Southwestern Petroleum Short Course

A Technique For Obtaining InSitu Saturations Of Underpressured Reservoirs

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ABSTRACT

Pressure coring offers a method for obtaining InSitu reservoir Saturations. However due to the requirement of pressure balance during coring it has henceforth been limited to use in reservoirs with pressure gradients greater than 0.25 psi per foot. This paper will describe techniques used to obtain the first known successful pressure cores taken using a foam mud system; thereby extending the useful range of pressure coring to under-pressured reservoirs. Stable foam is a compressable Non-Newtonian fluid that requires special design considerations when used in conjunction with pressure coring. Careful well design is necessary to insure bottom hole pressure during drilling and coring operations does not fall below reservoir pressure. This can easily occur if foam degradation and nonlinear pressure gradients are not considered. A complete technique for using foam to pressure core, including well design, field implementation, and core handling is presented in this paper. This technique includes a well bore design, a pressure analysis method, a method of selecting optimal foam design, a description of logistics, an empirical calibration test, and a description of pressure coring operations and core handling.

INTRODUCTION

The Wellman Unit is located approximately 12 miles southwest of Brownfield, Texas and was discovered in the early 1950°s. It is a reefal Wolfcamp feature on the northwest edge of the horseshoe atoll. The reservoir is fairly small in areal extent, covering only 1320 productive acres, but has a gross thickness at the center of the feature of nearly 800 ft. Due to this large thickness the reservoir has been estimated to have contained an original oil in place

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of 100-175 MMBO. It has a moderately active waterdrive and from discovery until unitization, in December of 1978, was produced under primary depletion methods with an allowable of approximately 7300 BOPD. After unitization in December of 1978, Union Texas Petroleum Corporation became operator and initiated secondary recovery pressure maintaince operations in July of 1979. Pressure response was almost immediate and the allowable was subsequently raised to 9300 BOPD. Original reservoir pressure was 4100 psi at 9300 ft., but under primary depletion the pressure had declined to 1050 psi. Since this was below the original bubble point pressure (estimated to be approximately 1300 psi), a small secondary gas cap was formed at the crest of the structure. Subsequent to the successful implementation of secondary recovery operations, it was concluded that tertiary recovery evaluations should be begun. This tertiary recovery study hinged on accurate residual oil saturation values for both the secondary gas cap and below the water-oil contact.

In April of 1980 engineering design was begun to develop a method of obtaining these required residual oil saturations. Discussions with tertiary recovery consultants indicated that pressure coring would be the most accurate method for obtaining residual saturations and InSitu GOR°s at the Wellman Unit. This assumed that a practical method could be found to obtain the pressure cores. The major problem stemmed from the fact that pressure balance is an absolute requirement for successful pressure coring. Too large an overbalance during coring operations will result in flushing of the core with mud filtrate, thereby altering the core saturations and properties. Underbalance during coring operations will result in an exuding of core fluids and alter the InSitu saturations. In order to obtain pressure balance at the Wellman Unit a bottom hole coring pressure of approximately 1250 psi would be required at 9200 ft. This yields a 0.14 psi per foot hydrostatic pressure gradient, or approximately 2.6 lb/gal equivalent fluid weight. With this requirement in mind figure 1 indicates that the only acceptable drilling fluid to obtain the 2.6 lb/gal gradient would be a foam system. Investigations, however have indicated that this use of foam as a pressure coring media had never been successfully performed. As a result there were many unknown elements concerning foam behavior during coring operations. Most importantly, it is necessary to be able to predict bottom hole pressure behavior during coring operations, resulting from surface variations in foam composition and annular back pressure.

