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The Use of Turbodrills in Coiled Tubing Applications

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Proposal

Coiled tubing (CT) has evolved in recent years to include more complex applications in drilling and remedial work. As wellbores have extended deeper, the challenges of intervening with CT have increased. For years the limitation in CT work was the coiled tubing itself. However, with advancements in metallurgy and manufacturing processes, the applications where CT can be utilized have expanded to include deeper, hotter, and more complex wellbores. The challenges of performing this work have now been directed at providing reliable equipment.

One of the main challenges in these more hostile environments is temperature. At elevated temperatures, work performed with motors becomes very erratic and unreliable. To perform this work, alternate methods have to be analyzed. One solution is the use of downhole turbines or turbodrills. Turbodrills have been used in the drilling industry for decades. It is only recently, however, that the benefits derived by turbodrills have been applied to CT for drilling and workover operations. With the remedial work CT is now required to perform, turbodrills are a natural fit as they address the issues which limit motor performance. This paper analyzes the applications and developments in turbodrills with analysis of recent runs on CT.

Introduction

Over the last 15 years, CT has expanded to encompass a broad range of applications, which, previously only rotary rigs could execute. These applications range from CT's original intent for workover and remedial operations, albeit with much greater capabilities today than when originally introduced, to drilling grass root wells, completions, and pipelines. As with many oilfield products, it was during the 1980's that CT made great advancements. Materials science was progressing to new frontiers and, with new materials, coupled with better manufacturing and quality processes, the CT itself became stronger and larger in diameter. These two combinations pushed the envelope where CT could be reliably utilized for deeper and more complex applications.

It was also in the mid 1980's when focused efforts on reducing costs associated with extracting hydrocarbons became more closely scrutinized. The evolving reliability of CT exemplified a low cost alternative for remedial operations versus a standard workover or drilling rig. At a fraction of the traditional cost, remedial operations could be undertaken to improve recovery rates, with the added benefit that said operations could be undertaken without killing the well. Identifying the shortcomings then proved quite simple: the functionality and flexibility of tools deployed on CT were surpassed by the CT itself and focused efforts were required to design downhole tools specifically for CT.[1]

It wasn't long before the economic benefits of using CT were translated to the drilling environment. The benefits were numerous: smaller footprint, smaller volumes of drilling fluids to be handled, smaller volumes of drill cuttings requiring handling, faster rig up time, faster tripping time, reduced noise levels, and fewer personnel requirements. All of these led to an overall reduced environmental impact and generally a safer operation.[2] An underlying benefit of drilling with CT is Underbalanced Drilling (UBD). This benefit was realized at an early stage in remedial applications, as workover operations could be carried out without introducing kill fluids into the wellbore. By design, drilling with CT fits perfectly with UBD operations, provided penetration rates are adequate and reservoir targets can be hit.

Coiled Tubing Drilling (CTD) has evolved dramatically in the recent past. Initially operations were limited to extending existing wellbores. These operations have been commonplace in Alaska for many years. In the early 1990's the challenge of drilling grass roots wells began. By the turn of the century many of the challenges pertaining to this operation had been overcome and today over 7,000 wells have been drilled with CT, with approximately 750-850 new wells being added each year.[3]

The vast majority of wells drilled with CT , however, have been less than 3,500 feet deep and there are still economic hurdles that must be overcome to drill deeper with CT. One of the most conspicuous hurdles is the lack of reliable motor performance. To date operations have been designed around the failure of the motor and limited to typically no more than 60 hours of operations before tripping and replacing the motor. When out of the hole, it is standard operating procedure to inspect for pieces of rubber from the motor stator in the bit nozzles.[4]

History of Turbodrills

The turbine concept was introduced over a century ago, in 1884, as a single stage axial flow apparatus. Some 17 years later, in 1901, Spindletop was drilled using a rotary drilling system. It was over 20 years before evaluation of the original downhole turbodrill was again evaluated. In the early 1920's significant design modifications to turbodrills were implemented, resulting in the multistage, axial flow turbodrill. This was the predecessor of today's turbodrill.

Over the next few decades, the technology made only minor advancements to the power and bearing sections. Then, in 1982, the first steerable turbodrill was introduced for directional applications. Although rather crude in design, it was very successful for specific applications. The design incorporated an offset eccentric stabilizer on the bearing section to initiate the bend for directional work. In 1992, an improved version of the steerable turbodrill was brought to market. By employing a bend on the bearing section, directional work could be better initiated and maintained. That same year a new PDC thrust bearing was introduced for higher-end drilling applications, where standard bearings had proven inadequate. Since 1992, materials research and development have aided in improving the reliability and durability of not only the previously mentioned bearings, but also all of the component parts of the system. This also enabled smaller OD designs to be built and run in varying applications. In 1997, the next generation of steerable slimhole turbodrills was successfully run in a CTD operation. This was the first CTD application seen by turbodrills. Since that time, smaller sizes of turbodrills have been developed and many wells have utilized this technology for both CTD and UBD.

