DISC CUTTER TECHNOLOGY APPLIED TO DRILL BITS

March 1997

A Paper prepared for

the

U. S. Department of Energy's Natural Gas Conference
March 24 - 27, 1997
Houston, Texas

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1.0 INTRODUCTION

The use of disc type cutters is firmly ensconced in tunnel boring, big hole drilling and other large diameter mechanical excavation methods. It is a proven methodology, and the most energy efficient mechanical rock excavating tool known. As far as small diameter cutterheads and drill bits are concerned, disc cutters had two disadvantages.

a. The disc cutters available require very high thrust.

b. The large saddle mounds preclude close kerf spacing.

The Earth Mechanics Institute (EMI) laboratory of the Colorado School of Mines (CSM) is one of the best equipped experimental laboratories for research and development of mechanical excavation tools. Since its founding in 1974, it has been studying and testing excavation methods, and has become well known for the computer models which describe the excavation process. These models recognize many variables which affect excavation rate. Among these, cutter "foot print" size, cutter diameter and blade thickness are among the more significant parameters.

In 1992, the laboratory began testing small diameter, cantilever mounted cutters designed and built by Excavation Engineering Associates, Inc. (EEA). This was in response to a need for a hard rock core drill, in which liquid drilling fluids were not permitted. The efficient rolling single disc cutter, which on large equipment could be operated without a cooling fluid, seemed to be the only possibility. Early performance data was so encouraging that additional applications research continued.

Small cutterheads of 18, 28 and 32 inches were designed and built by EEA. These heads were aimed at the budding micro-tunneling and directional drilling industry. At the time, this industry was using drag type tools almost exclusively, and was restricted to soils and very soft rocks. An obvious need existed for tools capable of attacking hard rock and boulders. Perhaps the small disc cutters, Mini-discs, could address this problem.

The 32 inch head was tested in a variety of rock types and conditions in the laboratory, again with exciting results.

Engineers from Gas Research Institute (GRI) heard about the research and visited the Laboratory to see the equipment and inspect the test results. In effect, GRI laid down a challenge to utilize the Mini-disc technology on heads (bits) as small as 7 7/8 inches diameter. After a short study, the goal appeared to be feasible and GRI awarded the contract. Subsequently, two bit sizes were built, 13 1/8 inch and 7 7/8 inches diameter. A series of Laboratory tests was conducted, first at atmospheric pressure at the CSM Laboratory and then in a pressure chamber at FlowDril.

2.0 BACKGROUND

2.1 Development of Disc Cutters in Tunnel Boring

The development of the disc cutter was an evolutionary process, starting in 1956 when an engineer, James Robbins, placed them on a small TBM on a Toronto sewer job. In moderately hard rock, this TBM set the astonishing record of 105 ft in a single day, and more importantly, made a profit for the contractor. From then on, The Robbins Company grew to dominate the market. By 1980, the few surviving companies in the TBM field had all converted to large saddle mounted single disc cutters.

In the early days of disc cutter use, there was more art than science in the use of disc cutters. Cutters seemed to work pretty well when they cut in concentric circles spaced at about 3.0 inches. The cutting action was not well understood, and the industry was dominated by small but dedicated companies who had little funding for R&D. The cutters were working and there were greater problems with main bearings, seals and structure of the machine.

Disc cutters have also found common use in large diameter shaft drilling. In this application the efficiency of the disc cutter has paid off in severe ways including:

a. Disc cutters allow an existing rig to be used for larger holes.

b. With a given rig, a disc cutter equipped cutterhead will drill faster; in many cases double the penetration rate.

c. Disc cutters tend to ball up less than the wide multi-row types.

d. Disc cutters are cheaper to buy and are rebuildable.

As far as cutters were concerned, the basic observation was made that the harder they were pushed, the deeper they sank into the rock, and the machines penetrated faster. As a result, cutter capacity went from 20,000 lbs on a 12 inch cutter, to 40,000 lbs on a 15.5 inch cutter to 60,000 lbs on a 17 inch cutter and now 75,000 lbs is claimed for 19 and 20 inch cutters. Onward and upward, always increasing in size and weight as larger and larger bearings were needed. What the manufacturers in the “capacity war” did not recognize was that each time performance was enhanced by greater load capacity, the increase in cutter diameter offset a portion of the advantage. By the time cutter diameter reached 19 and 20 inches, the advantage of increased load capacity was almost completely offset by diameter increase.

2.1.1 Disc Cutter Usage in Shaft Drilling

Since 1979, as part of the Chicago Tunnel and Reservoir Project (TARP), hundreds of drop shafts were drilled to direct storm water into the huge underground water storage caverns. Many of these holes were 99 inches diameter. Also, in the congested urban environment where the work yard was 1/4 acre or two barges in size, oil well drilling style rigs could not be utilized.

The opportunity arose to step away from traditional drilling technology and find alternate ways to operate. Robbins Company built two compact but powerful hydraulic rigs. The largest of the two, the 121BR had a lifting capability of 1.25 M lbs and a torque of 365,000 ft-lbs up to 6 rpm. A typical 99 inch disc drill "bit" is shown in Figure 1.

Figure 1
99 Inch Drill Cutterhead

The rig torque and lift capability were designed with disc cutters in mind, but initially the client insisted on using more traditional cutters. These were two-row carbide insert units, however, which used interchangeable saddle mounts with disc cutters. Progress was slow and on the third hole, we were allowed to use a disc bit. The comparison is below.

	RPM	Torque	WOB	Penetration
Insert bit	6	300,000 ft-lbs	300,000 lbs	1.5 ft/hr
Disc bit	6	150,000 ft-lbs	250,000 lbs	3.0 ft/hr

The next hundred shafts were drilled with disc equipped cutterheads. The best shaft in the first series was drilled at up to 7 ft/hr with an average 4.14 ft/hr.

2.1.2 The Science of Disc Cutters

Scientific analysis of rock excavation physics was undertaken in 1975 at the CSM Laboratory where a machine called a Linear Cutting Machine (LCM) was designed and built. This machine, shown on Figure 2, could be set up with any type of full scale cutting tool which could be tested against real rock samples. Depth of cut, spacing between cuts and type of rock could be varied and tri-axial forces on the tool measured. A whole matrix of data could be gathered and analyzed under laboratory conditions. The major variables of both rock and machine could be identified. Data analysis provided some interesting insights. Of the machine variables, disc cutter diameter and blade width proved to be just as important as the load.