THEORY

When a conventional core is cut, and brought to the surface the pressure on that core and fluids in it is gradually reduced from reservoir pressure to atmospheric pressure. During this pressure reduction dissolved gases in the fluids are liberated and flush much of the liquid saturation out of the core. For this reason conventional core saturation data is not an accurate representation of bottom hole conditions. To obtain a core which would have saturations equivalent to those of the reservoir, it was necessary to develop a technique to maintain reservoir pressure on the core until such time as it could be analyzed in the laboratory. In 1970 Exxon Production Research Company was granted a patent for the pressure core barrel. This barrel is similar to a conventional core barrel in that it consists of a stationary inside barrel and rotating outside barrel to cut the core. The major difference, however, is that the barrel may be tripped to close a valve at the top and the bottom of the barrel at bottom hole conditions. In this manner the reservoir pressure and fluid saturations may be maintained as the core is brought from reservoir pressure and temperature to surface pressure and temperature. Once on the surface the entire barrel is frozen in its sealed condition to immobilize the fluids and trap any of the free gas saturation. Once frozen into an immobile state the core may then be depressurized. The inner barrel is removed from the outer barrel and sent to the laboratory for analysis. At the laboratory the inner barrel is stripped from the actual core. The core is sectioned into appropriate lengths, placed in a sealed chamber and allowed to thaw out. During this thawing process the evolved gas and liquids are collected and measured. The remainder of the core is then analyzed for saturations in a conventional manner. A summing is then performed to determine original reservoir saturation conditions.

One of the most critical requirements for successful pressure coring operations is an accurate bottom hole pressure balance, as stated before, and the fluid properties of the coring fluid. McFall (1) has described the ideal pressure coring fluid as one which exhibits minimum invasion in an overbalanced condition, is nonreactive with reservoir rocks and fluids, provides good drilling properties, is stable, has a low freezing point to allow easy removal of frozen cores, and has a moderate viscosity to prevent a large change between static and dynamic bottom hole pressures. It is perhaps the last point which is one of the more critical concerns in the selection of a coring fluid. The dynamic bottom hole pressure must be accurate, predictable and not substantially greater than the static (or pseudostatic) bottom hole pressure. This requirement is due to the nature of the trip mechanism which closes the valves to trap the core in its pressured state. In order to trip the core barrel and close these valves a steel ball must be dropped down the drill pipe, to engage a sliding mechanism in the top of the barrel. In order for this to be accomplished the coring and associated fluid pumping must be stopped until the ball is inserted and sent to bottom. Therefore the core will be cut under the dynamic coring pressure exhibited by the fluid but will be trapped at the static pressure that is present when the barrel is tripped. It is quite conceivable that if the dynamic and static pressures vary dramatically that the core could be flushed while being cut and yet caught in an under-pressured condition. This was one of the major considerations to be evaluated before foam could be used as a pressure coring media. Lorenz (2) defines a stable foam as a completly mixed, liquid external, air-liquid mixture of a homogeneous nature. Stable foam as a drilling media was introduced in 1970 by Chevron Research Company, and has been successfully used for many years. Primarily foam has been used as a workover fluid to reduce hydrostatic pressure. This increases the amount of underbalance during drilling and increases penatration rate. Additionally, foam has a very good solids carrying capability for use in situations where a low annular velocity is expected.

