DOWNHOLE VIBRATION MONITORING & CONTROL SYSTEM FINAL REPORT – PHASE II

Starting date:	June 1, 2004
Ending Date:	January 31, 2006
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Submitting Organization	APS Technology, Inc. 800 Corporate Row Cromwell, CT 06416

DISCLAIMER

ABSTRACT

The objective of this program is to develop a system to both monitor the vibration of a bottomhole assembly, and to adjust the properties of an active damper in response to these measured vibrations. Phase I of this program, which entailed modeling and design of the necessary subsystems and design, manufacture and test of a full laboratory prototype, was completed on May 31, 2004.

The principal objectives of Phase II were: more extensive laboratory testing, including the evaluation of different feedback algorithms for control of the damper; design and manufacture of a field prototype system; and, testing of the field prototype in drilling laboratories or test wells. The specific tasks were modified in November, 2005 and these tasks are used as the basis of organization for this report.

The laboratory testing at TerraTek Laboratories was completed in January, 2006. ***These tests demonstrated that the DVMCS can maintain more consistent weight-on-bit, decrease vibration and increase the rate of penetration.***

With the exception of Task 10 (Ordering all long lead items for field prototypes), all of the tasks outlined have been completed and form the basis for the field testing and commercialization in Phase III, which is scheduled to end in January, 2007.

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Executive Summary

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Task 1: Develop final prototype development & testing plan

This task was completed early in this Phase, and then modified slightly in November, 2005. The tasks below represent this revised plan.

Task 2: Complete detailed design of prototype system using CAD

Redesign of laboratory prototype

The redesigned valve now has the coils located in the non-reciprocating portion of the tool. This lends itself to a more reliable electrical connection and better protection of the coils from the abrasive MR fluid.

Design of feedback system

The laboratory results of Phase I were analyzed to determine which particular feedback algorithms, and which input data, were likely to result in the most efficient control of the DVMCS. Two algorithms were identified for further study using the laboratory prototype:

? *Minimum WOB variation*. In this algorithm, the relative motion of the two halves of the DVMCS is used as a proxy for the approximate WOB. The algorithm minimizes the change in DVMCS motion, thereby keeping WOB constant. A memo describing this algorithm and its implementation is attached as **Appendix A.**

? *Hardening algorithm*. The first algorithm may have some difficulties near the extremes of motion. Under certain conditions, it might cause the DVMCS to ‘lock up’ and effectively remove all damping from the system. To remedy this possible problem, a ‘hardening algorithm’ was developed, which uses a quadratic factor, also based on the relative motion of the DVMCS. This approach is described in **Appendix B**.

Intermediate prototype design

The design of the field prototype evolved considerably over the course of this phase. Among the areas added or changed in the design are:

? Addition of a battery-powered, self-contained unit to record accelerations at the bit. (This is for evaluation purposes, and will likely not be a part of the commercial tool.)

? Addition of a battery to the DVMCS to preserve the absolute position when the tool is powered down.

? Elimination of the WOB sensor, as we will use the absolute deflection of the DVMCS as a proxy for this measurement.

? Development of a connector to transfer power and data between the turbine-alternator unit and the DVMCS sub.

According to the revised Statement of Work, the laboratory prototype design was modified to allow the prototype to be run in the drilling laboratory at TerraTek. Among the changes were:

? Replace the instrumented “bit” element with the appropriate bit box.
? Install the battery-operated vibration monitoring sub
? Install the internal motion controller input.
? Manufacture new upper sub to interface with the TerraTek commutator.

Task 3: Build mockups for laboratory testing

The revised laboratory mockup was built with the modifications described above. it was tested on our test bench, using the sweep algorithm. During testing, it was noted that the motor and gear train of the test bench could not provide sufficient power at higher frequencies without overheating or tripping the controller circuit breaker. Testing was therefore limited to 1.5 Hz. The initial results indicated a deviation from our earlier static testing and the model predictions. Given these two problems, testing of the feedback algorithms was postponed until the causes were better understood.

A new gearbox/motor combination was designed and installed in the test bench. A viscometer was procured, and was modified to include magnetic coils, to study the properties of our ‘home-made’ MR fluid *vs.* the Lord commercial fluid. Testing showed no differences in the fluids. (See below.)

Task 4: Test mockups in laboratory and analyze performance

<u>Preliminary Tests & Analysis</u>

A preliminary analysis of the dynamic test data showed variations in the dynamic stiffness of the damper varied over ranges from 11% (at 5,000 lbs. WOB) to 80% (at 10,000 lbs. WOB). These are significantly below the ranges predicted by the modeling and earlier static tests. Several explanations were posited for these findings:

? It was possible that the passive parts of the system – the oil-filled Belleville springs, the compensation system, and general friction – themselves provided significant dynamic stiffness, which reduces the relative effect of the DVMCS. To study this effect, the MR fluid was drained from the valve the system response using only the passive components.

  This test showed that viscous damping in the spring stack had a negligible effect on the overall damping, ruling this out at as cause of the lack of range. The tests did show, however, that the spring rate was slightly higher than assumed. The modeling was modified to reflect this fact.

? The difference in the results could be attributed to differences in the magnetic permeability of the alloys used in the damper construction, which result in lower magnetic fields than predicted. To study these results, several parallel approaches were used.

  o The magnetic fields in the gaps was measured directly.

  - Additional modeling was performed and alternate coil designs studied.
  - The permeability of the alloys was measured directly.

Analysis of the test data showed that the field in the damper gaps was only 60-90% of that required for saturation of the MR properties of the fluid. The increase in viscosity of the fluid was also less than was predicted by the Lord literature. The results of this analysis are in **Appendix C**, which also compares the results with the magnetic modeling of the damper.

The residual magnetic fields around the components were measured to be quite high, even in low coercivity 'nonmagnetic' materials. The low coercivity means, however, that a small reverse field can remove this residual magnetism. These tests and analyses are summarized in **Appendix C**, below.

? We used a 'home made' MR fluid for our testing, since the commercial fluid displayed unsatisfactory settling properties. It was possible that this fluid does not display the range of viscosities under the influence of the magnetic field that the commercial fluid does. To evaluate this possibility, we purchased a commercial viscometer, and modified it to allow the measurement to be made while applying a magnetic field to the fluid. Also, the properties of both the Lord and 'home made' MR fluids were analyzed for their viscosity properties.

The results of these tests are included in **Appendix D**, below In short, the tests showed that the home made MR fluid was comparable in properties to the commercial one, and that it allowed us to adjust the magnetic properties of the fluid by varying the ratio of iron to base oil.

Based on these results, the laboratory prototype external control circuitry was modified to include an demagnetization algorithm, and the earlier testing was repeated. The results were markedly improved and are presented below.

Implications for Redesign

The above tests led to several obvious conclusions:

? The damping of the inert components is not a significant factor in the overall damping coefficient of the DVMCS.

? The MR fluid used does not change its properties in a manner that would explain the lack of dynamic range observed in the first tests.

? The most significant cause of the results observed earlier was the residual magnetization of the components of the damper.

Further testing with demagnetization

Based on the above, a demagnetization algorithm was built into the laboratory control apparatus and our earlier dynamic testing was repeated. The demagnetization process was extremely effective as illustrated by **Figure 1**, below.

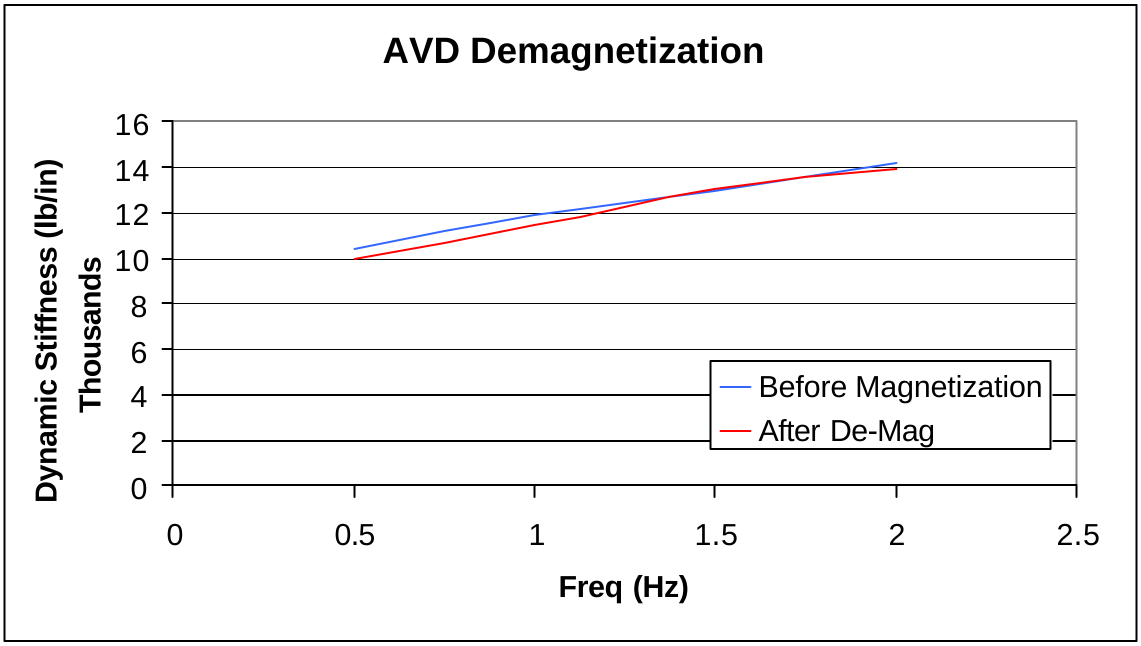

Figure 1: Effect of demagnetization on performance of MR damper

With the demagnetization circuit in place, a dynamic range of 7:1 was achieved at lower frequencies, and 10:1 at higher frequencies, as seen in **Figure 2**, below. This represents a significant improvement over the earlier results.

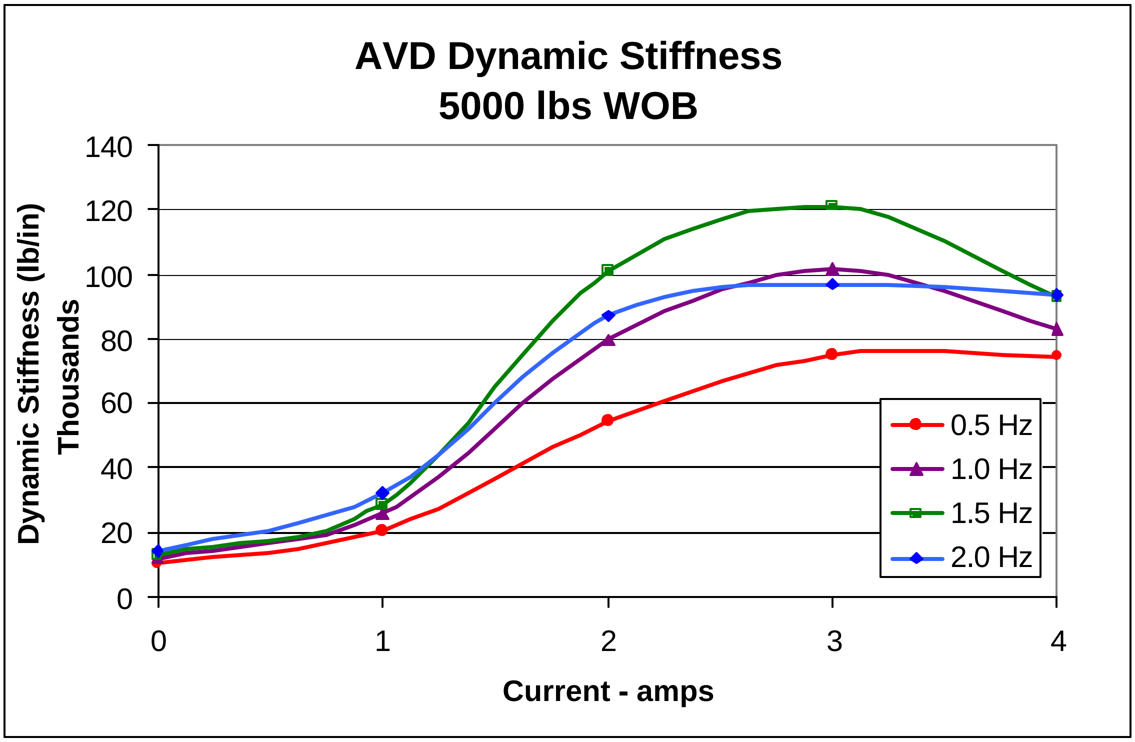

Figure 2: Performance of MR damper with demagnetization circuit operating

Task 5: Redesign mockups based on test results

Based on the above observations, several changes were made in the design.

? The coil circuit was modified to demagnetize the valve components when the field is to be reduced.

? In order to allow a wider choice of materials for the valve components, the valve was moved *above* the Belleville spring. This decreases the amount of load the valve must bear and allowed the alloys to be chosen on the basis of their magnetic properties and resistance to damage by the mud, rather than particularly on their strength.

? The damper design was 'inverted', putting the coils in the outer housing and leaving the mandrel a constant diameter. Calculations show that this geometry will generate much higher fields. It also greatly simplifies assembly, since the mandrel, which must be carefully slid into the housing, will have an even surface. A sketch of the new design is shown below in **Figure 3** . The coils are the orange features in the sketch.

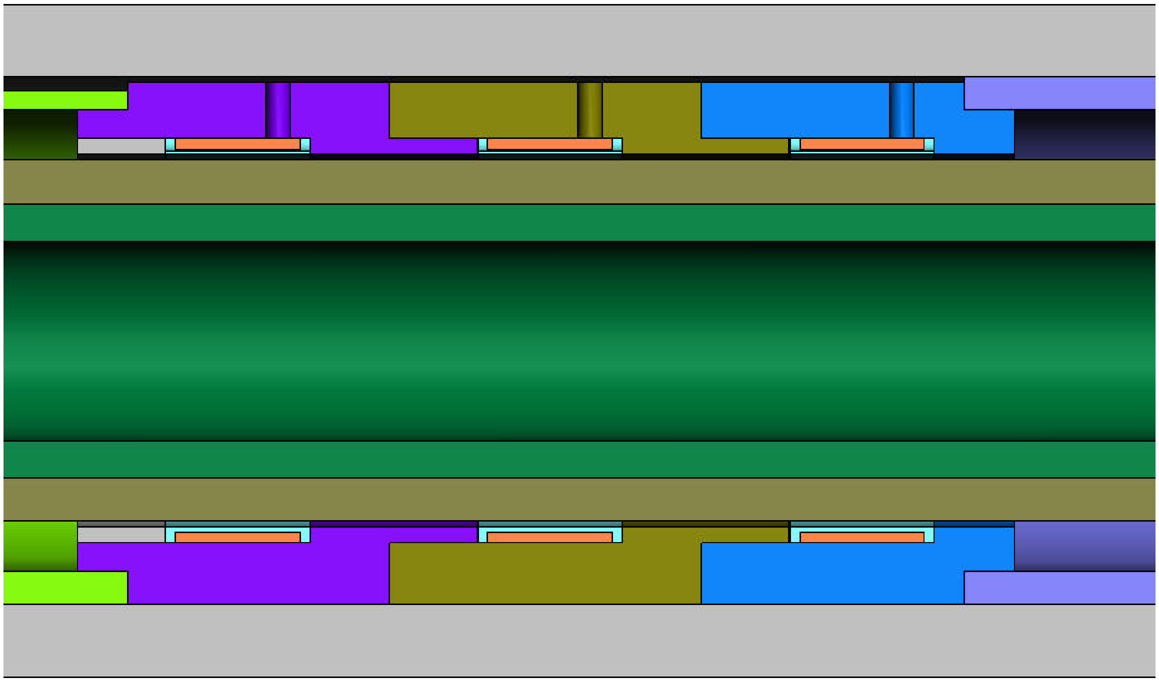

Figure 3 Schematic of redesigned MR damper section

Task 6: Build revised mockup

The revised mockup was constructed with the changes described above.

Task 7: Retest mockups in laboratory and analyze performance

The reworked prototype, with external coils, was tested on our laboratory test bench, described in the Phase I Final Report[1]. (A picture of the test bench is included in Reference 3.)

The test data were analyzed by our analytical specialist, Mark Wassell, and his conclusions are included in **Appendix E**. The dynamic range of the revised damper circuit was less than that of the original. This was attributed to two factors:

? The reworked mandrel was slightly smaller than the original, which resulted in a larger gap. This, in turn, reduced the ‘power off’ damping coefficient and also reduced the applied field for a given current.

? The reworked mandrel still had some of the internal structure of the original coil winding slots. While these were filled in, the interfaces might interfere with the magnetic flux lines, decreasing the efficiency of the magnetic circuit.

Despite these results, it was decided to go ahead with the testing using the current design. Since the ‘power off’ coefficient was quite low, the gap was reduced to increase the dynamic range. Time considerations prevented the manufacture of a new mandrel and the testing proceeded with the existing one.

Task 8: Refit laboratory mockup for use in drilling laboratory

The new and revised components of the prototype were manufactured and assembled with the changes described above. The test procedure and matrix were developed, and four test formations were designed and built. These each consist of a slab of hard granite mounted at an angle of 10º within a larger hard concrete block. (See **Figure 4**-**Figure 8**.) The contrast in hardness at the inclined interfaces was designed to induce significant vibration in the drilling, which will serve as a test of the efficiency of the damper and its feedback algorithms. [Note that the holes shown in **Figure 4** are schematic only, and do not represent the planned drilling pattern.]

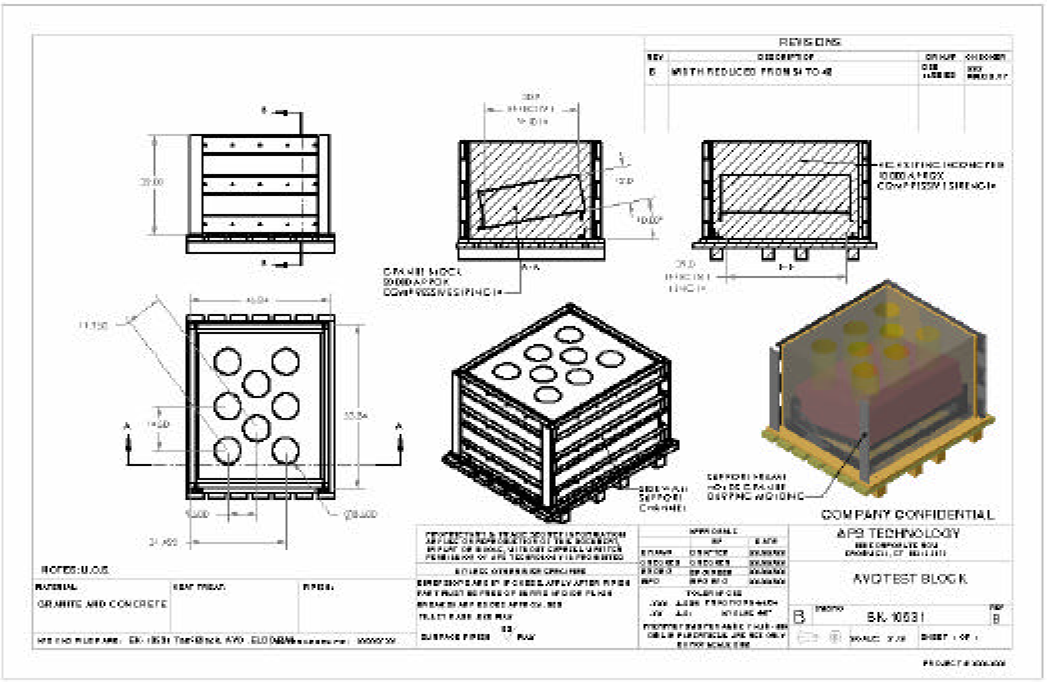

Figure 4: Drawing of test blocks for drilling lab testing

Figure 5: Granite blocks and concrete molds ready for assembly

Figure 6: Positioning granite block at 10º angle before concrete pour

Figure 7: Pouring concrete for first block

Figure 8: Finished blocks begin setting process

Task 9: Test in drilling laboratory

The tests were run from January 23-27, 2006. A summary of the results is included as **Attachment F**. The conclusions reached from analysis of the data include:

1. The vibration levels measured through the tests were fairly benign. These were in the 5 – 25 g level.
2. Significant bit wear occurred during the tests. For a conventional collar, the ROP at the end of the tests was 60% of the ROP at the start of the tests. To account for this the ROP rates were corrected based on a linear degradation of the bit for each hole drilled. Other drilling results, such as WOB, TOB acceleration, have not been corrected for bit wear.
3. Even with the benign drilling conditions the DVMCS showed its ability to improve ROP. ***While drilling through concrete, the DVMCS improved ROP by 10 – 15%. For granite the improvement was up to 11%***. While drilling through granite at 120rpm with 15,000 WOB the ROP actually dropped by 2%; however, lighter damping might improve this situation. The lighter damping case was not run.
4. The optimum drilling condition occurs when the DVMCS internal travel is ~0.17”. If the drilling becomes too smooth, the ROP actually drops. There appears to be an optimum travel and WOB fluctuation that produces the best ROP. We believe that some vibration may improve cutting efficient, but this has not been proven.

5. The DVMCS tool significantly decreased the WOB fluctuations compared to the conventional drill collar. ***The DVMCS reduced the WOB fluctuation by 60%.*** This should be even more beneficial under high vibration conditions.
6. The DVMCS displacement was 0.25” for the power off state and 0.13” at full power. The dynamic stiffness varied from 4200 lb/in to 17,800 lb/in. These ranges should significantly improve for the commercial tool. Upon disassembly of the DVMCS tool, it was found that the brass bobbins for the damper coils had become slightly magnetic. This would have reduce the performance of the magnetic coils.
7. The tool was disassembled after the completion of the tests to inspect the seals and bearings. Both the bearings and the seals were still in good working order

Task 10: Complete procurement of long-lead items

The testing described in Appendix I resulted in some considerable changes in the design of the prototype. These include the following:

? The internal position monitor (LVDT) did not produce sufficient signal within the collar to control the feedback loop, and it was necessary to rely upon an external sensor during the TerraTek testing. This has necessitated a complete redesign of the LVDT, which is currently underway. Tests with a ¼-scale model were very promising and a full-scale laboratory prototype is currently being assembled.

? Assembly of the laboratory prototype, and its conversion to the drilling lab prototype, demonstrated that the current design was overly complicated and extremely difficult to assemble, and not commercially viable.

? Furthermore, potential commercial partners indicated a strong preference for a system which can be integrated into their existing shock subs. A significant part of the DVMCS (bearings, Belleville springs, *etc*.) is very similar to a shock sub, with the key addition being the active feedback and control system.

Based on these considerations, the use of our existing prototype in the field was not considered practical and began a redesign. The result is a much improved tool. In particular:

? The hydraulic compensation system was modified so that it uses a single reservoir at the top of the tool. By eliminating the lower reservoir, the bottom end of the tool becomes essentially identical to a standard shock sub. This permits its integration into existing products and will greatly reduce manufacturing costs.

? A reconfiguration of the tool permits greater flexibility in assembly and maintenance. In particular, it will not be necessary to depressurize the MR fluid section to perform routine maintenance.

? The part count has been significantly reduced.

This redesign was only completed in April, and is shown in **Appendix G**. Task 10 is, therefore, ongoing.

Task 11: Update economic, market and environmental analyses

Economic & Market Analysis

A “bottom up” economic model was prepared for the DVMCS. In this model, typical drilling costs are input for the particular market. Some basic assumptions are made about the improvement provided by the DVMCS, how these savings are to be shared by the service company and its clients, to generate an anticipated revenue per job. The estimated number of jobs per year is also estimated.

To estimate costs, we included: cost of purchasing the units; number of units needed to support one job; cost of money; anticipated repair costs and schedule; overhead, *etc*. On this basis, one can calculate the ROI and payback period for our customer (*i.e.*, the oilfield service or supply company) on purchasing systems. Preliminary calculations show that, with reasonable, conservative assumptions, the DVMCS represents a very attractive investment, even for simple vertical well drilling. In deep, hard rock or off-shore drilling the paybacks are enormous. One example of the results of the model is shown in **Table 1** , on page 17. The model can be refined as the parameters become better defined during Phase III.

To balance this model, we also commissioned a “top down” model for several APS products and potential products. the DVMCS[*]. This model, produced by Spears & Associates, looked at the total domestic drilling market projections, estimated the value of this product, including rig time savings, repair and replacement costs for damaged products, *etc*. It also assume reasonable sharing of these savings among the end user, service company and supplier (*i.e.*, APS.) It also indicated an enormous market for this product. An excerpt of this study, dealing with the DVMCS, is attached as **Appendix H**.

These studies have been confirmed by the level of customer interest in these tools from several service and supply companies. The results of the testing at TerraTek have only heightened this interest. We anticipate signing one or several non-exclusive agreements to provide this DVMCS, or at least the active parts of it, before the end of Phase III. We furthermore anticipate the generation of revenues from the sale or leasing of the “precommercial” prototypes during 2006.

Environmental analysis

The DVMCS is, by and large, a standard piece of oilfield hardware. The only non-standard substance is the magnetorheological fluid (MRF). The MRF consists of iron filings suspended in a high-temperature synthetic oil, and therefore poses no more environmental risks than the oil itself, which are minimal. The development of the DVMCS therefore poses no significant environmental risks.

Task 12: Update financing plan

The financing plan is now based upon the very likely formation of partnerships with one or more service and supply companies to market the DVMCS. Several have expressed

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[*] Note: This study was part of a general business model and was not charged to this contract.

interest. We fully anticipate that we will earn revenue through the sale or lease of the precommercial prototypes, and this will fully support the efforts of Phase III and beyond. There are several models for the commercialization of the DVMCS, including:

- Construction and sale of the tools by APS Technology. In this model, APS would manufacture the entire tool and sell it to oilfield tool or service companies.
- As an alternative, APS could set up an operation to lease the tools. We are investigating this option for several other of our products. As the tool may be most useful in very specific environments, our customers may prefer this option.
- Sale of the active elements of the DVMCS. Based upon discussions with potential customers, this appears to be the most likely option. The customers would manufacture the conventional components of the DVMCS (bearings, Belleville springs, *etc*.) Our customers can, in all probability, manufacture these items at lower cost, or adapt their standard parts. APS would provide the active elements, and the software to control them.
- To allow APS to fully share in the potentially enormous market for this tool, a royalty based on usage would be charged, except possibly in the leasing option.

Task 13: Submit Phase II final report

This document constitutes the final report on Phase II.

Table 1: Economic Model of DVMCS for Service Company User

REVENUE CALCULATION

TYPICAL JOB	QUANTITY	RATE	PER JOB TIME	PER JOB COST	ANNUAL
DAYS	25.0				
COST PER DAY		$ 28,000			
TOTAL DRILLING COST				$ 700,000	
NO OF TRIPS	7.0				
HOURS PER TRIP		12.0			
TRIPPING HOURS			84.0		
MAINTENANCE HOURS/DAY	2.0				
MAINTENANCE HOURS			50.0		
DRILLING HOURS			466.0		
AVD SAVINGS					
ROP INCREASE		10%			
DRILLING HOURS SAVED			42.4		
TRIPS AVOIDED	2				
TRIPPING HOURS SAVED			24.0		
NET TIME REDUCTION			66.4		
COST SAVINGS				$ 77,424	
PERCENT TO SERVICE CO		50%			
SERVICE CO GROSS REV				**$ 38,712**	
NUMBER OF JOBS	12				
ANNUAL REVENUE					**$ 464,545**

COST CALCULATION

COST OF TOOL	$ 200,000				
TOOLS/JOB	2.5				
TOTAL TOOL COST	$ 500,000				
USEFUL LIFE (years)		5			
DEPRECIATION (s/l)					**$ 100,000**
INTEREST RATE	6.0%				
INTEREST COST					**30,000**
TOOL REFURBISHMENT	$ 12,000				
DRILLING HOURS/REFURB		500			
NUMBER OF REFURBS/YR		11			
MAINTENANCE COSTS					**$ 132,000**
DEPLOYMENT COSTS/JOB	$ 3,000				
TOTAL DEPLOYMENT					**$ 36,000**
TOTAL ANNUAL COST					**$ 298,000**

PAYBACK CALCULATION

NET PROFIT	**$ 166,545**
ROI	**33.3%**
PAYBACK (YEARS)	**3.00**

Other

A paper on the early work on this project was given at the National Gas Technologies II Conference in February, 2004[2]. A paper on this project was also presented to the American Association of Drilling Engineers National Technology Conference in April, 2005[3].

