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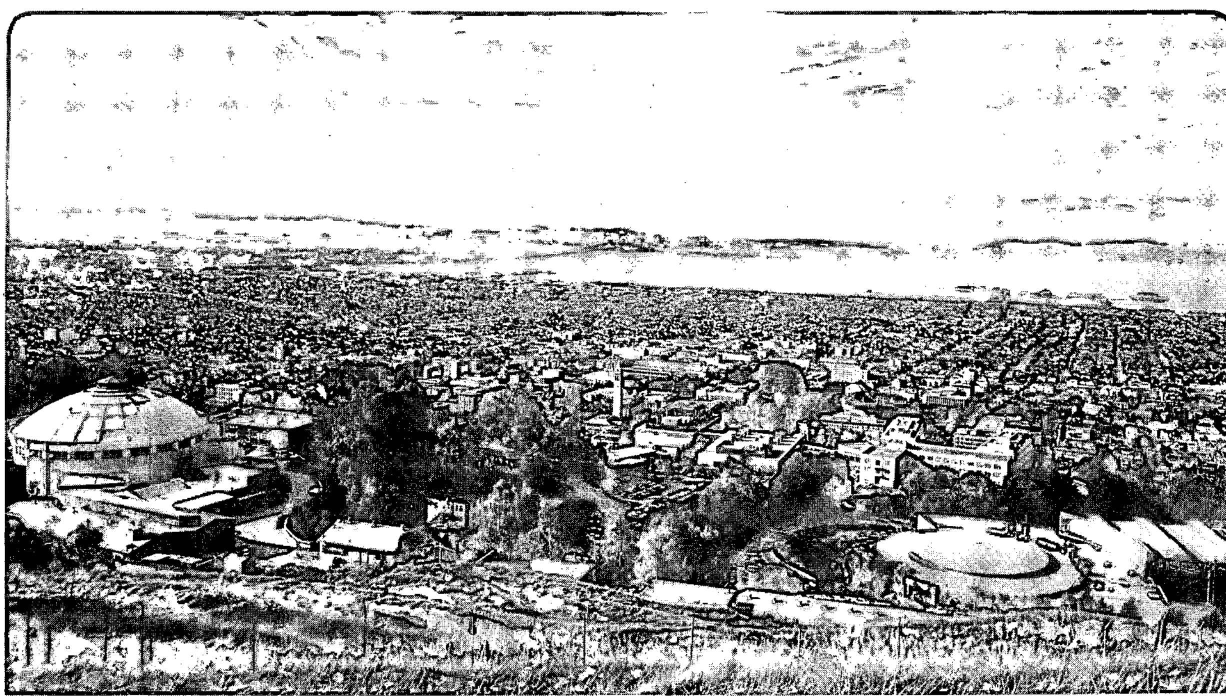
EARTH SCIENCES DIVISION

Applicability of Petroleum Horizontal Drilling Technology to Hazardous Waste Site Characterization and Remediation

C. Goranson

September 1992



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Acknowledgments

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1.0) Introduction

Horizontal wells have the potential to become an important tool for use in characterization, remediation and monitoring operations at hazardous waste disposal, chemical manufacturing, refining and other sites where subsurface pollution may develop from operations or spills. Subsurface pollution of groundwater aquifers can occur at these sites by leakage of surface disposal ponds, surface storage tanks, underground storage tanks (UST), subsurface pipelines or leakage from surface operations. Characterization and remediation of aquifers at or near these sites requires drilling operations that are typically shallow, less than 500-feet in depth. Drilling operations may be as shallow as 20 feet or reach depths of 1000 feet or more at some locations. Due to the shallow nature of polluted aquifers, waste site subsurface geologic formations frequently consist of unconsolidated materials. These unconsolidated materials normally consist of sand, clay, gravels, boulders or mixtures of these materials. Fractured, jointed and/or layered high compressive strength formations ("hard rock", such as basalt, granite, limestone, etc.) or compacted caliche type formations can also be encountered. Some formations are unsaturated and have pore spaces that are only partially filled with water. In addition, completely saturated underpressured aquifers may be encountered in areas where the static ground water levels are well below the ground surface. Each of these subsurface conditions can complicate the drilling and completion of wells needed for monitoring, characterization and remediation activities.

Various types of hazardous materials may exist in polluted subsurface aquifers. In some cases combinations of chemicals may exist in the subsurface. Methods available for destruction, removal, immobilization or characterization of contaminants are both site dependent and pollution species dependent. Volatile organic compounds (VOC's) can typically be divided into four chemical families (Ciccolella and Holt, 1992) hydrocarbons, halo-hydrocarbons, nitrogen compounds, and oxygenated compounds. These volatile organic compounds constitute a major portion of the chemicals encountered in contaminated aquifers. VOC's can be found in liquid, dissolved and vapor states. Separate phase liquid VOC's are termed non-aqueous phase liquids (NAPL) when encountered in the subsurface. Some VOC's have densities greater than that of water and are termed dense non-aqueous phase liquids (DNAPL). Vapor phases are normally found in the unsaturated or partially saturated portions of the subsurface (vadose zone). DNAPL's have a density greater than water and can accumulate at geologic contacts or along the top of low permeability layers.

The utility of vertical wellbores for characterizing aquifers and remediation operations is limited by the small areal volume sampled by each well. In addition, characterization and remediation of aquifers located directly beneath potential leakage sites may be difficult in that vertical wells cannot be drilled through waste ponds, underground storage tanks or surface storage tanks due to the non-availability of surface locations. The unavailability of surface locations at manufacturing and refining sites also limits the use of vertical wells in subsurface investigation and remediation operations. In addition, there is concern that drilling operations could cause contamination of previously non-polluted formations located directly below the surface storage area.

Horizontal wells or wells inclined to vertical (directionally drilled wells) can be used for contaminated aquifer characterization and remediation in cases where surface drilling locations for vertical wells are not available. Horizontal wells can be used for characterization and remediation operations under surface disposal ponds, underground storage tanks, for drilling beneath manufacturing and refining sites, along subsurface pipelines, along surface drainage channels and in other areas where surface locations are not available. In comparison to vertical wells, horizontal wells can also increase the areal volume of reservoir sampled in investigative operations.

Horizontal and inclined wells can also be used for characterization and remediation activities along formation bedding boundaries and geologic contacts. Horizontal drilling also has application in fractured geologic formations. In areas where sets of vertical fractures or steeply dipping jointing planes exist in the subsurface formation, horizontal or directionally drilled wells can intersect a greater number of fractures than can vertically drilled wells (Pasini and Overby, 1969).

Horizontal wells may also have application where subsurface permeability barriers need to be created to reduce or eliminate vertical or lateral off site movement of contaminants. Horizontal wells can assist in the placement of subsurface barriers to be created with grouting materials, bentonite clay slurries or assist in the placement of foam that can be used to reduce aquifer permeability (Radke et al., 1983; Persoff et al., 1989).

From a remediation standpoint, recent reports (Langseth, 1990, Kaback written communication) have shown that horizontal remediation wells can increase, in comparison to vertical wells, the amount of contaminants removed during production operations. In the petroleum literature (Joshi, 1988), horizontal wells have also shown increased petroleum production rates when compared to vertical wells. Reservoir engineering calculations show a theoretical increase in petroleum production of 2 to 6 times for horizontal wells versus vertical wells with similar well (reservoir) pressure drops. Directionally drilled slant wells, drilled at angles of 60° to 70° to the produced aquifer, can increase productivity 2 to 3 times over vertical wells with similar well (reservoir) pressure drops. In all cases, the increase in productivity of horizontal wells over vertical wells is dependent on horizontal well length, reservoir height and the ratio of vertical to horizontal permeability. Figure 1 illustrates the productivity enhancement for horizontal versus vertical wells for several reservoir characteristics.

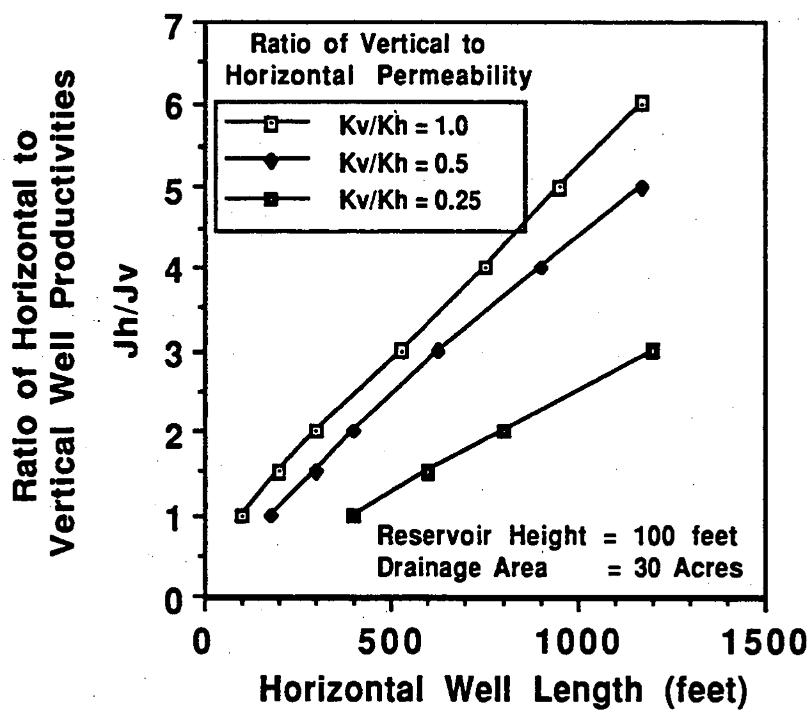


Figure 1) Ratio of Horizontal Well to Vertical Well Productivity Versus Horizontal Well Length (after Joshi, 1991)

The predicted productivity increase for horizontal wells versus vertical wells used in remediation operations has been demonstrated in field tests. Two shallow (<175 feet deep) horizontal wells have recently been completed at the Department of Energy Savannah River Site for use in an in situ air stripping demonstration project (Kaback et al., 1989; Looney et al., 1991; Kaback, 1992, written communication).

The in situ air stripping demonstration project involved the drilling and completion of one horizontal well drilled below the water table and a second horizontal well drilled into the unsaturated zone and located vertically above the horizontal well completed below the groundwater table. Air was injected into the well completed below the groundwater table. The upper horizontal well was used to extract vapors from the unsaturated zone and vapors stripped from the groundwater during air injection into the well located below the groundwater table. During the vapor extraction only phase of the demonstration project the horizontal well completed into the vadose zone illustrated a five fold increase in VOC recovery over a vertical well completed into the unsaturated zone. On a daily basis, the mass of contaminants produced from this horizontal well demonstration project was comparable to an eleven well 500 gpm pump and treat system operating at the site (Kaback, et al, unpublished report). Due to the difference in the methods used to recover the contaminants, direct comparisons between horizontal and vertical wells cannot be made. However, the ability for horizontal wells to recover contaminants in the vadose zone and their use in in situ air stripping projects was demonstrated.

As noted from the discussion above, horizontal wells have several benefits over vertical wells in subsurface investigations and remediation at contaminated sites. Horizontal drilling operations in groundwater characterization and remediation work, however, offer unique problems, when compared to horizontal drilling operations in the petroleum industry. The shallow nature of contaminated aquifers requires that short and medium radius (< 300 feet radii) horizontal wells be drilled. Horizontal well depths may need to be as shallow as 20 feet with lengths of several hundred feet. These shallow depths require the use of short and ultra-short radii wells. The unconsolidated formations that may be encountered at these shallow depths can make the drilling of short and medium radius horizontal wells difficult.

Unconsolidated shallow formations can create wellbore stability problems when penetrated by vertically drilled wells. Hole washout, stuck pipe and poor hole cleaning leading to large amounts of fill upon drillpipe addition are but of a few of the problems associated with the drilling of unconsolidated formations. In many formations the vertical stress is greater than the horizontal stress, therefore unconsolidated formations that exhibit borehole stability problems when drilled vertically will, most likely, have more severe stability problems when penetrated by horizontal wells. Furthermore, the stress state around the well is axisymetric, adding to the borehole stability problems. In addition to difficulties associated with borehole stability, other drilling problems are common to both remediation drilling activities and petroleum drilling operations. Loss of drilling fluid circulation, or loss of fluid to a particular aquifer being penetrated, is a problem during drilling in permeable unsaturated or underpressured aquifers. Loss of circulation is a concern in remediation operations in that drilling fluids can be contaminated with pollutants during the drilling process. Subsequent loss of drilling fluids to previously uncontaminated aquifers is a major concern. This loss of drilling fluid may increase the volume of contaminated soil to be remediated or mask the extent and nature of contamination. Production of contaminants entrained in drilling fluids is of concern to operating personnel and may necessitate extensive decontamination of the drilling equipment.

Technology needs common to both petroleum and remediation operations include the need to drill horizontal wells along geologic contacts or bedding planes, well completions perpendicular to fracture planes and joints, isolation of pristine groundwater aquifers from contaminated aquifers (or productive oil formations in the petroleum industry), sand production during flowing operations and the need for long gravel packed intervals in low permeability formations are but a few common aspects related to drilling activities. In addition, small surface locations for drilling equipment, noise abatement when drilling in congested areas, the need for biodegradable drilling fluids and the use of dry drilling systems to reduce the amount of material to be disposed at the surface are also common areas of concern.

In response to the need for horizontal wells in contaminated site investigations, petroleum service and supply companies with directional and horizontal petroleum well drilling experience and equipment have become involved in groundwater remediation drilling and completion operations. The shallow depths and unconsolidated nature of contaminated groundwater systems has brought about new drilling rig designs. These drill rig designs allow for the drill rig mast to be angled to the vertical. For a given radius of curvature of the well, the angled mast drilling rig reduces the vertical depth to which the well must be drilled before the well reaches a horizontal configuration. These newly designed drilling rigs can also incorporate closed loop drilling fluid systems that reduce hazards to operating personnel from contaminants entrained in the drilling media. In addition to petroleum drilling equipment and supplies, several existing angled mast drilling rig systems, termed river crossing equipment in this report, are being used for groundwater remediation work. River crossing equipment was designed for placement of petroleum, natural gas, utility equipment, water and sewerage pipelines below rivers and other types of surface obstacles. These river crossing drilling rigs have the ability to push and rotate the drill string. In some cases, the river crossing drilling equipment uses a rotatable concentric washover string. Recent designs use small diameter casing as the washover string. The concentric washover string reduces drillpipe contact with the wall of the hole thereby reducing borehole stability problems in unconsolidated formations. In addition, the concentric washover pipe reduces hole stability problems associated with washouts caused by the circulating fluid due to the fact that the major portion of the circulating fluid is confined within the annular area between the drillpipe and washover string. Most of the equipment used in river crossing drilling operations has been adapted from the petroleum industry.

Various types of subsurface support equipment used in the petroleum industry can be readily adapted to remediation and characterization drilling activities. Drilling along the top of low permeability layers, along geologic contacts and directly below the groundwater table can be assisted with measurement while drilling (MWD) equipment that continuously monitors the location of the drill bit. In addition, formation evaluation measurement while drilling (FE-MWD) systems that include geologic logging tools are also available. Steerable bottom-hole drilling assemblies that use positive displacement downhole mud motors in conjunction with various stabilizer and bent sub assemblies allow for directional control while drilling wells along geologic contacts, bedding planes or contamination boundaries. In addition, these steerable drilling systems can assist in location of wells for in situ air stripping, bioremediation operations and groundwater barrier development. Well completion equipment from the petroleum industry, such as, external casing packers for production zone isolation, external casing packers with integral cement stage collars to insure adequate primary casing cement jobs, pre-packed sand or gravel liners for production intervals and submersible electric pumps with downhole vapor separators are all types of subsurface equipment with application to groundwater remediation activities.

Surface drilling support equipment available from the petroleum industry can also be adapted to characterization and remediation drilling operations. This equipment includes mud de-gassers and mud liquid-vapor separators which are used for removal of natural gas and hydrogen sulfide vapors from drilling fluids in the petroleum industry. These devices can be used to remove vapor contaminants dissolved in the drilling fluid during drilling operations in polluted aquifers. Aerated drilling fluids have densities less than water and can assist in drilling of underpressured aquifers and unsaturated formations. Aerated fluid drilling can use mud-gas separators and mud de-gassers to separate air and dissolved contaminant vapors from the drilling fluid. Mud decanting centrifuge systems that separate high density drilled particles from the drilling fluid are also available. In addition, these centrifuge systems can be used to remove drilled solids and contaminated drilled solids from the mud system. These dry type drilling systems, as they are termed in the petroleum industry, can reduce surface disposal costs of generated drilling wastes.

This report describes some of the equipment that is available from petroleum drilling operations that has direct application to groundwater characterization and remediation activities. A brief discussion of petroleum directional and horizontal well drilling methodologies is given to allow the reader to gain an understanding of the equipment needed to drill and complete horizontal wells. Equipment used in river crossing drilling technology is also discussed. The final portion of this report is a description of the drilling equipment available and how it can be applied to groundwater characterization and remediation activities.

2.0) Petroleum Directional and Horizontal Drilling Operations

There are several types of wells that are drilled at an angle to vertical in petroleum drilling operations. Wells drilled at angles of 86° or less from vertical are normally termed deviated wells or directional wells (Markle, 1987). Deviated wells are drilled at an angle to vertical with no control over azimuth (magnetic orientation) of the well. Deviated wells drilled at an angle to vertical to intercept a subsurface target located at a particular depth and azimuth from the surface location of the well are termed directionally drilled wells. Directional wells are drilled to allow for multiple wells to be drilled from one surface location, for interception or avoidance of fault zones, drilling through steeply dipping reservoirs, drilling to subsurface zones inaccessible from surface locations, for sidetracking of the well to drill around equipment lost in the wellbore, for interception of oil reservoirs located along salt domes and for repositioning of the borehole to intercept particular reservoir horizons. Figure 2 depicts the different uses of directionally drilled wells. Directionally drilled wells fall into three categories (Eastman Whipstock, 1984); continuous build, build and hold angle, and build, hold angle and drop angle (S-type). Figure 3 shows the various types of directionally drilled wells.

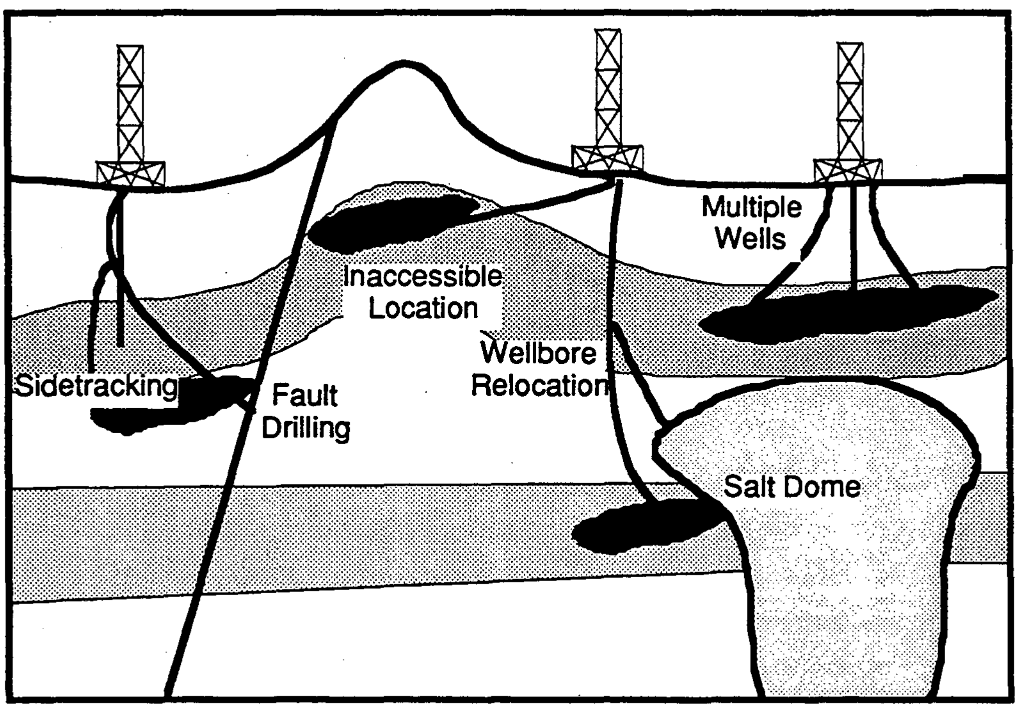


Figure 2) Various Uses for Directionally Drilled Wells

Wells drilled and completed at angles between 86° to 100° from vertical are termed horizontal wells. The first horizontal petroleum well drilled in the US. (Joshi, 1991) was completed in the California Midway Sunset Oil Field in 1942 (horizontal wells for petroleum operations had been drilled from tunnels prior to this well). This well was drilled as a lateral drain hole from an existing vertical well. The well was reportedly drilled using flexible drillpipe and a mud motor. There are several types of horizontal petroleum wells drilled. The wells are termed, horizontal well; a well designed and drilled from surface to be completed at an angle of 86° or greater from vertical and, drain holes; a well drilled from an existing vertical well with a final completion interval 86° or greater from vertical. Drain holes are also termed laterals. Another type of well completion type is termed a radial well. Radial wells are wells that are drilled at angles greater than 100° from vertical (i.e., in an upward direction from an existing vertical, deviated or horizontal well). Radial wells have been completed at angles up to 150° and can be initiated from directionally drilled or horizontal wells (Gardes Directional Drilling, 1989).