Under normal conditions a stable foam is a Non-Newtonian, compressable fluid which behaves as a Bingham plastic fluid (3). Reference 3 served as an initial guideline for determining the proper method to evaluate both dynamic and static bottom hole conditions for foam. Further it demonstrates the nonlinear nature of foam and reinforces the necessity for computer solution. Using the charts presented in this reference it was ascertained that air rates of less than 500 scf/min would be sufficient to provide enough stable foam for coring operations. This indicated that a single compressor-foam generator package should be sufficient for most applications to 10,000 ft. Millhone, et al (4) has presented evidence that over this expected air injection rate (i.e. 300 to 500 scf/min), the change in bottom hole pressure should be reasonably linear through a small rate change. Additionally, a change in liquid injection rate for a given air injection rate results in a reasonably predictable bottom hole pressure behavior. This allows a limited amount of empirical or field measurements to be applied to and adjust any computer solutions. The requirements, beyond bottom hole pressure, for a foam as a coring fluid would be predictable and repeatable foam quality , a stable foam regime from top to bottom, and an easily adjustable and predictable foam analysis method to compensate for changes in reservoir conditions during coring operations (i.e. an influx of gas, water or lost circulation). The basic theories of both foam as a drilling media and pressure coring operations are compatible. However, to date there has been little investigation done into the properties of foam which affect the ability to obtain a successful pressure core. The depth of invasion of foam as a coring fluid has considerable impact on its use as a coring fluid. It was hypothesized that being a fluid external air-fluid mix, the bubble size should be reduced as the foam was compressed but as long as the pressure did not reach the collapse point of the bubble, the bubbles and their entrained fluid should remain reasonably larger than the pore throat size of the rock matrix. This would limit or prevent invasion of the core. In order to substantiate this hypothesis it was decided that during coring operations the fluid used to mix the foam would be tagged with a tracer material. The core would then be analyzed for invasion. Another area in which little data was available was the effect of foam on the pressure core barrel O-ring sealing surfaces. Both cooling and lubricity problems could exist when used in conjunction with the Stratapax (tm) coring bit. Laboratory tests were designed and run by the pressure coring contractor and indicated general compatibility. Full compatibility would require an actual field test, however. The rate of collapse of the foam under static conditions was also another area of both concern and insufficient data. A high collapse rate would create a rapidly declining bottom hole pressure during the shut down to trip the core barrel and a very slow collapse rate would allow foam build up on the surface during coring operations. An empirical test to measure the bottom hole pressure and rate of pressure decline in the foam during the 10 minute barrel trip time was devised. This test was scheduled to be run prior to pressure coring operations. In order to prevent the build up of foam on the surface should the breakdown take too long, a foam breaker tank was connected into the flowline and through check valves to a flare line. This tank would then hold the foam during its collapsing period and would allow a diesel based foam breaker to be introduced at the surface to aid in the separation of liquid from gas. Internal to the pressure core barrel is a coring gel which fills the inner barrel and is displaced as the core is cut. The chemical reaction between the foam and this coring gel was also to be considered.

DESIGN AND EQUIPMENT

In order to undertake a foam pressure core there are five major groups of equipment which must be evaluated and specified independently prior to their organization into a complete system. These are: 1. Drilling rig and associated equipment. 2. Foam generating unit and associated equipment. 3. Tracer survey fluid and storage. 4. Pressure core barrels and equipment. 5. Bottom hole pressure measuring equipment.

Figure 2 illustrates the blowout preventer and rotating head arrangement required for pressure coring operations. In order to properly maintain bottom hole pressure while using foam, a good rotating head capable of holding up to 500 psi of back pressure is required. Additionally valves should be installed on the conventional flowline so that fluid may be either diverted over the shale shaker in normal operations or through the back pressure choke on the foam line during coring operations. Any killing fluids which might be pumped behind or after the foam will be substantially heavier than the foam; it is very possible for the well to go on a vacuum. In this condition, unless a full opening double check valve arrangement is installed somewhere between the flare and the rotating head in the foam line it is possible for the flare to be drawn through the foam line and down into the well bore. For this reason the flowline check must not be eliminated.

The foam unit selected was self contained and could supply up to 450 scf/min of air and up to 32 gal/min of soap solution. Both air and soap were pumped into a foam generator whose output was then connected through a valve arrangement into the discharge line of the conventional rig mud pump and then into the stand pipe line. Additionally the contractor selected had an excellent foam pressure and quality calculation program. This program was made available via a modem connection. In this manner, on site calculations were made with a portable computer terminal and phone connection. During pressure coring operations the annular back pressure gauge as well as the control for the adjustable choke on the foam line must be monitored and controlled from a central location. This will require a small diameter high pressure hose from the choke back to the control regulator which should be placed at the foam generator control panel.

Tritium was selected as a tagging material to evaluate depth of invasion during coring operations. This choice was primarily due to the fact that it is a Beta particle emmitter and will not affect normal nuclear logs. Consultation with the analysis laboratory indicated that concentrations of tritium as much as five to ten times lower than the maximum permissable concentration as specified by the Environmental Protection Agency would be acceptable for providing reliable indications of core invasion. When dealing with these low concentrations it was determined that to insure adequate mixing and dispersion of tracer material two 500 barrel storage tanks would be set separately from the normal fresh water source and tagged. These tanks were then manifolded through a valve arrangement so that either the conventional fresh water or the tagged water could be used in the liquid phase of the foam.

