Well architecture design as defined in this chapter involves the determination of pipe setting depths and sizes for a deep vertical or low angle directional, abnormally pressured well, as driven by several factors including:

- Well depth;
- Desired final well tubing and production casing size (well utility);
- Depth vs formation pressure and fracture gradient profiles;
- Well hazards and anomalies;
- Regulations.

High-angle and horizontal well architecture design is not specifically addressed by the example well that will be used in this chapter. In horizontal wells, casing configurations, shoe depths and casing sizes are driven by both fracture gradient limitations at the farthest reach of the horizontal productive section and the need to sustain a high circulating mud weight to maintain wellbore stability in the long wellbore. In a horizontal drilled section, the height and weight of the rock above (overburden) is fixed. Therefore, the fracture gradient in a horizontal drilled section remains fairly constant over its length. Consequently, the length of the horizontal section that can be drilled will be limited by the fracture gradient at the end of the wellbore. When drilling, as the horizontal section of hole gets longer, the combination of the mud weight and the circulating pressure drop in the annulus (ECD) increases to a maximum at the end of the hole section below the bit. Therefore, when the ECD begins to approach the fracture capacity at the furthest point in the well, drilling must stop. The size of the casings set just prior to drilling the horizontal section, and, therefore, also the hole size that can be drilled, will determine what circulating rate ECD and mud weight combined circulating pressure at the end of the drilled section will be. Comparing the combined circulating pressure to the fracture capacity of the hole will then establish the size of the casings that must be set at the starting point of the horizontal section in order to achieve drilling the desired length of horizontal section. Although horizontal well architecture design is not addressed in this chapter, Chapter 2 on well construction design will address horizontal completions.

The most important information that is needed to develop a well plan is the pore pressure and fracture gradient versus depth data for the area. The amount and quality of the data that is available to develop these curves will vary with the geologic and geophysical knowledge of the area being drilled, including offset well information. The pore pressure curves that are generated from the available information are used to determine the mud weight needed to control the formation pressures while drilling. The fracture gradient curves are used to help establish the upper limit of mud

ty formations in the hole section being drilled. The process of comparing required mud weight to drill deeper vs the risk of fracturing the lower stress formations in the interval is then used to determine where casing must be set to cover the lower integrity zones before drilling deeper where higher mud weights are required.

1.2 Building the pore pressure and frac gradient curves

In some cases, such as when drilling a rank wildcat, offset well information may not exist, and seismic and regional geological data combined with other similar field analogs is all that is available. For many years, the industry has had methods to process this data to result in a pore-pressure prediction. While this process requires substantial capability, it is possible, available and commonly used. Models exist today to permit calculations of fracture gradient in most of the world's geologic basins. In any case, with this data, the geologists and engineers ultimately produce a set of anticipated pore pressure and fracture gradient vs depth curves.

Scientists believe, and earth studies support, the theory that the Earth was formed in a marine environment; and that the pressures in fluid trapped in permeable and porous subterranean formations generally increase with depth. These fluids and materials including saltwater, dead plants, animals and microorganisms were buried along with sand, clay and other rock materials and compressed by the increasing weight of long term deposition of layers of the rock materials above. These layers of material are called overburden (as introduced above), and are the results of the way they were deposited and buried as the earth was formed over billions of years. It is also believed that the decomposition of the plants and animals buried under intense pressure from the overburden and heat ultimately became oil and gas. This oil and gas or trapped saltwater then fills the voids or fractures between the particles in the buried rocks. The deeper the formation is buried, the greater the weight of the rock above and therefore the greater the compaction and the trapped fluid's pressure. In some cases, however, anomalies can exist where trapped fluids and gas have escaped via fractures, faults or permeable formation paths toward the surface or to other originally lower-pressured formations. When this happens it will result in a pressure reversal. A pressure reversal is when a lower-pressure formation exists below a higher-pressure formation, or when a higher pressure than expected is encountered at shallower depths in a well.

