DEVELOPMENT OF TURBODRILL TACHOMETER

— FINAL REPORT —

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EXECUTIVE SUMMARY

The objective of the study was to develop a tachometer for use with the METC turbodrills. Tachometers are needed to allow efficient operation of the turbodrills. The operating speed of the turbodrills is now unknown, resulting occasionally in excessive operating speeds and rapid bit wear. In some applications, good tachometers could increase the footage drilled per bit run and greatly reduce drilling costs.

This project resulted in the successful testing of a prototype turbodrill tachometer. The tachometer utilizes a set of partially blanked turbine blades in the motor section of the turbodrill which produce one pressure pulse each time the turbodrill rotates one revolution. The pressure pulses are transmitted through the drilling mud in the drill pipe to the surface where they are detected and processed. The frequency of the pulse signals is a direct measure of the turbodrill rotary speed.

Numerous laboratory tests of the pulse tachometer were conducted at Maurer Engineering's turbodrill facility in Houston, Texas. Initial attempts at detecting the 10 to 25 psi mud pulse signals in field applications with an oscilloscope were unsuccessful due to excessive pump noise. Even with desurgers in the rig flow lines to dampen the pump noise, the signals could not be detected. A spectrum analyzer was then successfully utilized in processing the dynamic pressure signals. Motor test stand comparisons of the mud pulse tachometer with direct magnetic and optical tachometers usually demonstrated excellent agreement.

The tachometer performed well at depths in excess of 10,000 feet in Los Alamos Scientific Laboratories' EE-2 geothermal well. Water was

used as the drilling fluid in these tests. The tachometer allowed continual monitoring and control of the LASL turbodrill speed. This attributed, in large part, to the success of the LASL turbodrills. Over 20 successful turbodrills were made using the tachometer.

Although attenuation is greater in viscous drilling mud than in water, theory indicates that the pulse tachometer should be effective with viscous muds even at depths of 10,000 to 20,000 feet.

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I. INTRODUCTION

Extensive studies conducted by the Department of Energy have shown that large quantities of methane can be produced by drilling horizontal holes in coal seams. High drilling costs preclude the use of this technique in most areas. In an attempt to reduce the drilling costs, the Morgantown Energy Technology Center has initiated a program with Maurer Engineering Inc. on the development of a new line of turbodrills which are specifically designed for use on methane drainage projects. These turbodrills, which operate at speeds of 300 to 2,000 RPM, drill several times faster than conventional rotary bits operated at speeds of 50 to 150 RPM (Maurer and Wise, 1979).

The major limitation of turbodrills is that it is often difficult to operate them efficiently since their operating speed is unknown. The turbodrill speed is a function of bit torque and therefore can vary widely under normal drilling operations. This can result in excessive rotary speed and premature failure of the drill bits.

The objective of this program was to develop a simple, reliable turbodrill tachometer which allows the driller to continually monitor and control the speed of turbodrills. The mud pulse tachometer developed on this project has been successfully used to depths in excess of 10,000 feet in a Los Alamos Scientific Laboratories geothermal well at Fenton Hill, New Mexico. The system is fully operational and should operate effectively in 1,000 to 2,000 foot deep methane drainage or in situ coal gasification wells.

II. BACKGROUND

Turbodrills were first used to drill oil wells in the 1920's. Their use increased to point where they are now widely used for both directional and straighthole drilling. The turbodrill consists of a turbine section which powers the drill and a bearing pack section which contains thrust bearings which allow weight to be applied to the drill bit. Figure 1 shows a schematic of the Morgantown Technology Center (METC) methane drainage turbodrill. This turbodrill is designed to operate with water as the drilling fluid. Approximately 10 percent of the drilling fluid is diverted through the bearings for cooling and lubrication.

Figure 1. METC Methane Drainage Turbodrill

This turbodrill can be sealed to allow the thrust bearings to operate in oil as demonstrated in Figure 2.

Figure 2. Sealed Turbodrill

The METC turbodrill is designed for rapid drilling of directional methane drainage holes as represented in Figure 3. The METC turbodrills can be used for drilling directional holes for in situ gasification of coal seams as depicted in Figure 4.

Figure 3. Methane Drainage Hole

Figure 4. In situ Coal Gasification System

The turbine section of the turbodrill contains 50 sets of turbine blades as shown in Figure 5. The change in momentum of the drilling fluid being pumped through the blades produces torque on the rotor blades, thereby turning the shaft and the drill bit.

Figure 5. Turbine Blades

The turbines can operate at any speed from stall to runaway (2,000 to 4,000 RPM) as represented in Figure 6. Maximum torque (T_0) is developed at stall and the torque decreases linearly to zero at the runaway speed (N_R). The turbodrill speed in the field is controlled by the bit torque which is directly related to the bit weight.