Pressure coring support facilities include a 30 ft. square hardwood board pad at the end of the catwalk for barrel handling and cleaning. At the end of this board pad a large stable support such as a piece of drill collar set in concrete should be available to provide a hoisting line from the pressure core area to the rig floor. Behind this the pressure core barrel maintaince building must be set. Auxillary to this building is an air compressor and a generator, also a fresh water connection should be supplied. Figure 3a is a diagram of the bottom hole assembly required for pressure coring. It should be noted that no jarring equipment can be used in this assembly and that every internal diameter from the top of the pressure core barrel to the surface must be large enough to pass a 1.25 inch diameter steel tripping ball.

The remaining piece of equipment required is a test assembly very similar to a conventional drill stem test tool. This assembly is shown in figure 3b. At the bottom of the drill pipe and drill collars is a conventional inside recording drill stem test pressure recorder. Below that is a cross-over to connect to a positive choke, this choke stimulates the pressure drop across the bit and has an opening equivalent to the total area of the jets in the core bit. Below the choke is a standard perforated drill stem test sub which records outside drill pipe (annular) pressure. Additional support equipment for the pressure coring operations is a large quantity of dry ice to freeze the cores, freeze boxes to transport the frozen core from the location to the laboratory, a location large enough to conveniently support all five major pieces of equipment and the supporting manpower, and proper living quarters to support the 24 hours a day operations.

APPLICATION

Concurrent with equipment design and specification was an overall planning effort. The first phase of this plan consists of determining the exact number and location of all pressure cores to be cut. In the Wellman 7-6, these pressure cores and associated conventional cores were designed to each serve a specific function. Figure 4 illustrates both the cross section through the Wellman Unit and the approximate coring program. The first pressure cores located in the gas cap would allow the determination of residual oil saturation to gas expansion The next set of cores would be conventional cores to locate the gas-oil contact. Next would be a set of pressure cores to determine the InSitu GOR in the upper portion of the oil column. A series of conventional cores was next to provide a calibration point for open hole logs; this was followed by another pressure core to determine InSitu GOR in the lower portion of the oil column. This permits analysis of any changes throughout this rather large vertical section. The following set of cores would be conventional cores to locate the current water-oil contact. This was to be followed by another set of pressure cores to determine the residual oil saturation behind the water incroachment. The last set of cores was an optional set to determine the lithological changes between the main reef and the underlining Pennsylvanian formations.

In order to minimize the possibility of sticking the pressure core barrel it was necessary that the casing design allow casing to be set to the top of the reef. A liner could then be run through the reef subsequent to coring operations. This requires a bottom up casing design approach. Since the pressure core barrel bit is 6-1/2 in. O.D., a minimum of 7-5/8 in. pipe is required to clear this size bit. This would be set to the top of the reef. The surface and intermediate casing strings must then be sized accordingly. The small hole I.D. limits conventional core diameter to approximately 3 in. In order to maintain the ability to follow the pressure core with a conventional core without the need of underreaming operations immediately following each core a special 3 in. by 6-1/2 in. core bit was ordered. In this particular application, due to the long vertical interval a "one pass" under reaming operation became an economic necessity. An additional consideration in this particlar well was that the well would be used as a CO2 injector should it be determined from subsequent studies that CO2 injection was feasable. This required special consideration for acid gas design in both casing and well head. Once the coring plan, casing design and drilling prognosis were completed, it was time for a pre-spud meeting. All primary contractors for each of the major pieces of equipment as well as mud suppliers and chemical contractors were present at the pre-spud meeting. During this meeting, location design was performed. This assured a proper amount of working area for each contractor and exactly where they were to rig up on location. Additionally connection design and sizing took place for the interconnected foam-tracer and mud-foam connections. Chemical compatability between surfactants, pressure core barrel, and mud and corrision companies was then evaluated and selections were made to insure complete compatability in all phases. Perhaps the most important portion of the pre-spud meeting is the coordination of timing for each piece of equipment. Each piece must be available at the proper time and then coordinated with other contractors in order to eliminate down time.

