Optimization of Mud Hammer Drilling Performance – A Program to Benchmark the Viability of Advanced Mud Hammer Drilling

Quarterly Progress Report

Reporting Period Start Date – April 1, 2003

Reporting Period End Date – June 30, 2003

Author; Arnis Judzis, TerraTek

Report Date – July, 2003

DOE Award Number – DE-FC26-00NT40918

TerraTek, Inc.
400 Wakara Way
Salt Lake City, UT 84108

DISCLAIMER

ABSTRACT

This document details the progress to date on the OPTIMIZATION OF MUD HAMMER DRILLING PERFORMANCE – A PROGRAM TO BENCHMARK THE VIABILITY OF ADVANCED MUD HAMMER DRILLING contract for the quarter starting April 2003 through June 2003.

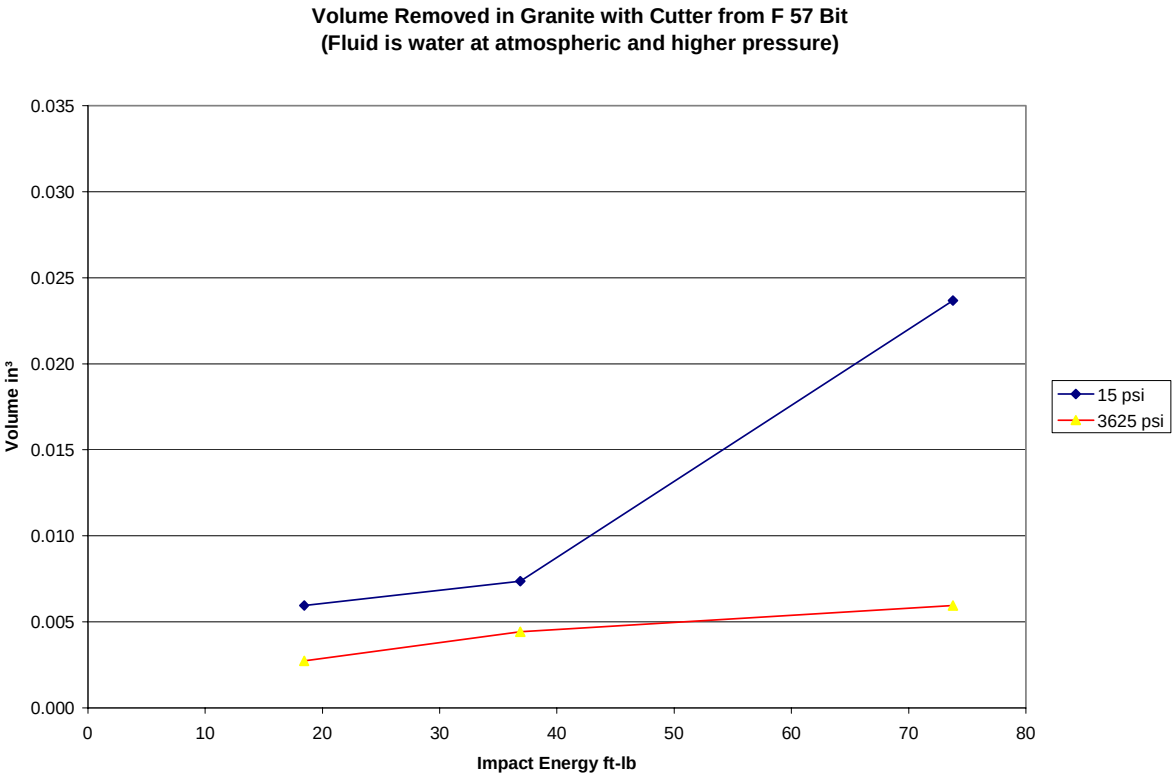
The DOE and TerraTek continue to wait for Novatek on the optimization portion of the testing program (they are completely rebuilding their fluid hammer). Accomplishments included the following:

- Hughes Christensen has recently expressed interest in the possibility of a program to examine cutter impact testing, which would be useful in a better understanding of the physics of rock impact. Their interest however is not necessarily fluid hammers, but to use the information for drilling bit development.
- Novatek (cost sharing supplier of tools) has informed the DOE project manager that their tool may not be ready for 'optimization' testing late summer 2003 (August – September timeframe) as originally anticipated. During 3Q Novatek plans to meet with TerraTek to discuss progress with their tool for 4Q 2003 testing.
- A task for an addendum to the hammer project related to cutter impact studies was written during 2Q 2003.
- Smith International internally is upgrading their hammer for the optimization testing phase. One currently known area of improvement is their development program to significantly increase the hammer blow energy.

