	\$121	\$54	\$1,800		4.0	152.5					*
H. TOTAL Hanford (1995)	822	data***	\$263	\$121	\$54	\$1,800		8.6	95.7					*
I. TOTAL Hanford (1995)	822	data***	\$263	\$121	\$54	\$1,800		8.6	95.7					*
J. Scenario 1	100	row H (downtime inc)	\$263	\$121	\$54	\$1,800	\$4,456	1.0	95.7	\$0	\$6,795	\$136	\$587	\$75
Mud Rotary														
K. TOTAL Sandia (1993)	2954	data (downtime inc)	\$263	\$152	\$90	\$2,660		12.0	246.2					*
L. Scenario 2	300	row K (downtime inc)	\$263	\$152	\$90	\$2,660	\$9,056	1.2	246.2	\$4,500	\$17,413	\$348	\$1,365	\$64
M. Scenario 3 (10 hr/day)	150	estimate	\$263	\$152	\$90	\$2,660	\$5,606	0.6	250.0	\$4,500	\$12,005	\$240	\$884	\$88
Sonic, Barber/Simco														
N. TOTAL Sandia (1993)	773	data (downtime inc)	\$263	\$121	\$54	\$2,250		15.0	51.5					*
O. Scenario 2	300	row N (downtime inc)	\$263	\$121	\$54	\$2,250	\$9,056	5.8	51.5	\$0	\$24,714	\$494	\$2,693	\$93
P. Scenario 3 (10 hr/day)	150	estimate	\$263	\$121	\$54	\$2,250	\$5,606	1.0	150.0	\$0	\$8,294	\$166	\$713	\$61

* Total cost per foot was calculated for the scenarios only.

** Harrison-Western rig was used in 1992; CRADA rig was used in 1994-95.

*** Total hours for completion were 68.75 hours. The report did not break out hours for repair so the same number of completion days was used for downtime included and excluded.

Table 4. Cost of drilling technologies--completion.

actual demonstrations at the Hanford and Sandia sites. The metrics and costs are expanded upon in the Appendix.

7.1 Scenario One

Table 2 indicates and Figure 9 graphically depicts the performance of sonic vs. cable-tool given the performance data of the initial Arid-site VOC ID at Hanford. Given these results, sonic is cost effective compared to cable-tool — it can complete a well for about one-third

9.6 ft/drum in difficult drilling compared to sonic's 46.3 ft/drum. Savings for a completed well are \$584/ft (65%) for clean sites, and \$589/ft (64%) and \$634/ft (66%) for a hazardous site (regular and difficult respectively). If mixed wastes are assumed, the cost savings increase to as much as \$718/ft (difficult/mixed), due to the higher cost of mixed waste treatment (estimated at \$1337/drum vs. \$491/drum [13]). This represents a 67% cost savings.

7.2 Scenario Two

Table 2 indicates and Figure 10 graphically depicts

Figure 9 Scenario 1—Cost comparison of sonic vs. cable-tool at Hanford.

the cost. While the nature of the waste (clean or hazardous) has some role, the main driver is cable-tool's slow drill rate. Under the assumption of a clean site, a sonic borehole costs \$411 less per foot drilled than cable-tool (\$244/ft vs. \$655/ft). This represents a savings of 63%. For hazardous waste sites and difficult drilling, the advantage of sonic is slightly increased to 64% due to cable-tool's greater secondary waste generation $[(\$716 - \$255) / \$716 = 0.64]$. Volk [4] reported a waste generation of

9.6 ft/drum in difficult drilling compared to sonic's 46.3 ft/drum. Savings for a completed well are \$584/ft (65%) for clean sites, and \$589/ft (64%) and \$634/ft (66%) for a hazardous site (regular and difficult respectively). If mixed wastes are assumed, the cost savings increase to as much as \$718/ft (difficult/mixed), due to the higher cost of mixed waste treatment (estimated at \$1337/drum vs. \$491/drum [13]). This represents a 67% cost savings.

Figure 10 Scenario 2—Cost comparison of sonic vs. mud rotary at Sandia.

in a mix of clean and hazardous areas, the “break-even” point is of interest. That is, at what percentage of mud rotary wells whose drilling waste requires processing as hazardous or mixed waste, does sonic become economically superior? Figure 11 indicates that for drilling in combined sites of which at least 40% are hazardous (or for a single borehole/well where the probability of hitting contamination is greater than 40%), sonic becomes the more cost-effective technology.

sites the cost savings for sonic drilling is \$139/ft (38%)

per borehole (\$226 vs. \$365). The sonic advantage for a completed well under hazardous conditions is \$110/ft (\$319 vs. \$429—26% total cost savings). For a mixed waste site, the cost savings for sonic increases to \$539/ft (\$253 vs. \$792—about one-third the cost) to drill the borehole.

Clearly, based on cost and environmental considerations, sonic should be seriously considered for large-scale drilling efforts in a hazardous site.

If the condition of the site is uncertain, (i.e., the site is uncharacterized), or if one plans a series of boreholes

Figure 11 Scenario 2—Sensitivity to percent hazardous waste.

7.3 Scenario Three

Table 2 indicates and Figure 12 graphically depicts the performance of sonic vs. both cable-tool and mud rotary given somewhat ideal estimates for sonic perfor-

Figure 12 Scenario 3—Cost comparison of sonic vs. cable-tool and mud rotary.

mance. As the sonic drill has achieved these quoted drill rates at Sandia, and noting that the lower drill rates achieved for 1992 were with older technology rigs and/or in an investigative (rather than “production”) mode, the applied drill rates may not be as overly optimistic as they first appear. Certainly, more “mature” demonstration

numbers validating these estimates are desirable. Given the estimates, the results suggest that sonic may be cost competitive with mud rotary even at clean sites, and far superior to cable-tool. Under the assumption of a clean site and regular drilling, a sonic borehole costs \$14 more per foot to drill than mud rotary (\$147/ft vs. \$133/ft). For

clean and difficult, sonic has a 12% cost savings over mud rotary (\$166/ft vs. \$188/ft). For hazardous waste sites, sonic's drilling cost is about 57% cheaper per borehole than mud rotary for both regular and difficult drilling. If mixed waste is instead assumed, the cost advantage becomes larger still. Completion costs are nearly equivalent for the two technologies. Again, based on cost and environmental considerations, sonic must be seriously considered for large-scale drilling in a hazardous site.

8. Ongoing and Future Developments

There have been important advances in the technology of sonic drilling over the short time span of the four demonstrations included in this report. Improvements by Water Development Corporation in the drill head, drill string, air spring, and other mechanics of the sonic drilling system have greatly improved the performance, reliability, and cost effectiveness of sonic drilling.

This is demonstrated by the separate Hanford demonstrations in which the 15-year-old Harrison-Western rig and the new improved CRADA rig were tested at the same sites, yet experienced very different performance and downtime. Because the geological conditions and the basic drilling technology are the same, the improved performance (from 8.9 ft/day with the old rig to 39.8 ft/day with the new) can be attributed to the technological improvements made in the sonic rig.

Recent improvements in the sonic drilling system have already made it a viable drilling technology for environmental restoration. However, this does not mean that development of sonic drilling has or should be stopped. There are still several aspects of sonic drilling that can be improved. Currently, efforts are underway at both Sandia and Hanford to analyze acoustical data taken during drilling. If patterns in this acoustical data can be

found that correspond to failure of the drill pipe, an acoustical monitoring system could be designed for the sonic drilling rig. Such a monitoring system would be able to predict drill pipe failure before it actually occurs. The drill string could then be carefully withdrawn and replaced before the time consuming task of fishing broken drill string from the borehole would be required. Such information can also be used to assist in the drilling process itself by indicating when the system is approaching non-resonance. The investigation of the feasibility of a control module for remote operation in hazardous and high-level waste sites, is also planned.

