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Aphron-Base Drilling Fluid: Evolving Technologies for Lost Circulation Control

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Abstract

Drilling depleted reservoirs is fraught with a host of technical and economic problems that often make it unprofitable to further develop some mature fields. Most of the problems center around uncontrollable losses in the large fractures that commonly characterize these reservoirs. Frequently, less expensive drilling fluids will be used in a particular interval, even though it may have the propensity to damage the formation. The reasoning holds that such fluids will offset the high costs of losing more expensive muds to the formation.

A specialized invasion control drilling fluid has been developed to drill reservoirs prone to lost circulation. This fluid combines certain surfactants and polymers to create a system of "micro-bubbles" known as aphrons that are encapsulated in a uniquely viscosified system. These aphrons are non-coalescing, thereby creating a micro-bubble network for stopping or slowing the entry of fluids into the formation. The unique viscosity builds to create a resistance to movement into and through the zone, thus generating a true non-invasive and at-balance fluid. Test data confirms its enhanced hole cleaning and suspension properties.

This paper describes the development and application of the specialized "micro-bubbles"-base drilling fluid for controlling downhole mud loss and formation damage. The authors will detail the laboratory methods used to generate appropriate formulations, the operational procedures, and field applications.

As detailed in the paper, this novel drilling fluid relies entirely on "micro-bubbles" network bridging and does not contain any conventional particulate agent for sealing the loss zone. Therefore, the fluid can be pumped through narrow drill pipe, coil tubing and downhole tools. Case histories show that drilling problems are reduced, while drilling fluid losses are prevented or minimized dramatically.

Introduction

The drilling problems associated with the depleted reservoirs intrinsic to many of the mature fields throughout the world often make further development uneconomical. The water-wet sands that typify many of these zones propagate seepage losses and differential sticking, both of which are extremely expensive to correct. Uncontrollable drilling fluid losses frequently are unavoidable in the often large fractures characteristic of these formations. Furthermore, the typical laminated sand and shale sequences create conditions that can make drilling unduly expensive and dangerous when using conventional rig equipment. Consequently, these and a host of associated problems have led some operators to forgo continued development of these promising, yet problematic, reservoirs.

The overbalance pressure generated when using conventional drilling fluids is to blame for the majority of the loss circulation and differential sticking problems encountered when drilling these wells. The equipment required when using aerated muds or drilling underbalanced is often prohibitively expensive and meeting safety requirements can be an exhaustive effort. Furthermore, these techniques may fail to provide the hydrostatic pressure necessary to safely stabilize normally-pressured formations above the reservoir.

Recently, aphron (micro-bubble) fluid technology was employed to successfully drill depleted reservoirs in a major drilling campaign in California. Aphron technology entails the creation of a micro-bubble environment to control fluid invasion into the rock. The density of the fluid is not reduced substantially and no special equipment is required. Besides California, the technology has been used extensively in North and South America to drill fractured and depleted zones. The use of aphron-base drilling fluids has proved to be a successful and cost-effective alternative to drilling underbalanced.

Aphron Structure Description

An aphron comprises two fundamental elements:[1]

- A core that is commonly, but not always, spherical. Typically, the core is liquid or gaseous.
- A thin aqueous protective shell

The aqueous shell contains surfactant molecules positioned so that they produce an effective barrier against coalescence with adjacent aphrons. As illustrated in Fig. 1, the encapsulated shell protects the aphrons, which can attract one another to build up complex aggregates. It should be noted that the encapsulating soap film has both an inner and outer surface.[1] This phase has oriented surfactant molecules at the surface that are hydrophil pointing inwards and hydrophobe outwards.

Physically, the bubble in Fig. 2 is a sphere of gas separated from its surroundings by a thin soapy film. The hydrophilic head of the surfactant distributed on the molecular monolayer is oriented towards the bulk water, while its lipophilic tail is oriented towards the gas core[1]. Thus, the foam (Fig. 2) has a water-wet or hydrophilic boundary as opposed to the aphron, which has a hydrophobe boundary.

The advantage of gas-core aphrons is that they lump together, creating large aggregates. Perhaps surprisingly, these macro-structures behave in the same manner as the individual aphron (Fig. 3).

Through the meniscus that wraps all the individual colloidal gas aphrons, this macro-structure has the same liphophilic character and, to a certain degree, is believed to exhibit the same behavior when in contact with a water-wet formation[1].