Figure 6. Turbodrill Torque vs. Rotary Speed

It is important to accurately control the speed of the turbodrill because the turbodrill delivers maximum power output at 50 percent of the runaway speed as shown in Figure 7. Maximum power output of the METC turbodrills occurs at speeds of 1,000 to 2,000 RPM depending on the fluid flow rate.

Figure 7. Turbodrill Power Output vs. Rotary Speed

A serious limitation of turbodrills is the fact that the driller does not know the turbine speed while drilling. If the driller unknowingly applies excessive weight on bit, the turbodrill stalls and does not drill whereas if too little thrust is applied, the turbine speed becomes excessive and produces rapid failure of the drill bit. The excessive speed also reduces the life of the turbodrill thrust bearings.

III. SUMMARY OF PULSE ATTENUATION THEORY

This section summarizes mud pulse attenuation theory. A more complete description of the theory is given in the Appendix.

Theory indicates that the mud pulse attenuation "half depth," D, is of the form:

$$D = \frac{Kdc}{\sqrt{f} \times v} \quad (1)$$

where

d = effective internal pipe diameter (inches)

c = speed of sound in mud (ft/sec)

f = frequency (RPM)

v = viscosity (cs)

The "half depth" (D) is defined as the well distance over which the mud pulse signal attenuates to one-half its original strength. If the total well depth is twice the half depth, the signal strength at the surface will be one-fourth that of the original signal. Similarly, if the well depth is three times the half depth, the signal strength will be only one-eighth the original strength. The mathematical approach described in the Appendix gives a theoretical value for the constant (K) of $K = 38.3$ with the mixed units described above. This is approximately 8.6% higher than the value of $K = 35.3$ derived from the data of Patton shown in Figure 8. This excellent match is obtained using a pipe diameter equal to the ID of the tool joint, which is the smallest diameter in the drill string. This is also approximately the same as the ID of the collars.

Figure 8. Pressure Pulse Half Depths (Patton, et al, 1977)

For estimating pulse attenuation the following equation will be used

$$D = 35.3 \frac{d \times c}{\sqrt{f \times v}} \quad (2)$$

Lack of knowledge of the kinematic viscosity is a basic limitation to using the calculation in oil field and geothermal situations. As a first approximation, one may assume that the Bingham Plastic Viscosity (PV) of the drilling fluid is a good estimate of the absolute viscosity. To obtain kinematic viscosity, the absolute viscosity is scaled by fluid density. In oil field units

$$v \text{ (cs)} = PV \text{ (cp)} \frac{8.34}{\text{Mud Wt. (PPG)}} \quad (3)$$

Table 1 shows the effect of various parameters on attenuation of the pulse signal. The attenuation is much higher in drilling mud than in water because mud has a higher kinematic viscosity (50 cs vs 1 cs). For example; when drilling at 600 RPM with 3-inch bore drill pipe, the

half-life distance is 18,600 feet in water compared to 3060 feet in mud. This indicates that transmission may be a problem in heavily weighted muds (i.e., muds with high viscosity). Attenuation also increases with increased rotary speed. For example, when drilling with mud and 3-inch inside diameter drill pipe, the half-life distance decreases from 5,300 to 2,160 feet as the rotary speed is increased from 200 to 1,200 RPM. This indicates that it may be difficult to detect turbodrill rotary speed under typical turbodrill runaway conditions (2,000 to 4,000 RPM).

Attenuation half depths can also be obtained utilizing nomographs (see Nomogram Solution to the Attenuation Calculation, Appendix III).

Table 1. Effect of Different Variables on Signal Attenuation

<u>Drilling Fluid</u>	<u>Mud Rotary Speed (RPM)</u>	<u>Mud Sonic Velocity (ft/sec)</u>	<u>Pipe Kinematic Viscosity (cs)</u>	<u>Signal Inner Diameter (in)</u>	<u>Half-Life Distance (ft)</u>
Water	200	4,300	1	2	21,500
Water	600	4,300	1	2	12,300
Water	1,200	4,300	1	2	8,800
Water	200	4,300	1	3	32,200
Water	600	4,300	1	3	18,600
Water	1,200	4,300	1	3	13,100
Water	200	4,300	1	4	42,900
Water	600	4,300	1	4	24,800
Water	1,200	4,300	1	4	17,500
Mud	200	5,000	50	2	3,530
Mud	600	5,000	50	2	2,040
Mud	1,200	5,000	50	2	1,440
Mud	200	5,000	50	3	5,300
Mud	600	5,000	50	3	3,060
Mud	1,200	5,000	50	3	2,160
Mud	200	5,000	50	4	7,060
Mud	600	5,000	50	4	4,080
Mud	1,200	5,000	50	4	2,880

IV. DESCRIPTION OF PULSE TACHOMETER

The pulsing tachometer produces one pressure pulse each time the turbodrill rotates one revolution. These pressure pulses (5 to 50 psi) are transmitted through the drilling mud in the drill pipe to the surface as demonstrated in Figure 9. Instrumentation on the rig floor monitors the frequency of the pressure pulses. This frequency is monitored continually in real time and is a direct measure of the turbodrill rotary speed.

