

Final Report

Electric Drilling Motor for Coiled Tubing Drilling - Phase I

*Prepared by:
CTES, L.C.
Conroe, Texas*

Gas Research Institute

*Drilling and Completion Group
March 1996*

GRI 95/0428

FINAL REPORT

**ELECTRIC DRILLING MOTOR FOR COILED
TUBING DRILLING - FEASIBILITY STUDY
PHASE I**

Prepared by:

Kenneth R. Newman and Lyndon R. Stone
CTES, L.C.
9870 Pozos Lane
Conroe, TX 77305

Prepared For:

GAS RESEARCH INSTITUTE
8600 W. Bryn Mawr Avenue
Chicago, IL 60631

Contract No. 5095-210-3342
October 1995

GRI DISCLAIMER

LEGAL NOTICE This report was prepared by CTES, L.C. as an account of work sponsored by the Gas Research Institute (GRI). Neither GRI, members of GRI, nor any person acting on behalf of either:

- a. Makes any warranty or representation, express or implied, with respect to the accuracy, completeness, or usefulness of the information contained in this report or that the use of any apparatus, method, or process disclosed in this report may not infringe privately owned rights; or
- b. Assumes any liability with respect to the use of, or for damages resulting from use of, any information, apparatus, method or process disclosed in this report.

REPORT DOCUMENTATION PAGE	1. REPORT NO. GRI-95/0428	2.	3. Recipient's Accession No.
4. Title and Subtitle Electric Drilling Motor for Coiled Tubing Drilling - Phase I		5. Report Date October 1995 (date prepared)	
		6.	
7. Author(s) Kenneth R. Newman and Lyndon R. Stone		8. Performing Organization Rept. No.	
9. Performing Organization Name and Address CTES, L.C. P.O. Box 2178 Conroe, TX 77305-2178		10 Project/Task/Work Unit No. 13.23	
		11. Contract(C) or Grant(G) No. (C) 5095-210-3342 (G)	
12. Sponsoring Organization Name and Address Gas Research Institute		13. Type of Report & Period Covered Final Report May 1995 - October 1995	
		14.	
15. Supplementary Notes			
16. Abstract (Limit: 200 Words) Open hole drilling with coiled tubing (CT) is a relatively recent development in the oil and gas industry. Using continuous pipe to drill has many advantages over jointed pipe drilling because of the elimination of the pipe joints. Major improvements include tripping speed, sealing around the pipe and thus pressure control, location size, safety and environmental concerns. However, there are limitations associated with CT drilling (CTD) that must be addressed for this drilling technique to reach it's full potential. Since the CT cannot be rotated, a downhole motor must be used. Moineaux type positive displacement mud motors are typically used for CTD. These motors are expensive for the short drilling life (25 to 100 hours) that they last before needing to be replaced. In early 1995, the Gas Research Institute commissioned this Phase I study to determine the feasibility of using an electric drilling motor instead of a moineaux type mud motor. This Phase I feasibility study accomplished the following: <ul style="list-style-type: none"> • A review of historical and current electric drilling motor technology was performed • A conceptual design for an electric drilling motor for CTD was developed • A cost estimate for an electric drilling motor system was developed • A market analysis was performed This feasibility study concluded that an electric drilling motor system for CTD is feasible, and that such a system would have significant benefits over current motor technology.			
17. Document Analysis a. Descriptors Slimhole, coiled tubing, drilling, drilling motors, electric motors, bottom hole assembly b. Identifiers/Open-Ended Terms c. COSATI Field/Group			
18. Availability Statement Release Unlimited		19. Security Class (This Report) Unclassified	21. No. of Pages 28
		20. Security Class (this Page) Unclassified	22. Price

Research Summary

Title	Electric Drilling Motor for Coiled Tubing Drilling - Phase I
Contractor	CTES, L.C.
Principal Investigators	Kenneth R. Newman Lyndon R. Stone
Report Period	May 1995 - October 1995 Final Report
Objective	The objective of this study was to determine if the use of a coiled tubing conveyed electric drilling motor system is technically and economically feasible for use in oil and gas well drilling.
Technical Perspective	<p>Using coiled tubing (CT) to drill open hole was first attempted in Canada in the 1970's. In 1991 the first recent CT drilling (CTD) experiments were performed. Since 1991 there has been a tremendous interest in this drilling technique, with more than 300 CTD operations being performed in 1995.</p> <p>The continuous tubing used for CT is bent when it is spooled on and off of the reel. The fatigue damage that occurs in the CT due to this repeated bending will eventually cause the pipe to fail. As the diameter of the CT increases the fatigue damage increases and thus the expected life of the tubing decreases. Although CT is being built as large as 4.5" in diameter, the "fatigue life" limits the practical diameter for drilling to 2 3/8". Limiting the CT diameter limits the hole size that can be drilled with CTD which causes CTD to become a subset of slimhole drilling (SHD).</p> <p>CTD has the following additional advantages over conventional SHD:</p> <ul style="list-style-type: none">• Full well control - CT is usually used on live wells and is thus capable of working with wellhead pressure. This allows safe underbalanced drilling and minimizes the fast kick concerns• Less pipe handling - Since joints of pipe are not being handled less manpower is needed and safety is increased

- Increased tripping speed - CT can be run in the hole (RIH) or pulled out of the hole (POOH) at speeds in excess of 150 ft/min which is several times faster than joints can be tripped.
- Cable - It is possible to place a cable inside the CT allowing electrical power and measurements while drilling

Disadvantages of CTD compared to SHD are:

- Motor Drilling - The CT cannot be rotated which means a drilling motor must be used. Conventional moineaux type mud motors are expensive and are often not reliable.
- Hole Diameter - As was noted above, CTD is limited to SHD.

An electric drilling motor system would capitalize on one of the advantages of CTD, cable in the CT, and use this advantage to improve one of the disadvantages, motor drilling. Electric lines are currently used on many CTD jobs to measure downhole properties in real time while drilling. The Russians have used electric motors and electric cables in conventional drill pipe to drill many millions of feet. The motor design is similar to the motors used for electric submersible pumps (ESPs).

Technical Approach

This feasibility study was performed by first obtaining information on past and current electric drilling motor (EDM) systems used with jointed pipe. Based on this information a conceptual design was performed for a CTD EDM system. The power and speed characteristics of a conventional mud motor were used to set a basic specification for the EDM system.

Once a conceptual design was completed, a preliminary technical report was sent to various CTD personnel in the industry for review and comment. A market analysis was performed based on information available on the CTD industry, input from the review of the preliminary technical report, and the cost analysis from the preliminary conceptual design.

Results

This study shows that a EDM system for CTD is technically feasible. Such a system would be more expensive than the conventional mud motor systems being used today. However, it would also be more reliable and would have motor parameters such as speed, torque and power available through the motor controller at surface. This feedback of downhole parameters is much more expensive with a conventional mud motor system. The EDM system would be capable of working in some niche markets where it's advantages would give it a significant market advantage when compared to a conventional CTD system.