TABLE OF CONTENTS

INTRODUCTION

The focus of the Introduction for this quarter will be on some recently studied information on hammers and impact testing from Clausthal University performed a number of years ago. Fluid hammers at the beginning of the 1990s were proposed for the European deep drilling research (KTB) effort. As such some studies were commissioned for hard impermeable rocks such as granite. The information also shows that fluid hammer performance can indeed be improved though challenges remain. Example information cross-plotted from a Ph.D. dissertation (referenced at the end of this progress report) has been summarized below:



EXECUTIVE SUMMARY

Background

On January 9th of 2001, details of the Mud Hammer Drilling Performance Testing Project were presented at a "kick off" meeting held in Morgantown. Industry support is high and the importance to the drilling industry, as the business challenge of "hard rock drilling", was presented by John Shaughnssy of BP Amoco. The Industry Partners for this program are SDS Digger Tools, Novatek, BP Amoco, and ExxonMobil. A test program was formulated and prepared for presentation at a meeting of the Industry Advisory Board in Houston on the 8th of February. The meeting was held and the DOE approved a test program was after thorough discussion.

DOE's National Energy Technology Laboratory highlighted the Mud Hammer Project at an exhibit at the Offshore Technology Conference April 30 through May 3, 2001. TerraTek assisted NETL personnel with presentation materials appropriate for the project and a demonstration sample of 'hard rock' drilled in TerraTek's wellbore simulator.

TerraTek completed 13 drilling tests by beginning July in Carthage Marble and hard Crab Orchard Sandstone with the SDS Digger Tool, Novatek tool, and a conventional rock bit. Overall the hammers are functioned properly at 'borehole' pressures up to 3,000 psi with weighted water based mud. Clearly the Department of Energy goals to determine hammer ***benchmark rates of penetration*** and ***ability to function at depth*** are being met. Additionally data on drilling intervals and rates of penetration specific to flow rates, pressure drops, rotary speed, and weights-on-bit have been given to the Industry Partners for detailed analysis. SDS and Novatek have gained considerable experience on the operation of their tools at simulated depth conditions. Some optimization has already started and has been identified as a result of these first tests.

TerraTek completed analysis of drilling performance (rates of penetration, hydraulics, etc.) for the Phase One testing which was completed at the beginning of July. TerraTek also convened jointly with the Industry Advisory Board for this project and DOE/NETL a 'lessons learned meeting' to transfer technology vital for the next series of performance tests. Both hammer suppliers benefited from the testing program and are committed to pursue equipment improvements and 'optimization' in accordance with the scope of work.

PDVSA joined the advisory board to this DOE mud hammer project end 2001 and formally committed funds (cost sharing) for the upcoming effort in testing at TerraTek. Additionally, TerraTek, DOE, and BP America (one of the industry contributing partners) has completed a publication entitled "World's First Benchmarking of Drilling Mud Hammer Performance at Depth Conditions".

In accordance to Task 7.0 (D. #2 Technical Publications) TerraTek, NETL, and the Industry Contributors successfully presented a paper detailing Phase 1 testing results at

the February 2002 IADC/SPE Drilling Conference, a prestigious venue for presenting DOE and private sector drilling technology advances. The full reference is as follows:

> IADC/SPE 74540 "World's First Benchmarking of Drilling Mud Hammer Performance at Depth Conditions" authored by Gordon A. Tibbitts, TerraTek; Roy C. Long, US Department of Energy, Brian E. Miller, BP America, Inc.; Arnis Judzis, TerraTek; and Alan D. Black, TerraTek. Gordon Tibbitts, TerraTek, will presented the well-attended paper in February of 2002. The full text of the Mud Hammer paper was included in the last quarterly report.

The Phase 2 project planning meeting (Task 6) was held at ExxonMobil's Houston Greenspoint offices on February 22, 2002. In attendance were representatives from TerraTek, DOE, BP, ExxonMobil, PDVSA, Novatek, and SDS Digger Tools. PDVSA has joined the advisory board to this DOE mud hammer project. PDVSA's commitment of cash and in-kind contributions were reported during the last quarter. Strong Industry support remains for the DOE project. Both Andergauge and Smith Tools have expressed an interest in participating in the 'optimization' phase of the program. The potential for increased testing with additional Industry cash support was discussed at the planning meeting in February 2002.

Presentation material was provided to the DOE/NETL project manager (Dr. John Rogers) for the DOE exhibit at the 2002 Offshore Technology Conference. Two meeting at Smith International and one at Andergauge in Houston were held to investigate their interest in joining the Mud Hammer Performance study.