Another area of possible concern is the potential impact of resonant energy transfer to the surrounding soils. As part of the Westinghouse Hanford Company CRADA, extensometers and accelerometers were placed in an array surrounding the drilling rig to investigate this possibility.

As part of the CRADA, a significant effort has been established to investigate and ameliorate the high drill pipe failure rate. Effort has been focused on pipe, joint, and casing development, including failure analysis, wet magnetic particle inspection [2], and eddy current examination [14]. Note that significant headway had already been made in sonic head reliability (evident in performance differences between first and second integrated demonstrations).

9. Health and Environmental Risk

The most significant reduction in health and environmental risk that sonic drilling provides over conventional technologies is the minimal amount of waste generated. Under difficult drilling conditions cable-tool drilling requires the addition of water to create a mud lubricant, while mud rotary drilling requires thousands of gal-

lons of mud to be in circulation regardless of the conditions. Sonic drilling, however, even under the most difficult conditions does not require the addition of any drilling fluids. In known or suspected contamination sites this greatly reduces risk to both workers and to the environment. Continued development of instrumentation for the sonic drill head is planned. Remote operation is a long-term goal which would be beneficial for drilling in hazardous and high-level waste sites.

10. Regulatory Approval

The use of any technology in the environmental area is tightly constrained by regulations at both the state and national level. In order for any new environmental technology to be considered an available tool for general application it must acquire regulatory approval. Drilling operations undertaken as part of the Hanford CRADA were noted to be in compliance with OSHA 1910 General Industry Standards, and other industry standards required by DOE Order 5480.4, as well as a site-specific Health and Safety plan in accordance with Code of Federal Regulations (CFR) 1910.120. Wells were completed in compliance of Washington Administrative Codes WAC-173-160. They concluded that "there are no apparent safety or health issues that would prevent ResonantSonic™ drilling activities from complying with Hanford health and safety standards and applicable federal regulations [2]."

11. Summary

The intent of this report is to create an unbiased picture of a new environmental technology, sonic drilling, and to estimate its relative cost effectiveness. This report covers a period where the ResonantSonic™ technique is at an early stage of development, thus caution

must be stressed in applying the results of the cost analyses. It is most likely that the first, and possibly second, scenarios yield conservative estimates of the performance benefits of the technology. The third scenario uses estimates, which although based on observed field performance, needs further technology demonstration to be validated. In the early tests the most critical problem was downtime, which was dominated by failure rate of the drill string. While further development is warranted, and is continuing, initial results do indicate that sonic drilling can be a beneficial and cost-effective technology for drilling activities pertaining to the characterization and remediation of hazardous waste sites in a number of applications. At this time, several advantages of the sonic technology are evident:

- **Cost competitive compared to cable-tool at Hanford.** Under Scenario 1, sonic offers a cost savings of at least 60% (a savings of \$584 to \$718 per 100-foot well).
- **Cost competitive compared with mud rotary when drilling at a hazardous site.** Under Scenario 2, sonic's total cost is from \$110/ft to \$510/ft less expensive (26% to 60%).
- **No drilling fluid is needed, thus minimal secondary waste is generated.** This may be of fundamental importance as DOE sites become more stringent concerning waste generation and control.
- **No fluid interference on samples.**
- **Applicable to all formations.**
- **Minimal waste cuttings generated from the borehole (if the core is considered to be the sample).** Much of the displaced material is pushed into the hole wall.
- **Continuous core capability.** Ability to detect subtleties in lithologies.
- **Ability to drill angled holes.** The Angle rig demonstrated at Sandia was used to drill holes greater than 150 feet at 10 degrees from the horizontal. The Simco rig has been used at Hanford to drill and complete a 168-foot vapor extraction well angled at 45 degrees.
- **Capable of drilling deep boreholes (> 300 feet and 11 inches in diameter) with the combination Dresser rig.**
- **Fast borehole drilling compared to cable-tool.**
- **No need for temporary casing, and reduced cross-contamination problems compared to baseline technologies.**

Current technology limitations include:

- **Potential for drill pipe fracture due to the large vibrational loads.**
- **Potentially high sample temperatures, and thus possible compromising of VOC data, if sufficient care is not exercised in the drilling and sampling operations.**
- **Depth limitations with sonic-only rigs. While there is no firm limit, drilling is noted to be significantly tougher at depths greater than 300 feet.**
- **Problems with drilling in fine sand have been observed.**
- **Limited availability. There are few sonic drilling contractors compared to the baseline technologies.**

Significant progress has been made in addressing the early problems of failures and resultant downtime. Scenario 3 indicates a potential for cost-competitive drilling over a wider range of sites, and large advantages for hazardous sites.

Work is still needed to fully understand the potential for sonic under varying geologies, depths, and diameters. But it is evident from this report that there is a significant opportunity for sonic drilling for environmental work.

Acknowledgments

We gratefully acknowledge the assistance of the following people in the preparation of this report: Jerry Mercer, Daphne Neel, John McCord, and Bob Floran of Sandia National Laboratory; Greg McLellan, Ben Volk, and Lana Richterich of Westinghouse Hanford Company; Jeffrey Barrow of Water Development Corporation; Art Clark of U.S. Geological Survey, Denver; and Jeffrey Tucker and Peter Barnes-Smith of International Technology Corporation. This work was supported by the U.S. Department of Energy - Office of Technology Develop-

ment (EM-50) under Technical Task Plan Number No. AL-101201.

References

1. Jeffrey C. Barrow, "The Resonant Sonic Drilling Method," Ground Water Monitoring and Remediation (Spring 1994).
2. L. R. Richterich, "Phase 1 ResonantSonic™ CRADA Report," Westinghouse-Hanford Company report WHC-SD-EN-TRP-007, Rev. 0 (March 28, 1994).
3. S. R. Booth, L. K. Trocki, and L. Bowling, "A Standard Methodology for Cost- Effectiveness Analysis of New Environmental Technologies," Los Alamos National Laboratory report LA-UR-91-3251 (June 22, 1993).
4. B. W. Volk, "Results of Testing the Sonic Drilling System at the Hanford Site, September 1991 to May 1992," Westinghouse-Hanford Company report WHC-SD-EN-TRP-002, Rev. 0 (October 26, 1992).
5. Jerry Mercer, Sandia National Laboratory, private communication (5/23/94, 6/13/94).
6. Jeff Barrow, Water Development Corporation, private communication, 8/25/93.
7. "Handbook of Suggested Practices for the Design and Installation of Ground Water Monitoring Wells," Environmental Protection Agency report EPA/600/4-89/034 (March 1991).
8. Fletcher G. Driscoll, Groundwater and Wells, Second Edition (Johnson Division, St. Paul, Minnesota, 1986).
9. Art Clark, U.S. Geological Survey, Denver, private communication (8/23/93).
10. Greg McLellan, Westinghouse Hanford Company, private communication (8/26/93).
11. B. W. Volk, G. W. McLellan and B. R. Cassem, "Sonic Drilling System Technology Demonstration at the Hanford Site," Westinghouse Hanford Company report WHC-SD-EN-TP-022, Rev.1 (December 22, 1993).
12. Greg McLellan, Water Development Corporation,

private communication regarding Redox Manipulation Experiment results (12/95).