An abstract has been submitted to the IADC/SPE Asia Pacific Drilling Technology Conference, 13 - 15 Nov 2006, in Bangkok, Thailand. We also plan to submit an abstract to either the SPE Annual Technical Conference & Exhibition (24-27 Sept 200, San Antonio) or to the SPE/IADC Drilling Conference 20-22 February, 2007,Amsterdam.) If this abstract is accepted, we plan to withdraw the one for the APDTC.

Units

To be consistent with standard oilfield practice, English units have been used in this report. The conversion factors into SI units are given below.

1 ft. = 0.30480 m
1 g = 9.82 m/s
1 in. = 0.02540 m
1 klb. = 4448.2 N
1 lb. = 4.4482 N
1 rpm = 0.01667 Hz
1 psi = 6984.76 Pa

References

[1] M.E. Cobern, "Downhole Vibration Monitoring & Control System, Phase I Final Report, 31 August, 2004"

[2] M.E. Cobern & M.E. Wassell, "Drilling Vibration Monitoring & Control System," presented at the Natural Gas Technologies II Conference, Phoenix, 8-11 Feb 2004

[3] M.E. Cobern & M.E. Wassell, "Laboratory Testing of an Active Drilling Vibration Monitoring & Control System," presented at the AADE National Technical Conference & Exhibition, Houston, 5-7 April, 2005, paper AADE-05-NTCE-25.

Appendix A: Minimum WOB Variation

APS advanced product support
TECHNOLOGY

MEMORANDUM

TO: **Marty, Dan, Bill, Doug, Carl**

FROM: **Mark Wassell**

DATE: **August 17, 2004**

SUBJECT: **AVD Sensor Algorithm**

CC:

Scope

I ran through a number of analyses to get some data for the AVD sensor algorithm. These analyses look at the vibration data that can be easily measure during operation downhole.

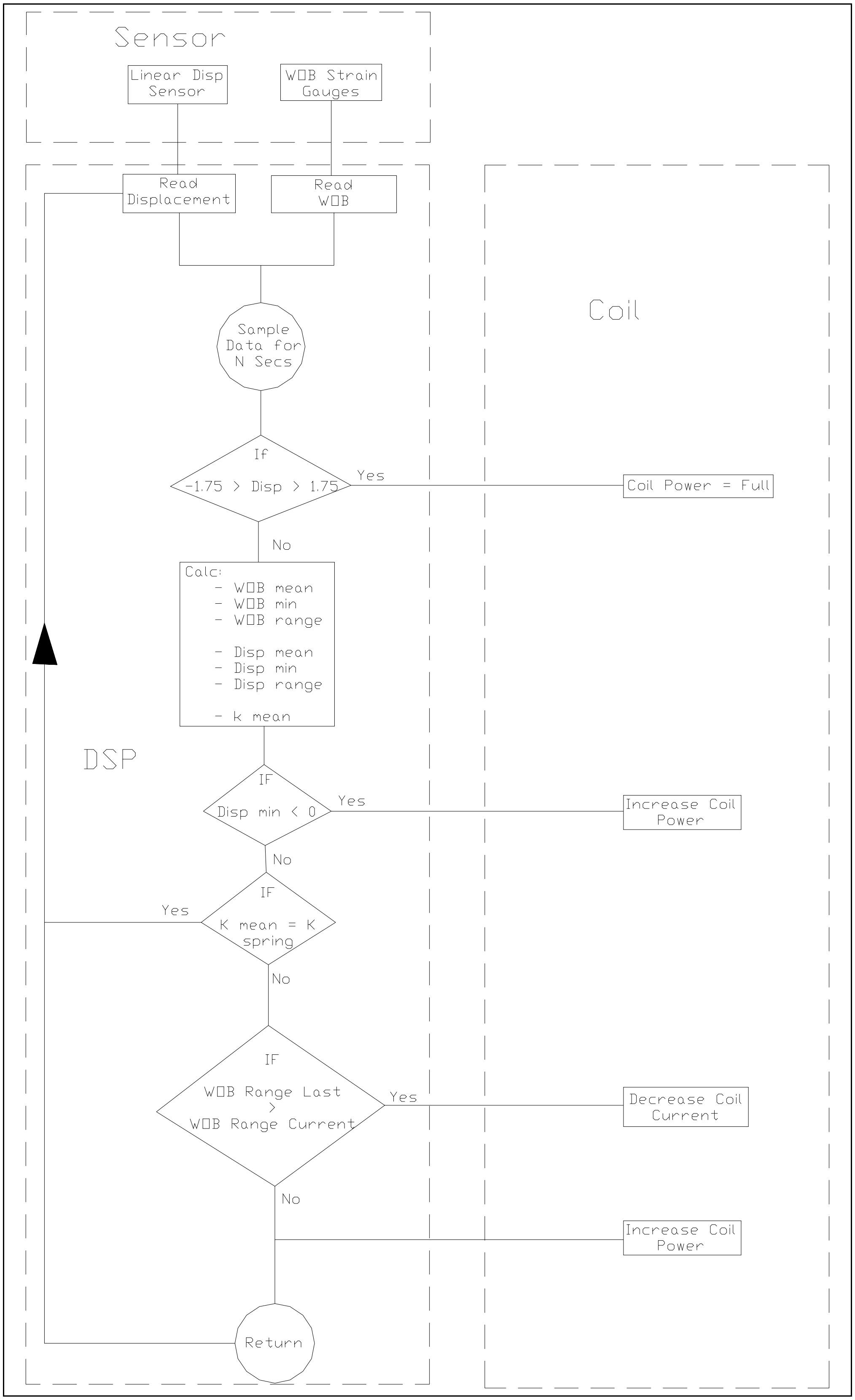
Summary

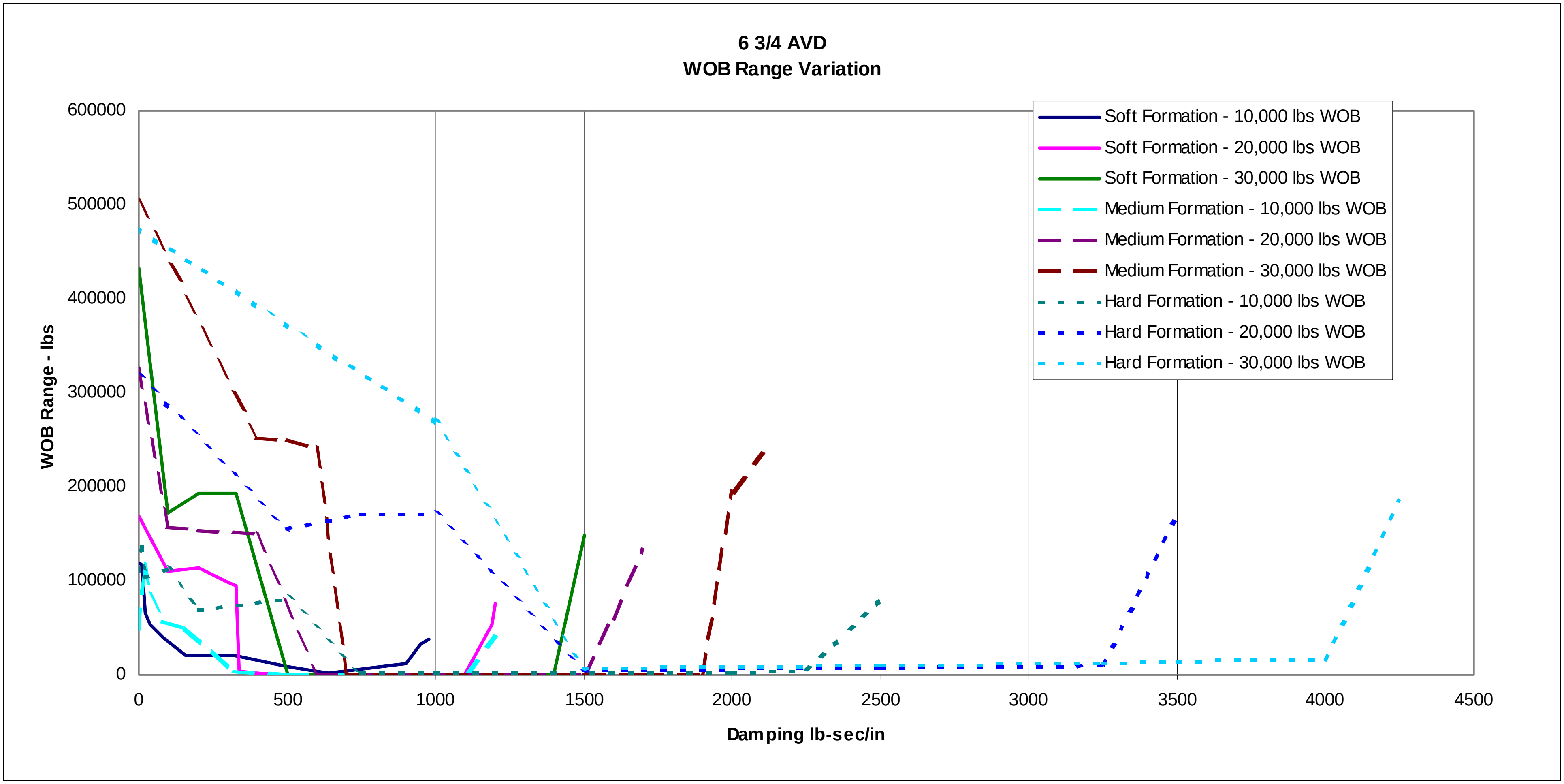
1. It is easy to determine whether the system damping is optimal because the WOB range and the displacement range are minimized. However, when the system does not have optimum damping it is difficult to determine whether there is too much or too little damping.
2. This method uses the absolute linear displacement between the upper and lower housings and the fluctuating WOB to determine whether the damping needs to be adjusted.
3. The WOB measurement needs only to be a relative measurement and therefore does not require the accuracy of the typical WOB tool. Drift, pressure and temperature effects do not need to be included into the measurement, only the range and the average need to be measured.
4. The linear displacement sensor must measure absolute position for this method.
5. One indication that the damping is optimized is that the WOB range is minimal. However, the high the applied weight on bit the greater the WOB range. Therefore without knowing the desired or actual WOB it is difficult to tell whether the system has been optimized.
6. The analysis also shows that when the dynamic spring rate of the system equals the static spring rate the system has been optimized. In general if the dynamic spring rate is greater than the static spring rate, then damping level is to low. If

the dynamic spring rate is less than the static spring rate then the damping is to high.

7. If the minimum displacement is negative then the damping level is to low. However, for high WOB the minimum displacement is positive. Therefore this is only useful at low WOB.

Figure 1 - Damping Control Schematic




6 3/4 AVD
WOB Range Variation
WOB Range - lbs
600000
500000
400000
300000
200000
100000
0
0
500
1000
1500
2000
2500
3000
3500
4000
4500
Damping lb-sec/in
Soft Formation - 10,000 lbs WOB
Soft Formation - 20,000 lbs WOB
Soft Formation - 30,000 lbs WOB
Medium Formation - 10,000 lbs WOB
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Hard Formation - 10,000 lbs WOB
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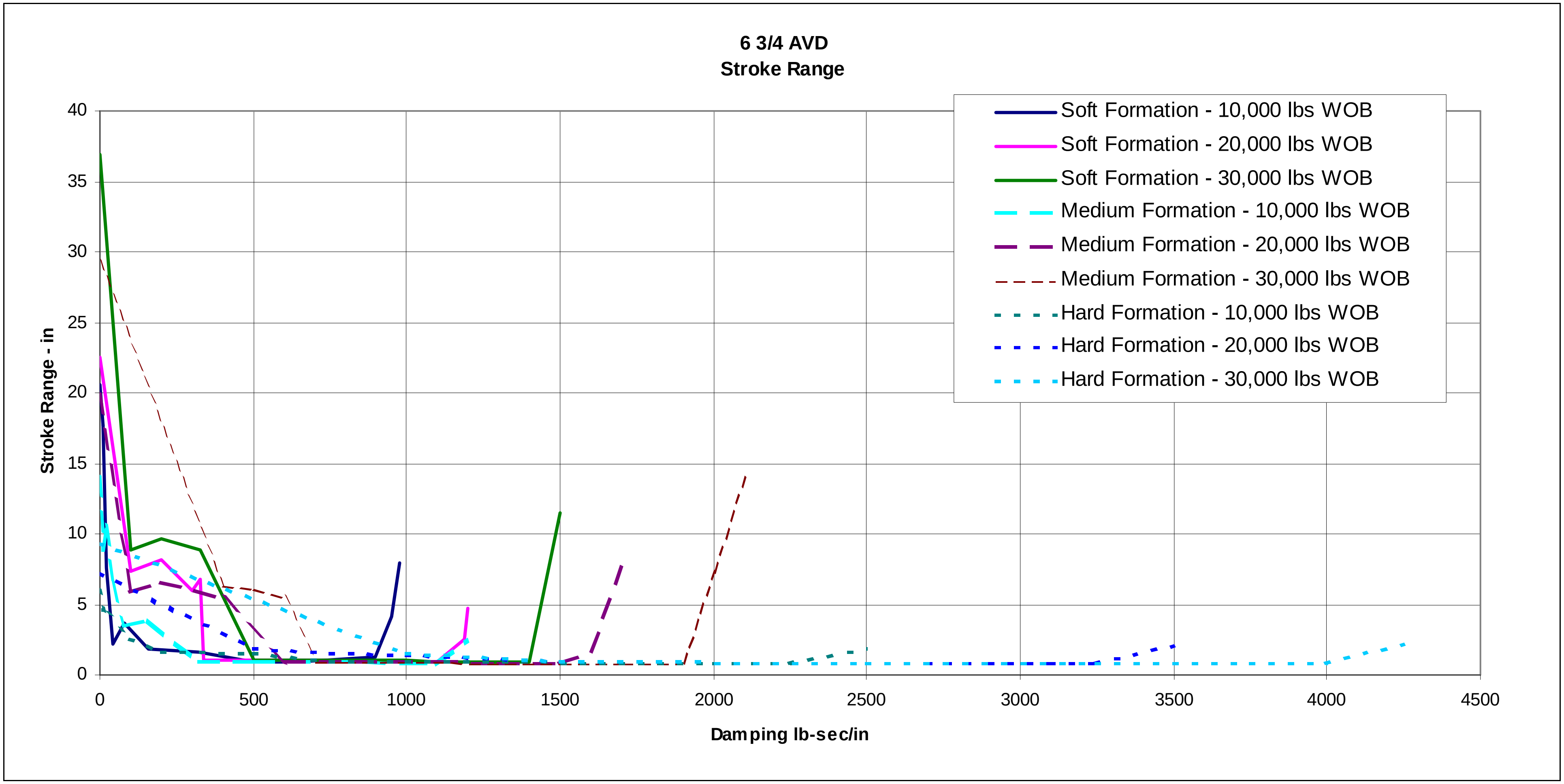
6 3/4 AVD
Stroke Range
Stroke Range - in
40
35
30
25
20
15
10
5
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0
500
1000
1500
2000
2500
3000
3500
4000
4500
Damping lb-sec/in
Soft Formation - 10,000 lbs WOB
Soft Formation - 20,000 lbs WOB
Soft Formation - 30,000 lbs WOB
Medium Formation - 10,000 lbs WOB
Medium Formation - 20,000 lbs WOB
Medium Formation - 30,000 lbs WOB
Hard Formation - 10,000 lbs WOB
Hard Formation - 20,000 lbs WOB
Hard Formation - 30,000 lbs WOB

Appendix B: Hardening Algorithm

AVD – Hardening Damper Scheme

Scope

This scheme uses the relative position of the AVD inner housing to the outer housing to set the MR damping. Analysis shows that the greater the travel of the damper the higher the required damping level. Analysis shows that lighter WOB requires less damping than higher WOB. The analysis also shows that the greater the stroke the greater the required damping. The analysis below shows that this concept works for varying amounts of WOB and ROP.

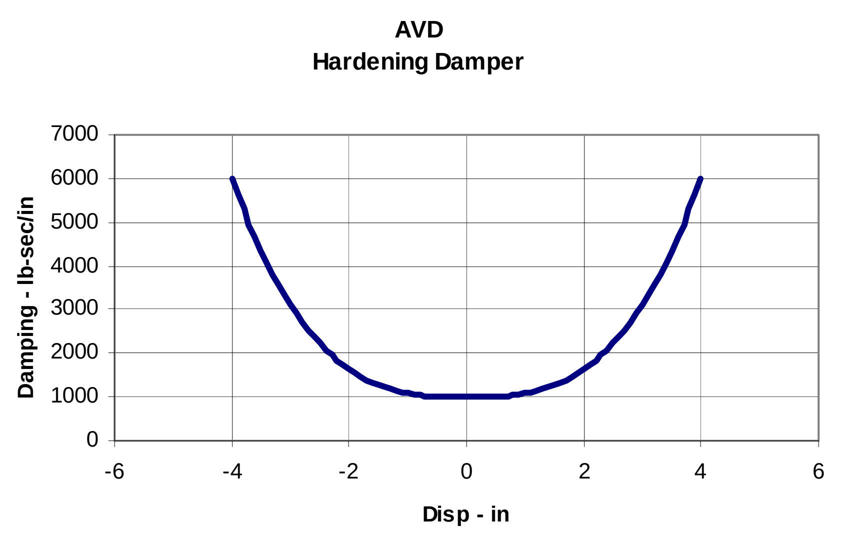
Analysis

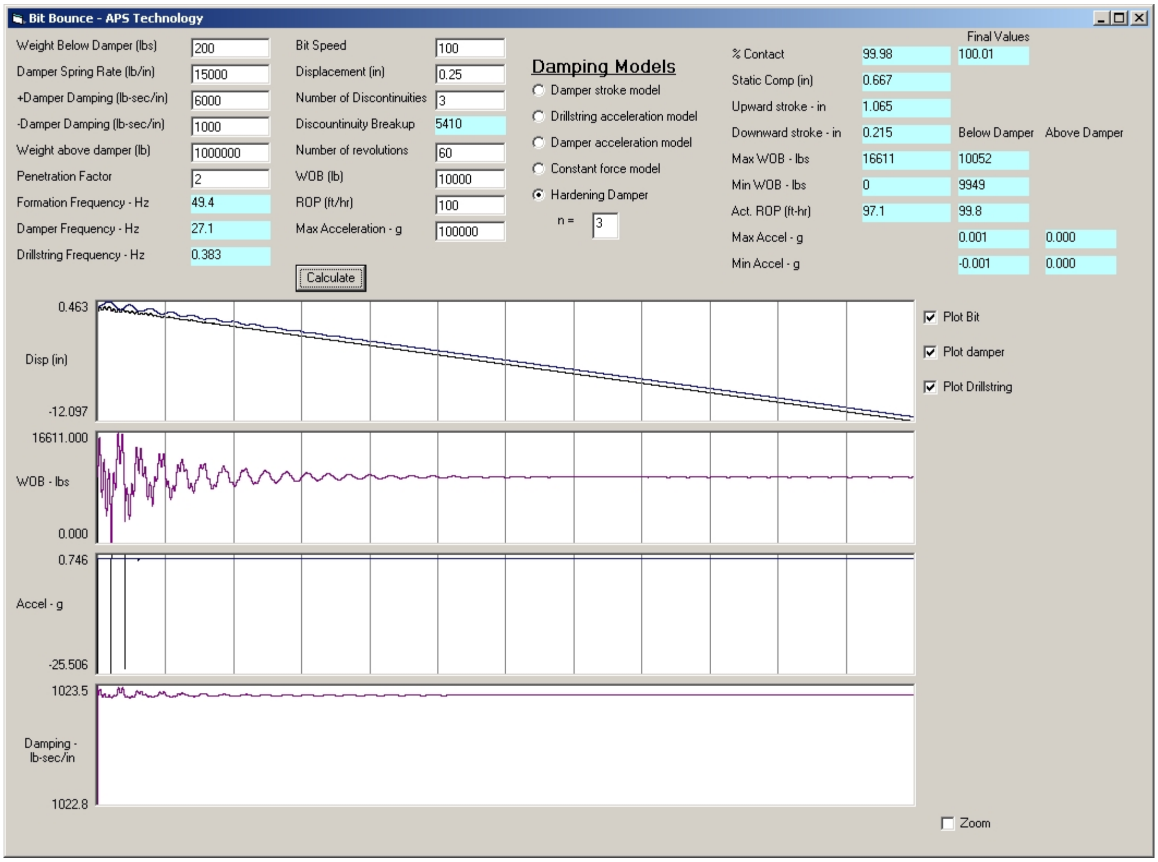
The hardening equation:

$$c = A \times d^n + B$$

where:

c = damping (lb-sec/in)
$A = (\text{damp}_{\text{max}} - \text{damping}_{\text{min})}) / \text{disp}^{\ n}$
B = Min damping





Weight Below Damper (lbs) 200
Damper Spring Rate (lb/in) 15000
+Damper Damping (lb-sec/in) 6000
-Damper Damping (lb-sec/in) 1000
Weight above damper (lb) 1000000
Penetration Factor 2
Formation Frequency - Hz 49.4
Damper Frequency - Hz 27.1
Drillstring Frequency - Hz 0.383

Bit Speed 100
Displacement (in) 0.25
Number of Discontinuities 3
Discountinuity Breakup 5410
Number of revolutions 60
WOB (lb) 10000
ROP (ft/hr) 100
Max Acceleration - g 100000

Damping Models

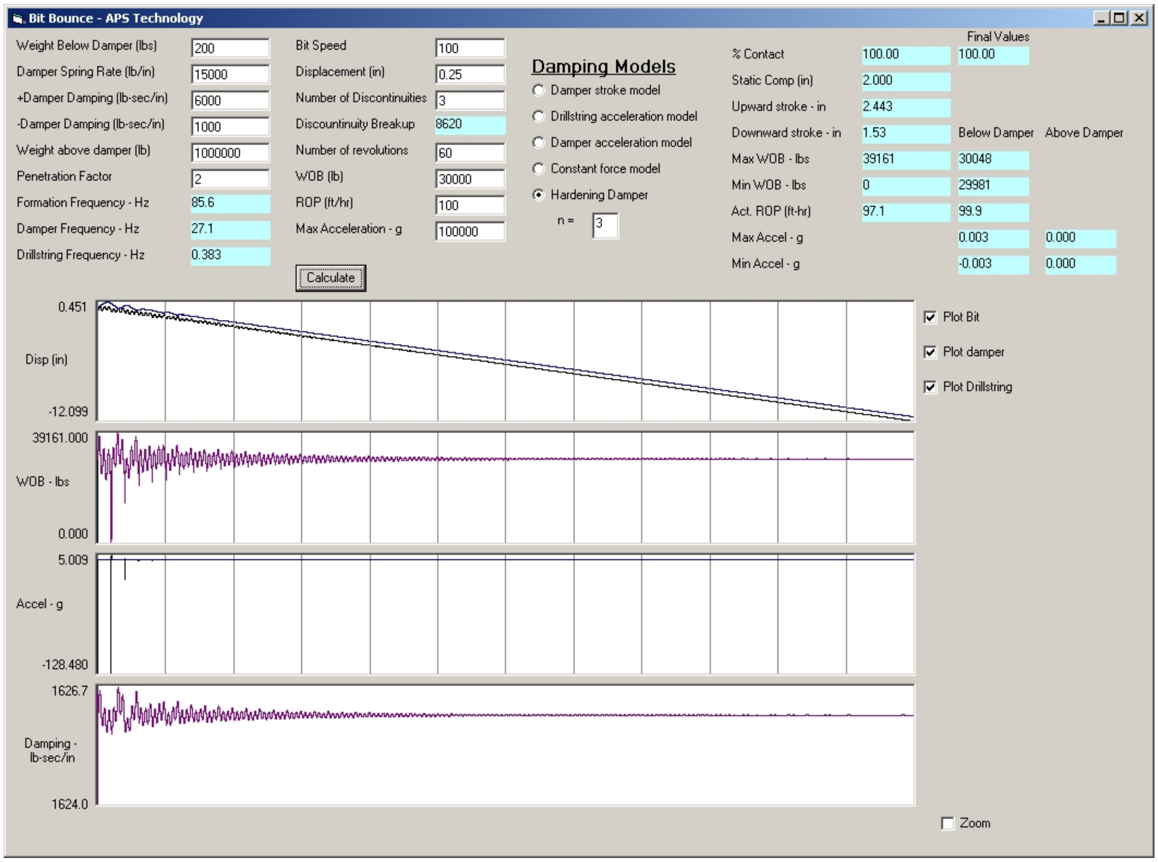
- ○ Damper stroke model
- ○ Drillstring acceleration model
- ○ Damper acceleration model
- ○ Constant force model
- ● Hardening Damper

n = 3

		Final Values	
% Contact	99.98	100.01	
Static Comp (in)	0.667		
Upward stroke - in	1.065		
Downward stroke - in	0.215	Below Damper	Above Damper
Max WOB - lbs	16611	10052	
Min WOB - lbs	0	9949	
Act. ROP (ft-hr)	97.1	99.8	
Max Accel - g		0.001	0.000
Min Accel - g		-0.001	0.000

☑ Plot Bit
☑ Plot damper
☑ Plot Drillstring

☐ Zoom



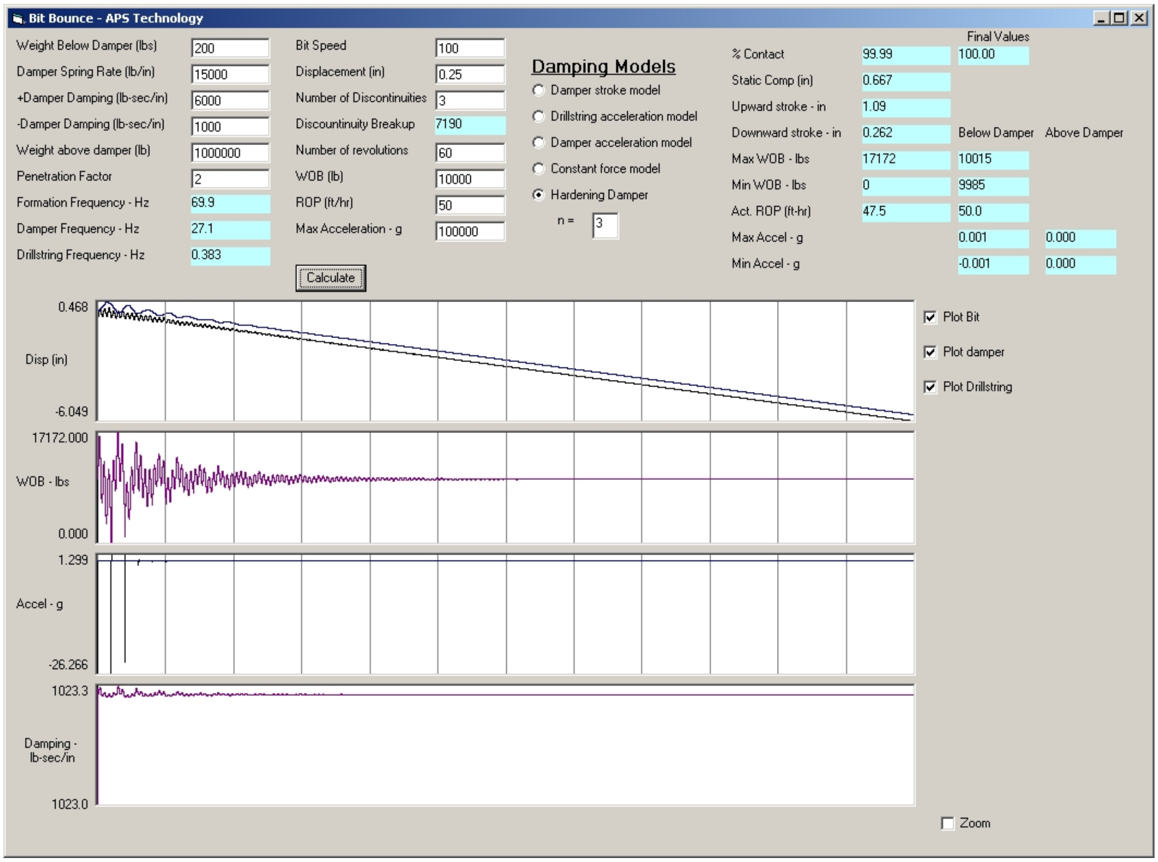
Weight Below Damper (lbs)	200	Bit Speed	100
Damper Spring Rate (lb/in)	15000	Displacement (in)	0.25
+Damper Damping (lb-sec/in)	6000	Number of Discontinuities	3
-Damper Damping (lb-sec/in)	1000	Discountinuity Breakup	8620
Weight above damper (lb)	1000000	Number of revolutions	60
Penetration Factor	2	WOB (lb)	30000
Formation Frequency - Hz	85.6	ROP (ft/hr)	100
Damper Frequency - Hz	27.1	Max Acceleration - g	100000
Drillstring Frequency - Hz	0.383		

