Final Scientific / Technical Report

“A Heliportable Sonic Drilling Platform for Microhole Drilling and Exploration”

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Building Value through Discovery & Innovation

Principal Investigator

Peter A. Lucon

130 North Main Street

Suite 600

Butte, MT 59701

(406) 497-5212

plucon@resodyn.com

Authorized Representative

Lawrence C. Farrar

130 North Main Street

Suite 600

Butte, MT 59701

(406) 497-5252

lcfarrar@resodyn.com

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SIGNIFICANCE, BACKGROUND INFORMATION, AND TECHNICAL APPROACH

1.1 Identification and Significance of the Problem or Opportunity, and Technical Approach

1.1.1 Introduction

Exploration and development of new energy resources in remote and environmentally sensitive areas can benefit greatly from a reduction in the size of drilling equipment and the associated equipment for its operation. In particular, microhole sonic drilling technology can significantly reduce costs for: 1.) drilling equipment size, 2.) well construction, 3.) placement of subterranean instrumentation and 4.) exploratory drilling costs. The ultimate goal of the project is to provide reliable, small footprint, instrumentation deployment systems that can operate at lower costs and in environmentally sensitive areas that are not accessible to conventional drilling systems. Sonic drilling, combined with an advanced control technology, termed **ResonantSonic Tracking™ (RST™)** is proposed as a method to meet the DOE requirements.

Sonic drilling, Figure 1, is an advanced drilling technique having great advantages for obtaining relatively undisturbed core samples that are needed to gather subterranean environmental data. By being able to extract core samples without cutting/grinding the soil as is done when using a rotary drill, provides a drilling method to establish a “true,” or undisturbed profile of the subterranean geology. In addition, sonic drilling is valuable and uses a unique method for the minimization, or even elimination, for the use of drilling fluids, or the production of cuttings that are brought to the surface as ground penetration occurs. However, the sonic drilling process is highly complex and, as such, requires unique and advanced operator skills. Moreover, the depth that current sonic drilling methodology is usable is limited, with practical drilling depths not exceeding 1,000 feet (Boart, 2002). The DOE and industry have expressed a need for microhole drilling up to 1,500 feet, as well as increased depth capabilities for conventional sonic drilling technology (DOE 2005). Moreover, in addition to the advantages specified above, for many lithologies, sonic drilling penetration rates can be 2 to 3 times greater than achievable using auger systems.

Figure 1. Resonant Sonic Drilling

1.1.2 Sonic Drilling Background

Sonic drilling is a unique drilling process and differs significantly from the conventional drilling methods. The sonic drill head imparts low-frequency, high-force vibrations to the drill string at its resonant frequency to effectively penetrate virtually any formation. Sonic drilling gains its advantage over conventional drilling techniques by essentially establishing a “resonant condition” on the steel drill string in phase with the other waves to create a “standing wave” as shown in Figure 1 above. In this resonant condition, each induced energy pulse is exactly

superimposed on each reflected energy pulse wave. In the standing wave condition of resonance, the drill string expands and compresses causing the drill string to dilate and contract over its length with each alternating phase. The net effect is that the drill string is capable of accepting the maximum power from a sonic drill head and delivering that power directly to the drill bit.

As presented above, sonic drilling is enabled by the use of mechanically-driven sound energy to put the drill string into resonance. The value of a resonating drill string is that large amounts of energy can be concentrated at the drill string bit to create strong penetrating forces. Moreover, the sonic drilling process also causes the entire drill string to vibrate. The typical vibration frequency of the drill string, nominally 60 to 200 Hertz, essentially decouples the drill string from the surrounding soil, enabling the drill string to see relatively low friction forces as it penetrates the earth (Bernat, 1997).

However, the key to being able to successfully, and efficiently drill holes in the earth, it is essential to keep the drill string at resonance throughout the entire drilling process. There exists a complex relationship between the drilling parameters and the resulting drilling penetration rate. This complex relationship affects the power utilization efficiency, as well as the ability of the drill string to penetrate the earth. In addition, the collective factors for drill string penetration are also a function of both the drilling process conditions and the subterranean geophysical conditions. Because of the complexity of coupled factors, and lack of information (measurements of the drill string performance), even the most skilled technicians cannot obtain optimal performance from the sonic drilling system. ***In fact, findings from the work undertaken in this project show that measures that need to be taken to fully enable sonic drilling for maximum performance and efficiency are counterintuitive. Hence, would not even be implemented by skilled operators.*** As such, there is a compelling need for an automated control system to maintain the drill string at optimal sonic drilling operation.