13. Ben Volk, Westinghouse Hanford Company, private communication (1/14/94).

14. R. L. Hockey, R. H. Ferris and D. M. Riechers, "Eddy Current Examination of Sonic Drill Pipe," prepared for Ground Water Well Services, Westinghouse Hanford Company (February 1994).

Bibliography

M. D. Campbell, J. H. Lehr, *Water Well Technology* (McGraw-Hill Book Company, New York, NY, 1973).

A. D. Henriksen and S. R. Booth, "A Practical Guide to Evaluating the Cost Effectiveness of New Environmental Technologies," Los Alamos National Laboratory report LA-UR-93-4485 (December 1993).

Means Heavy Construction Cost Data, 8th Annual Edition (1994).

"Discount Rates of Cost-Effectiveness, Lease Purchase, and Related Analyses," Office of Management and Budget Circular A-94, ed. R. Darman, to Heads of Executive Departments and Establishments (October 29, 1992).

V. J. Rohay and G. V. Last, "Emerging Site Characterization Technologies for Volatile Organic Compounds," presented at the *Technology Information Workshop*, (Albuquerque, New Mexico, May 19-21, 1992), Pacific Northwest Laboratory report PNL-SA-20989.

B. R. Cassem, "Phase II Resonant Sonic CRADA," Westinghouse Hanford Company report WHC-SD-EN-TRP-009, Revision 0 (March 1995).

Appendix

Table A-1. Cable-Tool Costing Notes (Borehole)

See lines A-F in Table 3. Cost of drilling technologies—borehole.

1. **Depth (feet)**
(A,B) 1073 feet is the total depth of 10 holes drilled in 1992 at Hanford with a cable-tool rig as part of the field demonstration of the sonic drilling system. Per report WHC-SD-EN-TRP-002, Rev.0, p. 54.
(C-F) Scenario depths.
2. **Formation**
(A,B) Mix of conditions, primarily considered "difficult."
"Regular" and "difficult" for cable-tool are used only for waste generation numbers.
3. **Drilling Rate Information**
Per report WHC-SD-EN-TRP-002, Rev.0.
4. **Rig Cost (\$ per day)**
\$117
Total cost of the cable-tool rig: \$200,000
Cost amortized @ 5% per year over 15 years: \$19,268
33 working weeks per year (33 * 5 days per week): 165
\$19,268 / 165 = \$117
\$200K estimate per report WHC-SD-EN-TRP-002, Rev.0., p. 10.
5. **Repair/Maintenance of Rig (\$ per day)**
\$101
Daily rental rate per report WHC-SD-EN-TRP-002, Rev.0., p. 10.
6. **Fuel Cost (\$ per day)**
Included in column 5.
The fuel is already included in the above daily rental rate per report WHC-SD-EN-TRP-002, Rev.0., p. 10.
7. **Personnel Cost (\$ per day)**

Driller	\$60/hour * 8 hours	=	\$480
Driller Assistant	\$41/hour * 8 hours	=	\$328
Field Team Leader	\$59/hour * 8 hours	=	\$472
Geologist	\$59/hour * 8 hours	=	\$472
Site Safety Officer	\$65/hour * 8 hours	=	\$520
Health Physics Technician	\$49/hour * 8 hours	=	\$392
Sampling Scientist	\$59/hour * 8 hours	=	\$472
Sampling Technician	\$48/hour * 8 hours	=	\$384
TOTAL			\$3,520

Personnel and burdened salary estimates OK'd by Lana Richterich, Westinghouse Hanford Company, 1-94.
(E,F) Personnel cost calculated at 10 hours per day to compare with Sandia's 10-hour days.
8. **Drilling Days (number)**
(A) 132.9 (downtime included), per report WHC-SD-EN-TRP-002, Rev.0., p. 54.
(B) 84.9 (downtime excluded), per report WHC-SD-EN-TRP-002, Rev.0., p. 53.
(C-F) Drilling Days = Depth / Average Drilling Rate
9. **Average Drilling Rate (feet per day)**
(A,C,D) 8.1 (downtime included), per report WHC-SD-EN-TRP-002, Rev.0., p. 54.
(B) 12.6 (downtime excluded), per report WHC-SD-EN-TRP-002, Rev.0., p. ES-5.
(E,F) 12.6 * 1.25 = 15.8 (downtime excluded) for 10-hour day comparisons.
10. **Waste Generated (drum)**
(A,B) 61.0 total drums for all holes, per report WHC-SD-EN-TRP-002, Rev.0., p. 55.
(C,E) Depth / (60 ft/drum) for regular drilling + 1 drum (decontaminating rig).
Per report WHC-SD-EN-TRP-002, Rev.0., p. ES-5.
(D,F) Depth / (9.6 ft/drum) for difficult drilling + 1 drum (decontaminating rig).
Per report WHC-SD-EN-TRP-002, Rev.0., p. ES-5.
11. **Waste Disposal Cost (\$ per borehole)**
Waste Generated * Cost per drum

Hazardous waste	\$491 per drum
Mixed waste	\$1337 per drum
LLW	\$464 per drum

Estimates provided by Ben Volk, Westinghouse Hanford Company, 1-94 (overhead is included in costs).
12. **Mobilization/Demobilization Cost (\$ per borehole)**
These costs were estimated to be \$4,500. The cost includes approvals, preparation, a scheduler, team assembly and transport to the site, field equipment set up and check out, electricity and water arrangements, etc.
13. **Site Preparation/Fencing Cost (\$ per borehole)**
These costs were obtained from the Means Heavy Construction Cost Data, 8th Annual Edition, 1994. The site preparation is related to site clearing at \$0.10 per square foot. The fencing cost is for a 6-foot high chain-link fence at \$13.30 per linear foot. Both of these costs were applied to an assumed area of 100 feet by 100 feet.

14. **Borehole Cost Before Permitting and Taxes (\$)**
 $((\text{Rig Cost} + \text{Repair/Maintenance Cost} + \text{Fuel Cost} + \text{Personnel Cost}) * \text{Drilling Days}) + \text{Waste Disposal Cost} + \text{Mob/Demob Cost} + \text{Site Prep Cost}$
15. **Permitting Cost (\$ per borehole)**
 The permitting costs were obtained from Means Heavy Construction Cost Data, 8th Annual Edition, 1994. This cost was calculated as 2% of the total job cost excluding taxes.
16. **Taxes (\$ per borehole)**
 The costs associated with taxes were obtained from Means Heavy Construction Cost Data, 8th Annual Edition, 1994. The sales tax was calculated using the current New Mexico (January 1995) gross receipts tax rate of 6.0625%. Social security and unemployment taxes were applied to the personnel costs at rates of 7.65% and 7.30%, respectively.
 $((\text{Rig Cost} + \text{Repair/Maintenance Cost} + \text{Fuel Cost}) * \text{Drilling Days} * .060625) + (\text{Personnel Cost} * \text{Drilling Days} * .1495) + ((\text{Mob/Demob} + \text{Site Prep} + \text{Permitting Cost}) * .060625)$
17. **Total Cost (\$ per foot)** Assumes non-hazardous waste so there are no waste disposal costs.
 $(\text{Borehole Cost Before Permitting and Taxes} + \text{Permitting Cost} + \text{Taxes}) / \text{Depth}$

Table A-2. Cable-Tool Costing Notes (Well Completion)

See lines A-D in Table 4. Cost of drilling technologies—completion.

Note: Costs for rig, repair/maintenance, and fuel are taken from Table A-1. It is assumed that extra waste is not generated with all well completion activities.