Damping Models

○ Damper stroke model
○ Drillstring acceleration model
○ Damper acceleration model
○ Constant force model
● Hardening Damper
n = 3

		Final Values	
% Contact	100.00	100.00	
Static Comp (in)	2.000		
Upward stroke - in	2.443		
Downward stroke - in	1.53	Below Damper	Above Damper
Max WOB - lbs	39161	30048	
Min WOB - lbs	0	29981	
Act. ROP (ft-hr)	97.1	99.9	
Max Accel - g		0.003	0.000
Min Accel - g		-0.003	0.000

☑ Plot Bit
☑ Plot damper
☑ Plot Drillstring
☐ Zoom



Bit Bounce - APS Technology

Weight Below Damper (lbs)	200
Damper Spring Rate (lb/in)	15000
+Damper Damping (lb-sec/in)	6000
-Damper Damping (lb-sec/in)	1000
Weight above damper (lb)	1000000
Penetration Factor	2
Formation Frequency - Hz	69.9
Damper Frequency - Hz	27.1
Drillstring Frequency - Hz	0.383

Bit Speed	100
Displacement (in)	0.25
Number of Discontinuities	3
Discountinuity Breakup	7190
Number of revolutions	60
WOB (lb)	10000
ROP (ft/hr)	50
Max Acceleration - g	100000

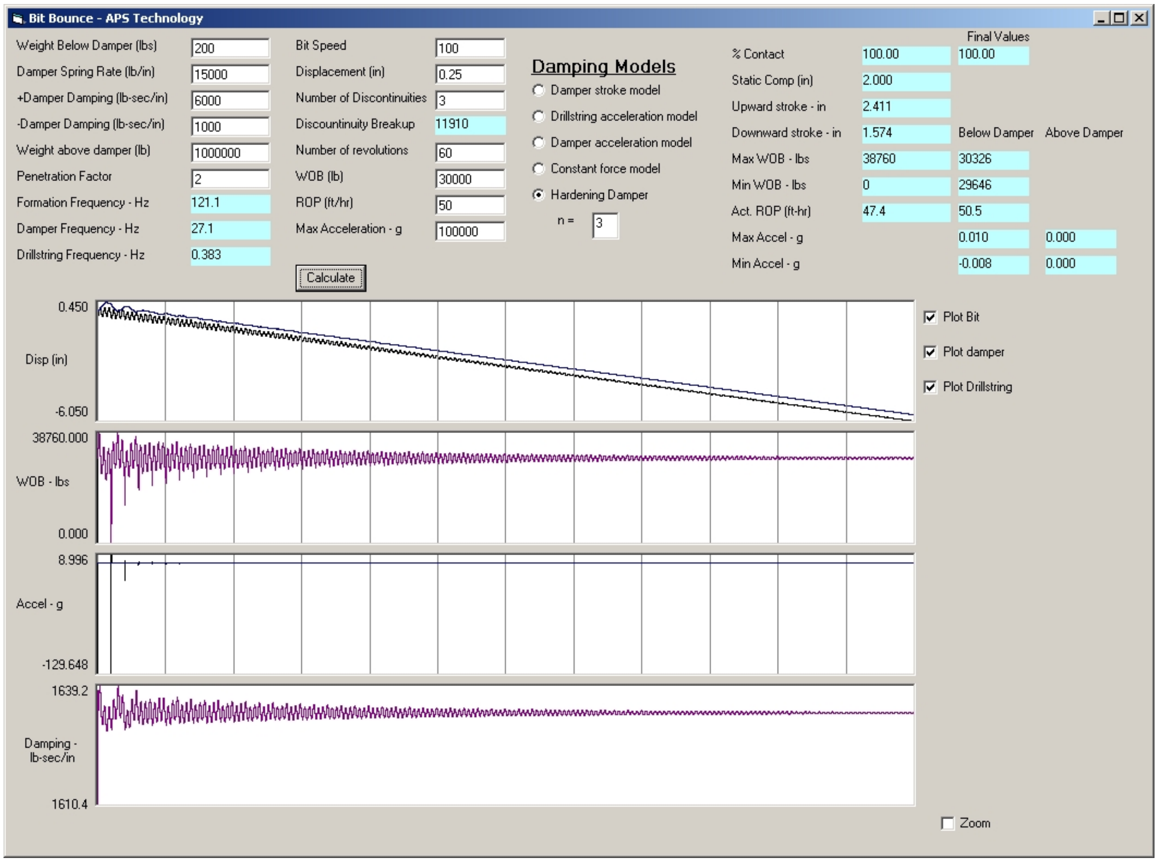
Damping Models

- ○ Damper stroke model
- ○ Drillstring acceleration model
- ○ Damper acceleration model
- ○ Constant force model
- ● Hardening Damper

n = 3

		Final Values	
% Contact	99.99	100.00	
Static Comp (in)	0.667		
Upward stroke - in	1.09		
Downward stroke - in	0.262	Below Damper	Above Damper
Max WOB - lbs	17172	10015	
Min WOB - lbs	0	9985	
Act. ROP (ft-hr)	47.5	50.0	
Max Accel - g		0.001	0.000
Min Accel - g		-0.001	0.000

- ☑ Plot Bit
- ☑ Plot damper
- ☑ Plot Drillstring
- ☐ Zoom



Weight Below Damper (lbs) 200
Damper Spring Rate (lb/in) 15000
+Damper Damping (lb-sec/in) 6000
-Damper Damping (lb-sec/in) 1000
Weight above damper (lb) 1000000
Penetration Factor 2
Formation Frequency - Hz 121.1
Damper Frequency - Hz 27.1
Drillstring Frequency - Hz 0.383

Bit Speed 100
Displacement (in) 0.25
Number of Discontinuities 3
Discountinuity Breakup 11910
Number of revolutions 60
WOB (lb) 30000
ROP (ft/hr) 50
Max Acceleration - g 100000

Damping Models

○ Damper stroke model
○ Drillstring acceleration model
○ Damper acceleration model
○ Constant force model
● Hardening Damper
n = 3

		Final Values	
% Contact	100.00	100.00	
Static Comp (in)	2.000		
Upward stroke - in	2.411		
Downward stroke - in	1.574	Below Damper	Above Damper
Max WOB - lbs	38760	30326	
Min WOB - lbs	0	29646	
Act. ROP (ft-hr)	47.4	50.5	
Max Accel - g		0.010	0.000
Min Accel - g		-0.008	0.000

☑ Plot Bit
☑ Plot damper
☑ Plot Drillstring
☐ Zoom

Appendix C: Magnetic Testing

Daniel E. Burgess

February 25, 2005

OBJECTIVE

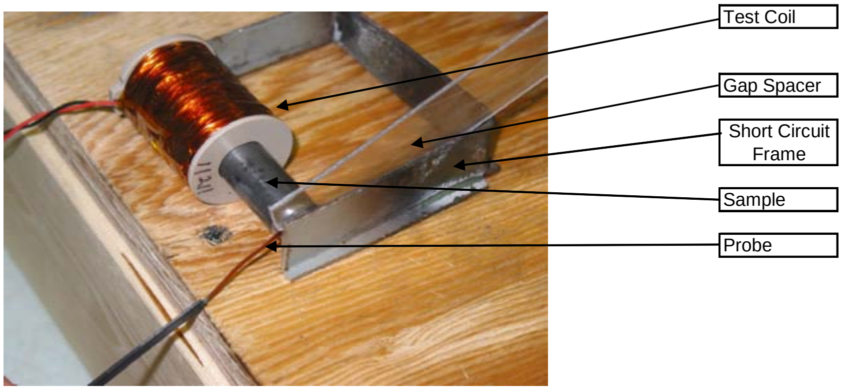
The magnetic testing was performed to investigate the properties of ferromagnetic materials in a magnet field as relates to the axial valve of the Down Hole Vibration Damper.

TESTING

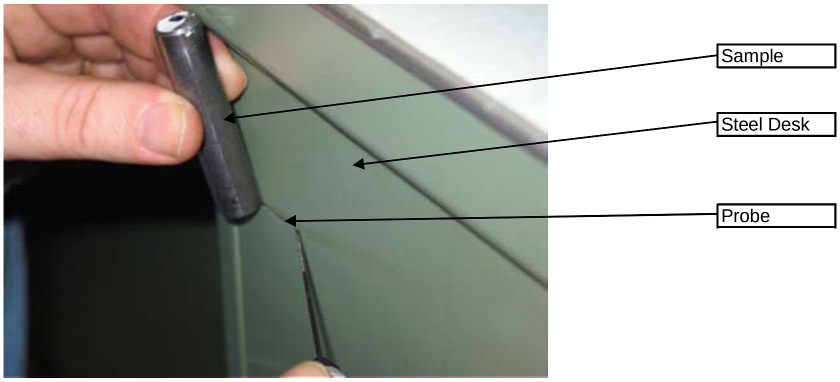
The testing consisted of 3 sets of tests the first was to examine how materials behaved in a magnetic field. The second to test what happens if a strong magnet is placed into a variable shunt devise, and the third testing on the test mandrel used in our DVM valve.

The first test involved using a common coil to charge equal length samples with the identical amperages and measuring the resulting magnetic fields. Peak magnetic field strength was recorded with various current settings. Then the coil was turned off and residual field strength was recorded both in and out of the fixture (outside the fixture does not take into account the residual field in the fixture itself).

	1018	**12L14**	**4140**
Initial reading (kGauss)	0.006	0.108	0.1
Coil at 1 amp (kGauss)	1.7	1.73	1.6
Coil Off (kGauss)	0.35	0.35	0.45
Coil 2 amps (kGauss)	2.5	2.9	2.4
Coil Off (kGauss)	0.39	0.35	0.59
Residual measured outside (kGauss)	0.36	0.14	0.54
Percent of Highest field residual	14%	5%	23%
Comments		Low residual as measured outside leads me to believe that the short circuit bar was retaining a high enough field to alter off state measurements	

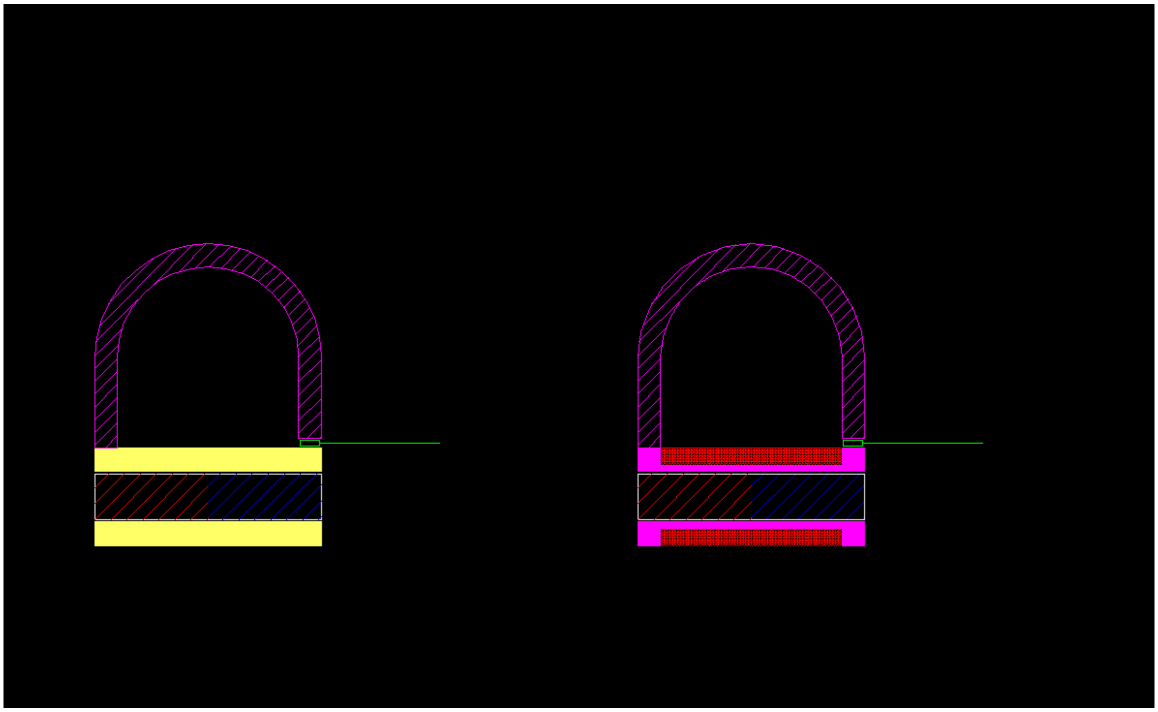


The measurement device is pictured here. A steel frame shorts the poles with a fixed gap at one end maintained by a spacer with a slot that provides space to insert the probe. The coil is a wound boben designed and produced for the RSM solinoids. The current in each test is precisely the same and coil orientation is the same.



This is how residuals were measured outside the frame. A steel desk was used to short the poles with the probe between the desk and the sample, the highest atainable reading was recorded.

The second test performed was to test if it was possible to use the coils to shunt or bias a piece of “magnetically soft” iron to short out the ends of a permanently biased magnetic bar that runs through it’s center. The goal here being that we could use 4140 or some other high strength steel, but most likely having a high residual field, through the center of the valve; and band around it with a magnetically soft material to shunt out that field.



Above is a sketch of the test setup used. A bar magnet, made of Alnico 5 being 2.5 inches long with an OD of .5 inches, was installed in two separate fixtures. The first fixture made of nylon and having the same OD and ID as the second. The flux was then measured using a loop of HyMU80 a material that has very high permeability and very low coercivity. This approximates the field reaching the OD of the fixture in a very low permeability gap such as if it were in Air. The gauss reading in the "air gap" was **1.365 kGauss**. The bar magnet was then placed in the second fixture which comprised a HyMu80 barbell shaped core wrapped with a coil having an OD of 1 inch an ID of .7 inches and a length of 2 inches. The flux was again measured using the same setup as before. (The loop was passed through a demagnetizing coil between each test.) The gauss level through the HyMu80 loop was **3.64 kGauss**. The coil was then energized with .5 amps (which should generate approximately 1.1 kGauss) so that the field generated would match the field inside the bar magnet in effect repelling the field out into the loop, which gave it a reading of **5.12 kGauss**. It should be noted that the field generated was higher than the sum of individual readings of the magnet and electromagnet. When energized in the opposing direction which should create a short in the bar magnet, the field measured in the HyMu80 loop was **0.00 kGauss**. And when power was cut the residual field was **1.34 kGauss** which is much less than the original reading, however if the bar magnet is removed and reinstalled the reading is the same as before.

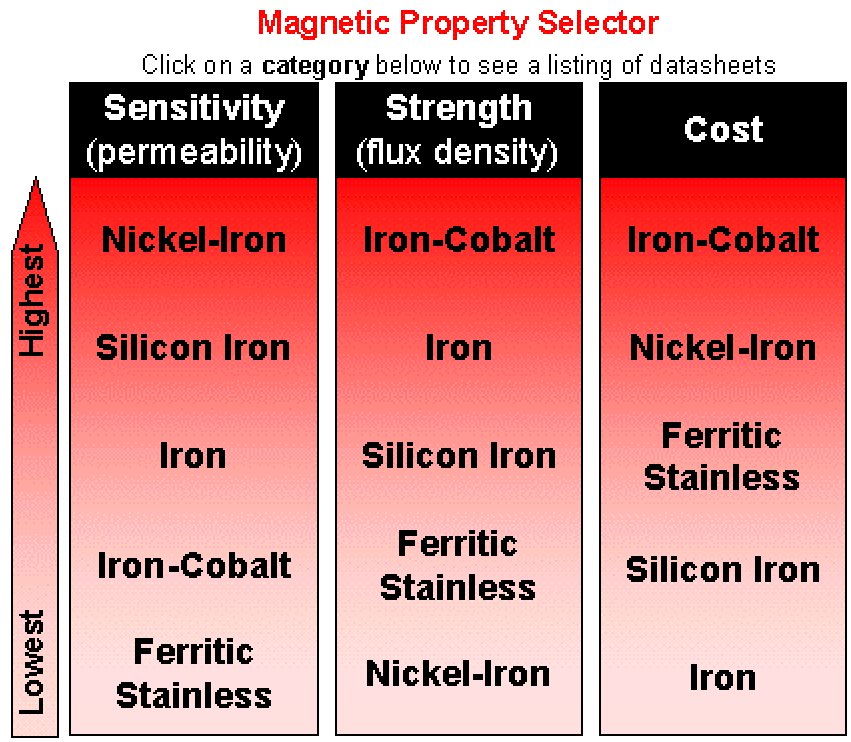
The third round of testing consisted of testing the MR coil to try and determine what the residual fields were and how to remove them. The highest residuals were actually found to be in the extension tubes where they neck down close to the mandrel. The shorter of the tubes had a field of 260 Gauss the longer was 350 gauss. Unfortunately these relatively high fields are at the point of greatest impact on the MR fluid (at the entry to the valve). Based on the testing of materials and knowing how the 4140 behaves magnetically we recognized that this area would be very difficult to demagnetize. However we were able to change the geometry of the part to make the strong field have negligible effects on the MR fluid. In the test piece we opened up the bore from .078 clearances to .2575 clearances. This is 3 times more clearance and assuming that the field falls off with the square of the distance this should reduce the field strength to just 10% of it's original strength. In the new design we have further increased the clearance between the mandrel and tubes to .502 inches. So the magnetic field effect should be only about 2.4% of the original field, or 8.5 gauss.

The second highest residual fields occurred within the valve itself and were approximately 150 gauss as measured in air (later tests showed this to be 1.4 kGauss in the MR fluid). This is still high enough to thicken the fluid to the point where excessively high damping will be created. This cannot by solved by material selection (as any material will have a residual field) or by geometry because for obvious reasons the valve geometry needs to develop a high field in a tight gap. Thus in order to move to a lower off state residual field you would have to perform some type of demagnetization technique to remove any residual field. With this in mind some tests on the damper section were performed using trace amounts of MR fluid to concentrate the field. In this test we reversed the field applied to the coils but held the current low so that the reversed field exactly matched the residual field. (The 4 amp field used during testing resulted in a residual of approximately 1.4 kGauss; this was equivalent to a 1.26 amp field.) We found that this created a near zero field at the point we had been measuring but other points had residual field of lower magnitude than the initial residual field but with reverse polarity, and still high enough to cause potential problems (approximately 200 gauss) To eliminate these fields we again reversed the polarity of the coil again an fed it an even lower current (.1 amps was found to work well). This canceled out the reverse polarity residual and left us with field that ranged from -20 Gauss to +60 Gauss; this is only 4% of the initial residual field and is not enough to create any appreciable damping. This is how we stumbled upon the stepwise demagnetization technique. We attempted to repeat the results using 120 VAC voltages but found that at 60 Hz the impedance is too great to put the required current through the coil, this meant it was not a viable solution, especially downhole.

ANALYSIS

In the first experiment we discovered that different materials will have different field strength when charged by the same coil with the same power. This is the effect of the permeability of the material but also the saturation density. The permeability is similar to resistance; it tells us how easily the field will flow through the material. The saturation density is simply the maximum flux that can be transmitted. In these tests it is very unlikely we got anywhere near the saturation point. A third property is the coercivity, which we had wrongly assumed was a representation of how much residual field would remain after the magnet had been turned off. However in the course of these experiments we found that the residual field even in low coercivity materials can be quite high. Observations during the second test showed that the HyMu80 used in testing was retaining a field, quite a high field of approximately .35 kGauss. Similar to the values attained in testing materials such as 1018 or 4140. However the field was easily reversed. Coercivity is a measure of how easy it is to create and or reverse a field in the material. Fields weaker than the coercivity point will have no magnetic effect on the material. Coercivity is not a measure of maximum residual field, rather it is the minimum field required to develop a response in the material, and therefore represents the lowest possible field that will remain after demaging. The lower the coercivity the material has the easier it is to reverse the field and therefore to demagnetize also weaker fields still affect it so it can be demagnetized to a lower level.

Mild steels are not magnetically soft enough for the applications we are attempting hear 1018 has far too high a residual field. The 12L14 (which is a variant of low carbon steel to which lead and phosphorus are added to improve machining) may be a good candidate however finding published magnetic properties on this alloy has proven difficult since it is not considered to be among the “electrical irons” which are optimized for magnetic performance. The Ideal material would have a high permeability, a high saturation density, a low coercive force, and low residual magnetism. Below is a chart published by Carpenter Steels.



Magnetic Property Selector

Click on a **category** below to see a listing of datasheets

	Sensitivity (permeability)	Strength (flux density)	Cost
Highest	Nickel-Iron	Iron-Cobalt	Iron-Cobalt
	Silicon Iron	Iron	Nickel-Iron
	Iron	Silicon Iron	Ferritic Stainless
	Iron-Cobalt	Ferritic Stainless	Silicon Iron
Lowest	Ferritic Stainless	Nickel-Iron	Iron

This shows that the best materials for us to use would be the irons and silicon irons. The silicon irons are a bit higher in strength and corrosion resistance and may therefore be the better choice.

The experiment with the magnet inside the coil proved interesting. It was possible to create a zero gauss field quite easily, and it was possible to create a very high field without much power. In addition it leads to the belief that we could counter a weak residual field with another weak field of opposite polarity. This conclusion is reached because the residual field after the power reversal is so much lower than the residual field before reverse power was applied. Before applying power the magnetic field was 3.64 kGauss and after reversing the field it dropped to 1.34 kGauss. That means the shunt is conducting approximately 2.3 kGauss preventing it from being exposed to the HyMu loop. This is most likely caused by the internal residual fields within the HyMu shunt continue to be polarized in such a way that it drained off some of the flux preventing it from getting to the test loop.

The results from the shunting test lead us to research various demagnetization techniques. A paper by a company called Annis who make demagnetization equipment lists the several methods available. We could heat it past the curie temperature of iron (the Curie temperature is the temperature at which a material looses its ferromagnetism) however the Curie temperature for iron is over 700°C so this option will not work on our valve. Another method is to exactly oppose the field with another field. This would prove difficult since it requires sensors located at strategic points within the mr valve section. It is however very close to what we successfully attempted during the third experiment. The final option is to expose the steel to a field of cyclically reversing polarity with a slowly diminishing intensity. Most commonly an AC field is used, however our findings were that at frequencies that we would get from the alternator the voltage would be insufficient to drive the required current. So we adapted a military technique called "stepwise deperming" that was developed during WWII (and is still used today) to demagnetize submarines. It uses a DC source that is switched in such a way as to reverse the polarity after each cycle and a voltage regulator to reduce the current gradually. We developed a circuit to switch DC voltage back and for the while lowering the amplitude continuously. This method uses our available power and does not require sensors in the valve nor much additional circuitry.

Our stepwise deperming circuit has been shown to work well during preliminary testing. It was not ready to do a full size test, however we accomplished the same thing manually and were able to bring the sub down to near zero gauss. The system was driven as follows: -4 amps, +3.75, -3.5, +3.25, -3, +2.75, -2.5, +2.25, -2, +1.75, -1.5, +1.25, -1, +0.9, -0.8, +0.7, -0.6, +0.5, -0.4, +0.3, -0.2, +0.1, -0.05, +0.02, -0.01 amps. The entire series of steps took approximately 2 minutes to complete by hand, the circuit running at 10 Hz could do a similar series in 1.25 seconds. A series such as this could be performed at every pumps on / power up to start the tool fresh after every new stand was made up. If a sudden reduction is needed during routine drilling an abbreviated series such as -2, +1, -0.5, +0.1 could be done in a mere fraction of a second.

CONCLUSIONS

1. All materials retain a residual field, but the proportions of residual fields vary from one material to the next and are often not published.

2. Coercivity is not a measure of maximum residual field, rather it is a representation of the minimum field required to develop a response in the material, and therefore represents the lowest field that will remain after demaging.

3. A permanent magnet setup can be used to generate high magnetic fields with low power consumption; however power will be required to go to an off state.

4. A variable shunt device can be used to minimize the effects of residual fields on the fluid but cannot eliminate them without the use of power.

5. Regardless of what material is used, to attain an off state of near zero Gauss we will have to perform a demagnetizing technique

6. The best demagnetizing technique available to us down hole is to periodically reverse the fields applied and gradually lower the field intensity to demagnetize the materials (stepwise deperming).

7. Downhole ready circuits to demagnetize the sub have been successfully built and tested, and we have shown that the technique does indeed work.

Appendix D: MR Fluid Viscosity Testing

Joe Nord

February 25, 2005

OBJECTIVE

Determination of the optimum mixture of magnetorheological (MR) powder and oil to use in the Active Vibration Damper (AVD) tool. It is important that the MR mixture have a broad range of viscosities that increase as an increasing magnetic field is passed through it. It is desirable for the fluid to be as close to Newtonian as possible meaning that it's viscosity isn't affected by shearing. We will also compare the viscosity of the homemade MR fluid with a commercially available Lord brand MR fluid.

TESTING

Equipment

Figure 4 shows a model of the test fixture and **Figure 2** shows a photo of the apparatus. An electromagnet sends the magnetic field through steel mounting brackets and into the aluminum sample container. A rotational viscometer was used to determine the viscosity. The viscometer spindle was lowered into the sample container, which measures the torque required for the spindle to rotate at different speeds. A vane spindle with 4 blades (**Figure 3**) was used, which works better than the traditional disc spindle for fluids that have solids suspended in them.