Project Implications

The use of CT for drilling is steadily increasing. While CTD can't compete with conventional drilling methods for most wells, it does appear to be competitive in some niche areas such as re-entry drilling. One factor hindering the use of CTD is the relatively short life of the mud motors used for drilling with CT. This feasibility study indicates that EDMs may be more effective than mud motors for CTD. The next step would be to design, build and test a prototype CT EDM system. The decision for GRI to participate in the next phase will depend upon a clearer understanding of the application of CTD for gas wells and a strong indication of industry support, from both producers and service companies, for this project.

Steve Wolhart
Senior Project Manager, Drilling and Completion

Table Of Contents

1. EXECUTIVE SUMMARY.....	1
1.1. Historical and Current EDM Technology.....	1
1.2. Conceptual Design Summary	1
1.3. Advantages and Disadvantages	2
1.3.1. Advantages	2
1.3.2. Disadvantages	2
1.4. Market Analysis.....	2
1.5. Recommendations	3
2. HISTORICAL AND CURRENT TECHNOLOGY	3
2.1. Patent Search Results	3
2.2. Electrodril Project.....	4
2.3. EDMs in the CIS	5
2.4. Comparison of Electrodril and CIS.....	6
3. CONCEPTUAL DESIGN	7
3.1. Mud Flow Path.....	7
3.2. Motor Power and Length	7
3.3. Motor Diameter.....	8
3.4. Torque Limiting.....	8
3.5. Speed Reduction.....	8
3.5.1. Gear Reduction	9
3.5.2. Increased Motor Poles	9
3.5.3. Variable Speed Drives	10
3.5.4. DC Motors	10
3.5.5. Harmonic Reduction Devices.....	10
3.6. Cable	10
3.7. Surface Equipment	12
4. EDM SYSTEM COST ESTIMATE.....	12
5. MARKET ANALYSIS	13
5.1. CTD Summary	13
5.2. CTD Markets	14
5.3. Feedback from Preliminary Technical Report	15
5.4. EDM System Market Analysis Summary	15

6. FIGURES.....	17
6.1. Figure 1 - Progressive Cavity Motor Specification Compilation	17
6.2. Figure 2 - Surface Area vs Horse Power for 3.75" EDM	18
6.3. Figure 3 - EDM Lengths for Various OD and HP	18
6.4. Figure 4 - Torque vs Speed Characteristics at Different Line Frequencies.....	19
6.5. Figure 6.1 - CTD Market Growth.....	20

Supplemental Documents

 EDM Related Patents

 Russian Documents

 Russian Document Translations

 Electrodril Documents

1. Executive Summary

The purpose of this study was to determine if using an electric drilling motor (EDM) system would be more effective than a conventional progressive cavity (PC) "mud" motor for coiled tubing drilling (CTD) applications. This study was performed as follows:

- A review of historical and current EDM technology was performed.
- A conceptual design was performed to determine the technical feasibility of an EDM for CTD and to determine the approximate cost of such a system.
- A preliminary technical report was written based upon the results of these studies and sent to 35 people interested in CTD for their input.
- A market study was then performed based on this and other market input.
- Recommendations were made based upon the results of the above studies.

1.1. *Historical and Current EDM Technology*

A project called the Electrodrill Project was performed by General Electric and the US Department of Energy in the 1970's. The purpose of the project was to develop an EDM to work with jointed pipe. A very complicated cable system was developed to run the cable in jointed drill pipe. This cable system and its multiple downhole wet connections was the downfall of this project. The electric drilling motor performed satisfactorily in the testing that was done.

The largest use of EDMs has been in the CIS. EDM systems have been used successfully since 1961 to drill with jointed drill pipe. The multiple electrical connections in the cable due to the jointed pipe are a source of problems, but the advantages (given below) still outweigh the disadvantages when directional drilling in low pressure gas reservoirs, at least in the Apsheron peninsula of the CIS. EDMs are probably being used for other applications in the CIS, but specific information on these other applications was not available for this study.

1.2. *Conceptual Design Summary*

A conceptual design for a system including the EDM, cable and surface equipment was performed. The purpose of this conceptual design was to determine if there are any major technical obstacles which would prevent the complete development of such a drilling system and to determine the cost of such a system. Wherever possible off-the-shelf equipment was used in this conceptual design. It was assumed that an EDM would require output torque and RPM comparable to a PC drilling motor of the same outside diameter.

From the conceptual design it was determined that this system is technically feasible for motor diameters 4.75" and larger outside diameter. A summary of the cost estimate of such a system is:

• Surface Equipment	\$56,000
• Cable (varies with length)	\$96,000
• Bottom Hole Assembly	\$45,500

1.3. *Advantages and Disadvantages*

The following is a list of the advantages and disadvantages of an EDM system when compared to a conventional PC motor system:

1.3.1. Advantages

- Longer operating life - mean time between failure (MTBF)
- Allows the use of specialty drilling fluids which are detrimental to PC motors
- Higher operating temperature than PC motors (400°F vs 250°F)
- Synergy with high data rate telemetry systems
- Allows electrical sensors to be placed at the bit with more ease
- Motor performance parameters available from speed controller, no sensor needed
- Closed loop automatic drilling control system easy to implement. Set down weight could be controlled based on motor torque or other parameters.
- High electrical power available for other possible BHA functions - orientation tool, solenoids to divert mud flow, tractor, thrust and rotational anchors
- Less restriction in mud flow through BHA, allows better hole cleaning and cooling, better for LCM circulation

1.3.2. Disadvantages

- More equipment on location
- More specialized equipment, float subs, CT with cable inside, disconnects, etc.
- Cable reduces flow area of tubing
- Higher capital cost
- Additional safety considerations

1.4. *Market Analysis*

Based on this study CTES believes there is a significant market for an EDM system in CTD. The initial market would be comprised of several niche markets. These niche markets would be:

- High cost areas - the reduction in trips due to the increase in MTBF when using an EDM would more than offset the additional cost of the EDM system
- High temperature drilling - the EDMs can work in high temperature formations in which PC motors will not work
- Low pressure, high permeability reservoirs - the EDMs do not hinder the pumping of lost circulation material

- Special drilling fluids - the EDM system can withstand drilling fluids that would damage PC motors, such as some oil based muds, diesel, air, nitrogen and foam.

Once the capital investment is made for an EDM system and it has become an accepted/proven system for these niche markets, CTES believes that the system will gain wide acceptance in the general CTD market due to the improved MTBF.

1.5. Recommendations

Based on the results of this study, CTES recommends that a EDM system be developed.

- Emphasis should be placed upon development of a complete system, not just the EDM component.
- An EDM with a hole through the shaft, allowing the drilling fluid to pass through the shaft instead of around the outside is preferable. The up front engineering and development cost is greater than using a conventional ESP motor, but the benefits of such a motor would justify the cost.
- Cable designs without a full outer armor should be considered to minimize the diameter and the cost.
- A non-directional drilling BHA should be developed with optional sensors and telemetry for pressure and formation measurements while drilling.
- A directional drilling BHA should be developed which integrates the sensors, telemetry, EDM, directional control, emergency release, check valve and mechanical connection functions.