Technical Attributes

There are many special criteria that are associated with the successful implementation of downhole motors with CT operations. One major concern when running a CT job is that it is often difficult to get significant weight on bit (WOB) to maximize the rate of penetration (ROP) through the drilling interval. As mentioned above, another situation that is often prevalent in many CT jobs being run today is the presence of a severe environment, especially in the form of high temperature. Although significant advancements have been made in the technology and manufacturing of CT, the structural integrity of the CT, especially when compared to traditional drill pipe, is still a concern. As a result of its relative weakness, the stress and vibration created during the drilling process must be carefully controlled to prevent failures. The torque generated by the drill bit during drilling is also an important parameter to monitor as it too can have a detrimental effect on the CT system. Additionally, as some of the current CTD work is directional, and as much of the future utilization of this technology will include complex directional programs, the directional capabilities of the downhole motor utilized for the CTD work is of paramount importance to the successful implementation of CT technology. Finally, with respect to the current and future implementation of CTD with complex directional plans, the hole quality has a very strong effect on drag seen by the CT. Since CT is not very resistant to buckling loads, getting weight transferred to the bit for drilling plays a vital role in successfully completing these directionally complex wellbores.[6] The technical attributes of the turbodrill are an excellent fit with CT operations, providing a smooth wellbore with little vibrational effects in the system during drilling.

Weight on Bit

One of the biggest challenges associated with drilling on CT is the transfer of weight to the bit. As a result of the fact that it is difficult to get much WOB for drilling, the associated ROP of the section is often lower than desired. However, this effect is somewhat mitigated by the use of a downhole motor, which, of course, is a mandatory piece of equipment for any CT job. The reason that the effect is mitigated by the use of a downhole motor is that the ROP associated with a run on CT is directly related to the RPM used to drive the bit. RPM is a very influential factor in drilling on CT because fixed cutter type bits are used nearly exclusively with CT, and RPM is a very important factor in the drilling mechanism of fixed cutter type bits (PDC drill bits, diamond impregnated drill bits, natural diamond drill bits, etc). Roller cone type drill bits are not commonly used on CT jobs due to the fact that they require a lot of WOB to drill effectively, and also because the availability of roller cone drill bits is sparse in smaller hole sizes.

In the field of fixed cutter drill bits, the ROP in a given section is driven by the RPM of the drive mechanism (whether downhole motor or rotary) and the resultant depth of cut (DOC) that is produced by the weight that is applied to the bit. While it is generally true that different formations and applications respond differently, in terms of cutting efficiency, to the relative DOC, it is nearly universally true that, in coiled tubing drilling, more RPM means more ROP. In other words, there are many applications that may actually be drilled more effectively by a fixed cutter drill bit (i.e. a PDC drill bit) run with a high WOB to create a very large DOC. However, since high WOB is not an option with coiled tubing, RPM has the greatest influence on ROP improvements. To put it another way, since the ROP of a fixed cutter drill bit is a product of the DOC and the RPM (ROP = DOC * RPM, assuming equivalent units), and since the DOC is primarily produced by the available WOB, in an environment where WOB is limited (as with CTD), RPM is the key driver for ROP.

Of the two types of downhole motor that are commercially available for CT jobs, the turbodrill is a much better fit in terms of weight on bit management than the PDM, due to the ability of a turbodrill to reliably operate at a much higher RPM. As a general rule, turbodrills are capable of more than double the RPM of the highest speed PDMs available on the market. In addition to the increased RPM potential, turbodrills are also capable of much higher torque for a given RPM than a positive displacement motor. It is a common misconception in the industry that PDMs are more powerful tools than turbodrills. The fact of the matter is that, because turbodrills are capable of sustaining very high pressures, they are much more powerful drilling tools than are PDMs. Turbodrills are capable of sustaining much higher pressures than PDMs because the mechanism of converting hydraulic power to mechanical power in a turbodrill is done entirely with metallic components. The power generation section of the turbodrill consists of a number of turbine stages, a stage consisting of a rotor and stator configuration (Figures 1 and 2). This setup allows fluid to pass through each stage where the fluid flow is redirected from the stator to the rotor resulting in a rotational force on the rotor that is transferred to the shaft and down to the drill bit. In contrast, mechanical power is created in a PDM (Moineau principle) through the eccentric rotation and sealing arrangement of a metallic rotor and an elastomer stator.[7] The misconception in the industry that a PDM is a more powerful tool than a turbodrill is mainly driven by the fact that turbodrills operate at relatively low values of drilling torque in comparison to PDMs. However, RPM and torque are inversely proportional in the design of downhole motors. Therefore, the reason that turbodrills generally produce less torque is because they typically run at much higher RPM ranges than do PDMs. In considering the fact that high RPM is beneficial to increased ROP for CT applications, turbodrills are actually capable of much higher torque output when operating at high RPM than are positive displacement motors. For example, a 2-7/8" turbodrill operates at an RPM range (operating speed, not runaway speed) of 1,100-2,000 RPM, with a maximum torque output of 255 ft-lb. By comparison, a brand new 2-7/8" PDM (2-3 lobe, 7 stage) is quoted to run at a maximum of 845 RPM (low end of range = 369 RPM) with 182 ft-lbs of torque.[8] As discussed earlier, in the design of downhole motors, RPM and torque are inversely proportional. Therefore, given that the turbodrill already produces higher torque than the high speed PDM, if the RPM of the turbodrill were reduced to the RPM of PDM in this example, it would create many times more torque (2000/845*255 = 603 ft-lbs of torque @ 845 RPM with a speed reduction ratio of 2.3). For reference, the technology to reduce the speed of a turbodrill in order to maximize torque output is being realized. There are many different sizes of turbodrills currently available that include the ability to reduce the output speed in order to increase the output torque. Therefore, in summary, since RPM is such a significant factor in promoting good ROP in areas where weight transfer to the bit is difficult, as in CTD, the turbodrill is an excellent tool for the job due to its unparalleled ability to provide reliable, high RPM along with substantial drilling torque.