The need for automated sonic drilling control has been previously identified and efforts to provide automated control have been attempted, but have been unsuccessful (Barrow, 1995). However, it is significant to note that these previous efforts have not been attempted using a fundamental understanding of the parameters involved, either physically, or analytically. Hence, the goal to develop a much-needed, automated drilling methodology for sonic drilling was heretofore unachievable. The RST™ technology approach differs by establishing a fundamental understanding of the resonant system, from which dynamic analytical models to use in quantifying all aspects the resonant system were assembled.

1.1.3 Overall Technical Approach to Achieve the Opportunity

Efficient and productive use of sonic energy for drilling requires that the drill string be operated at resonance. As mentioned above, there are several parameters that contribute to the drill string resonance. Fortunately, the sonic drilling system can be analytically modeled with the appropriate boundary conditions applied. In addition, using the analytical model and the proper instrumentation, it has been determined that a methodology can be developed to automatically control and optimize the sonic drilling process. In order to lay the groundwork for the validity of RST™ technology approach as an automated sonic drilling control technology, some theoretical background information is provided below.

1.1.4 Basic Theory of a Resonating-Sonic Drilling System

An initial principal to be established in these discussions is that the concept of a resonating system has mechanical advantages, which can be utilized to do useful work. This development will start off with the introduction of a generalized, single degree of freedom system, then the analysis can be further expanded for the application of sonic drilling.

1.1.4.1 Single Degree of Freedom System

A resonant system is said to be on resonance when the input power is being directly transferred to the damping of the system, without expending energy within the system itself. This occurs at particular frequencies where the inertial forces counter the stored energy forces generated by the motion. The resonant condition is best described by the use of a single degree of freedom system, which is also a typical lumped parameter system. The single degree of freedom system, described in Figure 2, has a single mass coupled to the ground through means of a spring and a damper. The spring has a spring constant 'k' that defines the springs' resultant force when compressed or elongated. The damper has a damping constant associated with it that defines the resultant force when the damper is being compressed or elongated at some velocity.

Figure 2. Single Degree of Freedom System

Equation 1. Governing Differential Equation

$$m \cdot \frac{d^2}{dt^2} x(t) + c \cdot \frac{d}{dt} x(t) + k \cdot x(t) = F_o \cdot \sin(\omega_f t)$$

Inertia Forces
Damping Forces
Stored Forces
Input Forces

By analyzing the diagram displayed in Figure 2 and drawing the corresponding free body diagram, displayed in Figure 3, the governing differential equation (GDE) of motion, depicted in Equation 1, can be derived from Newton's second law of motion or force balance, shown by Equation 2. Newton's second law states that the force acting on an object is equal to its mass multiplied by its acceleration. The governing differential equation relates all the known system constants to the input force through means of the resultant motion of the system 'x(t)'.

Figure 3. Free Body Diagram

Equation 2. Newton's Second Law

$$\sum F = m \cdot a$$

Equation 3. Motion Solution

$$x(t) = X \cdot \sin(\omega_f t + \phi_d)$$

The input force is sinusoidal, so the resultant solution x(t) is also assumed to be sinusoidal, displayed in Equation 3, where 'X' is the displacement amplitude, ' ω_f ' is the input forcing frequency, 't' is the time, and ' ϕ_d ' is the phase angle offset between the input forcing sinusoidal function and the displacement. The assumed solution, Equation 3, is then placed into the governing differential equation (GDE), Equation 1, and the resulting equation is shown in Equation 4. By examining Equation 4 it can be observed that there will be a particular frequency in which the inertia forces, caused by the mass, will directly offset the

stored force, established by the spring. This frequency is the undamped natural frequency ' ω_n ' of the system and can be found to have the relation, shown

in Equation 5, the square root of the spring rate divided by the mass. At the systems undamped natural frequency ' ω_n ' the phase angle between the input force and the spring force is always - 90 degrees. This condition makes the damping forces in phase with the input forces.