18. **Depth (feet)**
 (A,B) 726 feet is the total depth of 8 wells completed in 1992 at Hanford with a cable-tool rig. No wells were completed for 4B and BH-3 so these depths were excluded.
 (C,D) Scenario depths.
19. **Completion Rate Information**
 See Table A-1, #3.
20. **Rig Cost (\$ per day)**
 $\$117$
 Total cost of the cable-tool rig: $\$200,000$
 Cost amortized @ 5% per year over 15 years: $\$19,268$
 33 working weeks per year (33 * 5 days per week): 165
 $\$19,268 / 165 = \117
21. **Repair/Maintenance of Rig (\$ per day)**
 $\$101$
22. **Fuel Cost (\$ per day)**
 Included in column 21.
 The fuel is already included in the above daily rental rate, per report WHC-SD-EN-TRP-002, Rev.0, p. 10.
23. **Personnel Cost (\$ per day)**

Driller	$\$60/\text{hour} * 8 \text{ hours}$	=	$\$480$
Driller Assistant	$\$41/\text{hour} * 8 \text{ hours}$	=	$\$328$
Field Team Leader	$\$59/\text{hour} * 8 \text{ hours}$	=	$\$472$
Site Safety Officer	$\$65/\text{hour} * 8 \text{ hours}$	=	<u>$\\$520$</u>
		TOTAL	$\$1,800$

Personnel and burdened salary estimates OK'd by Lana Richterich, Westinghouse Hanford Company, 1-94.
 (D) Personnel cost calculated at 10 hours per day to compare with Sandia's 10-hour days.
24. **Material Cost (\$ per well)**

Well head	$\$196$
Well pad	$\$300$
Hydrostar pump	<u>$\\$1200$</u>
	TOTAL $\$1,696$

Stainless steel casing	$\$15 \text{ per foot}$
Stainless steel screen	$\$35 \text{ per foot}$
Filter pack	$\$11 \text{ per foot}$
Grout	$\$8 \text{ per foot}$

These dollar per foot costs have been proportioned accordingly from cubic feet so they can be multiplied by the linear depth.
 Material and cost estimates OK'd by Lana Richterich, Westinghouse Hanford Company, 1-94.
 Well is assumed to have SS casing for the entire depth except for a single 20 foot SS screen intake. Annular materials are a 20 foot filter pack around screen, with the remaining depth assumed to be grouted. Total material cost: $= 1696 + (\text{depth}-20) * (15+8) + 20 * (35+11) = 2156 + (23 * \text{depth})$
25. **Completion Days (number)**
 (A) 46.9 (downtime included), per report WHC-SD-EN-TRP-002, Rev.0, p. 54.
 (B) 31.3 (downtime excluded), calculated from Completion Rate of 23.2 ft/day — $726/23.2 = 31.3$
 (C-D) Completion Days = Depth / Average Completion Rate
26. **Average Completion Rate (feet per day)**
 (A) 15.5 (downtime included), per report WHC-SD-EN-TRP-002, Rev.0, p. ES-5.

- (B) 23.2 (downtime excluded), per report WHC-SD-EN-TRP-002, Rev.0, p. ES-5.
 (D) $23.2 * 1.25 = 29.0$ (downtime excluded) for 10-hour day comparisons.
27. **Mobilization/Demobilization Cost (\$ per borehole)**
 These costs were estimated to be \$4,500. The cost includes approvals, preparation, a scheduler, team assembly and transport to the site, field equipment set up and check out, electricity and water arrangements, etc. This mob/demob charge is added to the cable-tool and mud rotary completion estimates, but not sonic because the same rig is used for completion as for drilling.
28. **Well Completion Cost Before Permitting and Taxes (\$)**
 $((\text{Rig Cost} + \text{Repair/Maintenance Cost} + \text{Fuel Cost} + \text{Personnel Cost}) * \text{Completion Days}) + \text{Material Cost} + \text{Mob/Demob Cost}$
29. **Permitting Cost (\$ per borehole)**
 The permitting costs were obtained from Means Heavy Construction Cost Data, 8th Annual Edition, 1994. This cost was calculated as 2% of the total job cost excluding taxes.
30. **Taxes (\$ per borehole)**
 The costs associated with taxes were obtained from Means Heavy Construction Cost Data, 8th Annual Edition, 1994. The sales tax was calculated using the current New Mexico (January 1995) gross receipts tax rate of 6.0625%. Social security and unemployment taxes were applied to the personnel costs at rates of 7.65% and 7.30%, respectively.
 $((\text{Rig Cost} + \text{Repair/Maintenance Cost} + \text{Fuel Cost}) * \text{Completion Days} * .060625) + (\text{Personnel Cost} * \text{Completion Days} * .1495) + ((\text{Material Cost} + \text{Mob/Demob} + \text{Permitting Cost}) * .060625)$
31. **Completion Total Cost (\$ per foot)**
 $(\text{Well Completion Cost Before Permitting and Taxes} + \text{Permitting Cost} + \text{Taxes}) / \text{Depth}$

Table A-3. Harrison-Western and CRADA Sonic Costing Notes (Borehole)

See lines G-M in Table 3. Cost of drilling technologies—borehole.

1. **Depth (feet)**
 (G,H) 938 feet is the total depth of 11 holes drilled in 1992 at Hanford with the sonic rig, per report WHC-SC-EN-TRP-002, Rev.0, p. 54.
 (I) Two 305-foot wells drilled in 1994 at Hanford during Phase II CRADA, per report WHC-SD-EN-009, Rev. 0.
 (J,K) Sixteen shallow wells drilled in 1995 at Hanford using XT-70-E multipurpose rig, per Redox Manipulation Experiment report.
 (L,M) Scenario depth.
2. **Formation**
 (G,H) Mix of conditions, primarily considered "difficult."
 "Regular" and "difficult" for this rig and scenario are used only for waste generation numbers.
3. **Drilling Rate Information**
 Per report WHC-SD-EN-TRP-002, Rev.0, WHC-SD-EN-TRP-009, Rev. 0, and personal communication with Greg McLellan 12/95.
4. **Rig Cost (\$ per day)**
 Total cost of the H-W rig: \$400,000
 Cost amortized @ 5% per year over 15 years: \$38,537
 33 working weeks per year (33 * 5 days per week): 165
 $\$38,537 / 165 = \234
 \$400K estimate per Jeff Barrow, Water Development Corporation, 8-93.
 CRADA Rig Cost: Using Barber/Simco rig cost of \$263 per day (see Table A-7).
5. **Repair/Maintenance of Rig (\$ per day)**
 $\$121 = (20000 / 165)$
 Estimate of \$20,000 per year for repair and maintenance, per Jeff Barrow, Water Development Corporation, 8-93.
 Using Barber/Simco repair/maintenance cost of \$121 per day for the CRADA repair/maintenance cost (see Table A-7).
6. **Fuel Cost (\$ per day)**
 \$72
 Estimate of 60 gallons of diesel fuel per day at \$1.20 per gallon, per Jeff Barrow, Water Development Corporation, 8-93.
 Using Barber/Simco fuel cost of \$54 per day for the CRADA fuel cost (see Table A-7).
7. **Personnel Cost (\$ per day)**

Driller	\$60/hour * 8 hours	=	\$480
Driller Assistant	\$41/hour * 8 hours	=	\$328
Field Team Leader	\$59/hour * 8 hours	=	\$472
Geologist	\$59/hour * 8 hours	=	\$472
Site Safety Officer	\$65/hour * 8 hours	=	\$520
Health Physics Technician	\$49/hour * 8 hours	=	\$392
Sampling Scientist	\$59/hour * 8 hours	=	\$472
Sampling Technicians (2)	\$48/hour * 8 hours * 2	=	\$768
			TOTAL \$3,904

Need 2 sampling technicians due to rapid penetration of sonic.
 Personnel and burdened salary estimates OK'd by Lana Richterich, Westinghouse Hanford Company, 1-94.
8. **Drilling Days (number)**
 (G) 105.7 (downtime included), per report WHC-SC-EN-TRP-002, Rev.0, p. 54.
 (H) 39.2 (downtime excluded), calculated from Drilling Rate of 23.9 ft/day — $938 / 23.9 = 39.2$
 (I) 10 days to drill 305-foot well, 20 days for both 305-foot wells per report WHC-SD-EN-009, Rev 0 and personal communication with Greg McLellan 12/95.