Figure 9. Turbodrill Tachometer

The pressure pulses are produced by blanking approximately 40 percent of the blades of one turbine rotor and 40 percent of the blades of one turbine stator as demonstrated in Figures 10 and 11.

Figure 10. Blanked Turbine Stage (Side View)

Figure 11. Blanked Turbine Blades (Top View)

As the rotor stage turns with the turbine shaft, the blanked blades in the rotor stage pass over the blanked blades in the stationary stator stage. The flow area through the blanked blades therefore varies cyclically as the turbine shaft rotates. When the blanked blades are directly opposite each other, 40 percent of the flow area is blanked whereas when the blanked areas are offset, 80 percent of the flow area is blanked as reflected in Figure 12. The latter case restricts flow through the blades and produces a pressure pulse which can be detected at the surface. The pressure pulse is approximately sinusoidal at the surface and it is in phase with the changing blade area as shown in Figure 13. Under typical operating conditions, this dynamic pressure signal has an amplitude of 10 to 25 psi. In addition to this dynamic signal, the restriction in flow produces a static pressure increase of 50 to 100 psi.

Figure 12. Varying Blanked Area

Figure 13. Pressure Pulses at Surface

Ultimately the pulse tachometer will become an integral part of an advanced directional drill system which allows continual monitoring and control of the drilling operation as depicted in Figure 14.

Figure 14. Advanced Directional Drilling System

V. SYSTEM COMPONENTS

There are five basic components to the pulse tachometer system:

1. Rig pumps
2. Desurgers
3. Pulsing Blades
4. Surface pressure transducers
5. Spectrum analyzer

Rig Pumps

Rotary drilling rigs utilize duplex and triplex mud pumps to provide fluid circulation. Drilling fluid is pumped down the inside of the drill pipe and up the annulus between the drill pipe and the wellbore as shown in Figure 15. The drilling mud carries the rock cuttings to the surface where they are removed by a shale shaker. No changes need to be made to the mud pump or to the circulation except for the addition of extra pressure desurgers in the flow lines.

Figure 15. Drill Rig Circulation System

Desurgers

The duplex and triplex pumps used on rotary drilling rigs produce severe pressure fluctuations (± 100 to 300 psi) which overshadow the pressure fluctuations (10 to 50 psi) produced by the pulsing tachometer blades. Hydrodyne Industries ten gallon desurgers (Type AA30-10) of the type shown in Figure 16 were used to reduce the pressure fluctuations produced by the pump. The desurgers are charged to about 70% of the surface operating pressure for maximum efficiency. Up to four desurgers were required during the field tests.

Figure 16. Hydrodyne Industries Mud Desurger

The pressure fluctuations produced by duplex and triplex pumps can be severe. Figure 17 shows a laboratory test with an oil field triplex frac pump where the pressure into the turbodrill (upper curve) fluctuated from 1460 to 1960 psi (1710 ± 250 psi). This test was conducted at a turbodrill rotary speed of 620 RPM and at a flow rate (water) of 302 gpm. The lower curve corresponds to the pressure beneath the turbine blades inside of the turbodrill. It is interesting to note that the pressure fluctuations pass through the turbine blades essentially unchanged except for amplitude.

Figure 17. Pressure Fluctuations Without Desurger

Figure 18 shows the pressure fluctuations under identical conditions with one desurger charged to 980 psi. In this case the pressure fluctuation is reduced to ± 50 psi. This is an acceptable level since the pressure pulses produced by the pulsing blades are typically of much higher frequency (300 to 1000 cpm) than the pump pressure fundamental frequency (50 to 200 cpm).

Figure 18. Pressure Fluctuations With Desurger

The field tests have shown that good desurgers are essential with the mud pulse tachometer. Without good desurgers, the pulsing signals cannot be separated from pump noise even at shallow depths; with desurgers, the tachometer performed well at depths in excess of 10,000 feet.

Surface Pressure Transducers

In all our tests the pressure pulses were detected using Teledyne-Taber Model 206 0-5000 psi pressure transducers on the standpipe flow line (Figure 19). These transducers utilize strain gage bridges which were powered by a Gentran Inc. Model GT-403G Transducer Indicator. This unit both conditioned the signal and provided an analog readout of steady-state pressure.

Figure 19. Pressure Transducer

Spectrum Analyzer

Initially, an attempt was made at processing the pressure pulses directly from an oscillograph record of the pressure signal. Early tests demonstrated that this was not possible due to the high amplitude of the pump noise, even with desurgers in the flow lines.

Attempts were then made to use a spectrum analyzer to process the pulse tachometer signal. These tests were successful with desurgers on the flow lines. The spectrum analyzer displays the fundamental and harmonic frequencies of the pump noise in addition to the pulse

signal. Since the pump speed (i.e. fundamental frequency) is known, it is relatively easy to differentiate the pulse signal from the pump noise.