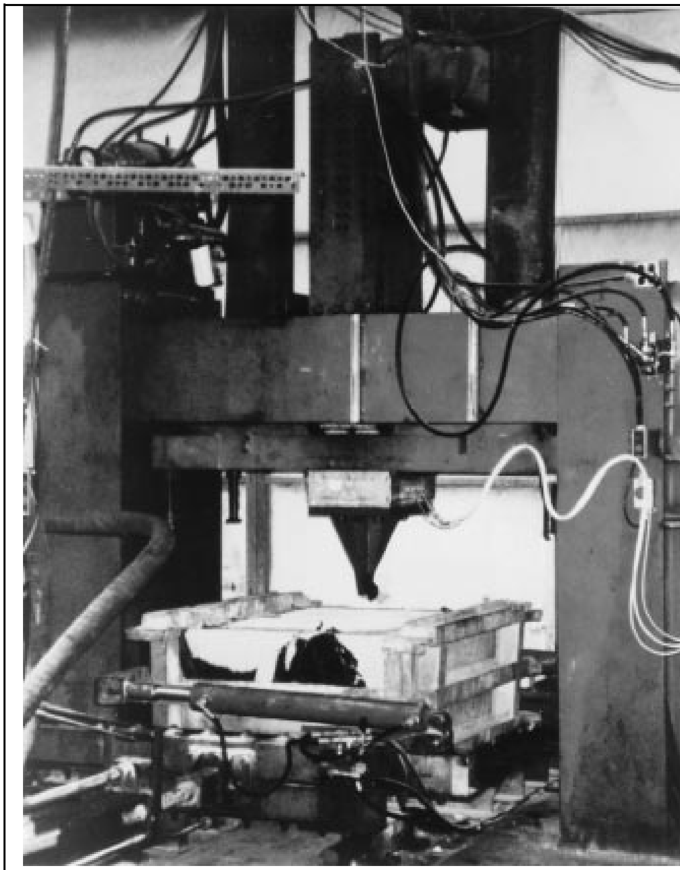


Figure 2
Linear Cutting Machine

2.1.3 Traditional Small Bore Rolling Cutters

The principal hard rock cutting tools for small diameter cutterheads (or bits as they are called by the drilling community) are multi-row carbide insert cutters, button row cutters, cone shaped cutters, strawberry cutters, and even random spaced carbide buttons. Many of the applications for small cutterheads depend on a drill string or a center drive socket to deliver the thrust and rotary power. Torque and power are more limited, therefore, than on the huge direct drive TBMs. When applied with low thrust, cutters indent the rock less and spacing between the cuts or kerfs must be reduced to assure efficient chipping of the rock. Some cutter types have reduced spacing to the extreme, where they produce only dust and sand.

As shown on Figure 3, a large penalty is paid for making small particles or powder. The curve shows the relationship between energy consumed by the machine and the average particle size generated. A ton of rock can be excavated with less energy if cuttings are brought out in large particles. In an instrumented test, an off-the-shelf 9 1/4 inch tri-cone bit required 80 hp-hr/ton in well cured concrete and 120 hp-hr/ton in basalt. Compare this with 3 to 7 hp-hr/ton that disc cutters achieve on large diameter cutterheads. Yet the single rolling disc cutter is only beginning to be utilized on small diameter excavating tools.

Until recently, the smallest production single discs were 15.5 and 14 inches diameter, while the smallest special order discs were 12 inches. But even the 12 inch cutters, with their large saddle mounts occupy too much cutterhead "real estate" to use effectively on small diameter cutterheads. Traditional manufacturers and users of single disc cutters have felt that a cutter of significantly smaller diameter could not be robust enough to survive the high forces necessary to excavate hard rock.

2.1.4 The Mini-Disc Development

The incentive for designing a small disc started by playing iterative games with the predictive computer program. This exercise quickly showed that the two most effective ways of improving performance which could be controlled by the designer were cutter diameter and blade width. In addition, the concept of specific energy of excavation, in terms of energy consumed per unit of mass or volume excavated was realized. Plotting data from both laboratory and field data produced the curve shown in Figure 3.

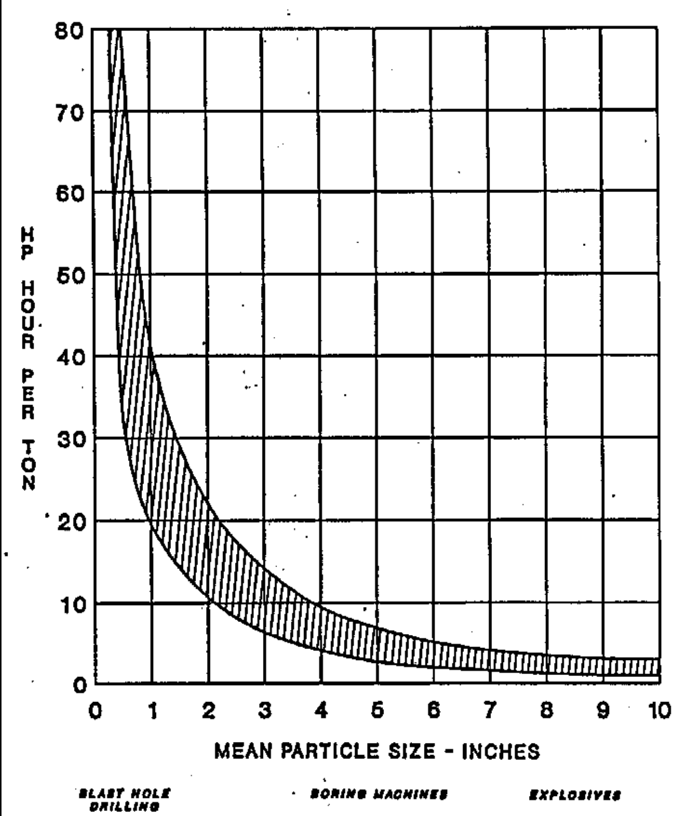


Figure 3
Excavation Energy Related to Particle Size

The tri-cone bit was producing cuttings that were the consistency of fine to coarse sand. If average particle size could be increased only a small amount, according to Figure 3, a significant improvement in performance could be had.

To achieve the results desired, a cutter in the traditional design with saddle mounts as shown in Figure 1 could not be considered. To be successful, the concept must utilize cantilever mounted cutters. With cantilever cutters, cutter kerfs can be close or far as desired, and could be placed on the head where out-of-balance forces could be minimized. To do this, the center shaft with respect to the cutter diameter had to be large. If traditional double row tapered bearings were used, diameter to meet the load capacity would be so large, there would be almost no room for cutter blade. Cutter design approach had to be re-thought; traditional design concepts just would not meet the goals.

2.1.5 Linear Cutter Machine Tests

Excavation Engineering Associates, Inc. decided to take on the small disc design challenge. Prototype cutters were designed and built in both an all steel and a hard metal insert version. They are shown in Figure 4. The first tests were run on the LCM at the CSM Laboratory to determine the performance potential. A very hard 43,000 psi (297 MPA) rock was chosen as the first test sample to shake out any weaknesses as quickly as possible. Figure 2 shows this test series underway.