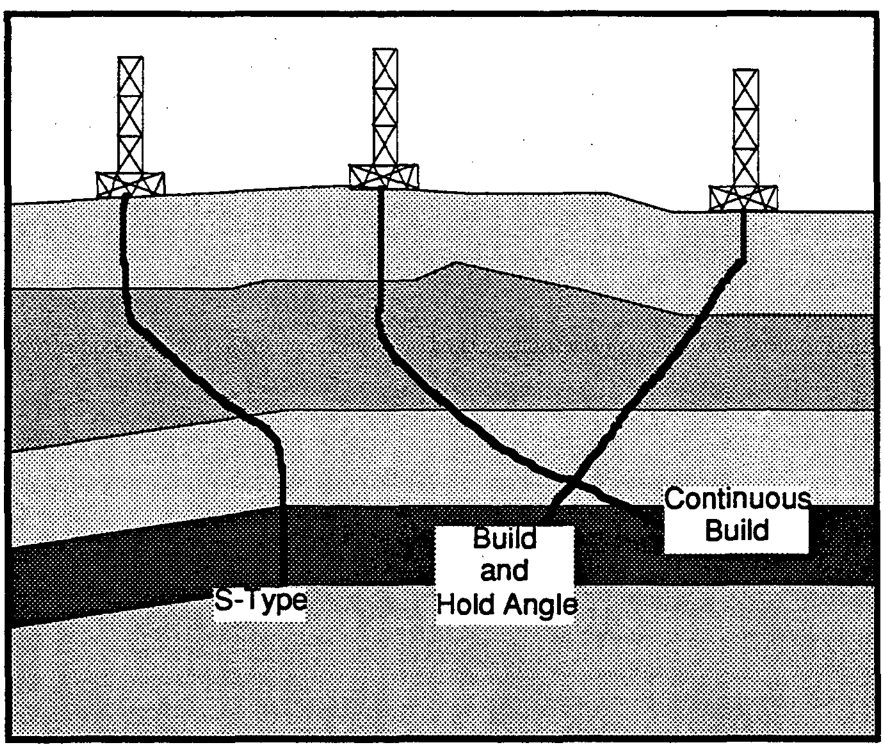


Figure 3) Types of Directionally Drilled Wells

Horizontal wells are placed into four categories based on the radius of curvature of the well from the vertical to the horizontal section. The radius of curvature between vertical and the point at which the well reaches horizontal relates to the vertical depth required to reach horizontal. In addition, the lateral distance from the point at which curvature was initiated from a vertical well is also related to the radius of curvature. For example, a long radius horizontal well drilled from a vertical well with a radius of curvature of 1000 feet indicates the well will reach a horizontal position at a vertical depth of 1000 feet from the point of initial deflection (kick-off point). In addition, the lateral distance from the surface location of the kick-off point to the point that the well reaches a horizontal position will also be 1000 feet. Horizontal well classifications are shown in Figure 4. Horizontal wells are classified as ultra-short radius, short radius, medium radius and long radius.

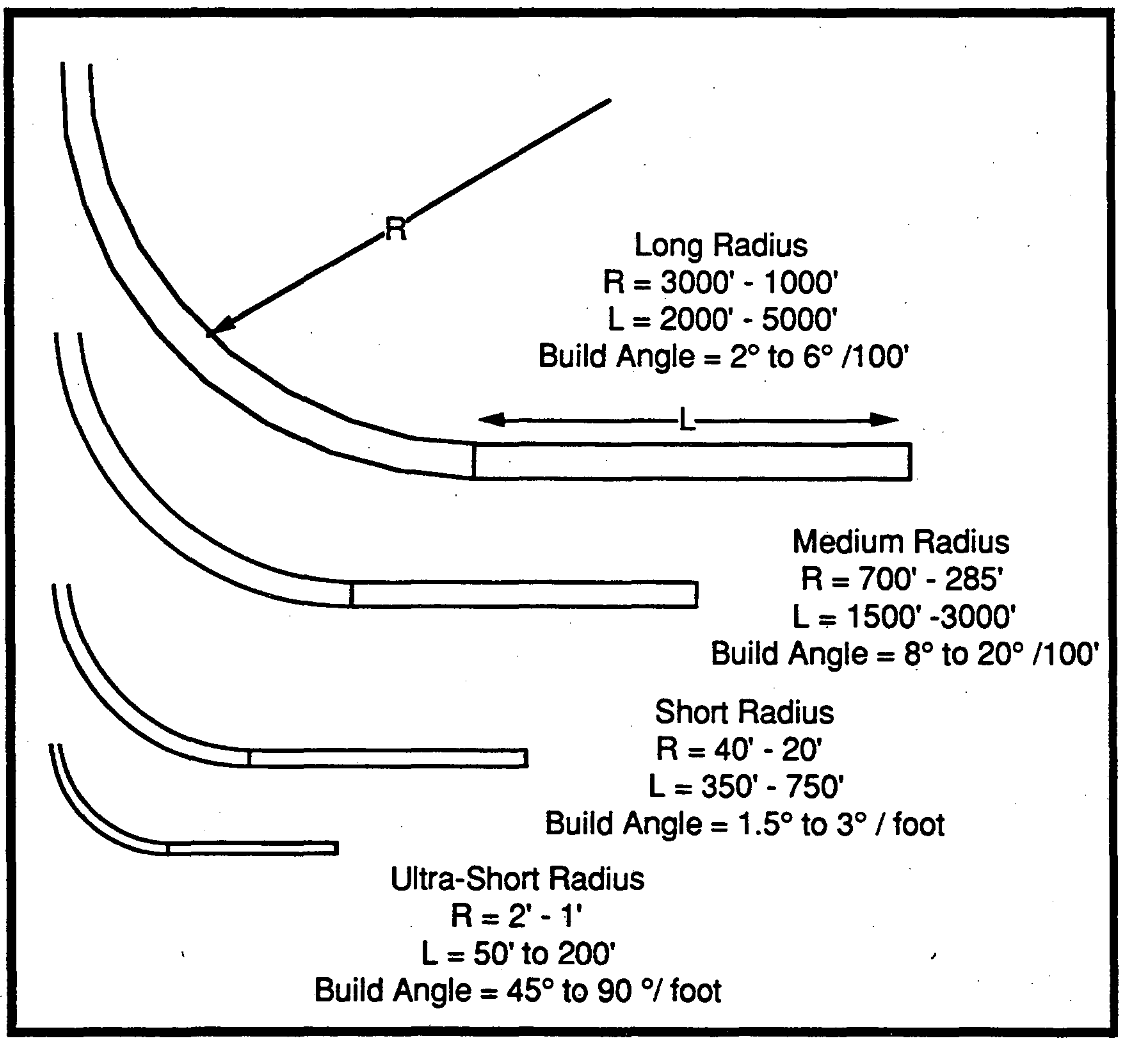


Figure 4) Classification of Horizontal Wells

The formation type and formation compressive strength influence the length of the horizontal section of the well. In addition, the maximum length of the horizontal section of the well is also dependent on the radius of curvature of the well. This is due to the fact that the radius of curvature of the well controls the size (diameter) of the drilling equipment that can be run through the curved portion of the hole without imparting stresses above failure loads to the downhole drilling equipment. In turn, the drilling equipment size determines the maximum amount of weight that can be realized at the bit face. Weight at the bit face is developed from the drillpipe and drill collars located in the vertical and near vertical portions of the hole. The size of the drilling assembly (drillpipe, collars, stabilizers and drill bit) controls the maximum weight that can be placed on the bit due to compressive buckling forces that develop in the drilling assembly during the drilling operation. The tendency for the drillpipe to buckle along with the associated fatigue stress limits the weight at the bit face, and therefore, the maximum length of the horizontal section.

3.0) Drilling Methods for Directional Wells

Well deflection from vertical in directional wells is initiated by one of several available methods. Both initial deflection angle and direction are normally maintained within specific limits during the deflection operation. The rate at which the angle of inclination to vertical is built as the borehole is drilled ahead is termed the build angle (or build rate), given in terms of increase in angle per 100 feet. The build angle can be controlled by the choice of bottom-hole assembly used, the bit rotation speed (in rotary drilling operations) and the amount of weight on the bit. During the deflection operation build angles vary but typically are 2° to 6° per 100 feet for directional wells. After deflection from the vertical hole is completed, drilling is continued with angle build type drilling assemblies until the final well inclination is reached. After the final angle has been reached, stabilized drilling assemblies are used to maintain angle. The drilling assembly used in the directional portion of the well is dependent on whether angle building, angle holding or angle dropping operations are required to control the well trajectory. Build angles with standard rotary drilling equipment can be as high as 20° per 100 feet. Azimuth is not always controlled during the initial deflection period. However, azimuth and inclination can be controlled to ±2° with proper bottom-hole drilling equipment during the well deflection operations (Eastman Christensen, 1991).

There are various methods used for creating the initial well deflection. One method for initiating deflection is to use a casing "whipstock" or open hole whipstock. Whipstocks can be removable or permanent and come in various diameters. The whipstock consists of an inverted steel wedge that is concave at the top side. This concave portion of the whipstock acts as a guide for the drill bit and drillpipe. Normally, a borehole smaller in diameter than the final hole is drilled during deflection initiation. The hole is redrilled and opened to the final hole diameter once the deflection operation is completed. Once appropriate deflection and azimuth are obtained the whipstock can be removed (if it is of the removable type) or it is left in place. Whipstocks are usually used in wells that have previously been drilled to depths deeper than the point at which well deflection is required. Normally whipstocks are used to drill to another subsurface location from an existing borehole or to drill around equipment lost in the well.

Another deflection method, used in soft formations, is the "Jet Bit" method. The jet bit method uses a standard drilling bit with two of the three bit jets plugged (or two of the bit jets are reduced in size). This method is rather simple in that the drilling assembly is lowered into the well and oriented. The drillpipe is moved up and down several feet while pumping mud through the drillpipe. The jetting action of the mud causes the hole to be washed out on the side of the hole with the large diameter jet. Drilling and washing action is continued until the desired direction and deflection is obtained.

Surface rotation of the drillpipe in the whipstock deflection method and the jet bit non-rotation deflection method offer little control in the magnetic direction (azimuth) in which the well is drilled. Mud motors and "bent sub" combinations allow for inclination and directional control and have become the most widely used method for deflection initiation and rapid angle build directional drilling operations. Bent subs are short sections of pipe with a diameter similar to that of the mud motor or drill collar. Bent subs are machined with a particular angle to the axis of the pipe, usually between 1/2° to 3°. The bent subs are placed directly above the mud motor. The mud motor is located directly above the drill bit. Mud motors are available with integral bents subs, or bent housings as they are termed. In some cases, two pipe bends can be located within the bottom portion of the drilling assembly. The two bent subs, along with the drill bit, allow for three points of tangency at which the drilling assembly is in contact with the wall of the hole. These three points describe an arc along which the hole will be drilled (see Figure 5).

$$\text{Radius Drilled (R)} = \frac{L1 + L2}{2 * \sin(\partial)}$$

$$\text{Angle Build-up Rate} = \frac{2 * \partial}{L1 + L2}$$

Where ∂ is the Bit Offset Angle

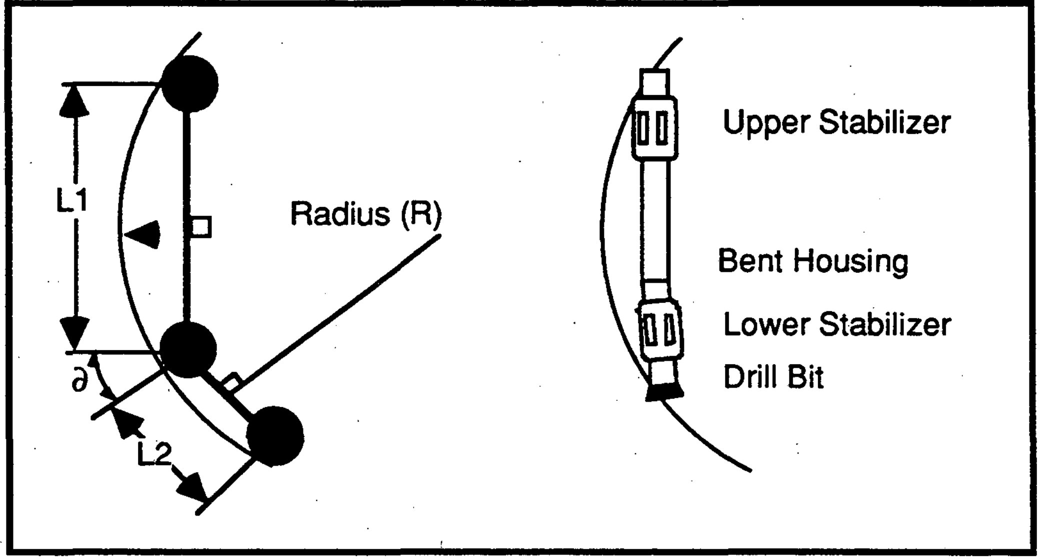


Figure 5) Three Point Geometry Build Angle Calculation Method

Mud motors used in the directional operations convert the energy of the mud flowing axially through the drillpipe to rotational energy. The energy generated causes rotation of the drill bit through a drive shaft system. During the deflection portion of the directional drilling operation the drillpipe is not rotated and bit rotation is developed from the mud motor. Rotation of the bent sub-motor assembly causes the drilling assembly to rotate around its center of mass and no hole deviation can be realized. Drilling operations without drillpipe rotation are termed drilling in sliding mode due to the fact that the drillpipe slides down the hole without rotation during this period. The lack of rotation of the drillpipe and bottom-hole assembly makes it difficult for the drilling assembly to slide down the well. This is due to the sliding friction factor being greater than the dynamic (rotating) friction factor. The friction force developed between the drilling assembly and the wall of the hole reduces the amount of weight than can be realized at the bit face, especially in highly deviated holes. Penetration rates are reduced due to this reduction in bit weight. In order to overcome the sliding friction forces, steerable drilling assemblies that use a combination bent sub and drilling motor (Smith

International, 1991; Eastman Christensen, 1991) are available. In the steerable system rotation of the drillpipe, motor and bent sub assembly allows the well to drill along a straight path. If corrections to inclination or direction are needed, the drillpipe rotation is stopped, the mud motor and bent sub are re-oriented and the mud motor is used to correct the inclination and direction of the well.

The mud motor and bent sub system for directional and steerable drilling assemblies normally use measurement while drilling (MWD) equipment to determine bit face orientation during the drilling process. The MWD equipment is located directly above the mud motor. MWD equipment uses tri-axial accelerometers and triaxial flux-gate magnetometers located above the mud motor to determine hole direction and inclination. Orientation of the bit face can be obtained from calculations based on data obtained from inclination and direction measurements along with knowledge of the orientation of the bent sub with respect to the measurement point. Other methods for measuring hole angle and direction that utilize tools that are periodically run down the drillpipe on wireline (single or multi-shot magnetic orientation and gyroscopic devices) are also available.

There are two types of mud motors available (Petroleum Engineer, 1991): the turbine vane type and the positive displacement type. The turbine vane type mud motors are capable of high speeds and use a multistage radial stator and vane type system. These motors were first used in the USSR in 1934. Use outside of the USSR began around 1959 (Burgoyne et al., 1986). The turbine motors have a series of blades set at an angle of 45° to 50° from the axis of the motor. Rotational energy is developed from the velocity and volume of drilling fluid moving past the vane and stator portions of the pump. The converted axial to rotational energy turns a shaft that causes bit rotation. Turbine mud motor diameters are small and rotational speeds are high. The turbine mud motors can be stacked to develop additional rotational torque. Integral bent motor housings can not used with turbine type motors and bent subs placed above the motor sections are required for angle building.

The high rotational speeds of the turbine type motors and low torque are not readily adaptable to roller cone type bits. Roller cone type bits drill by crushing of the rock. This rock crushing requires high weight on bit (WOB) and high rotational torque. High rpm's tend to rapidly wear out the roller cone bit bearings, cause wear on the side faces of the bit (gauge wear) and can be destructive to the teeth of the roller cone bit. In addition, high The low torque output of the turbine motor reduces the

WOB that can be used, thereby reducing the penetration rate of the bit. Drag type bits have been developed that drill by shearing the rock face (Moore, 1986; Burgoyne et al., 1986). These bits have no moving parts and can withstand high rotational speeds, limited only by the amount of heat generated at the impact point between the bit and hole face. Because of the abrasivity of typical rocks, only diamonds were originally resistant enough to use as cutting points in drag bits. However, in the mid 1970's, synthetic diamond materials were developed and used as drill bit cutter materials. These synthetic materials are termed Polycrystalline Diamond Compact (PDC), Thermally Stable Polycrystalline Diamond (TSP) or, more generally, Thermally Stable Diamond (TSD). Drill bits made with these materials offer high rates of penetration and long lives in soft non-abrasive formations, such as certain types of shale. However, penetration rate and bit life is severely reduced in formations with appreciable quartz content. Drag bits, therefore, are well suited to the high speed turbine type drill motors. However, it should be noted that while drag bits are available for only certain types of formations, roller cone drill bits are available to drill every type of formation encountered (Moore, 1986). Therefore, drag bits are normally used in areas where formations to be encountered are well documented.

Turbine motors have been replaced by the positive displacement motor (PDM) in most operations requiring low drill bit speeds, high drill bit torque and high WOB (Von Flatern, 1991). The PDM motor can be used in combination with a bent sub or integral bent subs that are built into the motor housing (termed bent housings). The bent sub consists of a threaded connection located above the PDM with a fixed angle of tilt to the center line axis of the hole. Mechanical and hydraulic bent subs that allow for the angle of the bent sub to be changed in the field (Bardin, 1989) or by downhole hydraulic operation (Jourdan and Mariotti, 1989) are available . Bent sub tilt angles vary between 1/2° and 3°. Motors with integral bent housings that allow for field adjustment of motor tilt angle (Computalog, 1991) are available. In addition, hydraulically adjustable stabilizers that can be adjusted downhole during the drilling operation (Eddison, 1990) are available .

The mud motor and bent sub deflection method consists of orienting the motor, bent sub and drill bit assembly at the point of deflection (kick-off point). The bit is allowed to drill ahead along the curve governed by the combination of bent sub motor angle and integral stabilizers mounted on the motor housing. The amount of build angle that can be achieved is dependent on the diameter of the stabilizers and the distance between the contact points between the wall of the hole and the stabilizers and drill bit. Under-gauge stabilizers are used to increase the build rate of the drilling assembly. The calculation of the rate of build uses three point geometry. Figure 5 shows this information and the method for calculation of the angle build characteristics of the bent sub-motor assembly (Karlsson 1985). Surveys are run periodically to determine azimuth coordinates and amount of deflection. Orientation of the bottom-hole assembly is adjusted to meet required deflection and azimuth as the well is drilled. MWD equipment can be used to determine real time bit face orientation, allowing for correction of hole direction and inclination as the well is drilled.

After desired inclination and azimuth have been obtained, conventional rotary drilling methods can be used to directionally drill the borehole. There are three methods involved in directional drilling after well deviation has been initiated. The three principle methods are termed fulcrum, stabilization and pendulum. The three methods (Eastman Whipstock, 1984) are dependent on whether building, holding or dropping of well inclination is required. The drilling assembly stiffness, weight on bit and rotational speed assist in controlling the rate of angle change. Each of the directional drilling methods uses stabilizers or reamers located at specific points along the drilling assembly. Stabilizers and reamers are the same diameter of the drill bit and have additional cutting surfaces located along the side of the tool. These cutting surfaces are designed to contact the wall of the hole. The location of the stabilizers is dependent on whether build, drop or hold angle activities are required.

The fulcrum principle is used to build additional well angle after deflection is initiated. In the fulcrum method a stabilizer or reamer is placed directly above the drill bit. The rate of angle build is dependent on the stiffness of the pipe above the stabilizer. Weight on the drill bit causes the pipe above the stabilizer to be pushed towards the lower wall of the hole. This causes a pivoting action about the lower stabilizer with the result that the bit is forced upwards, thereby increasing the angle of the hole as it is drilled. Stabilizer placement controls whether angle is increased or decreased as the hole is drilled ahead.

The pendulum principle is used to reduce the well angle, such as would be needed in an S-type well completion or when the well is returned to vertical after drilling around equipment lost in the hole. In this method the stabilizer directly above the drill bit is removed and a stabilizer is placed some distance above the drill bit. The location of this stabilizer is dependent on drilling assembly diameter and bit weight. Gravity forces the collar and drill bit located below the upper stabilizer to the low side of the hole, thereby causing the well angle to drop (therefore the term "pendulum" method). In all cases rotation speed and weight on bit assist in controlling the angle build or drop rates.

After the well has reached its final angle, constant well inclination is maintained with the use of "stiff" drilling assemblies. Stiff drilling assemblies use a combination of large diameter drill collars and stabilizers or reamers. The hold angle drilling assembly uses a stabilizer or reamer located directly above the drill bit with a large diameter drill collar separating it from an additional reamer. If stiffer assemblies are needed additional stabilizers and reamers can be added.