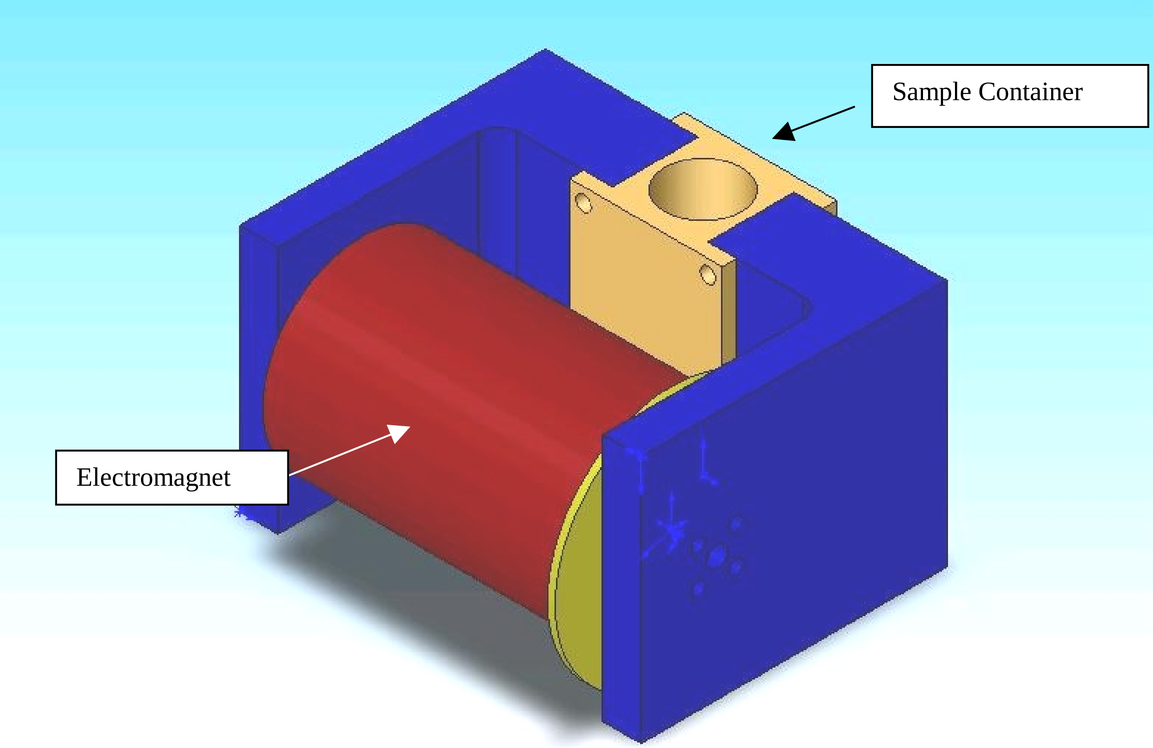


Figure 1: Diagram of magnetic circuit for sample container

Figure 2: Photo of the viscometer test apparatus

Figure 3: 4-vane spindle

A gaussmeter was used to determine the field through the sample container. **Figure 4** below shows the results. At relatively low flux levels the fluid became too viscous to measure. The highest current we could send to the coil was 2 amps, which relates to 240 gauss.   Even though the fluid is highly viscous at this flux level, the Lord literature says it is not yet magnetically saturated at this point.

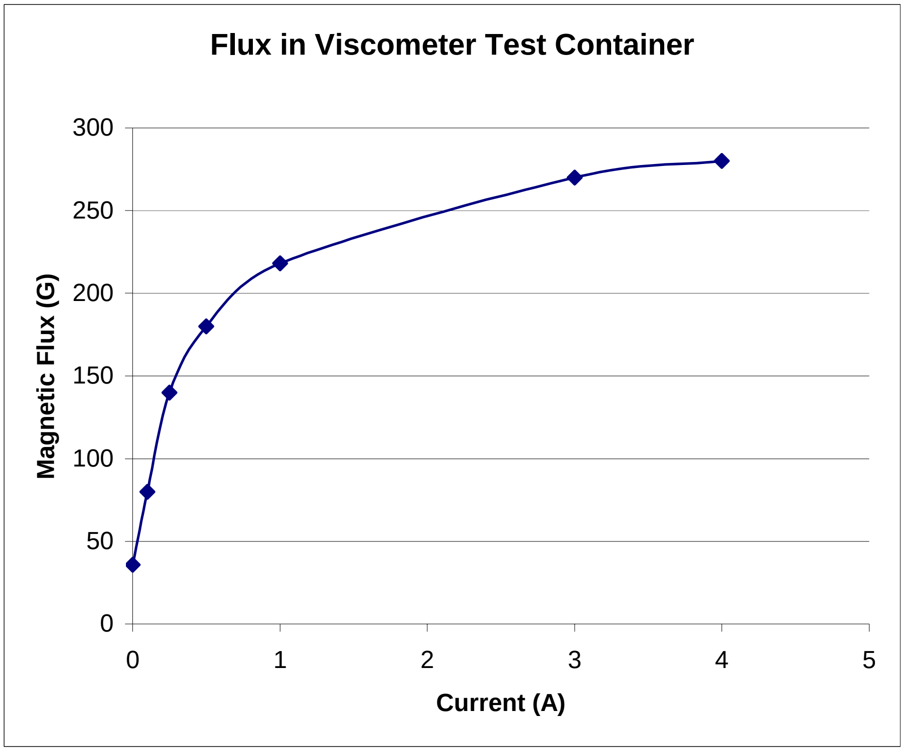


Figure 4: Magnetic flux levels observed in viscometer test container

The rotational viscometer displays three outputs: viscosity, percentage of torque, and rotational speed (RPM). The viscosity is programmed to be accurate when using a 500 mL beaker and a spindle guard. The high cost of the MR fluid and the difficulty involved in putting a magnetic field through a container of this size led to the use of a much smaller sample container (approx 37 mL). Appendix A shows the formulas that were used to convert the torque and rotational speed output of the viscometer into apparent viscosity, shear rate, and shear stress.

Procedures

Initial testing on the AVD sub was performed using an 8:1 mass ratio MR fluid. *i.e.*, 8 parts MR powder mixed with 1 part Mobil 624. Viscosity testing was performed with the 8:1 mixture, 6:1, 4:1, 2:1, and a Lord brand silicone-based MR fluid. All of the homemade MR mixtures ran well in the viscometer. The Lord fluid was much more difficult. An important step in determining the apparent viscosity is a plot of the log of the angular velocity versus the log of the torque. For the Lord fluid, these plots were not straight lines. Most sloped downward and then upward while others never even sloped upward. The slope determines the flow behavior index, which is a measure of how it behaves under shear. A flow behavior index above 1 becomes more viscous under shear and an index less than 1 is less viscous under shear. The flow behavior index was so difficult to determine for the Lord fluid that it is unlikely that the calculated apparent viscosity, shear rate, and shear stress are correct.

Plots were created (see **Results**, below) of the flow behavior index (**Figure 5**), consistency index (**Figure 6**), and yield stress (**Figure 7**) as a function of the magnetic flux in the sample container. The Lord fluid is shown as a dashed line to show that it may not be accurate. The flow behavior index is a measure of how the viscosity reacts to shear. As the MR mixture ratio was increased, the flow behavior index increased and became closer to 1 (closer to Newtonian). All of the flow behavior indexes were below 1 so the apparent viscosity reduced as the shear rate increased. The consistency index in **Figure 6** is an index of the viscosity at low shear rates. As the MR mixture ratio was increased the consistency index increased. For the magnetic flux levels that we were able to send into the sample cup the consistency index had a broader range as the mixture ratio increased. It is unclear if this would change under higher levels of magnetic flux. The yield stress in **Figure 7** is the shear stress required to initiate flow. If the shear stress of the viscometer spindle is lower than the yield stress of the fluid then the spindle will not rotate. The yield stress also has higher values and a broader range as the mixture ratio is increased.

In order to compare the homemade mixtures to the Lord brand MR fluid plots using the raw viscometer data were created. **Figure 8** - **Figure 11** show the viscosity output versus the rotational speed for different magnetic flux levels. The absolute viscosities are based on using a 500 mL beaker and spindle guard, so they are not accurate. The curves do, however, show good comparative data. For all flux levels, the 6:1 MR mixture ratio plot was closest to the Lord fluid.

RESULTS

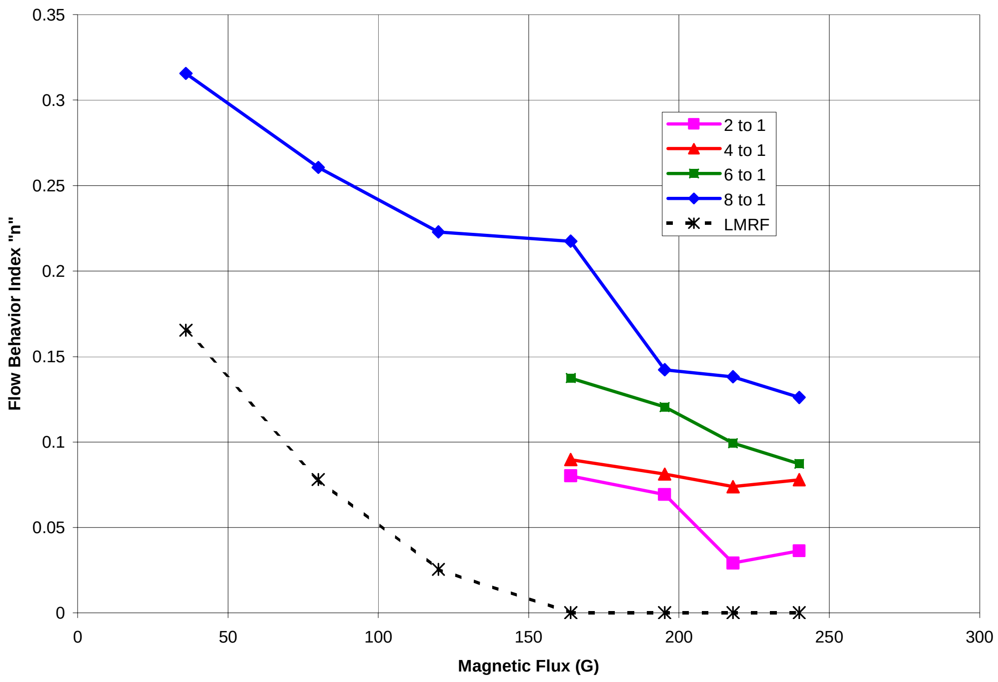


Figure 5: Comparison of Flow Behavior Index

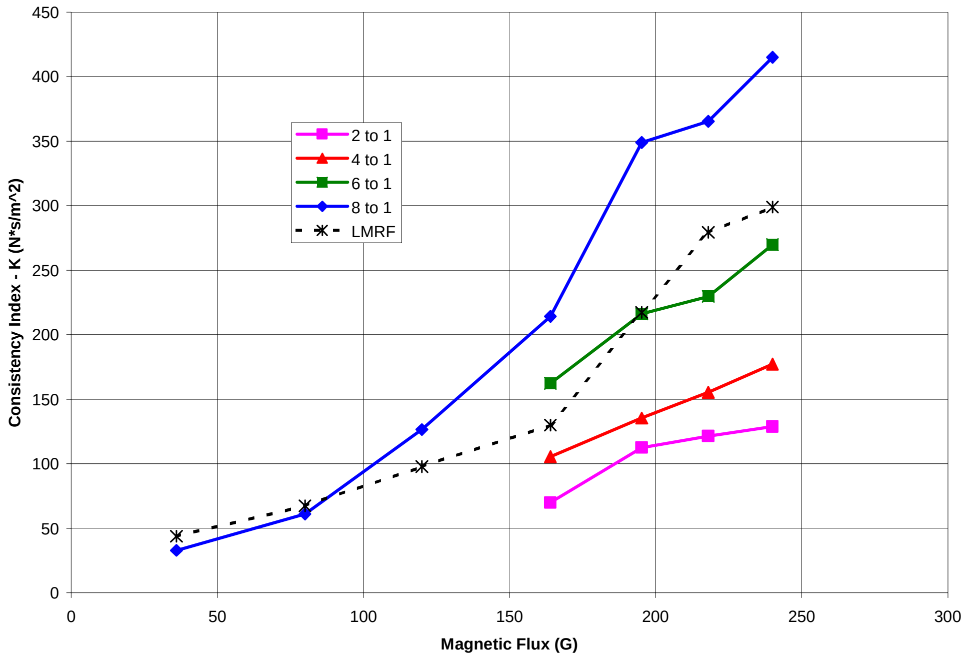


Figure 6: Comparison of Consistency Index

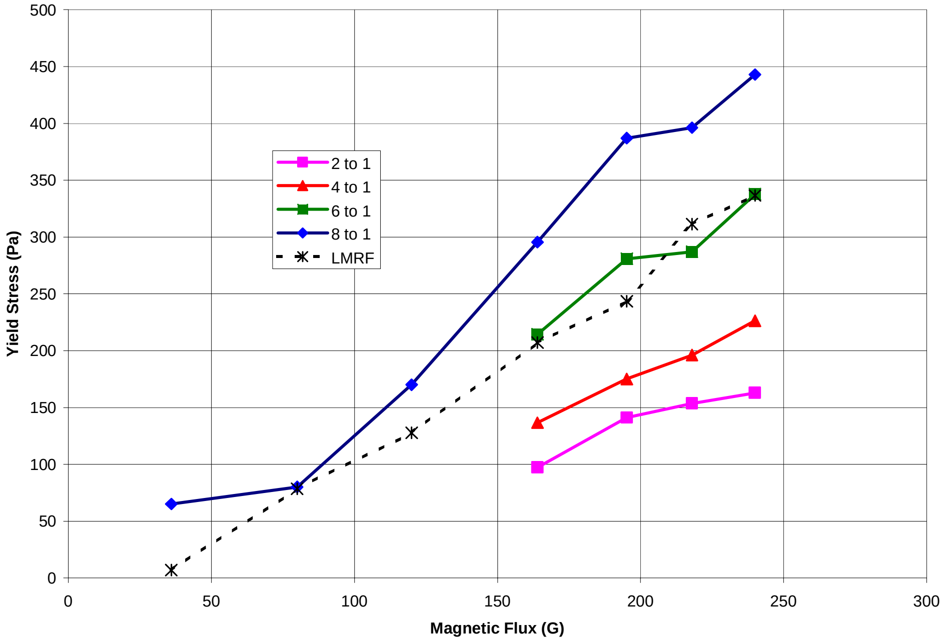


Figure 7: Comparison of Yield Stress

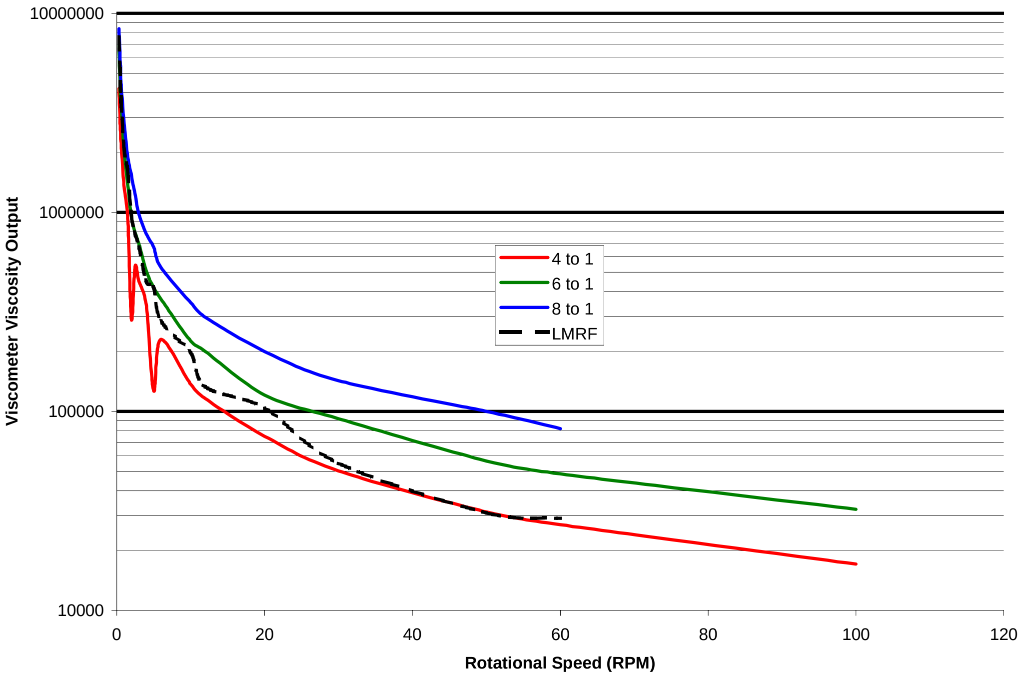


Figure 8: Comparison of Viscometer Output at 0.4A (164 Gauss)

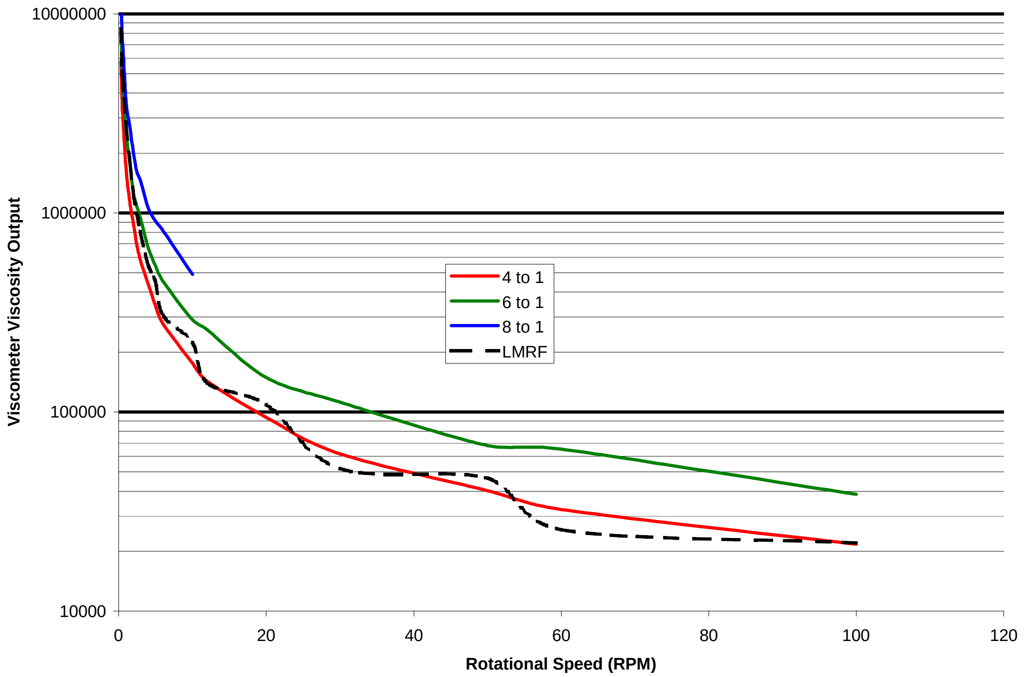


Figure 9: Comparison of Viscometer Output at 0.7A (195 Gauss)

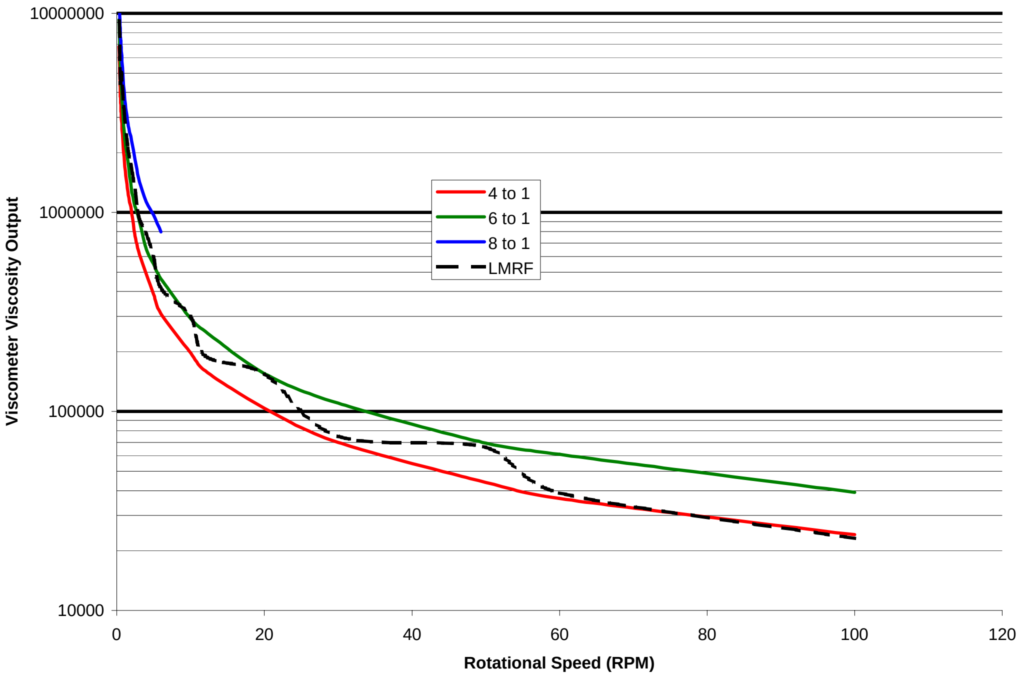


Figure 10: Comparison of Viscometer Output at 1 A (218 Gauss)

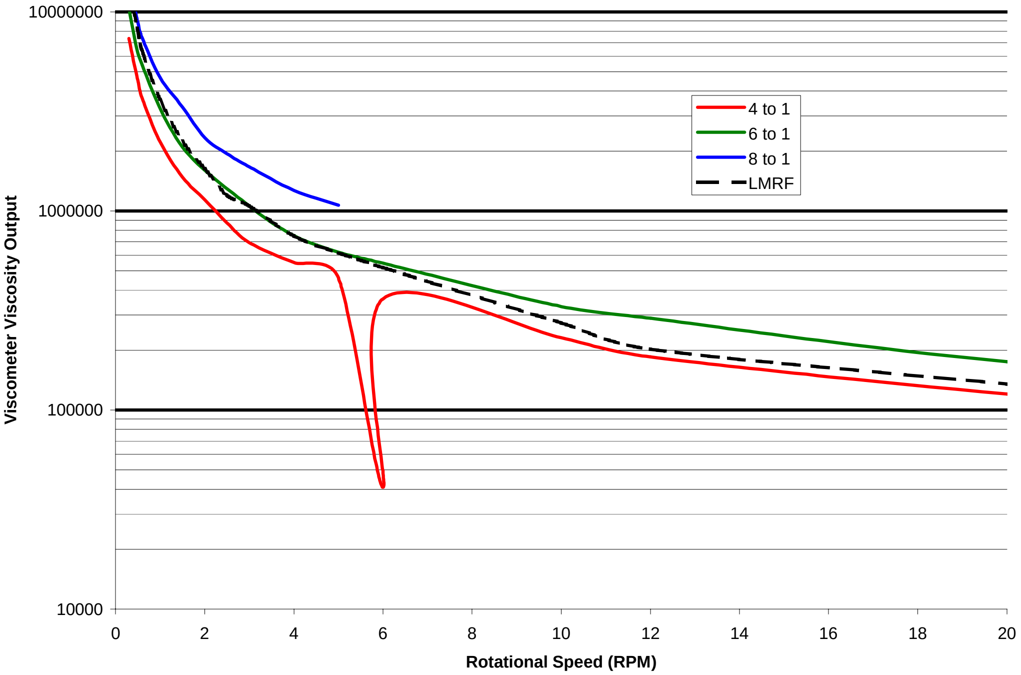


Figure 11: Comparison of Viscometer Output at 2 A (240 Gauss)

CONCLUSIONS

The fluid with the highest ratio of MR powder had the best viscosity properties. The higher ratio fluids had a broader range of viscosities over the same range of magnetic flux, and they were closer to being Newtonian. However as the ratio is increased the viscosity increases. If a lower viscosity is needed to give the minimum damping in the tool then a lower mixture may be needed. The 6:1 and 4:1 homemade mixtures were the most similar to the Lord brand MR fluid. Lord is highly experienced with MR fluid so they have probably done additional optimization based on the cost of powder, rate of settling out, and other factors. Taking Lord's experience into account it is recommended that we use the 6:1 ratio fluid in the AVD tool. The 4:1 mixture also had viscosities close to the Lord brand fluid, but 6:1 is more suitable because of its wider range of viscosities.

APPENDIX A: VISCOSITY CALCULATIONS

angular velocity = ω
RPM = N

$$\omega := 2\cdot\pi\cdot\frac{N}{60}$$

A plot of the Log of Torque v. Log of angular velocity determines the flow behavior index (η) and a constant A. The slope is η and the y intercept is the Log of A. This was proven with the calibration fluid. η was equal to 1 which means that it is Newtonian. The constant A provided the correct viscosity 5060 cP using additional equations listed below. For a Newtonian fluid the consistency factor (K) is equal to the viscosity (μ).

flow behavior index = η
consistency factor = K

$$K := \frac{A}{2\cdot\pi\cdot Rb^{2}\cdot L\cdot\left[\frac{2}{\eta\cdot\left[1-\left(\frac{Rb}{Rc}\right)^{\frac{2}{\eta}}\right]}\right]^{\eta}}$$

Spindle radius = Rb
Effective Spindle Length = L
Cup radius = Rc

shear rate = SR

$$SR := 2\cdot\frac{2\cdot\omega}{\eta\cdot\left[1-\left(\frac{Rb}{Rc}\right)^{\frac{2}{\eta}}\right]}$$

shear stress at the spindle = SS

$$SS := \frac{T}{2\cdot\pi\cdot Rb^{2}\cdot L}$$

apparent viscosity = μa

$$\mu a := K\cdot SR^{\eta-1}$$

Appendix E: Testing of DVMCS Prototype with Outer Coils

M Wassell

Nov 16, 2005

Scope

For manufacturing and assembly considerations the MR damper coils have been moved to the outer sleeve. The coil grooves on the inner shaft were filled with a material similar to the shaft, allowing for a continuous magnetic field path. The load range was also increased so that tests could be conducted up to 15,000 lbs WOB. The original tests could only be performed at lower WOB (5,000 lb WOB). Higher loads exceeded the capabilities of the motor and test frame.

