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Phase III ResonantSonic® Report

D. R. Newcomer (Compiler)

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J. R. Friley

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B. V. Johnston

September 1996

Prepared for the U.S. Department of Energy
under Contract DE-AC06-76RLO 1830

Pacific Northwest National Laboratory
Operated for the U.S. Department of Energy
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Subsurface Contaminant Focus Area

Pacific Northwest National Laboratory
Richland, Washington 99352

Summary

This report describes the testing and results of the ResonantSonic® drilling technology. This work was conducted under a Cooperative Research and Development Agreement (CRADA) established between the U.S. Department of Energy, Pacific Northwest National Laboratory,^(a) and Water Development Hanford, Inc. Technical direction of the CRADA was assigned to Westinghouse Hanford Company. Funding was provided by the U.S. Department of Energy's Office of Science and Technology (EM-50) through the Plumes Focus Area (currently the Subsurface Contamination Focus Area).

Phase I activities occurred in 1993 and focused on improvements to components of the ResonantSonic® drilling system. Laboratory analyses were conducted on drill pipe in the areas of metallurgy, fatigue failure, and thread design. The performance of the ResonantSonic® drilling method was evaluated during drilling support of characterization/remediation projects. Angle-drilling capability was successfully demonstrated for installation of a vapor extraction well.

Phase II activities occurred in 1994 and were a continuation of Phase I. Phase II included component modifications to the drilling system; development of a simulator tool for the drilling system, which required a finite-element model analysis of the drill string; a preliminary cost evaluation against the cable-tool drilling method; and continued evaluation of the ResonantSonic® drilling technology applied at a number of well-installation sites.

Phase III activities were completed in fiscal years 1995 and 1996 and focused on the effort to complete the two remaining CRADA objectives (demonstrate operational efficiency and reliability of the ResonantSonic® drill head in various geologic conditions; evaluate effect of ResonantSonic® drilling on nearby structures and buildings). Field activities to complete the first objective were conducted by Water Development Hanford, Inc. through a contract with Hanford's Environmental Restoration Contractor, Bechtel Hanford, Inc. All vadose zone- and groundwater-monitoring wells installed in fiscal year 1996 were successfully drilled by Water Development Hanford, Inc. to support many characterization and remediation investigations at waste-disposal areas on the Hanford Site.

A model of drill-string dynamics was developed for studying various drilling configurations and loading conditions. The purpose of the model was to identify operational behavior under various geologic conditions and applications. Modeling simulations of the dynamic behavior of the sonic method for drilling and penetrating applications showed a predictable behavior pattern that was, for the most part, consistent with field experience. The dynamic model is a valuable engineering tool that can be used to develop the ResonantSonic® drilling method beyond its current capability.

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Instrumentation testing indicated that a load cell can be a valuable aid for operating the ResonantSonic® drill system. Coupled with predictions from the dynamic modeling simulation, the load cell can be useful for predicting operational regimes that are damaging to drill-string equipment. A variable gain accelerometer provided valuable information for the validation of the dynamic model. In addition, the accelerometer data contain "signature" spectra that can be used to indicate changes in the behavior of the drill system. This can be useful for improving maintenance procedures, to minimize unscheduled downtime, and to minimize relatively costly equipment failures. The signature analysis technique is the recommended procedure for improving maintenance programs for the ResonantSonic® drilling system.

A primary concern of the ResonantSonic® drilling method involves failure of the threaded connector that joins the 10-ft (3-m) sections of drill pipe. The results of the modeling analysis to investigate stress levels and fatigue strength of drill-pipe threaded joints showed that the pin contact configuration is the best design based on the fatigue factor.

In fiscal year 1995, questions were raised regarding the possible influence of ResonantSonic® drilling on the quality of core samples and on the productivity of hydrogeologic formations. An independent review panel was formed and, based on the available data, determined that there is insufficient evidence to conclude that ResonantSonic® drilling causes irrecoverable formation damage. More documentation is needed from wells drilled by the ResonantSonic® method before any evaluation of formation damage effects can be made. It was recommended that controlled field testing be conducted to evaluate these influences if a quantitative comparison is required between ResonantSonic® drilling and cable-tool drilling.

To complete the second objective, soil-vibration tests were conducted to determine the effects of vibration shock waves produced by the ResonantSonic® drill on nearby buried structures (e.g., underground storage tanks). Data were collected from downhole instrumented boreholes located 10 and 20 ft (3 and 6 m) from the drill hole. The data showed small soil accelerations that yielded a horizontal maximum of 0.04 g. This indicates that vibrations produced by the sonic drill do not adversely affect nearby structures.

The advantages of the ResonantSonic® drilling method are that it requires no circulation of water or drilling fluids to penetrate formations and is capable of drilling at fast rates (up to 1 ft/s [0.3 m/s] in some formations). This fast drilling rate can result in lower operational costs compared to the cable-tool drilling method, assuming that the objective of the well design has been achieved. The drill rig is capable of drilling at any angle (from 15 degrees off horizontal to vertical) and generates minimal to no waste cuttings during the drilling process. Continuous, relatively intact cores can be retrieved using the ResonantSonic® drilling method.

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1.0 Introduction

A Cooperative Research and Development Agreement, referred to as a CRADA, is a process that was enacted by Congress in 1989 to pursue and encourage technology development between private industry, the U.S. government, and its contractors. The primary goal of this cooperative agreement is to provide a flexible mechanism that enables the timely development of mutually beneficial technologies.

The purpose of the CRADA discussed in this report allows the partners to pursue enhancements to the ResonantSonic® drilling technology for compatible drilling applications at government and private industry sites. The CRADA field work discussed herein was conducted in three phases at the Hanford Site over the period of fiscal years 1993 through mid-1996.

The ResonantSonic® drilling system was tested at the Hanford Site in fiscal year 1991-1992 under the auspices of the Drilling Technology Development Program and the Environmental Restoration Program. The purpose of that program was to develop, test, and demonstrate drilling methods that are environmentally acceptable, safe, efficient, and cost effective when drilling and sampling in hazardous and radioactive waste sites. The cable-tool method has historically been the primary drilling method employed for characterization and remediation projects at the Hanford Site. The cable-tool method can be used reliably in a wide variety of geologic conditions and yields continuous, relatively intact core samples. However, the disadvantages of this method are that the penetration rates are slow relative to most other drilling techniques, resulting in higher costs, and drilling at angles off vertical is not practical.

This report represents the completion of ResonantSonic® drilling program test activities under this CRADA between the U.S. Department of Energy, Pacific Northwest National Laboratory, and Water Development Hanford, Inc. Technical direction of the CRADA was assigned to Westinghouse Hanford Company. Pacific Northwest National Laboratory and Westinghouse Hanford Company are U.S. Department of Energy contractors at the Hanford Site and Water Development Hanford, Inc. is the industry partner.

The Standard Practice for Use of the International System of Units (ASTM 1994) is in use at the Hanford Site; however, the measurements taken in the conduct of this CRADA are the usual and customary units used in the well-drilling industry. Therefore, we have chosen to use English units followed by their metric equivalent in parentheses (to comply with SI) in this report.