Figure 20 shows a typical record from the spectrum analyzer where the turbodrill was operating at 1080 RPM. The turbodrill speed is determined by moving the light spot cursor to the peak of the pulse signal. In this laboratory test, the pulse signal indicates that the turbodrill was operating at 1080 RPM (18.0 Hz) compared to a reading of 1079 RPM with an optical tachometer. This demonstrates that the pulse tachometer is very accurate. In fact, in all of the laboratory tests, the pulse tachometer was accurate within one percent.

Figure 20. Spectrum Analyzer Record

Any high quality spectrum analyzer can be used to analyze the pulse signals. In initial tests, a Nicolet Scientific Corporation Model 466A Spectrum Analyzer was used successfully. In later tests, good results were obtained with a Hewlett Packard Model 3582A Spectrum Analyzer. Both instruments worked equally well with the turbodrill pulse tachometer.

VI. LABORATORY TESTS

The mud pulse tachometer was tested in 5-3/8 inch and 7-3/4 inch turbodrills in Maurer Engineering's turbodrill test stand in Houston (Figure 21). A dynamometer was used to apply a torque load to the turbodrills and thereby operate them at speeds from stall to 2500 RPM. A magnetic pickup tachometer was used to measure the rotary speed to the nearest RPM.

Figure 21. Turbodrill Test Stand

Two desurgers were used during the laboratory tests (Figure 22). These desurgers effectively dampened the pressure fluctuations in these tests.

Figure 22. Mud Desurgers

Figure 23 shows the Nicolet Scientific Corporation Model 446A Spectrum Analyzer used on some of these tests.

Figure 23. NSC Spectrum Analyzer

The laboratory tests demonstrated that the mud pulse tachometer was accurate and reliable at all speeds from stall to 2500 RPM. Figure 24 shows a test at 360 RPM and Figure 25 shows a test at 846 RPM. In all tests, the electrical and pulsing tachometers were accurate within a few RPM (i.e., within one percent). Although this sophisticated electronics equipment worked well in the laboratory and field tests, a simplified analog or digital readout is needed for use by drillers on the rig floor.

Figure 24. Pulse Tachometer Record (360 RPM)

Figure 25. Pulse Tachometer Record (846 RPM)

The pulse tachometer was also used to measure the speed of the turbodrills during a series of laboratory tests conducted at Terra Tek's Drilling Research Laboratory (DRL) in Salt Lake City in April 1979. Figure 26 shows the turbodrill in this full scale drilling rig and Figure 27 shows DRL instrumentation used during the tests.

Figure 26. DRL Mud Pulse Tachometer Tests

Figure 27. DRL Instrumentation

The mud pulse tachometer worked very well during these tests, the data corresponding closely to measurements made with other tachometers. These laboratory tests demonstrated the feasibility of the mud pulse tachometer.

VII. FIELD TESTS AND RESULTS

In 1979, the mud pulse tachometer was tested in Los Alamos Scientific Laboratories' EE-2 hot, dry rock geothermal well at Fenton Hill, New Mexico as shown in Figure 28. Four desurgers were used in the mud flow line to dampen the pump noise. A pressure transducer was used in the standpipe flow line on the drill rig. Water is used on all of the Fenton Hill wells because of the low formation fluid pressures encountered in these wells.

Figure 28. LASL EE-2 Geothermal Well

Figure 29 shows the LASL turbodrill containing the mud pulse tachometer in the Brinkerhoff drill rig used on the LASL Well.

Figure 29. Turbodrill Containing the Mud Pulse Tachometer on EE-2 Well

The mud pulse tachometer performed very well during these tests to depths in excess of 10,000 feet. Attenuation of the signal transmitted through the mud in the drill pipe did not appear to be a problem. Figure 30 shows a typical signal obtained during the LASL field tests. The representative rotary speed was 546 RPM when this measurement was made.

Figure 30. LASL EE-2 Pulse Tachometer Record

Although the pump noise produced several spikes on the spectrum analyzer record, it was easy to differentiate the tachometer signal from the pump noise for four reasons: (1) the fundamental pump speed was known, (2) the pump noise produced several harmonics which helped identify them, (3) the pulse signal slowly moved back and forth on the screen as the turbine speed varied whereas the pump signal remained stationary and (4) the pump signal is harmonic and produces steep spikes whereas the pulse signal is not harmonic and produces a broader band signal. For these reasons, it was easy for the drillers and rig crew to identify the pulse signal. They quickly learned to use the tachometer as a tool to optimize the operation of the turbodrills. The success of the turbodrill in LASL's operations can be attributed in a large part to the use of the METC tachometer. The tachometer allowed the tool pushers and drillers to more effectively use the turbodrills. This test demonstrated

that the pulse tachometer should work effectively in METC's 1000 to 2000 foot deep methane drainage and insitu coal gasification wells.