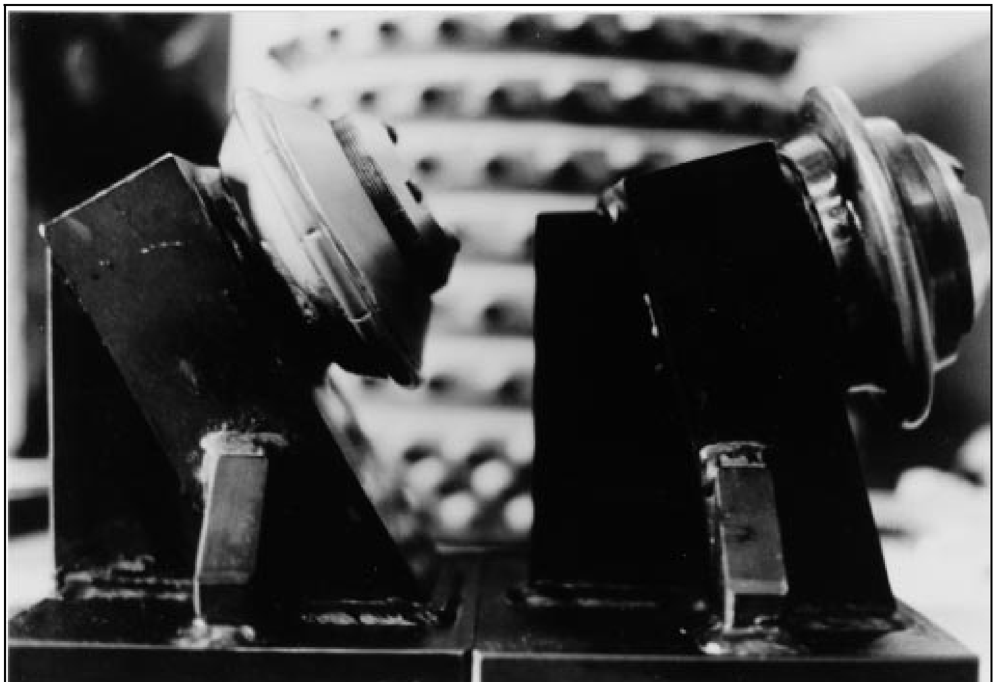


Figure 4
Prototype Cutters, 5.0 Inch

Results were beyond expectation. Figure 5 shows the most significant summary plot, the Thrust vs. Penetration curve. At 2.0 inch spacing, a penetration of .125 inch was achieved with only 11,700 lbs of thrust. To put this achievement into perspective, a standard 17 inch TBM cutter requires over 60,000 lbs to achieve this penetration in the same rock.

Also, the specific energy measured at 2.0 inch spacing was only 6.9 to 8.5 hp-hr/ton. This was far superior to the best multi-row or button type cutters tested.

One cutter was loaded to failure. At 53,000 lobs load, and .3 inches penetration, the ring failed.

The cutters were extensively tested, two carbide designs, three all steel designs, at three angles on four different rock types. Undoubtedly, one of the most thorough series of tests conducted by CSM's Laboratory.

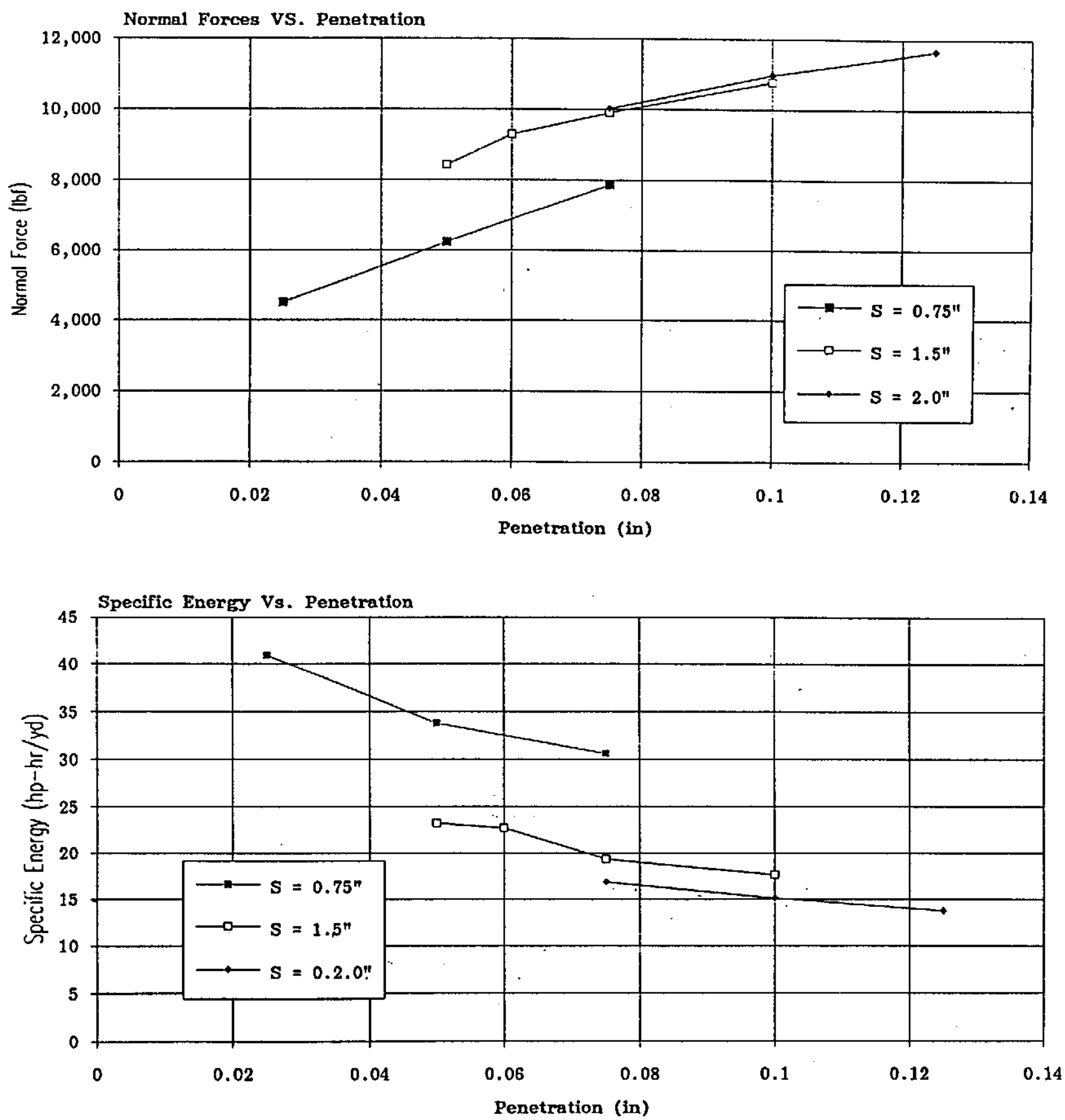


Figure 5
Linear Cutting Test Results, 43,000 psi Rock Sample
5 Inch Disc Cutter

2.1.6 The 13 1/8 Inch Mini-Disc Bit

The first drill bit experiments utilized a 5.0 Inch Mini-disc cutter, simply because the cutter design was proven, and a great deal of backlog data was available; data from the LCM tests and from a 32 inch cutterhead. A 13 1/8 inch bit diameter for the first tests was chosen simply because that was the minimum size that could be laid out using six each, 5.0 inch Mini-discs. Figure 6 is a photograph of the bit.