A brief description of the ResonantSonic® drilling program is given in Chapter 2.0. Phases I and II activities are contained in Chapters 3.0 and 4.0, respectively. More information on each of these activities can be found in Volk et al. (1993), Richterich et al. (1994), and Cassem (1995). The Phase III activities are outlined in Chapter 5.0. The conclusions drawn from the results and recommendations for further work to improve the ResonantSonic® drilling technology beyond its current capability are discussed in Chapter 6.0. The references cited in the text are given in Chapter 7.0.

2.0 Background

The sonic drilling technology was first developed in the 1960s. In the 1970s and 1980s, further technological advances were made and several drill rigs were designed and built for field applications. Water Development Corporation of Woodland, California, acquired the sonic drilling rigs and technology from Harrison-Western Drilling, Inc., Lakewood, Colorado. Water Development Corporation, and subsequently Water Development Hanford, Inc., developed upgrades and more reliable components and is now the current owner of the patent rights to the ResonantSonic® drilling technology.

Field testing of the ResonantSonic® drilling system was initiated at the 300-FF-5 Operable Unit in the Hanford Site's 300 Area in September 1991. Testing was conducted using a trailer-mounted 1976 model of a Hawker-Siddeley sonic drill under subcontract to Harrison-Western Drilling, Inc.

Eleven wells and miscellaneous boreholes were drilled using the sonic method. The method was then compared with the cable-tool method used to drill 10 nearby wells. The drilling rate using the sonic method was improved by approximately twice that using the cable-tool method. Downtime resulting from pipe and drill-head failures averaged 28% for the Harrison-Western Drilling, Inc. rig compared to 4% for the cable-tool rig. Overall, compared to the cable-tool method, drilling costs were reduced by ~20% (Volk et al. 1992).

After the fiscal year 1991-1992 program, Westinghouse Hanford Company and the U.S. Department of Energy determined that the ResonantSonic® drilling method showed promise and equipment components should be enhanced in an effort to further improve productivity and reduce drilling costs. As a result, a CRADA was established in February 1993 between the U.S. Department of Energy, Pacific Northwest National Laboratory, and Water Development Corporation (now known as Water Development Hanford, Inc.) to further develop and test the ResonantSonic® drilling method. Pacific Northwest National Laboratory then coordinated with Westinghouse Hanford Company to act as the manager to oversee technical direction of the CRADA effort.

2.1 Drilling Technology Description

The ResonantSonic® drilling technology uses a combination of drill-string dynamics excited by an aboveground vibrating head and rotary power to drill in a variety of soils (Barrow 1994). High-frequency vibrations are transmitted through the drill pipe to create a dynamic cutting action at the drill bit face. The oscillator, or drill head, consists of two counterrotating rollers that cause the drill pipe to vibrate. The rollers are synchronized to ensure that the vertical force component is transmitted downward through the drill pipe or core barrel (Figure 2.1). The vibrations are isolated from the rig structure by an air spring. When the drill pipe is in resonance, the maximum axial displacements of the pipe, a function of its elasticity, are occurring. Resonance is the term used to describe the condition when the frequency of the vibrations is equal to the natural frequency of the drill pipe.

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Figure 2.1. ResonantSonic® Drilling System

The vibration of the drill pipe, coupled with the weight of the drill pipe and downward thrust of the drill head, allows for penetration of the formation. Concurrent with the resonant energy, the drill head can be rotated to assist in penetration and to ensure that the formation is always adjacent to the cutting surfaces of the drill bit. The force generated by the rollers ranges up to 150 Hz and creates up to 250,000 lb (113,000 kg) of force (Volk et al. 1993).

As the rotational and vibrational energy is generated, the drill pipe advances into the ground because the vibrational component literally causes the formation to yield beneath the drill bit. The drill string advances using minimal force, which is applied hydraulically with the drill head. The drill rig can generate a maximum of 10,000 lb (4,500 kg) of downward thrust. However, rapid penetration rates are commonly achieved with <1,000 lb (<450 kg) of downward thrust. The resonant energy transmitted along the length of the drill pipe substantially reduces the amount of friction between the drill pipe and the borehole wall.

As the hole is advanced, additional sections of the drill pipe (typically 5- or 10-ft [1.5- or 3-m] 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. Larger-diameter casing is advanced sequentially (commonly every 10 ft [3 m]) with the drill pipe.

A continuous core of the formation penetrated is commonly obtained without the use of circulation media (e.g., fluid or air). As is common with core-drilling processes, the length of core retrieved each time is dependent on the stability of the formations encountered. Using the ResonantSonic® method, the length of core retrieved is sometimes greater (core growth) than the distance drilled as a result of the displacement of the soil to the path of least resistance. Borehole integrity is maintained by the threaded drill casing that remains in the ground while the coring string is removed.

The ResonantSonic® drilling method has also proved successful in extracting drill pipe that was stuck when using other drilling methods. During the fiscal year 1991-1992 sonic drilling program, stuck casing in a cable-tool-drilled hole (150 ft [46 m] deep and 10 in. [25 cm] in diameter) was removed, and the well was successfully completed using the ResonantSonic® method.

Because the ResonantSonic® method is being compared to the baseline cable-tool method, which has been the primary drilling method employed at the Hanford Site in the past, a brief description of the cable-tool method is warranted. The cable-tool method uses percussion by repeatedly lifting and dropping a heavy string of drilling tools in the borehole (Driscoll 1986). The reciprocating action of the drill string crushes or loosens material, which forms a slurry with indigenous or added water at the bottom of the borehole. The accumulation of slurry reduces the effectiveness of the tools and is periodically removed from the borehole using a bailer.

3.0 Phase I

The first phase of the CRADA focused on improvements to components of the ResonantSonic® drilling system, including the drill pipe, drill head, drill bits, and soil-sampling equipment. Along with

this effort, ongoing laboratory analyses were conducted in the areas of metallurgical analyses, fatigue failure, and thread configuration to determine alternate drill-pipe configurations for later field testing. In addition, alternative uses of the ResonantSonic® method to support characterization/remediation projects and to investigate angle/horizontal drilling were evaluated during Phase I.

The 12 objectives of Phase I are given below, followed by a brief summary of each. Richterich et al. (1994) give a full description of testing and results of Phase I activities.

- 1) demonstrate efficiency and reliability of the ResonantSonic® drill head in penetrating variable geologic conditions
- 2) demonstrate angle-drilling capabilities with the ResonantSonic® method and determine areas for improvements
- 3) develop and install instrumentation system on the ResonantSonic® drill to electronically record the resonant drilling process
- 4) correlate recorded drilling measurements with geology encountered
- 5) test and evaluate sampling equipment and sample-handling methods to determine acceptable systems for both vertical and angle-drilling modes
- 6) demonstrate ResonantSonic® drilling can meet safety standards at the Hanford Site for drilling operations
- 7) demonstrate ability to maintain contamination control and minimize generated waste so the drilling system could be used for vadose zone characterization borings
- 8) demonstrate compliance with state regulations for completion of wells (e.g., filter pack, annular seals, etc.)
- 9) demonstrate ability to maintain minimal disturbance (comparable to cable tool) to soil samples during drilling and to achieve borehole depths and diameters consistent with project requirements
- 10) evaluate cost effectiveness of the ResonantSonic® drill versus the cable-tool drill when used for characterization of hazardous waste sites
- 11) determine vibration radial distance from the borehole generated by the ResonantSonic® method
- 12) drill and install a multiscreened, 4-in. (10.2-cm) dia., vapor-extraction well.