The "meniscus wrapping theory" is literally endorsed by the mechanism known as "Laplace Pressure." This theory simply states that when a flat liphophilic surface (i.e., plateau border from the aphron structure) dips into a water-wet liquid a contact angle will exist where the liquid and gas meet[1]. If two such "liphophilic charges" are close together, the effect of the two contact angles will be the generation of a curvature of the liquid surface between those two liphophilic droplets. This is known as a meniscus. This mechanism may cause the aphron macro-aggregate to be wrapped with a meniscus with the liphophilic character.

Aphron structure stability

The water lamella in the aphron structure will remain stable as long as the water film is viscosified and the minimum and maximum thickness criteria is respected[1].

First, a certain thickness is required for the water lamella to remain stable. According to the Thin Soap Film Thickness study by Clunie, et al[2], the water/film lamella is not stable if it is thinner than four microns or thicker than 10 microns. The study states in part that a minimum thickness created by the interaction between the water molecules and the hydrophilic parts of the surfactant must exist. As this "critical thickness" is altered, such as through the stretching effects when the aphron volume increases, the soap film will break.

Another phenomenon plays an important role in water lamella stability. This one has been described as "rate of transfer", which can be affected by the "Marangoni effect"[1, 3]. The water molecules from the lamella tend to leave the film and return to the bulk water (continuous phase). By viscosifying the water through the addition of a biopolymer the rate of transfer is reduced to a point where the aphron structure is stabilized.

Aphron structure is an energized micro-environment

An aphron is much more than a "gas bubble". The viscosified water lamella, in tandem with the surfactant layers, creates an "energized environment." First, when an aphron is generated inside a liquid, a new surface must be created, which increases in area in proportion with the growth of the bubble[1]. This expansion must be balanced by an increase in the pressure within the bubble (Laplace pressure), thus explaining why the aphron is associated with an "energized environment" or "pre-compressed structure."

Aphrons contain a gas nucleus of encapsulated air and compress when circulated down hole. The internal pressure of these micro-bubbles increases at a rate proportional to the external pressure being applied (Fig. 4). The combination of increasing pressure and temperature serve to energize the individual aphrons.

Once the drilling bit exposes a depleted formation, the aphrons immediately aggregate within the openings of low-pressure zones. There, a portion of the energy stored within each aphron is released, causing it to expand. The expansion continues until the internal and external pressures on the wall of the aphron are in balance. Figure 5 illustrates this energizing process.

As the energized micro-bubbles enter formation openings, they carry energy equal to that of the annulus. As the aphrons crowd into the openings, external Laplace forces increase dramatically, causing aggregation and an increase in Low Shear-Rate Viscosity (LSRV). The micro-environment created by this phenomenon forms a solids-free bridge.

Aphron bridging mechanism

The vast majority of reservoir formations are water-wet. As the oil/liphophilic phase is displaced by water, which wets the rock surfaces, capillary pressure is a driving force. An insular globule of non-wetting fluid moves only by virtue of the differential pressure applied across it within a moving wetting fluid[4, 5]. Before a globule can be displaced, this pressure differential must be sufficient to squeeze it through capillary restrictions, which offers resistance. The resistance to squeezing is known as the Jamin effect[6], which Gardescu[7] studied in detail. Gardescu showed the resistance offered to fluid displacement by a bubble of non-wetting fluid when squeezed from its original radius to the constriction radius to be[5, 7]:

$$\Delta p = 2\delta\,(1/r_1 - 1/r_2)$$

where,

Δp = capillary pressure (resistance)
δ = interfacial tension
r_1 = constriction (capillary) radius
r_2 = original radius

Although the Δp may be very small for a single bubble, the cumulative resistance of many bubbles may be large[4]. Based on the experiments conducted by the previously mentioned investigators, in view of the interconnected nature of the fractures/pores network in a porous medium it appears impossible to apply sufficiently large pressure gradients in the wetting phase[5].

Consider now these two concepts: the hydrophobic character of the colloidal gas aphron structure and the Jamin effect.

The aphron acts as a non-wetting fluid on a water-wet formation, while the Jamin effect prohibits it from entering the pore throats or fractures. However, it can be argued that the aphrons are working only at the capillary dimensions. Thus, what happens in the event the fractures or the pore throats are larger than the dimensions of the capillary? If it is subject to the Jamin effect, this is a limitation of the previously discussed theory and the questions are justified.