- (J) 165.3 hours/8 hours to get number of drilling days. 165.3 hours included drilling (74.75), sampling (31), decontamination (9.5), repair (43.05), and fishing (7.0), per Redox Manipulation Experiment report.
- (K) 115.25 hours/8 hours to get number of drilling days. 115.25 hours included drilling (74.75), sampling (31), decontamination (9.5) (excludes repairs and fishing considered downtime), per Redox Manipulation Experiment report.
- (L,M) Depth / Drilling Rate = Drilling Days
9. **Average Drilling Rate (feet per day)**
 (G) 8.9 (downtime included), per report WHC-SC-EN-TRP-002, Rev.0, p. 54.
 (H) 23.9 (downtime excluded), per report WHC-SC-EN-TRP-002, Rev.0, p. ES-5.
 (I-K) Depth / Drilling Days = Average Drilling Rate
 (L,M) Used 39.8 as drilling rate from Row J on Table 3.
10. **Waste Generated (drum)**
 (G,H) 18.0 total drums for all holes, per report WHC-SC-EN-TRP-002, Rev.0, Table 5.
 (I) Not available
 (J,K) 13 drums of waste per Redox Manipulation Experiment report.
 (L) 57.9 ft/drum for regular drilling, per report WHC-SC-EN-TRP-002, Rev.0, p. ES-5.
 (M) 46.3 ft/drum for difficult drilling, per report WHC-SC-EN-TRP-002, Rev.0, p. ES-5.
11. **Waste Disposal Cost (\$)**
 Waste Generated * Cost per drum
 Hazardous waste \$491 per drum
 Mixed waste \$1337 per drum
 LLW \$464 per drum
 Estimates provided by Ben Volk, Westinghouse Hanford Company, 1-94 (overhead is included in costs).
12. **Mobilization/Demobilization Cost (\$ per borehole)**
 These costs were estimated to be \$4,500. The cost includes approvals, preparation, a scheduler, team assembly and transport to the site, field equipment set up and check out, electricity and water arrangements, etc.
13. **Site Preparation/Fencing Cost (\$ per borehole)**
 These costs were obtained from the Means Heavy Construction Cost Data, 8th Annual Edition, 1994. The site preparation is related to site clearing at \$0.10 per square foot. The fencing cost is for a 6-foot high chain-link fence at \$13.30 per linear foot. Both of these costs were applied to an assumed area of 100 feet by 100 feet.
14. **Borehole Cost Before Permitting and Taxes (\$)**
 ((Rig Cost + Repair/Maintenance Cost + Fuel Cost + Personnel Cost) * Drilling Days) + Waste Disposal Cost + Mob/Demob Cost + Site Prep Cost
15. **Permitting Cost (\$ per borehole)**
 The permitting costs were obtained from Means Heavy Construction Cost Data, 8th Annual Edition, 1994. This cost was calculated as 2% of the total job cost excluding taxes.
16. **Taxes (\$ per borehole)**
 The costs associated with taxes were obtained from Means Heavy Construction Cost Data, 8th Annual Edition, 1994. The sales tax was calculated using the current New Mexico (January 1995) gross receipts tax rate of 6.0625%. Social security and unemployment taxes were applied to the personnel costs at rates of 7.65% and 7.30%, respectively.
 ((Rig Cost + Repair/Maintenance Cost + Fuel Cost) * Drilling Days * .060625) + (Personnel Cost * Drilling Days * .1495) + ((Mob/Demob + Site Prep + Permitting Cost) * .060625)
17. **Total Cost (\$ per foot)** Assumes non-hazardous waste so there are no waste disposal costs.
 (Borehole Cost Before Permitting and Taxes + Permitting Cost + Taxes) / Depth

Table A-4. Harrison-Western and CRADA Sonic Costing Notes (Well Completion)

See lines E-J in Table 4. Cost of drilling technologies—completion.

Note: Using the same costs as we did for the borehole for the following parameters: rig cost, repair/maintenance cost, and fuel cost. It is assumed that extra waste is not generated with all well completion activities.

18. **Depth (feet)**
 (E,F) 796 feet is the total depth of 9 holes completed in 1992 at Hanford with a H-W rig, per report WHC-SC-EN-TRP-002, Rev.0, p. 54. No wells were completed for BH-1 and BH-2 so these depths were excluded.
 (G) Two 305-foot wells drilled in 1994 at Hanford during Phase II CRADA, per report WHC-SD-EN-009, Rev. 0.
 (H,I) Sixteen shallow wells drilled in 1995 at Hanford using XT-70-E multipurpose rig, per Redox Manipulation Experiment report.
 (J) Scenario depth.
19. **Completion Rate Information**
 See Table A-3, #3.
20. **Rig Cost (\$ per day)**
 \$234
 Total cost of the H-W rig: \$400,000
 Cost amortized @ 5% per year over 15 years: \$38,537
 33 working weeks per year (33 * 5 days per week): 165
 \$38,537 / 165 = \$234
 CRADA Rig Cost: Using Barber/Simco rig cost of \$263 per day (see Table A-7).
21. **Repair/Maintenance of Rig (\$ per day)**
 \$121