Conclusions

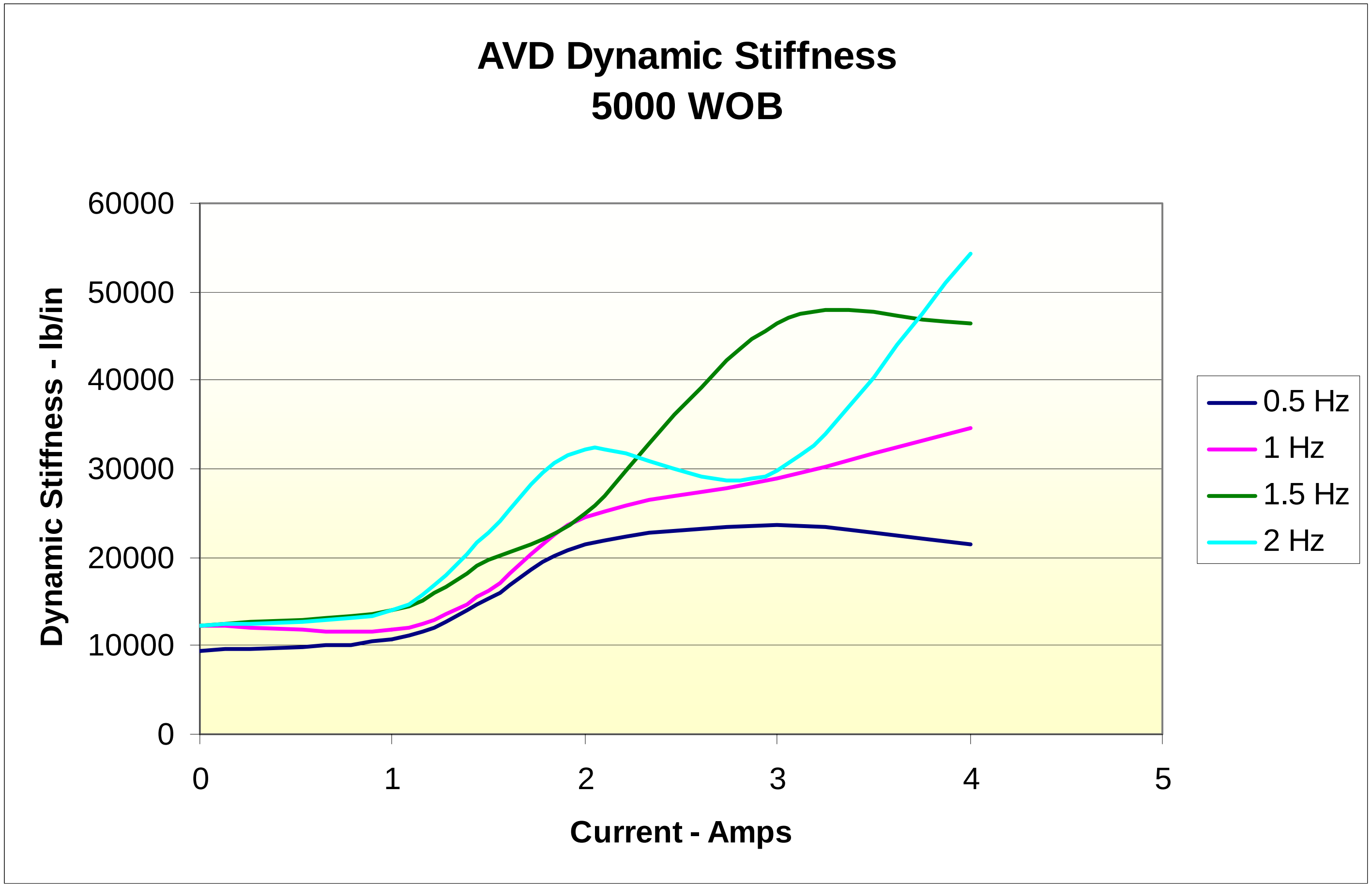
1. The results from this test are not as good as for the previous test with the coils mounted on the inner shaft. With the coils mounted on the outer sleeve, the maximum dynamic stiffness is 54,000 lbs / in. The previous tests, with the coils mounted on the inner shaft produced a dynamic stiffness of 120,000 lb/in
2. The dynamic stiffness of the outer coil in the off state is less than the off state for the inner coil.
3. The ratio of stiffness ranges from 2.5 to 4.6 for the new design. The inner coil design ratio is 7 to 10.
4. The dynamic stiffness decreases with the increase in WOB. At 5,000 lbs WOB the dynamic stiffness is 54,000 lbs/in, at 10,000 lbs it drops to 40,000 lbs WOB and at 15,000 lbs WOB it is 26,000 lbs /in.
5. Based on items 1 – 4 above, the gap should be reduced.
6. The dynamic stiffness reduction could be attributed to:
    - Damper gap – The reduced off state dynamic stiffness suggests that the gap could be reduced. This would significantly increase the on state damping, hopefully giving a higher damping ratio.
    - Losses due to filling in the old coil grooves
    - Fixture damping problems with the test fixture. – Each time we set up tests the pneumatic and hydraulic actuators operate differently. The wobble in the graphs could also be attributed to the pneumatic and hydraulic dampers.

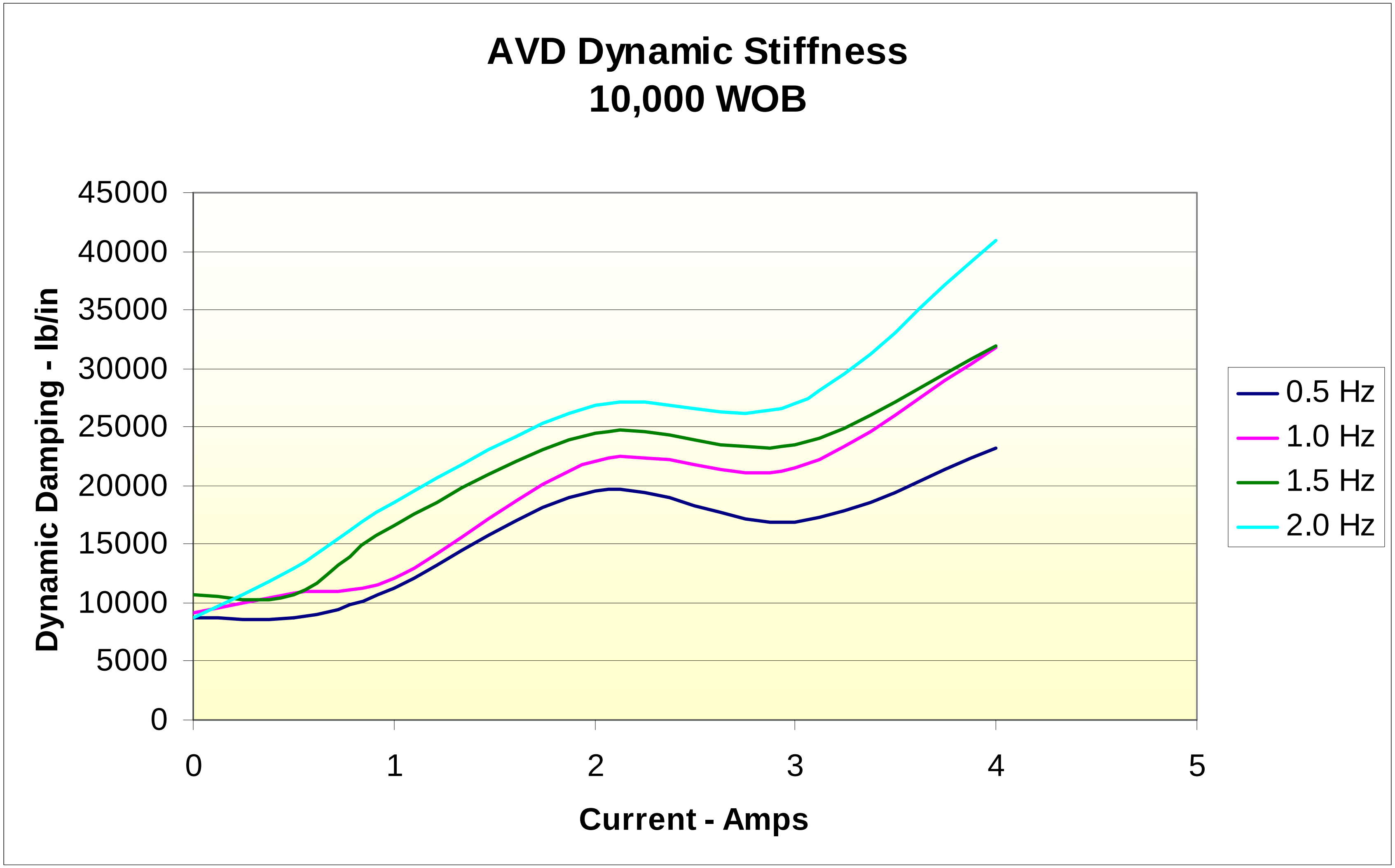
Discussion

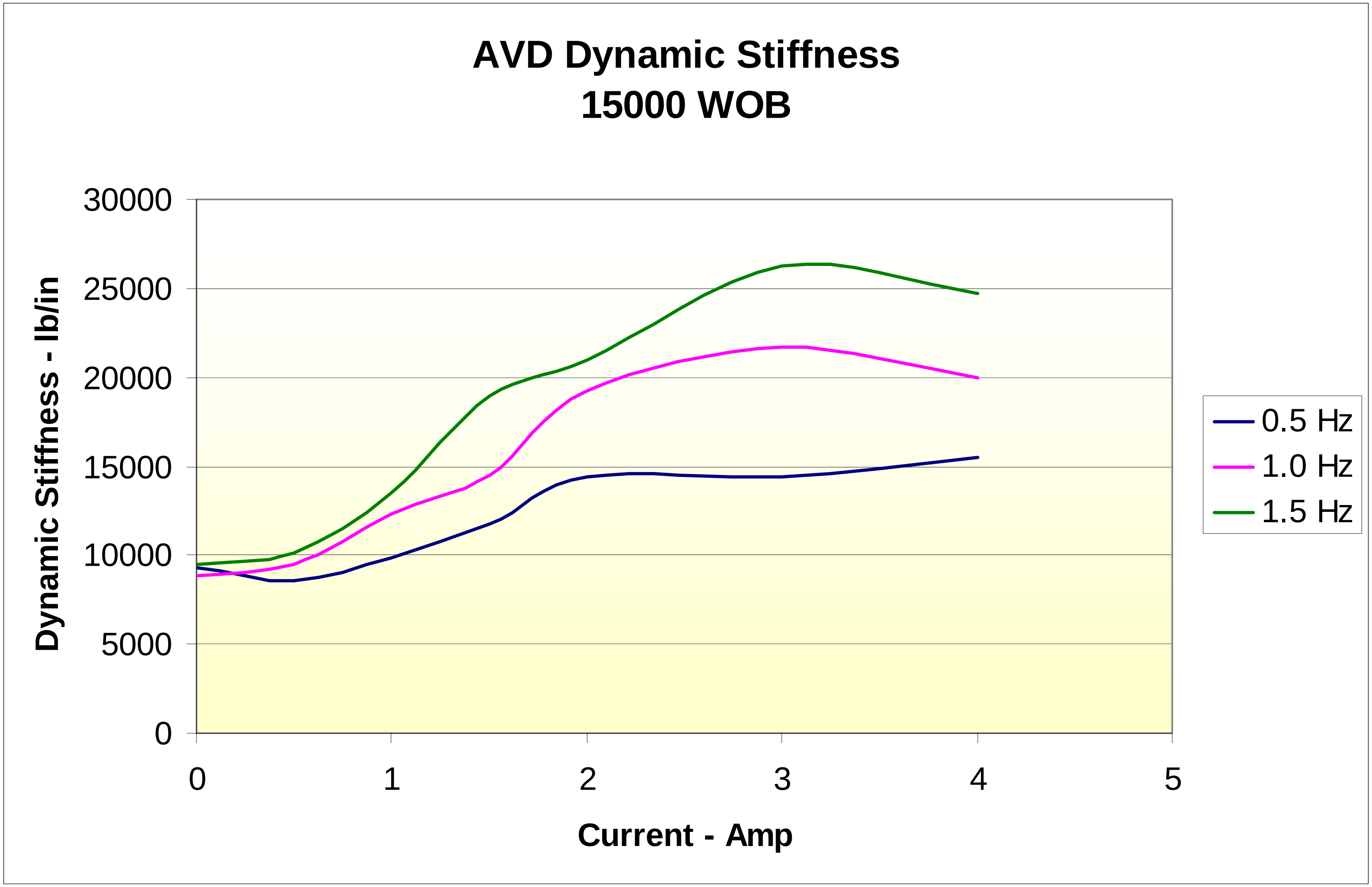
Test Parameters

- MR Fluid – 6:1 mixture
- Gap – 0.031”
- Valve materials – 410SS
- Cam displacement – 0.708”

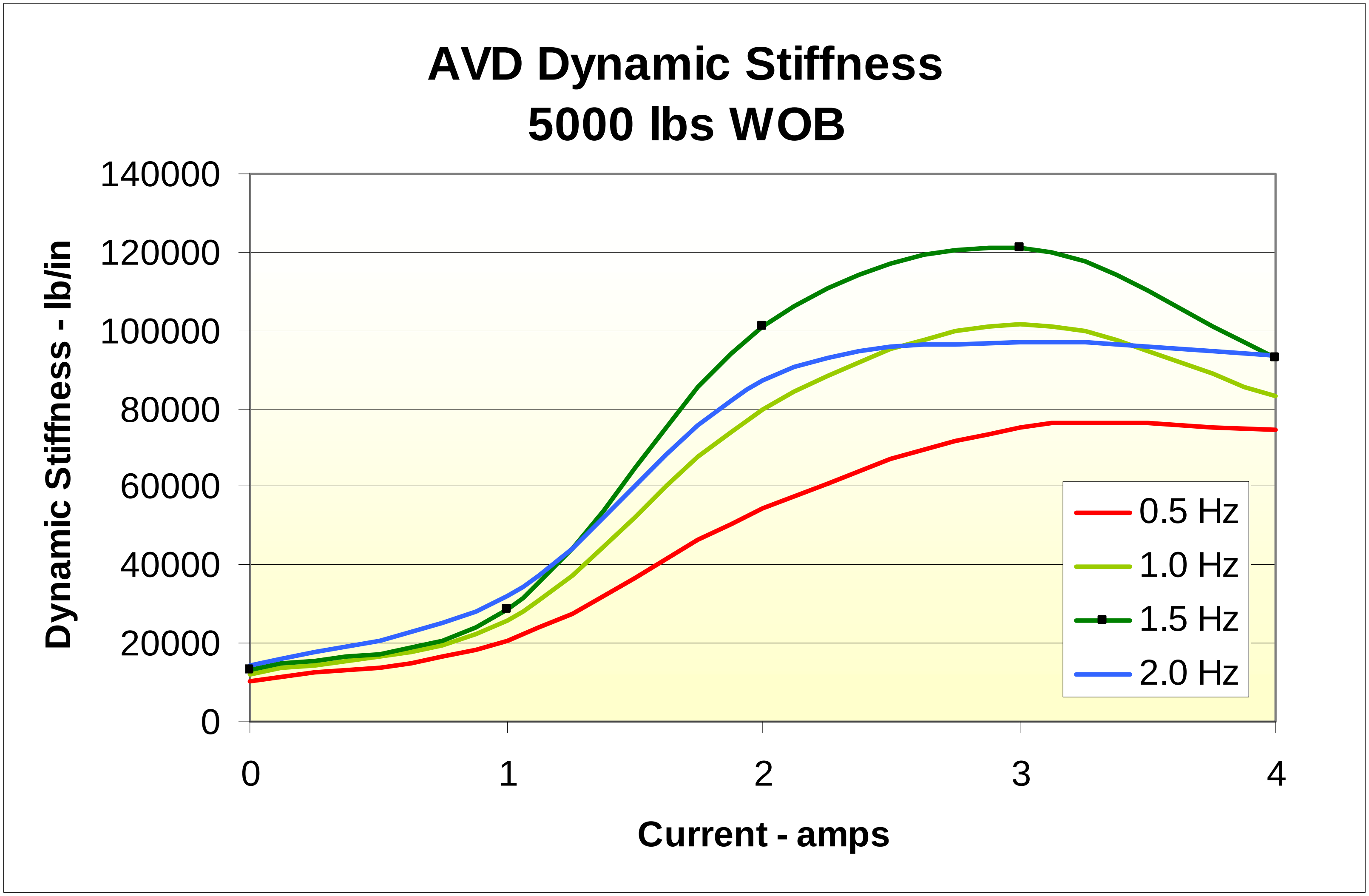
Outer Coil Results




AVD Dynamic Stiffness
10,000 WOB
Dynamic Damping - lb/in
45000
40000
35000
30000
25000
20000
15000
10000
5000
0
0
1
2
3
4
5
Current - Amps
0.5 Hz
1.0 Hz
1.5 Hz
2.0 Hz


AVD Dynamic Stiffness
15000 WOB
Dynamic Stiffness - lb/in
30000
25000
20000
15000
10000
5000
0
0
1
2
3
4
5
Current - Amp
0.5 Hz
1.0 Hz
1.5 Hz

Original Inner Coil Results



Scope

For manufacturing and assembly considerations the MR damper coils have been moved to the outer sleeve. The coil grooves on the inner shaft were filled with a material similar to the shaft, allowing for a continuous magnetic field path. The load range was also increased so that tests could be conducted up to 15,000 lbs WOB. The original tests could only be performed at lower WOB (5,000 lb WOB). Higher loads exceeded the capabilities of the motor and test frame.

Conclusions

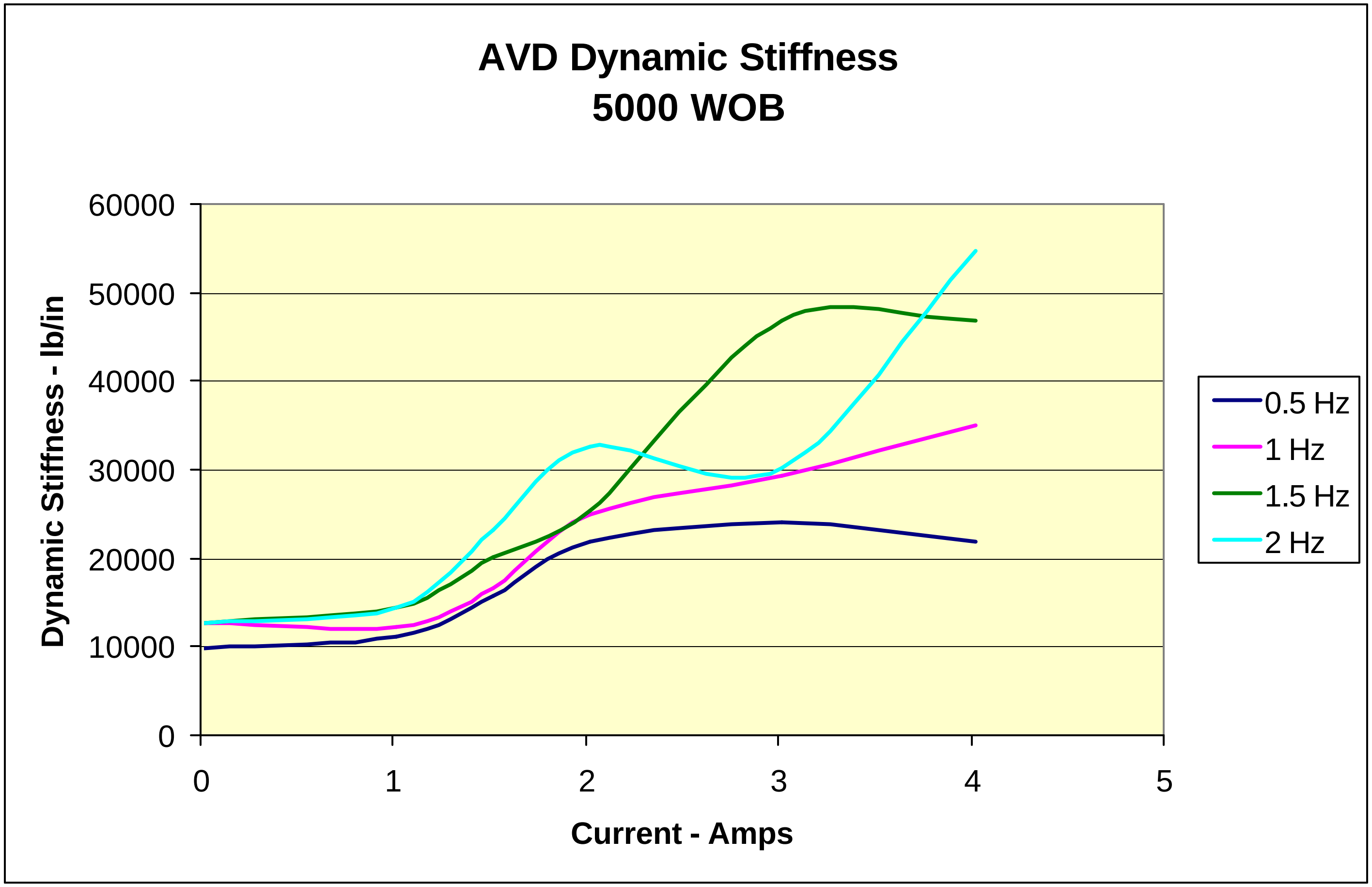
1. The results from this test are not as good as for the previous test with the coils mounted on the inner shaft. With the coils mounted on the outer sleeve, the maximum dynamic stiffness is 54,000 lbs / in. The previous tests, with the coils mounted on the inner shaft produced a dynamic stiffness of 120,000 lb/in
2. The dynamic stiffness of the outer coil in the off state is less than the off state for the inner coil.
3. The ratio of stiffness ranges from 2.5 to 4.6 for the new design. The inner coil design ratio is 7 to 10.
4. The dynamic stiffness decreases with the increase in WOB. At 5,000 lbs WOB the dynamic stiffness is 54,000 lbs/in, at 10,000 lbs it drops to 40,000 lbs WOB and at 15,000 lbs WOB it is 26,000 lbs /in.
5. Based on items 1 – 4 above, the gap should be reduced.
6. The dynamic stiffness reduction could be attributed to:
    - Damper gap – The reduced off state dynamic stiffness suggests that the gap could be reduced. This would significantly increase the on state damping, hopefully giving a higher damping ratio.
    - Losses due to filling in the old coil grooves
    - Fixture damping problems with the test fixture. – Each time we set up tests the pneumatic and hydraulic actuators operate differently. The wobble in the graphs could also be attributed to the pneumatic and hydraulic dampers.

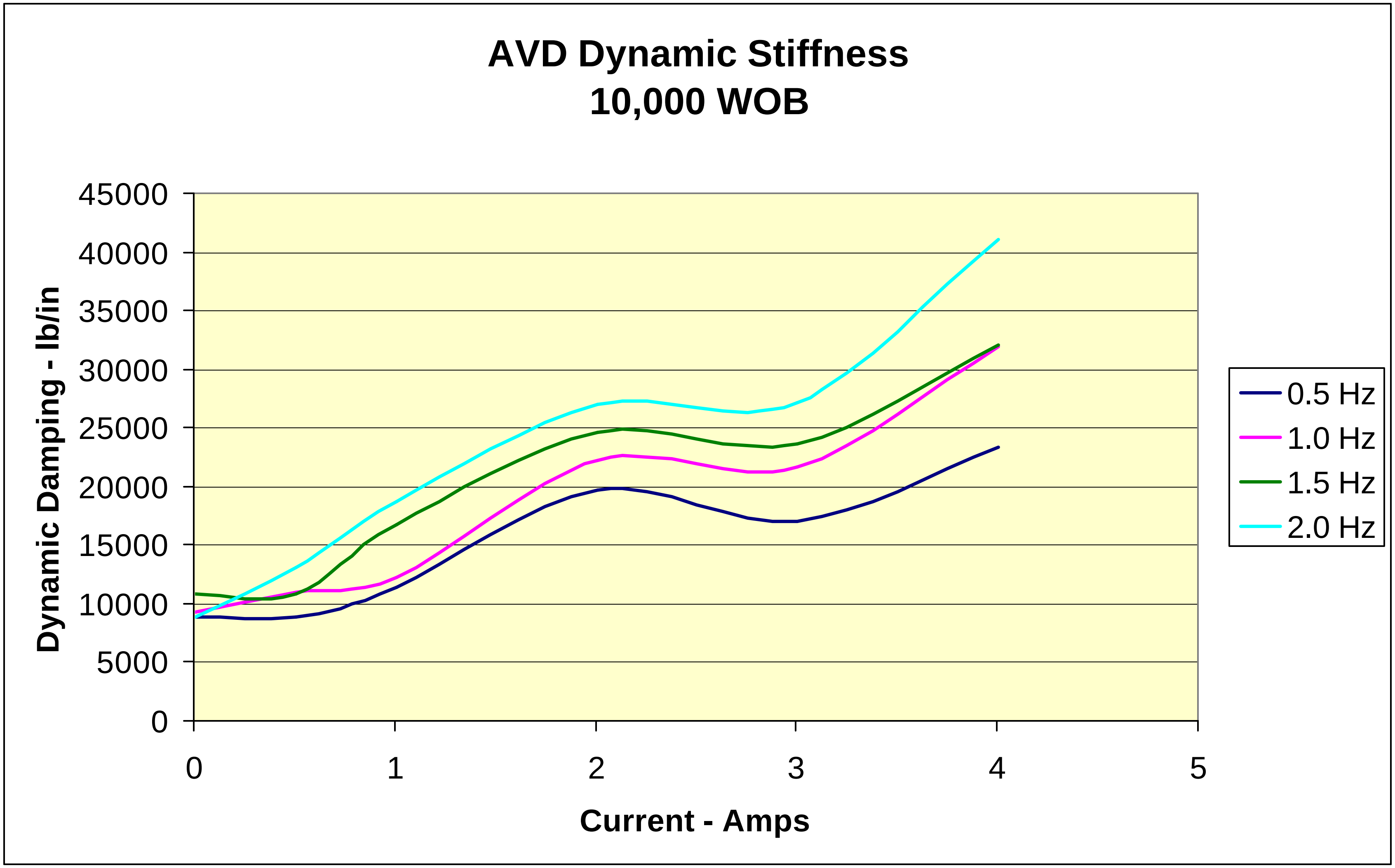
Discussion

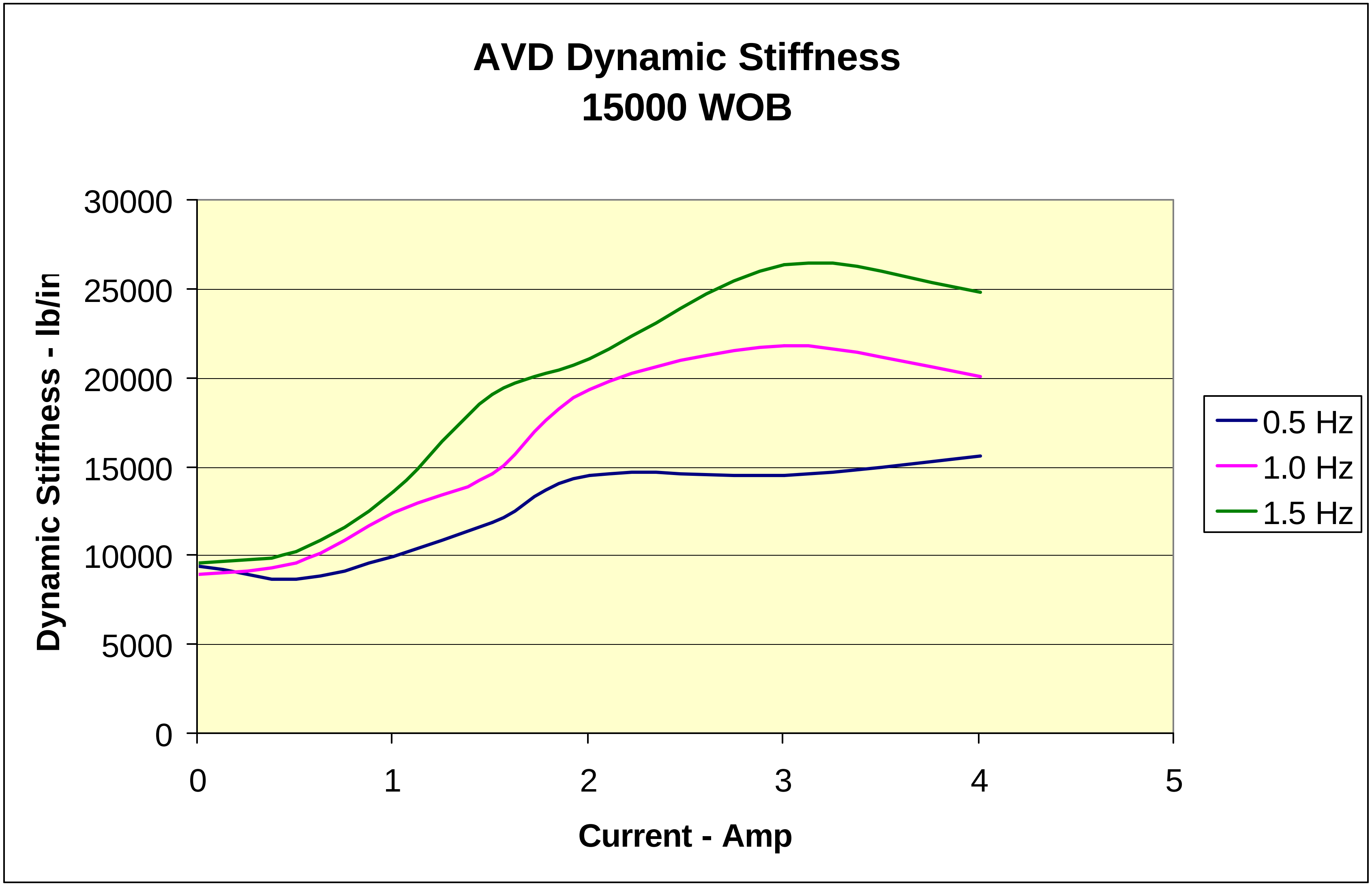
Test Parameters

- MR Fluid – 6:1 mixture
- Gap – 0.031”
- Valve materials – 410SS
- Cam displacement – 0.708”