2. Historical and Current Technology

A significant portion of this project involved reviewing work that has been done in the past and is currently being done in which EDMs are used with conventional jointed pipe to drill. To explore previous technology a patent search was performed. From the patents the Electrodril project was found and researched. Finally, information was obtained from the CIS regarding drilling currently being performed using EDMs.

2.1. Patent Search Results

A search was made in the U.S. Patent and Trademark office directed generally toward drilling using an electric down hole motor. The search resulted in eight (8) current patents being found.

5,060,737 Mohn	4,796,713 Bechem et al.
4,732,225 Jurgens et al.	4,592,432 Williams et al.
4,544,041 Rinaldi	4,436,168 Dismukes
4,227,584 Driver	4,185,703 Guerber

These patents are submitted as supplemental documents of this report. These patents have been reviewed by CTES and CTES believes that a CT conveyed electric drilling motor device would not infringe any of these patents.

Also included in the supplemental documents are two patents (2,609,182 & 2,662,735) which date back to 1952 and 1953. These patents describe oil and gas well drilling systems which employ EDMs. These early patents and knowledge of the GE "Electrodril" project, which is discussed later in this report, clearly show that there is substantial prior art in this area.

2.2. *Electrodril Project*

This project was a cost sharing venture between the U.S. Department Of Energy and the petroleum industry. The major private contractor in the project was the General Electric Company's Space Division. Amoco, Brown Oil Tools, Chevron, Dresser Industries, Roy H. Cullen Research, and Union Oil Co. also participated in the project. The project was begun in mid 1976 and stopped in late 1979 or early 1980.

The objectives, efforts and conclusions of this project are chronicled in four publications. Three of the publications are Final Reports submitted by GE to the Department of Energy at the conclusion of major milestones. The Phase I report was submitted in October 1977, the Phase II task B report was submitted April 1979 and the Phase II task C report was submitted in October 1979. The fourth publication is a paper presented by B.V. Traynor at the 1980 Drilling Technology Conference of the International Association of Drilling Contractors (IADC). These publications are included in the supplemental documents of this report.

The project called for the manufacture of three sizes of drilling systems. A 20 HP, 4.50" OD slimhole system, a 60 HP, 7.75" OD directional system and a 285 HP, 7.75" OD deep drilling system. Only the deep drilling system was ever fully deployed. A detailed description of each of these systems is given in B.V. Traynor's IADC paper. CTES reviewed this project through discussions with several people who were involved with the project.

The reasons given for GE's starting and more importantly ending the project were more for business reasons rather than technical problems.

- GE had invested in a number of energy related industries and was conducting R&D projects in all of them. In the late 1970's and early 80's GE decided to divest themselves of these industries and was therefore unwilling to continue funding of the project into the 80's.
- GE had developed the man made diamond technology. Most of the application and market for these diamonds were in the machine tool industry. GE saw an opportunity to significantly expand the fledgling diamond drill bit market if a drilling system which included and capitalized on the diamond drill bit's advantages could be developed. This system would be able to rotate the bit at higher RPMs, stay on bottom longer, and provide real time directional and bottom hole information.
- The system was targeted for the particular application of hard deep formations where conventional roller cone type drill bits did not perform well. The system

was designed to work with a conventional drilling rig and would be called out and deployed only when needed. This proved to be too much of a niche market and because of the substantial capital costs the pay back period was too long.

Deployment of cable through jointed pipe was one of the biggest challenges for this project. The cable system consisted of three, 5,000 ft. sections, four 1,000 ft. sections and eleven pre-wired 90 ft. stands of drill pipe. The 5,000 ft. and 1,000 ft. cable sections were wound on two drums which were situated on a 10 X 26 ft. skid along with a hydraulic power pack and operators console. The running procedure for this system was as follows:

- The BHA was made up on the pre-wired drill pipe and used to drill to 1,000 ft.
- The BHA was POOH and re-run with standard drill pipe.
- An electrical wet connect sinker bar on one of the 1,000 ft sections of cable was run and connected to the top of the drill pipe with a special hang off connector.
- The pre-wired drill pipe was then used to drill the next 1,000 ft.
- Once 5,000 ft was reached, the 1,000 ft sections of cable were replaced with a 5,000 ft section of cable.

Obviously this tedious procedure with many wet connections was time consuming, expensive and difficult to implement.

The engineers who worked on "Electrodril" believe it was a technical success. The major technical failures occurred with the downhole electrical connectors during the field test period. The problems were determined to be manufacturing QC related and assumed to be surmountable. The downhole instrument package apparently performed quite well during both field tests.

CTES believes that labeling "Electrodril" a technical success is a bit optimistic considering the tool was never deployed below 7,000 feet and managed to drill less than 100 feet of hole. Certainly the ruggedness of the system was never tested in a real downhole environment. It is encouraging that a CT conveyed "Electrodril" system will eliminate the major item that plagued the original project, that being the numerous wet, downhole power connections.

The project ended sometime in 1980 or 1981. The equipment was eventually sent to Sandia Laboratories in Albuquerque NM. in 1982. CTES made numerous telephone calls to Sandia and spoke with a number of individuals in trying to determine if any information or equipment is still there. No one at Sandia had any information on the disposition of the equipment.

2.3. EDMs in the CIS

The major use of EDMs for drilling oil and gas wells has been in the former USSR, now CIS. CTES sent a series of questions to key individuals working with these EDMs and managed to obtain information on the EDM program on the Apsheron peninsula. Two sets of documents were obtained, both in Russian, which were translated into English. These documents are included the supplemental documents of this report.

The CIS EDM program has been ongoing since 1961. In the west it was generally believed that the reason for developing a drilling system that does not require the drill pipe to rotate was because of the lack of quality drill pipe in the USSR. The documents offer other reasons for using the EDMs, at least on the Apsheron peninsula. The reasons given are as follows:

- EDMs tend to run at higher speeds than PC motors. In some formations higher bit speed coupled with diamond drill bits has resulted in 10 fold increase in penetration rate over conventional rotary drilling using tri-cone rock bits.
- EDMs do not restrict and do not depend upon the mud flow. Since Apsheron is an older field there are numerous depleted zones with low formation pressures and consequently severe lost circulation zones which must be penetrated when drilling new wells. The quantity and type of lost circulation material used to control mud loss apparently clogs PC type motors. Also pump rates are kept at a minimum to reduce hydrodynamic pressure.
- EDMs have good synergy with directional drilling systems. Due to the high density of production equipment on the surface vertical drilling is often not possible. Therefore numerous directional wells are drilled from one site. Their telemetry system is electrical and uses the cable for transmitting information up hole.
- Because of the numerous production facilities mains power is readily available in the area and can be brought to the drilling rig easily.

2.4. Comparison of Electrodril and CIS

Detailed descriptions of the Electrodril and CIS drilling systems are given in the appropriate appending documents. The following table is a brief comparison of the two systems.