In order to examine the resonant system, the GDE must be solved and the solution must be analyzed. By applying trigonometric relations to the manipulated GDE, Equation 4, the displacement amplitude ' X ' and phase angle ' ϕ_d ' are found, displayed in Equation 6 and Equation 7, respectively. From these two relations if the damping constant is very large, then it will override the inertia and spring effects and not allow the system to utilize the input force to perform work onto the system. In other words, as the damping constant ' c ' in Equation 6 gets larger, the displacement amplitude ' X ' gets smaller. This allows less energy to be utilized by the system damper. An analogy to this is the larger the resistor to be placed into an alternating current (AC) circuit, at constant voltage amplitude, the less flow of electrons it will allow, thus using less power through the resistor. In order to more easily quantify when the damping will take control of the system a damping ratio ' ζ ', displayed in Equation 8, will be defined as the ratio of the damping constant ' c ' to the critical damping value ' c_{cr} '. The critical damping value ' c_{cr} ' is found as the value of damping that will not allow the system to oscillate during a transient situation. The transient vibration frequency, ' ω_d ', or damped natural frequency, is found by the relation displayed in Equation 9. As the damping ratio approaches one, ω_d approaches zero. However, this is not the frequency where the max displacement occurs for a forced system. By taking the derivative of Equation 6, and solving for zero, the max displacement amplitude, displacement frequency ' ω_M ', displayed in Equation 10, is found. ω_M is real only when ζ is greater than one half of the square root of two. If ζ is large enough so that ω_M is zero or imaginary then X is maximized only at zero input frequency.

Equation 4. Manipulated GDE

$$\underbrace{-m \cdot \ddot{X}}_{\text{Inertia Forces}} + \underbrace{c \cdot \dot{X}}_{\text{Damping Forces}} + \underbrace{k \cdot X}_{\text{Stored Forces}} = \underbrace{F_0 \cdot \sin(\omega_f t)}_{\text{Input Forces}}$$

Equation 5. Undamped Natural Frequency

$$\omega_n = \sqrt{\frac{k}{m}}$$

Equation 6. Displacement Amplitude

$$X = \frac{F_0}{\left[\left(k - m \cdot \omega_f^2 \right)^2 + c^2 \cdot \omega_f^2 \right]^{0.5}}$$

Equation 7. Phase Angle

$$\phi_d = \tan^{-1} \left(\frac{c \cdot \omega_f}{k - m \cdot \omega_f^2} \right)$$

Equation 8. Damping Ratio

$$\zeta = \frac{c}{c_{cr}} = \frac{c}{2 \cdot m \cdot \omega_n}$$

Equation 9. Damped Natural Frequency

$$\omega_d = \omega_n \cdot \sqrt{1 - \zeta^2}$$

Equation 10. Max Amplitude Frequency

$$\omega_M = \omega_n \cdot \sqrt{1 - 2 \cdot \zeta^2}$$

Current sonic drills are powered by eccentric driven oscillators. The eccentric creates the input force in the direction outward from the axis of rotation through the eccentric mass as shown in Figure 4.

Figure 4. Rotating Eccentric Mass

Equation 11. Eccentric Force Magnitude

$$F_{ecc} = m_e \cdot R \cdot \omega_f^2$$

The force that is generated onto the supporting structure equals the inward acceleration 'A_N' multiplied by the eccentric mass 'm_e', shown in Equation 11. The force vector is going around the axis of rotation so in order to only have the force vector in a linear direction a second eccentric that is counter rotating, must be applied to the same supporting mass thus cancelling out all unwanted lateral forces and reinforcing the wanted axial forces. Because the sonic drills are typically driven by eccentrics the GDE changes to include the input force as the force amplitude. By analyzing the same single degree of freedom system displayed above in Figure 2, with a similar forcing function, for the sonic drill system will give an accurate representation of the sonic drill system performance. The sonic drill equations can be derived by following similar steps as described above.

1.2 Anticipated Public Benefit

1.2.1 Technical, Economic, Social and Other Benefits

Geophysicists are always looking for ways to reduce the costs associated with deploying seismic instrumentation. Seismic instrumentation in the subsurface yields many benefits including reduced noise, reduced travel paths, and greatly improved signal-to-noise ratios. Using conventional well construction is too expensive for solely monitoring, and production wells are generally too noisy for gathering quality data. The development of an environmentally-friendly microhole drilling system capable of being deployed to remote locations will be of a great benefit to geophysical exploration. The use of microholes in exploration efforts can improve conventional reflection surveying, locating sources of natural seismicity, vertical seismic profiling (VSP), and cross-well imaging capabilities.