The pulse tachometer was also used during two turbodrill tests at Gearhart Owen's (G.O.) plant in Fort Worth, Texas. Figure 31 shows the 5-3/8 inch METC turbodrill containing the mud pulse tachometer in the G.O. drill rig.

Figure 31. METC Turbodrill During G.O. Test

This test was conducted with drilling mud at a depth of approximately 500 feet. The turbodrill speed was successfully measured with the mud pulse tachometer during the test. Due to the short duration of the test only limited data could be obtained. Deeper tests are needed to determine if the pulse tachometer is as effective in drilling mud as it is with clear water.

VIII. CONCLUSIONS

The research and development of the turbodrill tachometer led to the following conclusions:

- A turbodrill mud pulse tachometer has been developed.
- Desurgers are required to reduce pump noise and a spectrum analyzer is required to separate the pulse signal from the pump noise.
- Mud pulse tachometers transmitting one pulse per revolution produce a strong signal even at rotary speeds up to 2000 RPM.
- In laboratory tests, the pulse tachometer was accurate to within one percent.
- The mud pulse tachometer performed well at depths in excess of 10,000 feet in LASL's EE-2 geothermal well. Water was used as the drilling fluid in these tests.
- The pulse tachometer is fully operational for use in future drilling operations with METC's 5-3/8 inch turbodrills.

IX. RECOMMENDATIONS

Although this project proved the pulse tachometer concept, limitations must be overcome before the system can be commercialized. The following are recommendations for providing basic information to overcome these limitations:

- Develop improved surface instruments for field use.
- Develop and test simplified methods for reducing pump noise and processing the pulse tachometer signal.
- Measure signal attenuation in field wells with different drilling fluids and compare with existing theory.
- Test blanked blades of different designs to determine if blades producing a harmonic signal or multiple pulses per revolution are easier to detect.

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APPENDIX I
PRESSURE PULSE ATTENUATION THEORY

A simple, basic theory based on Lamb has been used in this report to help understand the mud pulse attenuation problem. While the theory does not account for properties such as compressibility and dispersion, the usefulness of this approach is confirmed by data acquired by Mobil in the development of their mud pulse system.

Lamb has derived that the change in pressure amplitude for a wave traveling along a tube is given by:

$$p(x) = p_0 e^{-\frac{x}{\ell}}$$

where $\ell = \frac{dc}{v\beta}$

and $\beta = \sqrt{\frac{\sigma}{2v}}$

is a measure of the extent to which the influence of viscosity penetrates into the fluid.

Thus, $\ell = dc \sqrt{\frac{2}{v\sigma}}$

where

- d - inside radius of pipe, (ft)
- c - speed of sound (ft/sec)
- v - kinematic viscosity of fluid, (centipoise)
- σ - pressure pulse frequency (rad/sec)
- ℓ - distance in which amplitude falls to 1/e of its original value.

Expressing parameters in terms of English and oil field units

$$c = \sqrt{\frac{E}{.233\rho}} \quad \text{where } E = \text{bulk modulus lb/ft}^2 \\ \rho = \text{density, lb/gal}$$

$$\mu(\text{absolute viscosity, cp}) = \nu(\text{kinematic viscosity, cs}) \times \rho (\text{density, g/cc})$$

$$\text{Note: } 1 \text{ centipoise} = 1.45 \times 10^{-7} \text{ reyns } \left(\frac{\text{lb-sec}}{\text{in}^2} \right)$$

To convert μ (absolute) to reyns

$$\mu = \mu(\text{cp}) \times 1.45 \times 10^{-7} \frac{\text{lb-sec}}{\text{in}^2}$$

$$\mu = \mu(\text{cp}) \times 1.45 \times 10^{-7} (144 \text{ in}^2/\text{ft}^2) \frac{\text{lb-sec}}{\text{in}^2}$$

$$\nu \left(\frac{\text{ft}^2}{\text{sec}} \right) = \mu(\text{cp}) \times 2.09 \times 10^{-5} \frac{\text{lb-sec}}{\text{ft}^2} \times \frac{\text{g}}{\rho} \\ = 1.075 \times 10^{-5} \times \nu(\text{cs})$$

also see Marks page 230-231

$$\sigma = 2\pi f \text{ rad/sec}$$

where f is pressure pulse frequency in Hertz

The equation for damping of the pressure wave in a fluid may also be written in the form.

$$e^{\beta} = 2^{\alpha}$$

$$\beta \ln(e) = \alpha \ln(2)$$

where $\alpha = \frac{\beta}{\ln(2)}$

Thus the pressure pulse equation can be written

$$p(x) = p_0 2^{-\frac{x}{\ln(2)\ell}} = p_0 2^{-\frac{x}{D}}$$

where

$$D = \ln(2) \times \ell$$

= the distance in which amplitude falls to 1/2 of its original value.