Figure 6 illustrates the various principles. Additional combinations of stabilizers, reamers and collars will yield different build, drop or hold angles (Walker, 1986). The reader is referred to (Burgoyne et al., 1986; Moore, 1986; Mitchell, 1991) for discussions of various bottom-hole assemblies used in directional drilling operations.

In each of the above directional drilling practices, drill bit rotation is generated by rotation of the drillpipe. In these cases angle build or drop can be achieved. However, azimuth control is not possible. In order to drill the well to a specific three-dimensional coordinate a mud motor and bent sub combination is used in combination with standard directional drilling principles. Downhole mud motor drilling adds additional expense (usually equal to the hourly rate of the drilling rig for onshore operations) to the drilling operation. In addition, the mud motor equipment requires added costs in operating personnel, mud cleaning operations and, due to the increase in moving parts, can cause additional drilling operation down times for equipment repair.

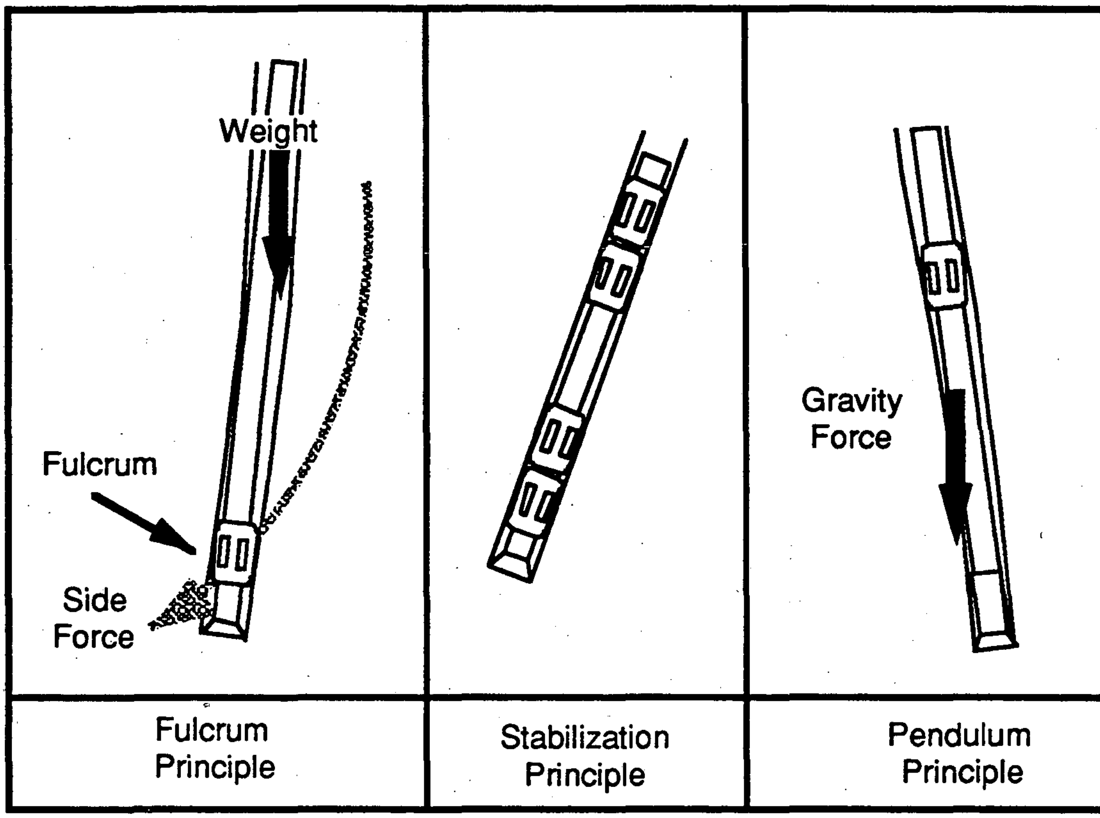


Figure 6) Pendulum, Fulcrum and Stabilization Directional Drilling Principles

In many directional operations performed today the steerable downhole motor system is used (Edlund, 1988; Barrett and Lyon, 1988; Stewart and Williamson, 1988; DeLucia, 1989; Whitten, 1989). The steerable system allows for drilling to take place in either a sliding or rotary drilling mode without having to remove drilling equipment from the hole to change the bottom-hole drilling assembly. These steerable assemblies, therefore, reduce drilling times by reducing the number of times the drilling assembly must be removed from the well. The steerable system uses a downhole mud motor in combination with small angle bent subs and stabilizers. In sliding mode drilling operations the drilling assembly can be oriented to build or drop angle using only rotation of the mud motor. Drillpipe rotation combined with mud motor rotation can be used to drill along a straight path. The sliding drilling mode uses the mud motor only and allows for changes in inclination or direction to be made. After the desired direction and inclination have been obtained, the bottom-hole assembly can be rotated to allow the well to be drilled along a straight path (termed the rotary drilling mode).

Various steerable drilling system configurations are available. One system consists of a mud motor with an integral double bent housing, termed a double tilted u-joint, or DTU (Eastman Christensen, 1991). Another system termed the double adjustable system uses an adjustable bent sub above a drilling motor with an adjustable bent housing. With the double adjustable drilling assembly various build rates can be set in the field. Steerable systems are normally limited in the amount of angle that can be built per 100 feet of hole drilled, usually 2° to 6° per 100 feet (Schuh, 1991). Dog legs up to 9.4° per 100 feet have been obtained in the field (Barrett and Lyon, 1988). However, limitations of 10° per 100 feet are noted due to cyclic stresses (Karlsson, 1989). During inclination or azimuth correction operations, drilling penetration rates can be reduced by as much as 75%. Figures 7a, 7b and 7c show various motor and bent sub assemblies used in directional drilling operations.

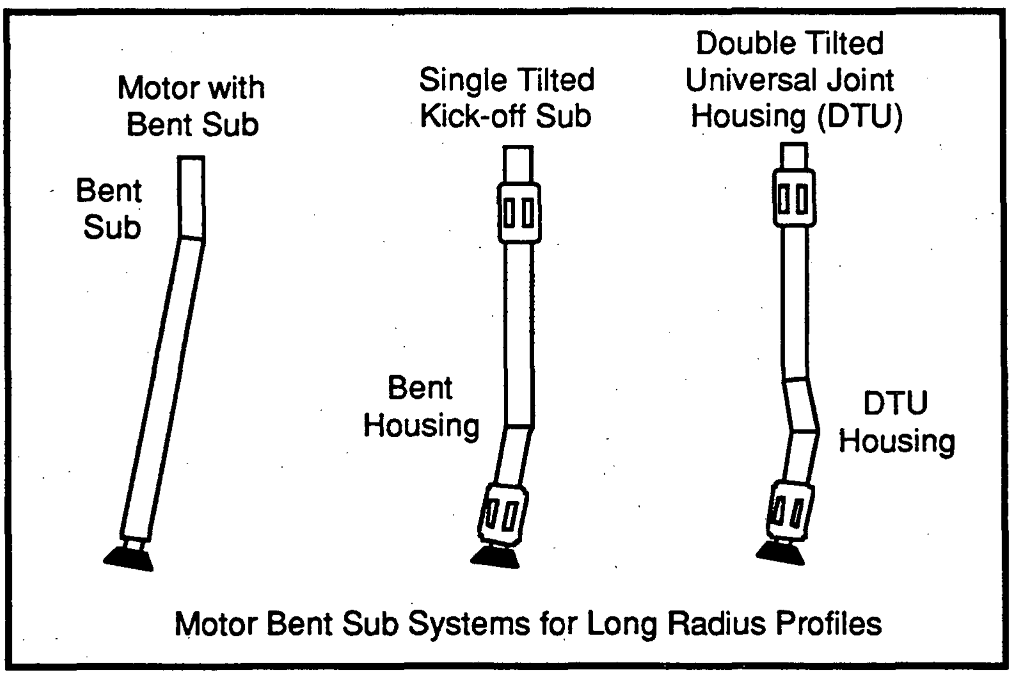


Figure 7a) Motor and Bent Sub Systems for Long Radius Profiles

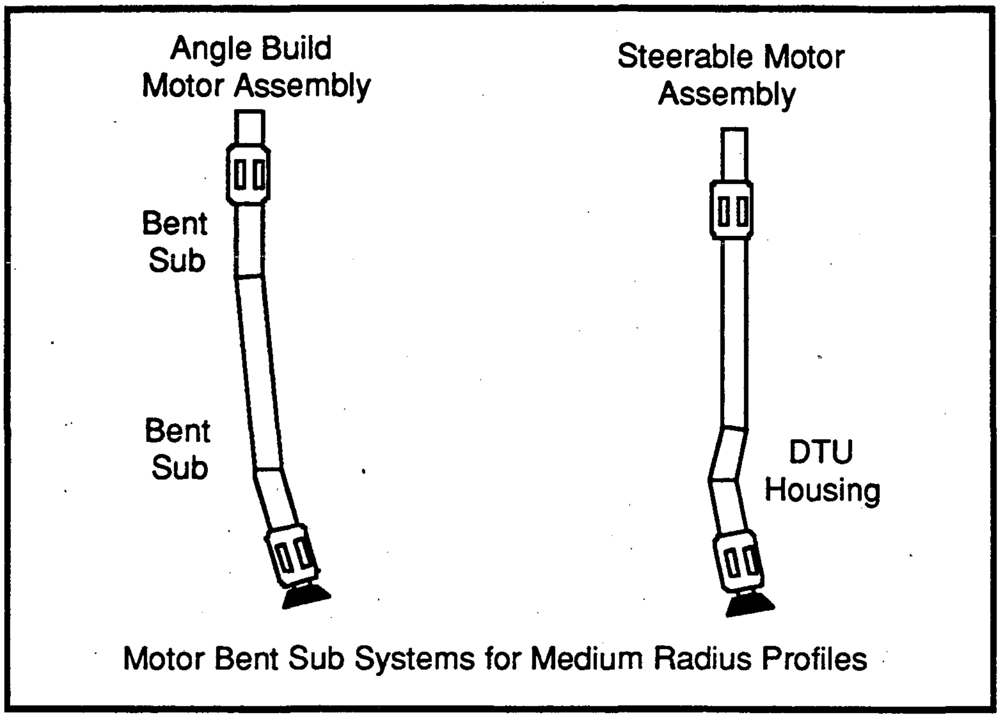


Figure 7b) Motor and Bent Sub Systems for Medium Radius Profiles

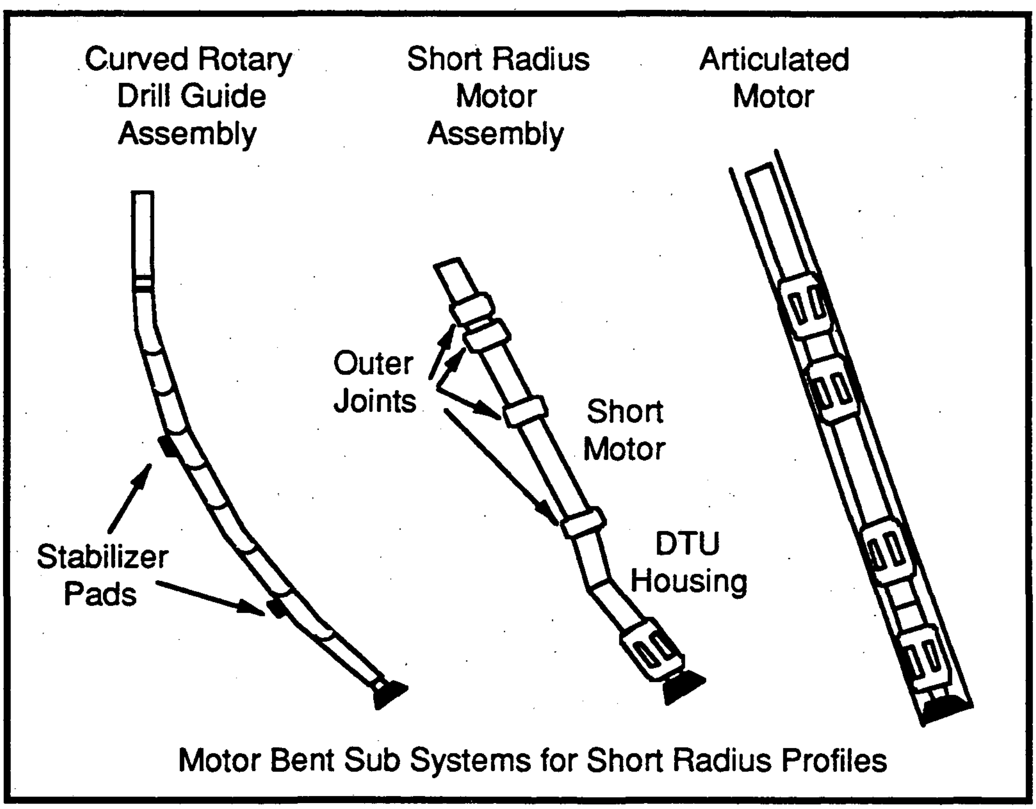


Figure 7c) Motor and Bent Sub Systems for Short Radius Profiles

4.0) Drilling Methods for Horizontal Wells

Horizontal drilling operations are becoming increasingly more popular in the petroleum industry. Horizontal wells are being drilled to address various reservoir development aspects including; reduction in water coning (Hansen, 1991) and gas coning in oil bearing formations, interception of vertical or steeply dipping fractures (Pasini and Overby, 1969; Slayton and Peach, 1990; Sheikholeslami et al., 1991), increased reservoir drainage area in low permeability or thin aquifers (Target, 1992), increased well productivity in suitable reservoirs (Giger, 1984; Babu and Odeh, 1989; Joshi, 1991) and drilling along formation contacts. Disadvantages of horizontal wells include increased drilling and completion costs (Mitchell, 1991). In addition, increased costs for re-completion, workover, electrical logging and reservoir testing are incurred. In many horizontal drilling operations the costs associated with subsequent horizontal wells have been reduced as site specific methods and techniques were developed (eg, Wilkirson 1988, Nazzal 1990). However, the additional cost of drilling and completion of horizontal wells can be offset by the increased well productivity and increases in recoverable reserves (Pocovi 1991).

There are various methods employed to drill horizontal wells. The drilling methods and type of drilling equipment are dependent on the type of horizontal well being drilled, the type of formation encountered and to some extent the depth of completion. The following sections describe various aspects of horizontal drilling.

4.1) Ultra-Short Radius Horizontal Wells

Ultra-short radius wells utilize water jetting techniques to drill multiple lateral drain holes from a single vertical well. Radii of curvature are of the order of 1 to 3 feet. The method is still in the development phase at this time (Dickinson et al., 1989; Karlsson et al., 1989). The method requires that a vertical well will be drilled to depth and underreamed in the lower portion of the hole to ≈24 inches in diameter. A whipstock device is lowered into the well on a 4 1/2 inch drill string. Small diameter (1 1/4 inch outside diameter) continuous ERW (electrical resistance welded) tubing is inserted into the 4 1/2 inch drill string. The continuous length 1 1/4 inch diameter tubing is run into the hole using what is termed as a coiled tubing unit (see below). The 1 1/4 inch tubing is turned from the vertical to a horizontal position by the whipstock device set in the underreamed portion of the hole. A series of rollers and slides within the whipstock device keep the small diameter tubing from buckling. At the forward end of the tubing is a water jet nozzle that is capable of boring (jetting) a hole as the tubing is pushed into the formation. The tubing is pushed into the formation by pressure developed in the 4 1/2 inch workstring. Water pressure used for the drilling operation varies between 5000 and 10,000 psi. The bottom-hole drilling equipment is shown in Figure 8.

Drilled hole diameters vary depending on formation strength, being typically less than 4 inches. Completion methods use either open hole completion, flexible pipe or 1 1/4 inch tubing. The 1 1/4 inch tubing used to drill the hole can be electrochemically cut off at the formation face, in which case, the jet bit drilling nozzle, which is considered expendable, is left in the hole. The pipe can also be perforated by electrochemical methods. Gravel packing of the horizontal section is possible.

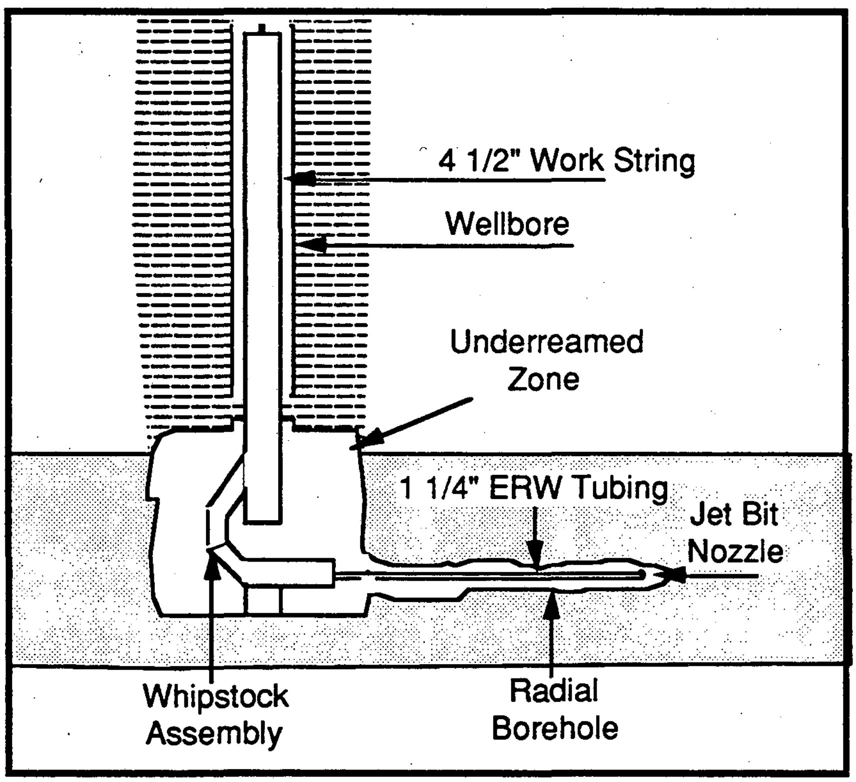


Figure 8) Ultra-Short Radius Downhole Drilling Equipment

A specialized directional survey device has recently been built and tested to pass through the 1 foot radius of curvature. Directional surveys of the borehole are performed after the horizontal sections have been drilled. In the original design the trajectory of the wellbore could not be maintained for distances greater than 30 feet (Dickinson et al., 1989). Recent developments have added a system of solenoid valves and side nozzles located behind the jet bit nozzle. The electrically controlled solenoid valves are attached to vertical and horizontal side water jets to control the course of the radial hole. In addition, a roll and vertical sensor system with surface readout has been added (Dickinson et al., 1992) to control the borehole trajectory. Horizontal lengths up to 105 feet have been drilled using the newly developed steerable water jet system.

4.2) Short Radius Horizontal Wells

Short radius wells can be drilled with build angles of 1.5° to 3° per foot of drilled length with curvature radii of 20 feet to 40 feet. The horizontal section of the well is usually limited to a maximum length of 1500 feet and is dependent on type of formation drilled and the type of drilling method being used. There are currently two types of short radius drilling systems used (Nazzal, 1990). These systems have been termed the rotary system and the articulated motor system.

4.2.1) Short Radius Rotary Drilling Methods

In the rotary drilling system a non-rotating curved drill guide is used to initiate deflection of the wellbore. The curved drill guide has a flexible shell with a preset radius of curvature. The flexible shell allows the curved drill guide to be straightened and pushed down the vertical portion of the wellbore. As the curved drill guide enters the open (un-cased) portion of the hole the drill guide imparts a side force as it begins to return to its initial preset radius of curvature. An orienting guide (whipstock) is set within the vertical section of the well on an inflatable packer to initiate deflection. Drill bit rotation is through a drive shaft located within the curved drill guide. The drill guide orientation can be changed by pulling up on the curved drill guide assembly. This engages the clutch attached to the drill guide. The drill guide can then be rotated to the particular orientation needed, based on the planned trajectory of the borehole. The drive shaft located within the non-rotating drill guide is rotated by the drillpipe through the clutch assembly located at the top of the curved drill guide. Figure 9 shows the curved drill guide assembly. The curved drill guide defines the final radius of curvature of the hole. Once the deflection operation is completed the curved drill guide is removed from the hole and drilling is continued using an angle hold assembly with articulated drillpipe (described in section 4.2.2). The angle hold assembly uses two under gauge stabilizers near the drill bit. The stabilizer diameters are varied to control inclination of the well. Inclination can be controlled to ±2° and azimuth to ±20° during drilling (Eastman Christensen 1990). Drillpipe must be removed from the hole to change the bottom-hole assembly for adjustment of well inclination. Horizontal lengths are typically between 200 and 400 feet.

Directional surveys use a gyro type device in the deflection portion of the well. In addition, periodic surveys of the well can be made with magnetic multi shot equipment that is run into the well on a special bottom-hole measurement assembly. The magnetic surveys are typically run at the end of curvature development and at total depth of the well.

