MATERIALS FOR DEEP OIL AND GAS WELL CONSTRUCTION

Reliable materials for deep well construction must have high strength and corrosion resistance at high temperatures.

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The increasing worldwide demand for oil and gas coupled with the fact that the peak of oil production has been reached or soon will be, has pushed the petroleum industry into drilling ever deeper wells. Well depths of 25,000 ft (7620 m) and greater are no longer unusual, and even deeper wells are expected.

Generally, increasing depth means increasing pressure and temperature. High-pressure/high-temperature (HPHT) wells have generally been considered wells in which temperatures and pressures at the bottom of the well exceed 300 to 350°F (149 to 177°C) and 10,000 psi (69 MPa), respectively. Many HPHT wells have already been drilled and completed in this category with great success and no unusual requirements for special materials.

Figure 1 illustrates some of these successful field applications, in addition to more recent activity in East Texas and the Gulf of Mexico. The industry has had to pursue ever more hostile conditions than the original HPHT limits stated above to keep up with demand. In this case, conditions exceeding 400°F (204°C) and 20,000 psi (138 MPa) at bottomhole have been labeled variously as Extreme HPHT (xHPHT) and Ultra HPHT. (The term HPHT is used throughout this article to include both extreme and ultra.)

This is where challenges will be for both the materials themselves and materials engineers in the petroleum industry for the future. Drilling these HPHT wells requires specialized methods and considerable planning, but the materials have largely remained steel drill pipe and steel components, although other alloys such as titanium are being considered.

However, the real materials challenges are in completing and producing the wells after they are drilled. This is the reason this article focuses on well construction rather than drilling.

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Drilling rig at sunset.

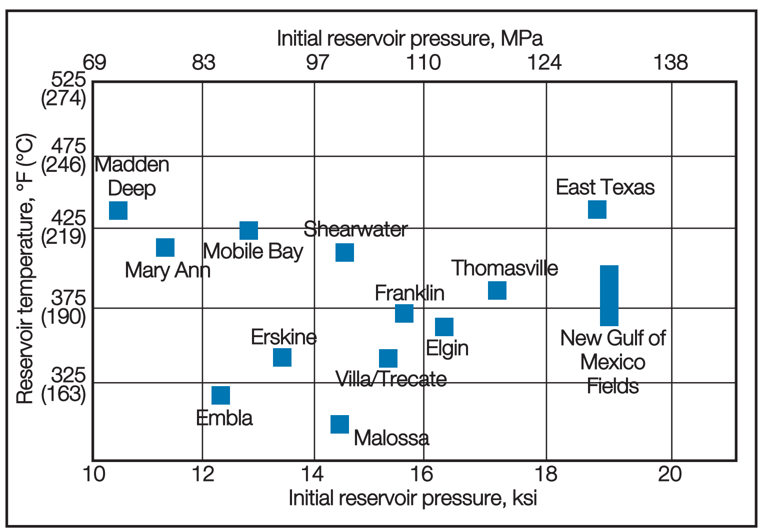

Fig. 1 — Some of the prominent HPHT fields in the world. Updated from Ref. 1.

Liners, tubing, and strings

Figure 2 shows a typical well completion for those unfamiliar with the industry terminology. Surface casing and some of the intermediate casing strings are not affected by HPHT conditions, and thus standard steel tubulars function well.

The major components that require greater attention and represent materials challenges are the liner at the bottom of the well, the tieback casing string, the tubing (and associated jewelry), and the Christmas tree, which is not shown but com-