SDS Digger Tools (Task 3 Benchmarking participant) apparently had not negotiated a commercial deal with Halliburton on the supply of fluid hammers to the oil and gas business. TerraTek is awaiting progress by Novatek (a DOE contractor) on the redesign and development of their next hammer tool. Their delay will require an extension to TerraTek's contracted program. Smith International has sufficient interest in the program to start engineering and chroming of collars for testing at TerraTek.

Shell's Brian Tarr then agreed to join the Industry Advisory Group for the DOE project. The addition of Brian Tarr was welcomed as he has numerous years of experience with the Novatek tool and was involved in the early tests in Europe while with Mobil Oil. Finally, Conoco's field trial of the Smith fluid hammer for an application in Vietnam was organized and has contributed to the increased interest in their tool.

Smith International agreed to participate in the DOE Mud Hammer program mid 2002 and chromed collars for upcoming benchmark tests at TerraTek, scheduled for 4Q 2002. ConocoPhillips had a field trial of the Smith fluid hammer offshore Vietnam. The hammer functioned properly, though the well encountered hole conditions and reaming problems. ConocoPhillips plan another field trial as a result.

DOE/NETL extended the contract for the fluid hammer program to allow Novatek to 'optimize' their much delayed tool to 2003 and to allow Smith International to add 'benchmarking' tests in light of SDS Digger Tools' current financial inability to participate. ConocoPhillips joined the Industry Advisors for the mud hammer program

and TerraTek acknowledges Smith International, BP America, PDVSA, and ConocoPhillips for cost-sharing the Smith benchmarking tests allowing extension of the contract to complete the optimizations tests.

During 4Q 2002, Smith International participated in the DOE Mud Hammer program through full scale benchmarking testing (5 tests) during the week of 4 November 2003. TerraTek acknowledges Smith International, BP America, PDVSA, and ConocoPhillips for cost-sharing the Smith benchmarking tests allowing extension of the contract to add to the benchmarking testing program. Following the benchmark testing of the Smith International hammer, representatives from DOE/NETL, TerraTek, Smith International and PDVSA met at TerraTek in Salt Lake City to review observations, performance and views on the optimization steps for 2003. The December 2002 issue of Journal of Petroleum Technology (Society of Petroleum Engineers) highlighted the DOE fluid hammer testing program and reviewed last years paper on the benchmark performance of the SDS Digger and Novatek hammers. TerraTek's Sid Green presented a technical review for DOE / NETL personnel in Morgantown on 'Impact Rock Breakage' and its importance on improving fluid hammer performance. Much discussion has taken place on the issues surrounding mud hammer performance at depth conditions.

At the start of 2003 the DOE and TerraTek continued to wait for Novatek on the optimization portion of the testing program (they are completely rebuilding their fluid hammer). ExxonMobil expressed interest in the possibility of a program to examine cutter impact testing, which would be useful in answering how hammers break rock and ultimately how to improve their performance. Additionally, The March 2003 issue of Drilling (American Association of Drilling Engineers) highlighted the DOE fluid hammer testing program. Information from Smith International, TerraTek and PDVSA (one of the Industry partners) provided interesting insights for the future of hammer technology. Finally, Novatek (cost sharing supplier of tools) informed the DOE project manager that their tool may be ready for 'optimization' testing late summer 2003 (August – September timeframe).

Current

Hughes Christensen has recently expressed interest in the possibility of a program to examine cutter impact testing, which would be useful in a better understanding of the physics of rock impact. Their interest however is not necessarily fluid hammers, but to use the information for drilling bit development. Novatek (cost sharing supplier of tools) has informed the DOE project manager that their tool may not be ready for 'optimization' testing late summer 2003 (August – September timeframe) as originally anticipated. During 3Q Novatek plans to meet with TerraTek to discuss progress with their tool for 4Q 2003 testing. A task for an addendum to the hammer project related to cutter impact studies was written during 2Q 2003 and submitted to the DOE project manager. Finally, Smith International internally is upgrading their hammer for the optimization testing phase. One currently known area of improvement is their development program to significantly increase the hammer blow energy.

EXPERIMENTAL

Experimental work for 'Benchmark' testing has been completed with the introduction of the Smith International hammer tests during the week of 4 November 2002. Experimental work completing Task 6 is awaiting Novatek's tool.