Using this theory, pressure attenuation expressed as attenuation "Half Depth" was calculated for the cases listed in Table I. A listing of the program and computer output is included in this section.

TABLE I
ATTENUATION CALCULATIONS

Case	I	II	III	IV	V
Pipe ID (in)	3.75	3.75	3.75	3.75	3.75
Freq. (Hz)	6	6	24	24	24
Drilling Fluid Bulk Modulus (PSI x 10 ³)	250	250	250	250	250
Mud Density (#/gal)	9	9	9	9	9
Kinematic Viscosity (cs)	10	30	10	20	30
Calculated Sound Velocity (ft/sec)	4149	4149	4149	4149	4149
Calculated "Half Depth" (ft.)	9972	5757	4986	3525	2879

Comparisons of the theory with a similar mathematical form, but incorporating experimental data are made in the following section.

PULSTAC 16:15CST 03/10/80

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2000THIS PROGRAM IS BASED ON THE SECTION, "DAMPING OF SOUND IN NARROW CHANNELS"
    IN LAMB'S HYDRODYNAMICS, PAGES 652 AND 653
210 PRINT,"INSIDE DIAMETER OF PIPE, INCHES"
215 INPUT,DIA
216 SR=DIA/2
220 PRINT,"PRESSURE PULSE FREQUENCY, CPS"
225 INPUT,SF
230 PRINT,"BULK MODULUS OF DRILLING MUD, PSI"
235 INPUT,E
240 PRINT,"DENSITY OF DRILLING MUD, LBS/GAL"
245 INPUT,GAM
250 PRINT,"VISCOSITY OF DRILLING MUD, CENTISTOKES"
255 INPUT,XNU
280 SA=SR/12
290 E=E*144
300 RHO=GAM*7.481/32.2
320 XNU=XNU*107.74/10**7
330 OMEG=2*3.14159*SF
340 SIG=OMEG
360 SC=SQRT(E/RHO)
370 CL=SA*SC*SQRT(2/(XNU*SIG))
371 CL2=CL*ALOG(2)
400 PRINT 10,SC
410 10 FORMAT(1X,"SPEED OF SOUND IS",F8.1,2X,"FT PER SEC")
420 PRINT 20,CL2
430 20 FORMAT(1X,"HALF PRESSURE DISTANCE IS",F8.1,2X,"FEET")
450 PRINT 30
455 30 FORMAT(///)
460 PRINT 40
470 40 FORMAT(2X,"DISTANCE",2X,"PRESSURE")
475 PRINT 50
480 50 FORMAT(3X,"(FEET)",5X,"RATIO",/)
490 DL=500
500 DO 100 I=1,21
510 XI=I-1
520 X=XI*DL
530 PR=EXP(-X/CL)
540 PRINT 110,X,PR
550 110 FORMAT(F9.0,4X,F7.5)
560 100 CONTINUE
570 PRINT 150
575 150 FORMAT(///)
600 BETA=SQRT(SIG/(2*XNU))
610 BETA1=1/BETA
620 PRINT 200,BETA1
625 200 FORMAT(1X,"1/BETA IS",F10.7,2X,"FT")
630 PRINT 210,SA
635 210 FORMAT(1X,"PIPE RADIUS IS",F10.5,2X,"FT",/)
640 STOP:END
```

READY

PASSWORD
#####M88A
ID:WJMTURBO
SYSTEM- F77
NEW OR OLD-
OLD PULSTAC

CASE I

READY
RUN

PULSTAC 12:41CST 03/10/80

INSIDE DIAMETER OF PIPE, INCHES?3.75

PRESSURE PULSE FREQUENCY, CPS?6

BULK MODULUS OF DRILLING MUD, PSI?250000

DENSITY OF DRILLING MUD, LBS/GAL?9

VISCOSITY OF DRILLING MUD, CENTISTOKES?10

SPEED OF SOUND IS 4149.3 FT PER SEC
HALF PRESSURE DISTANCE IS 9972.1 FEET

DISTANCE (FEET)	PRESSURE RATIO
0.	1.00000
500.	0.96584
1000.	0.93285
1500.	0.90099
2000.	0.87021
2500.	0.84049
3000.	0.81178
3500.	0.78405
4000.	0.75727
4500.	0.73140
5000.	0.70642
5500.	0.68229
6000.	0.65899
6500.	0.63648
7000.	0.61474
7500.	0.59374
8000.	0.57346
8500.	0.55387
9000.	0.53495
9500.	0.51668
10000.	0.49903

1/BETA IS 0.0023908 FT
PIPE RADIUS IS 0.15625 FT

PROGRAM STOP AT 640

RUN

PULSTAC 12:42CST 03/10/80

INSIDE DIAMETER OF PIPE, INCHES?3.75

PRESSURE PULSE FREQUENCY, CPS?6

BULK MODULUS OF DRILLING MUD, PSI?250000

DENSITY OF DRILLING MUD, LBS/GAL?9

VISCOSITY OF DRILLING MUD, CENTISTOKES?30

SPEED OF SOUND IS 4149.3 FT PER SEC
HALF PRESSURE DISTANCE IS 5757.4 FEET

CASE II

DISTANCE (FEET)	PRESSURE RATIO
--------------------	-------------------

0.	1.00000
500.	0.94158
1000.	0.88657
1500.	0.83478