- =(20000/165)
Using Barber/Simco repair/maintenance cost of \$121 per day for the CRADA repair/maintenance cost (see Table A-7).
22. **Fuel Cost (\$ per day)**
\$72
Estimate of 60 gallons of diesel fuel per day at \$1.20 per gallon, per Jeff Barrow, Water Development Corporation, 8-93.
Using Barber/Simco fuel cost of \$54 per day for the CRADA fuel cost (see Table A-7)..
23. **Personnel Cost (\$ per day)**
Driller	\$60/hour * 8 hours	=	\$480
Driller Assistant	\$41/hour * 8 hours	=	\$328
Field Team Leader	\$59/hour * 8 hours	=	\$472
Site Safety Officer	\$65/hour * 8 hours	=	\$520
			TOTAL \$1,800
- Personnel and burdened salary estimates OK'd by Lana Richterich, Westinghouse Hanford Company, 1-94.
24. **Material Cost (\$ per well)**
Well head	\$196
Well pad	\$300
Hydrostar pump	\$1200
	TOTAL \$1,696
- Stainless steel casing \$15 per foot
Stainless steel screen \$35 per foot
Filter pack \$11 per foot
Grout \$8 per foot
- These dollar per foot costs have been proportioned accordingly from cubic feet so they can be multiplied by the linear depth.
Material and cost estimates OK'd by Lana Richterich, Westinghouse Hanford Company, 1-94.
Well is assumed to have SS casing for the entire depth except for a single 20 foot SS screen intake. Annular materials are a 20 foot filter pack around screen, with the remaining depth assumed to be grouted. Total material cost: = 1696 + (depth-20)*(15+8) + 20*(35+11) = 2156 + (23*depth)
25. **Completion Days (number)**
(E) 39.1 (downtime included), per report WHC-SD-EN-TRP-002, Rev.0, p. 54.
(F) 26.5 (downtime excluded), calculated from Completion Rate of 30.0 ft/day — 796/30.0 = 26.5
(G) 2 days to complete 305-foot well, 4 days for both 305-foot wells per report WHC-SD-EN-009, Rev 0 and personal communication with Greg McLellan 12/95.
(H,I) 68.75 hours/8 hours to get number of completion days, per Redox Manipulation Experiment report.
26. **Average Completion Rate (feet per day)**
(E) 20.3 (downtime included), per report WHC-SD-EN-TRP-002, Rev.0, p. 54.
(F) 30.0 (downtime excluded), per report WHC-SD-EN-TRP-002, Rev.0, p. ES-5.
(G-I) Depth / Completion Days = Average Completion Rate
(J) Used 95.7 as completion rate from Row I on Table 3.
27. **Mobilization/Demobilization Cost (\$ per borehole)**
There are no mob/demob costs during well completion with a sonic rig because the same rig is used for completion as for drilling.
This mob/demob charge is only added to the cable-tool and mud rotary completion estimates.
28. **Well Completion Cost Before Permitting and Taxes (\$)**
((Rig Cost + Repair/Maintenance Cost + Fuel Cost + Personnel Cost) * Completion Days) + Material Cost + Mob/Demob Cost
29. **Permitting Cost (\$ per borehole)**
The permitting costs were obtained from Means Heavy Construction Cost Data, 8th Annual Edition, 1994. This cost was calculated as 2% of the total job cost excluding taxes.
30. **Taxes (\$ per borehole)**
The costs associated with taxes were obtained from Means Heavy Construction Cost Data, 8th Annual Edition, 1994. The sales tax was calculated using the current New Mexico (January 1995) gross receipts tax rate of 6.0625%. Social security and unemployment taxes were applied to the personnel costs at rates of 7.65% and 7.30%, respectively.
((Rig Cost + Repair/Maintenance Cost + Fuel Cost) * Completion Days * .060625) + (Personnel Cost * Completion Days * .1495) + ((Material Cost + Mob/Demob + Permitting Cost) * .060625)
31. **Completion Total Cost (\$ per foot)**
(Well Completion Cost Before Permitting and Taxes + Permitting Cost + Taxes) / Depth

Table A-5. Mud-Rotary Costing Notes (Borehole)

See lines N-Q in Table 3. Cost of drilling technologies—borehole.

- Depth (feet)**
(N) 2954 feet. Total depth from drilling chronologies of 4 wells completed in 1993 at Sandia as part of the "Site-Wide Hydrogeological Characterization Project." Fax from John McCord, Sandia National Laboratory, 6-94.
(O-Q) Scenario depths.
- Formation**
(N) Actual drilling was in a mix of lithologies.
- Drilling Rate Information**

Data per drilling chronologies fax from John McCord, Sandia National Laboratory, 6-94.
Estimates per Daphne Neel and Art Clark, 12-93.

4. **Rig Cost (\$ per day)**

\$263
Total cost of the mud rotary rig: \$450,000
Cost amortized @ 5% per year over 15 years: \$43,354
33 working weeks per year (33 * 5 days per week): 165
\$43,354 / 165 = \$263
\$450K estimate per Art Clark, USGS, Denver, 8-93.

5. **Repair/Maintenance of Rig (\$ per day)**

\$152 = (25000/165)
Estimate of \$10,000 to \$25,000 per year for repair and maintenance, per Art Clark, USGS, Denver, 12-93.

6. **Fuel Cost (\$ per day)**

Estimate of 100 gallons of diesel fuel per day at \$1.20 per gallon, per Art Clark, USGS, Denver, 12-93.

7. **Personnel Cost (\$ per day)**

Driller	\$60/hour * 10 hours	=	\$600
Driller Assistant (2)	\$41/hour * 10 hours * 2	=	\$820
Field Team Leader	\$59/hour * 10 hours	=	\$590
Geologist	\$59/hour * 10 hours	=	\$590
Site Safety Officer	\$65/hour * 10 hours	=	\$650
Health Physics Technician	\$49/hour * 10 hours	=	\$490
Sampling Technician	\$48/hour * 10 hours	=	\$480
			TOTAL \$4,220

Personnel per Daphne Neel (SNL), 12-93. Daphne said that at SNL all contracting personnel are ~ \$70 per hour regardless of activity. For simplicity we are using burdened salary rates from Westinghouse Hanford Company. Rates differ from site to site as do procedures. Ten-hour days per John McCord (SNL), 2-17-95.

8. **Drilling Days (number)**

(N) 42.0 days per drilling chronologies.
(O-Q) Drilling Days = Depth / Average Drilling Rate

9. **Average Drilling Rate (feet per day)**

(N) Depth / Drilling Days = Average Drilling Rate
(O) Used 70.3 as drilling rate from Row N Table 3.
(P,Q) Continuous core estimates used.

Estimates per Daphne Neel and Art Clark, 12-93.

Drill Rates (regular):	100 ft/day (continuous core)	160 ft/day (no core)
Drill Rates (difficult):	50 ft/day (continuous core)	100 ft/day (no core)

10. **Waste Generated (drum)**

(O-Q) = (12000/55 * (Depth/500)) + ((Depth/168) * 5)
Calculated from Art Clark's estimate of 10,000 to 12,000 gallons (218 drums) of waste from a 500' hole.
To compare Scenario 2 & 3 we added cleaning/decontaminating rinsate waste because the Sonic has this waste added in also. See Table A-7 Sonic Barber/Simco #10.

11. **Waste Disposal Cost (\$)**

Waste Generated * Cost per drum
Hazardous waste \$491 per drum
Mixed waste \$1337 per drum
LLW \$464 per drum

Estimates provided by Ben Volk, Westinghouse Hanford Company, 1-94 (overhead is included in costs).

12. **Mobilization/Demobilization Cost (\$ per borehole)**

These costs were estimated to be \$4,500. The cost includes approvals, preparation, a scheduler, team assembly and transport to the site, field equipment set up and check out, electricity and water arrangements, etc.

13. **Site Preparation/Fencing Cost (\$ per borehole)**

These costs were obtained from the Means Heavy Construction Cost Data, 8th Annual Edition, 1994. The site preparation is related to site clearing at \$0.10 per square foot. The fencing cost is for a 6-foot high chain-link fence at \$13.30 per linear foot. Both of these costs were applied to an assumed area of 100 feet by 100 feet.

14. **Borehole Cost Before Permitting and Taxes (\$)**

((Rig Cost + Repair/Maintenance Cost + Fuel Cost + Personnel Cost) * Drilling Days) + Waste Disposal Cost + Mob/Demob Cost + Site Prep Cost

15. **Permitting Cost (\$ per borehole)**

The permitting costs were obtained from Means Heavy Construction Cost Data, 8th Annual Edition, 1994. This cost was calculated as 2% of the total job cost excluding taxes.

16. **Taxes (\$ per borehole)**

The costs associated with taxes were obtained from Means Heavy Construction Cost Data, 8th Annual Edition, 1994. The sales tax was calculated using the current New Mexico (January 1995) gross receipts tax rate of 6.0625%. Social security and unemployment taxes were applied to the personnel costs at rates of 7.65% and 7.30%, respectively.
((Rig Cost + Repair/Maintenance Cost + Fuel Cost) * Drilling Days * .060625) + (Personnel Cost * Drilling Days * .1495) + ((Mob/

- Demob + Site Prep + Permitting Cost) * .060625)
17. **Total Cost (\$ per foot)** Assumes non-hazardous waste so there are no waste disposal costs.
(Borehole Cost Before Permitting and Taxes + Permitting Cost + Taxes) / Depth

Table A-6. Mud-Rotary Costing Notes (Well Completion)

See lines K-M in Table 4. Cost of drilling technologies—completion.