The greater overburden weight that occurs with depth also causes the rocks to be denser, stronger and under higher stress, which results in increasing fracture strength capacity, as the rocks are buried at deeper horizons. Typically, the fracture gradient strength vs depth curve increases rapidly at shallow depths as the rocks become increasingly com-

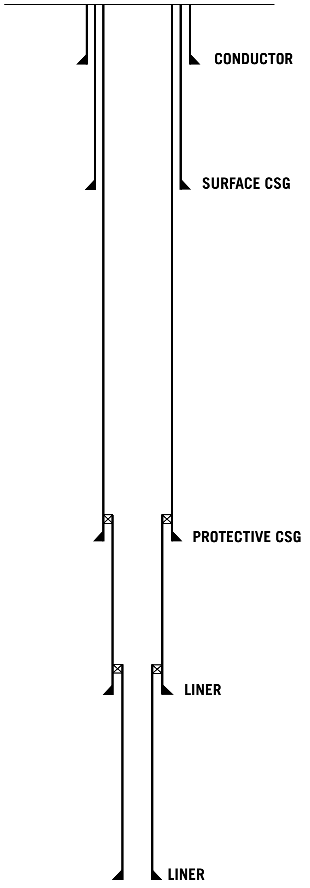

Figure 1-1: Typical deep well profile.

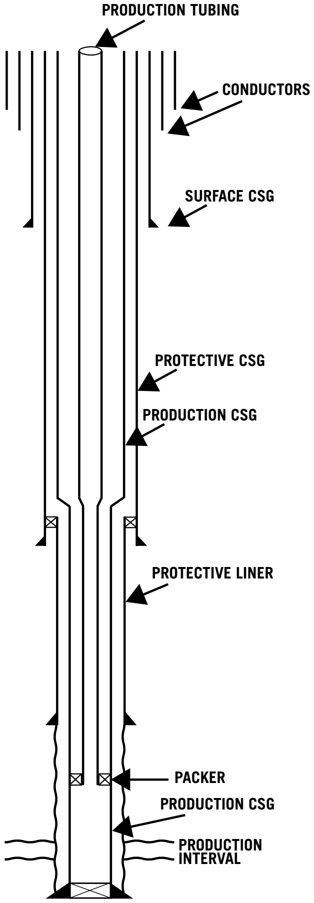

Figure 1-2: Typical completed deep well architecture.

pacted by the overburden. At deeper depth, the slope of the curve, or rate of fracture-gradient increase vs depth, declines as the rocks begin to reach a point where further compaction is not possible. Setting casing in the upper part of the hole will yield the greatest increase in frac gradient to help drill the well down. In the deeper part of very deep wells, the frac-gradient curve slope can nearly approach a vertical line. When this point is reached, the increase in fracture gradient with depth will be small, making deeper drilling very difficult. All this information is important in designing both the architecture and configuration of a well's casing program.

1.3 How to build the well architecture

The well architecture for a deep abnormally pressured vertical well (Figure 1-1) resembles an expanded telescope from the surface down with the largest outside diameter (OD) casing section at the top, followed by successively smaller OD casing sections inside, leading to the deepest and smallest diameter casing at total depth (TD). Each section of casing, starting at the top, isolates the interval of hole that it covers from circulating drilling fluid erosion. The casing also serves to isolate the lower integrity rocks placed behind pipe from the hydrostatic pressure that would be exerted by the typically higher density fluid needed to control higher formation pressures as the well depth increases.

The actual sizing (selecting of the outside and inside diameters of the pipe) of each casing string is done from the inside out, starting with the tubing. The tubing size is selected based on meeting the utility requirements for the well, such as desired producing rate, type of production (oil, gas or both) and operating pressures. Figure 1-2 shows a drawing of a typical deep, completed well with the production tubing running the length of the well from the surface to a depth just above the producing formation. The production tubing string provides the conduit through which the well will be perforated and produced.

A set of seals at the bottom end of the production tubing is stung into a packer or polished bore receptacle (PBR) set above the producing zone to provide pressure isolation between the tubing and casing annulus. The next casing out, or the casing where tubing is run within, is called the production casing. Its purpose is to provide well-pressure containover can be carried out in case of a tubing or completion failure. In sizing the production casing, the engineer should provide sufficient room between the tubing's connection OD and casing's ID to allow washover capability during a workover where the tubing has failed or become stuck. After the production casing is set, a clean, solids-free packer fluid should be circulated and placed in the casing all the way from bottom to the surface. The completion packer should then be installed inside the production casing, unless a polished bore receptacle (PBR) has been installed as part of the production casing string, at a desired depth above the producing zone. When the tubing is run to complete the well, it is landed in the packer or PBR, forming a seal between the anticipated producing flow stream inside the tubing and the production casing annulus, which is left with the light, clean, solids-free packer fluid above the packer or PBR. The setting depth of the production casing is always deeper than the tubing. It is always set across and below the producing zone to provide sufficient rathole (space between the packer and the bottom of the casing) for perforating and other production logging and producing operations.