RESULTS AND DISCUSSION

May 2003 Addendum proposal:

****

Mud Hammer Drilling – 'Understanding Rock Breakage'
CUTTER IMPACT STUDY

Addition of Task 8

Objective

Based on benchmark testing of fluid hammers to date, drilling performance (rates of penetration) has been determined to be satisfactory with respect to short term operation in weighted drilling muds containing solids and modest wellbore pressures. However at elevated wellbore pressures (ca. > 1500 psi), rate of penetration performance has not yet been optimized.

This addendum to the program proposes to study single cutter impact breaking of rock under various simulated borehole conditions. A literature survey of work performed to date and presented to NETL on December 17, 2002 by Sid Green, CEO TerraTek, showed that only little has been documented and understood in this area. Quantitative information is needed for single cutter tests to better understand stress effects, bit/cutter load and 'rpm' effect, fluid effects, rock effects, and cutter design.

Background Context and Industry Support

Industry players are also concerned that rapid commercialization of fluid hammers may be hindered by the lack of this fundamental information. The scope of the single cutter impact tests can help answer some of the basic questions pertaining to percussion drilling.

Shantanu Swadi, Senior Project Engineer with Smith International has stated the following:

" . . . . . the fundamental questions that we are trying to answer are the following:
1. Is there a significant difference in the way the rock breaks in air vs. fluid?
2. How does the energy required to break rock change with depth, hydrostatic pressure?
3. What, if any, threshold levels of blow energy exist for a given formation?
4. What is the best way to deliver percussive energy to rock as related to the intensity and duration of the stress wave?"

Input by operators (e.g. BP, ExxonMobil, PDVSA) has brought up similar needs for such a study. Jesse Holster, Drilling Advisor for ExxonMobil R&D, stated the following:

"The following items are important things to learn from single cutter impact tests for mud hammer applications.

1. As wellbore pressure increases, what will physically happen to the rock upon impact? Will there be fractures or simple ductile indentations into the rock?
2. The above effect of wellbore pressure needs to be established in several rock types, most important of which are sandstones, siltstones, carbonates and shales. I'm sure things like granite and metamorphosed rocks are important to some folks, but we rarely drill them. I expect they are important for geothermal applications and hence could be included.
3. What is the transition pressure from brittle failure to ductile indentations in each rock type (assuming there is a transition)?
4. Do rock permeability and pore pressure play a role in establishing the failure mechanics and if so, how?
5. I would expect failure to be a function of impulse loading (mass x velocity of impact). This parameter should be varied in the experiments.
6. What role does indexing play? First establish results for clean, single impacts. Then determine what results from a second adjacent impact and its spacing relative to the first. What happens if there is overlap? Is there some optimal overlap? What happens with zero overlap (repeat blows in the same spot)?
7. In those rocks at the wellbore pressures where simple indentations result, does a "glancing blow" help remove rock. In other words, if the impact occurs at some value of rotary speed of a bit such that there is translational motion in addition to the downward impact, will it assist in rock failure?"

Forward Plan

The first part of Task 8 is aimed to understand the effects of rock properties on impact cutting (or breaking). TerraTek proposes to conduct impact experiments using single cutters and different rock samples under downhole conditions. Two loading systems are planned in order to simulate impact loading over a wide range of impact conditions. A split Hopkinson pressure bar system will be modified to include a pressure vessel to simulate downhole conditions, up to about 5000 psi borehole pressures (see Figure 1 showing a picture of the system without pressure vessel attached). And, the TerraTek high strain rate loading system—with loading capability in the milliseconds—will use the same pressure vessel to provide a lower impact range of experiments, again under downhole conditions (see Figure 2 of the TerraTek high strain rate machine).

The test matrix will include variations in:

1. rock (formation) types—with expected rocks of Carthage marble, crab orchard sandstone (previously studied in various programs), Berea sandstone, and nugget sandstone,
2. borehole pressures—with maximum pressures up to about 5000 psi and with drilling muds as well as clean water,
3. confining pressure and pore pressure—to simulate different reservoir conditions including where possible underbalanced drilling and overbalanced drilling,
4. impact—including impact velocity (i.e. magnitude of the impact stress), wave frequency (i.e. rise time of the impact wave), impact duration (i.e. length of the impact pulse), and possibly novel wave loadings (i.e. varying the rise time, decay time, multiple waves, wave step loading, and the like), and
5. if possible several single cutters will be investigated.

The number of tests that can be undertaken is uncertain, though may exceed fifty in number depending on the complexity. The test matrix is critical in order to discover ‘first order’ effects with minimal number of tests. This will be the priority for the limited tests that can be conducted.