Note: Costs for rig and repair/maintenance are taken from Table A-5. It is assumed that extra waste is not generated with all well completion activities.

18. **Depth (feet)**
(K) 2954 feet. Total depth from drilling chronologies of 4 wells completed in 1993 at Sandia as part of the "Site-Wide Hydrogeological Characterization Project." Fax from John McCord, Sandia National Laboratory, 6-94.
(L,M) Scenario depths.
19. **Completion Rate Information**
See Table A-5, #3.
20. **Rig Cost (\$ per day)**
\$263
Total cost of the mud rotary rig: \$450,000
Cost amortized @ 5% per year over 15 years: \$43,354
33 working weeks per year (33 * 5 days per week): 165
\$43,354 / 165 = \$263
21. **Repair/Maintenance of Rig (\$ per day)**
\$152
=(25000/165)
Estimate of \$10,000 to \$25,000 per year for repair and maintenance, per Art Clark, USGS, Denver, 12-93.
22. **Fuel Cost (\$ per day)**
100 gallons * \$1.20 per gallon * .75 = \$90
Using 75% of borehole drilling fuel cost, per Daphne Neel, 12-93.
23. **Personnel Cost (\$ per day)**
Driller	\$60/hour * 10 hours	=	\$600
Driller Assistants (2)	\$41/hour * 10 hours * 2	=	\$820
Field Team Leader	\$59/hour * 10 hours	=	\$590
Site Safety Officer	\$65/hour * 10 hours	=	\$650
			TOTAL \$2,660
- Personnel per Daphne Neel (SNL) 12-93. Note different personnel and hours than borehole drilling. For simplicity we are using burdened salary rates from Westinghouse Hanford Company. Rates differ from site to site as do procedures. Ten-hour days per John McCord (SNL) 2-17-95.
24. **Material Cost (\$ per well)**
Well head	\$196
Well pad	\$300
Hydrostar pump	\$1200
TOTAL	\$1,696
-
Stainless steel casing	\$15 per foot
Stainless steel screen	\$35 per foot
Filter pack	\$11 per foot
Grout	\$8 per foot
- Based on material costs used at Hanford. See Table A-4 (H-W Sonic Well Completion), #24.
25. **Completion Days (number)**
(K) 12.0 days per drilling chronologies
(L,M) Completion Days = Depth / Average Completion Rate
26. **Average Completion Rate (feet per day)**
(K) Per drilling chronologies.
(L) Used 246.2 as completion rate from Row K, Table 4.
(M) Estimate of 250.0 based on drilling chronology data and OK'd by John McCord, 6-94.
27. **Mobilization/Demobilization Cost (\$ per borehole)**
These costs were estimated to be \$4,500. The cost includes approvals, preparation, a scheduler, team assembly and transport to the site, field equipment set up and check out, electricity and water arrangements, etc. This mob/demob charge is added to the cable-tool and mud rotary completion estimates, but not sonic because the same rig is used for completion as for drilling.
28. **Well Completion Cost Before Permitting and Taxes (\$)**
((Rig Cost + Repair/Maintenance Cost + Fuel Cost + Personnel Cost) * Completion Days) + Material Cost + Mob/Demob Cost
29. **Permitting Cost (\$ per borehole)**
The permitting costs were obtained from Means Heavy Construction Cost Data, 8th Annual Edition, 1994. This cost was calculated as 2% of the total job cost excluding taxes.
30. **Taxes (\$ per borehole)**

The costs associated with taxes were obtained from Means Heavy Construction Cost Data, 8th Annual Edition, 1994. The sales tax was calculated using the current New Mexico (January 1995) gross receipts tax rate of 6.0625%. Social security and unemployment taxes were applied to the personnel costs at rates of 7.65% and 7.30%, respectively.

$((\text{Rig Cost} + \text{Repair/Maintenance Cost} + \text{Fuel Cost}) * \text{Completion Days} * .060625) + (\text{Personnel Cost} * \text{Completion Days} * .1495) + ((\text{Material Cost} + \text{Mob/Demob} + \text{Permitting Cost}) * .060625)$

31. **Completion Total Cost (\$ per foot)**

$(\text{Well Completion Cost Before Permitting and Taxes} + \text{Permitting Cost} + \text{Taxes}) / \text{Depth}$

Table A-7. Sonic Barber/Simco Costing Notes (Borehole)

See lines R-U in Table 3. Cost of drilling technologies—borehole.

1. **Depth (feet)**

(R) 941 feet is the total depth of 4 holes drilled in 1993 at Sandia with the "Barber" sonic rig.

(S-U) Scenario depths.

2. **Formation**

(R,S) Actual drilling was in a mix of lithologies.

3. **Drilling Rate Information**

(R) Data per drilling chronologies fax from John McCord, Sandia National Laboratory, 6-94.

(S) Based on Row R, Table 3.

(T,U) Estimates per Jerry Mercer, Sandia National Laboratory, 11-93.

4. **Rig Cost (\$ per day)**

\$263

Total cost of the Barber/Simco rig: \$450,000

Cost amortized @ 5% per year over 15 years: \$43,354

33 working weeks per year (33 * 5 days per week): 165

$\$43,354 / 165 = \263

\$450K estimate per Jeff Barrow, Water Development Corporation, 8-93.

5. **Repair/Maintenance of Rig (\$ per day)**

$\$121 = (20000/165)$

Estimate of \$20,000 per year for repair and maintenance, per Jeff Barrow, Water Development Corporation, 8-93.

6. **Fuel Cost (\$ per day)**

\$54

Estimate of 45 gallons of diesel fuel per day OK'd by Jerry Mercer, Sandia National Laboratory, 12-93. Using \$1.20 per gallon for diesel fuel per Art Clark, 12-93.

7. **Personnel Cost (\$ per day)**

Driller	\$60/hour * 10 hours	=	\$600
Driller Assistant	\$41/hour * 10 hours	=	\$410
Field Team Leader	\$59/hour * 10 hours	=	\$590
Geologist	\$59/hour * 10 hours	=	\$590
Site Safety Officer	\$65/hour * 10 hours	=	\$650
Health Physics Technician	\$49/hour * 10 hours	=	\$490
Sampling Scientist	\$59/hour * 10 hours	=	\$590
Sampling Technicians (2)	\$48/hour * 10 hours * 2	=	\$960
			TOTAL \$4,880

Need 2 sampling technicians due to rapid penetration of sonic.

Personnel for Barber rig per Jerry Mercer, Sandia National Laboratory, 12-93. Ten-hour days for Barber rig per John McCord (SNL), 2-17-95. For simplicity we are using burdened salary rates from Westinghouse Hanford Company, 1-94. Rates differ from site to site as do procedures.

8. **Drilling Days (number)**

(R) 26.0 days per drilling chronologies.

(S-U) Drilling Days = Depth / Average Drilling Rate

9. **Average Drilling Rate (feet per day)**

(R) 36.2 (calculated from drilling chronologies)

(S) Used 36.2 as drilling rate from Row R, Table 3.

(T,U) Estimates (includes continuous coring) per Jerry Mercer, Sandia National Laboratory, 11-93.