1.4 Establishing casing setting depths required to drill to TD

Once the production tubing and casing are selected to meet the producing and other utility requirements for the well, they directly impact both the sizing of all outer strings needed to reach the final well depth and the hole size required to accommodate each casing string. After selecting the tubing and production casing, the next step is to select the casing and/or liner shoe depths that will be required to reach the production casing setting depth, starting from the surface. The actual sizing of each string of pipe will wait until after determining how many casing strings or liners will be required, and how deep each shoe will need to be set as the well is drilled down.

1.5 Conductor/conductors setting depth

In a typical land well the first casing string set at the surface is a conductor that can be cemented in a drilled hole or driven using a pile driver. The conductor serves three principle purposes:

- To prevent washout of the hole while drilling surface hole;
- To provide a means for diverting the drilling fluid being circulated down the drill string and returning up the annulus back to the rig circulating system for processing and return back down the well;
- To help, along with the surface casing, suspend the weight of the wellhead and subsequent tubing and casing strings that will be landed in the wellhead. For very heavy casing loads, more than one concentric conductor may need to be set and cemented inside load-bearing mats may be used where the outside conductor can be welded to it to provide some addition support. In an area where there is a possibility of encountering shallow gas while drilling the surface hole, the conductor should be outfitted with a diverter and be set deep enough to provide sufficient shoe integrity to allow diverting of flow a safe distance from the rig using a blooey line.

In offshore wells the first string set is often called the "structural casing." In shallow water depths, moderate but adequate soil strength is common just below the mudline, and the first string is usually driven with a pile driver. Where a hard seafloor exists the structural casing is cemented in a drilled hole. On deepwater wells, soil strength below the mud line is typically low, and the structural casing can be jetted using an internal retrievable downhole motor and bit extending under the casing. Once the desired depth is reached, the motor and bit assembly can then be disengaged from the structural casing and either pulled at this depth or used to drill additional hole to a deeper depth below the initial casing, where a second conductor can then be run and cemented. The depth for setting structural casing will usually depend on soil analysis information. On occasion, particularly when softer formations exist near the surface and when very heavy loads from the casing program are expected, it may be necessary to set more than one conductor. When this is required the procedure discussed above for drilling below the first structural casing string is used to drill the next section of hole to run and cement the concentric conductor back to the mudline. Where preset templates with slots for multiple wells are set on the ocean floor before drilling the wells, the templates are landed and set using piles at each corner that are jetted or drilled and cemented below the mudline to support and hold the structure in place. These templates serve only to help position and make flowline tie-in and control line connections, and to provide a means for accurate spacing of the well casings. The templates are not designed to help support the individual well loads which must be carried entirely by the structural casing and concentric conductors.

1.6 Designing well architecture for a complex well

Figure 1-3 shows formation pressure and fracture gradient curves vs depth for an example well that will be used for the remainder of this discussion. This example is for a land and/or a shallow water depth well (+/- 1,000 ft water depth, though this may vary) where fracture gradient build-up due to overburden begins in the shallow subsurface formations and builds steadily with depth. (In deepwater wells, formation fracture capacity builds very slowly below the sea floor and it can take 3 or 4 casing strings and/or liners just to drill to 6,000-8,000 ft below the mudline. This is because the