In addition to the above benefits, one Phase I reviewer stated that: "The new helicopter transportable system market is literally untapped, due to the lack of equipment to that has a small footprint, The helicopter portable sonic drilling system will open up opportunities to produce a small footprint, easily portable drilling system that should impact the environment much less than current drilling technology. This can then be used as exploratory rig to test geologic formations at much less cost than conventional portable small drilling rigs."

1.2.2 Commercial and Federal Sector Benefits

Carbon-Sequestration -- A likely application for inexpensive microhole well monitoring is in the implementation and management of carbon-sequestration. Microhole wells could be used for monitoring the carbon injection and long-term storage of CO₂ in depleted reservoirs. In the short term, this will support efforts for enhanced oil recovery (EOR) and eventually sequestration as a possible national policy solution in response to global warming. In a recent economic analysis performed for the National Energy Technology Laboratory, two cases for carbon sequestration combined with oil recovery were considered (DOE, 2005). As shown in

Table 1, the results suggest that if CO₂ sequestration is pursued by the U.S., nearly 12,700 million tons of CO₂ would be sequestered, 26,000 million barrels of incremental oil reserves would be recovered, and thousands of monitoring wells would be required.

The cost of the monitoring wells may be one of the greater barriers to a more widespread use of VSP for implementation of CO₂ in increased oil recovery (IOR). To properly monitor the movement of the CO₂ and oil bank within a reservoir, between three and five surveys are required, each costing \$400,000 (DOE, 2005). Reducing the construction cost of the monitoring well will make VSP more affordable for IOR projects and help it become the monitoring tool of choice for sequestration.

Coalbed Methane Basins (CBM) -- At least 25 native Alaskan communities have been identified as potential sites for coalbed methane production, as an alternative to paying for diesel-generated, state-subsidized electricity at rates that are three to ten times greater than the national average (Clough, 2000). According to economic studies (Foster, 1997), the current high costs associated with the site preparation, transportation of equipment, rig mobilization, and operating costs only present a marginal economic case for developing CBM at remote Alaskan locations. It is estimated that nearly 250,000 lbs of drilling, well-completion, and logging equipment is required for exploration at any given Alaskan site (Ogbe, *et al.*, 1998). Developing a less costly and environmentally benign drilling system will enable greater exploration, characterization, and development of these natural resources for economic benefits.

New Methodology for Hydrocarbon Exploration

Borrowing from the Phase I review comments: *"System developed should open new opportunities for exploration of hydrocarbons resource and lessen the impact on the environment. Create a new market with vast application potential in remote, low cost, shallow microhole drilling."*

1.2.3 Significance of the Market

The sonic drilling market includes applications for microhole drilling, installation of microprobes, well drilling and pile driving. In addition, the sonic drilling market growth is expected to be enhanced by increasing interest in microhole drilling for:

- Delineation of spillage "plume" prior to excavation or remediation
- Environmental site assessments
- Installation of monitoring or recovery wells
- Geotechnical investigations
- Piezometer installation
- Wellpoint installation
- Lightning conductor installation
- Seismic exploration
- Mineral exploration

The conventional sonic drilling technology retrofit market for the ResonantSonic Tracking™ (RST™) technology has not been comprehensively assessed, but our preliminary market assessment has pegged the potential installed base market for the technology at about 350 sonic drilling rigs worldwide. The large international players are Boart Longyear, who have just over 100 hundred pieces of sonic drilling equipment worldwide, and SonicSampDrill with about 50 units around the world. SonicSampDrill is represented in North America by Sonic Sampling & Supply, LLC, Woodacre, CA.