High Temperature

Many current and future applications of coiled tubing technology are in areas where high temperature is a significant concern for BHA reliability and life. This is true of both the drilling and remedial market. There has been much documentation in industry literature about the problems of reliability in these high temperature environments. Temperature resistance is another major benefit of the use of a turbodrill. Turbodrills available on the market today are capable of sustaining temperatures greater than 400°F without any adverse effects on overall tool reliability. This temperature resistance is a direct effect of the fact that turbodrills are nearly entirely metallic in composition. The power generation of a turbodrill is achieved with metallic turbine blades, and the bearing systems in today's turbodrills are also metallic and therefore very resistant to high temperatures (Figure 3). The problems with PDMs in high temperature environments are also well documented in industry literature.[9] Because turbodrills do not rely on any sealing arrangements containing elastomer components, the downhole temperature has little effect on the operation of the turbodrill.

Vibrations

There are many detrimental effects of severe vibrations on the drilling process. Excessive vibrations can cause premature bit wear and premature tool failures (MWDs, LWDs, etc). This is another area where the utilization of a turbodrill is beneficial on the overall effort of running a CT job. Because the rotor turns concentrically around the shaft, there is very little vibration inherent in the movement of a turbodrill. This is a very significant difference between a PDM and a turbodrill. On a PDM, the power generation is performed through the eccentric rotation of a rotor as it seals with an elastomer stator. The eccentric rotation of the rotor on a PDM creates significant vibrations that can be detrimental to the overall drilling process in a variety of ways. However, in contrast, the turbodrill is a completely concentrically designed tool, and therefore has very little vibration resulting from its operation (Figure 4 and 5).

Another major factor in the generation of vibrations is the drilling action of the bit, especially with fixed cutter drill bits. This is another area where high RPM is very beneficial to the overall process. When fixed cutter drill bits are run at high RPM, provided that they are durable enough to sustain drilling at that elevated RPM, the DOC is so small that vibrations resulting from drilling torque are kept to a minimum. Further, as turbodrilling technology has developed over the years, stabilization design for these systems has developed along with it to maximize overall performance, including vibration mitigation. Therefore, although it would seem likely that vibrations could be exacerbated by very high RPM, the mitigation of those vibrations through smooth drilling and good stabilization leads to overall smooth performance when turbodrilling.

Torque

In addition to the smooth running nature of a turbodrill assembly as a result of high RPM and low DOC, the design of the turbodrill itself also lends to very smooth torque response. This is another major difference between turbodrills and PDMs. In a PDM, torque builds up as weight is applied to the bit until the motor reaches a point of stall. With a PDM, the practice of stalling is actually very severe on the motor itself and can often lead to significant damage to the motor. Stalling a PDM can also create a very sizeable pressure spike in the system which can lead to the damage of other components associated with the job. On the other hand, with a turbodrill, stalling is not an issue. Because the general design of the turbodrill is such that the only physical contact between rotating and stationary components (rotor and stator components) is found in the radial and thrust bearings, when a turbodrill stalls, rotation simply stops and the fluid goes through the turbine blades in exactly the same manner as when the tool is running. It is just as safe to leave a turbodrill in the stalled condition as it is to leave it in the running condition. Additionally, the turbine blades used in today's turbodrills have a pressure signature that actually shows a decrease in pressure as the tool stalls. This is in complete contrast to a PDM. With a PDM, stalling is avoided at all costs due to the potential problems that can result, including pressure spikes. With a turbodrill, when the tool stalls, the pressure decreases, so in the overall planning of the section, the maximum pressure capacity of the rig can actually be more fully utilized. Another benefit to the operation of a turbodrill is how it comes out of the stalled condition. As mentioned, when a turbodrill stalls, it just means that the hydraulic energy going through the tool isn't high enough to produce the torque required at that moment, so the tool stops rotating. When that torque requirement is relieved (e.g. by picking up off bottom) the tool slowly starts spinning back up to speed. Because the energy is converted in a very different way with the sealing arrangement of a PDM, when a PDM comes out of the stalled condition, it is often a violent event with a quick release of energy in the form of high torque. The result of these two processes is a very different application of energy at the bit / formation interface. With a PDM, the speed and torque are applied in a much more drastic fashion, which can lead to erratic torque and bit damage. With a turbodrill, the torque and speed come back up slowly, allowing the bit to gradually spin back up to speed and start drilling again.