Aphron system composition

Table 1 shows the components of a typical aphron system. As shown, the high-LSRV base fluid consists of a high-yield stress-shear-thinning (HYSST) polymer coupled with fluid loss control additives that create and stabilize the aphrons within the system. An aphronizer surfactant is incorporated to achieve the desired concentration of micro-bubbles, which typically range from 8 – 14% by volume. As the concentration builds, it is not uncommon to observe an increase in the Brookfield LSRV to between 120,000 and 160,000 cP.

Once the system is circulated, the rheological properties are easily maintained to provide optimum hole cleaning, cutttings suspension and a high degree of control over the invasion of whole drilling fluid.

The organic and biodegradable polymers and non-caustic pH materials in the system have allowed it to meet Gulf of Mexico bioassay and Canadian micro-toxicity requirements.

California field experience

At this writing, aphron-base fluid invasion control systems had been used successfully in hundreds of wells worldwide. Because of its proven ability to allow operators to effectively and economically drill highly depleted formations, it was chosen to drill a highly fractured sand in Occidental's Elk Hills Operations near Bakersfield, CA (Fig. 6).

With its purchase for U.S.$3.52 billion, Elk Hills represents the largest divestiture of federal-owned property in the nation's history. Occidental holds a 78% interest in the property, which as of mid-2001 included 1,450 producing wells. More than 3,000 wells have been drilled on the 47,000-acre (75 sq miles) location.

The latest drilling campaign has targeted the 26R Miocene sands (Fig. 7), which are steeply dipping turbidite sandstone reservoirs. The sands contain separate reservoir units featuring distinct gas, oil and water contacts. The average permeability is 150-250 md with an average porosity of 23%. Many of the historical drilling problems are attributed to the average low reservoir pressure of 2.3 lb/gal equivalent mud weight (750 psi at 6,300-ft TVD).

Figure 8 is a schematic of the typical wellbore configuration in the Elk Hills operation. As shown, most of the wells are slotted liner completions requiring a non-damaging reservoir drill-in fluid.

Previously, the 26R reservoir was drilled with either an unweighted rheologically engineered water-base drill-in fluid system or a mineral oil-base drilling fluid. Historically, mud losses in the reservoir ranged from total to moderate (6-10 bbl/hr).

An 8.4 lb/gal solids-free reservoir drill-in fluid, containing 3% KCl to achieve the lowest possible weight, was first used on Well 334XH. Drilling fluid losses of more than 200 bbl/hr were encountered while drilling the lateral. Sized calcium carbonate pills (50 lb/bbl) were spotted through a bypass sub on top of the MWD and mud motor, which reduced losses to 40-50 bbl/hr. The persistent addition of calcium carbonate allowed drilling to continue with moderate losses. Nevertheless, 6,600 bbl were lost in the 500 ft drilled over six days.

Owing to the high losses and the cost of the rheologically engineered drill-in system, it was replaced with a low-solids, non-dispersed bentonite system. After spotting a 60 lb/bbl lost circulation pill, full returns were established and the lost circulation material was discarded at the shale shakers. Drilling resumed with a directional assembly with average losses of 10-15 bbl/hr. While the targeted TD was reached, clean-up was very difficult because of the clay-based system used in the lateral portion of the hole and the slotted liner completion.

The mineral oil-base system was employed on the next three wells (336H, 356XH and 312H). In those wells, losses ranged from 1,400 to 6,500 bbl/well. On another, a gel-based drilling fluid system was used, but circulation was never regained and the well was abandoned. On the average, drilling the highly depleted reservoir resulted in water-base and oil-base drilling fluid losses of 3,500 bbl/well.

In an attempt to minimize the downhole losses and successfully reach the target, the operator switched to a weighted 9.8 lb/gal aphron system. In a subsequent well the operator employed an un-weighted 8.4 lb/gal aphron-base drilling fluid system.

Both systems were mixed at the rigsite and mud plant. All the components mixed easily and no "fish eyes" were observed, despite the rapid mixing required at the rig site to maintain volume. Further, the micro-bubbles in the system had little effect on the pumps, MWD or mud motors. The shear-thinning characteristics of the fluid allowed for maximum efficiency of the solids control equipment.

Table 2 compares the final properties of the unweighted and weighted systems. The aphron system reduced losses per well to an average of 1,500 bbl with a typical 10% reduction in drilling time. More importantly, the operator was able to successfully reach the targeted TD, which had not been possible in many of the earlier wells because of the inability to regain and maintain circulation.