In addition to the “traditional” sonic drilling market potential, the technology offers an opportunity for a new market that has been identified by the US DOE in the formulation of the requirements in the RFP: *“Current Sonic rigs are limited to drilling depth of approximately 500 feet in depth. The proposed system should not require use of significant volumes of drilling fluid (mud or air). The ultimate purpose of these efforts is to provide reliable, small footprint, instrumentation deployment systems that can operate at lower costs and in environmentally sensitive areas no previously accessible to conventional drilling systems.”*

As one Phase I reviewer stated: *“Low impact exploration drilling systems are a critical niche drilling market because there have not been viable systems to fill the need and that can drill to reasonable depths. The market is not only hydrocarbon exploration but also mineral exploration. The current market is limited, proposal offers a usable viable system that opens opportunities to wide spread use and a market in the hundreds of millions of dollars of sales per year.”*

1.3 Degree to which Phase I has Demonstrated Technical Feasibility

This section provides an overview of the Phase I work, starting from the project purpose, then presenting the project objectives, followed by a presentation of the work that was conducted to achieve the objectives. In addition results are summarized to provide an argument that the Phase I project resulted in demonstrating feasibility of the technology.

1.3.1 Purpose of the Phase I Research

The Phase I research was designed to prove the feasibility of the Heliportable Microhole Sonic Drill that can drill to depths of 1,500 feet. This capability will greatly benefit the exploration and development of the new energy resources in remote and environmentally sensitive areas by reducing the drilling operation size and cost of well construction. The ultimate goal of the project is to provide reliable, small footprint, instrumentation deployment systems that can operate at lower costs and in environmentally sensitive areas not accessible to conventional drilling systems.

1.3.2 Phase I Project Objectives

The Phase I objective of this project was to demonstrate the feasibility of ResonantSonic Tracking™ to enable the development of a helicopter-portable sonic microhole drilling system capable of deploying seismic instrumentation to depths of 1,500 feet. Specific objectives to be achieved in the Phase I work (taken verbatim from the Phase I proposal) are:

Objective 1: Establish the instrumentation and methodology (algorithms and software) to automatically maintain the drill string in resonance (operate at maximum efficiency) throughout the drilling process. The following questions must be addressed:

- Can we accurately maintain the resonant frequency of a drill string that varies in length and impedance?
- Can we determine the damping characteristics of the drill string along its entire length?
- If locations of high damping are identified, can we change the operating frequency in order to reduce the damping in the affected area?

Objective 2: Include modular design features in the sonic drilling system that allow it to be

helicopter transportable and field assembled at remote sites. The following questions must be addressed:

- Is the system capable of having modules weighing less than 4,000 lbs. each?
- Can the entire drilling operation with all its modules weigh less than 32,000 lbs?
- Can we reduce the cost of drilling sonic-drilled microholes to between 30% and 50% of the cost of conventional drilling systems?

The project objectives were fully achieved and the salient questions posed were addressed. As will be proven below, the methodology discovered to achieve the positive outcome were found to be counterintuitive and counter to conventional practice. These important findings, coupled with the development of a comprehensive model of the sonic drilling process, provides a solid platform for successful development of a commercial technology as an outcome of Phase II.

1.3.3 Phase I Project Research Conduct

The Phase I research program was altered from the original plan. The Phase I work plan, as proposed, included a substantial amount of bench scale work, as well as use of drill string suspended in a surrogate well hole. After the project was initiated and some in depth analysis was completed, it was deemed more suitable that conclusive evidence on the feasibility of the proposed approach could only be gained through conduct of field testing a commercial sonic drilling rig that was suitably instrumented to gather drilling performance data. Hence, a sonic drilling system, owned by Water Development Technologies was located and its use was contributed to the project.

As it turned out, it was fortuitous that the field testing with a full scale sonic drill was substituted for the bench scale, surrogate approach, as the methodology discovered using the analysis and established from the experimental results using the commercial sonic drilling system, turned out to be both non-obvious and counterintuitive. If the Phase I work plan would have been conducted as originally planned, the results would not have clearly demonstrated this finding. Essentially, the planned bench scale work and surrogate drill string testing would not have provided credibility to the true nature of the sonic drill performance results, even though results using the analytical model showed these trends. Hence, it was critical, and fortuitous, to have the “real world” validation of the counterintuitive nature of the results.

The fundamental approach that was taken to establish an automatic and intelligent control methodology of the sonic drilling process was the development of an advanced control algorithm, which has been termed, **ResonantSonic Tracking™ (RST™)**. Because of the complexity of factors involved in the sonic drilling process, this control algorithm, it was essential to develop a fundamental understanding of the sonic drilling technology. Hence, much of the Phase I work was allocated to this effort, which will be detailed below.