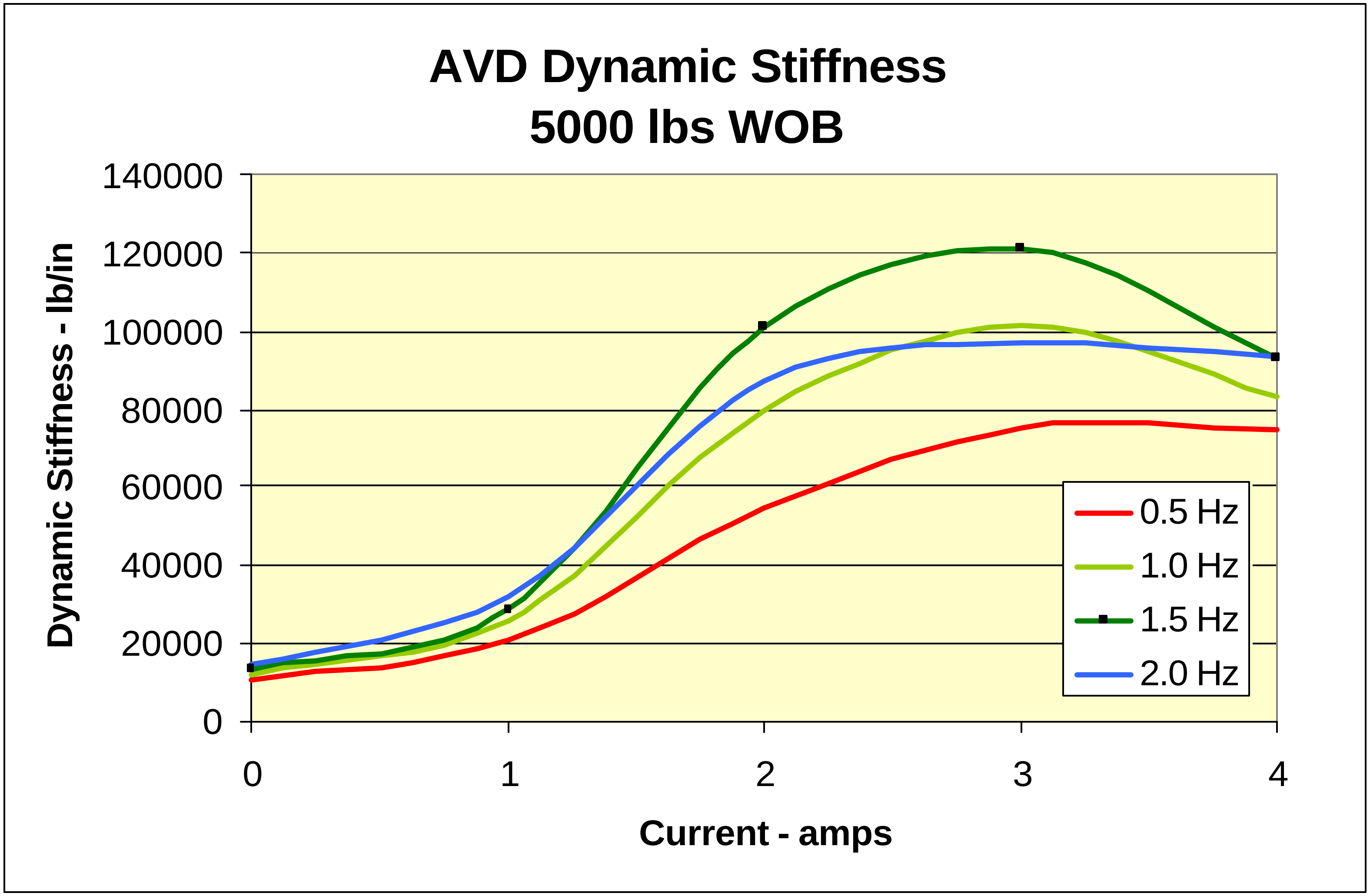
Outer Coil Results




AVD Dynamic Stiffness
10,000 WOB
Dynamic Damping - lb/in
45000
40000
35000
30000
25000
20000
15000
10000
5000
0
0
1
2
3
4
5
Current - Amps
0.5 Hz
1.0 Hz
1.5 Hz
2.0 Hz


AVD Dynamic Stiffness
15000 WOB
Dynamic Stiffness - lb/in
30000
25000
20000
15000
10000
5000
0
0
1
2
3
4
5
Current - Amp
0.5 Hz
1.0 Hz
1.5 Hz

Original Inner Coil Results



Appendix F: Analysis of TerraTek Results

Mark E. Wassell

April 16, 2006

Scope

Drilling tests of the Downhole Vibration Monitor & Control System (DVMCS), also referred to as the Active Vibration Damper (AVD), were performed at the TerraTek test facility in Salt Lake City. The drilling tests consisted of drilling a number of holes through concrete and granite test blocks. The tests blocks were constructed such that they would develop drilling vibrations. A one-foot thick granite block was sandwiched between an upper and lower section of concrete. The granite was mounted within the blocks at a 10^{o} angle. This arrangement was intended to develop increased vibration as the rock bit drill through the interface. A total of four test blocks were constructed. Each test block could accommodate 8 holes. The drilling simulator at TerraTek was used to drill the holes. The test rig could accommodate only a short drilling assembly, so the effects of the mass and length of the drillstring could not be properly accounted for in the tests. This also meant that the drilling vibration environment was fairly benign.

The intent of the tests were to:

- Determine the drilling performance of the AVD tool under various loading conditions.
- Compare the performance of the AVD to that of a standard drill collar
- Evaluate the bearings and seals under drilling conditions

A number of tests were performed while drilling each hole. Variables included:

- Formation material:
- Rotary speed
- Weight on bit (WOB)
- AVD damping

Conclusions

1. The drilling at TerraTek was fairly benign. The vibration levels were low and the changes in WOB were minor. Testing did not include any bit bounce. The TerraTek test rig, with its short BHA section, is ideal for drilling with standard collars. The short length minimizes axial vibration due its stiffness and high fundamental natural frequency.
2. Significant bit wear occurred during the tests. For a standard collar the ROP at the end of the tests was 60% of the ROP at the start of the tests. To account for this the ROP rates were corrected based on a linear degradation of the bit for

each hole drilled. Other drilling results, such as WOB, TOB acceleration, have not been corrected for bit wear.

3. Even with the benign drilling conditions the AVD showed its ability to improve ROP (Figure 11). While drilling through concrete the AVD improved ROP by 10 – 15%. For granite the improvement was up to 11%. While drilling through granite at 120rpm with 15,000 WOB the ROP actually dropped by 2%. However, lighter damping may improve this situation. The lighter damping case was not run.
4. The optimum drilling condition occurs when the AVD internal travel is ~0.17". If the drilling becomes too smooth, the ROP actually drops. There appears to be an optimum travel and WOB fluctuation that produces the best ROP.
5. The vibration levels measured through the tests were fairly benign. These were in the 5 – 25 g level.
6. The AVD tool significantly decreased the WOB fluctuations compared to the standard drill collar (Figure 13). The AVD reduced the WOB fluctuation by 60%. This should be even more beneficial under high vibration conditions.
7. The AVD displacement was 0.25" for the power off state and 0.13" at full power. The dynamic stiffness varied from 4200 lb/in to 17,800 lb/in. These ranges should significantly improve for the commercial tool. Upon disassembly of the AVD tool, it was found that the brass bobbins for the damper coils had become slightly magnetic. This would have reduce thed performance of the magnetic coils.

The tool was disassembled after the completion of the tests to inspect the seals and bearings. Both the bearings and the seals were still in good working order.

Recommendations

1. The AVD tool should be run in a test well under drilling conditions that would develop significant WOB fluctuations, including bit bounce.
2. An algorithm based on optimum tool displacement for a given acceleration should be developed and programmed into the tool.
3. The tool should also be programmed to perform stepped damping level sweeps during the testing. The tool should record displacement and acceleration and be time tagged for reference to ROP, rotary speed, WOB and formation.

Discussion

The AVD tests were performed at the TerraTek facility in Salt Lake City. TerraTek has a drilling simulator that is primarily used for testing bits. (See **Figure 9**, below.) The formation block is mounted in a pit beneath the drilling rig. The maximum BHA length that the drilling simulator can accommodate is approximately 30 feet. The WOB load is applied using hydraulic rams. This makes for a very stiff drilling structure, much stiffer than conditions that will occur under normal drilling, especially in the deep, hard rock drilling conditions for which the AVD was designed.

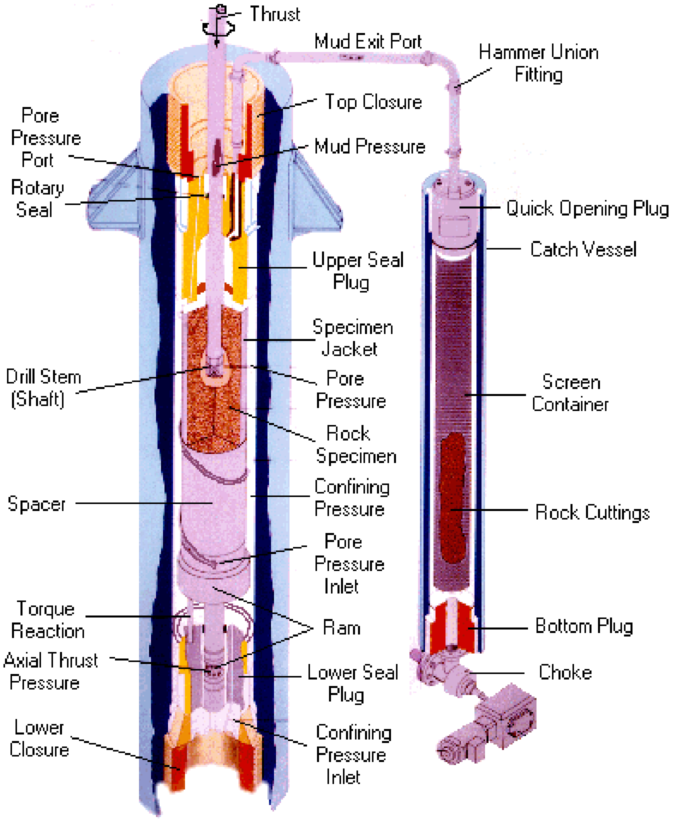
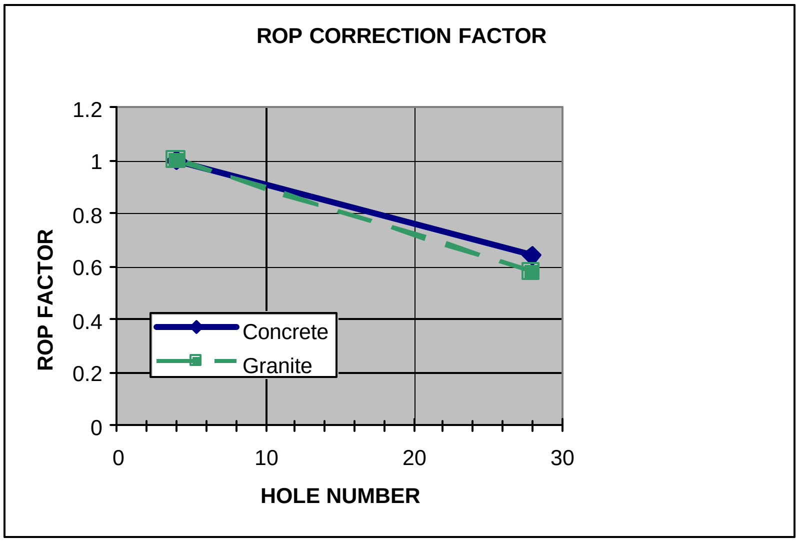


Figure 9: Layout of TerraTek Drilling Facility (courtesy of TerraTek, Inc.)

Special concrete and granite layered structures were built for the AVD tests. These were intended to induce as much axial drilling vibration as possible. To accomplish this the granite slab was placed on a 10^{o} angle between a top and bottom layer of concrete. This created an interrupted cut at the interface between the layers. Four tests blocks were built in which 8 holes each were drilled.

Baseline reference points were developed for the various conditions using a conventional drill collar in lieu of the AVD. At the completion of the AVD tests, the baseline was rerun to determine the affect of bit wear on ROP (Figure 10).

Figure 10



The ROP results for the AVD tool were corrected using **Figure 10** based on the drilled hole number. **Figure 10** shows that there was significant bit wear during the week long drilling tests.

A number of tests were performed in each of the holes varying the formation material, rotary speed, WOB and damping. The layered formation blocks gave four different formation scenarios for drilling:

? Concrete
? Concrete into granite
? Granite
? Granite into concrete
? A second layer of concrete

Holes were drilled through the different sections with different rotary speeds, WOB and AVD damping levels. The data recorded for each drilled section included:

? ROP
? TOB
? Acceleration
? AVD displacement

The data was sampled at frequency of 2000 samples per second.

Tests were also performed using an algorithm designed to optimize the AVD performance. The algorithm was developed based on analytical analysis for hard rock drilling. The algorithm was modified during the tests to improve the performance. The electronics feedback system broke down during the algorithm tests. Because the drilling conditions were benign and did not change significantly during testing, the algorithm could be approximated by adjusting the damping levels manually.

Results

Key: In each of these figures, the curves are labeled in the following manner: M-rrr-ww, where:

- M is the material being drilled – **C**oncrete or **G**ranite
- **rrr** is the rotary speed in rpm
- **ww** is the weight-on-bit (WOB) in klbs.

Furthermore, concrete data are shown as open points and common RPM-WOB combinations are shown by the same shape data points.

Figure 11

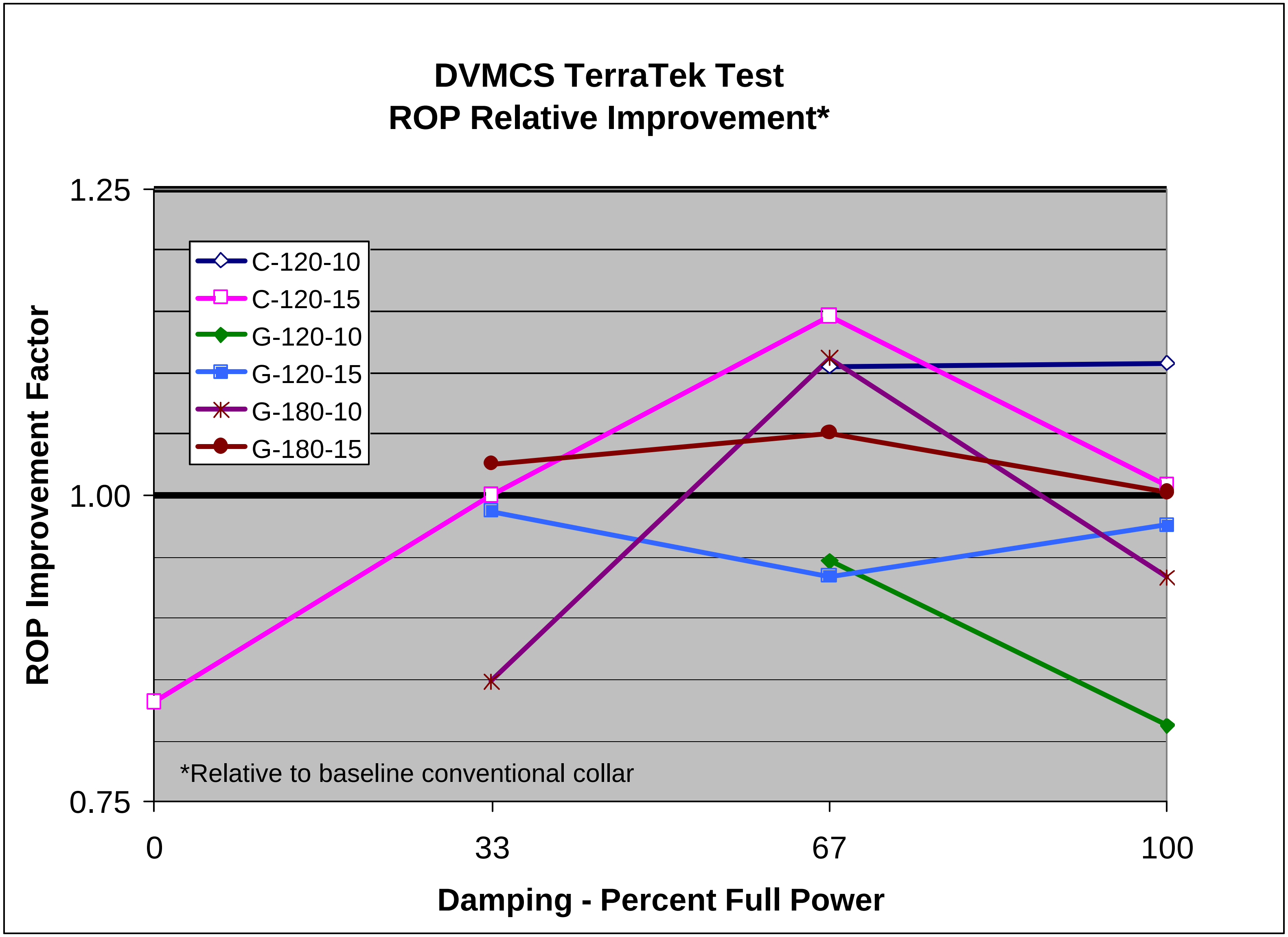

DVMCS TerraTek Test
ROP Relative Improvement*
ROP Improvement Factor
1.25
1.00
0.75
0
33
67
100
Damping - Percent Full Power
C-120-10
C-120-15
G-120-10
G-120-15
G-180-10
G-180-15
*Relative to baseline conventional collar

Figure 12

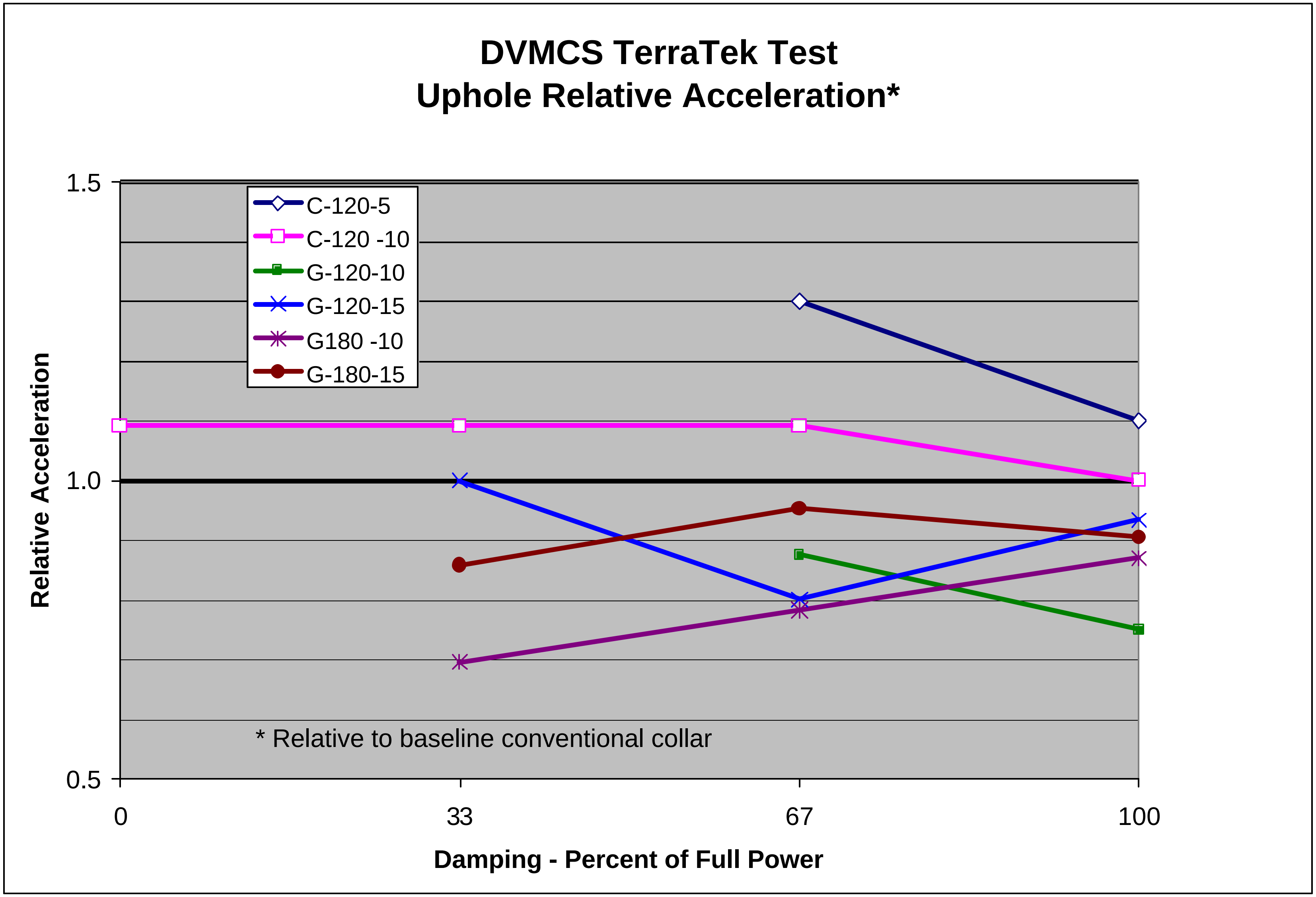

DVMCS TerraTek Test
Uphole Relative Acceleration*
1.5
1.0
0.5
Relative Acceleration
0
33
67
100
Damping - Percent of Full Power
C-120-5
C-120 -10
G-120-10
G-120-15
G180 -10
G-180-15
* Relative to baseline conventional collar

Figure 13

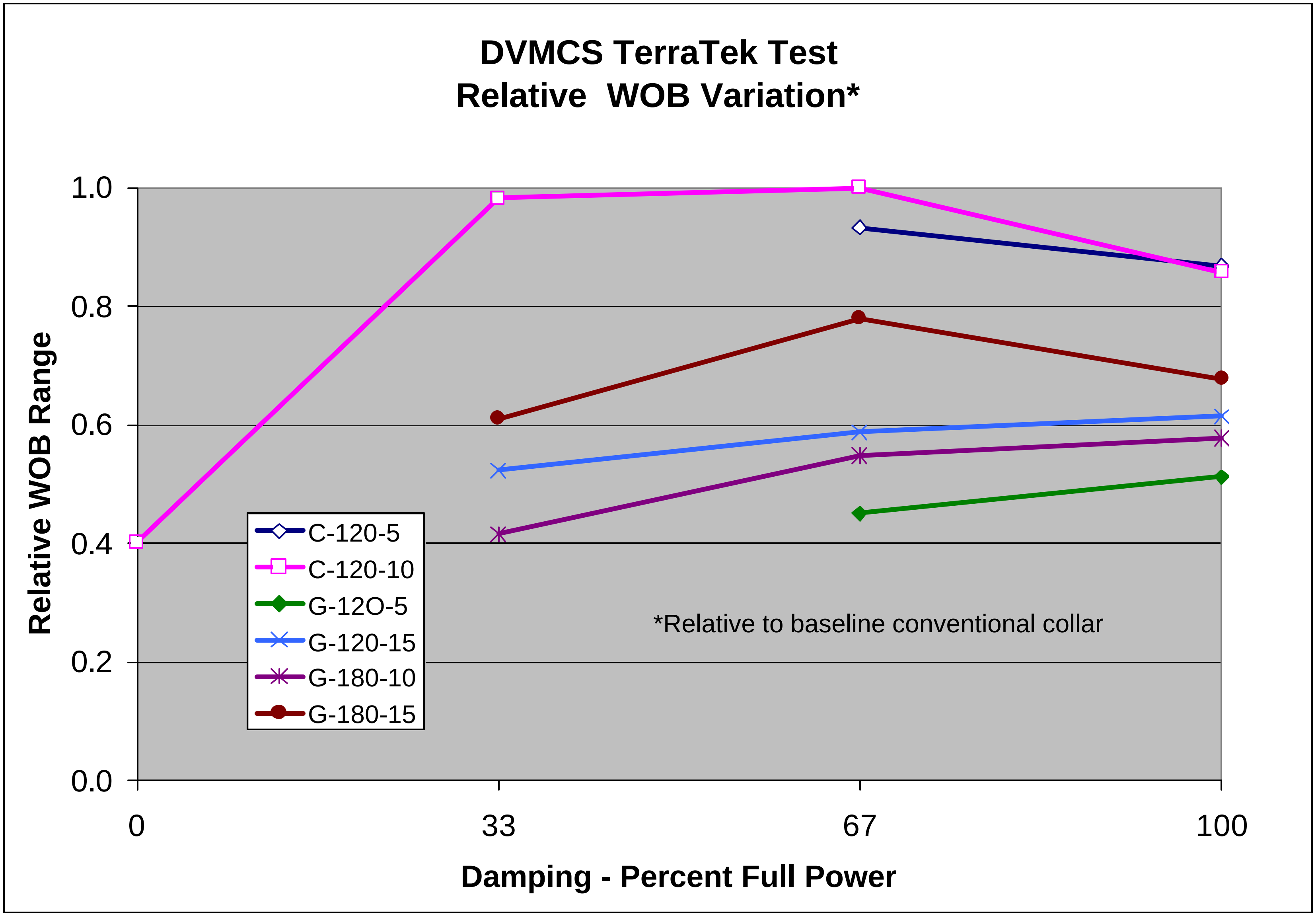

DVMCS TerraTek Test
Relative WOB Variation*
Relative WOB Range
1.0
0.8
0.6
0.4
0.2
0.0
0
33
67
100
Damping - Percent Full Power
C-120-5
C-120-10
G-12O-5
G-120-15
G-180-10
G-180-15
*Relative to baseline conventional collar