Electrodril	CIS
Down Hole Motor	
3 phase induction - 2 pole	3 phase induction - 8 pole
synchronous speed @ 60 Hz - 3,600 RPM	synchronous speed @ 50 Hz - 750 RPM
oil filled pressure compensated	oil filled pressure compensated
16:1 gear reduction	2:1 or 3:1 gear reduction
285 HP, 7.75" OD, 51' LG	281 HP, 9.5" OD, 44' LG.
60 HP, 7.75" OD, 36' LG.	168 HP, 7.25" OD, 41' LG.
20 HP, 4.5" OD, 25' LG.	100 HP, 6.5" OD, 40' LG.
Circulate around motor and gearbox	Circulate through motor and gearbox
Power Cable	
3-power conductors, 1 conductor for data	2-power conductors + drill pipe Use 1 power conductor for data

Surface Equipment	
Variable frequency drive w/ closed loop control	Transformer w/ multi-tap secondary
MWD	
Telemetry + other	Telemetry only
16 channels total	

3. Conceptual Design

This conceptual design was performed based on the comparison to a similar mud motor:

- 4.75" outside diameter (OD)
- Horsepower and torque similar to a 4.75" OD mud motor
- Temperature limits - in excess of 250°F
- Pressure limits - 15,000 psi ambient
- MTBF - in excess of 100 hours

The various components needed to construct this EDM system were examined in the conceptual design. The following sections of this report review the critical components that affect the design. Components not mentioned are existing and straight forward to implement.

3.1. *Mud Flow Path*

It was decided that a pump-around rather than a pump-through design would be used. This has the advantage that there are fewer rotating seals, and little or no modification need be done to a standard electrical submersible pump (ESP) motor. There is a disadvantage to a pump-around design. A sleeve is required to go over the OD of the motor to provide the flow path. In this design a tool OD of 4.75" was selected (discussed later). With a 4.75" tool OD a 3.75" OD motor would be used. This requires a 3.75" OD electric motor to generate comparable horse power to a 4.75" OD progressive cavity motor.

In the long term a pump through motor may prove to be more effective than a pump around design. However, this will require a complete new motor design.

3.2. *Motor Power and Length*

A compilation of PC motor specifications is shown in Figure 1. Drilllex and Roper motors in sizes from 1.688" OD to 4.75" OD were looked at. The motors were grouped by size and horse power output. An estimation of the length of an induction motor for a given OD and horse power was made by generating a curve of horse power vs. motor surface area for Centrillift 375 Series ESP motors. The curve is shown in Figure 2. From this curve an estimated motor length for a given OD and horse power could be calculated. Figure 3 shows the estimated motor length for selected OD and horse power combinations.

When comparing the length of PC motors as shown in Figure 1 to the estimated length of an equivalent electric motor as shown in Figure 3 it should be noted that the PC motor lengths are for the stator housing only. Additional length for bearing packs and end connections must be added. For an electric motor additional length for a torque limiting device and gearbox would have to be added. Therefore the lengths can not be used as a definitive comparison of PC vs. Electric motor length. This exercise does predict that electric motors will be about the same length or slightly longer than PC motors.

A motor design was selected to maximize the output torque of the motor at the lower speeds. This is accomplished by setting the rotor resistance equal to the rotor reactance. A theoretical family of Torque vs. Speed and Horse Power vs. Speed curves at different line frequencies is shown in Figure 4 and 5 respectively.

3.3. Motor Diameter

A 4.75" OD BHA was chosen for the conceptual design for the following reasons:

- The smallest OD ESP motor made by Centrilift is 3.75". Once this motor is enclosed in a housing to allow the mud to flow around the motor, the housing will have a 4.75" OD.
- 4.75" PC motors are one of the common sizes used in CT drilling.
- It was anticipated that even with gear reduction a two pole induction motor would rotate at a higher RPM than desired. As discussed below, a 4.75" flow through a gear reduction system is considered to be the smallest feasible.

As the diameter of the BHA increases the ease of developing this technology increases. CTES chose the 4.75" OD for the conceptual design because it is currently considered to be the lower limit of this technology and because this size is perceived to more closely fit the needs of the CT drilling industry.

3.4. Torque Limiting

The torque values shown in Figure 4 are smooth running values. Due to the inertia of the rotor and other rotating members torsional shock loads many times greater than these values are possible if the bit is stopped suddenly. A torque limiting device coupled to the output of the motor may be required to prevent catastrophic damage to the rotating members in such an occurrence. One company was found which had previously manufactured torque limiting devices with 3.25" OD, maximum break away torque of 5,200 in.-lb. (433 ft.-lb.) and 10.38" long. This company felt that they could manufacture a device to meet the requirements of this conceptual design.

3.5. Speed Reduction

The synchronous speed of a two pole induction motor is 3,600 RPM, which is considered to be much too fast for drilling. With a 4.75" OD tool a 5.75" - 6.5" bit would normally be run.

CTES spoke with experts in several bit and drilling companies to determine the RPM range for drill bits in this size range. Some argued that with small diameter BHAs it is

better to maximize rate of penetration with increased RPM rather than increased torque, because much of the small diameter BHA equipment can not with stand high torsional loads. Because of the numerous variables involved in drilling oil and gas wells it is not possible to establish an optimum RPM for a given type and size of drill bit, but a maximum RPM of 400 for PDC, TSP and Natural Diamond drill bits in this size seemed sufficient. At higher RPM's the bits remove material by grinding rather than cutting. This is much less efficient and the bits will over heat. Thus, 400 RPM was chosen as the upper speed limit for the conceptual design, with variable speeds below 400 RPM being desirable.

A speed reduction mechanism was the most challenging of the component designs necessary for the conceptual design. Several possible mechanisms were reviewed, each of which is discussed in the following sections.

3.5.1. Gear Reduction

A gear reduction system is the most obvious system to consider for speed reduction. The gearbox requires the following specifications:

- 3.75" OD for flow around or 4.75" OD for flow through
- 6:1 to 10:1 Reduction
- 3600 Maximum Input RPM
- 160 Ft.-Lb. Maximum Input Torque
- 78 HP Throughput
- 200 Hour Operating Life Before Redress

After reviewing a number of planetary gearbox manufacturer's catalogs and talking to sales reps and applications engineers it became apparent that there was no off-the-shelf gearbox which would meet these requirements. Two companies claimed they had made or could make a gear box that would meet these requirements, but would not cooperate in providing more information. CTES believes that a 4.75" flow through gear box is feasible, though this will probably be the most challenging component of the system.

3.5.2. Increased Motor Poles

The synchronous speed of an induction motor is given by the following equation;

$$\text{Speed(RPM)} = \frac{2 \times 60 \times \text{Frequency}}{\text{Number of Poles}}$$

Doubling the number of poles halves the speed. Unfortunately to maintain the same horse power output, the motor length must double also. In the smaller sizes (3.75" and less) there is not enough surface area in the motor housing for adding more coils. Consequently increasing the number of poles is not a solution for the 4.75" design, though it may be used for larger diameters.