Directional Capabilities

Another common misconception in the industry concerns the relative directional performance of the PDM versus the turbodrill. As mentioned earlier, it is actually the case that the turbodrill was the first steerable motor ever used in the industry. As time has gone by, turbodrills have developed steerable capabilities to the point where they can now regularly outperform PDMs in directional applications. There are many reasons for the excellent directional capability of the turbodrill, and nearly all of them are related to items already introduced earlier. First of all, although it isn't directly relevant to coiled tubing work, one major benefit to turbodrills over PDMs in standard directional work is found in the ROP potential in slide mode versus rotary mode. It is not uncommon for the ROP of a PDM run to be a fraction as high in slide mode as in rotary mode (i.e. ½ the ROP or less in slide mode). With a turbodrill, there is often no discernable difference in the ROP signature between slide mode and rotary mode. This is a very good example of why turbodrills are often more effective on CTD jobs. Since these jobs require 100% sliding, and turbodrills generally do a much better job with ROP in sliding mode, they generally perform better on CTD jobs.

Another major benefit to the use of a turbodrill in directional applications is the drilling torque requirement and the way that the torque is created. As discussed earlier, turbodrills are very smooth running tools, and the application of torque at the bit is gradual and consistent. As a result of this torque behavior, toolface control when running a turbodrill is correspondingly smooth and consistent. It is a direct result of this consistent toolface control, coupled with the enhanced stabilization discussed earlier, that produces excellent steerability. The stabilization that has been developed for turbodrills over the years has a very positive impact on hole quality – helping to prevent the generation of ledges or significantly oversized hole sections (Figure 6). As a matter of fact, it has been established in many applications that a turbodrill can achieve the same dogleg severity (DLS) as a PDM with ½ of the bend angle. In other words, a turbodrill with a 1° bent housing can achieve a similar DLS to a PDM with a 2° bend. As a result of the DLS capability of the turbodrill with lower bend settings, it is very rare to run a turbodrill with anything higher than a 1.25° bend. Using smaller bend settings helps to enhance the hole quality mentioned earlier, so all of these factors work together to improve the overall performance of the system.

As directional plans continue to get more complex with coiled tubing, the enhanced hole quality produced by turbodrills will have even greater effects. Since coiled tubing is never rotated, the ability of this tubing to transmit weight to the bit in deviated or even horizontal hole sections can be greatly diminished by poor hole quality. This same effect is seen in extended reach drilling with conventional drill pipe. When more of the drillstring (be it drill pipe or coiled tubing) is in contact with the hole wall, the drag on that drillstring increases significantly. If the drilled section is tortuous or inconsistent in nature, the drag on the drillstring is even greater. This is another area where the stabilization utilized on turbodrill runs is very beneficial. Because turbodrills drill consistent gage diameter, non-tortuous wellbores, and because they do not require much WOB to drill effectively, the use of turbodrills in deviated sections with coiled tubing can greatly enhance overall performance.

New Tool Designs

In an effort to extend the applicability of turbodrilling to coiled tubing operations, many new turbodrill designs and modifications are currently underway. One of the most significant developments in progress is the creation of a turbodrill that is much shorter than existing designs in order to enhance compatibility with coiled tubing equipment and lubricators. This new tool design has been specially created for coiled tubing, and specifically targets operating parameters and power output for CTD applications. Other developments currently underway to improve compatibility with CTD applications include specially designed turbine blades for these applications. These blades are being designed to maximize power output in the shortest possible tool configurations.

Case Histories

Turbodrills range in size from 2-7/8” to 9-1/2” tool OD and have drilled holes ranging from 3-1/4” to 17-1/2”. However, most of the experience with CTD and UBD has been in the 2-7/8” to 6-5/8” tool OD ranges. The first CTD job performed with turbodrills took place in the North Sea in May 1997. Using a 3-3/8” turbodrill with a 3-7/8” PDC bit, a well was deepened 518 feet from the original TD of 12,802 feet in an existing offshore field. The interval was drilled using 2” CT and the average ROP was greater than 25 fph. Downhole temperatures were in the 320 ^{o}F bottom hole temperature (BHT) range. The bottom hole pressure (BHP) on this well was 700 psi. This performance resulted in a great cost savings over the first attempt to deepen this well which resulted in 9 PDM failures where a cumulative 26 feet were drilled.