The ResonantSonic® rig and drill head were generally reliable throughout the Phase I testing period (Objective 1). Several vertical and angle-test bores were conducted with minimal downtime from drill-head failure. Between July and December 1993, a total of 900 ft (274 m) of monitoring wells and sample boreholes were drilled with the ResonantSonic® rig at the Drilling Technology Test Site and at

the Carbon Tetrachloride Expedited Response Action site, both shown on Figure 3.1. The Drilling Technology Test Site is located between the 200-East and 200-West Areas and the Expedited Response Action site is located in the 200-West Area.

To demonstrate angle-drilling capability (Objective 2), a vapor-extraction well (299-W15-223) was drilled and completed at a 45-degree angle to support the 200-West Area Carbon Tetrachloride Expedited Response Action (Richterich et al. 1994). This well was drilled to 168 ft (51.3 m) in < 8 working days. In 1 day, the well casing and screen (3-in. [7.6-cm] dia.) were installed and completed.

Phase I activities demonstrated compliance with health and safety standards (Objective 6), waste minimization and contamination control of generated waste (Objective 7), regulatory compliance with well-construction standards (Washington Administrative Code 173-160) (Objective 8), minimal disturbance to soil samples, and ability to achieve borehole depths and diameters consistent with project requirements (Objective 9). Various types of soil-sampling equipment and methods were tested and evaluated in both vertical and angle-drilled modes. It was determined that no single sampling method was exclusively advantageous over any other sampling method for any one drilling mode (Objective 5). Drilling rates ranged from 19.4 to 36.5 ft/d (5.9 to 11.1 m/d) for the ResonantSonic® method (Richterich et al. 1994).

During Phase I, many drill pipe and casing materials were tested to reduce the probability of failure. Although the tests yielded useful results, it was determined that further failure analysis of the drill pipe was necessary before any conclusive statements could be made. The results of the tests are documented in Richterich et al. (1994).

During fiscal year 1993-1994 (during Phase I and continuing into Phase II), ResonantSonic® drilling techniques supported several dual-purpose projects, which in turn showcased other technologies in support of the Environmental Restoration Program (Richterich et al. 1994). Significant project cost savings were realized by implementing this approach. Other development technologies were used at the same wells that were drilled by the ResonantSonic® method.

To complete the remaining objectives, further testing and development of the ResonantSonic® drilling technology were needed and were proposed for inclusion in the existing CRADA as follows: Objectives 1, 3, 10, and 11 were continued to Phase II. Objective 4, correlate recorded drilling measurements with geology encountered, was not begun because the instrumentation system in Objective 3 was not developed. Also, during Phase I, it was determined that Objective 12 be eliminated (Richterich et al. 1994).

4.0 Phase II

Phase II was the continuation of Phase I activities to develop the ResonantSonic® drilling technology. The Pacific Northwest National Laboratory and Westinghouse Hanford Company portion of the CRADA during Phase II was funded by the U.S. Department of Energy's Office of Technology and Development

Figure 3.1. ResonantSonic® Drilling Locations on the Hanford Site

through the Volatile Organic Compounds - Arid Site Integrated Demonstration. Water Development Hanford, Inc. also made a comparable contribution to the CRADA program. Phase II was conducted from December 1993 through December 1994 and consisted of eight objectives, three of which were the completion of Phase I Objectives 1, 10, and 11. To complete the testing, Phase I Objective 3 continued in Phase II and Phase III. The eight Phase II objectives are as follows:

- 1) test and evaluate ResonantSonic® drill-pipe configurations
- 2) demonstrate operational efficiency and reliability of the ResonantSonic® drill head in various geologic conditions
- 3) demonstrate retrievability capacity of volatile organic compound soil samples with average temperatures not exceeding 80°F (26.7°C)
- 4) demonstrate compliance with regulations and well-site construction standards for well completion (Washington Administrative Code 173-160 and generic well specifications in Reynolds [1992])
- 5) compare cost effectiveness of the ResonantSonic® drill with the cable-tool drill when used for detailed physical and chemical characterization of hazardous waste sites
- 6) evaluate effect of ResonantSonic® drilling on nearby structures (i.e., underground storage tanks) and buildings
- 7) demonstrate safe operation of ResonantSonic® drilling unit
- 8) demonstrate ResonantSonic® method in various applications to determine possible uses in support of environmental characterization and remediation activities.

Tests and results of the Phase II effort are contained in Cassem (1995) and Richterich et al. (1994) and are summarized here, along with additional activities not previously reported.

Testing and use of a wide variety of drill pipe continued at the Hanford Site (Objective 1). A cone penetrometer rod and various casing sizes (up to 11.75-in. [29.85-cm] dia.) were used. Pipe and thread couplings were optimized, and minimal failures occurred under normal usage.

Objective 2 was to demonstrate the operational efficiency and reliability of the ResonantSonic® drilling method in various geologic conditions. A concern of this drilling system is its higher potential for pipe failure resulting from vibrational effects on steel pipe. Because of the pipe failure, further research was necessary. As a result, a contract was placed with the Colorado School of Mines to develop a simulator model for the system. Version 1 of the ResonantSonic® drilling simulator was produced in September 1994. Because additional research was needed to fully understand drill-string dynamics, work on a dynamic finite-element model was initiated in mid-1995 (during Phase III; Section 5.1.2). Future Colorado School of Mines' activities were placed on hold pending completion of the finite-element model and evaluation of the ResonantSonic® drilling simulator.

Objective 3 was completed during 1993 and is reported in Richterich et al. (1994). Many actions were taken to successfully retrieve samples at an acceptable temperature for volatile organic compound analyses. Actions included modifying drilling techniques, using extended length split-tube samplers, lining samplers with material having a low thermal conductivity, and prechilling the samplers with dry ice in special coolers. Implementation of these actions is dependent on the data quality objectives of the core samples.

Just as in Phase I testing, the ResonantSonic® drilling method continued to demonstrate compliance with regulations and well-construction standards, and the drilling activities were completed in accordance with health and safety standards. Meeting these standards satisfied Objectives 4 and 7. No lost-time accidents occurred on any of the ResonantSonic® drill rigs from 1993 through 1996.