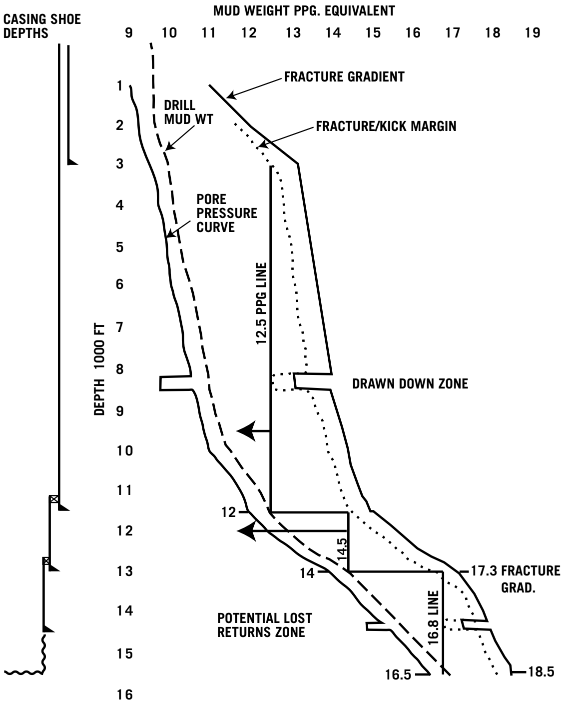

Figure 1-3: Pore pressure, fracture gradient, drill m.w., frac. gradient margin vs. depth for example well case and resulting casing shoe depths.

formation overburden from the rig to the mudline does not exist and is replaced by much lighter sea water, weighing about half of that of rock material, while the fluid in the riser exerts a full hydrostatic head of mud to the wellbore at a given depth all the way from the floating rig circulating system +/- 60 ft above sea level. Often the difference between pore pressure and fracture capacity in the shallow formations is no more than +/- 1 ppg. This results in having to set several casing strings in succession over short drilled intervals to avoid losses to the upper open formations as the mud weight is raised to control increasing pore pressure with deepening. As the well goes deeper and the effect of the formation overburden begins to help compaction and rock strength, the rate of fracture capacity build-up vs pore pressure increases, so that the amount of hole that can be drilled before having to set pipe can be lengthened. Even when this occurs, however, the difference between pore pressure and the fracture gradient of formations in deepwater wells will typically not exceed 2-2 ½ ppg.) The pore pressure and fracture gradient curves for the example well in Figure 1-3 are shown in equivalent pound per gallon mud weights. This example is intentionally complex to help demonstrate how important it is to leave options open to allow for contingencies if the wellbore conditions change from the expected or planned. (A simpler well example showing the process used for selecting the setting depths for casing shoes in a deep

entitled "Casing and Liners For Drilling and Completion," Gulf Drilling Series, Gulf Publishing Co. Refer to Chapter 3, paragraph 3.2.5.)

This example includes a drawn-down zone between 8,200 and 8,500 ft, as might be present when existing production in shallower horizons above the well's projected total depth has reduced formation pressures below the original gradient at that depth. Further, the example includes a potential lost returns zone below 14,200 ft and above 14,500 ft, which is just above the targeted production pay zone, starting at 14,700 ft, and the projected total well depth at 15,500 ft. These complexities have been added to the example case to help show how creative thinking can lead to options necessary to optimally and safely complete a well to its intended target.

1.6.1 Establishing a drilling mud weight schedule and fracture gradient safety factor

The annotated curves on Figure 1-3 show the:

- Well's predicted pore pressure;
- Mud weight for drilling the well (0.5 ppg over pore pressure);
- Predicted fracture gradient;
- Maximum drilling mud weight limit (fracture gradient safety margin) below fracture gradient vs depth that will be used for drilling each section of hole. The fracture gradient safety margin curve ranges from 0.5-0.7 ppg below frac gradient (dependent on regulations and/or knowledge of the area or section being drilled) to allow for handling a well kick, and to allow for surge pressures while tripping, and to account for equivalent circulating density (ECD) while drilling and circulating without fracturing the well. (Computer programs are available in industry for calculating surge and circulating pressures in a well system.)

The operational process used to determine when drilling should stop below each casing shoe is to drill ahead, raising the mud weight as dictated by the increasing pore pressure until the mud weight required is equal to the lowest fracture gradient safety margin allowed for the section of hole being drilled. The lowest fracture gradient margin normally, but not always, allowed occurs at the last open casing shoe above or a short distance below. When the mud weight required to drill deeper reaches this limit, drilling must stop and the section must be cased to protect it from higher hydrostatic pressure that would result from higher mud weights required to drill below this point.

1.6.2 Selecting the surface casing setting depth

Surface casing setting depth is determined by the following two drivers:

- Regulations primarily driven by rules to protect fresh water;
- The fracture gradient for the formations below the shoe, which must be high enough to allow drilling to the next casing point without losing mud, from the hydrostatic head of the mud weight required to drill to the desired depth. Sometimes hole problems from sloughing or swelling formations may force early setting of the surface casing which in turn will change the depth where the next casing will need to be set.