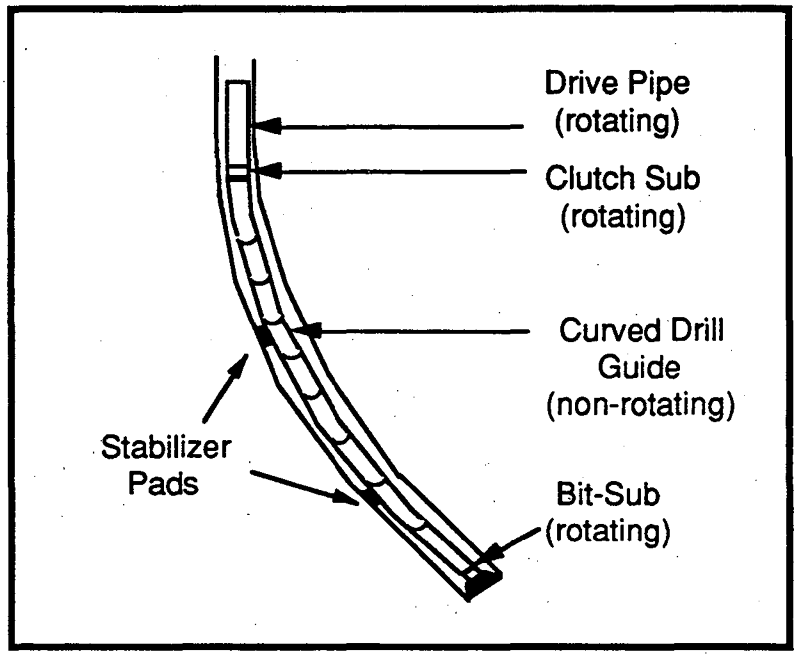


Figure 9) Curved Drill Guide Assembly for Short Radius Horizontal Holes

Due to the small radius of curvature, and therefore, high bending stresses along the curved portion of the well, the short radius well drilling equipment and well completion sizes are small. Typically drill bit diameters for the deviated and horizontal sections are limited to 4 1/2 inch to 6 inch. Liner completion diameters are dependent on drilled hole size and vary between 2 7/8 inch to 4 1/2 inch.

4.2.2) <u>Short Radius Articulated Motor Drilling Methods</u>

The short radius motor drilling assembly consists of a short (≈12 feet long) articulated steerable mud motor (see Figure 7c). Depending on hole size, additional mud motor sections can be added. Minimum curvatures of 40 feet radii can be drilled. Horizontal sections up to 1500 feet can be drilled (Eastman Christensen 1990), depending on the depth of the well and the formation being drilled. The mud motor system is used in both the deflection portion of the well and in the horizontal section.

The motor system is also steerable. The drill string is not rotated and all drilling takes place in the sliding mode.

Orientation measurements are made with gyro type devices and single and multi-shot magnetic devices. Real time tool face inclination and direction can be obtained. Magnetic orientation measurements are normally made with a special bottom-hole assembly at specific locations to check the well path. These measurements are normally made at the end of the curve and at total depth. Recent developments (Halliburton, 1992) allow short radius wells with drilled diameters of a minimum of 6 inch in diameter to use measurement while drilling (MWD) equipment. The MWD equipment can supply data on bit inclination and direction while drilling of the hole is taking place. Gamma logging and formation resistivity data can also be obtained in real time mode during the drilling operation. Currently, standard electrical well logging tool diameters and tool lengths prohibit use in short radius wells.

Well completions are similar to those used in the short radius rotary method.

4.3) <u>Medium Radius Horizontal Wells</u>

Medium radius wells are drilled with build angles of 8° to 20° per 100 feet of drilled length with corresponding radii of curvature of 700 to 285 feet. Depending on formation type, horizontal lengths up to 3000 feet can be drilled. Deflection is initiated with a motor and bent sub or with a bottom-hole whipstock, or both are used in some cases. The medium radius drilling assembly uses fixed position or steerable mud motor systems. Compressible service drillpipe or heavy weight drillpipe is used to drill the curved and horizontal portions of the well.

Hole diameter and casing sizes for medium radius holes vary, depending on the radius of curvature of the hole. Bit sizes of 4 3/4 inch to 9 7/8 inch can be used with maximum cased hole sizes of 2 7/8 inch to 7 5/8 inch, respectively. Larger hole diameters and well completions are possible. In addition, casing threads are being manufactured to withstand larger bending stresses and allow for larger diameter well completions (Hydril Company,. 1991).

Standard MWD equipment is available to provide directional information on the well as it is drilled. In addition, the larger radius of curvature allows that standard electrical logging tools can be used. However, placement of the standard electrical logging equipment at the hole bottom in wells with long horizontal sections is difficult due to frictional drag forces. Recent advancements in this area allow the use of small diameter (1 1/4 inch or 1 1/2 inch diameter) continuous coiled ERW tubing with a wireline located within the tubing. The coiled tubing is used to place the logging equipment in the horizontal section of the well. Similar systems are available that use wireline run inside of drillpipe for logging equipment placement.

4.4) Long Radius Horizontal Wells

Long radius wells are drilled with build angles of 2° to 6° per 100 feet and have curvature radii between 3000 feet to 1000 feet. Conventional drilling assemblies, similar to those used in directionally drilled wells, can be used to drill the hole. Standard bit and casing sizes can be used. Wells can be readily logged with standard electrical logging equipment. However, long horizontal sections require conveying equipment similar to that used in medium radius wells for placement of logging tools at the bottom of the well. Steerable mud motor drilling systems, in many cases, are used to control direction and angle of the well. MWD equipment can be used to obtain reservoir and well orientation information during drilling. MWD equipment is normally used in the horizontal section of the well.

5.0) Problems Associated With Drilling Horizontal Wells

There are several problem areas associated with horizontal drilling activities that are not realized in directionally drilled wells. Drilling difficulties are related to the radius of curvature of the well and the length of the horizontal section. Problem areas include maintaining weight on bit, drillpipe buckling, drag and torque loads, drillpipe fatigue during rotation in the curved portion of the hole, cuttings removal and hole stability.

The amount of weight that can be realized at the bit face is dependent on the weight of the drillpipe and collars located above the bit. The weight on bit is obtained from the drillpipe and drill collars located in the vertical and near vertical portion of the well. In horizontal drilling a portion of the weight of the drill string is lost in the curved and horizontal sections, due to gravity and frictional forces, to the wall of the hole. The frictional (drag) and torsional loads depend on well angle (Johancsik et al., 1984; Mueller et al., 1991). In addition, frictional forces vary, being dependent on whether the drillpipe is being rotated (dynamic friction) or the well is being drilled without drillpipe rotation (sliding friction). The amount of load transferred to the wall of the hole is proportional to the weight of drillpipe in the drilling fluid and to the curvature of the hole. The density of aluminum pipe is much less than that of steel and for this reason aluminum drillpipe has been used in the horizontal sections of the hole to reduce torque and drag. In addition to reduction of torque and drag, aluminum pipe has the ability to withstand rotating through curved hole portions with less fatigue than steel (Hansford and Lubinski, 1965). However, pipe flexibility due to the low modulus of elasticity of aluminum ($\approx$1/3 that of steel), leads to difficulties in controlling the trajectory of the well. In addition, handling problems during drilling seem to have limited its use (Tarr and Graham, 1990; Nazzal, 1990).

Frictional and gravity loads exerted on the wall of the hole reduce the amount of weight that can be applied to the bit. A typical drill string and bottom-hole assembly used for drilling medium radius horizontal wells is shown in Figure 10. Weight can be added to the drill stem above the curved and horizontal portion of the well (i.e., in the vertical portion of the well) to increase weight on bit. However, the pipe located in the curved and horizontal sections of the well may be subject to compressional loads. These compressional loads can lead to high drillpipe bending loads and buckling of the drillpipe. Buckling of the drillpipe may or may not lead to catastrophic pipe failure and the critical buckling load can be calculated (Schuh, 1991a). However, these bending loads can lead to drillpipe fatigue failure during rotation. The amount of compressional load that the drillpipe can withstand before failure has been determined (Lubinski, 1961; Hansford and Lubinski, 1965; Dawson and Paslay, 1984; Chen et al., 1990, Wu and Juvkam-Wold, 1990; Schuh 1991b). Compressible service drillpipe has been developed to reduce the buckling tendency of the drillpipe in wells with build angles greater than 15° per 100 feet (Dech, 1986; Karlsson and Bitto, 1990). The compressible service pipe can be rotated through curvatures up to 20° per 100 feet (Eastman Christensen, 1990). Compressible service drillpipe uses high strength material with wear knots attached at 10 foot or 7.5 foot intervals along its length. Wear knots have diameters similar to those of the drillpipe tool joint. This pipe reduces bending stresses caused by rotation through the curved section of the hole (Schuh, 1991a and 1991b) and has been shown to reduce rotary and axial torque, reduce the tendency for differential sticking and allow increased weight transfer to the bit.

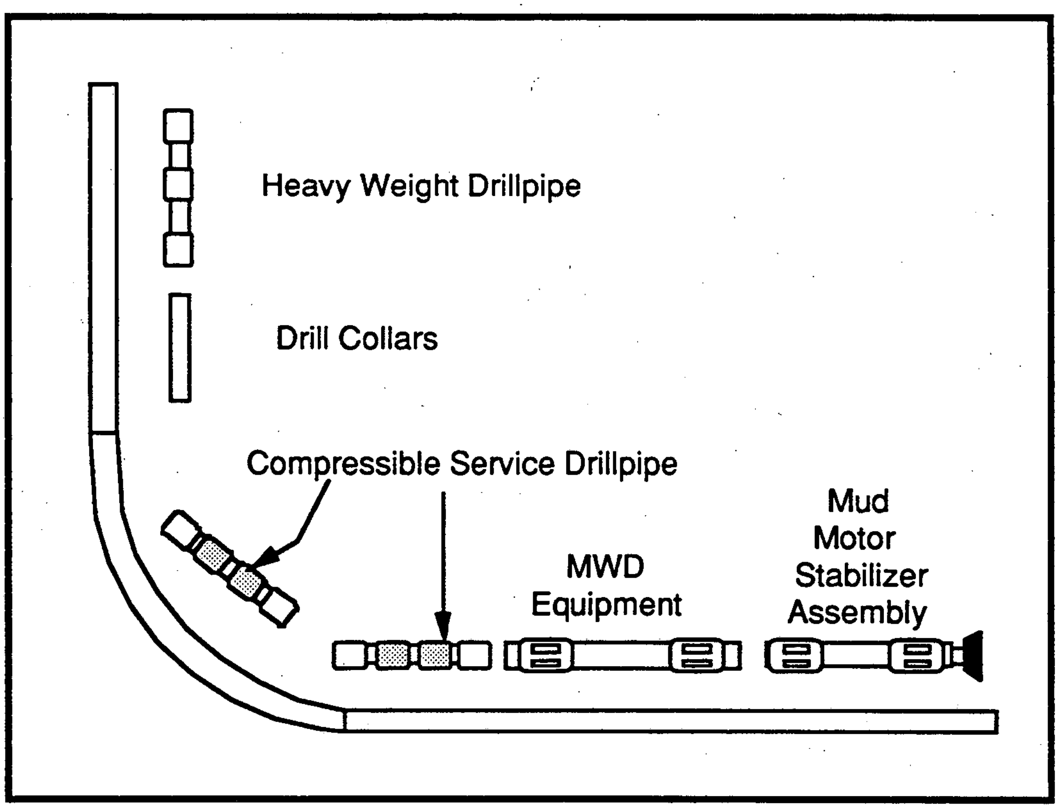


Figure 10) Typical Drill String and Bottom-hole Drilling Assembly Used in Medium Radius Horizontal Drilling Operations (after Dech, 1986)

Removal of cuttings from the curved and horizontal portions of the well is another area of concern in horizontal drilling operations. Drilled solids can build up on the low side of the hole, creating what is termed as cutting beds, in the horizontal section. In addition, these unstable cutting beds can form in the curved portion of the well. These unstable beds can flow into lower portions of the well when mud flow (circulation) is stopped. A build-up of cuttings in the hole can lead to higher sliding friction factors, thereby lowering the weight on bit available, higher rotating torque, increased drillpipe tension while pulling out of hole and can lead to stuck pipe. Flow velocities and mud properties that lead to laminar annular flow conditions have been shown to yield the best cleaning results in well angles up to 45°. Turbulent flow conditions offer the best cleaning results in wells with angles greater than 45° (Okrajni and Azar, 1986). Recent reports indicate that mud rheological properties are not important in turbulent flow and do not affect cuttings transport. However, plastic viscosity and yield point should be maintained to insure cuttings removal (Okrajni and Azar, 1986; Becker et al., 1991). Cutting transport models have been developed to describe the process (Gavignet and Sobey, 1989). Steerable drilling systems using drillpipe rotation have been shown to assist in removing cuttings from the well by agitating the cutting beds that develop (Karlsson et al., 1989; Slayton and Peach, 1990). In addition, the use of top-drive drilling equipment can assist in the drilling operation by allowing drillpipe rotation and mud circulation to be maintained during removal or entry of pipe into the well.

Borehole stability during directional and horizontal drilling operations is another area of difficulty. Stability problems can develop from mechanical stresses caused during the drilling operation, from adsorption of water and subsequent swelling by formations encountered (Yew et al., 1990), from in situ tectonic stress fields (Woodland, 1990) and from stress fields due to completion and production operations (Harvey, 1990; Fuh et al., 1991). Mechanical loads on the wall of the hole are developed during the drilling activity. Hole curvature is developed by force of the drilling assembly against the wall of the hole. In addition, rotation of the drilling assembly causes the bottom-hole assembly to be in contact with the wall of the hole in the curved and horizontal sections of the borehole. Additional mechanical stress is imparted to the formation in the horizontal section of the hole from stabilizers and drillpipe laying on the low side of the hole during the drilling operation. Turbulent flow of drilling fluids can also cause hole erosion in unconsolidated formations. The amount of damage imparted to the wall of the hole from these activities depends on time in the hole and the compressive strength of the rock.

In normal tectonically stressed areas the earth stresses are a maximum in the vertical (overburden) direction. Stresses in the two horizontal directions are equal and are normally considered to be proportional to the vertical stress. The pressure within the wellbore necessary to maintain borehole integrity in vertical wells will be less than that needed in horizontal wells. This is due to the fact that horizontal wells are subject to the overburden stress noted in the area. Borehole collapse (compressive failure of the wellbore wall) can develop if insufficient hydrostatic wellbore pressure exists during the drilling process or during production activities (Fuh et al., 1991). In addition, tensile failure (fracturing) of the rock or loss of circulation can develop if wellbore pressures are allowed to exceed certain limits, dependent on the formation material encountered (Fuh et al., 1991). Equations have been developed from empirical data to estimate the pressures required to maintain hole stability in the horizontal sections of the borehole based on the overburden stress and an additional value obtained from a leak-off test performed on a vertical section of the wellbore (Mitchell, 1991). The applicability of this equation to various formation types, including unconsolidated materials, is not known. However, rock mechanic calculations using measured rock parameters have been applied successfully to borehole stability problems related to drilling and production activities in consolidated formations (Fuh et al., 1988; Fuh and Loose, 1989; Woodland, 1990; Fuh et al., 1991; Kwakwa and Batchelor, 1991).

6.0) Drilling Rigs Used for Directional and Horizontal Wells

Various types of drilling rigs are used for drilling and completion of directional and horizontal wells. The drilling rigs, in all but the continuous coiled tubing drilling method for ultra-short radius wells, use some type of surface rotary action. In some cases, drillpipe rotation is combined with rotation developed by the mud motor. Different methods are available to generate the surface rotation of the drillpipe.

6.1) Rotary Drilling Rigs

The most prevalent rotary drilling method uses a kelly, kelly bushing and rotating table (for detailed discussion of rotary drilling rigs see, for example, Burgoyne et al., (1986) or Moore,(1986). Rotation is supplied to the drillpipe by rotating a table located on the rig floor which in turn rotates the kelly bushing which is attached with pins to the rotary table. The kelly bushing has a square or hexagonal internal face to accept the kelly. A square or hexagonal piece of pipe (the kelly) is inserted into the kelly bushing which in turn causes rotation to the drill string when the rotating table is turned. Weight is supplied to the drill bit by drill collars located at the bottom of the string above the drill bit. In some cases additional weight is supplied by hydraulic jacks that produce downward force to the drillpipe by pushing against the weight of the drilling rig. The kelly portion of the drilling equipment is removed before drillpipe is removed from the well, therefore drillpipe rotation and fluid circulation are not possible when removing or inserting drillpipe into the well.

Another method that develops rotation of the drillpipe at the surface is termed a top head drive. The drillpipe is rotated by either an electric or hydraulic motor attached to a drive head. The drive head is attached to slides (or gears in some cases) that are in turn attached to the derrick or mast (a derrick is a built in place structure whereas a mast can be lowered to the ground by rotation around pins located on the rig floor or substructure). The drive head system connects to the top most piece of drillpipe. The top head drive system has been used on small (<5000 foot drilling depth) drilling rigs for many years. In the recent past top head drives have been adapted to use on large drilling rigs (Hock, 1989). One advantage of the top head drive system is that fluid circulation and rotation can be maintained during periods when drillpipe is being removed or run into the hole. In addition, drillpipe lengths up to 90 feet can be removed or inserted into the hole in one section. This ability to circulate and rotate has shown advantages in drilling of horizontal and highly deviated wells (Hardman, 1989). Rotation reduces drag forces and agitates cuttings in the deviated and horizontal sections of the hole. Continuous circulation during removal and insertion of drillpipe into the hole assists in cutting removal. The top drive system is becoming common in offshore operations where holes are normally deviated from vertical and rig down time is expensive due to the high daily rig costs.

6.2) Continuous Core Drilling Equipment and Methods

Continuous core rigs are available that can drill horizontal and angled holes. These rigs are predominantly used in the mining industry. However, this drilling method is finding application in petroleum drilling operations (Walker and Millheim, 1990) and further research on the application to petroleum operations is ongoing (Bode et al., 1991). The continuous core rig mast can set at any angle from vertical, allowing for directional or horizontal wells to be drilled. Rotation is obtained from a chuck assembly that imparts rotational force to the drillpipe. Vertical movement of the chuck depends on rig size and varies from 2 feet to 10 feet. After reaching the maximum vertical chuck movement the chuck assembly must be moved up the section of drillpipe and reset to continue rotation. The system is similar to a top head drive system in that circulation and rotation can be maintained while pulling out of the hole or running into the hole. Weight on bit is achieved by hydraulic cylinders that push against the weight of the drill rig. The drilling operation uses small diameter (<3.5 inch) flush joint pipe and diamond drill bits. Drag bits have recently been developed for continuous core use (Walker and Millheim, 1990). Annular space between hole and drillpipe is about 1/2 inch. Drillpipe rotation speeds are on the order 800 to 1500 revolutions per minute (rpm). These high speeds cannot be used on standard rotary rigs due to vibration stresses that develop. In addition, the high rotating speeds necessitate the use of drag type or diamond type bits that have no moving parts. Cores are removed using a wireline retrievable coring system and the drillpipe does not need to be removed from the hole to obtain core samples. The high rotational speed in combination with a diamond bit means that low drill bit weights can be used while maintaining reasonable drilling rates. The small diameter holes require low mud flow rates during drilling, approximately 35 gpm for a 3 1/2 inch diameter hole. The low circulation rates, in combination with the coring operation, have advantages in areas with severe loss of circulation problems in that drilling can continue without cuttings being returned to surface. Several sizes of drill bits and drillpipe are available. The drillpipe and drill bits are designed such that the next size smaller drill string can be inserted inside the next larger size drill string. This has an advantage in that if a larger diameter string is stuck in the hole due to wellbore collapse the string can be cemented in place and the next smaller drilling string can be drilled through the larger string.

One disadvantage to this system is that directional and inclination control is not possible during drilling and coring operations. In addition, the small diameter completions limit continuous core wells from a production standpoint. However, the core equipment can be removed and a small diameter mud motor can be used to orient the hole. After hole orientation is completed, core drilling can be resumed. An additional problem is caused by the small annular space which requires rather high dynamic fluid pressures for cutting removal. Bottom-hole pressures vary widely with pumping rate and downhole pressure control is difficult.

6.3) Continuous Coiled Tubing Drilling Equipment and Methods

An innovative system has recently been developed for small diameter horizontal petroleum drilling operations (Pittard and Fultz, 1990; CUDD 1991, Littleton, 1992). This system utilizes small diameter (2 inch) continuous coiled tubing with a fluid driven steerable mud motor. A rotary drill rig is not needed for the drilling operation. The surface equipment consists of a coiled tubing unit, tubing injector head and mud pump system. The coiled tubing surface equipment is shown in Figure 11. A real time downhole steering package is incorporated to determine well orientation. The bottom-hole assembly uses bent subs, stabilizers and mud motors, similar to those used in standard horizontal drilling operations, but of smaller dimensions. The small diameter (2 7/8" outside diameter) mud motor rotates at high speeds (400 to 800 rpm) and drag type drill bits are used. The high motor rotation speeds and drag type bits allow for low bit weights while maintaining reasonable rates of penetration. Rates of penetration are about one-fourth those of conventional drilling methods (Littleton, 1992).