Figure 14

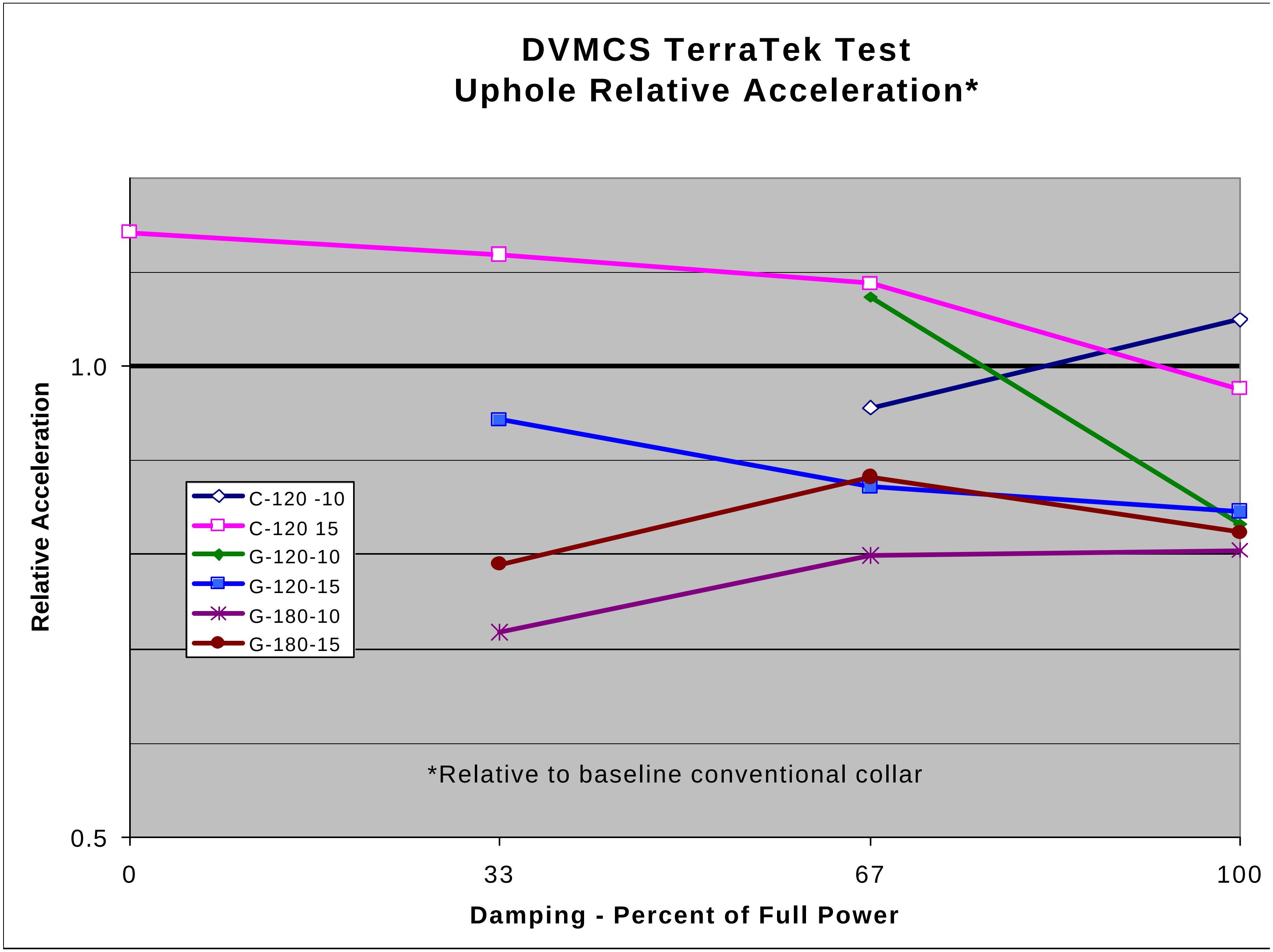

DVMCS TerraTek Test
Uphole Relative Acceleration*
Relative Acceleration
1.0
0.5
0
33
67
100
Damping - Percent of Full Power
C-120 -10
C-120 15
G-120-10
G-120-15
G-180-10
G-180-15
*Relative to baseline conventional collar

Figure 15

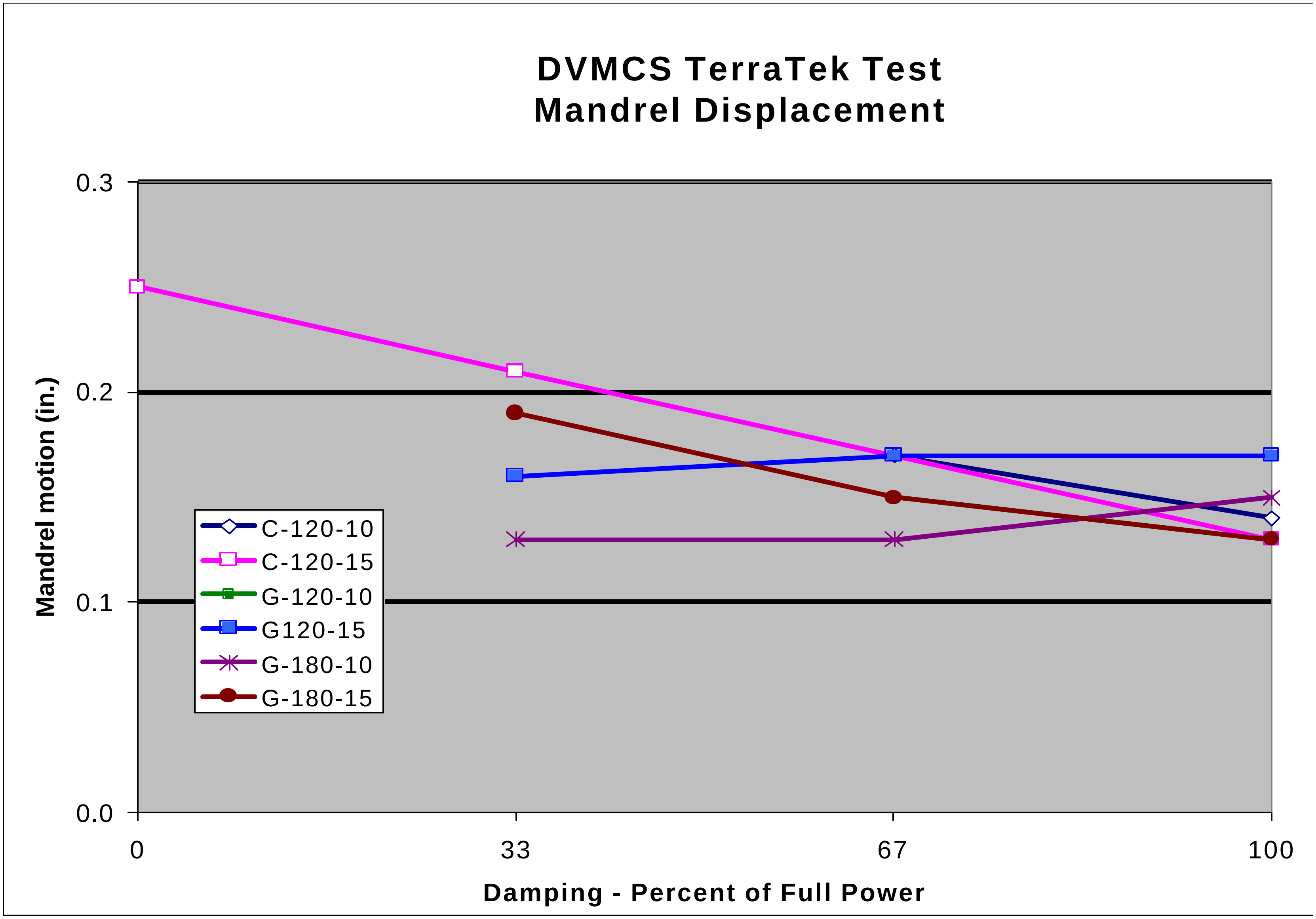
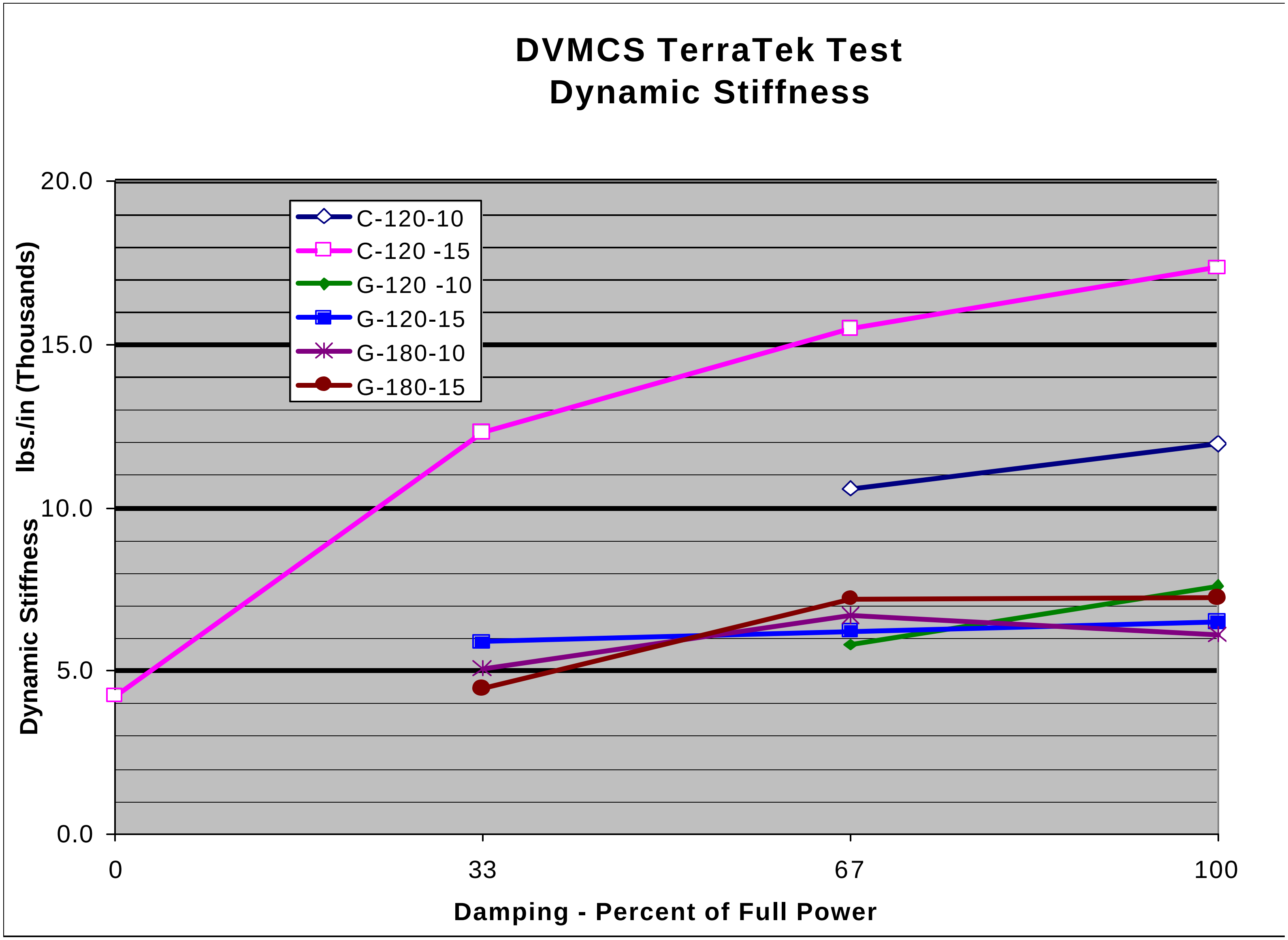

DVMCS TerraTek Test
Mandrel Displacement
Mandrel motion (in.)
0.3
0.2
0.1
0.0
0
33
67
100
Damping - Percent of Full Power
C-120-10
C-120-15
G-120-10
G120-15
G-180-10
G-180-15

Figure 16


DVMCS TerraTek Test
Dynamic Stiffness
C-120-10
C-120 -15
G-120 -10
G-120-15
G-180-10
G-180-15
20.0
15.0
10.0
5.0
0.0
0
33
67
100
Dynamic Stiffness lbs./in (Thousands)
Damping - Percent of Full Power

Collar

							WOB					TOB						ACC		
HOLE	HOLE #	MATERIAL	RPM	WOB	COLLAR	DAMPING	FREQ	MAX	MIN	AVE	RANGE	FREQ	MAX	MIN	AVE	RANGE	ROP	MAX	MIN	FREQ
2-1	2	CONCRETE	120	5000	COLLAR	NA	2	5388	4094	4741	1294	40	835	-506	164.5	1341	10	8	-7	
2-2		CONC-GRAN	120	5000	COLLAR	NA	3	6288	4100	5194	2188	44	941	-618	161.5	1559	8	11	-9	
2-3		GRANITE	120	5000	COLLAR	NA	2	5388	4329	4858.5	1059	40	786	-689	48.5	1475	4	12	-11	
2-4		GRANITE	220	5000	COLLAR	NA	5	5271	4541	4906	730	44	976	-506	235	1482	5	20	-12	
2-5		GRANITE	220	10000	COLLAR	NA	5	10600	9494	10047	1106	-	1323	-436	443.5	1759	12	32	17	
2-6		GRANITE-CONCRETE	120	5000	COLLAR	NA	2	5553	4565	5059	988	45	865	-560	152.5	1425	3	12	12	
3-1	3	CONCRETE	180	5000	COLLAR	NA	3	5576	4306	4941	1270	45	1118	-506	306	1624	17	13	-6	
3-2		CONCRETE-GRANITE	180	5000	COLLAR	NA	3	6218	4241	5229.5	1977	42	1043	-571	236	1614	21	11	-9	
3-3		GRANITE	180	5000	COLLAR	NA	3	5435	4447	4941	988	42	982	-520	231	1502	5	21	-10	
3-4		GRANITE	180	10000	COLLAR	NA	3	10941	9353	10147	1588	42	1348	-553	397.5	1901	10	23	-13	
3-5		GRANITE-CONCRETE	180	5000	COLLAR	NA	3	5459	4565	5012	894	42	992	-469	261.5	1461	4	19	-13	
4-1	4	CONRETE	120	10000	COLLAR	NA	6	11106	9176	10141	1930	46	1294	-471	411.5	1765	37	10	-10	
4-2		CONCRETE-GRANITE	120	10000	COLLAR	NA	1	11612	9106	10359	2506	28	1224	-682	271	1906	8	15	-11	
4-3		GRANITE	120	10000	COLLAR	NA	1	10788	9071	9929.5	1717	45	1082	-682	200	1764	7	16	-15	
4-4		GRANITE	120	15000	COLLAR	NA	1	15859	13918	14888.5	1941	42	1424	-471	476.5	1895	14	18	-13	
4-5		GRANITE-CONCRETE	120	10000	COLLAR	NA	2	10635	9129	9882	1506	44	1012	-471	270.5	1483	7	15	-11	
5-1	5	CONCRETE	180	10000	COLLAR	NA	3	11200	8706	9953	2494	42	1218	-759	229.5	1977	54	14	-8	
5-2		CONCRETE-GRANITE	180	10000	COLLAR	NA	3	10694	9282	9988	1412	42	1259	-682	288.5	1941	24	23	-11	
5-3		GRANITE	180	10000	COLLAR	NA	1	10737	9250	9993.5	1487	43	1424	-718	353	2142	10	23	-13	
5-4		GRANITE-CONCRETE	180	10000	COLLAR	NA	1	10765	9282	10023.5	1483	43	1412	-759	326.5	2171	10	24	-16	
6-1	6	CONCRETE	120	15000	COLLAR	NA	1	14247	11612	12929.5	2635	42	1471	-259	606	1730	70	11	-10	
6-2		CONCRETE-GRANITE	120	15000	COLLAR	NA	2	16176	13647	14911.5	2529	2	1559	-700	429.5	2259	13	15	-15	
6-3		GRANITE	120	15000	COLLAR	NA	2	15824	14024	14924	1800	42	1398	-598	400	1996	12	15	-15	
6-4		GRANITE-CONCRETE	120	15000	COLLAR	NA	2	16388	14129	15258.5	2259	43	1424	-429	497.5	1853	12	12	-14	
7-1	7	CONCRETE	180	15000	COLLAR	NA					0					0				
7-2		CONCRETE-GRANITE	180	15000	COLLAR	NA	3	16294	14353	15323.5	1941	3	1794	-606	594	2400	21	25	-18	
7-3		GRANITE	180	15000	COLLAR	NA	3	15812	14424	15118	1388	3	1553	-547	503	2100	19	21	-15	
7-4		GRANITE-CONCRETE	180	15000	COLLAR	NA	1	15941	11353	13647	4588	42	1553	-382	585.5	1935	22	20	-13	
8-1	8	CONCRETE	90	20000	COLLAR	NA	4	21706	18529	20117.5	3177	31	1965	-12	976.5	1977	69	6	-10	
8-2		CONCRETE-GRANITE	90	20000	COLLAR	NA	2	23753	17576	20664.5	6177	31	2345	-185	1080	2530	62	11	-11	
8-3		GRANITE	90	20000	COLLAR	NA	2	21247	18753	20000	2494	48	1718	-300	709	2018	17	13	-13	
8-4		GRANITE-CONCRETE	90	20000	COLLAR	NA	2	22500	17453	19976.5	5047	48	2324	-324	1000	2648	30	13	-14	

AVD

							WOB					TOB						ACC		
HOLE	HOLE #	MATERIAL	RPM	WOB	COLLAR	DAMPING	FREQ	MAX	MIN	AVE	RANGE	FREQ	MAX	MIN	AVE	RANGE	ROP	MAX	MIN	FREQ
4-1	12	CONCRETE	120	15000	AVD	0	4	15200	14141	14670.5	1059	20	1794	-182	806	1976	48.9	12	-8	6
4-1		CONCRETE	120	15000	AVD	1.257	4	15200	14141	14670.5	1059	20	1794	-182	806	1976	58.8	12	-8	6
4-2		CONCRETE-GRANITE	120	15000	AVD	0	1	15271	14376	14823.5	895	43	1512	-629	441.5	2141	15.41	17	-14	136
4-3		GRANITE	120	15000	AVD	SWEEP	2	15506	14329	14917.5	1177	43	1677	-516	580.5	2193	11.2	18	-13	4
4-4		GRANITE-CONCRETE	120	15000	AVD	0	2	15412	14471	14941.5	941	48	1512	-465	523.5	1977	10.24	17	-12	6
5-1	13	CONCRETE-GRANITE	180	15000	AVD	0	3	15506	14471	14988.5	1035	42	1559	-371	594	1930	20.65	20	-11	
5-2		GRANITE	180	15000	AVD	SWEEP	3	15506	14235	14870.5	1271	42	1746	-549	598.5	2295	14.71	22	-15	211
5-3		GRANITE-CONCRETE	180	15000	AVD	SWEEP	3	15647	14518	15082.5	1129	42	1512	-371	570.5	1883	16.32	21	-11	210
6-1	14	CONCRETE	120	5000	AVD	SWEEP	2	5176	4424	4800	752	2	1029	-647	191	1676	7.65	14	-11	11
6-2		CONCRETE-GRANITE	120	5000	AVD	1.335	3	5435	4541	4988	894	44	900	-647	126.5	1547	12.24	12	-10	11
6-3		GRANITE	120	5000	AVD	1.335	16	5082	4353	4717.5	729	35	829	-512	158.5	1341	3.3	12	-8	28
6-4		GRANITE	120	10000	AVD	SWEEP	3	10224	9447	9835.5	777	42	1300	-594	353	1894	4.05	14	-11	7
6-5		GRANITE-CONCRETE	120	10000	AVD	1.335	2	10271	9376	9823.5	895	42	1176	-559	308.5	1735	5	14	-8	11
7-1	15	CONCRETE	120	10000	AVD	2.66	2	10865	9065	9965	1800	36	1300	-388	456	1688	33.53	13	-11	105
7-2		CONCRETE-GRANITE	120	10000	AVD	2.66	3	11182	8959	10070.5	2223	37	1465	-562	451.5	2027	34.7	14	-10	11
7-3		GRANITE	120	10000	AVD	2.66	3	10129	9259	9694	870	41	1176	-718	229	1894	5.3	14	-11	7
7-4		GRANITE-CONCRETE	120	10000	AVD	2.66	2	10341	9235	9788	1106	45	1238	-547	345.5	1785	5.76	13	-12	11
8-1	16	CONCRETE	120	10000	AVD	4	2	10588	8912	9750	1676	45	1382	-471	455.5	1853	32.8	11	-7	11
8-2		CONCRETE-GRANITE	120	10000	AVD	4	2	11500	9135	10317.5	2365	36	1176	-388	394	1564	25.74	11	-9	211
8-3		GRANITE	120	10000	AVD	4	2	10341	9353	9847	988	32	1021	-447	287	1468	4.55	12	-9	11
8-4		GRANITE-CONCRETE	120	10000	AVD	4														
8-4.5		GRANITE	120	15000	AVD	4		15412	14235	14823.5	1177		1341	-347	497	1688	9.34	12	-11	
9-1	17	CONCRETE	120	15000	AVD	1.33	1	16294	13706	15000	2588	46	1676	-259	708.5	1935	59.47	12	-8	6
9-2		CONCRETE-GRANITE	120	15000	AVD	1.33	2	15694	14424	15059	1270	40	1553	-382	585.5	1935	12.53	15	-9	6
9-3		GRANITE	120	15000	AVD	1.33	2	15412	14471	14941.5	941	43	1418	-465	476.5	1883	10.01	12	-12	11
9-4		GRANITE-CONCRETE	120	15000	AVD	1.33	Not good data													
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10-2		CONCRETE-GRANITE	120	15000	AVD	2.66	1	16435	13941	15188	2494	38	1606	-606	500	2212	68.72	12	-11	5
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10-4		GRANITE-CONCRETE	120	15000	AVD	2.66		15294	14518	14906	776		1229	-559	335	1788	8.51	12	-11	
11-1	19	CONCRETE	120	15000	AVD	4		16153	13894	15023.5	2259		1718	29	873.5	1689	55.76	9	-11	
11-2		CONCRETE-GRANITE	120	15000	AVD	4		16153	13579	14866	2574		1718	29	873.5	1689	74.34	9	-11	
11-3		GRANITE	120	15000	AVD	4		15529	14424	14976.5	1105		1429	-259	585	1688	9.51	13	-14	
11-4		GRANITE-CONCRETE	120	15000	AVD	4	2	15412	14541	14976.5	871	35	1435	-224	605.5	1659	8.5	12	-11	11
12-1	20	CONCRETE	180	15000	AVD	1.33		16106	13941	15023.5	2165		1965	-94	935.5	2059	90.99	16	-12	
12-2		CONCRETE-GRANITE	180	15000	AVD	1.33		15412	14235	14823.5	1177		1512	-321	595.5	1833	15.44	21	-13	
12-3		GRANITE	180	15000	AVD	1.33		15318	14471	14894.5	847		1435	-224	605.5	1659	14.03	18	-14	
12-4		GRANITE-CONCRETE	180	15000	AVD	1.33		15247	14329	14788	918		1529	-206	661.5	1735	14.59	15	-14	
15-1	23	CONCRETE	180	15000	AVD	ALGOR-1	Bad data - Excessive WOB - No ROP data													
15-2		CONCRETE-GRANITE	180	15000	AVD	ALGOR-1	Bad data - No data in the file													
15-3		GRANITE	180	15000	AVD	ALGOR-1	Bad data - No data in the file													
16-1	24	CONCRETE	180	10000	AVD	ALGOR-2		10271	9212	9741.5	1059		1365	-294	535.5	1659	52.99	14	-5	
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16-3		GRANITE	180	10000	AVD	ALGOR-2		10224	9494	9859	730		1029	-294	367.5	1323	5.76	15	-8	
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17-6		GRANITE-CONCRETE	240	5000	AVD	0.158		5365	4259	4812	1106		912	-312	300	1224	3.88	19	-11	
17-7		GRANITE-CONCRETE	180	5000	AVD	0.158	Bad Data													
18-1	25	CONCRETE-GRANITE	180	15000	AVD	2.66		15459	14353	14906	1106		1294	-612	341	1906	16.22	20	-8	
18-2		GRANITE	180	15000	AVD	2.66		15506	14424	14965	1082		1382	-471	455.5	1853	12.38	20	-10	
18-3		GRANITE-CONCRETE	180	15000	AVD	2.66		16012	13518	14765	2494		1465	-265	600	1730	53.08	18	-8	
19-1	26	CONCRETE-GRANITE	180	15000	AVD	4		15529	14424	14976.5	1105		1471	-424	523.5	1895	12.58	21	-8	
19-2		GRANITE	180	15000	AVD	4		15365	14424	14894.5	941		1506	-224	641	1730	11.62	19	-12	
19-3		GRANITE-CONCRETE	180	15000	AVD	4	9	18425	11386	14905.5	7039	43	2041	-218	911.5	2259	22.05	19	-7	10
20-1	27	CONCRETE-GRANITE	180	10000	AVD	1.33		10412	9447	9929.5	965		1135	-429	353	1564	8.51	18	-4	
20-1A		CONCRETE-GRANITE	180	10000	AVD	0-1.33		10506	9824	10165	682		1053	-224	414.5	1277	14.93	20	-6	
20-2		GRANITE	180	10000	AVD	1.33		10224	9565	9894.5	659		1135	-229	453	1364	5.09	16	-7	
20-3		GRANITE-CONCRETE	180	10000	AVD	1.33		10224	9376	9800	848		1153	-329	412	1482	4.54	18	-4	
21-1	28	CONCRETE-GRANITE	180	10000	AVD	???		10329	8953	9641	1376		1341	-265	538	1606	34	17	-4	
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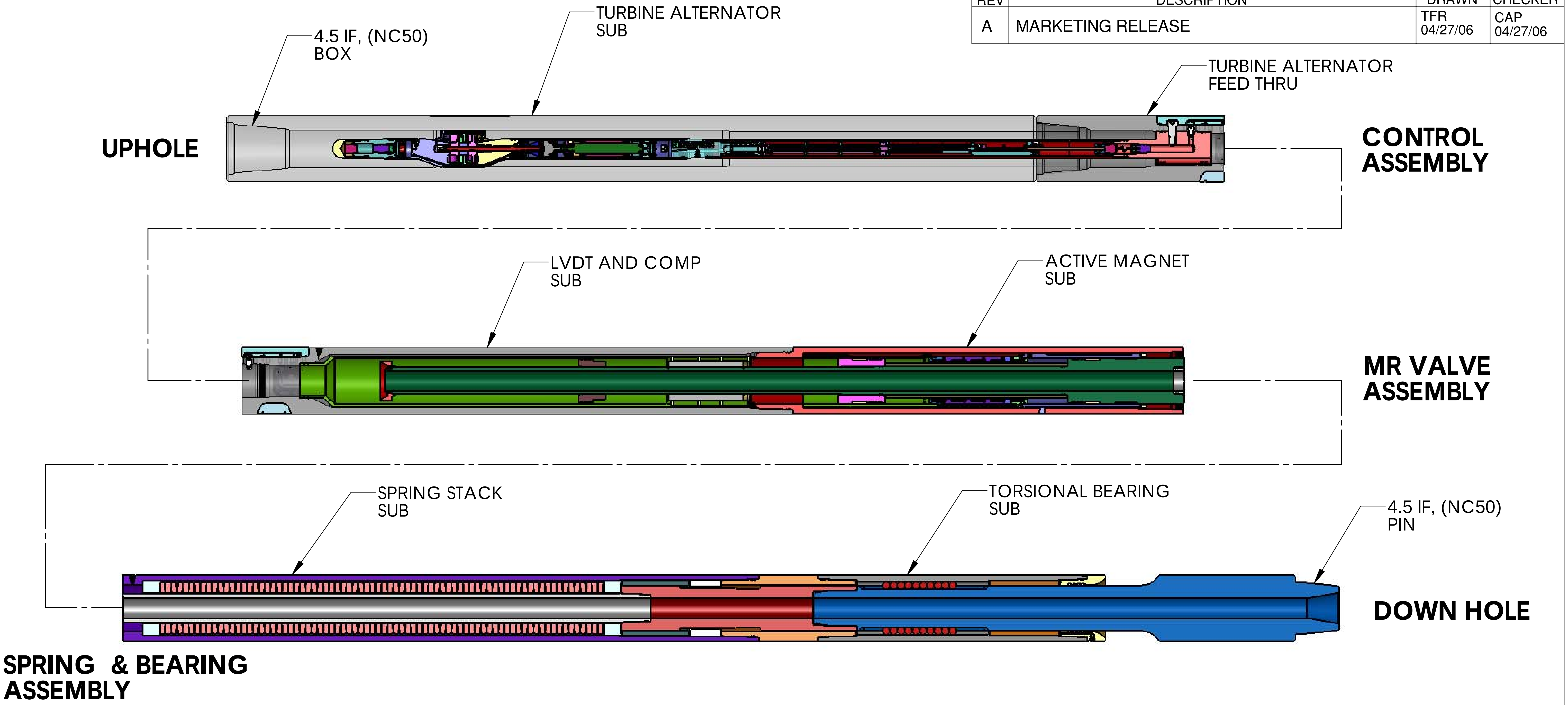
21-3		GRANITE	180	10000	AVD	4		10435	9518	9976.5	917		1206	-324	441	1530	5.6	20	-9	

Appendix G: Final Design of Field Prototype

REVISIONS

REV	DESCRIPTION	DRAWN	CHECKER
A	MARKETING RELEASE	TFR 04/27/06	CAP 04/27/06



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UNLESS OTHERWISE SPECIFIED
DIMENSIONS ARE IN INCHES & APPLY AFTER FINISH
PART MUST BE FREE OF BURRS AND/OR FLASH
BREAK SHARP EDGES APPROX .005
FILLET RADII .020 MAX
SURFACE FINISH 63 √ MAX

APPROVALS	BY	DATE
DRAWN	RZASA	04/27/06
CHECKED	CAP	04/27/06
ENGRG	DEB	04/27/06
MFG	BWP	04/27/06

TOLERANCES
.XXX ±.005 FRACTIONS ±1/64
.XX ±.01 ANGLES ±2°
INTERPRET DWG PER ASME Y14.5M-1994
DIMS IN PARENTHESIS ARE REF ONLY
DO NOT SCALE DWG

APS TECHNOLOGY
800 CORPORATE ROW
CROMWELL, CT 06416-2072

ACTIVE VIBRATION DAMPER ASSEMBLY

MATERIAL:	HEAT TREAT:	FINISH:
N/A	N/A	N/A

B DWG NO SK-10561 REV A

SCALE: 1/10 SHEET 1 OF 1

APS FILE : SK-10561 A ACTIVE VIBRATION DAMPER ASSEMBLY(MARKETING).SLDDRW

PROJECT # XXX-XXX

Appendix H: Excerpt from Spears Market Study

Markets and demand for new products from APS Technology

12 July 2004

Prepared by

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Introduction

APS Technology has several technologies in various stages of development – some in the earliest phases of design, others in the initial steps of production. Spears & Associates, along with Angie Smith and Derek Barnes (APS), prepared this initial evaluation of the addressable market[1] for each of seven technologies.