2000.	0.78601
2500.	0.74009
3000.	0.69685
3500.	0.65614
4000.	0.61781
4500.	0.58172
5000.	0.54773
5500.	0.51574
6000.	0.48561
6500.	0.45724
7000.	0.43052
7500.	0.40537
8000.	0.38169
8500.	0.35939
9000.	0.33840
9500.	0.31863
10000.	0.30001

1/BETA IS 0.0041409 FT
PIPE RADIUS IS 0.15625 FT

PROGRAM STOP AT 640

USED 3.21 UNITS

RUN

PULSTAC 12:43CST 03/10/80

INSIDE DIAMETER OF PIPE, INCHES?3.75

PRESSURE PULSE FREQUENCY, CPS?24

CASE III

BULK MODULUS OF DRILLING MUD, PSI?250000

DENSITY OF DRILLING MUD, LBS/GAL?9

VISCOSITY OF DRILLING MUD, CENTISTOKES?10

SPEED OF SOUND IS 4149.3 FT PER SEC

HALF PRESSURE DISTANCE IS 4996.0 FEET

DISTANCE (FEET)	PRESSURE RATIO
--------------------	-------------------

0.	1.00000
500.	0.93285
1000.	0.87021
1500.	0.81178
2000.	0.75727
2500.	0.70642
3000.	0.65899
3500.	0.61474
4000.	0.57346
4500.	0.53495
5000.	0.49903
5500.	0.46552
6000.	0.43426
6500.	0.40510
7000.	0.37790
7500.	0.35252
8000.	0.32885
8500.	0.30677
9000.	0.28617
9500.	0.26696
10000.	0.24903

1/BETA IS 0.0011954 FT
PIPE RADIUS IS 0.15625 FT

PROGRAM STOP AT 640

USED 3.19 UNITS

RUN

PULSTAC 12:44CST 03/10/80

INSIDE DIAMETER OF PIPE, INCHES?3.75

PRESSURE PULSE FREQUENCY, CPS?24

BULK MODULUS OF DRILLING MUD, PSI?250000

DENSITY OF DRILLING MUD, LBS/GAL?9

VISCOSITY OF DRILLING MUD, CENTISTOKES?20

SPEED OF SOUND IS 4149.3 FT PER SEC

HALF PRESSURE DISTANCE IS 3525.7 FEET

CASE IV

DISTANCE (FEET)	PRESSURE RATIO
--------------------	-------------------

0.	1.00000
500.	0.90638
1000.	0.82152
1500.	0.74460
2000.	0.67489
2500.	0.61171
3000.	0.55444
3500.	0.50253
4000.	0.45548
4500.	0.41284
5000.	0.37418
5500.	0.33915
6000.	0.30740
6500.	0.27862
7000.	0.25253
7500.	0.22889
8000.	0.20746
8500.	0.18804
9000.	0.17043
9500.	0.15448
10000.	0.14001

BETA IS 0.0016905 FT
PIPE RADIUS IS 0.15625 FT

PROGRAM STOP AT 640

USED 3.14 UNITS

PULSTAC 12:45CST 03/10/80

INSIDE DIAMETER OF PIPE, INCHES?3.75

PRESSURE PULSE FREQUENCY, CPS?24

CASE V

BULK MODULUS OF DRILLING MUD, PSI?250000

DENSITY OF DRILLING MUD, LBS/GAL?9

VISCOSITY OF DRILLING MUD, CENTISTOKES?30

SPEED OF SOUND IS 4149.3 FT PER SEC
HALF PRESSURE DISTANCE IS 2878.7 FEET

DISTANCE (FEET)	PRESSURE RATIO
--------------------	-------------------

0.	1.00000
500.	0.88657
1000.	0.78601
1500.	0.69685
2000.	0.61781
2500.	0.54773
3000.	0.48561
3500.	0.43052
4000.	0.38169
4500.	0.33840
5000.	0.30001
5500.	0.26598
6000.	0.23581
6500.	0.20907
7000.	0.18535
7500.	0.16433
8000.	0.14569
8500.	0.12916
9000.	0.11451
9500.	0.10152
10000.	0.09001

1/BETA IS 0.0020705 FT
PIPE RADIUS IS 0.15625 FT

PROGRAM STOP AT 640

USED 3.24 UNITS

APPENDIX II
EMPIRICAL CALIBRATION OF ATTENUATION THEORY

Theory indicates that the mud pulse attenuation "half depth", D , is of the form:

$$D = \text{CONSTANT} \left[\frac{d \times c}{\sqrt{f \times v}} \right]$$

where

d = effective internal pipe diameter (inches)

c = speed of sound in mud (ft/sec)

f = frequency (RPM)

v = viscosity (cs)

D = "half depth" (ft), the well depth that attenuates the mud pulse signal to one-half its original strength (2D means one-fourth remains, 3D means one-eighth, etc.)