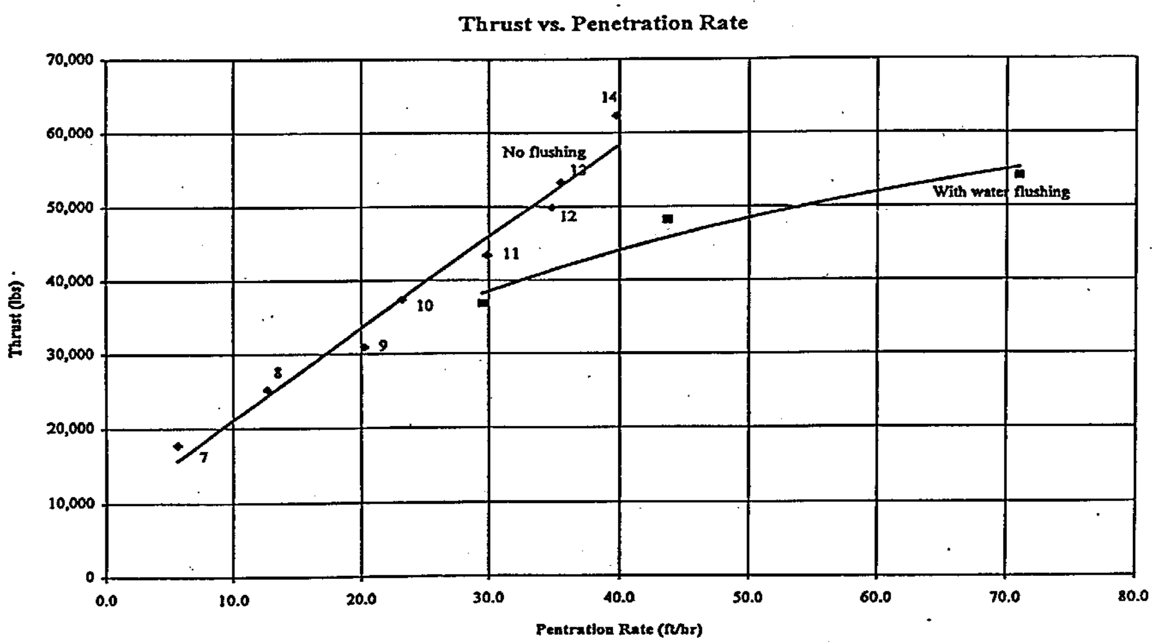
The cutter profile was set up such that the widest spacing between any two cutters was 1.5 inch. The azimuth of each cutter was established by a computer balance program. With only six cutters, and with extremely limited maneuvering space, perfect balance was not possible. Using the computer three-dimensional dynamic balance program, cutter positions were exchanged and then moved slightly to achieve minimum out of balance (whirling) and in addition, minimum moment about the axis of the bit.

Figure 6
13 1/8 Inch Diameter Drill Bit

2.1.7 13 1/8 Inch Bit Performance

Performance of the 13 1/8 inch bit was as good or better than expected. Performance tests were run in 10,000 psi limestone and a 25,000 psi Welded Tuff. Figure 7 shows the results in the hardest of the two rocks tested. A maximum penetration rate of just over 70 ft/hr was achieved with both rock types. This appeared to be a limit imposed by the cuttings removal capability of the bit.

Obvious from the curves shown, is the significance of good bit cleaning. At a constant 7,500 ft-lbs torque, penetration rate increased from 28 to 72 ft/hr when water flushing was used. And at a constant 55,000 lbs of thrust, penetration rate increased from 37 to 72 ft/hr when water flushing was employed.



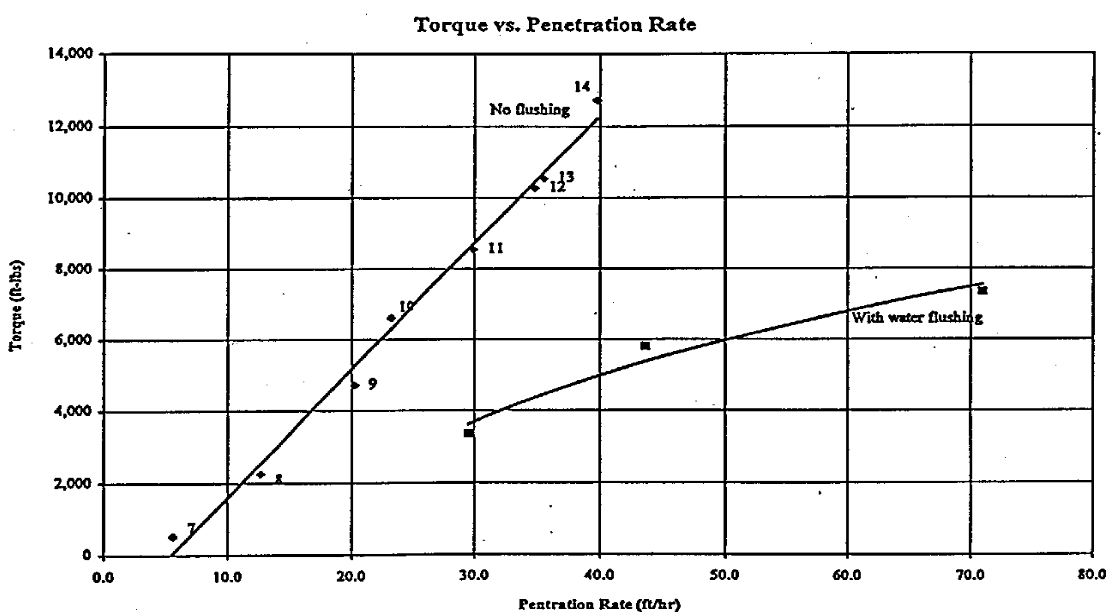


Figure 7
13 1/8 Inch Drill Bit Test Results, 25,000 psi Welded Tuff

Specific energy of excavation achieved was 15 to 19 hp-hr/ton. This could be compared with the 80 to 120 hp-hr/ton experienced with standard carbide cutter tri-cone bits.

Out of balance was not specifically measured but the bit was placed on the end of a 6 ft long, 10 inch drill string. While turning, a small out of axis turning was observed but this diminished when the bit contacted the rock. No significant out of balance was observed.