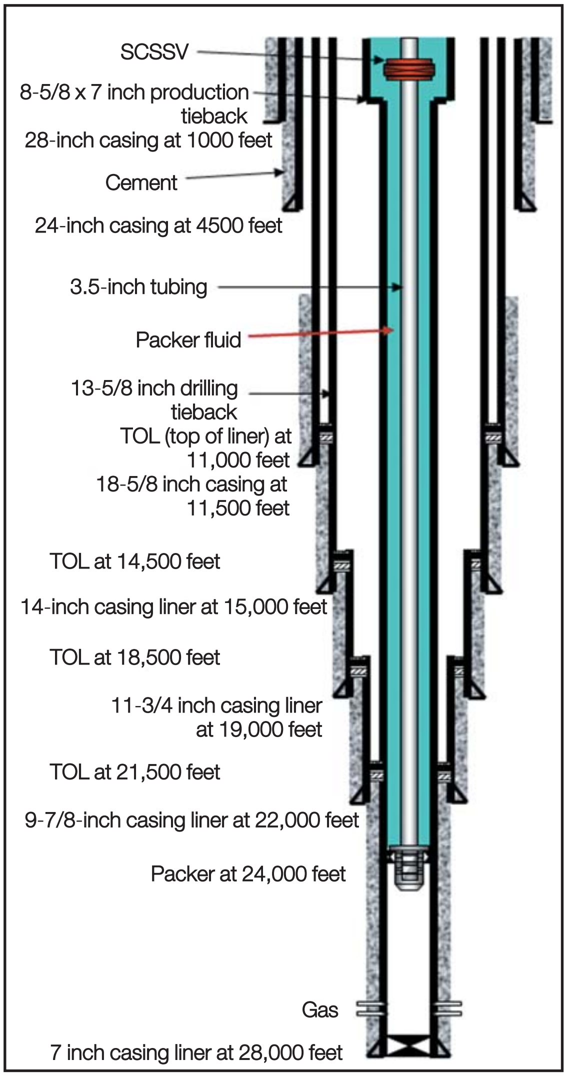

Fig. 2 — Example HPHT well schematic.

prises the stack of valves that go on top of the well to control the flow and the pressure of the well. Depending on the temperature, the pressure, the velocity, and the mix of corrodents present in the gas stream (H_2S and CO_2), materials can range from carbon and low-alloy steels to stainless steels, nickel-base alloys, and titanium alloys.

The specific materials challenges in HPHT wells can be placed in four broad categories:

- mechanical considerations,
- metallurgical issues,
- corrosion resistance, and
- manufacturing capability.

Mechanical considerations for well tubulars generally come down to resisting axial loads, burst, and collapse. These forces define the required strength and wall thickness of the tubulars for a particular application. However, with increasing strength, wall thickness, and rolling practice, anisotropy tends to increase, further complicating casing design.

Complications arise because of insufficient data on tensile properties in the transverse and radial directions of not only steel tubulars, but also, even more so, of cold-worked corrosion-resistant alloys (CRAs).

In addition, as the temperature of the well rises, strength shows a commensurate loss. This loss is also not well documented, but must be accounted for in the well design. It is unacceptable to simply extrapolate data for strength reduction with temperature from 300 to 550°F (149 to 288°C), and then simply hope that this estimate will suffice. Furthermore, the dearth of data for loss in strength with increasing temperature also affects surface equipment such as the wellhead and Christmas tree.

At present, no design guidelines or standards have been developed for 30,000 psi (207 MPa) surface equipment, especially at expected temperatures of 500 to 600°F (260 to 315°C). Furthermore, the current choice of Alloy 625 clad steel will be an unacceptable solution in the future, because the simple mass of steel to contain such high pressures would be so large that it would surpass the weight limits on offshore platforms.

Moreover, under current standards (NACE and API), no low-alloy steels have sufficient hardenability to achieve the strength needed in steel forgings with wall thickness in excess of 12 inches (30.5 cm), but still maintain good fracture toughness and not exceed the NACE MR0175/ISO 15156 hardness limit of HRC 22.

This means that solid forgings of either age-hardenable nickel-base alloys or titanium alloys will be required for surface equipment that must contain high pressure with little loss of strength at high temperatures, be corrosion resistant, and display good fracture toughness. Such alloys must also reduce the weight penalty for offshore applications.

Metallurgy issues

It is apparent that metallurgy issues are an integral part of solving purely mechanical requirements. This is further demonstrated by the limitations of heavy-wall tubulars. The standard steel alloy for casing and tubing that must resist failure from sulfide stress cracking (SSC), as specified by NACE MR0175/ISO 15156, is steel type AISI 4130 and its modifications (such as higher Cr and Mo as well as some Ti, Nb, and B).

However, deeper, higher-pressure wells require that wall thickness of the tubulars be increased, and/or the yield strength must be increased. Since NACE MR0175/ISO 15156 limits the yield strength (via the hardness) to approximately 100,000 psi (690 MPa) maximum, the only other available means to increase the resistance to mechanical loads is by increasing wall thickness.

In reality, this approach is also limited because of the hardenability limitations of alloys such as modified 4130. After the wall thickness exceeds about one inch (25.4 mm), the inability to fully through-harden steel tubulars leads to poor SSC resistance, which cannot be tolerated in high-pressure wells. The industry is now at a serious crossroad of trying to maintain mechanical integrity in HPHT wells and still meet the strict limitations on yield strength required by NACE MR0175/ISO 15156.