In Phase I and Phase II operations, downtime related to sonic head failure decreased to <10% versus 28% (Objective 5). Compared to baseline Hanford Site costs for the cable-tool method, the ResonantSonic® well-installation costs at the Bioremediation Site (see Figure 3.1) were \$188/ft (\$617/m) lower, or a 42% savings. In addition, even with maintenance, the final two wells were completed in 12 days, compared to an estimated 32 days for two cable-tool wells at the same depth. The Bioremediation Site was selected for cost comparison because it was the only operational site where a reasonable comparison could be made. To provide a fair comparison, cable-tool costs were based on numerous holes drilled with this method. Comparisons could not be made at other sites because it took longer and cost more because of planned testing, sampling, and/or equipment modifications. For a cost comparison to be valid, it must be assumed that the objective of the well design was achieved.

Wells were drilled at several locations on the Hanford Site to assess operations with different drill heads, geologic settings, and applications (Objective 8). The sites, activities, and results are summarized in Table 4.1 and the site locations are shown on Figure 3.1. Field documentation showed that the ResonantSonic® drilling method could drill in diverse formations with a variety of hole-diameter sizes (4 to 10 in. [10.2 to 25.4 cm]) and drill depths (up to 310 ft [94.5 m]).

5.0 Phase III

Phase III involved the completion of the final two objectives. The focus was primarily on Objective 2 (demonstrate operational efficiency and reliability of the ResonantSonic® drill head in various geologic conditions). The field testing involved with Objective 6 (evaluate effect of ResonantSonic® drilling on nearby structures and buildings) was conducted in Phase II; however, the correlation and evaluation of the field testing by using computer analyses was conducted in Phase III.

Table 4.1. Projects Where Sonic Drilling Methods have been Demonstrated

Project/Area	Well Number	Drill Method	Drill Date	Purpose
100-D Area (RCRA)	199-D8-4	Sonic	11/12/91	Groundwater monitoring
	199-D8-5	Sonic	10/28/91	Groundwater monitoring
Redox Barrier Demonstration	199-H5-2	Sonic	02/02/95	Injection
	199-H5-3(O)	Sonic/sonic push	03/03/95	Upper piezometer
	199-H5-3(P)	Sonic	03/03/95	Lower piezometer
	199-H5-4(O)	Sonic/sonic push	03/03/95	Upper piezometer
	199-H5-4(P)	Sonic	03/03/95	Lower piezometer
	199-H5-5(O)	Sonic/sonic push	03/03/95	Upper piezometer
	199-H5-5(P)	Sonic	03/03/95	Lower piezometer
	199-H5-6	Sonic/sonic push	03/03/95	Lower piezometer
	199-H5-7	Sonic/sonic push	03/03/95	Lower piezometer
	199-H5-8	Sonic	03/03/95	Lower piezometer
	199-H5-9	Sonic/sonic push	03/03/95	Lower piezometer
	199-H5-10	Sonic push	03/03/95	Lower piezometer
	199-H5-11	Sonic	03/03/95	Lower piezometer
	199-H5-12	Sonic push	03/07/95	Groundwater monitoring
	199-H5-13	Sonic/sonic push	03/07/95	Groundwater monitoring
	199-H5-14	Sonic	03/07/95	Groundwater monitoring
300-FF-5 Operable Unit (CERCLA)	699-S29-E16A	Sonic	09/06/91	Groundwater monitoring
	699-S22-E9A	Sonic	09/18/91	Groundwater monitoring
	399-8-5A	Sonic	10/09/91	Groundwater monitoring
300 Area	699-S40-E13A	Sonic	11/27/91	Groundwater monitoring
	699-S40-E13B	Sonic	11/22/91	Groundwater monitoring
	699-S40-E13C	Sonic	12/05/91	Groundwater monitoring
In Situ Bioremediation Demonstration	299-W11-33	Rotary/sonic	10/94	Characterization/ monitoring/injection
	299-W11-34	Rotary/sonic	10/94	Characterization/ monitoring
	299-W11-35(P,Q)	Rotary/sonic	11/94	Characterization/ monitoring
In-Well Vapor-Stripping Demonstration	299-W15-25	Rotary/sonic	01/95	Groundwater extraction
200-ZP-1 Operable Unit (CERCLA)	299-W15-29	Rotary/sonic	04/95	Injection
	299-W15-30	Rotary/sonic	05/95	Extraction
	299-W15-31A	Rotary/sonic	05/95	Extraction
	299-W15-32	Sonic/cable tool	06/95	Tracer testing
200-UP-1 Operable Unit (CERCLA)	299-W19-36	Sonic/cable tool	08/09/95	Injection
	299-W19-37	Rotary/sonic	08/29/95	Monitoring
	299-W19-38	Rotary/sonic	08/16/95	Monitoring
	299-W19-39	Sonic/cable tool	07/28/95	Extraction
	299-W19-40	Rotary/sonic	08/23/95	Monitoring
	399-B-2540 (temp)	Rotary/sonic	09/08/95	Monitoring
CERCLA = Comprehensive Environmental Response, Compensation and Liability Act of 1980.				
RCRA = Resource Conservation and Recovery Act of 1976.				

5.1 Objective 2

Objective 2 benefited from field activities conducted by Water Development Hanford, Inc. in fiscal years 1995 and 1996 through a contract with Bechtel Hanford, Inc. In support of Environmental Restoration Program investigations and remedial actions at the Hanford Site, several vadose zone- and groundwater-monitoring wells were drilled by Water Development Hanford, Inc. at many waste-disposal sites/areas. In addition, Water Development Corporation successfully drilled wells using the ResonantSonic® technology in many other locations, including California, Colorado, New Mexico, Indiana, and Texas. The Water Development Hanford, Inc. activities on Objective 2 for Bechtel Hanford, Inc. are summarized in Section 5.1.1.

A dynamic simulation tool was developed by Pacific Northwest National Laboratory in 1995 to simulate the ResonantSonic® drilling system under various geologic conditions and applications. The purpose of this design-based simulation tool was to identify operational behavior and predict loads in the drill string for various applications. Dynamic modeling efforts continued in fiscal year 1996 to refine the model analyses and were expanded to simulate additional drilling scenarios. The modeling results are discussed in Section 5.1.2.

The modeling effort was also to be used to evaluate instrumentation strategies for monitoring critical drill-string and system parameters. Instrumentation testing was conducted by Pacific Northwest National Laboratory and Water Development Hanford, Inc. in fiscal years 1995 and 1996 to explore instrumentation methods for improving ResonantSonic® drilling operations. The testing and results are discussed in Section 5.1.3.

Another element of Objective 2 was to model the drill-pipe thread joints. The most common failure of the drill string is the threaded connector that joins the 10-ft (3-m) sections of drill pipe. A recommendation was to continue to study the joint stresses using a finite-element model to investigate modifications to the threaded joint. The results of this investigation are discussed in Section 5.1.4.

In 1995, questions were raised regarding the possible influence of ResonantSonic® drilling on the productivity of hydrogeologic formations and on the physical and chemical characteristics of recovered core samples. To answer these questions, Westinghouse Hanford Company and Pacific Northwest National Laboratory jointly submitted an assembly of available data to an independent review panel. Records were taken from various projects at the Hanford Site. The review was to assist Bechtel Hanford, Inc. with the resolution of these concerns. Results of this independent review are discussed in Section 5.1.5.