2.1.8 The 7 7/8 Inch Mini-Disc Bit

After a design study, the 7 7/8 inch bit configuration was established as using five each, 3.25 inch diameter disc cutters. Maximum spacing between cutter kerfs was only 0.9 inches. Unlike the 13 1/8 inch bit, outside cutters for this bit were bolted onto the perimeter of the bit, using wedge shaped pedestals fitting into tapered slots. This configuration was chosen for ease of assembly and because more open space around the bit was available for the cuttings to escape. Only the center cutter pedestal was permanently welded in place.

The bit body was equipped with a 4 ½ inch "standard" API thread. Fluid passages were drilled into the bit body to direct water or mud to the face. Features not included in the 5.0 inch cutters used on the larger bit were incorporated into the 3.25 inch cutters used on the 7 7/8 inch bit. These included:

a. Each cutter was equipped with an individual pressure compensator/grease reservoir.

b. A metal-to-metal face seal was used in place of an elastomeric seal. The latter had abraded quickly when operating under slurry conditions.

c. Fit of the cutters was so close that the hub cap was installed by press fit, tack welded and sealed with Locktite. Larger cutters have threaded hub caps which take up more space.

Preliminary tests were run on the cutters in a slurry chamber. Cutters were run against a steel plate (to prevent advance) and the chamber, filled with a Bentonite, silica and gel slurry, was cycled between 0 and 40 psi. Seals, bearings and compensator completed a 50 hour test without difficulty.

Two 7 7/8 inch drill bits were built; the first was used for atmospheric testing at the CSM Laboratory. The second bit was equipped with high pressure passages and jetting nozzles and used for tests in a pressurized chamber with Bentonite mud as the circulation fluid. The 7 7/8 inch bit is shown in Figure 8.

In the CSM Laboratory, penetration rates of up to 126 ft/hr were obtained with 32,000 lbs WOB. Pressure was atmospheric, water flushing was used at a rate of about 30 gpm, and rotary speed was 57-60 rpm. Torque required was only 2,500 ft-lbs. Interestingly, there was little performance difference between the 10,000 psi Indiana Limestone and the 25,000 Welded Tuff. The top penetration rate in either rock, however, was governed by the geometry of the cutter. Since at maximum penetration rate, the cutter was indenting the rock about 0.4 inches, the cutter was literally rolling on the hub.

Under these circumstances, further increases in penetration rate would be limited regardless of additional weight or torque applied.

Figure 9 shows the test results in terms of WOB vs. penetration rate and torque vs. penetration rate.

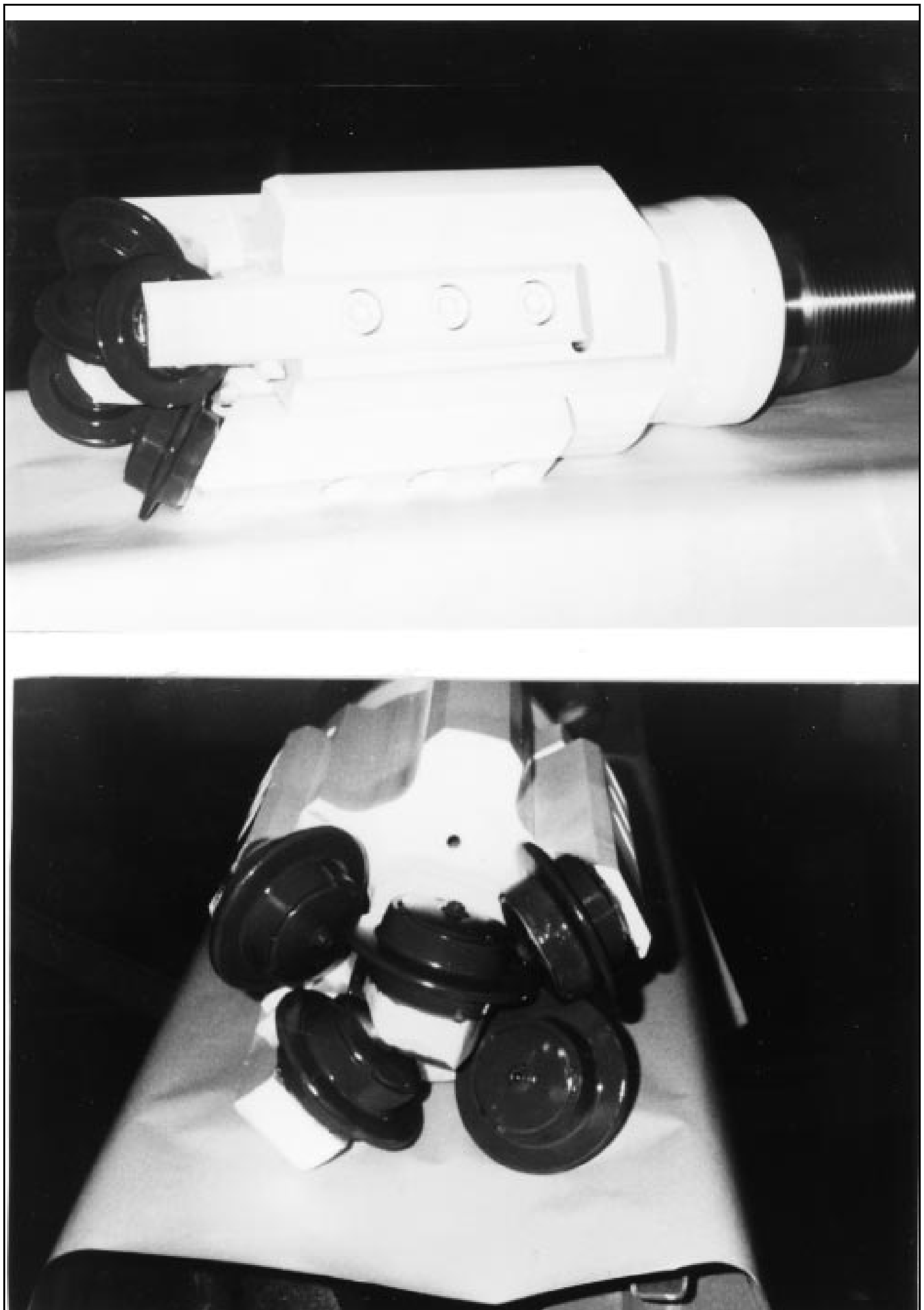
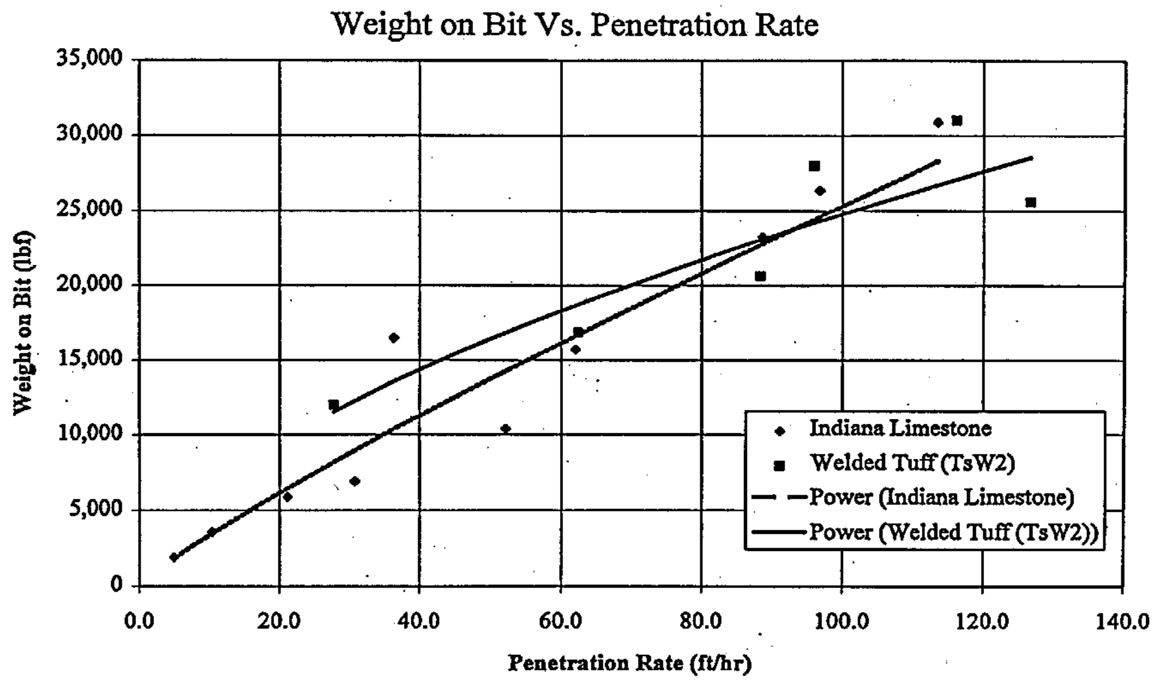