Hole diameters drilled to date are ≈4 inches. A recently completed well in the Austin Chalk reached a total horizontal length of 1458 feet (Littleton, 1992). The small diameter tubing cannot be rotated to correct the direction of the hole (Fultz and Pittard, 1990). However, a proprietary device is available to orient the drill bit and allow for azimuth and inclination control of the wellbore as it is drilled (SlimDril, 1992; CUDD, 1991). Recent experience in horizontal drilling indicates that the bottom-hole drilling assembly has a tendency to drift upwards (Littleton, 1992).

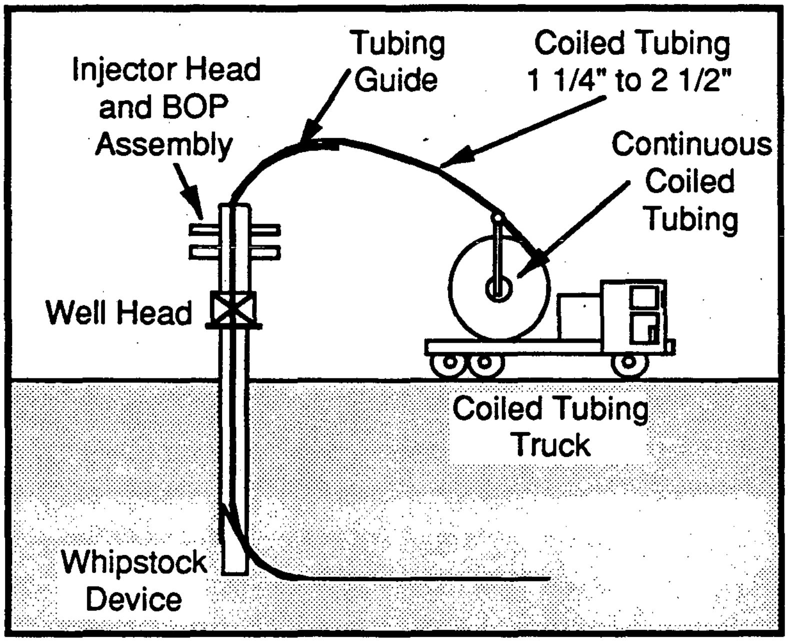


Figure 11) Coiled Tubing Surface Drilling Equipment

An advantage of the coiled tubing system is that fluid circulation can be maintained at all times. In addition, the standard surface blowout prevention equipment (BOP) and tubing injector head assembly allows for the well to flow during the drilling operation. Additional coiled tubing drilling systems are in the process of being built (CUDD 1991). One advantage of coiled tubing is the small radius of curvature that the tubing can bend through without pipe yield. The table given below shows the radius that the tubing can be bent around with the tubing at yield (assumes 75,000 psi tubing yield strength).

Radius of Curvature at Yield Strength for Coiled Tubing
(from Newman 1991)

Coiled Tubing Outside Diameter (inches)	Radius of Curvature at Tubing Yield (feet)
1	16.6
1 1/4	20.8
1 1/2	25.0
1 3/4	29.2
2	33.3
2 3/8	39.6

An additional method that uses coiled tubing and water jet drilling techniques is available. The system is used to drill ultra-short radius wells (Dickinson et al., 1989; Dickinson et al., 1992). In this system no rotation of the drilling equipment takes place. This method has been discussed above in the section on ultra-short radius horizontal wells. Inclination and directional control during the drilling operation is available.

6.4) River Crossing Drilling Equipment and Methods

Additional methods for drilling shallow horizontal holes are available that are not directly related to the development of oil and gas fields. The pipeline and utility industries have developed various methods for installation of pipelines, gas mains, power lines, sewer lines and telecommunication equipment beneath surface obstacles. These installation methods have been termed "Trenchless Technology" (Pipeline and Gas Journal Editorial, 1990). The methods include auger boring, impact moling, pipe jacking, jet cutting, microtunneling (sometimes termed mini-directional boring) and river crossing technology. Of interest to this study are "river crossing technologies".

River crossing technology is a recent development for drilling shallow directional horizontal holes for various types of pipelines. The drilling method uses various aspects of petroleum drilling technology to place pipelines beneath rivers, harbors and other surface obstacles. The method consists of directionally drilling the well from one side of an obstacle or bank of a river at an inclined angle, turning the well to horizontal for a given distance and then turning the well upward from horizontal to exit at the surface on the other side of a river or obstacle. The first subsurface river crossing operation was performed by Titan Contractors in 1972 beneath the Pajaro River in Watsonville, California (Cherrington, 1991). The longest crossing made to date is approximately 6000 feet (Hair, 1989). River crossing drilling methodologies and equipment vary depending on the type of geologic formations and length of hole to be drilled.

The surface drilling equipment consists of a slant mast drilling rig capable of operating at mast angles of 5° to 30° from horizontal (Szczupak, 1989). The system uses a top head drive device mounted on a skid or trailer. The trailer is attached with guy wires to the ground surface (or skid plates, pushed into the ground are used) to allow for pushing or pulling of the drillpipe and bit into and out of the hole as the hole is being drilled. In addition, the drill rig is capable of pulling a pipeline or other equipment from the exit point into the hole and back to the drilling rig after the hole has been drilled. Gear devices are affixed along the edge of the skid and on the drive head that allow the drive head to be pushed or pulled towards the hole opening. Push and pull loads of up to 800,000 lbs with 90,000 ft-lbs of rotational torque are available. Smaller models use hydraulic jacking and cable and pulley systems, similar to those used on small drilling rigs, for developing push and pull loads (BERCO, 1991). Build angles up to 15° per 100 feet are typical. Build angles up to 33° per 100 feet are possible (McKenney and Knoll, 1989). Trailer mounted units that develop smaller loads with footprints of 10 feet by 20 feet for short length shallow horizontal wells are also available (Michels, 1991). There are several types of river crossing drilling methodologies used at this time. Different types of bottom-hole assemblies are used, dependent on the type of formation to be drilled.

Early river crossing technology, which still has application today in unconsolidated formations, is a two stage process in which a pilot hole and washover drill string are concurrently drilled along a predetermined path. The drilling operation utilizes a small diameter (typically 2 7/8 inch drillpipe) pilot drill string, bent sub, mud motor and drill bit. In some cases the drill bit consists of a jet bit designed specifically for drilling (actually the term hydraulic washing or water jetting is appropriate) of clay or other unconsolidated materials. Periodic directional surveys are used to determine hole orientation. In either case the pilot string is normally rotated. The pilot string drill bit is advanced to a point where the drilling rate decreased, the pilot string can no longer be pushed ahead or directional control of the hole is not possible. At this time, a larger diameter pipe, typically approximately 5 inches in diameter, (termed a washover pipe in the petroleum industry) is rotated concentrically around the pilot string and advanced to within several feet of the bottom-hole assembly of the pilot string. A washover cutter bit is affixed to the outside diameter of the washover pipe to drill a hole somewhat larger than the washover pipe. The washover pipe is advanced over the pilot string to reduce friction losses between the pilot string and the open hole, to assist in cuttings removal and to provide vertical and lateral support to the pilot string for directional control of the hole. The drilling process continues with sequential drilling of the pilot string and washover pipe until the pilot bit assembly and the washover string daylight at the exit point of the hole. At this time the pilot string is removed through the washover pipe. If the hole diameter is to be increased in unconsolidated formations, a reamer device (sometimes termed a barrel reamer or fly cutter) is attached to the washover pipe at the far end of the hole. The reamer is attached to the washover pipe with a swivel connected to the pipe to be pulled back to the drilling rig through the hole created by the washover pipe and hole opening device. The size of the reamer device depends on the final pipe diameter that is to be pulled back into the hole. Pipe diameters up to 60 inches have been placed below river beds (Murphy Brothers, 1991). In some cases several drilling and reaming passes are made with different size drilling and reamer assemblies.

Another method of river crossing was developed for drilling consolidated materials and high compressive strength materials (McKenney and Knoll, 1989). Similar equipment is available for drilling of soft formations. This method uses conventional river crossing drilling rigs combined with recent advances in petroleum drilling technology. The drilling assembly consists of a tungsten carbide insert bit (TCI), a steerable air or mud powered motor, a measurement while drilling (MWD) device that allows for real-time surface readout of azimuth and inclination of the bit, drillpipe stabilizers and 5 inch diameter drillpipe. This drilling assembly is identical to that which would be used in a petroleum horizontal or directional drilling operation. TCI bits allow for drilling of formations with compressive strengths up to 40,000 psi (McKenney and Knoll, 1989). The steerable mud motor assembly, as mentioned above, allows for drilling in the sliding mode to make changes in hole direction. Straight, or angle hold, sections of the hole are drilled with rotation of the drillpipe in combination with rotation of the bit by the mud motor. The rotation of the drillpipe also assists in hole cleaning by agitation of the cuttings. The steerable system uses an integral bent housing mud motor in combination with string stabilizers to control well direction during drilling. Build angles up to 30° per 100 feet can be realized by varying the drillpipe size, mud motor size, bent sub angle (or motor housing bend angle) and stabilizer placement (McKenney and Knoll, 1989; Smith International, 1991). In most operations, the 5 inch drillpipe allows for a more rugged (stiffer) drill string and eliminates the need for the washover pipe to supply support to the pilot hole drill string. Hole openings can be drilled up to 42 inch in diameter by utilizing standard petroleum type hole openers. The hole opening procedure is performed in stages by successive increases in the diameter of the hole opener . After the drilling assembly has reached the exit point, the pipe to be placed in the hole is connected to the drillpipe and pulled back to the drill rig. Pipelines are not normally cemented in place in river crossing operations and the hole is allowed to collapse around the pipe.

A recently developed river crossing drilling method for soft formations uses externally flush (no tool joint) drillpipe (or casing) with high tensile and torsional load capabilities in combination with a "spud bit" (Cherrington, 1991). The system was developed due to problems, in soft formations, with the formation supporting the large diameter mud motors. One problem that had been noted in the past when drilling soft formations was that the mud motor drilling assembly vibrations had a tendency to cause the mud motor to settle into the soft formation. This made directional control difficult. The newly developed spud bit system has several mud circulating nozzles attached to a circular device. The nozzle bit erodes the formation as it is drilled. Design of the bits has focused on nozzle placement to reduce mud flow rates. The first 90 feet of the drill string is made of flexible high strength non-magnetic material. The use of the flush joint casing has allowed for drilled distances of 4000 feet to be obtained without use of the washover pipe system. Mud motor systems with milled tooth or TCI bits are used in high compressive strength formations. Pipe is placed in the hole as it is in the other river crossing methods mentioned above.

An additional horizontal drilling method used in the utility industries to drill below surface obstacles is termed the small diameter guided boring system (Hair, 1989b). These systems drill hole diameters up to 12 inches in diameter at depths up to 20 feet with curvature radii of 100 feet and horizontal lengths up to 400 feet (Charles Machine Works, 1991). Surface access along the length of the horizontal section is usually required because each of the systems uses remote surface sensing in order to determine the bit location. However, an electromagnetic MWD system is now available for larger hole diameters (Guided Boring Systems, 1991). There are two types of systems in use depending on formation characteristics. In soft formations (compactible soils) a percussion type device is used. The percussion type tool uses an air operated downhole hammer with a slanted anvil faced bit with spiraled tail fins located behind the anvil face. Direction is controlled by unlocking the tail fins and allowing the bit to drill ahead, without rotation, along a path determined by the direction of the anvil face. During straight drilling the spiral tail fins are locked. As the bit is advanced, by hammer percussion and pushing on the end of the drillpipe, the tail fins cause the anvil face to rotate at a constant rate, thereby eliminating the deflection caused by the anvil face. Weight to the bit is developed from jacking against a frame structure located at the surface or in a shallow open pit. Variations of the bottom-hole assembly and surface equipment are available depending on hole diameter, horizontal length to be drilled and type of formation drilled. A second microtunneling system uses a downhole air operated motor in combination with a bent sub. Various types of rock drill bits are available. Directional control is similar to that used in the steerable mud motor systems mentioned above, i.e. by either mud motor rotation of the bit or combination mud motor and drill rod rotation. Development of various downhole tools and other equipment have been funded by various utility operators (Gas Research Institute, 1987) and additional development on these systems is being performed (Dunn, 1992).

In addition to the small diameter percussion, motor and rotary systems mentioned above, water jet drilling technology is also being developed to drill small diameter holes for utility installations. Several companies are in the process of developing this technology.

6.5) Environmental Drilling Equipment and Methods

Several petroleum drilling service companies have designed slant mast drilling rigs expressly for environmental horizontal drilling operations. In addition, several of the river crossing companies have begun supplying services and equipment for environmental characterization and remediation activities utilizing horizontal wells. The slant mast mud rotary drilling rigs have the capability of being oriented in 15° increments from vertical to 60° from vertical (30° from horizontal), thereby allowing for larger radius curves to be drilled to reach a horizontal orientation at shallow depths. Horizontal well sections can be set at depths of 18 feet to >300 feet, horizontal lengths up to 500 feet, azimuth control of ±2° with vertical depth control of ±5 feet (Karlsson and Bitto, 1990). The environmental drilling rigs can also incorporate closed loop mud systems that use steel surface mud pits. One system uses a dual string drilling system in combination with an underreamer type drill bit and mud motor. This equipment was designed to address the problems associated with drilling in unconsolidated formations normally found in shallow depositional environments. The underreamer, or expanding drill bit as it is termed, drilling system allows for casing to be inserted while the well is being drilled. High density polyethylene (HDPE) casing is inserted, as the well is drilled, into the hole through the curved section and cemented in place. The HDPE casing was chosen based on its flexibility and strength. The mud motor is specially designed to meet the conditions encountered in shallow wells and is one-fifth the length of similar positive displacement motors used in petroleum drilling operations. Rather than a bent sub or bent motor housing for angle building, eccentric stabilizers located on the mud motor are used for inclination control in the angle build section. The bottom-hole drilling assembly is shown in Figure 12.

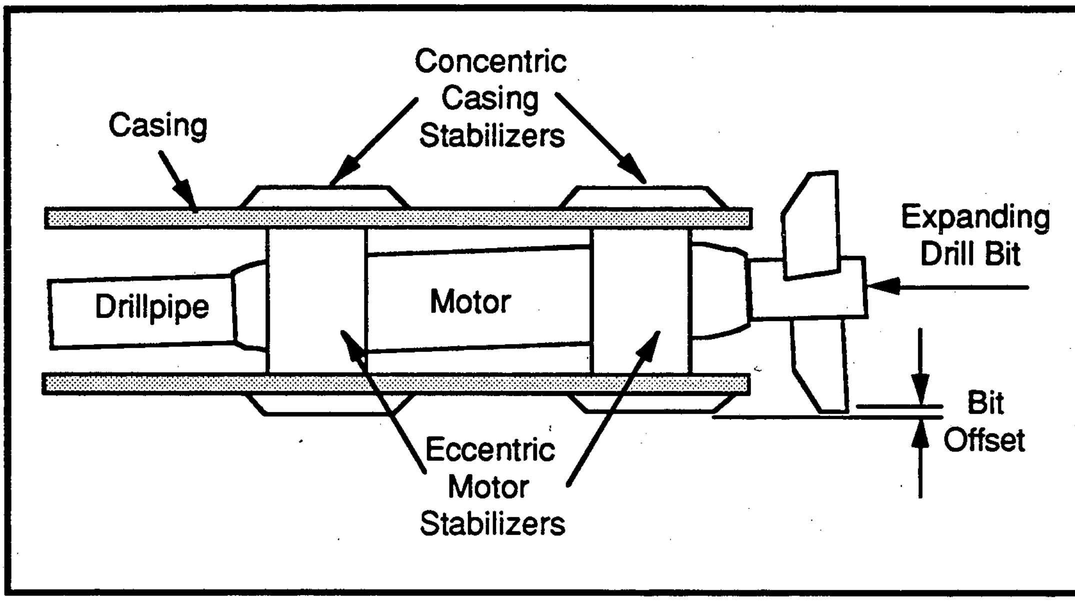


Figure 12) Bottom-hole Drilling Assembly Used in Environmental Horizontal Drilling Operations (after Karlsson and Bitto, 1990)

The curved portion of the hole is drilled with the stabilizers set to drill, typically, on a curvature radius of 100 feet. For drilling of the straight portion of the hole the stabilizers are reset to allow for a small amount of directional control (i.e., a small bit offset is developed by the location of the eccentric stabilizers). The straight portion of the hole is drilled by rotating the tool face from side to side (i.e., drilling to the left of the borehole axis, then rotating the bit 180° and drilling to the right of the borehole axis). Vertical adjustment to the hole can be made by locating the tool face in an up or down direction, depending on the course direction needed. HDPE slotted casing can be used in the horizontal section. Other types of casing materials are available. A mud pulse MWD telemetry system is used to obtain real time data on inclination and course azimuth of the wellbore. Gravel packing is possible using polyethylene beads. In addition, a newly created HDPE well screen is available that incorporates circular perforations covered by a stainless steel mesh. The drilling rig requires an area of approximately 45 feet by 65 feet. Additional information on the drilling equipment and methods is available in (Karlsson and Bitto, 1990). An additional petroleum service company is in the process of providing similar equipment and services. The equipment should be available by the middle of 1992 (Bailey, 1992). Drilling specifications for this equipment are not available at this time.

River crossing drilling technology is also being used for characterization and remediation at environmental sites. The drilling system incorporates the washover pipe method described above. The washover pipe is used to prevent hole collapse, to provide a sealed conduit for bringing cuttings and drilling fluid to the surface, to reduce drag and torque and to provide a larger hole size for gravel packing, if required. In addition, methods for cementing of the pipe before entering hazardous plumes have been developed. Coring operations can also be performed (Cherrington Environmental, 1991). Several other companies that specialize in river crossing operations are beginning to become involved in environmental work (Kaback, 1992).

7.0) Subsurface Drilling and Production Equipment

There are various types of subsurface equipment used in directional and horizontal drilling operations. Some of the downhole equipment is similar to that used in vertical drilling operations or is self explanatory and is, therefore, not discussed in this report. This equipment includes drill bits, reamers, stabilizers, bent subs, drill collars and drillpipe. However, specialized equipment used in directional and horizontal drilling operations will be discussed.

7.1) Mud Drilling Motors

The positive displacement motor (PDM) is based on the Moineau Principle. The system consists of a rubber lined spiral cavity with an elliptical cross section in which is located a helicoidal steel rotor. The number of lobes of the helicoidal rod is one less than the number of lobes of the stator, per stage. This allows for a volume of mud to move through the space created by this missing lobe. Mud pumped through the motor causes the helicoidal rod to turn. Initial designs used a ratio of 1:2 (stator to rod lobes). This design yields a speed range of 250 rpm to 500 rpm with low torque. Increasing the number of lobes in the motor reduces the volume of the vacant lobe, thereby reducing the speed of the motor and increasing torque (Von Flatern, 1991) (Note that this is similar to a screw having either fine or course threads. Fine threads allow for a greater torque to be developed for a given rotation speed.). PDM motors are available in different rod to stator lobe designs to offer various bit speeds and torque combinations. A drive shaft connected to the helicoidal rod delivers power from the steel rod to the drill bit. Speed reduction gear boxes are available. These gear box devices reduce rotation speed and increase torque. Rotation speeds vary from 85 to 2000 rpm with flow rates up to 1200 gallons per minute (gpm). Flow rates required to operate the motor and rotational speeds are dependent on the ratio of the number of rotor lobes to stator lobes. Typical ratios are 1/2, 3/4, 5/6 and 9/10. High rotational speeds are only available for the small diameter motors. Sizes range from 1 3/4 inch to 11 1/4 inch diameter with flow rates varying from 20 gpm to 1200 gpm, respectively. Motor size chosen is dependent on hole size to be drilled. The following table indicates typical motor size versus hole size (variations are possible). Another advantage of the PDM is that motor torque is proportional to drillpipe pressure (actually pressure drop across the motor) and motor speed is proportional to flow rate through the motor (Burgoyne et al., 1986). Therefore, monitoring of the PDM operation is relatively simple.

Turbine type motors are also available, however, their limited operating range, high speed, low torque and long lengths limit their use. In addition, monitoring of motor performance is not possible with turbine type motors. The low torque capacity of the turbine motor can lead to stalling of the motor. It is not possible, as it is with the PDM motor, to monitor the mud flow system to determine if the turbine motor has stalled. Bent housings are not available for use with turbine type motors, therefore, steerable drilling assemblies are not available. Research is still ongoing in the development of turbine motors for use in horizontal drilling operations (Von Flatern, 1991).

Motor Size versus Recommended Hole Size
(After Eastman Christensen)

Motor Size (OD Inches)	Hole Size Range (Inches)
1 3/4	1 7/8 - 2 3/4
2 3/8	2 7/8 - 3 1/2
3 3/4	4 1/4 - 5 7/8
4 3/4	6 - 7 7/8
6 1/4	7 7/8 - 9 7/8
6 3/4	8 3/8 - 9 7/8
8	9 1/2 - 12 1/4
9 1/2	12 1/4 - 17 1/2
11 1/4	17 1/2 - 26

7.2) Specialized Drillpipe

Drilling in short and medium radius horizontal holes requires special drillpipe due to the bending stresses associated with the curvature of the hole. In addition, in order to supply weight on the bit during drilling of the horizontal portion of the hole it is required that the drillpipe be in compression. Compression of the drillpipe causes buckling and therefore, additional stresses are generated.