5.1.1 Hanford Site Environmental Restoration Applications

In April 1995, Water Development Hanford, Inc. was awarded a multiyear contract for environmental drilling services by Bechtel Hanford, Inc. This contract covers the use of several drilling technologies, including sonic coring. Water Development Hanford, Inc. was the only entity to respond to the request for proposal on the use of sonic drilling.

The first task of this contract was initiated in early April 1995 for the installation of two large-diameter groundwater-extraction wells and one monitoring well to support the 200-ZP-1 Operable Unit pump-and-treat project in the Hanford Site's 200-West Area. This task utilized sonic-assisted air-rotary drilling and sonic coring to complete the wells. Between April and September 1995, Water Development Hanford, Inc. received over a dozen orders to support Bechtel Hanford, Inc.

Recently, Water Development Hanford, Inc. initiated the use of ResonantSonic® push technology to provide small-diameter accessways to expedite the characterization and remediation process. These small-diameter pushes have been cost effectively deployed through the boulder and cobbly geologic conditions of the 100 Areas.

Table 4.1 identified the sites where groundwater-monitoring wells were installed using the ResonantSonic® technique. The use of ResonantSonic® drilling and Water Development Hanford, Inc.'s field management resulted in documented invoiced cost savings of 25% and >50% reduction in time to install the wells.

5.1.2 Dynamic Modeling of ResonantSonic® Drill System

During 1993-1994, an instrumentation system was developed by Westinghouse Hanford Company to monitor output from the sonic drill head. The goal was to define boundary conditions of various operational parameters in the ResonantSonic® drilling simulator developed by the Colorado School of Mines. However, field tests conducted in December 1994 yielded data that could not be correlated, and unresolved questions existed with proposed options to modify the drill rig's instrumentation system. The primary uncertainties included which drill-rig parameters to measure, suitability of measuring instruments, and reliability of measurements during full-scale operations. Based on these concerns, it was decided to develop a design-based dynamic simulation of the ResonantSonic® drilling system and investigate alternative instrumentation schemes. The instrumentation schemes are discussed in Section 5.1.3.

The dynamic simulation was conducted by Pacific Northwest National Laboratory's Engineering Mechanics Group, beginning in April 1995. The fiscal year 1995 simulation results were useful but were limited because of uncertain modeling input parameters. In fiscal year 1996, the modeling effort was continued through the CRADA but was expanded to include the use of more realistic or field-measured modeling parameters and more example runs to simulate various drilling situations.

5.1.2.1 1995 Results

The 1995 analysis was performed using Analysis Systems (ANSYS®) finite-element code version 5.0, a large-scale, general purpose code for solving several classes of engineering analyses (Swanson Analysis Systems, Inc. 1994). This versatile code is capable of simulating the dynamic behavior of the ResonantSonic® drilling system under various operating conditions. The one-dimensional model developed for the analyses simulated the drill head with 100 ft (30 m) of 4.75-in.

(12.1-cm) drill pipe, which was modeled as truss elements. Boundary conditions were applied with only axial motion allowed along the length of the drill string. The top portion of the model was designed using a lumped mass with a harmonic load to simulate the force effects of the counterrotating rollers. A terminal impedance was applied to provide an approximate simulation of the stiffness and energy-absorbing characteristics of the geologic media in the vicinity of the drill bit. The model accounts for energy dissipation along the drill string. This was achieved by employing dampers distributed along the length of the drill string to simulate columnar friction, effects of structural damping, and energy dissipation from the relative motion at thread locations. The rationale for selecting values for the terminal impedance parameters was taken from Wolf (1988).

A series of three modeling analyses were performed in fiscal year 1995. The first analysis, model run A, was a steady-state frequency response of the drill string without dampers along its length. Also, no columnar friction or structural damping was considered. The second analysis, model run B, was identical to the first, except that dampers were considered along the length of the drill string to simulate structural damping. The third analysis, model run C, was a time-domain simulation, in which dampers were used along the length of the drill string and a gap was applied between the bottom of the drill string and the terminal impedance. These three modeling analyses were refined in fiscal year 1996; the results are discussed in Section 5.1.2.2.

The model developed in the fiscal year 1995 effort was useful for studying various aspects of the ResonantSonic® drilling technology. The amplitudes predicted from the modeling study for steady state are not unlike those observed in the field. However, it was apparent that uncertainties of modeling parameters needed to be verified by controlled field tests. Therefore, instrumentation field tests were conducted in fiscal year 1996 to provide the empirical data, as discussed in Section 5.1.3. Once the instrumentation testing was complete, additional dynamic simulations were performed in fiscal year 1996 to refine the model.

5.1.2.2 1996 Results

In fiscal year 1996, the modeling effort was continued through the CRADA and expanded to specifically include:

- use of field measurements on an instrumented head to determine such variables as damping and terminal impedance
- use of a more realistic head-support stiffness
- expanded series of example runs to simulate various drilling situations.

The field-testing portion of the fiscal year 1996 work is discussed in Section 5.1.3.

The modeling analyses were performed using upgraded version 5.2 of the ANSYS® finite-element code. The one-dimensional model developed for the analyses simulated both steady-state and transient modes. Just as in the fiscal year 1995 work, the model accounted for energy dissipation along the drill string, stiffness and energy-absorbing characteristics of the geologic media in the vicinity of the drill bit, and elastic and geometric properties of the drill string.

A series of ten modeling analyses under steady-state and transient conditions were performed, including the three fiscal year 1995 models. The dynamic loadings used for the three earlier models were found to be substantially underestimated, so they were redone in fiscal year 1996. The additional simulations were run with different drill-string lengths under various loading responses and parameter conditions. A summary of the simulations is presented in Table 5.1.

Table 5.1. Summary of Drill-String Simulations

Model Run	Loading Type	Parameter Conditions	Drill-String Configuration
A	Steady state	No dampers considered; no gap applied	100 ft (30 m) 20-ft (6-m) sections
B	Steady state	Dampers considered; no gap applied	100 ft (30 m) 20-ft (6-m) sections
C	Transient	Dampers considered; gap applied at bottom of drill string	100 ft (30 m) 20-ft (6-m) sections
D	Steady state	No dampers considered; no gap applied; top spring considered	100 ft (30 m) 20-ft (6-m) sections
E	Transient	No dampers considered; gap applied at bottom of drill string	100 ft (30 m) 20-ft (6-m) sections
F	Steady state	15% critical damping	100 ft (30 m) 20-ft (6-m) sections
G	Transient (68 Hz)	15% critical damping; no columbic damping	100 ft (30 m) 20-ft (6-m) sections
H	Steady state	15% critical damping	150 ft (46 m) 10-ft (3-m) sections
I	Transient (51 Hz)	15% critical damping; hold-down load applied	150 ft (46 m) 10-ft (3-m) sections
J	Transient (90 Hz)	15% critical damping; hold-down load applied	150 ft (46 m) 10-ft (3-m) sections

Results from model run A showed the presence of three resonances (15, 67.5, and 137.5 Hz). The mode shape at 15 Hz consisted of the entire drill string moving up and down in unison. The mode shape at 67.5 Hz consisted of the top and bottom of the drill string moving in opposite directions with a nodal point (point with no relative motion) located approximately one third the string length from the driver head. The mode shape at 137.5 Hz consisted of two nodal points with the top and bottom of the drill string moving in the same direction while the middle portion of the string moves in the opposite direction.