3.5.3. Variable Speed Drives

Variable speed drive systems are common for synchronous induction motors. These systems vary the motor speed by varying the frequency of the power supply. Typically the frequency can be varied from 5 to 120 HZ, but the motor will begin to cog (run rough) at frequencies below 20 HZ. For this application the frequency would range from 30 HZ to 60 HZ which would result in synchronous speeds of 1,800 to 3,600 RPM respectively. These drives are microprocessor based and provide:

- A wide range of real time and historical data which would be useful in determining downhole parameters such as bit life, torque, and speed
- System protection by allowing the operator to set voltage and current limits
- Monitoring and shut down under fault conditions
- Analog inputs, outputs and PID loop control capability

Coupling the variable speed drive I/O to a hydraulic control circuit on the coiled tubing unit would provide an automatic closed loop drilling control system

3.5.4. DC Motors

DC motors are capable of running at variable speeds and have an better torque speed curve for drilling. However, DC motors were eliminated from consideration for the following reasons:

With standard brush type DC motors the maximum terminal voltage is limited to 240 volts. At higher voltages arcing will occur between brushes and commutator. Brush dust aggravates the problem. This low voltage system would make the cable much too large.

DC brushless type motors could accommodate the higher terminal voltage but would require very expensive rare earth type magnetic materials to generate the required horse power. It is uncertain that the size vs. horse power requirements could be achieved. Also these motors require internal electronics some of which must rotate to sense speed and position and would not work in an oil filled environment.

3.5.5. Harmonic Reduction Devices

Harmonic or cyclodial type speed reducing devices were investigated. The reduction on these devices is very high, usually starting at 50:1. In the smaller sizes they also were incapable of transmitting the required torque.

In summary, a gear box speed reduction combined with a variable speed drive for a synchronous induction motor was chosen for this conceptual design.

3.6. Cable

Possible cable designs were reviewed with a cable manufacturer. Two cable designs were chosen for the conceptual design depending on the length desired.

One design is for 12,000 ft and the second design is for 18,000 ft. The cables would have the following characteristics:

- Round, double spiral wrap armored, self supporting cable
- Three power conductors and minimally one data conductor. Additional data type conductors could be placed in the cable to fill interstices
- The 18,000 ft. cable would have #6 AWG copper conductors while the 12,000 ft. cable would have #8 AWG conductors.
- Average theoretical impedances for the two cables were calculated assuming a surface temperature of 80 deg. F and a bottom hole temperature of 200 deg. F..

18,000 ft. #6 AWG Copper $Z_c = 8.418 + j .705$ ohms

12,000 ft. #8 AWG Copper $Z_c = 8.924 + j .534$ ohms

- Maximum surface line voltage would be around 2,000 Vac, and 30 - 35 amperes line current
- 18,000 ft. would have an approximate OD of 0.939" and the 12,000 ft. would have an approximate OD of 0.838"

The cable will reduce the cross sectional flow area of the coiled tubing. The following table shows the percentage reduction in flow area for mid weight range 2", 2.375", 2.875" and 3.50" OD coiled tubing.

Coiled Tubing		Cable OD	Area Reduction
OD	ID		
2.00"	1.688"	.838"	24.60%
2.00"	1.688"	.939"	34.30%
2.375"	2.063"	.838"	16.50%
2.375"	2.063"	.939"	23.0%
2.875"	2.563"	.838"	10.70%
2.875"	2.563"	.939"	14.90%
3.50"	3.15"	.838"	7.00%
3.50"	3.15"	.939"	9.80%

Other, less conventional, cable designs are probably feasible. CTES chose these conventional designs for this conceptual design.

Installation of cable inside CT has historically been quite expensive. Since the CT used for CTD has a very limited life (as little as 2 wells), this expense could have a significant impact on the cost of the well. However, a cable injection system has been developed by CTES which allows the installation of a cable inside CT while it is still on the reel, significantly reducing the installation cost. 20,000 ft of 7/16" cable

has been installed in 2" CT. Current versions of this system are only capable of handling cables up to ½" in diameter. It is possible to build a larger version of this system to handle larger cable. For further information on this system see SPE 30679, "Development of a Coiled Tubing Cable Installation System".

3.7. Surface Equipment

The following surface equipment would be required. The equipment is readily available from ESP suppliers and power generator rental companies. The equipment would be trailer or skid mounted.

- Diesel Powered, 480 VAC, 70 KVA, 3 phase power generator
- Variable Frequency Drive, 480 VAC Input, 66KVA, 3 phase
- Step up Transformer, 480 Volt primary, 1039/2591 wye secondary, 100 KVA
- High power collector for mounting on the CT reel
- High power pressure feed through connection

Surface cable would be the same as the down hole cable or standard ESP cable armored but not self supporting.

4. EDM System Cost Estimate

The following costs are the best estimates available. CTES believes that the cost of the cable in particular can be reduced significantly if more than one cable were to be built. Likewise, the cost of the BHA could be reduced if a new motor was designed specifically for this application.

Surface Equipment

Power Generator	\$16,000
Variable Frequency Drive	\$14,000
Transformer	\$6,000
Surface Connections, Wiring, Collector	\$20,000
Total Surface Equipment	\$56,000

Cable

\$8.00/ft. X 12,000 ft.	\$96,000
\$8.33/ft. X 18,000 ft.	\$150,000

Bottom Hole Assembly (4.75")

Induction Motor	\$25,000
Seal Section	\$4,000

Torque Limiting Device	\$2,000
Gearbox	\$4,500
Housing, Connectors, Thrust bearing	\$10,000
Total BHA	\$45,500

A 4.75" PC motor sells for a list price of \$20,500. Allowing an additional \$10,000 for connectors, release joints, etc. a conventional BHA would cost about \$30,500. Thus the BHA for an EDM system will be more expensive than a conventional PC motor BHA.

5. Market Analysis

5.1. CTD Summary

Using CT to drill open hole was first attempted in Canada in the 1970's. In 1991 the first recent CTD experiments were performed. Since 1991 there has been a tremendous interest in this drilling technique. Figure 7 shows the growth in CTD activities since 1991.

The continuous tubing used for CT is bent when it is spooled on and off of the reel. The fatigue damage that occurs in the CT due to this repeated bending will eventually cause the pipe to fail. As the diameter of the CT increases the fatigue damage increases and thus the expected life of the tubing decreases. Although CT is being built as large as 3.5" in diameter, the "fatigue life" limits the practical diameter for drilling to 2 3/8". Limiting the CT diameter limits the hole size that can be drilled with CTD which causes CTD to become a subset of slim hole drilling (SHD).

CTD has the following advantages over conventional jointed pipe SHD:

- Full well control - CT is usually used on live wells and is thus capable of working with wellhead pressure. This allows safe underbalanced drilling and minimizes the fast kick concerns
- Less pipe handling - Since joints of pipe are not being handled less manpower is needed and safety is increased
- Increased tripping speed - CT can be run in the hole (RIH) or pulled out of the hole (POOH) at speeds in excess of 150 ft/min which is several times faster than joints can be tripped.
- Cable in CT - The lack of joints in the CT allows a continuous cable to be installed. Special systems have been developed to aid in the installation of these cables. Often a cable is placed inside the CT allowing electrical control and measurements while drilling. A larger cable could be used to power an EDM.