In review, the sonic drill utilizes the concept of resonance to transmit the input energy from the sonic driver to the tip of the drill string, or bit face, in order to penetrate into the ground.

Because of the discovery of counterintuitive and non-obvious discovery, the feasibility to reach the goal of 1,500 feet with a microhole sized sonic drill string has been determined to be feasible. This discovery led to the ability to size the appropriate sonic driver to drill to these depths and enabled the weights and size of a sonic drilling system to be smaller than

anticipated. This achievement enabled the Phase I goal to demonstrate feasibility for the development of a Heliportable Microhole Sonic Drill. The counterintuitive finding that was established from test results, shows that by using conventional sonic drill operation knowledge there can be over 90% loss of usable power from the sonic driver being delivered to the drill bit for drilling.

Through the use of RST™ the sonic drill will be able to utilize near 100% of the useful energy being delivered to the eccentrics to drive the sonic drill. RST™ will revolutionize the sonic drilling industry and enable heliportable microhole sonic drilling to become possible. RST™ technology has shown to increase the sonic drill efficiency by over nine times that obtained by conventional sonic drill operator methodology for certain operating conditions. See Figures 5 and 6. The data used to derive Figures 5 and 6 were generated during the Phase I tests. In addition, it appears that the RST™ technology can be extended to have advanced features, such as mapping of the drilled material and may also be useful in evaluating drill string integrity.

One of the problems of the sonic drills is the fatigue and failure of the drill strings. However, by examining the data in the Phase I the drill string can be tested to see if any potential cracks exist for failure. This would be advantageous to save valuable needed time in the field in retrieving a broken drill string.

Advantages for utilization of ResonantSonic Tracking™ (RST™) technology:

Figure 5. The bar charts presented above show efficiency of Input Power to power being delivered to Drill Bit for the three different operating points; 'A', 'B' and 'C'. (These are the same 'A', 'B' and 'C' operating points that were shown in Figure 1.) Even though the Input Power was increased for the operating points 'A' to 'C' in ascending order, the energy transfer efficiency is decreasing. The point of this figure is to graphically illustrate that when the sonic drill system is incorrectly controlled, severe losses in drill penetration performance result.

The means to overcome these huge losses in drilling efficiency is to provide automated control, ResonantSonic Tracking™ (RST™). RST™ is needed because the operating conditions needed to maintain the best drilling performance as the drill string penetrates the earth are not achievable by manual control and are counterintuitive.

Figure 6. Sonic drilling performance data, labeled as 'A', 'B' and 'C', above, were obtained to establish the sonic drilling performance over a range of different operating conditions and to evaluate the ResonantSonic Tracking™ (RST™) technology as a means to improve drill string penetration rate and power transfer efficiency.

The optimum operating point for this specific test and series of formations, labeled 'A', shows that the drill bit is receiving nearly 100% of the Input Power to utilize for drilling at the Drill Bit. The drill string was measured to be in resonance at this point. This operating condition resulted in a high penetration rate, about 5 ft/min.

The method used to obtain and maintain this optimal operating point is "not-obvious" and it has been determined that this condition can only be achieved, and maintained, by use of automated control methodology, which is simultaneously monitoring, evaluating and controlling the status of the drill string and the sonic head.

During operating condition labeled 'B' the Transferred Power to the Drill Bit is about 22% less than the Input Power to the Sonic Driver. This operating condition occurs at the resonant condition of the drill string, but not at optimal operating conditions. This operating condition is typical for operator-controlled system and it is perceived by a trained operator that conditions are optimal.

Two performance characteristics can be observed from a comparison of the two power functions for conditions moving from operating condition 'B' to 'C'. First, as the operator adjusts the Input Power past the peak power level to the Drill Bit, the Power to the Drill Bit plummets. This is a result of the drill string falling off of resonance and the drill string penetration rate slows from the nominal 5 ft/min at condition 'A' to about 3 ft/min at 'B' for this specific test and series of formations. Secondly, as the operator takes action to keep the drill string moving downward, condition 'C', it becomes clear that the Power Transferred to the Drill Bit decreases. This decrease in power transferred from the Driver to the Drill Bit (loss of 83%) was accompanied by a reduction in the drill string penetration rate for this specific test and series of formations, slows from the nominal 3 ft/min at condition 'B' to about 1 ft/min at 'C'.