Figure 8
7 7/8 Inch Disc Bit

2.1.9 7 7/8 Inch Bit Testing at Simulated Depth

The second bit was equipped with flow passages and nozzles to permit a mud flow rate of about 260 gpm at a nozzle pressure drop of 500 psi. This unit was shipped to FlowDril Corporation where they have a test facility where drilling at depth can be simulated. The test rig includes a chamber that can be pressurized to about 3,000 psi. The chamber holds a 30 inch long rock sample, up to 17



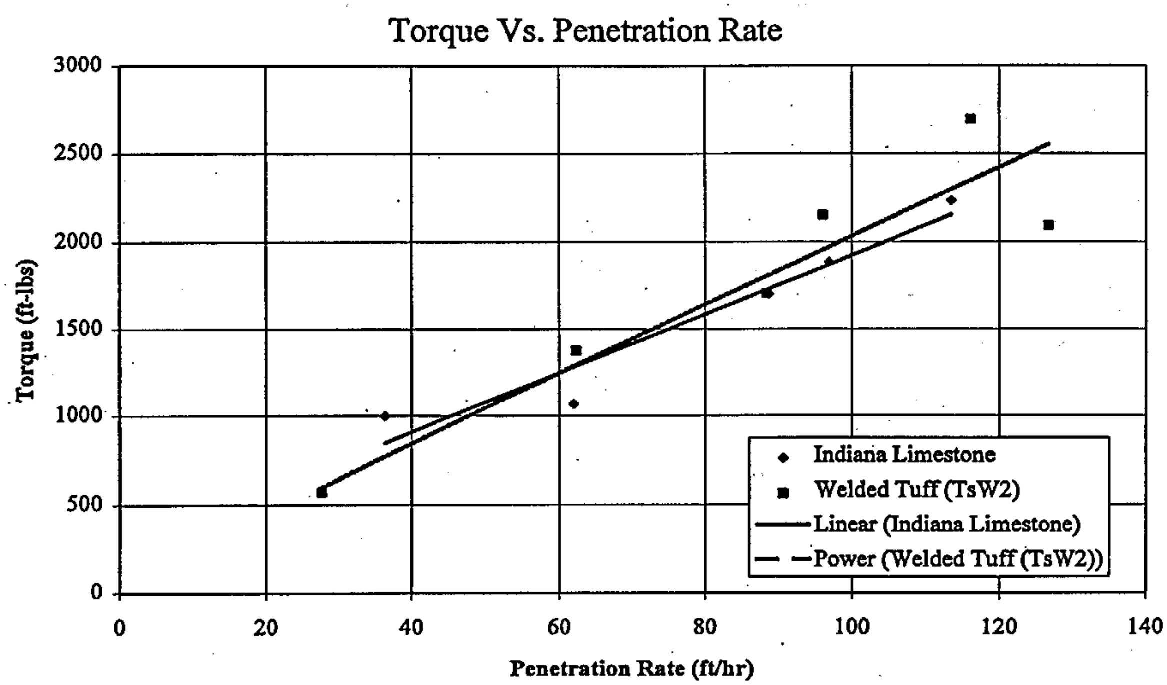


Figure 9
7 7/8 Inch Bit Drilling Test Results, Atmospheric

inches diameter. Samples of Welded Tuff and Indiana Limestone were used so direct comparisons could be made with the previous atmospheric tests.

Initially, tests were to be run at a constant rpm, circulation rate and WOB, with chamber pressure varied in increments of 500 psi. This procedure did not work well as the various “constants” could not be held. Therefore, chamber pressure was held constant while WOB was varied. A great deal of data was obtained, including a comparative run in the Limestone with a standard tri-cone bit.

To make sense of the data, in which every parameter was a variable, multiple regression analyses were conducted. Results were formatted in Excel and plots made. Logarithmic regression curves showed the closest correlation to actual data. Correlation was between 91 and 94%.

Figure 10 shows the fall-off in performance with pressure. While dramatic degradation was observed with the disc bit, a standard tri-cone bit was adversely affected as well. In fact, under similar conditions and at the highest pressure tested, the disc bit still drilled about 20% faster than the standard bit. Figure 11 shows ROP vs. WOB and Figure 12 shows Torque vs. Pressure.

This data also illustrates the importance of increasing WOB as pressure (depth) increases. In sandstone, 20,000 lbs WOB at atmospheric produced 65 ft/hr, 20,000 lbs WOB at depth produced only 5 ft/hr. Increasing WOB to 30,000 lbs doubled penetration to just over 10 ft/hr.