Recently, on a deep development well in the continental US, the intention was to go beyond where previous production casing was set to log deeper sands for evaluation. Due to hole problems, the 5-3/4” hole could not be drilled to the desired target depth, resulting in a 4” liner having to be run and hung off in the 7” casing. Using a 2-7/8” Turbodrill, 120 feet of 3-1/2” hole was drilled to a total depth of 19,595 feet. Using a diamond bit, the ROP averaged 4 feet per hour operating in 19.1 ppg drilling fluid and 370 ^{o}F BHT. Utilizing a turbodrill made the exploitation of the lower formations economically possible and resulted in a potentially new production interval in the existing field.

UBD is ideal for turbodrilling. Excluding the year 2003, turbodrills have drilled over 100,000 feet equating to over 7,600 operating hours specifically in this application in the UK, Venezuela, Norway, Argentina, Canada, Holland, Oman, Indonesia and the US. The holes drilled ranged in size from 3-7/8” up to 10-5/8”. The longest run consisted of 308 continuous drilling hours, the longest interval drilled was 6,478 feet, the highest gas ratio seen during operations was 88%, and 44% of the overall drilled footage was steered. The longest drilled interval of 6,478 feet with a diamond impregnated bit set a world record which still stands. Correspondingly, the longest operating time of 308 hours occurred on this same well. This performance beat the surpassed the previous world record by 1,333 feet. The world record well was drilled from 10,676 feet to 17,154 feet at an average ROP of 33.1fph with 5,224 feet (81%) of the footage being rotated and 1,254 feet (19%) being steered. In all UBD operations, turbodrills have a Mean Time Between Failures (MTBF) greater than 3,600 hours.

Turbodrills have primarily been utilized in the drilling market, however, there are some case histories in the remedial market where turbodrill performance has been unheralded. In the central North Sea, a 2-7/8” turbodrill with a PDC bit was utilized to drill out 1,502 feet of cement in a 4-1/2” liner. This was completed in a single trip and the BHT was 392 ^{o}F.

In other applications, a specific area in the Middle East adopted 2-7/8” turbodrills for remedial cleanout operations following high failure rates with PDMs. Operating at downhole temperatures of 302 °F the maximum exposure time for PDMs in this application had been 18 hours. Since being adopted, turbodrills have been used successfully in each instance.

Conclusions

Over the past 20 years, CT technology has expanded to include not only complex remedial and workover operations, but drilling operations - from both wellbore extensions to grass root wells. Although there are some 7,000 plus wells drilled with CT, and many more worked over each year, there are still hurdles that must be overcome to make CT viable in more complex environments. Turbodrilling technology has made many strides in closing these technological barriers for CT, both in drilling and remedial operations. The design of the turbodrill lends itself ideally to many CT applications. By using speed rather than weight to drill, performance on CT can be enhanced, and, in some instances, optimized.

Having no elastomers in the system, the turbodrill is also well suited for performing in high temperature environments, where other downhole motors frequently fail. The concentric design of the turbodrill power shaft also makes for efficient use with CT. When drilling or milling, the turbodrill has little vibration, so there is little lost energy in the system.

When evaluating toque and power on a comparative basis, the torque required for the turbodrill to perform is actually lower than that of PDMs due to cutting characteristics. The higher torque of the PDM can, in fact, be detrimental to the operation, as when the motor stalls with the added weight required to drill or mill, the release of energy in the system can be catastrophic. In turbodrilling operations, stalling simply means the system has stopped, and, since the parts in relative motion with one another do not touch, nothing happens to the tool other than fluid flowing through the system without the shaft turning.

The consistent torque and low vibration of the turbodrill are also beneficial when performing directional work. In CTD, the assembly is in the slide mode throught the process. While turbodrilling, the low reactive torque allows the tool face to stay steady so that well direction can be maintained. It has historically been proven that the ROP differential between sliding and rotating with a turbodrill is negligible.

To economically exploit the deeper depths in remedial and drilling applications using CT, turbodrills will be an integral part of the BHA. As documented by the case histories, where these tools have been utilized, their performance has been superior.