10. **Waste Generated (drum)**

(S-U) = $(\text{Depth}/168) * 5$ drums — Based on WHC-SD-EN-TRP-007, Rev. 0, report of 5 drums of cleaning/decontaminating rinsate waste for a 168 foot borehole. It was noted that this amount can be reduced by hand cleaning. Waste generated from cuttings is negligible, if core is considered to be sample. Approximately the same waste as pro-rating the 1992 waste data.

11. **Waste Disposal Cost (\$)**

Waste Generated * Cost per drum

Hazardous waste \$491 per drum

Mixed waste \$1337 per drum

LLW \$464 per drum

Estimates provided by Ben Volk, Westinghouse Hanford Company, 1-94 (overhead is included in costs).

12. **Mobilization/Demobilization Cost (\$ per borehole)**

These costs were estimated to be \$4,500. The cost includes approvals, preparation, a scheduler, team assembly and transport to the site, field equipment set up and check out, electricity and water arrangements, etc.

13. **Site Preparation/Fencing Cost (\$ per borehole)**

These costs were obtained from the Means Heavy Construction Cost Data, 8th Annual Edition, 1994. The site preparation is related to site clearing at \$0.10 per square foot. The fencing cost is for a 6-foot high chain-link fence at \$13.30 per linear foot. Both of these costs were applied to an assumed area of 100 feet by 100 feet.

14. **Borehole Cost Before Permitting and Taxes (\$)**

$((\text{Rig Cost} + \text{Repair/Maintenance Cost} + \text{Fuel Cost} + \text{Personnel Cost}) * \text{Drilling Days}) + \text{Waste Disposal Cost} + \text{Mob/Demob Cost} + \text{Site Prep Cost}$

15. **Permitting Cost (\$ per borehole)**

The permitting costs were obtained from Means Heavy Construction Cost Data, 8th Annual Edition, 1994. This cost was calculated as 2% of the total job cost excluding taxes.

16. **Taxes (\$ per borehole)**

The costs associated with taxes were obtained from Means Heavy Construction Cost Data, 8th Annual Edition, 1994. The sales tax was calculated using the current New Mexico (January 1995) gross receipts tax rate of 6.0625%. Social security and unemployment taxes were applied to the personnel costs at rates of 7.65% and 7.30%, respectively.

$((\text{Rig Cost} + \text{Repair/Maintenance Cost} + \text{Fuel Cost}) * \text{Drilling Days} * .060625) + (\text{Personnel Cost} * \text{Drilling Days} * .1495) + ((\text{Mob/Demob} + \text{Site Prep} + \text{Permitting Cost}) * .060625)$

17. **Total Cost (\$ per foot)** Assumes non-hazardous waste so there are no waste disposal costs.

$(\text{Borehole Cost Before Permitting and Taxes} + \text{Permitting Cost} + \text{Taxes}) / \text{Depth}$

Table A-8. Sonic, Barber/Simco Costing Notes (Well Completion)

See lines N-P in Table 4. Cost of drilling technologies—completion.

Note: Costs for rig, repair/maintenance, and fuel are taken from Table A-7. It is assumed that extra waste is not generated with all well completion activities.

18. **Depth (feet)**

(N) 773 feet. Total depth from drilling chronologies of 2 wells completed in 1993 at Sandia as part of the "Site-Wide Hydrogeological Characterization Project." Fax from John McCord, Sandia National Laboratory, 6-94.

(O,P) Scenario depths.

19. **Completion Rate Information**

(N,O) See Table A-7, #3.

(P) Estimate per Jeff Barrow, WDC 6-94, and based on 168-foot well completion in one day at Hanford (CRADA report).

20. **Rig Cost (\$ per day)**

\$263

Total cost of the Barber/Simco rig: \$450,000

Cost amortized @ 5% per year over 15 years: \$43,354

33 working weeks per year (33 * 5 days per week): 165

$\$43,354 / 165 = \263

21. **Repair/Maintenance of Rig (\$ per day)**

\$121

$= (20000 / 165)$

Estimate of \$20,000 per year for repair and maintenance, per Jeff Barrow, Water Development Corporation, 8-93.

22. **Fuel Cost (\$ per day)**

\$54

Estimate of 45 gallons of diesel fuel per day OK'd by Jerry Mercer, Sandia National Laboratory, 12-93. Using \$1.20 per gallon for diesel fuel per Art Clark, 12-93.

23. **Personnel Cost (\$ per day)**

Driller	\$60/hour * 10 hours	=	\$600
---------	----------------------	---	-------

Driller Assistant	\$41/hour * 10 hours	=	\$410
-------------------	----------------------	---	-------

Field Team Leader	\$59/hour * 10 hours	=	\$590
-------------------	----------------------	---	-------

Site Safety Officer	\$65/hour * 10 hours	=	\$650
---------------------	----------------------	---	-------

TOTAL \$2,250

We did not have completion well data from Jerry Mercer for the Barber rig so we are using personnel and burdened salary estimates for the Simco rig. Lana Richterich, Westinghouse Hanford Company, 1-94 gave us estimates for the Simco rig. Ten-hour days per John McCord (SNL), 2-17-95.

24. **Material Cost (\$ per well)**

Well head	\$196
-----------	-------

Well pad	\$300
----------	-------

Hydrostar pump	\$1200
----------------	--------

TOTAL \$1,696

Stainless steel casing	\$15 per foot
------------------------	---------------

Stainless steel screen	\$35 per foot
------------------------	---------------

Filter pack	\$11 per foot
-------------	---------------

Grout	\$8 per foot
-------	--------------

- Based on material costs used at Hanford. See Table A-4 (H-W Sonic Well Completion), #24.
25. **Completion Days (number)**
 (N) 15.0 days per drilling chronologies.
 (O,P) $\text{Completion Days} = \text{Depth} / \text{Average Completion Rate}$
 26. **Average Completion Rate (feet per day)**
 (N) Per drilling chronologies.
 (O) Used 51.5 as completion rate from Row N, Table 4.
 (P) Estimate per Jeff Barrow, WDC 6-94, and based on 168 foot well completion in one day at Hanford (CRADA report).
 27. **Mobilization/Demobilization Cost (\$ per borehole)**
 There are no mob/demob costs during well completion with a sonic rig because the same rig is used for completion as for drilling.
 This mob/demob charge is only added to the cable-tool and mud rotary completion estimates.
 28. **Well Completion Cost Before Permitting and Taxes (\$)**
 $((\text{Rig Cost} + \text{Repair/Maintenance Cost} + \text{Fuel Cost} + \text{Personnel Cost}) * \text{Completion Days}) + \text{Material Cost} + \text{Mob/Demob Cost}$
 29. **Permitting Cost (\$ per borehole)**
 The permitting costs were obtained from Means Heavy Construction Cost Data, 8th Annual Edition, 1994. This cost was calculated as 2% of the total job cost excluding taxes.
 30. **Taxes (\$ per borehole)**
 The costs associated with taxes were obtained from Means Heavy Construction Cost Data, 8th Annual Edition, 1994. The sales tax was calculated using the current New Mexico (January 1995) gross receipts tax rate of 6.0625%. Social security and unemployment taxes were applied to the personnel costs at rates of 7.65% and 7.30%, respectively.
 $((\text{Rig Cost} + \text{Repair/Maintenance Cost} + \text{Fuel Cost}) * \text{Completion Days} * .060625) + (\text{Personnel Cost} * \text{Completion Days} * .1495) + ((\text{Material Cost} + \text{Mob/Demob} + \text{Permitting Cost}) * .060625)$
 31. **Completion Total Cost (\$ per foot)**
 $(\text{Well Completion Cost Before Permitting and Taxes} + \text{Permitting Cost} + \text{Taxes}) / \text{Depth}$