The model calculated that drill-string loads typically exceed applied load by a wide margin at resonant conditions. The model calculated that, at resonance, points along the drill string do not necessarily vibrate in phase with one another. Peak-to-peak bit displacements were 0.15 in. (0.38 cm) at 15 Hz, 0.36 in. (0.91 cm) at 67.5 Hz, and 0.44 in. (1.12 cm) at 137.5 Hz. Peak axial loads for the three resonant conditions were 13,000, 150,000, and 300,000 lb (6,000, 68,000, and 140,000 kg, respectively).

Results from model run B were similar to those from model run A. The addition of damping along the length of the drill string reduces displacements and drill-string force levels. In model run C, the addition of the gap element produced consistent results with what was expected. The peak-to-peak variation of force at the bit was approximately one third less than that for model run B. Results of the remaining analyses were consistent with those of model runs A and B for steady-state conditions and with those of model run C for transient conditions.

A comparison was made between string loads required to cause fatigue failures of a 4.75-in. (12.1-cm) threaded joint and drill-string loads predicted in the fiscal year 1996 modeling effort. The fatigue calculations were performed by Pacific Northwest National Laboratory during fiscal year 1994. At that time, Pacific Northwest National Laboratory did not have accurate drill-string loads to perform these calculations. Because fatigue failures were occurring, it was determined that assumed values of 32,000 to 67,000 lb (15,000 to 30,000 kg) would cause fatigue problems, depending on the thread design. The modeling results indicate that loads well in excess of this range can be generated if the drill string is operated close to resonant conditions.

The model developed in this effort was useful for studying various aspects of the drilling technology. Specific drilling aspects simulated included 4.75-in. (12.1-cm) dia. mid-body type drill pipe, vertical drilling in a cased hole, and terminal impedance governed by the geologic media of the drill site. The simulation results showed that the predicted amplitudes for steady operation are not unlike those observed in the field. Drilling with different pipe sizes, in angled holes, or in different geologic media would likely involve different terminal impedance and damping. It was recommended that additional field data be collected to determine modeling input parameters for a wider range of operating conditions.

5.1.3 Instrumentation Testing

Instrumentation system concepts for improving the operational efficiency and reliability of the ResonantSonic® drilling system were tested briefly in the field in fiscal year 1995 and then refined for further testing in fiscal year 1996. A significant portion of the fiscal year 1996 work was devoted to instrumentation and testing. Pacific Northwest National Laboratory's Engineering Mechanics Group performed engineering evaluations and consultation in cooperation with Water Development Hanford, Inc. to develop the instrumentation system.

5.1.3.1 1995 Results

As discussed in Section 5.1.2, a drill rig was instrumented in fiscal year 1994 to aid the operators and provide data to refine the Colorado School of Mines' ResonantSonic® drilling simulator. The instrumentation was selected to measure most of the physical parameters of the system and was made up of transducers and signal conditioners of reasonable quality. The instrumentation system was tested in the field for a short period in early fiscal year 1995.

The purpose of the early tests was to measure the most significant physical parameters that were readily measurable and to attempt to correlate the data with current operational experience and intuition. It was determined that the data were consistent but did not correlate well. Based on the results, the instrumentation system needed to be refined.

5.1.3.2 1996 Results

In fiscal year 1996, Pacific Northwest National Laboratory worked with Water Development Hanford, Inc. to continue to validate useful instrumentation concepts. An instrumentation work plan was developed to identify the scope and work schedule. The plan was to provide a work scope that provided the most direct improvement in the operation of the sonic drill.

The instrumentation concepts included a load cell and accelerometer installed in the sonic head. Data collected from the load cell can give the operator a feedback mechanism for loading the drill string. An accelerometer can give the operator mechanical vibration information from the drill string and drill rig itself. The information can provide the operator better insight into the behavior of the ResonantSonic® drilling system, allowing for fine tuning of the drilling rig controls and parameters in real time.

A series of three instrumentation tests were conducted in early May 1996 at Water Development Hanford, Inc.'s Drilling Technology Test Site near the main entrance to the 200-West Area (see Figure 3.1). This area contains sand and gravel formations typical of the Hanford Site. The tests were conducted using a 4.75-in. (12.1-cm) dia. drill pipe lowered into a 9-in. (22.9-cm) dia. cased hole previously drilled to a depth of 100 ft (30 m).

During the first phase of testing, a series of tests were conducted while the drill string hung freely in the cased hole. This was to determine the effect of structural damping as the frequency approached the resonance of the drill string. The drill pipe was then advanced into the formation below the bottom of the cased hole, and data were acquired for the second phase of testing. The results indicated that the signal-to-noise ratio for most of the instruments was not adequate, thus providing unreliable data.

To overcome this problem, a third series of tests were implemented at the site. An additional accelerometer with an adjustable gain was installed on the rig to verify the operation of the fixed gain accelerometer installed for the second series of tests. Data were collected while the drill bit was advanced beyond the bottom of the cased hole.

The load cell provided valuable data that indicated moderate periodic loads while the drill string maintained good penetration rates and very high, short-duration loads when the drill stopped penetrating. Figure 5.1 shows the periodic load condition at 65 Hz with a penetration rate of 5 ft/min (1.5 m/min). The net offset indicates a pull-down force of 4,000 to 6,000 lb (2,000 to 3,000 kg) and a dynamic load of $\pm 10,000$ lb ($\pm 5,000$ kg). After the drill bit stopped advancing, the load pattern changed dramatically. The load pattern (Figure 5.2) shows impulse loads exceeding 200,000 lb (90,000 kg) for 2 to 5 ms. These high loads can damage drill pipe very quickly.

Two load-instrumentation concepts to provide continuous load data to the operator are workable with the sonic drill. One uses a piezoelectric load transducer implanted in the oscillator head. The other uses a more typical strain gage transducer in series with the drill string. The strain gage load cell offers most of the advantages of the piezoelectric transducer without the need to partially redesign the oscillator housing. An instrumentation system using one of these concepts would provide the operator with loads experienced by the drill string in real time. This would allow the operator to know when to reduce excessive loads to limit damage to the drill string.

Data collected with the adjustable gain accelerometer provided valuable information for the validation of the dynamic model. In addition, the spectra data contained baseline information for determining the mechanical vibration signature of the sonic drill head. Figure 5.3 shows the spectrum (magnitude of frequency response versus frequency [dBVrms]) for the periodic load condition and Figure 5.4 shows the spectrum after the drill bit stopped advancing. These plots represent a signature of each of the operating conditions.