The second part of Task 8 will be to assess the cutter-rock interaction—based on the experimental data—under the impact conditions with high borehole pressures. TerraTek will seek to define rock breakage and rock removal in terms of quantifiable impact and borehole pressure for a given rock type and for a given cutter. Some analysis will be performed to consider an ‘energy’ model (considering energy into the rock) versus an ‘impact’ model (considering impact stress magnitude) for rock removal.

These data would then be the basis for industry design of improved cutters and bit designs to allow optimum rock removal from mud hammers. TerraTek will seek to disseminate the program results through

open publication, direct meetings with appropriate industry players, and most importantly through direct industry participation in the program during the program performance.

Figure 1. Hopkinson Bar Equipment

Figure 2. High Rate Test Machine

Schedule and Milestones

Task 8 can be done concurrently with Task 6 'Optimization Testing'. On approval, the addendum work could start July 1, 2003 with an expected duration of six (6) months. Milestones will include the following:

Ready equipment for impact testing	end August 2003
Incorporate pressure vessel capability	end September 2003
Test data on various rock samples and single cutters	end December, 2003
Analysis of cutter-rock data	end February, 2004
Report for Task 8	end March, 2004

Supporting Cost Detail

Direct Labor Rates

Where identifiable we have used the actual direct labor rates of the employees proposed for use on this program, otherwise composite rates have been used.

Indirect Rates

The indirect rate at TerraTek for booking, billing and forward pricing are all the same. Costs are segregated into pools. The rates and methods of computation are as follows:

Category	Rate	
Fringe	30 %	Direct Labor Dollars
Overhead	122%	
G&A	N/A (0)	

Travel Summary

One two-person trip for 3 days to NETL	**$1800.00**
One one-person trip for 2 days SLC to Houston	**$ 800.00**
Consultant travel 5 days to Salt Lake City from Boston	**$2000.00**

Total $4,600

DETAIL DESCRIPTION OF COST ELEMENTS

		TOTAL EST COST
1	Supply of Services and Materials from Industry Cost Sharing - SC:	50,000

2 DIRECT LABOR

Category	Hours	% Hrs.	Rate	Salary Amount	Fringe Rate 30.00%	Fringe Amount
PI - Alan Black	40.0	6.4%	46.54	1,861.60	13.96	558.48
PI - Wes Martin	40.0	6.4%	36.20	1,448.00	10.86	434.40
Proj. Mgr. - Arnis Judz:	40.0	6.4%	48.08	1,923.20	14.42	576.96
Sr. Eng. - J. Sandstrom	20.0	3.2%	35.00	700.00	10.50	210.00
Engineering Assistant	400.0	63.7%	17.00	6,800.00	5.10	2,040.00
Sr. Technician	80.0	12.7%	17.00	1,360.00	5.10	408.00
Contract Admn.	8.0	1.3%	33.66	269.28	10.10	80.78
TOTAL	628	100.0%		14,362.08		4,308.62

			Rate	Base	Cost
3	Total Labor w/ Fringe				18,670.70
4	LABOR OVERHEAD		1.22	18,671	22,778
5	TRAVEL (SEE ATTACHED DETAIL)				4,600
6	CONSULTANT				8,000
7	DIRECT MATERIAL				18,500
8	OTHER (Testing Services Standard Commercial Items)				40,000
9	TOTAL DIRECT COSTS				71,100
10	DIRECT COST OVERHEAD EXPENSE (122% of Line 9)				86,742
11	TOTAL ESTIMATED COST				249,291
	Indirect Cost			109,520	
12	Cost Share Partners:				
	BP Amoco		10,000		
	ExxonMobil		5000		
	PDVSA				
	Novatek				
	Smith International		35000		
	SDS Digger Tools				
13	Total Share Cost	20.06%			50,000
14	Net Proposed Total Contract				199,291

****

CONCLUSIONS

- Benchmarking of the Smith International fluid hammer was completed in November 2002.
- Tasks 1, 2, 3, 4, and 5 are completed in the original format, now complete also with respect to Task 3 Smith tool benchmarking during 4Q 2002.
- Task 6 started having concluded a Planning Meeting to determine the test matrix for the next phase of testing. The Industry Advisors will reconvene an additional time prior to formalizing the optimization test matrix.
- Task 7 D2 completed with formal presentation / paper as encouraged by DOE/NETL.
- Novatek is delaying TerraTek's completion of Task 6, however the DOE is aware of this and they are separately funding the re-build of the Novatek hammer in another project.

REFERENCES

Ralf Luy, "Untersuchung zur Wirksamkeit des Bohrprozesses beim drehschlagenden Bohren unter hohen hydrostatischen Drucken", Dissertation Doktor-Ingeneurs, Technischen Universitat Clausthal (Germany), December 18, 1992