Conclusions and Lessons Learned

The driving forces behind using the aphron-base drilling fluid system was to minimize downhole losses and allow the operator to reach the TD objective in the troublesome 26R sands of the Elk Hills operation. Both of these objectives were achieved. The experience on the two Elk Hill wells also led to a number of recommendations that could further improve performance on future projects:

- It is imperative to properly match the pore pressure with the fluid density. Drilling in an excessively overbalanced condition can exceed the ability of the aphron system to prevent and/or control losses into the formation.
- Whether using an unweighted or weighted system, choosing the appropriate candidate reservoir is critical. The ideal targeted formation for the aphron system is one with highly tortuous pore throats or fractures, which will permit the aphrons to form a bridge.
- The LSRV should always be maintained at more than 50,000cp. If the LSRV drops, it is highly recommended that drilling be suspended until the mud properties are restored. Since the system relies on high-viscosity lamella for aphron structure stability, a certain level of LSRV is essential at all times for optimum bridging.
- Even with an unweighted system, it is important to consider the surfactant depletion as it is consumed on the drill cuttings and/or in the borehole. Indequate surfactant concentration can lead to increased downhole losses.

Acknowledgements

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SI Metric Conversion Factors

bbl	X 1.5897	E-01 = m^3	
°F	X (°F-32) X 5/9 = °C		
ft	X 3.048	E-01 = meters	
gal	X 3.785	E-03 = m^3	
in	X 2.540	E-02 = meters	
lb	X 4.536	E-01 = kg	
ppb	X 2.853	E+00= kg/m^3	
ppg	X 1.198	E+02= kg/m^3	
ppg	X 1.198	E-01 = Specific Gravity (SG)	

Table 1 – Formulation of a typical aphron system

Component	Functions	Formulation
Base fluid (freshwater or brine)	Provides continuous phase for system	0.974 bbl/final bbl
Soda ash	Hardness buffer	0.25 lb/bbl
Biopolymer blend	Viscosifier	5.0 lb/bbl
Polymer blend	Fluid-loss control and thermal stabilization	5.0 lb/bbl
pH buffer	PH control	0.5 lb/bbl
Surfactant	Aphronizer	1.0 lb/bbl
Biocide	Biocide	5.0 gal/100 bbl

Table 2 – Comparison of the properties of the aphron systems used at Elk Hills

System properties	Unweighted system	Weighed system
Drilling fluid density (lb/gal)	8.6	10.5
Plastic viscosity (cP)	9	11
Yield point (lb/100 ft^2)	47	52
10sec/10min (lb/100 ft^2)	28/34	23/27
Fluid loss (cc/30 min)	9.0	11.0
LSRV (cP)	60,000+	40,000+

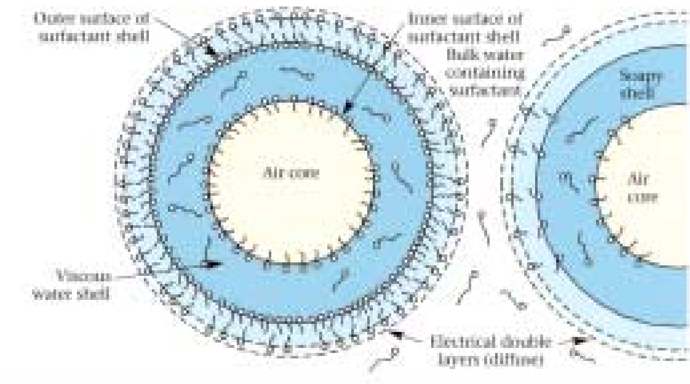

Fig. 1 – Structure of colloidal gas aphron[1]

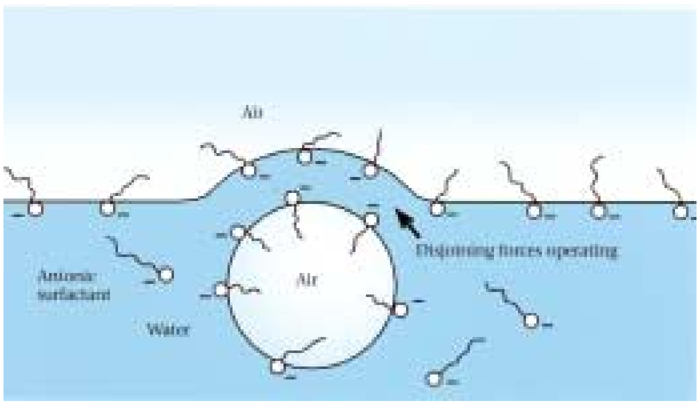

Fig. 2 – Structure of standard foam[1]