Contrary to conventional belief, and as shown in this figure, the maximum power to the driver does not always directly correlate to the maximum power being delivered to the drill bit. During operating condition labeled 'C' the maximum input power to the sonic driver was being achieved, however at this same point the minimum amount of energy was being delivered to the drill bit.

1. Tracking to insure maximum input energy being delivered to the drill bit
 - a. Has shown to have more than 400 % increase in power to the drill bit.
 - b. Drill penetration rates increased for large penetration resistance changes:
 - i. Along the drill string length.
 - ii. At the drill bit.
2. Monitoring system to insure longevity of drill string sections:
 - a. Monitors force input to ensure the stresses are within fatigue limits of that all times.
 - b. Provides indication of crack development in drill string. (This capability has not been proven from results that have been obtained to date, but there is strong evidence that this can be accomplished from the data being collected.)
3. Automatic algorithm based control system that seeks the optimum penetration rates.
4. Mapping of formation being drilled:
 - a. By monitoring the damping caused at the drill tip the types of soils can be mapped. Typically in sonic drilling, they are bring up cores that tell them the lithology of formations being penetrated.
 - b. Establish the resonant mode that should be used subsequent in drilling to avoid potential high damping zones, e.g., a predictive model.
5. By drilling with this control system the need for flushing fluid will be minimized and less waste will be generated.
6. Core samples will be taken faster.
7. Operator intervention for maximum sonic head performance unnecessary allowing for the faster training of operators to take over sonic drilling machine operations.
8. The control system will be durable, robust, and safe for all weather conditions.

It is important to note the DOE goal of sonic microhole drilling to 1,500 feet is achievable utilizing a 30 hp, or slightly larger, motor.

1.3.4 Feasibility Design of Heliportable Microhole Sonic Drilling System

The Heliportable design was based on the objectives set forth in the Phase I proposal. As described below the feasibility of the Heliportable design was successful by making the modules weigh less than 4,000 lbs each and making the total weight of all the modules less than 32,000 lbs.

A detailed first order design was performed and is summarized below through brief explanations for each of the 7 modules.

MODULE 1, Sonic Drill Platform:

The sonic drill platform will include the sonic head, hydraulic cylinder to generate the push or pull force, hydraulic cylinder for the compaction of the sonic drill platform, mast, base, and brackets and fittings. A conceptual design utilizing the below design constraints and calculation overviews is displayed in Figure 7. The corresponding weights for each of the designed components for the sonic drill platform are tabularized in Table 1.

Sonic Head

Through calculations provided in Section 1.3.5.3 the sonic head must be able to deliver greater than 30 hp. SonicSampDrill sells a stand alone sonic head capable of 38 hp, which will be chosen for the feasibility study.

Figure 7. To Scale Conceptual Design of Module 1

Push or Pull Cylinder

The mast and base must be able to withstand the max extraction force of 15,000 lbf based on 1,500 feet of drill pipe. The alternating force generated is $\pm 31,500$ lbf by the SonicSampDrill sonic head. This

alternating force is mitigated by isolation springs that will only allow 1% transmission of the alternating force to react on the mast. The max possible push down force is 6,000 lbf static based on current sonic drill technology. The hydraulic cylinder push force was designed with a safety factor of 15% and the pull force with 30% so the corresponding design loads are 7,500 lbf and 20,000 lbf respectively. The piston stroke needs to be 10 feet to accommodate unloading and loading of the drill pipe with a 2 foot section sticking out of the ground for RST™ software measurement. The push or pull cylinder must use existing standard pressures of 3000 psi. Thus, the final cylinder size comes out to a 4" diameter bore with a 2 inch diameter rod, which will weigh approximately 425 lbs.