Signature analysis is a technique that was developed to analyze the behavior of large, rotating machinery and is the suggested technique for a maintenance program for the sonic drill. The technique holds promise for minimizing unscheduled downtime and relatively costly equipment failures during sensitive operations. Components of the instrumentation system to employ this technique include an accelerometer, a signal conditioner for the transducer, and a Fast-Fourier Transform analyzer. The analyzer provides a real-time frequency-domain plot of the dynamic behavior of the system and is used to record a "signature" frequency spectrum under normal operating conditions. New spectra can then be compared to the "signature" to indicate changes in the behavior of the system. This technique allows the operator to recognize familiar trends and helps predict operational problems.

Figure 5.1. Periodic Load Waveform While Drilling (1 kip = 1,000 lb)

Figure 5.2. Impulse Loads when Drill Bit Stops Advancing (1 kip = 1,000 lb)

Figure 5.3. Vibration Spectrum from Accelerometer on Drill String

Figure 5.4. Vibration Spectrum with Drill String Stopped at ~110 ft (34 m)

5.1.4 Modeling Analysis of Drill-Pipe Threaded Joints

A concern of the ResonantSonic® drilling method involves failure of the drill string. The most common failure is in the threaded connector that joins sections of drill pipe. A recommendation made in 1994 on stress levels and joint fatigue strength was to investigate modifications to the threaded joint. In 1996, several modifications of the threaded joint were investigated using the ANSYS® general finite-element analysis. The model was two-dimensional and axisymmetric. A 4.75-in. (12.1-cm) outside diameter drill string was selected for the analysis. Five different drill-pipe thread-joint designs were analyzed: pin contact, shoulder contact, simultaneous contact, full contact, and modified full contact.

Three load cases were considered for each analysis. The first case was the joint assembly torque. Actual data were not available, so the joints were loaded so as to give an approximate peak stress of 67% of the yield strength or 94,000 lb/in.² (6,600 kg/cm²). This loading was achieved by creating the mesh such that the male threads overlapped the female threads. Equilibrium was achieved by resolving the contact surface penetration and developing stresses throughout the model.

The next two load cases considered were compression and tension through the joint. These are representative of the peak loads on the joint during the cyclic operation of the drill. A 5,000-lb/in.² (400-kg/cm²) load was applied in both the compressive and tensile directions. This corresponds to a 33,000-lb (15,000-kg) axial force. The stress results from these load cases were used in the fatigue calculations.

Figure 5.5 shows the finite-element mesh used for the analysis of the pin contact configuration. This joint is designed such that the end of the pin makes contact with the bottom of the box on the assembly. Figure 5.6 shows the von Mises stress resulting from assembly torque. The peak stress occurs in the region at the end of the pin where it makes contact with the box. Figures 5.7 and 5.8 show the stress at the peak compressive and tensile load, respectively. The magnitude and distribution of these loads differ little from the assembly stress levels in Figure 5.6. This suggests that the alternating stress is low and that the fatigue factor will be governed by the mean stress.

Fatigue factors for the thread-joint designs are 0.72 for pin contact, 1.24 for shoulder contact, 1.02 for simultaneous contact, 1.36 for full contact, and 1.25 for modified full contact. Figure 5.9 shows the distribution of the fatigue factor for the pin contact design. The peak value of 0.72 occurred in the root of the first thread in the box. This value indicates that this joint should not fail in fatigue at these load levels.

The results showed that the pin contact configuration is the best design based on the fatigue factor. However, this joint design transmits only 14% of the maximum load allowed in the drill string based on yielding of the connecting tube.

Figure 5.5. Pin Contact Element Plot

Figure 5.6. Pin Contact Von Mises Stress - Assembly Torque

Figure 5.7. Pin Contact Von Mises Stress - Compression

Figure 5.8. Pin Contact Von Mises Stress - Tension

PLOT NO. 1
 NODAL SOLUTION
 STEP=9999
 SEQV (AVG)
 DMX =.255E-07
 SMN =.001585
 SMX =.717976
 .001585
 .1
 .2
 .3
 .4
 .5
 .6
 .7

Figure 5.9. Pin Contact Fatigue Factor

5.1.5 ResonantSonic® Drilling Impacts on Sample Quality and Hydrogeologic Formation Properties

A technical review panel, formed by the Plumes Focus Area Technical Team, was requested by the Hanford Site Technology Group to review the ResonantSonic® drilling technology to answer questions raised regarding the technology. The purpose of the review panel was to assist Bechtel Hanford, Inc. in the evaluation of the technology's possible impact on the physical and chemical characteristics of recovered core samples and on the productivity of hydrogeologic formations as a result of unrecoverable formation damage. The review panel consisted of recognized experts in the fields of drilling, hydrogeology, geology, and geophysics.^(a) The review was initiated on March 12, 1996 and concluded on April 11, 1996.

After the data were reviewed and conclusions drawn, recommendations were made by the review panel to conduct controlled field experiments if quantitative information on the quality of ResonantSonic® sampling were required. Formation damage caused by the different drilling methods and the effectiveness of well development associated with each drilling method could also be assessed in a controlled field test. It was recommended that direct side-by-side field testing be conducted in two adjacent wells: one drilled by the ResonantSonic® method and the other drilled by the cable-tool method.

5.1.5.1 Sample Quality

One objective of the review was to compare the ResonantSonic® core-sampling technique to other sampling methods, including the cable-tool drive barrel, the split-spoon sampler, and the Shelby tube. However, after reviewing all pertinent data, the review panel concluded that there were insufficient data to preclude the use of ResonantSonic® sampling, depending on the data quality needs. It was believed by the panel that ResonantSonic® sampling is comparable to other percussion sampling methods.

Four areas that could potentially affect the quality of the ResonantSonic® core samples were identified:

- development of excessively high temperatures during sampling
- recovery of a longer column of material in the barrel than can be accounted for in the interval advanced

(a) Review panel consisted of James H. Cobbs (Cobbs Engineering), Cliff Farrell (Bechtel Corporation), Carol Eddy-Dilek (Westinghouse Savannah River Company), and Norman Harthill (Blackhawk Geosciences).

- distortion and/or disassembly of the sample structure
- development of a "rind," apparently resulting from sheared material, on the outside of the sample.

Only the development of excessively high temperatures was unusual compared to other sampling methods. The documentation indicated successful efforts to control these temperature effects by various means. Other than the temperature problem, the reviewed information did not demonstrate unique problems with ResonantSonic® sampling that are not found with other percussion-type sampling.

It was determined that sample quality assessments have been subjective and qualitative and that there was a general lack of documentation on how the samples were collected, for what purpose, and the degree to which samples met the data objectives. Therefore, it was concluded that the reviewed documentation was insufficient to quantify differences between the various sampling methods and drilling techniques.

Based on a consensus of the review panel, a relative ranking of the effectiveness of different types of sampling methods to minimize sample disturbance for various formations is presented below.

For deliberately controlled sampling:

- in consolidated material, rotary coring provides the least-disturbed samples, while split-spoon samples (either driven by ResonantSonic®, cable tool, or drive hammer) would be the most disturbed
- in unconsolidated, fine-grained material, a Shelby tube provides the least-disturbed samples, followed by split-spoon sampling (either ResonantSonic® or other percussion method)
- in unconsolidated, coarse-grained material, small, discrete, split-spoon samples (either ResonantSonic® or other percussion method) are best.