Once the well was spudded, it was drilled conventionally to 50 ft. above the expected reef top. Casing was then set and the hole was displaced in stages with foam and a conventional drill bit. Drilling then continued to the reef top and samples were circulated approximately each 10 ft. until the top of the reef was encountered. This allowed approximately 60 ft of hole below the casing seat to allow the coring assembly to be "buried". The drilling assembly was pulled out of the hole and the pressure test assembly was run back to bottom. Stable foam circulation was initiated and stablized and the bottom hole pressure correlation test was performed. This test was designed to start at zero annular pressure and increment in 50 psi steps with a 10 to 15 minute interval in each step. When a final annular pressure of 350 psi was achieved the back pressure was reduced to 200 psi and was stablized for 20 minutes. The equipment was then shut in for 10 minutes to simulate the time required to drop the tripping ball into the barrel. The test recorders were then pulled out of the hole plotted with measured pressures versus computer calulated pressures (See Figure 5). This figure was developed for 450 scf/min air and 23 gal/min soap solution at 9200 ft.

A simple least squares fit between calculated and measured data was then obtained. This fit was found to have a correlation coefficient of 1.0002 and is represented by the equation:

The shut in pressure drop that occured during the 10 minutes simulating barrel trip time was found to be 225 psi. From the results of this test, the exact foam coring conditions to be used were then selected. (These are discussed under data and results)

The pressure core barrel was then run in the hole and foam circulation was obtained and stablized at the desired conditions. Coring operations then began and the 8 ft. pressure core was cut on November 1, 1980 from a total depth of 9250 ft. to 9258 ft. in 15 minutes. The barrel was then raised approximately 3 ft. off bottom and the lower kelly valve was closed. When this happened an immediate rise in stand pipe pressure indicated to the foam unit operator to shut down and bleed off the stand pipe. Once done, the kelly was disconnected above the valve and the steel trip ball was layed on top of the valve. The kelly was then reconnected, the foam unit started, pressure brought back up to approximate circulating pressure and the kelly valve was then opened. This allowed the ball to fall freely to bottom and trip the barrel. The core barrel was then removed from the hole without rotating the drill pipe and layed down into a container of dry ice. The pressure on the core barrel was measured at this time and found to be very close to the predicted value. Freezing was then continued for approximately 8 hours and the inner barrel was then removed from the outer core barrel. The inner barrel was halved into two 4 ft. sections and placed in a freeze box with dry ice for shipment to the laboratory. A 4 in. long section of core at both the top and bottom were removed and placed separately in the box for shipment to an additional laboratory to evaluate the depth of invasion of the foam.

DATA AND RESULTS

The desired core barrel pressure was 1250 psi. In order to calculate what annular back pressure would be required to achieve this 1250 psi bottom hole pressure, the following method was used. First the pressure drop between circulating and shut in pressure from the bottom hole pressure measurement test was found to 255 psi. This was added to the 1250 psi desired for a circulating bottom hole pressure during coring of 1505 psi. Using equation 1, this desired circulating pressure would correlate to a calculated circulating pressure of 1132 psi. Using linear interpolation between the 50 psi and 100 psi annular back pressure points in figure 5, it was determined that 90 psi annular back pressure should be held during coring operations Therefore when the first pressure core was cut, 450 scf/min of air and 23 gal/min of soap soluton were pumped down the drill pipe and 90 psi of annular back pressure was held. After the core was cut,sealed, and brought to the surface the pressure was measured to be 1288 psi.

Using the above described technique, a total of eleven pressure cores were taken. Of these pressure cores there were three which failed to trap pressure and reached the surface with 0 psi on the core. All three failures were ascertained to be due to the premature failure of an O-Ring in the pressure core barrel nitrogen precharge reservoir. These O-Rings were non-moving, in no contact with wellbore fluids, and seated in machined stainless steel. For this reason it is not expected that the failures are related to the foam mud system. The remaining eight pressure cores were recovered with very nearly the same correlation between calculated and actual pressures as the first core. The last of these pressure cores was cut from a depth of 9870 ft. to 9886 ft.

The two largest problems encountered during pressure and conventional coring operations were poor recovery and very critical pressure balance requirements. Due to the highly fractured and vugular nature of the Wellman Unit Wolfcamp reef, much of the cores were recovered as fractured rubble. Additionally, high permeability and a large net pay section created a very fine line between fluid influx and total lost circulation (often as small as 10 psi annular pressure). Both of these problems were also experienced in conventional coring of offset wells earlier in the the life of the field.