Mast

The size of the mast was then sized for the defined loads above, displayed preliminary cross section in Figure 8. The cross section was designed so as to get a first order weight required to handle the loads. The mast must withstand a

Table 1. Weight Break Down for Module 1

Item	Manufacturer	Weight (lbs)
Sonic Head	SonicSampDrill	600
Hydraulic Cylinder (Push and Pull)	custom	425
Hydraulic Cylinder (Tilt)	custom	250
Mast	Resodyn	550
Base	Resodyn	835
Brackets and Fittings	Resodyn	340
Total Weight		3000

Mast Cross Section

Figure 8. Conceptual of Mast Cross Section (Channel)

force of 28,290 lbf that could be generated by the hydraulic cylinder specified at 3,000 psi. The cross section of the channel, displayed in Figure 9 will be a 6" X 6" X ½ " thick 'C' channel. The equivalent stress is 3,140 psi thus leading a safety factor of 11.5 with A36 hot rolled steel. The masts length needs to be 14 feet based on the stroke of the sonic head, thus the total weight of the mast is 425 lbs. The sonic head will have to have some slide mechanism, which will be about 125 lbf based on previous sized slide mechanisms. The total mast weight is 550 lbs.

Base

The base needs to react all the forces from the mast and be stable. The base must be 10' X 10' to adequately ensure stability of the sonic head during adverse conditions. The materials used are 3" X 6" X ¼" structural tube. The total weight is 835 lbs.

MODULE 2, Hydraulic / Pneumatic Skid:

The hydraulic/pneumatic skid is designed to incorporate the power generation, hydraulic control, and auxiliary systems. The weight breakdown of the hydraulic/pneumatic skid is displayed in Table 2. The

Table 2. Weight Break Down for Module 2

Item	Manufacturer	Weight (lbs)
Diesel Engine	Deutz (BF6L913)	1425
Hydraulic Control Module	custom	920
Compressor and Storage Tank	custom	850
Skid	Resodyn	700
Brackets and Fittings	Resodyn	100
Total Weight		3995

hydraulic/pneumatic skid was designed to drive the sonic head and the other auxiliary applications, such as push or pull force. Based on the hp rating of the sonic head and comparable sized sonic rigs the Deutz 132 Hp continues motor was specified. The hydraulic control module and weight were taken from an existing design by Boart Longyear, (Boart Longyear) to give a total weight of the hydraulic control module of 920 lbs. The compressor and storage tank are to incorporate any air tools and air for drilling. The tank was sized to 35 cfm at 175 psi and have a storage tank of 80 gallons. The total weight of the air tank came to 850 lbs. The skid, brackets, and fittings to hold the equipment during transport came to 800 lbs total to handle all the transport stresses. A visual design of the hydraulic / pneumatic skid is displayed in Figure 9, which takes into all the design constraints listed above. The total physical size of the skid lies on a foot print 10' X 6'.

Figure 9. Scale Visual of Module 2

MODULE 3, Equipment and Sonic Tools Skid:

General skid for supporting tools and equipment weights approximate 4,000 lbs. This will include any air tools, mechanics tools, special drilling tools, pipe lube, etc. The weight breakdown for the equipment and sonic tools skid is displayed in Table 3.

Table 3. Weight Break Down for Module 7

Item	Manufacturer	Weight (lbs)
Supporting Tools and Equipment	Resodyn	4000
Total Weight		4000

MODULES 4 - 7, Drill Pipe:

The drill pipe models have to contain a total of 1500 feet of CP63 drill rod (2.5 inch OD and 1.6 inch ID) microhole sized drill pipe. Each of the bundles of pipe will contain 375 feet of drill pipe and weigh a total of 3700 lbs. The contents of each of the drill pipe modules is displayed in Table 4.

Table 4. Weight Break Down for Modules 3-6		
Item	Manufacturer	Weight (lbs)
375 Feet of CP63 drill Pipe	SonicSampDrill	3700
Total Weight		3700

1.3.5 Summary

In summary, the Phase I objectives were fully achieved the execution of a program that included the:

- Development of a comprehensive model of the sonic drill technology and interaction of the dynamic drilling parameters with the impedance of the earth.
- Operation and measurement of the sonic drilling process in the field at full scale.
- Comparison of the analytical and experimental results to form an objective and quantified approach to describe the fundamental phenomena and to develop a methodology for automated control of the sonic drilling process.
- Conceptual design of a modular sonic drilling system that can be transported to remote sites by helicopter.

As a result, the feasibility of a commercially viable sonic drilling technology that can produce microholes up to 1,500 feet in depth, and that is field deployable to remote, environmentally sensitive sites via a helicopter, has been demonstrated.

1.4 References

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