Disadvantages of CTD compared to SHD are:

- Motor Drilling - The CT cannot be rotated which means a drilling motor must be used. Conventional PC type mud motors are sometimes not reliable, thus the consideration of an EDMs.
- Jointed pipe handling - Jointed pipe may need to be run for casing, tubing or liner. A conventional CT unit cannot handle jointed pipe. Special units are being developed with this capability.

The advantages of CTD often significantly out weigh the disadvantages. With many of wells drilled to date CTD has proven to be both an economical and a technical success.

CTD systems are not able to compete with conventional drilling rigs in all markets. The drilling motor BHA for CTD may cost as much as 20% of the total day rate for the system. Since CTD is a new drilling technique, significant capital investments are needed to purchase these systems. In some markets, such as vertical wells on land in the lower 48 states in the US, these new systems find it difficult to compete with the abundant, fully depreciated, rigs which do not require a drilling motor. However, in other markets such as offshore re-entry directional drilling, CTD can be competitive because of the low mobilization cost when compared to a rig.

5.2. CTD Markets

The major markets for CTD to date are:

- Re-entry Drilling - Accessing new areas in the reservoir or an adjacent reservoir through an existing wellbore is significantly less expensive than drilling a new well. The largest savings occur when the re-entry drilling can be performed without pulling the existing completion. Most re-entry drilling requires directional drilling.
- Well Finishing - A rig is used to drill the well down to the reservoir and set the casing. CTD is then used to drill underbalanced in the reservoir to reduce or eliminate the formation damage which would be caused by overbalanced drilling fluids. Sometimes the gas lift system in the well is used to create the underbalanced condition, and other times a light weight drilling fluid is used (often using nitrogen, air or foam). Some well finishing has been directional and some has been straight hole drilling.
- New Wells - CTD has been used for new shallow slimhole wells both for gas production and for water injection wells. It has also been used to drill gas relief wells to release sub-surface gas or to relieve pressure from around a well with leaking tubulars in a near blowout situation. New well drilling has typically been straight hole drilling.

The largest number of wells to date have been in the new well market because these wells tend to be inexpensive and numerous. The largest technical emphasis has been placed on the directional re-entry drilling. Well finishing is still often done with a conventional rig using a rotating BOP. It is believed that CTD will take over most of this market in the future.

5.3. *Feedback from Preliminary Technical Report*

There was a lot of interest in the Preliminary Technical report which was sent to 35 people in the industry. The following is a list of key points raised by some of these individuals:

- The most important advantage of an EDMs is improved MTBF. The Russians claim 240 hours MTBF for their EDMs. This may be somewhat optimistic, but even if a 120 hour MTBF is the average it is 2 to 3 times greater than the average PC motor MTBF. In current CTD efforts many extra trips are made due to problems with PC motors. If the increased MTBF saves one trip on a CTD job it will more than offset the additional expense of the EDM system.
- Some formations could use high speed diamond bits, possibly eliminating the need for a gear box. This would apply most to deep gas drilling where there is usually hard rock. The high speed would also be better for window milling operations.
- The decrease in the flow area in the CT due to the cable increases the pressure drop in the CT. However, there is no pressure drop through an EDM. These two affects are approximately equal and opposite, making them neither an advantage or a disadvantage.
- The preliminary technical report points out some unanswered questions for some elements of the EDM system. The description of two relevant historical projects and our own commitment to CTD make us believe that a phase two of the project has a good chance of satisfactorily answering those questions. This EDM system involves "assembly of existing technologies" more than "invention". This gives a higher expectation of success.
- Due to the significant disadvantages (higher capital cost, more equipment on location...) the use of EDMs will probably be limited initially to a small 'niche' market (i.e.: providing a motor where conventional PC motors cannot operate; high temperature (>300deg) or the use of specialist drilling fluids that are detrimental to the elastomer stators in PC motors, certain oil based muds). It is within these 'specialist areas' where a higher cost could be justified that we would entertain the use of an EDM.

5.4. *EDM System Market Analysis Summary*

Based on this market analysis CTES believes there is a significant market for an EDM system in CTD. The initial market would be comprised of several niche markets. These niche markets would be:

- High cost areas - the reduction in trips due to the increase in MTBF (mean time between failure) when using an EDM would more than offset the additional cost of the EDM system
- High temperature drilling - the EDMs can work in high temperature formations in which PC motors will not work
- Low pressure, high permeability reservoirs - the EDMs do not hinder the pumping of lost circulation material

- Special drilling fluids - the EDM system can withstand drilling fluids that would damage PC motors, such as some oil based muds, diesel, air, nitrogen and foam.

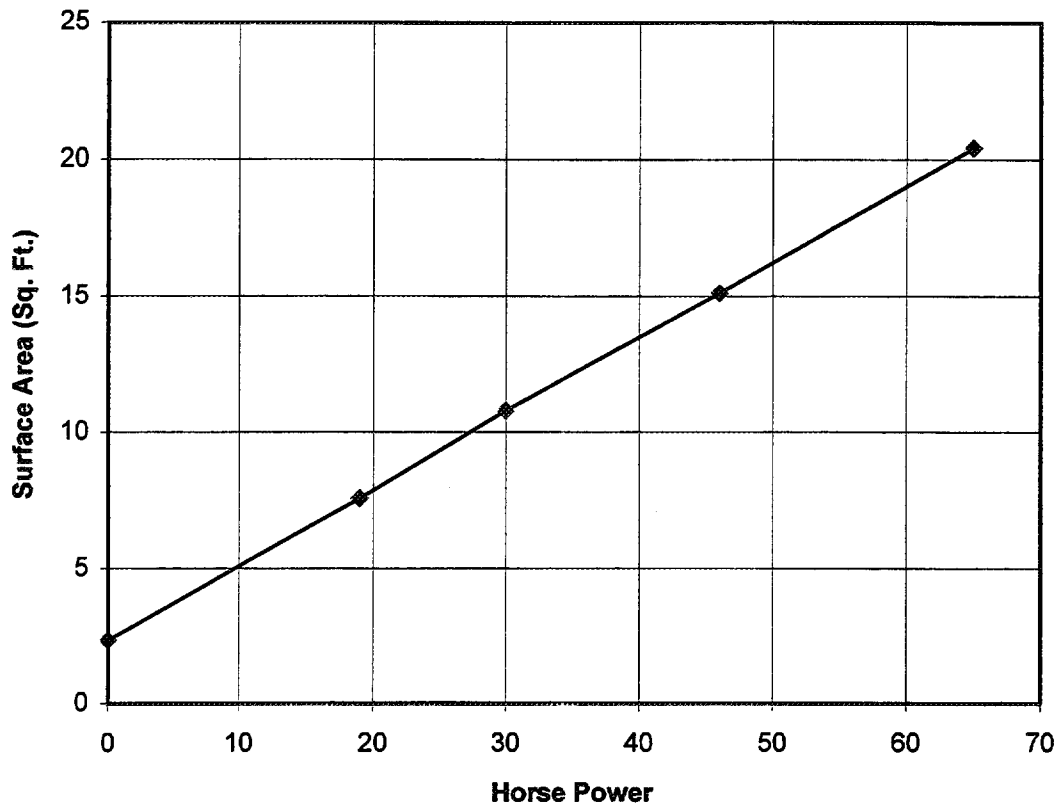
Once the capital investment is made for an EDM system and it has become an accepted/proven system for these niche markets, CTES believes that the system will gain wide acceptance in the general CTD market due to the improved MTBF.