Figures 13, 14 and 15 show similar curves for the 25,000 psi strength Welded Tuff. The most interesting observation is the fact that at the same WOB, ROP was actually higher in the 25,000 psi Welded Tuff than in the 10,000 psi Limestone. The main difference in the two rock types besides compressive strength is porosity. The Welded Tuff is completely impervious while the Limestone is extremely porous. The drilling mud, under pressure, filling the pores of the rock greatly increases its apparent strength. This phenomenon is seen in a minor way in porous saturated vs. dry rock in atmospheric tests, but never to the degree seen here (by us mining folks, that is).

3.0 SUMMARY

To date, the laboratory tests are very encouraging. At atmospheric and low pressure conditions, the disc bit penetration rates are outstanding. The performance degrades rapidly with pressure (depth) and especially in porous rock formations. Although the fall-off rate was disappointing, the disc bit still showed a 20% advantage over a conventional tri-cone bit under similar conditions.

The data also indicated that performance improved rapidly with higher Weight on Bit. The direction for future effort is clear. Improve the structural capacity of the cutters to accept higher loads. The 1997 project goals are to increase the load capacity of the bit, and then gain some field in the ground experience.

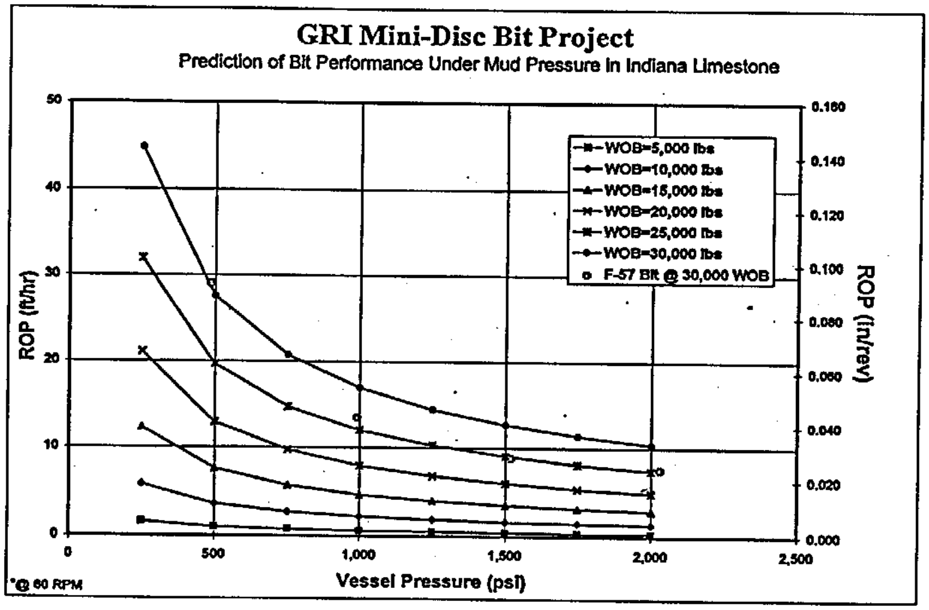


Figure 10
7 7/8 Inch Bit, ROP vs. Vessel Pressure, Limestone

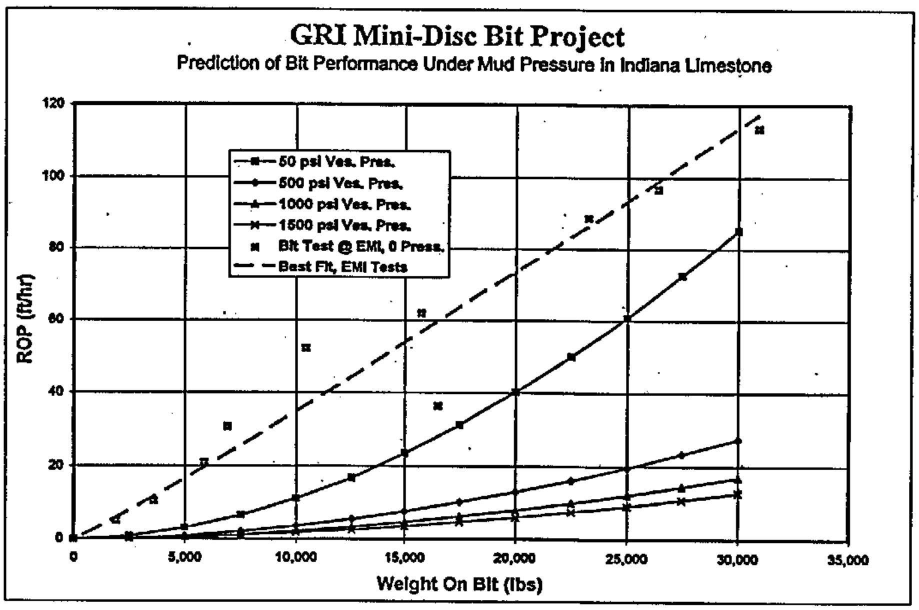


Figure 11
7 7/8 Inch Bit, ROP vs. WOB, Limestone

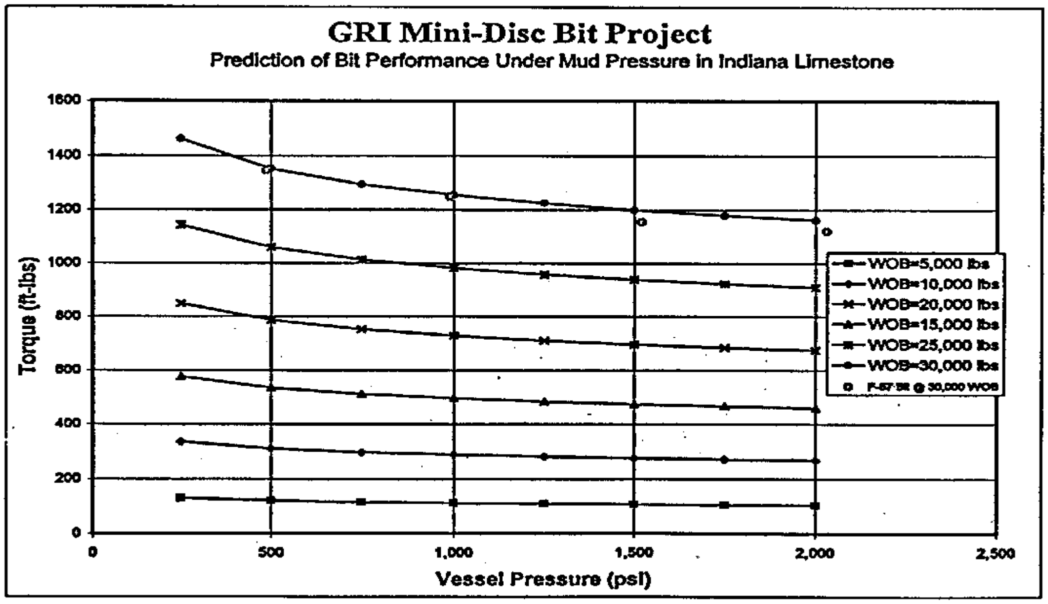


Figure 12
7 7/8 Inch Bit, Torque vs. Vessel Pressure, Sandstone

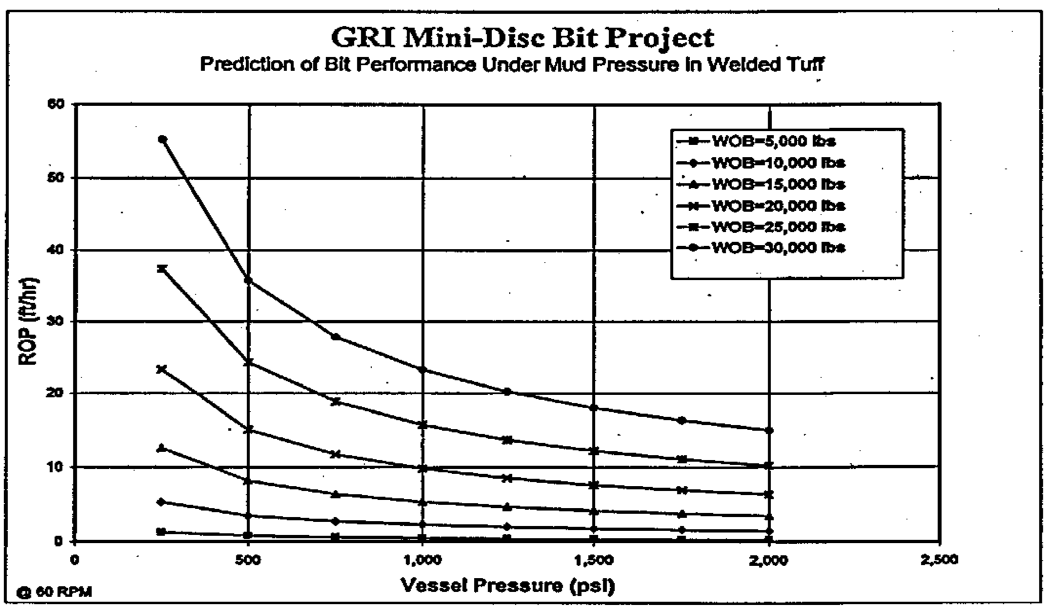


Figure 13
7 7/8 Inch Bit, ROP vs. Vessel Pressure, Welded Tuff

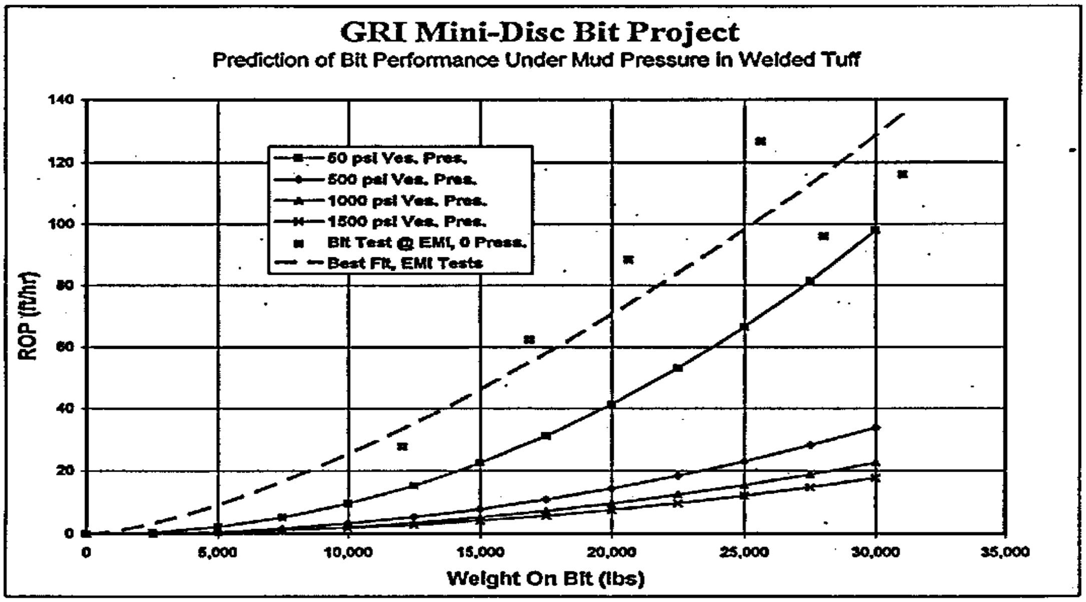


Figure 14
7 7/8 Inch Bit, ROP vs. WOB, Welded Tuff

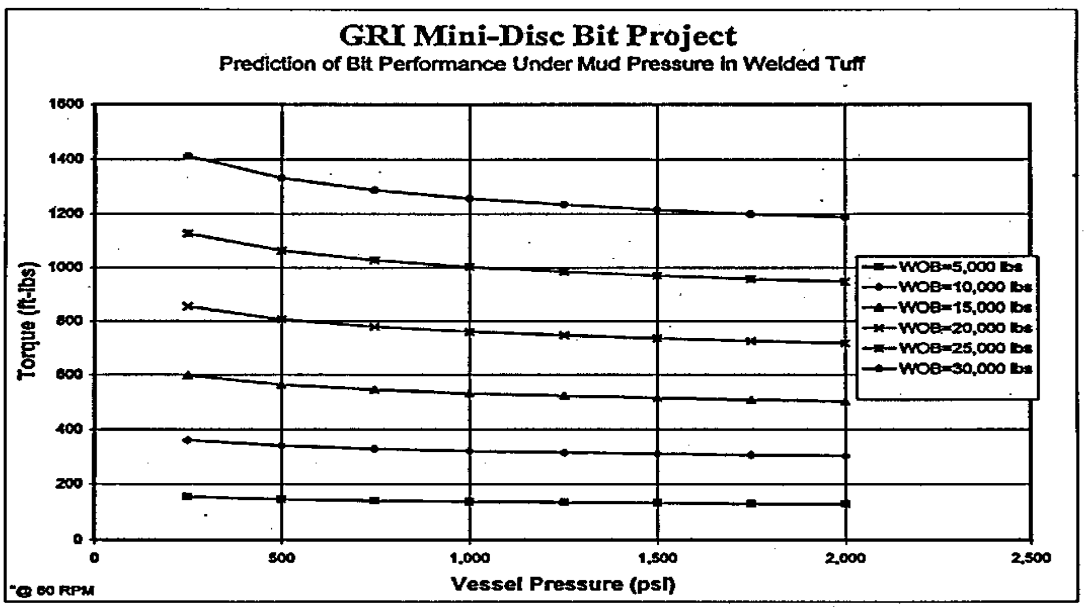


Figure 15
7 7/8 Inch Bit, Torque vs. Vessel Pressure, Welded Tuff