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Nomenclature

BHA = Bottom Hole Assembly
BHP = Bottom Hole Pressure
BHT = Bottom Hole Temperature
CT = Coiled Tubing
CTD = Coiled Tubing Drilling
DLS = Dog Leg Severity
DOC = Depth of Cut
ERD = Extended Reach Drilling
F = degrees in Fahrenheit
LWD = Logging While Drilling
MTBF = Mean Time Between Failures
MWD = Measurement While Drilling
OD = Outside Diameter
PDC = Polycrystalline Diamond Compact
PDM = Positive Displacement Motor
psi = pounds per square inch
ROP = Rate of Penetration
RPM = Revolutions per Minute
TD = Total Depth
UBD = Underbalanced Drilling
WOB = Weight on Bit

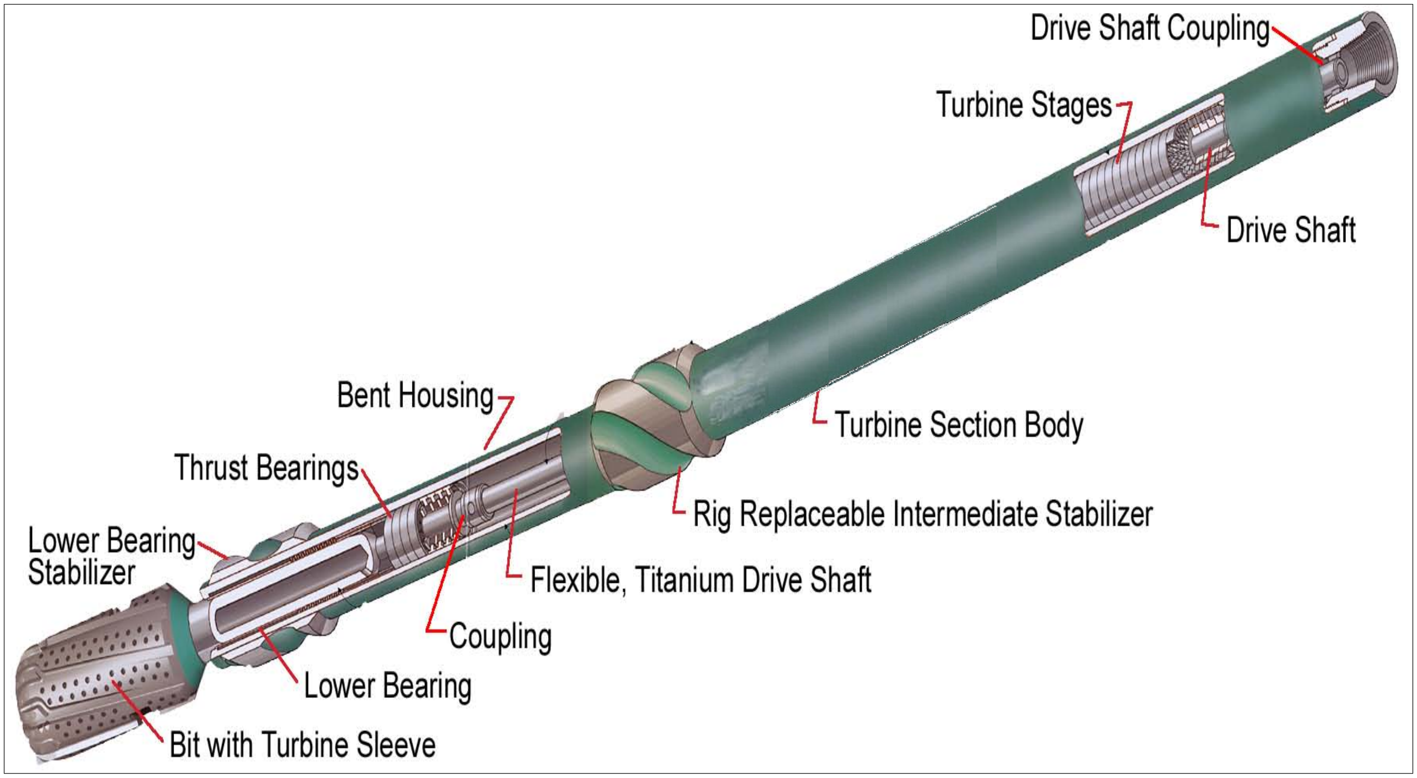


Figure 1: Turbodrill

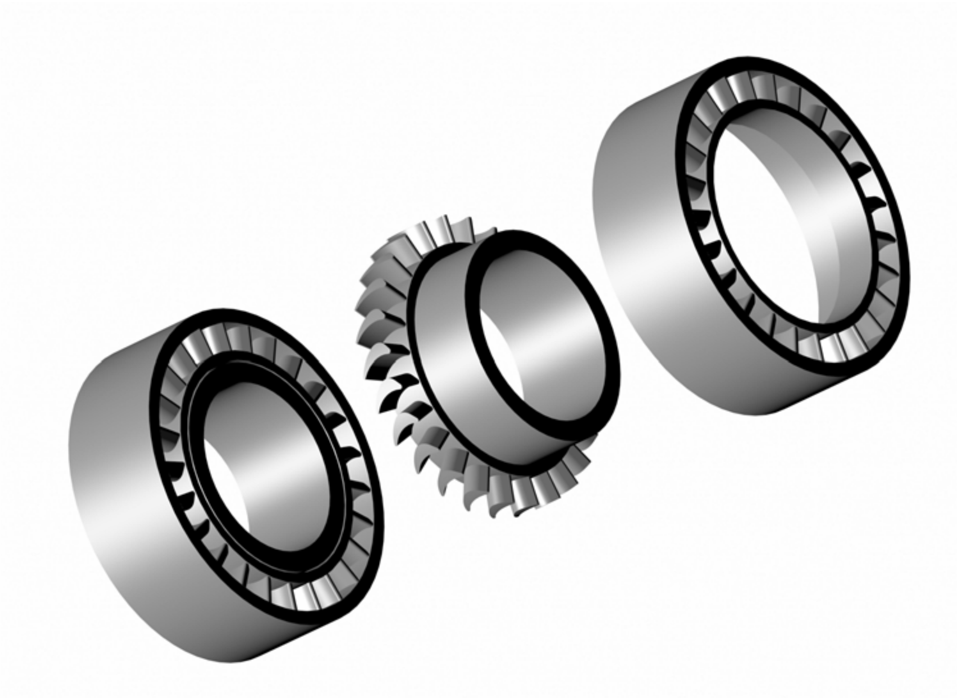


Figure 2: Turbine Blade Stage (Right to left: Stator, Rotor, Full Stage)