As an example for economic comparison a vertical deepening offshore Gulf of Mexico was considered. The day rate for the CTD system without the BHA was estimated at \$24,000 per day. The rate for a conventional PC motor BHA was estimated at \$3,000 per day. The rate for an EDM system was estimated at \$4,000 per day. Thus the conventional system had an estimated total day rate of \$27,000 per day while the total day rate for the EDM system was estimated at \$28,000 per day. However, if a trip needed to be made because of a motor related problem, a 6 hour trip would cost \$6,750 at the \$27,000 per day rate. Thus, improved motor reliability could reduce the cost of the job. Also, the EDM system would provide surface readouts of motor speed, torque and power which would not be available from the conventional system. Sensors and a telemetry system to provide this same information with a conventional system would cost an estimated additional \$4,000 per day.

6. Figures

Size	Flow Rate (Q)	Press (P)	Speed (S)	Torque (T)	Length (L)	Water HP (WHP)	Brake HP (BHP)	Efficiency	BHP/Area
OD - Stages - Rotor/Stator	GPM	PSI	RPM	ft-lbs	in.	WHP=(Q*P) /1714	BHP=(S*T)/ 5252	BHP/WHP	bhp/sq. in.
1.688 - 4S - 3/4	22	800	1400	37.5	88.8	10.27	10.00	0.973	0.021
1.688 - 2S - 5/6	42	500	700	75	88.8	12.25	10.00	0.816	0.021
1.75 - 3S - 1/2	35	450	1440	22	54	9.19	6.03	0.656	0.020
1.75 - 3S - 3/4	20	450	625	28	50	5.25	3.33	0.635	0.012
1.75 - 4S - 5/6	60	600	720	75	62	21.00	10.28	0.490	0.030
2.063 - 1S - 4/5	50	150	275	67	41	4.38	3.51	0.802	0.013
2.063 - 2S - 1/2	45	300	1080	24.5	64	7.88	5.04	0.640	0.012
2.063 - 2S - 4/5	50	300	280	110	68	8.75	5.86	0.670	0.013
2.063 - 3S - 4/5	60	450	770	68	62	15.75	9.97	0.633	0.025
2.125 - 3S - 5/6	42	750	850	95	109.2	18.38	15.38	0.837	0.021
2.125 - 3S - 5/6	65	750	600	125	109.2	28.44	14.28	0.502	0.020
2.375 - 3S - 5/6	50	300	340	70	58.5	8.75	4.53	0.518	0.010
2.375 - 6S - 1/2	50	900	975	83	114.63	26.25	15.41	0.587	0.018
2.375 - 4S - 1/2	50	450	575	95	117	13.13	10.40	0.792	0.012
2.375 - 6S - 4/5	50	900	700	115	69	26.25	15.33	0.584	0.030
2.375 - 3S - 5/6	42	750	850	95	109.2	18.38	15.38	0.837	0.019
2.375 - 2S - 5/6	80	500	600	168	109.2	23.34	19.19	0.822	0.024
2.875 - 3S - 4/5	70	450	310	180	76.63	18.38	10.62	0.578	0.015
2.875 - 3S - 6/7	80	450	450	165	61.13	21.00	14.14	0.673	0.026
2.875 - 3S - 7/8	90	750	642	265	91.2	39.38	32.39	0.823	0.039
2.875 - 2S - 7/8	125	500	400	400	102	36.46	30.46	0.835	0.033
3.375 - 4S - 1/2	180	600	960	248	152	63.01	45.33	0.719	0.028
3.375 - 5S - 1/2	180	750	780	310	183	78.76	46.04	0.585	0.024
3.500 - 4S - 1/2	180	600	960	245	152	63.01	44.78	0.711	0.027
3.500 - 4S - 4/5	120	600	300	480	123.75	42.01	27.42	0.653	0.020
3.500 - 3S - 7/8	120	450	225	625	81.75	31.51	26.78	0.850	0.030
3.500 - 3.8S - 7/8	150	450	225	690	133.75	39.38	29.56	0.751	0.020
3.500 - 2S - 9/10	110	500	400	300	123.6	32.09	22.85	0.712	0.017
3.500 - 3S - 7/8	90	750	642	265	135.6	39.38	32.39	0.823	0.022
3.500 - 2S - 5/6	160	500	365	650	134.4	46.67	45.17	0.968	0.031
4.75 - 2S - 5/6	250	500	350	950	124.8	72.93	63.31	0.868	0.034

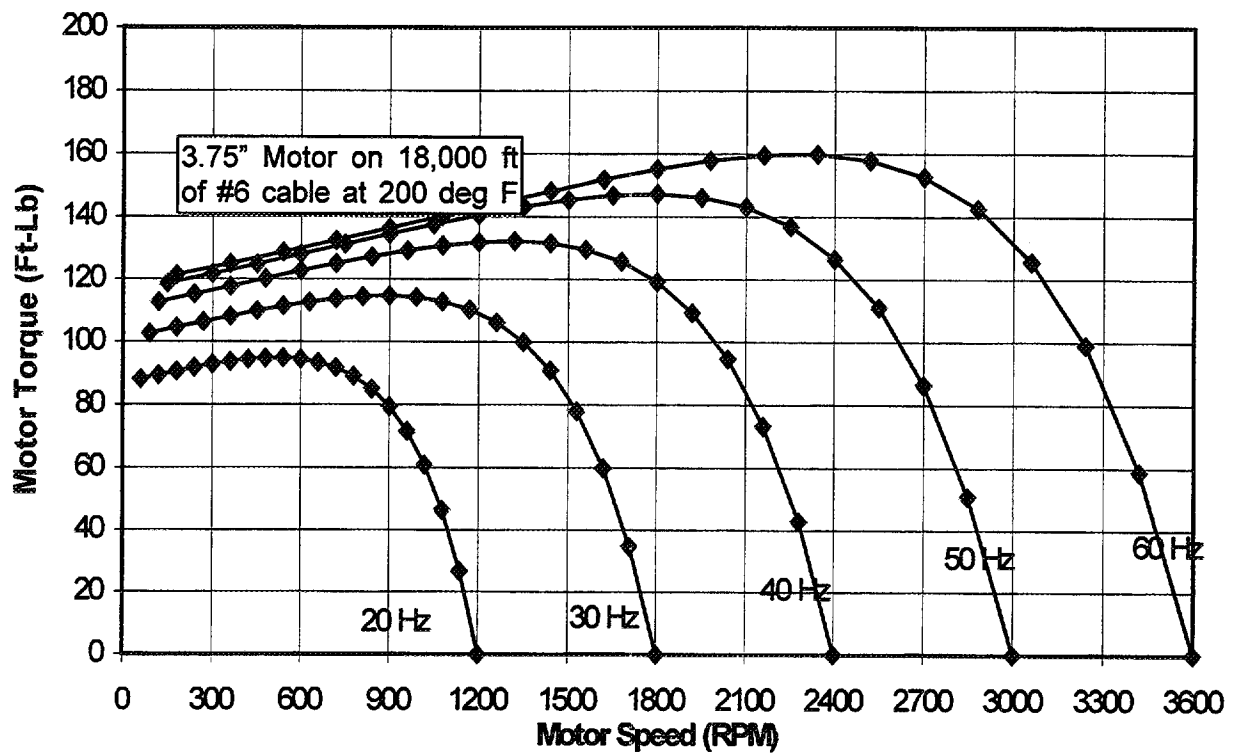
6.1. Figure 1 - Progressive Cavity Motor Specification Compilation