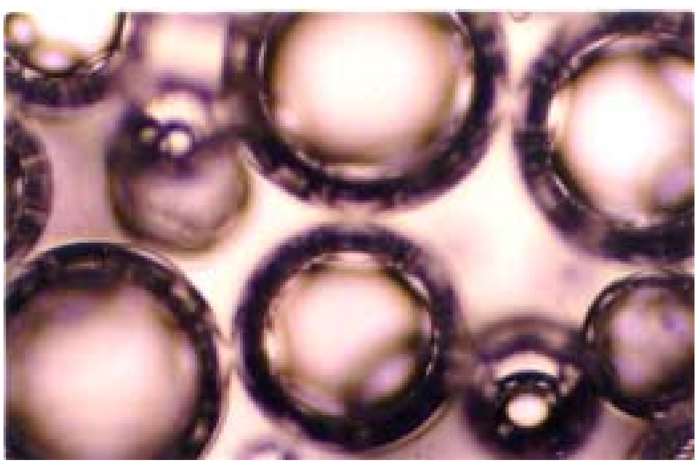

Fig. 3 – The gas-core aphrons can lump together, creating large aggregates and these macro-structures behave in the same manner as the individual aphron

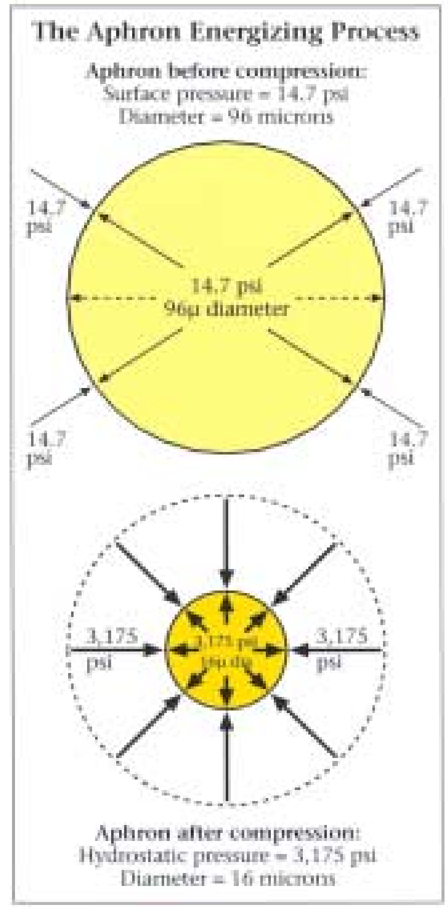

Fig. 4 – The aphron energizing process

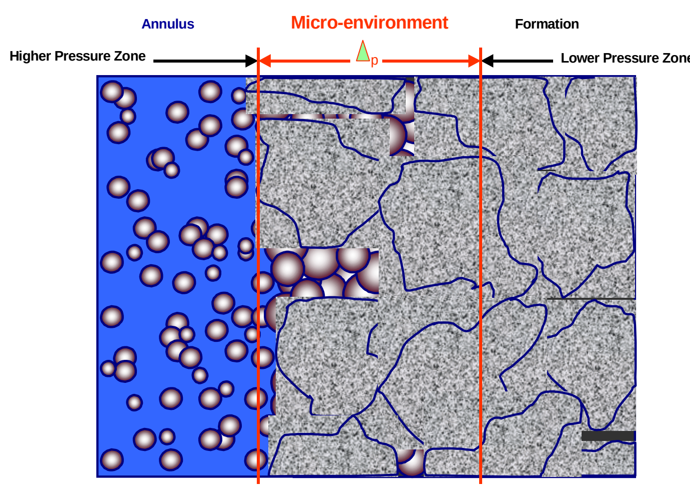

Fig. 5 – When the bit enters a low-pressure zone, the energized aphrons aggregate instantaneously within the formation, creating a micro-environment bridge, preventing invasion of whole drilling fluid, filtrate and solids