At present, no easy solutions that involve low

Table 1 — Corrosion-resistant alloys for casing liners and tubing

Group	Alloy (common name)	Nominal composition, wt %
Martensitic stainless steels	410, 420 (13Cr)	12Cr
Super martensitic stainless steels	Super/Hyper 13Cr	12-13Cr, 4-5 Ni, 1-2Mo
Duplex stainless steels	2205	22Cr, 6 Ni, 3Mo
Super duplex stainless steels	2507, DP3W	25Cr, 7 Ni, 3.5Mo, N, W
Nickel-base alloys	825, 2242	22Cr, 42 Ni, 3 Mo
	2550	25Cr, 50 Ni, 8Mo, 2 W, 1 Cu
	G50	20Cr, 52 Ni, 9Mo
	C276	15Cr, 65 Ni, 16 Mo, 4 W
	718	20 Cr, 52 Ni, 3 Mo, 5 Cb, 1 Ti, 0.6 Al
	925	21 Cr, 42 Ni, 3 Mo, 2 Ti, 2 Cu, 0.4 Al
	725	20 Cr, 57 Ni, 8 Mo, 3 Cb, 1.5 Ti
Titanium alloys	Grade 5 (Ti-6-4)	6 Al, 4V
	Ti-6-2-4-6	6 Al, 2 Sn, 4 Zr, 6 Mo
	Grade 19 (Beta C)	3 Al, 8 V, 6 Cr, 4 Zr, 4 Mo

alloy steels are available; the only acceptable alloys are high-strength CRAs such as martensitic and duplex stainless steels, nickel-base alloys, and titanium alloys. However, NACE MR0175/ISO 15156 arbitrarily caps the service temperatures of nickel-base alloys and the duplex stainless steels at 450°F (232°C) maximum, but has no similar restrictions for carbon and low alloy steels. Table 1 presents some of the many alloys currently available or planned for tubing strings, casing liners, and other accessories. Because of the strength-versus-hardness dilemma, current HPHT wells are faced with the possibility of CRA casing tieback strings (see Figure 2) but at great cost compared to low-alloy steels.

Another important metallurgical concern for which little or no data are available is the potential for deleterious phases to form during long-term well aging at temperatures in excess of 400°F (204°C), primarily for the CRAs. The aging of stainless steels and nickel-base alloys over 20 to 30 years of exposure may encourage the precipitation of phases such as Sigma, Mu, and Laves, which could lower fracture toughness and strength. Likewise, titanium alloys are expected to be susceptible to further aging under long-term exposure in HPHT well conditions, but with unknown results.

Coupled with all of the above mechanical considerations is the need for the primary path for conveyance of the oil and gas to the surface (casing liner and tubing) to be corrosion resistant, and most often to meet the requirements of NACE MR0175/ISO 15156. Little data are available for the corrosion resistance of the CRAs listed in Table 1 at temperatures that exceed ~ 450°F (232°C), and even less above this temperature.

Although titanium alloys such as Ti-6Al-4V and Ti-6-2-4-6 appear to have the requisite corrosion resistance under HPHT conditions, very limited data exists to support this notion. Thus, considerable laboratory testing is still needed for titanium alloys as well as many of the current nickel-base alloys under these more extreme HPHT conditions.

Finally, manufacturers are currently limited in the production of large-diameter CRA tubes with high strength (stainless steels and nickel alloys) that must be cold worked to achieve the needed strength for such deep wells. The emerging need for tubing strings and casing tieback strings with nominal outside diameters of 8-5/8, 9-5/8, and 10-3/4 inches is, for the present, limited by the lack of worldwide capability to actually produce these large diameter strings and still maintain suitable strength and usable lengths of 30 to 40 ft (9 to 12 m).

The future needs for reliable materials in deep HPHT wells around the world are already here, since drilling of such wells is in progress or in some cases has already been completed. However, because of materials requirements and the lack of sufficient data under HPHT conditions, the industry is limited in its ability to produce oil and gas from these wells. These ever more-severe well conditions may, in fact, surpass the ability of nickel-base alloys and titanium alloys to function satisfactorily for the long term . Thus, completely new materials that have not been applied in the petroleum industry up to this time may be required.

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Reference

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