In the example here, planned setting depth for surface casing is 3,000 ft with 9.8-ppg mud in the hole. (Refer to Figure 1-3.) The anticipated fracture gradient at 3,000 ft is 13.2 ppg. Since the data shows that there is a drawn-down producing zone between 8,200 and 8,500 ft that is expected to break down at 13.2 ppg, there is no need to push the surface casing shoe deeper to gain more fracture gradient capability at the shoe. The drawn-down producing zone fracture gradient below 8,200 ft and the shoe fracture gradient at 3,000 ft will both limit how high the mud weight can be increased to push the intermediate hole as pore pressure increases with depth. The 3,000 ft surface casing setting depth also exceeds the fresh water protection regulatory requirement depth.

1.6.3 Drilling below surface casing to the protective casing setting depth

After running and cementing the surface casing at 3,000 ft and nippling up the BOPs, the plan is to drill out the shoe to test for cement integrity and to establish the formation fracture gradient below the shoe. If the test results are good, indicating that the shoe formation integrity is about 13.2 ppg, then drilling ahead can proceed while raising the mud weight as scheduled, based on pore pressure increasing with depth. The plan calls for carrying an 11-ppg mud weight when the hole is drilled across the drawn-down producing zone at 8,500 ft. But below this depth, the well will require increasing the mud weight as drilling proceeds into the transition zone. Depending on the quality of the available information on the fracture gradient for the drawn-down zone, it may be wise to test for hole integrity at this depth up to the mud weight that will be needed to drill and to run and cement casing at the projected setting depth of 11,500 ft. The expected fracture gradient at the drawn down zone is 13.2 ppg, and the fracture gradient safety margin drilling mud weight is 12.5 ppg. The test mud weight for the section should be equal to the required fracture gradient mud weight of 13.2 ppg to ensure that the drilling mud weight of 12.5 ppg will have a safety margin to handle a potential kick and to account for surge pressures and ECD while drilling. The procedure for doing this test would be to slowly raise the mud weight towards 13.2 ppg with the drill string sitting on bottom at the base of the drawn-down zone and to monitor for potential losses. If ECD for the system is 0.2 ppg, then the actual test mud weight of the circulating fluid would be 13 ppg, which, when combined with the ECD, would be equal to 13.2 ppg on bottom.

What are the possible results and consequences of running the weight-up test? If mud losses occur when weighting-up, the drill-ahead plan must be changed accordingly, and the intermediate casing must be set shallower than planned. If the weight-up test is good, then the well can drill ahead while letting the mud weight drift back a little towards the scheduled weight for this depth. As the well gets deeper, it is anticipated that the mud weight must be raised back to 12.5 ppg as the hole approaches a depth of 11,500 ft. Drilling must be stopped when the mud weight reaches 12.5 ppg, because the fracture gradient safety margin will have been reached at both the surface casing shoe and at the drawn down zone depths. As shown on Figure 1-3, the mud weight limit can be displayed graphically as a 12.5 ppg mud gradient vertical line extended upward from 11,500 ft towards the surface casing shoe at 3,000 ft. (Note that both the fracture gradient safety margin at the loss zone depth and at the surface casing shoe are aligned with the 12.5 ppg mud gradient line.)

A protective casing (intermediate) string will be set and cemented at this point from 11,500 ft to the surface and landed and sealed in the wellhead hanger to provide the burst rating capability needed to drill deeper. The lower pressure-rated surface casing will be covered and isolated by the intermediate protective casing, which is designed to handle the mud weights or a kick, should one occur, as drilling proceeds towards the higher geopressured sections of the well below this depth.

1.6.4 Drilling below protective casing towards the next casing point

After cementing the casing and testing the BOPs, the plan will be to drill out the shoe and test for cement integrity and formation leak-off, or fracture gradient capacity at this depth. If the test is good and the fracture gradient is 15 ppg equivalent are greater, as shown in Figure 1-3, drilling ahead can continue. If the leak-off is low, a squeeze is necessary. The fracture gradient safety margin limit at this shoe will be set at 14.5 ppg, a ½ ppg below the fracture gradient. Pressure in this section is expected to build gradually until the mud weight reaches 14.5 ppg at a depth of about 13,000 ft. At this point the mud weight required to control the formation pressures is equal to the fracture gradient safety margin limit at the last casing shoe and drilling must stop to set pipe before drilling ahead. The pipe selected is shown