The table shown below indicates, for a specific pipe diameter, the type of drillpipe used in the curved portion of the hole depending on the build angle and radius of curvature.

Build Angle Limitations of Drillpipe, Heavy Weight Pipe and Drill Collars
(From Oil and Gas Journal Editorial, 1990)

Build Angle (°/100 ft)	Radius of Curvature (feet)	Design and Material of Pipe
5	1200	Drill Collar
10	600	Heavy weight pipe with one or two central wear pads
20	300	Drillpipe with two to three wear pads (compressible service drillpipe)
40	150	Protected steel with wear knots (compressible service drillpipe)
80	75	Titanium pipe with wear knots (compressible service drillpipe)
160	35	Articulated pipe High Strength Carbon fiber Steel reinforced hose

Flexible (articulated) pipe is normally used in the curved portion of short radius horizontal wells. Articulated (flexible) drillpipe and flexible drill collars are available in various sizes. The flexible drillpipe eliminates bending stresses in the curved portion of the hole. However, buckling loads are still developed.

Compressible service drillpipe is available for drilling with build angles greater than 15°/100 feet. The compressible service pipe reduces pipe body stresses that develop by reducing the effective length of the pipe. Compressible service pipe has additional wear pads (or wear knots as they are termed) that restrict the lateral movement of the pipe, thereby, decreasing bending stresses. Large reductions in stress can be realized between standard drillpipe and drillpipe with wear knots (McKnown, 1989). Figure 13 shows the various types of drillpipe used in horizontal drilling operations. Drillpipe is available in various sizes, lengths and number of wear knots. Wear knots are normally the same diameter as the pipe tool joints with lengths equivalent to that of two tool joints.

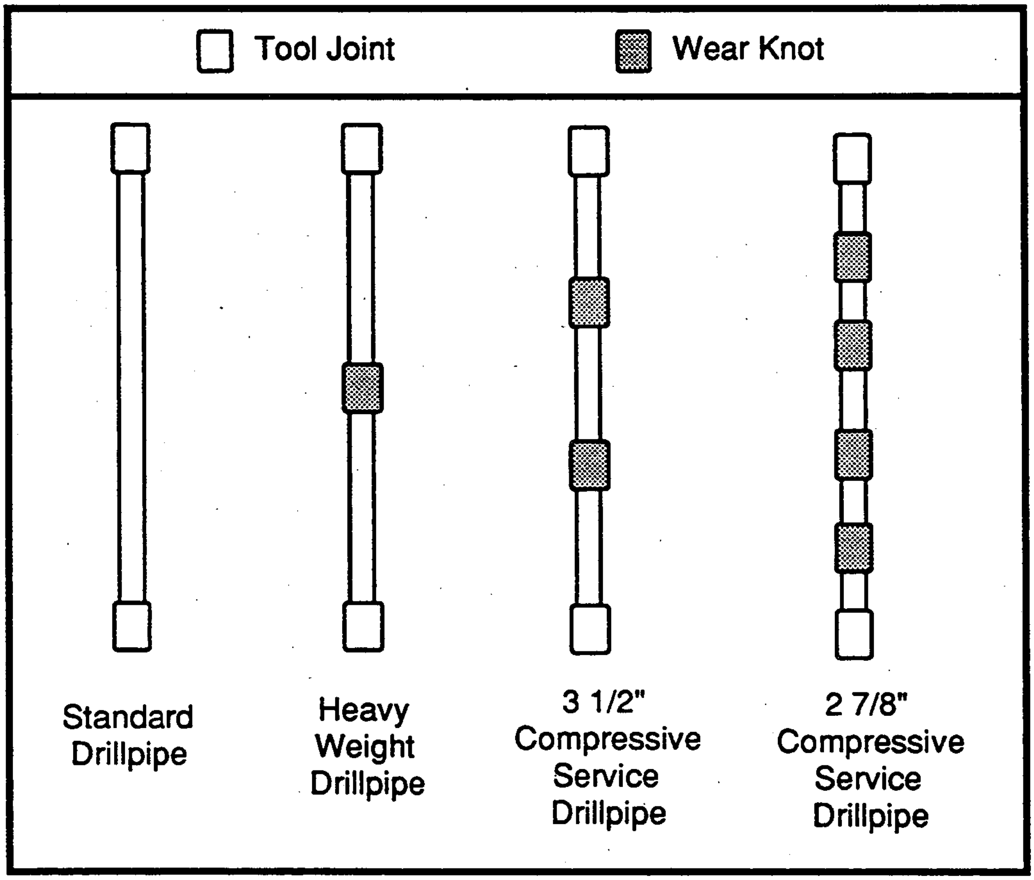


Figure 13) Types of Drillpipe Used in Horizontal Drilling Operations

7.3) Measurement While Drilling Equipment (MWD)

Measurement while drilling equipment has been discussed in previous sections relative to supplying real time information on hole inclination, direction and tool face orientation. The first commercially available system came on the market in 1978 (Fontenot, 1986). Inclination and direction of the wellbore are self explanatory. Tool face orientation (or Tool Face Indicator) gives information on the path which the bit will drill along. The tool face indicator uses calculations based on the directional and inclination measurements for the bottom-hole assembly being used and the orientation of the bend with respect to the high side of the hole. Additional data on formation properties (termed formation evaluation measurement while drilling or FE-MWD) and drilling dynamics can be obtained during the drilling activity. There are several methods available for transmission of data to the surface or data can be stored directly in the MWD tool and downloaded when the tool is retrieved at the surface. The MWD systems are beginning to become modular so that various combinations of tools are available. In addition, most MWD systems are wireline retrievable, i.e. the MWD internal instrumentation can de retrieved from bottom-hole by running a wireline through the drillpipe and latching on to the MWD system and pulling the equipment to surface. In this way equipment can be replaced without removing the drillpipe from the hole or retrieved if the hole collapses and the drillpipe is stuck in the hole.

7.3.1) MWD Signal Transmission

There are several methods of signal transmission for moving data obtained from the MWD equipment to the surface. These include electric wireline methods, in which an electric cable is inserted inside the drillpipe, mud pulse; either positive or negative pulse, and electromagnetic methods. Wireline systems are normally run in conjunction with steering tools; tools that yield information only on inclination, direction and tool face angle. However, the wireline methods are beginning to be used with directional and formation evaluation MWD equipment.

The electric wireline method uses an electric conductor (or conductors) covered by two opposite wound armor cable layers. The electric cable is inserted inside the drillpipe through the top of the drillpipe (kelly) or through a side-entry sub located in the drill string below the ground surface. The original wireline directional orientation system uses a pack-off swivel (a device that squeezes a piece of rubber concentrically around the wireline to stop drilling fluid from escaping to atmosphere during drilling and fluid circulation operations) device located at the top of the kelly. Drilling with a mud motor takes place for one joint of drillpipe. At this time the bottom-hole electronic steering tool assembly is brought to the surface with the wireline, a joint of drillpipe is added, the steering tool equipment is run back to bottom-hole and drilling is resumed. This system is somewhat time consuming in that the MWD or steering tool has to be pulled to the surface each time a joint of drillpipe is to be added to the drilling string.

Side entry subs are devices that allow the wireline to be inserted into the side of the drillpipe at a particular point below the ground surface. This method allows for a portion of the wireline to be within the drillpipe while a portion of the wireline is located within the annular section between the drillpipe and the well casing. The side entry sub is normally kept within the vertical section of the wellbore and within the cased portion of the hole. The side entry sub allows the well to be drilled ahead with a mud motor for, in some cases, several hundred feet before the wireline needs to be removed so that the wire line is not damaged (i.e., damaged by pinching of the cable between the drillpipe and the well casing). At this point the drillpipe is removed from the well to the point at which the side entry sub is encountered, the side entry sub is removed and the MWD equipment is removed from the bottom of the well with the wireline. At this time additional drillpipe is added below the point where the side entry sub was previously located, the MWD equipment is set back to the bottom of the well and the side entry sub is repositioned near the top of the well. At this point drilling commences. Rotation of the drillpipe is not allowed in either of the above wireline MWD systems.

Another wireline orientation tool uses what is termed a wet connect system (Ensco, 1992). This system is similar to the side entry sub system in that a connection point for the wireline and MWD equipment is located within the drill string below the ground surface. However, the wet connect system has a connector that is attached to a sub within the drillpipe. The wireline is kept within the drillpipe during the drilling operations. The system uses a pack-off system attached to the top of the kelly with a subsurface electrical connector that can be connected and disconnected easily. This allows the well to be surveyed during either rotary or mud motor drilling operations. During mud motor operations the system is connected and the orientation data can be obtained during real time. During rotary operations the electrical connection system is disconnected with the wireline left in the drillpipe. Orientation data is obtained by reconnecting the system during connections (when additional lengths of drillpipe are added). A disadvantage of the system is that the wireline above the subsurface wet connect device must be removed before additional drillpipe can be added. The advantage of the system, over the standard wireline and side entry sub method, is that rotary drilling operations are possible and the length of cable that must be removed, when drillpipe is added, is reduced.

The mud pulse system is the primary transmission system used with MWD and FE-MWD equipment. The system operates by sending a pressure pulse through the mud system to a pressure transducer located at the surface (Fontenot, 1986; Burgoyne et al., 1986). The pressure pulses can be generated by various methods. One method opens a solenoid valve to the annulus, thereby dropping the pressure in the drillpipe.

This is termed a negative mud pulse system due to the pressure drop in the drillpipe. Another method is to have a valve located within the drillpipe that closes for a short time period, generating a pressure increase in the drillpipe. This method is termed a positive mud pressure pulse due to the increase in the pressure in the drillpipe. In each case, the series of pressure pulses generated are read as a binary encoded signal by a computer system connected to a pressure transducer at the surface. Another type of device, termed a mud siren, generates a continuous wave in which phase shifts are measured and interpreted as binary encoded data signals.

Power is supplied to the downhole MWD equipment through a battery pack, from a small voltage generating turbine located at the top of the MWD tool or from a small electric generator located at the bottom of the MWD equipment. Battery life is limited by the rate of data transmission and wellbore temperature. Typical battery life is on the order of 100 to 200 hours, depending on well temperature and the amount of data being sent to the surface or stored in memory. Systems are designed to use both turbine and battery power. The turbine powered transmission systems yield longer downhole life. In some devices, mud weight, mud viscosity, sand content of mud, mud gas content and use of loss of circulation material may be limited to some extent.

An electromagnetic transmission system has recently been developed for MWD (and FE-MWD) data transmission to the surface (GeoServices, 1992). The system uses the propagation of electromagnetic waves from the downhole MWD tool through the drillpipe to a sensor located at the surface. Depth limitation is reportedly about 10,000 feet. One advantage of the electromagnetic system is that it does not require fluid circulation and, therefore, can be used during drilling at sites where loss of circulation is common. In addition, air, air-foam or aerated drilling fluid operations can be performed with MWD equipment in the hole. Loss of circulation material can be used. The tool has no mechanical (moving) parts and battery power requirements are low. It should also be noted that wireline systems can also supply MWD data during drilling with aerated fluids.

7.3.2) Formation Evaluation Measurement While Drilling Equipment

There are numerous measurement while drilling formation evaluation tools on the market at this time and new tools are being designed to meet specific needs. The location of the measurement devices within the MWD tool vary. In some cases the measurement devices are located within stabilizer sections to insure proper standoff (known distance from the sources and receivers to the borehole wall). Due to regulatory requirements, radioactive sources used in some types of formation evaluation tools (neutron and gamma logs) must be removable. This requires that the radioactive sources be wireline retrievable. This is to allow for the sources to be retrieved if the drillpipe were to become stuck in the hole. Therefore, the radioactive source materials are attached along a common wire within the MWD tool to allow the sources to be removed with a wireline run through the drillpipe. However, removal of the radioactive sources may be difficult if the drill equipment fails (breaks).

The MWD devices are modular in design, that are either built as integral drill collar subs that can be screwed together or come as insert devices that are placed within the drill collars or stabilizer sections. Various standard formation evaluation tool combinations are available.

The types of FE-MWD tools available at this time include:

<u>Natural Gamma Ray</u>

Measures the natural gamma ray intensity of the formation to determine sand and clay contents.

<u>Focused Gamma Ray</u>

The gamma sensor is surrounded for 3/4 of the circumference of the tool by a Tungsten shield yielding a 90° window. When coupled with a directional sensor the tool can measure the gamma signal in different radial directions along the borehole wall during rotary drilling. Used for drilling along formation contacts.

<u>Spectral Gamma Ray</u>

Yields total gamma ray and spectral analysis for Thorium, Potassium and Uranium content. May be adjustable to other gamma ray spectra. Typically 256 channel energy spectra data can be obtained.

<u>Neutron Porosity</u>

Data are obtained on neutron porosity by formation bombardment with neutron sources.

Density and Photoelectric Effect (PE)

Uses a radioactive source similar to that used in the neutron tool and allows for measurement of the formation density and the formation photoelectric factor. Used to make determinations of lithology.

Resistivity

Various devices are available including short normal and focused lateral resistivity devices. In addition, a 2-MHz electromagnetic propagation tool is available that allows for formation resistivity measurements. This device emits a 2-MHz wave into the formation. The amplitude and phase shift of the generated wave are measured at two different receivers and are an indication of near wellbore and formation resistivity. Used to determine porous zones. Resistivity devices that use pads that contact the wall are not practical when drilling.

7.3.3) Drilling Dynamics Measurement While Drilling Equipment

Data can also be obtained on the downhole drilling parameters as the well is being drilled. The data that can be obtained include:

Downhole Weight on Bit

Allows for measurement of downhole weight on bit. When compared to surface weight on bit can used to determine rotating and sliding friction parameters.

Downhole Torque

Measures drilling torque near bit. Data can be combined with downhole weight on bit to estimate rock properties.

Downhole Vibration

Used to monitor vibrations that could damage bottom-hole assembly.

Downhole Voltage Generation

Voltage created from turbine can be used to determine that flow rate through drillpipe remains constant. Used to detect drillpipe washouts.

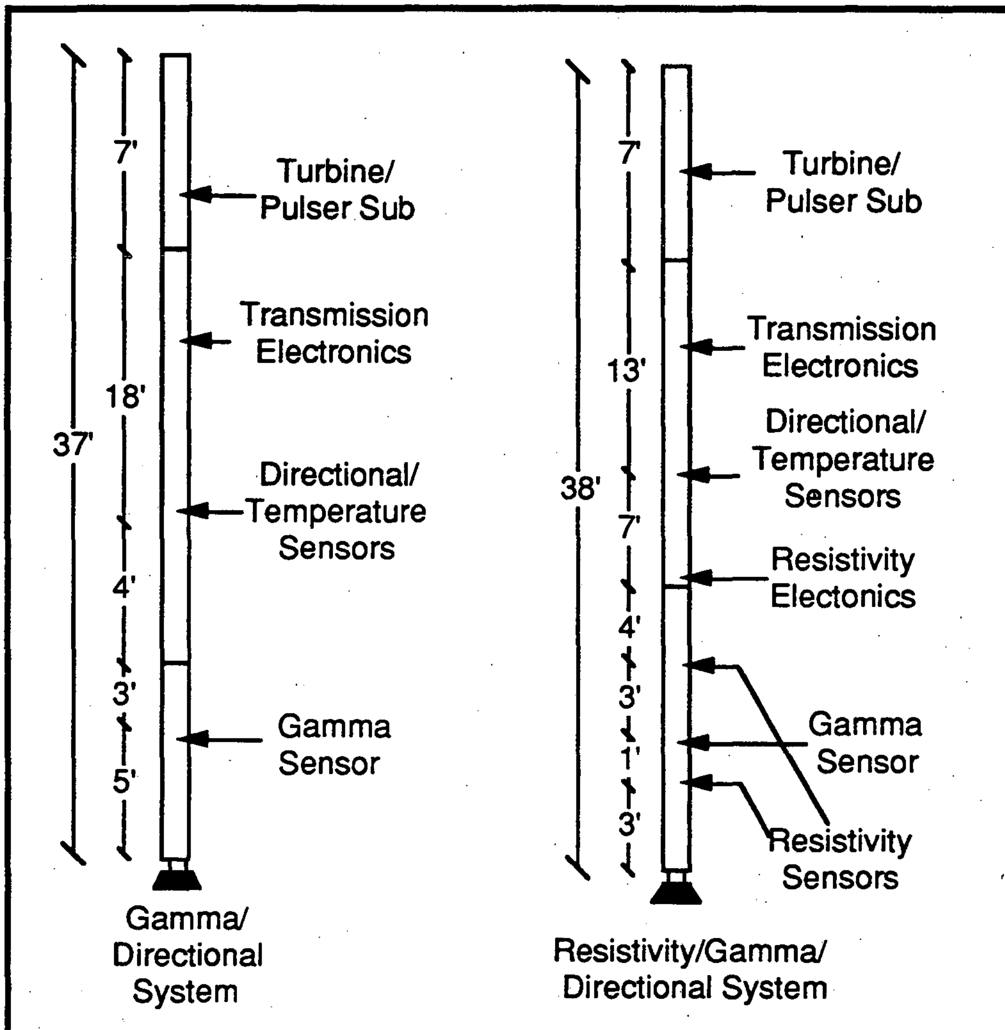
Downhole Temperature

Obtains data on circulation temperature. Used in cementing operations. Can be used to estimate formation temperature and information on fluid influxes into the wellbore or fluid losses to the formation.

Downhole Pressure

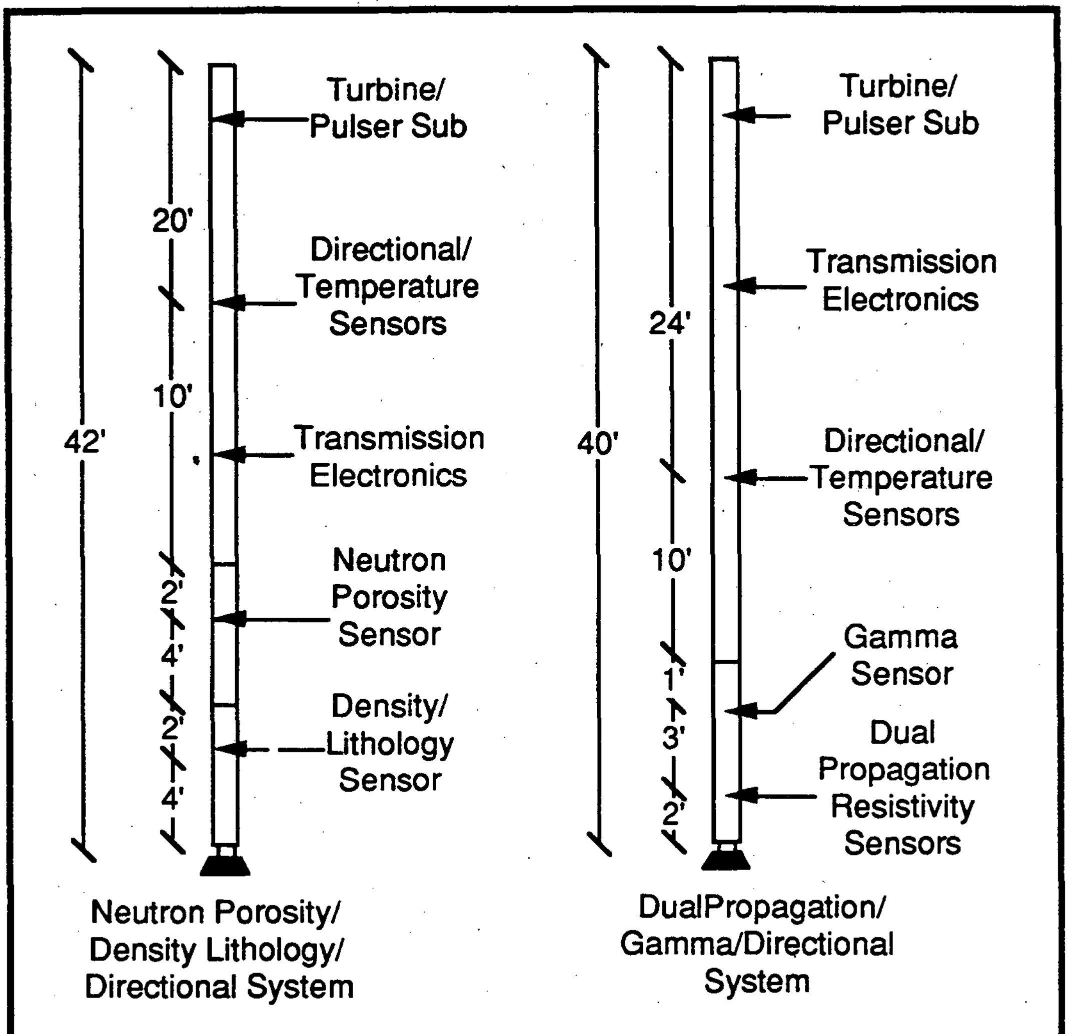
Measures pressure inside and outside of the drillpipe. Used for designing and monitoring drilling hydraulics program. Can also be used to determine drillpipe integrity.