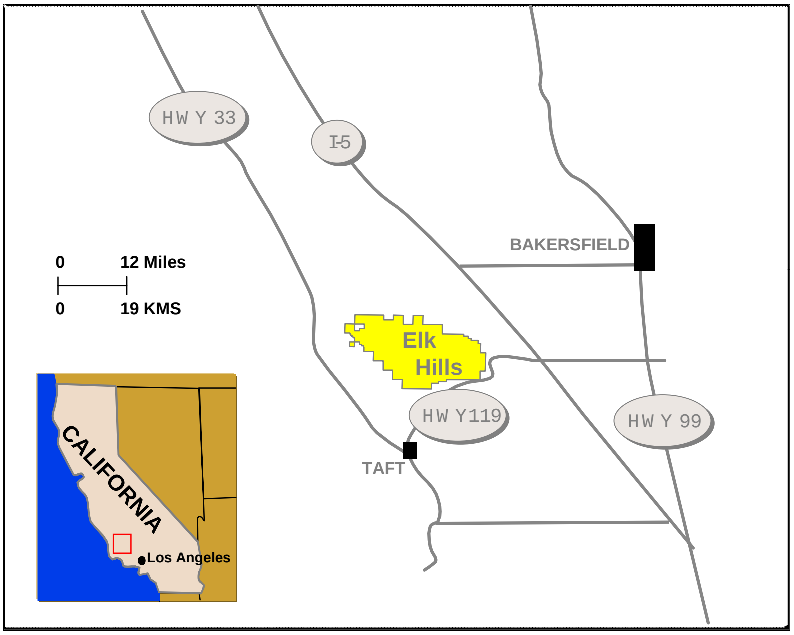

Fig. 6 – Location of Elk Hills operation

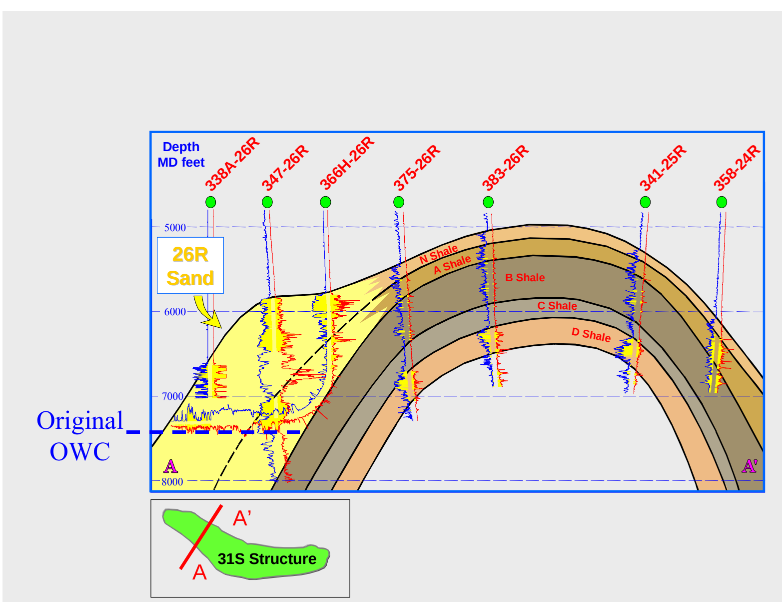

Fig. 7 – The 26R Miocene sands are steeply dipping turbidite sandstone reservoirs.

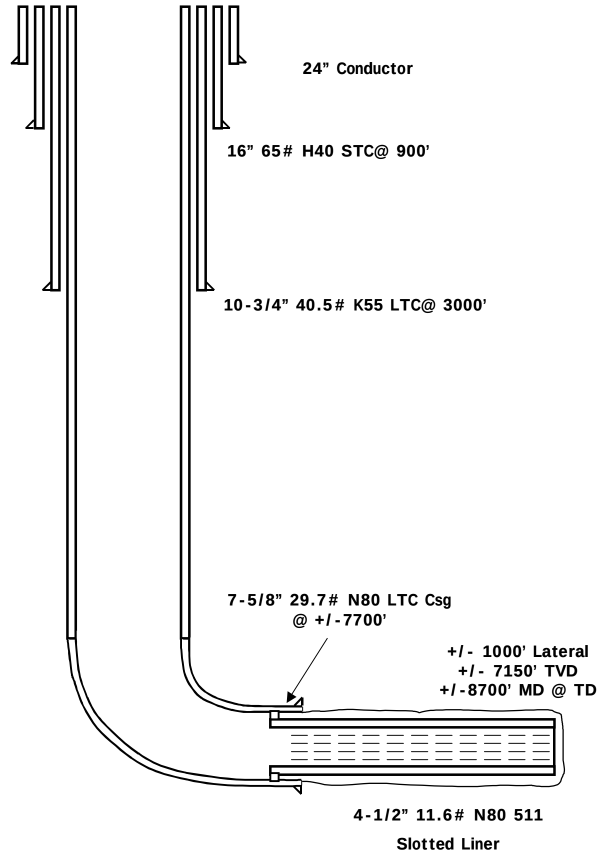

Fig. 8 – Typical Elk Hills well construction