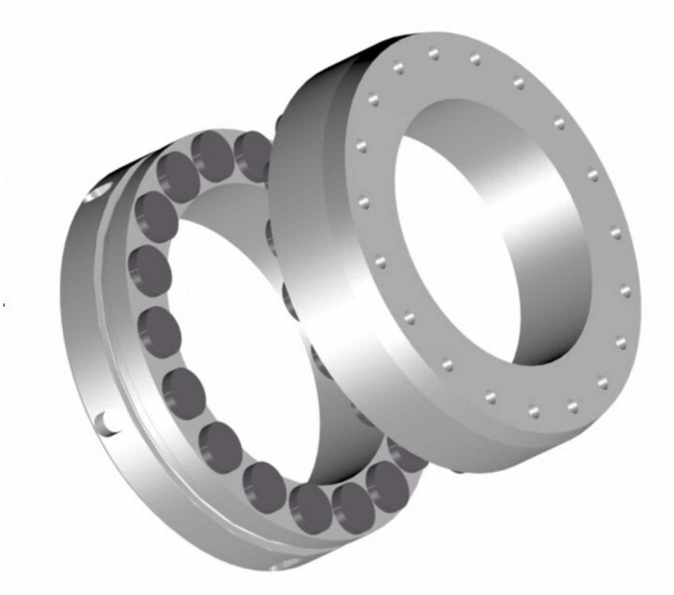


Figure 3: PDC Bearing

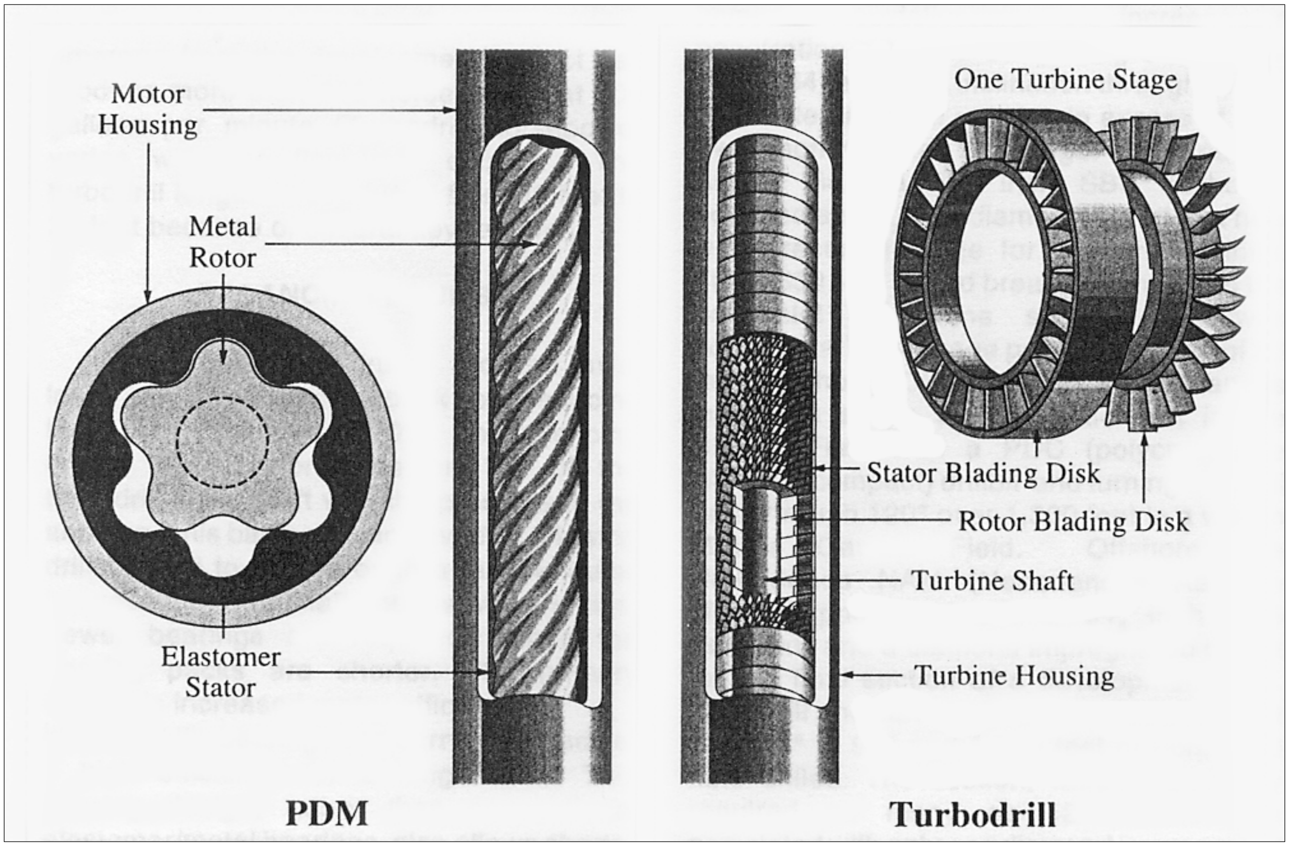
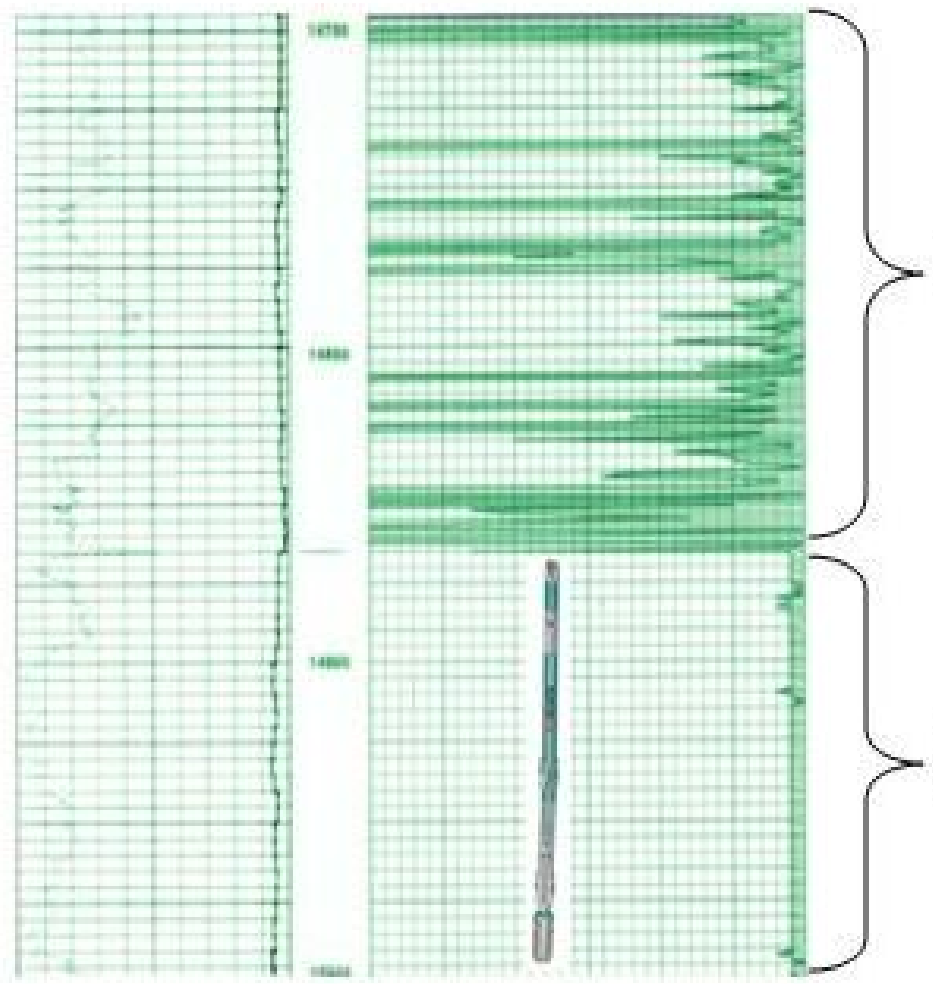


Figure 4: PDM versus turbodrill



Section Drilled by PDM

Section Drilled by turbodrill

Figure 5: Vibration of PDM versus Turbodrill

Figure 6: Stabilized Turbodrill