Each of the devices noted above, in most cases, can be run separately or run in various combinations. The number of tools that can be run in any given bottom-hole assembly is dependent on the rate that data is to be acquired and the amount of power required to run the tool combination. Surface computer analysis programs are available to interpret the data. Various computer programs are available to determine down hole drilling conditions, such as; weight on bit problems, hole sticking. In addition, computer analysis programs are available for formation evaluation and lithology identification. Figures 14a and 14b show various combinations of tools and typical lengths of equipment. It should be noted that smaller diameter and shorter length equipment are available and new equipment is being designed for use in short radius horizontal wells.



Note: These Measurement Systems are Located above the Drilling Motor and Bent Sub Assemblies Which are Typically 40' Long

Figure 14a) Directional and Formation Evaluation Measurement While Drilling Tool Combinations



Note: These Measurement Systems are Located above the Drilling Motor and Bent Sub Assemblies Which are Typically 40' Long

Figure 14b) Directional and Formation Evaluation Measurement While Drilling Tool Combinations (con't)

7.4) Submersible Electric Pumps

There are several types of downhole well pumps used in the petroleum industry that would have application in remediation operations. One type of pump is the downhole submersible electric pump. Electric submersible pumps are available in various metallurgical combinations to meet corrosive and abrasive conditions. Various spray coatings are also available for corrosive service. Pump flow capacities are available from 3 gpm to 3000 gpm (maximum available brake horsepower is 1000 Hp, larger sizes can be ordered). Variable electric frequency drives are available for control of flow rate and pressure. Downhole rotary gas separators are also available. These gas separation devices use centrifugal force to separate gas from the fluid. The gas flow is pushed into the annulus through a flow divider, with fluid flowing upwards through the production pipe. Gas is removed by production through the annulus between the production tubing and well casing.

Downhole hydraulic jet pumps are also available. These pumps can pump both liquid and entrained gas, can be run in a horizontal position and have no moving parts. The hydraulic jet pump uses a jet nozzle in combination with a throat and diffuser section. The high pressure (low velocity) inlet fluid is converted to a low pressure (high velocity) stream by the nozzle assembly. The reduced pressure at the nozzle outlet allows wellbore fluid to enter the inlet fluid stream. The diffuser section lowers the velocity, increasing the pressure, allowing the fluid to be "pumped" from the well. Flow rates up to 500 gpm have been realized in actual field operations (TRICO, 1991).

Hydraulic downhole piston pumps are also available. These pumps can also produce mixtures of fluid and gas. The system uses a surface pumped inlet fluid to drive a downhole hydraulic piston engine. The piston engine drives a double acting piston pump that pumps fluid from the well. The system is capable of flow rates up to 250 gpm and fluid lifts up to 14,000 feet.

8.0) Surface Equipment

There are numerous surface devices used in vertical and horizontal drilling operations. Much of the equipment is used in high pressure oil and gas operations and is not discussed here. However, certain types of equipment may have application in characterization and remediation operations. The surface equipment discussed is relevant to drilling fluids containment and mud and cuttings cleaning operations.

8.1) Blowout Prevention Equipment

There are various types of blowout prevention equipment used in the oil and gas industry. Most of the equipment is designed for well control in high pressure operations. However, a device termed a rotating head is used to allow the well to flow during the drilling operation. Rotating heads can be used during aerated drilling operations in underpressured aquifers or during drilling operations where artesian well pressures are encountered. Surface pressures up to 500 psi can be contained while rotating. Rotating heads are available with or without integral mud flow line flanging equipment. The system consists of a conical or cone shaped rubber element located above the mud flow line (pitcher nipple). The rubber element is designed to seal around the drillpipe or kelly and stops fluid from flowing vertically to the rig floor. Drilling fluid is diverted out the horizontal mud line to the shale shaker and mud pits. The conical rubber seal is attached to a metal disk which seats on a system of ball bearings. The top portion of the rotating head is fitted with a square or hexagonal (dependent on the type of kelly being used) shaped section that allow the kelly to be inserted into the head and provide rotation to the rubber element. This allows for the conical rubber portion to rotate at the same speed as the drillpipe eliminating rotating friction and increasing seal life. Only sliding friction created from moving pipe in and out of the hole imparts wear to the rubber sealing element.

Another type of device termed a pneumatic diverter is available. This device is used during drilling for setting of the surface pipe (conductor casing or the first casing inserted into the ground). This device has an inflatable rubber bag that can expand against the wall of the hole. The device has a retractable rubber sleeve located on the top for sealing the annular space between drillpipe and hole during drilling. This device is not designed to withstand high pressures.

In addition to the rotating head a device termed an annular or spherical blowout preventer (sometimes termed a "bag" preventer) is also available. This device contains an elastomeric packing element that can be compressed by a piston and wedge system located below the rubber element. The piston causes the rubber element to expand inwards, sealing off the annular space between the preventer body and the drillpipe or collars. The preventer can be closed to completely seal off the wellbore.

Another device that is required during drilling with aerated fluids or drilling in areas with artesian formation pressures (i.e., during conditions with positive wellhead pressures) is what is termed a drillpipe float. The drillpipe float consists of a short sub and is located directly above the bit or above the mud motor or MWD equipment. The drillpipe float consists of a ball, flapper or dart type assembly that allows flow through the drillpipe in only one direction, downwards towards the bit. The device is used to stop flow of fluids upward through the drillpipe when drilling equipment is being removed from the well. Similar devices, termed string floats, are also available for use in air drilling operations.

8.2) <u>Mud Cleaning and Gas Separation Equipment</u>

Mud cleaning equipment is available to reduce the solids content of the mud, to separate drilled cuttings from the drilling fluid and separate gas encountered in the subsurface from the drilling fluids. In most petroleum drilling operations steel surface mud tanks are used to contain the mud and provide cutting settling and mud mixing areas. The first level of solids separation from the drilling fluids is termed the shale shaker. Shale shakers are available in different sizes and are vibratory devices (i.e., the screens are vibrated in a oscillatory fashion that imparts a transverse force to the screen in the direction of cuttings movement). The shale shaker consists of a single horizontal screen or a set of two screens located one above the other. Screens are available in different mesh sizes. Dual screen systems have an upper and lower screen. Normally the screen mesh sizes are different for the dual screen system with the upper screen having larger openings than the lower screen. Mud enters onto the top screen and flows downward through the holes in the screens, returning to the mud pit. The cuttings are separated from the drilling fluid and left on the screen(s). The vibratory action of the screens causes the cuttings to be moved off of the screen. Conventional shale shakers remove particles above 200 microns. High performance shale shakers are now available to remove particle sizes above 75 microns. The viscosity of the mud has a large influence on the cuttings removal efficiency of the shaker system. High viscosity fluids have a tendency to plug the screen causing fluid to flow over the top of the screen rather than flowing through the screen and returning to the mud pit.

The second stage of drilled solids separation from the circulating medium consist of hydrocyclones. These devices remove particle sizes from 20 to 175 microns. The devices are termed desanders and desilters, dependent on the size of particles removed. The devices are essentially small diameter centrifugal separators. Mud enters tangentially into the device which resembles an inverted right hand cone. Solids are thrown against the wall of the clone (as it is called) and fall towards the bottom of the cone by a combination of gravity forces and the tangential velocity, which yield a resultant downward force. Fluid exits through the top of the system with solids exiting out the bottom. The desanders and desilters are beginning to be replaced by high performance shale shakers due to the fact that the hydrocyclone performance is severely degraded by increases in mud density and viscosity.

Decanting centrifuges are available to remove particles down to 2 to 3 microns. These devices allow for separation of particles from the mud with the output consisting of damp solid particles with no free water. The centrifuges were originally designed for separating barite (a mud weighting material used to increase mud density for drilling in high pressure formations) from the mud stream so that it could be returned to the mud system. Recently, centrifuges have been used in environmentally sensitive areas to remove the drilled solids from the mud system, essentially offering what is termed as a dry drilling system (Malachosky et al., 1991). The decanting centrifuge system consists of a horizontal steel cylinder shaped as a cone. The centrifuge system rotates at high speeds (1600 to 3250 rpm). Within the steel cylinder an auger rotates in the same direction but at a slower speed due to a gear reducer. Inlet of mud takes place through the center of a hollow axle that is located in the center of the auger assembly. Centrifugal force pushes the drilled solids against the side of the centrifuge. Silt and sand sized particles are scraped along the length of the centrifuge by the auger system. Solids exit through the end of the centrifuge with no free liquid. Liquid is returned to the mud system. Up to 7 tons per hour of dry solids can be removed with one centrifuge system. Figure 15 is a schematic representation of the decanting centrifuge system.

Several companies offer packages that use various combinations of shakers, hydrocyclones, mud cleaners and centrifuges mounted on either a skid or wheeled trailer. In addition to these packages, chemical treatment solid waste management systems are available that work in conjunction with the mechanical solids treatment equipment. The chemical treatment systems use liquid polymers to coagulate and flocculate drilled clay size solids. The polymers allow coagulation of particles which essentially increase the size of the particles fed into the centrifuge systems, allowing individual particle sizes less than 2 to 3 microns to be removed from the circulating fluids.

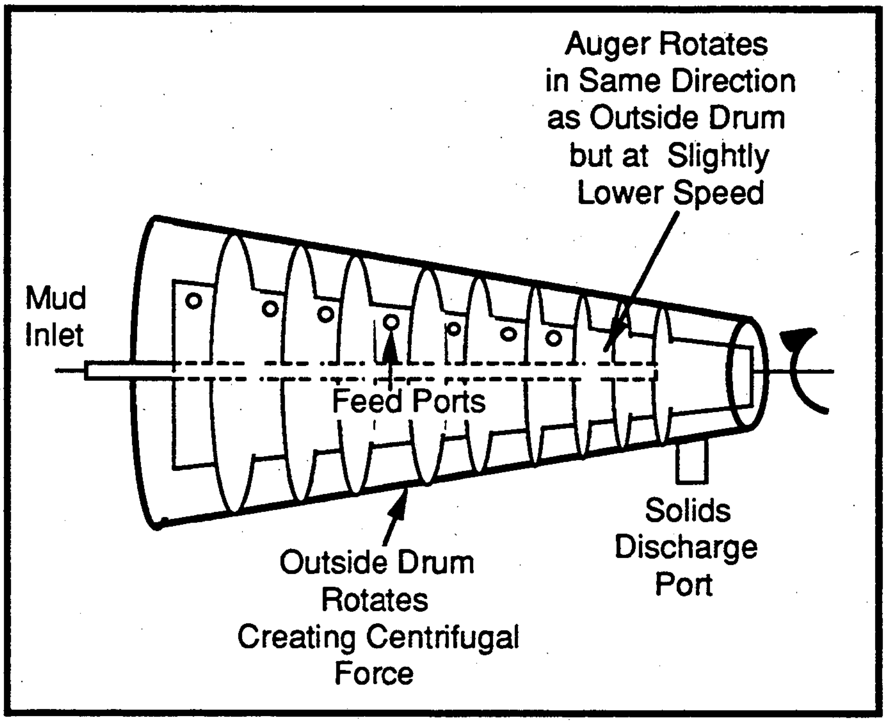


Figure 15) Decanting Centrifuge Mud Cleaning Equipment

In addition to the mud solids cleaning devices, equipment is available to separate entrained gas from the circulating fluid media. These liquid-gas separators were originally designed in 1951 (Swaco-Geolograph, 1991) to remove toxic hydrogen sulfide and oxygen from the mud system. The system consists of a cylindrical tank, either positioned vertically or horizontally, with a system of internal baffles. A vacuum pump is used to draw the mud into the tank and to discharge the gas to atmosphere or to a remotely located propane fueled flare system. Throughput mud flow rates can be as high as 1000 gpm. Centrifugal type de-gassing equipment is also available. A typical vertically oriented vacuum de-gassing system is shown in Figure 16.

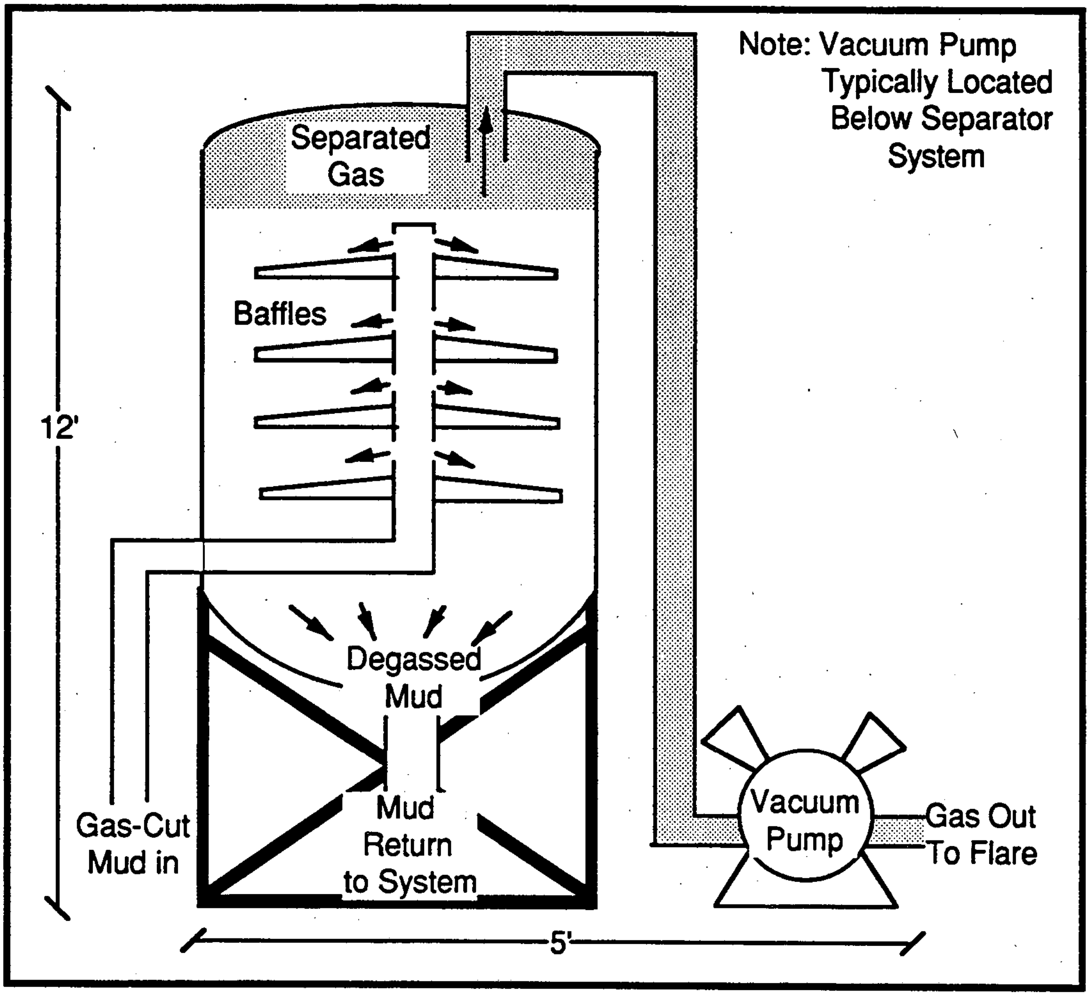


Figure 16) Vertically Oriented Mud De-Gasser Equipment

9.0) Discussion of Petroleum Horizontal Drilling Technology for Characterization and Remediation Activities

Many of the hazardous waste sites that require characterization and remediation are located in areas where the formations to be drilled are unconsolidated. The unconsolidated materials can consist of clays and sand mixtures to unconsolidated poorly cemented cobbles and boulders. In addition, many of the aquifers to be investigated and remediated are shallow and unsaturated, with a vadose zone overlying the saturated portion of the aquifers. In most cases, both the saturated and vadose zones are to be characterized and remediated.

9.1) Drilling Operations in Shallow Unconsolidated Formations

Each of the above formation conditions can cause problems in drilling and completion of horizontal wells. In horizontal drilling, the bent sub, stabilizer and mud motor system create curvature of the hole by imparting a force to the wall of the hole. In unconsolidated (soft) formations hole enlargement due to fluid circulation (washouts) and gouging of the hole wall from the bottom-hole assembly can cause problems in angle building and directional control of the well. Drilling in formations with large cobbles and boulders creates different problems. Directional control of the hole is difficult due to the tendency of the drill bit to veer off when the edge of a boulder is encountered. In addition, unconsolidated sand and clays and the poorly cemented nature of cobble and boulder formations can create hole stability problems.

In some cases, directional and inclination control problems caused by boulders and cobbles or the inability to maintain hole trajectory due to soft formations can be overcome, to some extent, by reduction in weight on bit. However, the penetration rate can be reduced drastically and reduced penetration rates increase well costs. Reduction in mud circulation rates to decrease hole washouts in unconsolidated formations can lead to drillpipe sticking problems due to poor hole cleaning. Each of the above conditions can make the drilling of short radius horizontal holes difficult and expensive in shallow unconsolidated formations.

Drilling methods that reduce the severity of the radius of curvature of the hole are available in the river crossing and environmental drilling technologies. The increase in hole radii allows larger diameter bottom-hole drilling assemblies to be used. Furthermore, the large radii holes allows for the drillpipe to be rotated increasing hole cleaning ability and providers for stiffer drilling assemblies that assist in maintaining control of hole inclination and direction.

River crossing and some environmental drilling technologies use angled drilling masts. These angled masts allow the hole to become horizontal at lesser depths for a given radius of curvature. However, an increase in the overall length of the well (and therefore well cost), above that for a horizontal well initiated from a vertical well, is realized. From a development standpoint, river crossing drilling utilized the angled mast drilling equipment due to the fact that large diameter pipelines were to be placed in the holes after completion. Large diameter pipes require that the curvature radii be large to reduce bending stresses and prevent buckling of the pipeline. In environmental drilling operations the angled mast type rig has been chosen due to the unconsolidated nature of the aquifers under scrutiny, that require the use of large curvature radii and the fact, in many cases, that shallow horizontal wells are required.

Some environmental rotary drilling operations allow the production casing to be pulled along with the drill bit as the hole is drilled. Insertion of the production casing as the well is drilled reduces hole washout problems, problems associated with hole stability and increases the ability to directionally control the hole. However, a wing type hole opener must be used in the drilling operation. This wing type hole opener system drills a hole that is larger in diameter than the casing. The casing is inserted during the drilling process. In order to remove the hole opener drill bit the wings on the hole opener fold into the drill bit so that the drilling assembly can be pulled out of the hole without having to remove that casing. This wing type hole opener has application in soft unconsolidated sandy and clay type formations. However, application of the wing type hole opener in cobble and boulder formations is questionable due to the fragile nature of the folding arms. Therefore, the ability to push the production string along with the drill bit as the hole is drilled is, most likely, not possible in cobble and boulder type formations or in high compressive strength (hard) formations. This limits the application of the environmental type drilling rig operation (with its ability to insert casing as the hole is drilled) to soft formations, at this time. Other types of hole openers with folding drilling arms are available for high compressive strength formations and it is assumed that this problem is being looked into and bit development for hard formations is taking place.

River crossing technology that uses the pilot string and washover pipe method has application in both soft unconsolidated formations, poorly cemented cobble and boulder type formations and in high compressive strength formations. Environmental drilling equipment using this technology is available. The washover string is run in conjunction with the pilot drill string system to provide bottom-hole assembly support, assist in maintaining borehole diameter (reduce hole washout problems) and reduce borehole stability problems associated with drilling fluid eroding the borehole.

The conclusion to the above discussion is that angled drilling mast rigs are the most suitable for horizontal drilling operations in shallow formations encountered in some characterization and remediation programs. The environmental type drilling rig that has the ability to drill the hole while inserting the production string has application, at this time, for drilling of soft formations. At this time, it may not be possible to use this simultaneous drill and set casing method in high compressive strength formations. However, the environmental drilling rigs can still use conventional type drilling assemblies, and therefore, have application in all types of formations. The use of river crossing technology with the pilot string and washover pipe system also has application in all types of formations.

It should be noted that the other drilling technologies discussed above (see Section 6) may also have application to characterization and remediation operations. Continuous coiled tubing drilling operations are an important development for drilling with air or mud in unconsolidated formations. The coiled tubing allows for circulation to be maintained during all of the drilling operations (since there are no pipe connections to be made). The smooth continuous tubing (no tool joints) reduces friction losses. The tubing is not rotated and borehole stability problems associated with drillpipe hitting the borehole walls are reduced. The ability to circulate continuously increases hole cleaning ability and may overcome the problems associated with hole cleaning due to non-rotation of the tubing (agitation of the cuttings in the hole from drillpipe rotation increases hole cleaning ability). In addition, tubing costs are low and loss of tubing in the well due to hole collapse does not lead to large expenditures, when compared to conventional drilling equipment. It should be noted that continuous tubing has been rotated using mud motors in vertical holes during well cleanouts.