The mathematical approach described earlier gives a theoretical value for the constant (K) of $K = 38.3$ with the mixed units described above. This is approximately 8.6% higher than the value of $K = 35.3$ derived below from the data of Patton. This excellent match is obtained using a pipe diameter equal to the ID of the tool joint, which is the smallest diameter in the drill string. Also this is approximately the same ID as the collars.

From this point forward, the empirical calibration of the theory will be used.

Calibrating against the data of Patton:

$$D = 10^4 \text{ ft}$$

$$d = 2.5 \text{ in}$$

$$c = 4300 \text{ ft/sec}$$

$$f = 24 \frac{\text{cyc}}{\text{sec}} \left(60 \frac{\text{sec}}{\text{min}} \right) = 1440 \text{ RPM}$$

$$v = 1 \text{ cs}$$

$$\text{CONSTANT} = K$$

$$= D \times \frac{\sqrt{f \times v}}{d \times c}$$

$$= 10^4 \times \frac{\sqrt{1440}}{2 \times 5(4300)}$$

$$K = 35.3$$

$$D = 35.3 \frac{d \times c}{\sqrt{f \times v}}$$

This equation can be used to calculate the half-depth for the range of variables expected in field operations (Table II).

Lack of knowledge of the kinematic viscosity is a basic limitation to using the calculation in oil field and geothermal situations. As a first approximation, it may be assumed that the Bingham Plastic Viscosity (PV) of the drilling fluid is a good estimate of the absolute viscosity. To obtain kinematic viscosity, the absolute viscosity is scaled by fluid density. In oil field units

$$v(\text{cs}) = \text{PV (cp)} \frac{8.34}{\text{Mud Wt. (PPG)}}$$

TABLE II
CALCULATION OF HALF-DEPTH FOR THE
EXPECTED RANGE OF VARIABLES

	<u>Maximum Range</u>		<u>Typical Range</u>	
	Low	High	Low	High
d(inch)	5	2	4	2.5
c(ft/sec)	5000	4000	4500	4300
f(RPM)	3000	1	1200	20
v(cs)	50	1	20	5
D(1000 ft)	2.3	282.4	4.1	37.9

APPENDIX III

NOMOGRAM SOLUTION TO THE ATTENUATION CALCULATION

The calculation of attenuation "Half Depth" can be usefully expressed in nomogram form. The nomogram is derived and presented here.

Nomogram Calculation

$$D = 35.3 \frac{d \times c}{\sqrt{f} \times v}$$

let $d = 3$, $c = 4500$

$$D(1000 \text{ ft}) = \left(\frac{476.6}{\sqrt{f}}\right) \times \left(\frac{1}{\sqrt{f}}\right)$$

Half Depth (1,000 ft)

Freq. (RPM)	$v = 1$ $D =$ 476.6 $\left(\frac{1}{\sqrt{f}}\right)$	$v = 1$ $D =$ 276.1 $\left(\frac{1}{\sqrt{f}}\right)$	$v = 1$ $D =$ 150.7 $\left(\frac{1}{\sqrt{f}}\right)$	$v = 1$ $D =$ 87.0 $\left(\frac{1}{\sqrt{f}}\right)$	$v = 1$ $D =$ 47.7 $\left(\frac{1}{\sqrt{f}}\right)$
1	476.6	275.1	150.7	87.0	47.7
10	150.7	87.0	47.7	27.5	15.1
100	47.7	27.5	15.1	8.70	4.77
1,000	15.1	8.70	4.77	2.75	1.51
10,000	4.77	2.75	1.51	0.87	.48

The attached figure is a graphical solution to the equation for calculating "half depth." Four quantities must be known; f , v , d and c . To illustrate determining D , an example from B. J. Patton's paper is used.

$$f = 24 \text{ Hz} = 24 \times 60 = 1,440 \text{ RPM}$$

$$d = 2.5" \text{ as the internal diameter of tool joints on } 4\text{-}1/2" \text{ drill pipe}$$

$$c = 4,300 \text{ ft/sec}$$

$$v = 1 \text{ cs}$$

Enter the graph at the top with $f = 1,440$. Go to the $v = 1$ line. To correct for pipe diameter and sound velocity, calculate the product $d \times c = 10,750$; move horizontally right to the point approximating this value. Now read $D = 10,000 \text{ ft}$ on the lower scale.

Figure 32. Attenuation Nomograph