The technologies fall in two categories:

Drilling Technologies

- High temperature turbine alternator
- Low cost MWD
- Active vibration dampener
- Rotary steerable motor
- Survey-While-Drilling
- Automatic Driller

Production Technologies

- Petromax

Six of the technologies are systems which, when taken to the wellsite by the appropriate company, can be sold as a service to the end user – the oil company. One – the high temperature turbine alternator – is a component for high-end electrical systems used for downhole logging, drilling or other services.

Summary

Based on an analysis of the markets these seven technologies are most likely fit and on a projection of those markets based on activity drivers, the table below outlines our estimate of the total addressable market for each product:

APS-addressable markets by product

Product	Addressable Market Units	2003	2004	2005	2006	2007
HT Turbine Alternator	High End LWD & RS Systems	1080	1200	1240	1350	1430
Low Cost MWD	Footage (Millions)	55	61	60	62	64
Active Vibration Dampener	Footage (Millions)	186	206	200	204	207
Rotary Steerable Motor	Footage (Millions)	90	100	97	100	102
Survey While Drilling	Footage (Millions)	152	168	163	164	166
Automatic Driller	Footage (Millions)	3	3	3	3	3
Petromax	Flow measurement spending (Millions)	$9	$11	$13	$15	$18

APS will prepare estimates of market penetration and resulting sales revenue in a separate document. On the following pages are discussions of the drivers of demand and short evaluations of each technology.

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[1] By "addressable market" we mean that portion of the market – drilled footage, logging systems, etc. – that an APS product could reasonably expect to serve given the right technology, the right price and the right service company.

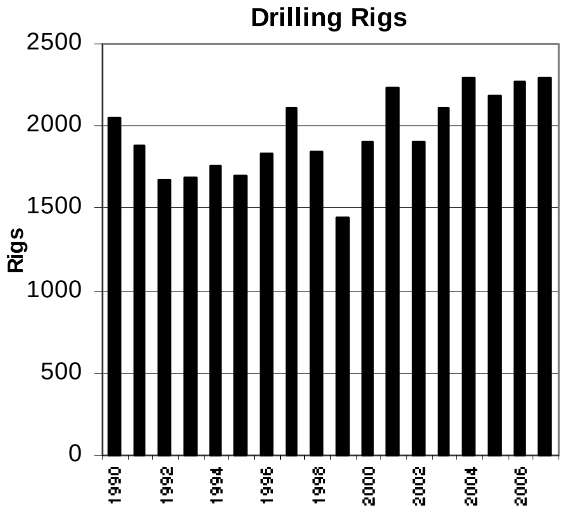
Drivers of demand

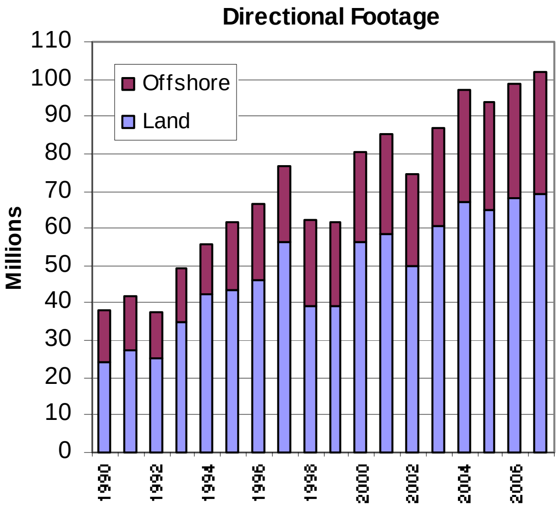
Drilling Technologies

Demand for drilling technologies is generally driven by the following factors:

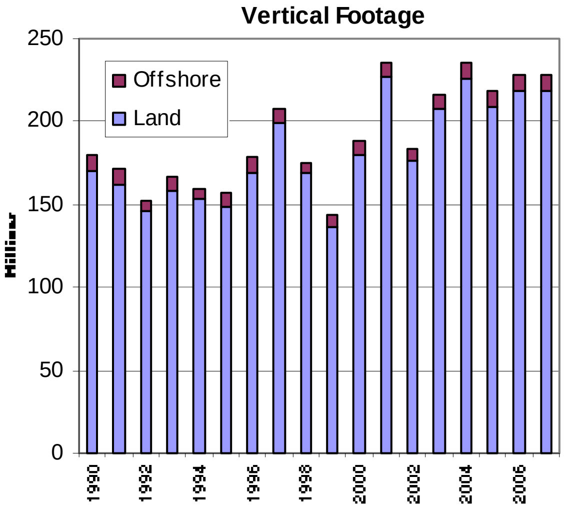
- Drilling activity
- Directional drilling activity
- Revenues related to directional drilling and LWD services

Global drilling activity has remained fairly flat since 1990, with little change through 2007, but directional drilling footage during that same period has been growing strongly, although Spears' forecast predicts a downward correction in 2005:

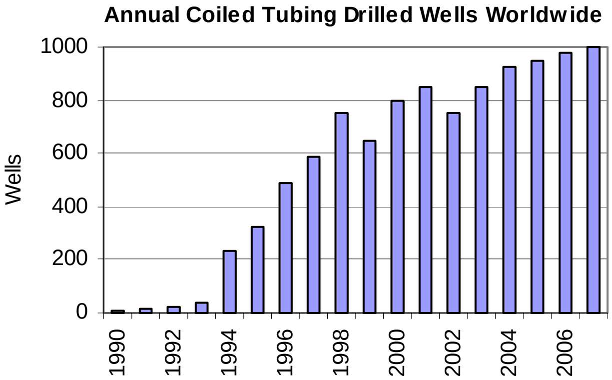


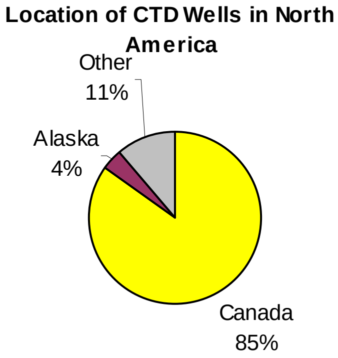


Some of the products APS is considering developing also serve the vertical drilling market. Survey-While-Drilling, for example, is targeted at the vertical section of any hole, whether on land or offshore – even the directionally drilled offshore wells usually have vertical hole sections. As the chart below shows, vertical footage ties more closely to rig count than directional footage:

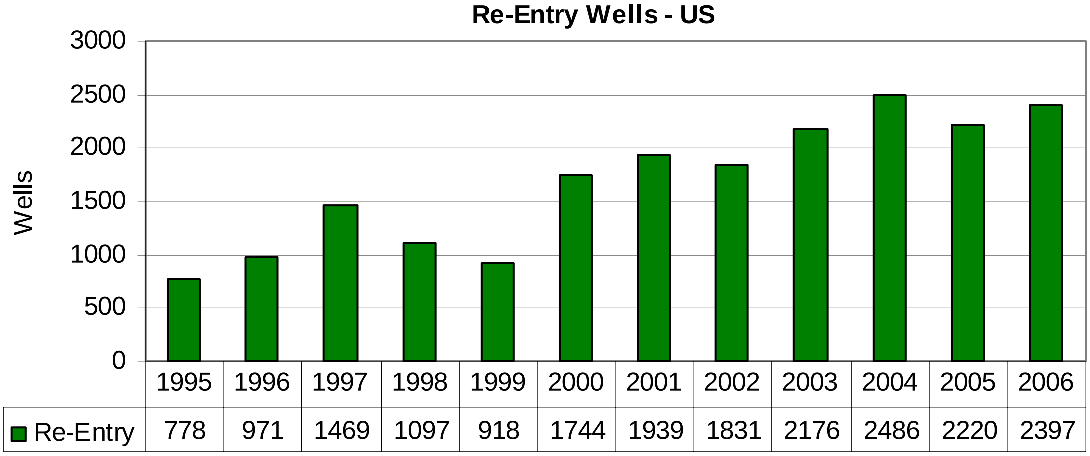


APS Technology has an automatic or self-propelled driller that appears to fit well with coiled tubing drilling applications. BP has kept two or more CTD units employed for the last several years on thru-tubing re-entry work on the North Slope. As the charts below indicate, about 800 wells per year are drilled with coiled tubing in North America (the largest CTD market by far) and about 85% of the wells are in Canada. These Canadian wells are, for the most part, shallow, straight holes drilled from the surface to TD:



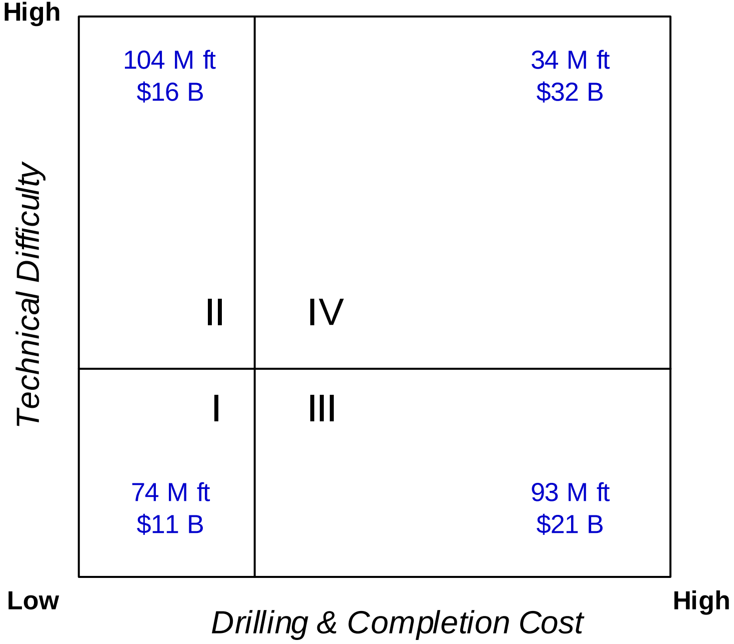


Another indicator of potential opportunity for the automated driller is the number of re-entry wells being drilled in mature fields today. No information is available for the rest of the world, but the chart below of re-entries in the US is a good indicator of the trend throughout the industry:



	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006
🟩 Re-Entry	778	971	1469	1097	918	1744	1939	1831	2176	2486	2220	2397

APS Technology's new products can address several types of drilling applications, from extreme condition wells to shallow, low cost wells, but none address exactly the same sub-divisions of the global drilling market. Therefore, we have divided the global drilling market into four segments, or sub-divisions, to more properly describe the wells and drilling applications each product will serve. The graphic below for 2003 shows the approximate drilling and completion spending found in each sub-division and the approximate number of feet of hole drilled – the size of each box is proportioned to drilling and completion spending in that segment:



Global Drilling Market

Segmented by Cost & Difficulty of Drilling

Footage – 305 million feet

D&C Spending - $80 billion

Drilling in the four segments can be described as follows:

SEGMENT I:	Shallow land drilling as is typically found in North America, South America and other <5000' applications. Also includes some shallow water development drilling. These holes have low rig costs and are technically simple to drill.
SEGMENT II:	More technically difficult wells, but still with fairly low drilling costs, such are found in the horizontal drilling plays of the Austin Chalk or in certain Middle East and African provinces.
SEGMENT III:	Can include offshore development drilling from jackups, like the Gulf of Mexico Shelf, deep land drilling and some international offshore work. Rig costs are higher, but well profiles are still technically simple.
SEGMENT IV:	These high cost, technically challenging wells include all deepwater drilling, high temperature/high pressure drilling and deep GOM Shelf work. Also includes remote or international exploration operations.

During 2003, Segment I drilling represented 74 million feet of hole drilled and about $11 billion in drilling and completion spending while Segment IV drilling was 34 million feet and $32 billion in D&C spending. All four sub-divisions together saw 305 million feet of hole drilled and completed at a cost of $80 billion.

Looking forward, with international drilling rising and North American drilling peaking, the overall forecast of drilling through 2007 is fairly flat, although 2004 will be up 10% over 2003. The table below records Spears' forecast of drilling activity (footage) by segment and by directional vs. vertical, for the period 2003-2007[2]:

Footage Drilled by Segment (Millions)

		2003	2004	2005	2006	2007
SEG I	Directional	16	18	17	18	19
SEG II	Directional	34	38	37	38	39
SEG III	Directional	28	31	30	31	32
SEG IV	Directional	10	11	11	12	13
	Sub Total	*88*	*97*	*95*	*99*	*103*
SEG I	Vertical	58	64	62	62	63
SEG II	Vertical	70	77	75	75	76
SEG III	Vertical	65	72	70	70	71
SEG IV	Vertical	24	27	26	26	26
	Sub Total	*217*	*240*	*233*	*234*	*236*
	TOTAL	**305**	**337**	**328**	**333**	**339**

D&C spending should increase 10% as well in 2004 to $88 billion. For the reasons listed above, Spears expects spending to plateau through the balance of the period:

D&C Spending by Segment (Millions)

		2003	2004	2005	2006	2007
SEG I		$11	$12	$12	$12	$12
SEG II		$16	$18	$17	$17	$18
SEG III		$21	$23	$23	$23	$23
SEG IV		$32	$35	$34	$36	$37
	TOTAL	**$80**	**$88**	**$86**	**$88**	**$90**

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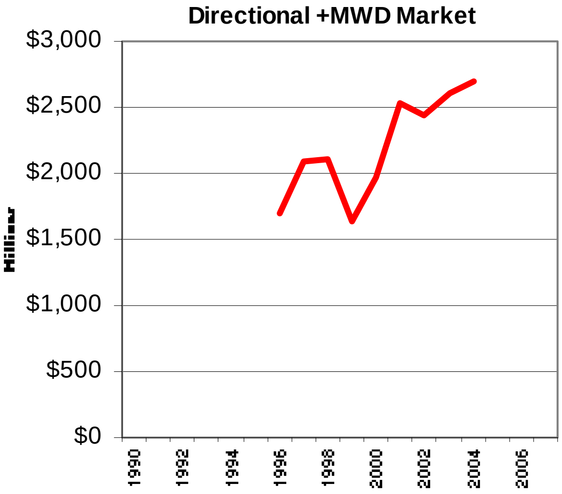
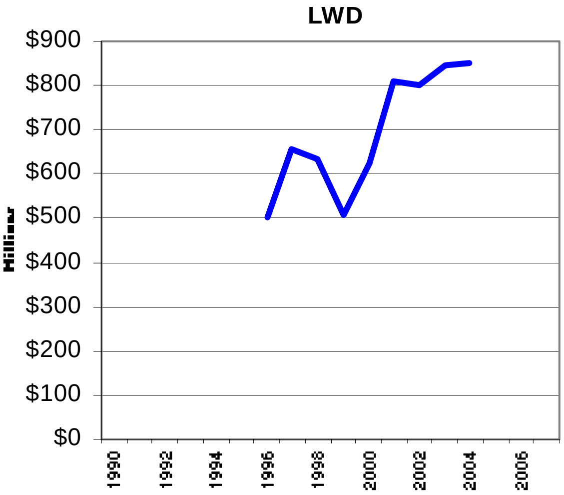
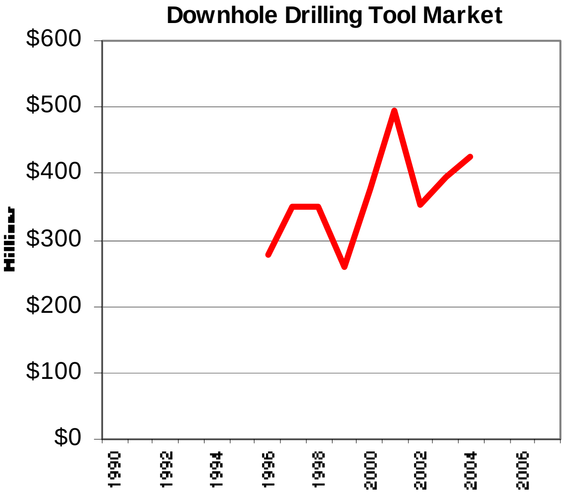
[2] Forecast is subject to change depending on oil and gas prices going forward. This forecast is based on Spears' June 2004 *Drilling and Production Outlook*.

Spending on directional & MWD services has grown strongly over the last 7 years and the future looks sound:





The "health" of the DD+MWD+LWD market dictates the cycle of the downhole drilling tools business, which is the category where we track drilling motors, bottomhole assemblies, MWD systems, fishing tool manufacturing and so on. As the following chart indicates, the downhole drilling tool market peaked in 2001 and has been on a rebound in 2003, a rebound that should extend into 2004 and beyond:



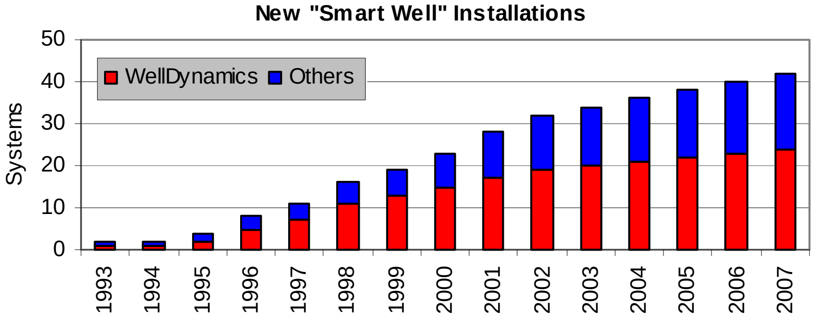
While we are certain that the oilfield service sector will continue to cycle into the future and that some of the wildest cycling will be seen within the directional drilling segment, we believe that the short, medium and long term futures of the market segment will continue to be positive and that the customer will seek more and more downhole technology solutions to avoid buying expensive drilling rig days. For the directional drilling services and equipment market **we project a 6% annual growth through 2007**.

Production Technologies

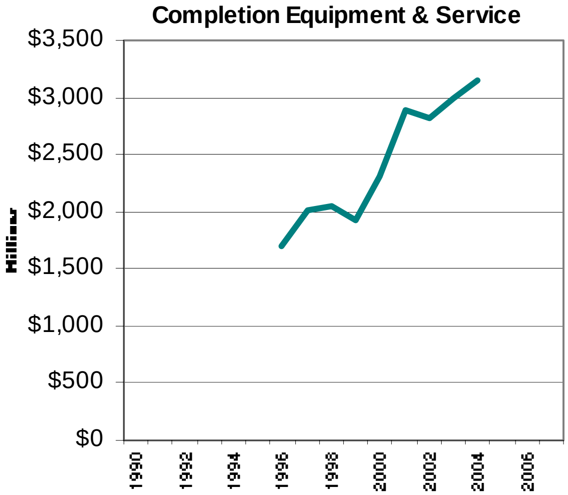
Demand for high-end production technologies is generally driven by these factors:

- Multi-zone completions
- Development of complex reservoirs
- Deepwater development drilling
- High operating cost environments

We have no easily accessible metrics to show that increasingly **complex reservoirs** are being developed around the world, nor is there a measure for multi-zone completions. We can, however, show how other technologies that are related to these types of developments have grown or been adopted over the years. For example, intelligent completions – sometimes called “smart wells” – have grown from fewer than 5 per year a decade ago to 35- 40 per year currently - an annual **growth rate of 22%**[3]:



Another indicator of the move toward more exotic wellbores is the trend in spending on completion equipment and services – packers, multilateral junctions, sliding sleeves and, as shown above, smart completions. Spending on completions is accelerating faster **(8% per year)** than the growth in drilling activity, suggesting a move toward complex wells:



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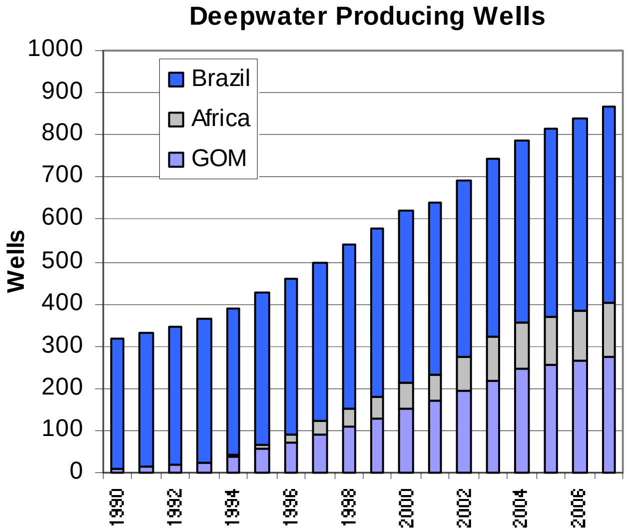
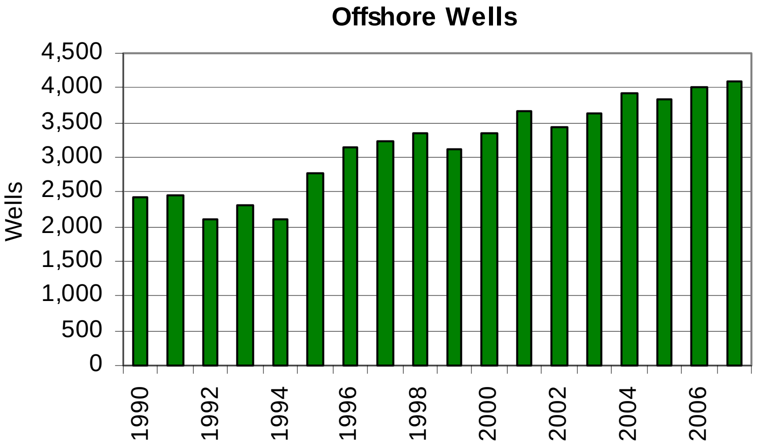
[3] Source: Spears & Associates, Inc., September 2003. Graph represents annual sales of WellDynamics (Halliburton and Shell joint venture) and all others, including Baker Hughes, Schlumberger, Weatherford and BJ Services. This market may be peaking. WellDynamics now makes more money on parts and accessories than on complete systems.

Production is moving into deeper and deeper waters. Today zones are being tested that lie in waters almost 2 miles deep. As the chart below indicates, **the deepwater producing well population is growing about 6% per year**:



The highest cost regions, in terms of drilling and operating costs, are offshore. Offshore drilling has been on a secular growth trend for years and is projected to continue at an average **annual growth rate of 4% per year**, as seen on the following graph:



Drilling technology: Active vibration dampener

APPLICATION: Increasing drilling speed is a major economic advantage in all drilling, as is the protection of expensive BHA components from the shock and vibration environment. The best applications for AVD are deep, hard rock holes and high day rate drilling, like deepwater and international, when LWD and RS systems are in the hole.

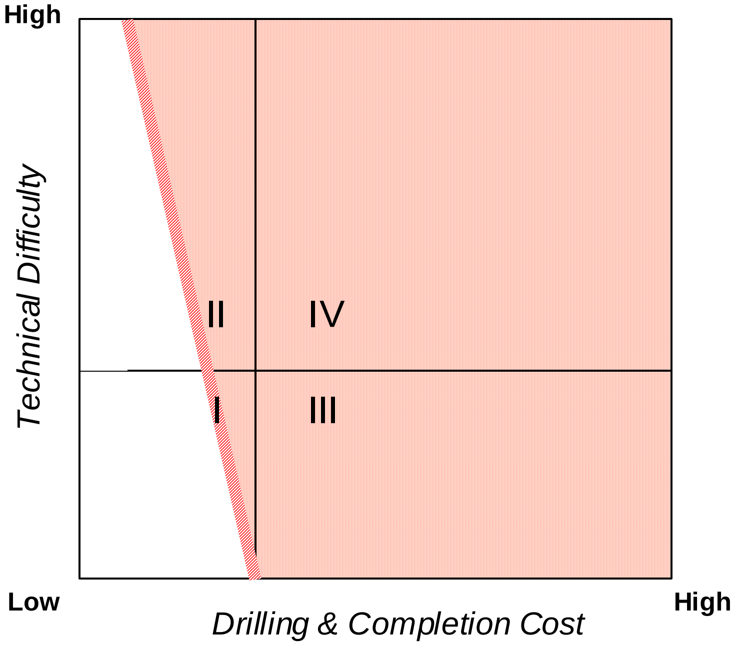
CUSTOMER: The operating company drilling engineers will mandate the use of these systems as a result of faster drilling. Delivery to the field will be either through the existing directional companies, specialty rental companies, or through an APS-established service group.

VALUE: Increased ROP and the mitigation of shock and vibration are a part of every drilling operation, but some situations are more problematic than others. Drilling engineers recognize the important value of keeping the bit properly engaged at the desired instantaneous weight-on-bit, and in protecting the integrity of their systems. The efficiencies of faster ROPs and less idle time from unnecessary trips create a lower cost well for the customer.

COMPETITION: No system is on the market that actively measures and dampens shock and vibration. Baker Hughes and others have devices that measure these parameters, allowing the driller to modify the drilling process, but no system evaluates and solves the problem downhole. The primary competition is from doing nothing at all.

ADDRESSABLE MARKET: The AVD is designed to work in all Segment III and IV applications where high day rate drilling costs can be significantly reduced through improved drilling efficiencies. AVD also applies to about half the Segment II wells and a small fraction of the low-end wells:

Active Vibration Dampener
Addressable Global Drilling Market



AVD addresses about 60% of the footage drilled each year – almost 200 million of the 305 million feet drilled in 2003:

AVD-addressable market by segment
(Millions of Feet)

		2003	**2004**	**2005**	**2006**	**2007**
SEG I	Directional	2	2	2	2	2
SEG II	Directional	17	19	18	19	20
SEG III	Directional	28	31	30	31	32
SEG IV	Directional	10	11	11	12	13
	Sub Total	*57*	*63*	*61*	*64*	*66*
SEG I	Vertical	6	6	6	6	6
SEG II	Vertical	35	39	38	38	38
SEG III	Vertical	65	72	70	70	71
SEG IV	Vertical	24	27	26	26	26
	Sub Total	*130*	*143*	*139*	*140*	*141*
	TOTAL	**186**	**206**	**200**	**204**	**207**

EXPECTED GROWTH: We believe that the market will rapidly adopt an active vibration dampener once it has been proven to work. As the product matures we expect it to become a familiar component in the package of downhole services found at the rig site.