9.2) Drilling Operations in Unsaturated Formations (Vadose Zone Operations)

Many of the characterization and remediation operations take place in the vadose zone. The depth, and therefore thickness, of the vadose zone varies considerably from site to site. Some sites have vadose zones up to 1000 feet thick. The unsaturated conditions in the vadose zone can cause problems when drilling with fluids. Vadose zone formation pressures are near atmospheric, whereas wellbore pressures when drilling with fluids will be near hydrostatic, based on a fluid filled wellbore. This causes the pressure along the length of the borehole to be much greater than the in situ formation pressure. For example, for a 500 foot deep hole with a mud weight of 8.5 pounds per gallon (ppg), a density similar to that of water, the pressure at the bottom of the hole will be approximately 220 psi. If permeable formations are encountered, loss of drilling fluid to the formation (loss of circulation or LOC) can occur. The LOC problem can normally, be eliminated, after occurrence, by use of LOC material, or in the worst case, the zone can be plugged off with cement. However, this changes the natural conditions of the aquifer being investigated. The LOC can also flush away pollutants that were in the aquifer, thereby eliminating the ability to detect the pollutants during fluid or material (core) sampling operations or formation electric logging operations. Another problem associated with LOC is that, if the mud is contaminated with pollutants and LOC occurs, additional aquifers may be polluted.

Problems associated with the drilling and possible loss of circulation of drilling fluids in under pressured vadose zones can be met by the use of air injection in the drilling operations. Aerated drilling fluids can be used to reduce the hydrostatic heads by reduction in the density of the drilling fluid. Aerated drilling fluid densities of 4 ppg can be obtained. The air can be injected into the mud stream or drilling can be performed with aerated water. Mixtures of air and foam can also be used. The advantage of using aerated fluids is that fluid properties that assist in hole cleaning, such as yield strength and plastic viscosity, can be maintained. In addition, required air volumes are low and standard PDM mud motors can be used, as long as the volume of fluid through the mud motor is maintained to manufacturers specifications (Nickles, 1992).

Dry air can also be used for drilling of the vadose zone. However, air drilling requires high velocities, typically on the order of 3000 to 5000 feet per minute, for adequate hole cleaning in vertical wells (Angel, 1958; Lyons, 1984). Volumetric air requirements for horizontal drilling are still being researched. The high wellbore velocities can cause hole stability problems in unconsolidated materials. Coiled tubing drilling equipment would be well suited for horizontal air drilling in that air circulation can be continuously maintained during drilling operations.

The use of drilling technologies that insert casing or utilize washover pipe for the drilling operation can reduce hole erosion problems. Air drilling PDM motors that can be used in directional drilling operations have been developed and field tested (Shale, 1991). The modified air drilling PDM motor has a short life expectancy when compared to mud type motors (approximately 50 hours). The air drilling PDM system was developed in conjunction with an adjustable kick off sub, an adjustable bent sub and u-joint housing to allow for a steerable drilling assembly. Build rates of up to 20°/100 feet are possible. In addition to the PDM type drilling motor an air turbine motor prototype has also been developed and field tested (Lyons, 1990). Additional work needs to be performed on air drilling motor assemblies and hole cleaning requirements during air drilling operations.

Another difficulty with drilling and completion in underpressured vadose zones is associated with the installation and cementing of well casing. Unsaturated zones can be highly permeable. Loss of circulation material can be used to seal these formations during the drilling operation and light weight aerated drilling fluids can be used. However, the casing must be cemented in place. Typical cements have densities that are two times that of water. Therefore, although it may be possible to reduce formation losses while drilling with the use of LOC material or aerated fluids, it may be difficult to obtain an adequate cement job on the production casing string due to formation fracturing or LOC problems developing.

Some of these problems can be overcome using intermediate or light weight cements (Benge et al., 1982). Intermediate weight cements use combinations of silica flour and glass beads mixed into the cement. Densities of intermediate weight cements can be as low as can be as low as 1 1/2 times that of water (13 lb/gal). Light weight foamed cements have been developed with densities that are three-quarters that of water (6 lb/gal). These light weight cements are made by mixing nitrogen gas with the cement as the cement is being pumped into the annular well space. These light weight cements have been used in various areas to overcome specific problems including cementing through low pressure intervals and through vugular loss of circulation zones (McElfresh and Boncan, 1982). It should be noted that these types of cements usually have low compressive strengths.

In addition to the light weight cements, various types of casing hardware are available that reduce the length of fluidized cement column in the annular section at any given time. This equipment allows the cement to be set in stages. The devices use sliding sleeves located within the casing to isolate preset lengths of the casing. A reduction in the hydrostatic head at the bottom of the cemented section is realized. In addition, in severe loss of circulation areas external casing packers can be used. External casing packers are rubber sections of material run on the outside of the casing. An internal sleeve located on the inside of the casing wall can be opened to allow fluid from inside the casing to escape into the rubber packer element. This allows the packer to inflate until it contacts the outside of the hole. Integral casing cement collars and external casing packers are available. These external casing packers and integral cement stage collars are typically set above the LOC or low pressure zone and cement is pumped to the surface above the low pressure zone. A combination of intermediate weight or light weight cement and casing cementing hardware is sometimes used.

Additional problems are associated with the cementing of casing in the horizontal portion of the well Keller et al., 1987; Crook et al., 1987; Sabins, 1990). These problems are associated with free water, eccentric pipe, mud filter cake and solids settling to the low side of the hole. Cementing operations need to take these problem areas into account for a successful cement job to be completed.

9.3) Formation Evaluation Measurement While Drilling Equipment

Formation evaluation measurement while drilling equipment is available for use in drilling operations. Focused gamma ray tools can be used for wellbore control if DNAPL's are expected to be lying along geologic contacts or on top of low permeability layers. In addition, the gamma ray tool used in combination with neutron or lithology tools can be used to maintain horizontal boreholes within thin sand beds and insure that deeper clay or low permeability layers are not penetrated (i.e., reduce the chance of contaminants migrating vertically downwards due to penetration of confining beds). Density lithology and resistivity tools can be used in saturated systems to determine formation types and other aquifer properties when run in combination with other tools.

Gamma ray MWD tools can also be used in areas where radioactive species are expected. Spectral gamma ray MWD systems are available. These MWD tools can be used to determine if the drilling assembly is approaching radioactive contaminants. Identification of an increase in gamma counts may allow for the drilling assembly and surface equipment to be saved or a reduction in the cost of decontamination of the drilling equipment may be realized. Research in the use of MWD gamma ray tools needs to be performed.

One disadvantage of the MWD equipment is its location relative to the drill bit. In most cases the distance from the MWD equipment to the drill bit is greater than 40 feet (see Figures 14a and 14b). Shorter length (≈12 feet long) small diameter motors are available. These motors can be used in drilling formations that require low torque and low weight on bit. Penetration rates may be reduced. In addition, the use of MWD equipment in air drilling operations will require the use of electromagnetic signal transmission to obtain real time data at the surface. Vibration forces during the air drilling activity may damage the MWD equipment. Research in this area also needs to be performed.

9.4) Mud Cleaning and Formation Material Sampling

An area of concern in drilling with fluids, as mentioned above, is the possibility of the pollution of pristine aquifers by loss of circulation of drilling fluids that are contaminated during the drilling operations. A mud de-gasser system will allow for the removal of entrained gases from the drilling fluid. A standard petroleum type flare system that uses propane to assist in the burning of produced gases can be used to reduce contaminants to compounds acceptable for atmospheric discharge. Modifications to the standard petroleum vacuum assisted de-gasser system could be made to allow for air stripping of the drilling fluid. The use of aerated drilling fluids in the drilling operation would create an air stripping system that utilizes the wellbore and de-gasser system. Further investigation into the use of de-gasser systems is warranted.

Mud cleaning centrifuges can remove particles from the drilling fluid down to about 3 microns. The centrifuge system can reduce the amount of waste to be disposed at the surface by maintaining the condition of the mud for re-use and separating the cuttings from the fluid. Moreover, the centrifuge system can be used to obtain samples of the formations being drilled. It may be possible to determine formation grain size distribution from centrifuged solid material. The method would require drilling, for example, a 5 or 10 foot section of hole and running the centrifuge and circulating fluid until no further solid particles are obtained from the centrifuge. Again, further research needs to be performed on the use of this equipment in environmental characterization and remediation operations.

A combination of the use of aerated drilling fluids, a mud de-gasser system and centrifuge mud cleaning system would allow for cleaning of the mud, sampling of the formation being drilled and sampling of aquifer contaminants. Flow rate measurements of the gas removed from the drilling mud, in combination with gas chromatography, would allow for a determination of the magnitude and type of organic pollutants in the subsurface. Further research needs to be carried out in this area.

9.5) Production Operations

The use of electric submersible pumps may allow for pumping in the horizontal sections of the wellbore. Downhole rotary gas separators may be used in areas where contaminant concentrations are high and partial pressures of the gas are such that either free gas is available in the formation and wellbore or gas breakout occurs as the fluid enters the pump. The submersible pump and rotary gas separator can be used to simultaneously remove both liquid and gas from the wellbore by using a vacuum pump on the well annulus to remove the separated gas. Fluid would be removed from the wellbore through the pump tubing.

Jet type pumps can also be used to pump liquid-vapor mixtures. These pumps can be run in the horizontal section due to the fact that the jet pump has no moving parts. The use of an air lift system may also be possible. Air lifting of fluid and gas using a nozzle diffuser system, similar to that in liquid jet pumps, is possible for removal of liquid and gas. In addition, air lift pumping may assist the surface air stripping operations by allowing the air to be in contact with the fluid for longer period of time (i.e., the air is in contact with the fluid in the wellbore). Again research in to this area is warranted.

10.0) Conclusions and Recommendations

Many of the drilling techniques used in petroleum drilling operations have direct application to waste site horizontal drilling activities. Most of these techniques are beginning to be applied. However, the shallow nature of waste site drilling operations and the unconsolidated nature of the formations encountered at many sites increases the challenge to drilling personnel.

Much of the equipment used in petroleum horizontal drilling operations can be used in waste site characterization and remediation activities. However, some research is needed in various areas including horizontal air drilling operations, the use of mud de-gassers to remove contaminants from drilling fluids, the use of centrifuges to allow for a determination of drilled formation grain sizes and in the downhole liquid-gas separators and jet type fluid pumps.

The use of measurement while drilling equipment including formation evaluation tools may increase in waste site characterization and remediation activities. These tools can assist in locating the horizontal bores along specific boundaries and at particular locations within contamination plumes. However, the cost of using this equipment can be as much as the daily drilling costs for onshore drilling equipment. The total coat of a combination mud motor, MWD and dry drilling system can be as high as two to three times the normal daily rate of the drilling rig. However, the advantages with respect to reduced drilling time, ability to place the well at particular points to reduce the number of wells to be drilled and prevent additional contamination of pristine aquifers and reduction in disposal costs may offset the cost of the use of this type equipment. In addition, increased use of this equipment in areas other than petroleum operations may spawn additional equipment manufacturers and suppliers and eventually lower the price of the equipment.

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12.0) Companies Contacted for Information on Drilling Services and Equipment

In the course of preparing this report numerous companies were contacted to obtain up to date information on drilling services and equipment. Following is a list of the companies that were contacted or from which technical brochures were obtained. This is only a partial list of the companies that supply various services, materials and equipment to the petroleum industry.

List of Companies Contacted

Deep Petroleum Service Companies

Company	Address	City	State	Zip	Phone	Name	Type of Equipment
Gardes Directional Drilling	PO Box 92593	Lafayette	LA	70507	(318) 234-6544	Robert Gardes.	Horizontal and radial drilling consultants Bottom Hole Assembly (BHA) equipment
Maurer Engineering	2916 West T.C. Jester	Houston	TX	77018	(713) 683-8227	W. McDonald	Horizontal drilling engineering consultants
The Bob Fournet Co.	Box 52245	Lafayette	LA	70505	(318) 233-4433	Bob Fournet	Petroleum directional drilling consultants and equipment
Wilson Downhole Services	Box 1492	Houston	TX	77251	(713) 237-3592		Horizontal drilling equipment and consulting services

Logging Companies Using Wireline or Small Diameter Continuous Tubing

Company	Address	City	State	Zip	Phone	Name	Type of Equipment
Gearhart Industries	Box 1936	Fort Worth	TX	76101	(817) 293-1300		Electrical logging equipment manufacturers and services
Haliburton Logging Services	Box 42800	Houston	TX	77242-8048	(713) 596-6700		Electrical logging using small diameter coiled tubing

Well Completion and Cementing Equipment Companies

Company	Address	City	State	Zip	Phone	Name	Type of Equipment
Baker Service Tools	Box 40129	Houston	TX	77240-0129	(713) 466-1322		Well completion equipment
Completion Tool Comp.	4265 San Felipe Ste 400	Houston	TX	77027	(713) 961-3336	Ted Price	Completion equipment for horizontal wells
Davis Corp.	Box 177	Healdton	OK	73438	(405) 229-1280		Cementing and completion equipment
Dowell Schlumberger	1155 N. Daring Ashford Ste 600	Houston	TX	77079	(713) 556-7700		Cementing services and completion equipment
Gemoco-Sequa Engineered Services, Inc.	PO Box 7036	Houma	LA	70361	(504) 872-3266		Cement equipment and external casing packers (ECP)
Houston Well Screen	11939 Aldine-Westfield Rd.	Houston	TX	77093	(713) 449-7261		Pre-gravel packed well screens
Howard Smith Screen Comp	Box 666	Houston	TX	77001	(713) 869-5771	Johnnie Jackson	Pre-gravel packed well screens
Hydril	5721 Perkins Rd.	Oxnard	CA	93033	(805) 986-1654	John Harris	Well casing designed for horizontal wells
Insituform	Box 181071	Memphis	TN	38118	(901) 363-2105		In-place pipe repair
Otis Engineering Headquarters	Box 819052	Dallas	TX	73581-9052	(214) 418-3000		
Ray Oil Tool Co. Inc.	Box 51384	Lafayette	LA	70505	(318) 837-4768	Rat Mikolajczyk	Completion equipment for horizontal wells

Well Completion and Cementing Equipment Companies (con't)

Company	Address	City	State	Zip	Phone	Name	Type of Equipment
Schlumberger	5000 Gulf Freeway Box 2175	Houston	TX	77252 -2175	(713) 928-4000		Electrical logging services
TAM International	4620 Southerland	Houston	TX	77092	(713) 462-7617	Ed Stewart	Downhole inflatable casing packers
Texas Iron Works	Box 35729	Houston	TX	77235	(713) 729-2110		Completion equipment for horizontal wells

River Crossing Drilling Companies

Company	Address	City	State	Zip	Phone	Name	Type of Equipment
BecField Drilling Services	11111 Katy Freeway Suite 1004	Houston	TX	77079	(713) 932-1900	James Kerr	Drilling mud motors and horizontal drilling consultants
Drilled Crossings Inc.	Box 486	Arnaudville	LA	70512	(318) 754-7804	John Richard.	River crossing drilling and equipment w/ remediation experience
Horizontal Drilling International	Pole Newton Parc Saint Christophe	95864 Cergy Potoise Cedex	France		(33-1) 34 22 709 60	LP Bildeau	River crossing drilling and equipment
J. D. Hair and Associates	324 S. Main Ste 500	Tulsa	OK	74103	(918) 587-9012	J.D. Hair	Consultant in river crossing drilling and engineering
Land and Marine Engineering	15311 W. Vantage Parkway	Houston	TX	77032	(713) 590-4202	Neil Smith	River crossing drilling and equipment
Laney Directional Drilling	Box 1376	Humble	TX	77347	(713) 987-2673	Scooter Hamil	River crossing drilling and equipment
Michels Pipe Line Construction	Box 128	Brownsville	WI	53006-0128	(414) 583-3132	Dale Michels	River crossing drilling and equipment
Murphy Bros.	3150 Fifth Ave.	East Moline	Il	61244	(309) 752-1227	L.D. Garrett	River crossing drilling and equipment
Sheehan Pipe Line Construction	1924 South Utica	Tulsa	OK	74104	(918) 747-3471		Construction company do not have own equipment

River Crossing Drilling Companies (con't)

Company	Address	City	State	Zip	Phone	Name	Type of Equipment
Smith International Directional Crossings	Box 60068	Houston	TX	77205 -0068	(713) 443-3370	Frank McKenney	River crossing drilling and equipment-Petroleum horizontal drilling and equipment

MWD and Mud Motor Equipment Companies

Company	Address	City	State	Zip	Phone	Name	Type of Equipment
ComputaLog	6671 SW Freeway, Ste 410	Houston	TX	77074	(713) 779-1971	Tom Hicks	MWD equipment and mud motors
DMI-ESP	118 Thruway Park	Broussard	LA	70518	(318) 837-3102		Small diameter wireline steering equipment, mud motors and electrical logging
ENSCO	1445 Ross Ave, Ste 2700	Dallas	TX	75202-2792	(214) 922-1500	Chris McCartney	Mud motors, MWD and equipment
GeoServices	14902 Henry Rd.	Houston	TX	77060	(713) 820-5908	M. Lahitte-Crohare	MWD, electrical logging and consulting services for petroleum drilling
Haliburton Geodata	Box 42800	Houston	TX	77242-8048	(713) 596-6700	Bob Tillman	MWD
Horwell Engineering and Services	177 Napolean Bonaparte	Rueil-Malmaison	France		(33-1) 47 08 61 45		MWD and horizontal drilling consultants
Sperry-Sun	PO Box 60070	Houston	TX	77205	(713) 987-5100		MWD and drilling consultants
Teleco Sonat	Drawer 490	Broussard	LA	70518-0490	(318) 856-7201		MWD, mud motors and horizontal drilling consultants

Submersible Down Hole Electric Driven Pump Companies

Company	Address	City	State	Zip	Phone	Name	Type of Equipment
Centrilift	600 Rock Creek Road West	Norman	OK	73069	(405) 321-1471	Dave Ling	Submersible electric pumps
REDA Pump	Box 1181	Bartlesville	OK	74005-1181	(918) 661-2000		Submersible electric pumps
TRICO	3040 East Slauson Ave	Huntington Park	CA	90255	(213) 586-8800	Richard Luebke	Submersible electric, jet and hydraulic activated pumps

Shallow Utility Installation Companies

Company	Address	City	State	Zip	Phone	Name	Type of Equipment
FlowDril Corp.	22404 66th Ave. South	Kent	WA	98032-4801	(206) 395-0200		Utility installation with water jet equipment
Charles Machine Works, Inc. (Ditch Witch)	Box 66	Perry	OK	73077-0066	(405) 336-4402		Utility installation with impact moling and motor drilling
Guided Boring Systems	2916 West T. C. Jester	Houston	TX	77018	(713) 683-8961	William McDonald	Drilling rig and drilling equipment manufactur er for small diameter directional utility installation

Auger Boring Companies

Company	Address	City	State	Zip	Phone	Name	Type of Equipment
Iseki Inc.	4365 Executive Park Dr. # 360	San Diego	CA	92121	(619) 597 -9500		Auger boring
Neptune Coring LTD.	171515 - 106A Ave.	Edmonton	Albert a	T5S 1M7	(403) 472- 6999	Bruce Campbell	Auger boring

Horizontal Environmental Drilling Companies

Company	Address	City	State	Zip	Phone	Name	Type of Equipment
Cherrington Environmental	222 Big Hollow Lane	Houston	TX	77042	(713) 953- 1913	David May	River crossing drilling and equipment. remediation experience
Drilex- Environmental Services Division	Box 801114, 77280- 1114	Houston	TX	77041	(713) 880- 8888 (800) 421- 2056	Bill Bailey	Drilling equipment and services for horizontal remediation wells
Eastman Christensen Environmental Services	PO Box 670968	Houston	TX	77267	(713) 785- 4642	Ron Bitto	Drilling equipment and services for horizontal remediation wells

Horizontal Drilling With Small Diameter Tubing or Continuous Coiled Tubing

Company	Address	City	State	Zip	Phone	Name	Type of Equipment
CUDD Pressure Control	Box 5483	Arlington	TX	76005	(817) 695-1157	Andy Howell	Horizontal drilling with small (≈2") diameter continuous coiled tubing
Longyear Company	PO Box 1000	Dayton	NV	89403	(702) 246-0297	John Mastor	Angle core drilling and equipment manufacturer
SlimDril	Box 924328	Houston	TX	77292-4328	(713) 957-0727	Fred Pittard	Horizontal drilling with small (≈2") diameter continuous coiled tubing
Tonto Drilling	2701 West 900 South	Salt Lake City	UT	84104	(801) 974-0645		Horizontal core hole drilling
WellSpring Drills	Box 553	Covelo	CA	95428	(707) 983-6982	Steve Cardone	Small portable horizontal drilling equipment for slope drains

Drilling Fluids and Mud Cleaning Equipment Companies

Company	Address	City	State	Zip	Phone	Name	Type of Equipment
Kelco Oil Field Group	3300 Bingle Rd.	Houston	TX	77055	(713) 895-7575	Ronald Bolen	Drilling mud for horizontal wells
Sun Drilling Products					(800) 962-6490		Drilling mud and engineering for horizontal wells
SWACO Geolograph	Onne Seine Court, Ste 410	New Orleans	LA	70114	(504) 368-0491	Paul Hanson	Mud gas separators, mud centrifuges and mud dewatering equipment

Surface Located Remote Pipe Sensing Equipment Companies

Company	Address	City	State	Zip	Phone	Name	Type of Equipment
GeoSciences Inc.					(805) 496-0300	Bill Harrison	Pipe location using surface sensing
Radio Detection Corp.	35 Whitney Rd.	Mahwah	NJ	07430	(201) 848-8070		
Gas Research Institute	8600 West Brynn Mawr Ave.	Chicago	IL	60631	(312) 399-8100	S. Kramer	Fund horizontal gas drilling research projects