For sample materials (drill cuttings) collected while penetrating but with major stratigraphic control desired:

- continuous coring dual-tube drill pipe reverse circulation, ResonantSonic® continuous core (including long split barrel), and cable-tool drive barrel are best, followed by air rotary, and finally, by cable-tool hard tool.

Based on findings of the review panel, it was recommended that 1) definitive information be acquired on the ResonantSonic® sampling method that details the degree to which the samples provide the type and quality of data for which they were collected; 2) a systematic procedure be developed for reporting the conditions during sample collection so that sample quality assessments can be made; and 3) if quantitative information is required, controlled field testing be conducted to determine the most appropriate and effective sampling method.

5.1.5.2 Hydrogeologic Properties

Some wells installed at the Hanford Site using the ResonantSonic® drilling method did not yield expected production rates. It has been suggested that the ResonantSonic® drilling method caused formation damage and/or reduced formational permeability to yield the apparent low productivity. However, other factors can cause low yields, including geologic heterogeneities, inappropriate well design, poor well-completion practices, and inadequate well development. Because of these factors and the available documentation, the review panel determined that there is insufficient evidence to conclude that ResonantSonic® drilling causes irrecoverable formation damage. More documentation is needed from wells drilled by the ResonantSonic® method before any evaluation of formation damage effects can be made.

It was recommended by the review panel that additional hydrologic testing, designed specifically for examining formation damage (skin effects), be conducted in existing extraction wells. The panel recommended that a controlled field experiment be conducted by installing one well using the ResonantSonic® drilling method and installing another well using the cable-tool method, both installed adjacent to each other in similar hydrogeologic conditions. The wells would be installed under controlled conditions and with proper documentation to ensure good well design, completion, and development. Hydrologic testing (i.e., variable stress-level slug tests and/or slug interference tests along with the diagnostic use of pressure derivatives) designed specifically to address skin effects would be conducted in the wells to assess formation damage and to evaluate the effectiveness of well development. An independent method, such as borehole geophysics, should be used as a control to define the hydrogeologic conditions of the zone to be tested. The panel also recommended that records of the time and costs be kept on the drilling and development of these wells to examine the cost tradeoff between a rapidly drilled well (and the time required to develop the well) versus a slowly drilled well (and its time required to develop the well). Specific details of the controlled field test were suggested to be included in a prepared test plan.

5.2 Objective 6

Objective 6 was to determine the effect of ResonantSonic® drilling on nearby buried structures (e.g., underground storage tanks). Field activities for Objective 6 were completed in November 1994 and are discussed in the Phase II report (Cassem 1995). The drill was field tested at the Hanford Site. The ResonantSonic® field test results were evaluated and correlated with computer analysis results in fiscal year 1995.

5.2.1 Vibration Analysis

Soil vibration tests were conducted by ICF Kaiser Engineers Hanford in November 1994 to determine the effects of vibration shock waves produced by the ResonantSonic® drill on nearby buried structures. The purpose is to determine how close a ResonantSonic® drilling operation can be placed to that

structure without adversely affecting its integrity. Information on accelerations of the soil was gathered from two downhole instrumented boreholes located 10 to 20 ft (3 to 6 m) from the drill hole, which reached 60 ft (18 m) in depth. Each hole was constructed with polyvinyl chloride pipe to a depth of 60 ft (18 m) and contained 7 triaxial accelerometers per hole that fed vibration (wave) information through digital oscilloscopes to personal computers. A total of 42 channels of data were collected with 6 computers. A detailed discussion of the field testing is reported in Cassem (1995).

The maximum acceleration recorded during the field test was $<0.2 \text{ in./s}^2$ ($<0.5 \text{ cm/s}^2$). For most of the data, the frequency of vibration was recorded as $\sim 105 \text{ Hz}$, which matches the drill head frequency of vibration. There was some inconsistency in the precise time that data were collected from each computer.

The sonic drill was modeled with a soil-structural-interaction model called SASSI (a System for Analysis of Soil-Structure Interaction). Although the SASSI analysis model is similar to the field test, it is a viscoelastic model that cannot simulate the contact and friction effects at the bottom of the drill hole. The finite-element model resulted in small accelerations at the 10- and 20-ft (3- and 6-m) locations of the instrumented holes. The modeled accelerations were larger than the measured test data by a factor of 70. However, some of the test data saturated some of the channels on the recording instrumentation, indicating that magnitudes of acceleration were higher than could be recorded.

The analysis and testing results showed small soil accelerations at the given distances, indicating that there is no cause for concern in using the sonic drill next to buried structures. The conservative analysis case yielded a horizontal maximum acceleration of 0.04 g , which is much lower than the existing waste tank seismic analyses of 0.2 and 0.39 g at the Hanford Site.

6.0 Conclusions and Recommendations

The ResonantSonic® drilling method is able to rapidly penetrate Hanford Site geologic formations. Rapid penetration can be cost effective, assuming that the well-design objective has been met. Wells were installed in record time and at considerable cost savings per well (Cassem 1995).

The ResonantSonic® drilling method has the following advantages:

- installs wells at any angle from 15 degrees off horizontal to vertical
- decreases well-drilling and completion time, resulting in lower cost for wells installed successfully according to the well-design objective intended
- handles wide range of casing sizes for various types of wells or observation points

- minimizes generation of cuttings and contains waste
- penetrates Hanford Site's semiconsolidated sands, gravels, and cobbles without the addition of circulating media
- obtains intact, recoverable core samples for field or laboratory analyses.

The ResonantSonic® drilling method has the following limitations:

- requires more operator experience to run the drilling system
- creates potential damage by vibrational effects to steel pipe, requiring more frequent maintenance of the drill string and enhanced rig control by the drilling operator.

The soil vibration analysis showed measurable, but small, soil accelerations, indicating that there is no cause for concern in using the sonic drill next to buried structures. As with all drilling technologies, formation damage and/or reduction of formation permeability and porosity immediately surrounding the borehole may not be completely recoverable. This is important if the purpose of the well is characterization of the surrounding formation or aquifer yield.

The following improvements to achieve additional benefits are recommended:

- monitor instrumented drill rig for several months during routine operations to observe critical parameters and system performance and to compare results with computer simulations over a wider range of drilling applications
- develop and demonstrate the ResonantSonic® drilling simulator as a predictive tool
- conduct controlled field testing to evaluate the ResonantSonic® drilling method's influence, compared to the cable-tool method, on sample quality and on hydrogeologic characteristics of formations if a quantitative comparison is needed
- explore SASSI or other applicable model to simulate compaction/consolidation effects induced by ResonantSonic® drilling in formation materials surrounding the borehole and, thus, evaluate the extent of potential permeability and porosity reductions.

Evidence of the success of this technology has been shown by the multiyear contract awarded to Water Development Hanford, Inc. by Bechtel Hanford, Inc. to install vadose zone- and groundwater-monitoring wells in support of the Hanford Environmental Restoration program.

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