6.2. Figure 2 - Surface Area vs Horse Power for 3.75" EDM

Motor OD (In)	Horse Power	Surface Area (Sq. Ft.)	EDM Length (Ft.)
1.688	10	5.13	11.6
1.75	10	5.13	11.2
2.063	15	6.52	12.1
2.125	15	6.52	11.7
2.375	20	7.92	12.7
2.875	30	10.71	14.2
3.375	45	14.89	16.9
3.5	45	14.89	16.3
4.75	60	19.07	15.3

6.3. Figure 3 - EDM Lengths for Various OD and HP



6.4. Figure 4 - Torque vs Speed Characteristics at Different Line Frequencies

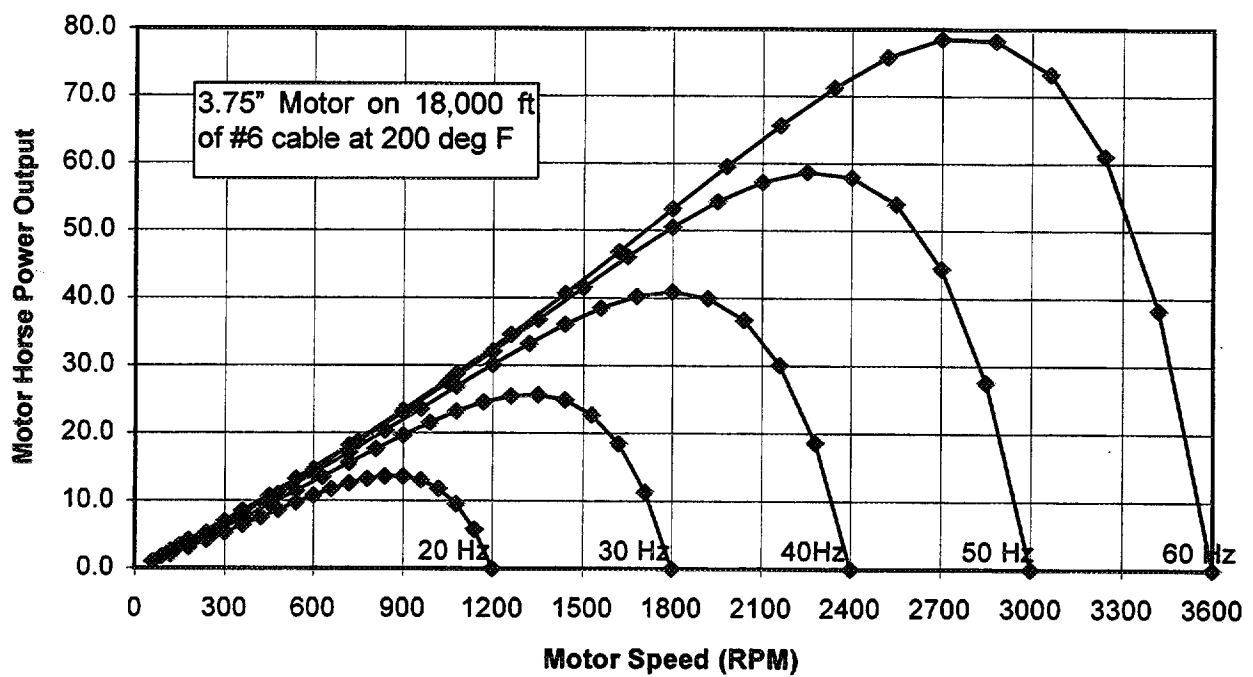
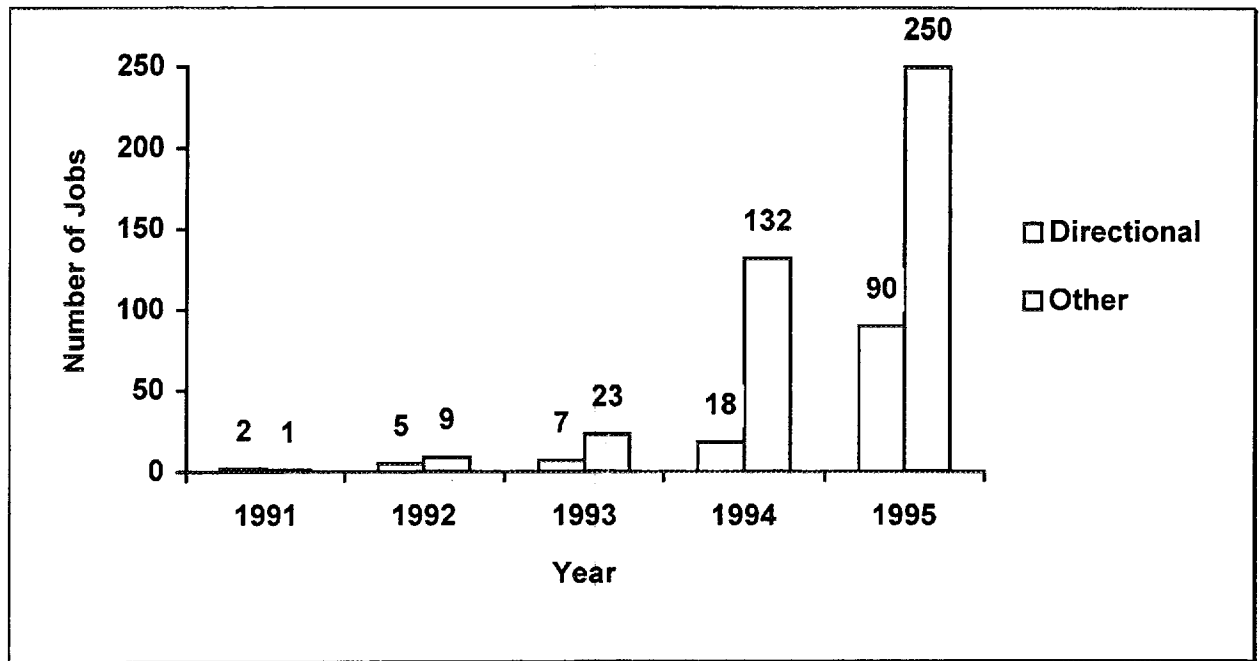


Figure 5 - HP vs Speed Characteristics at Different Line Frequencies



6.5. *Figure 6.1 - CTD Market Growth*