The results of the Tritium tracer invasion test indicated that as previously hypothesized there was no measurable invasion into the core matrix. There was, however, foam invasion into the large fractures and vugs of the core. This was easily corrected out of the analyses due to the different salinity of the water used for foam generation and the water in the reservoir.

An additional benefit to using foam as a coring media was found when the laboratory analyses were performed. The foam itself was primarily gaseous and the fluid phase was small enough that none of the traditional mud chipping was required to process the core. This increased the speed in which the cores could be analyzed by a factor of nearly two. Additionally, the gas which made up the foam was composed primarily of nitrogen and oxygen (which did not exist in the reservoir in significant quantities) and could be corrected out of the analysis for the highly fractured and/or vugular cores.

Figure 6 is a plot of the depth versus actual drilling time as well as the original drilling time estimate. The close agreement between actual and planned operation timing led to a final cost to drill, core, complete, and place on production that was within 15% of the original estimates. The incremental costs associated with pressure coring, core analysis, required pipe design, etc. caused the total well cost to be approximately 40% higher than would have been expected from a "normal" well in this field.

CONCLUSION

The success of these operations indicate that with the proper care and design considerations, foam can be used as a coring media for either conventional or pressure coring in underpressured reservoirs. Further, foam appears to have distinct merits as a coring fluid from a laboratory analysis standpoint. At this point in time, it is still necessary to do an empirical correction to insure acceptable agreement between desired and actual coring pressures. Due to the large number of individual services which have to be coordinated during a foamed pressure coring operation, logistics and planning prior to spudding the well are very important.

NOMENCLATURE

Pc = Calculated bottom hole pressure - psi

Pm = Measured bottom hole pressure - psi

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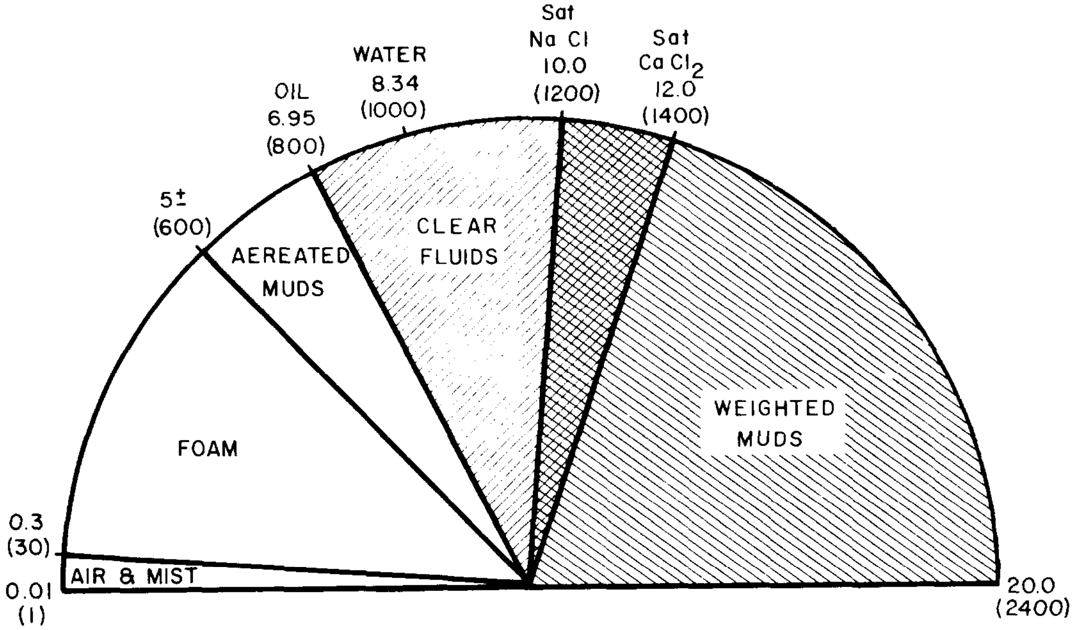

Fig. 1 – Densities of various drilling fluids – lb/gal (kg/m^3)

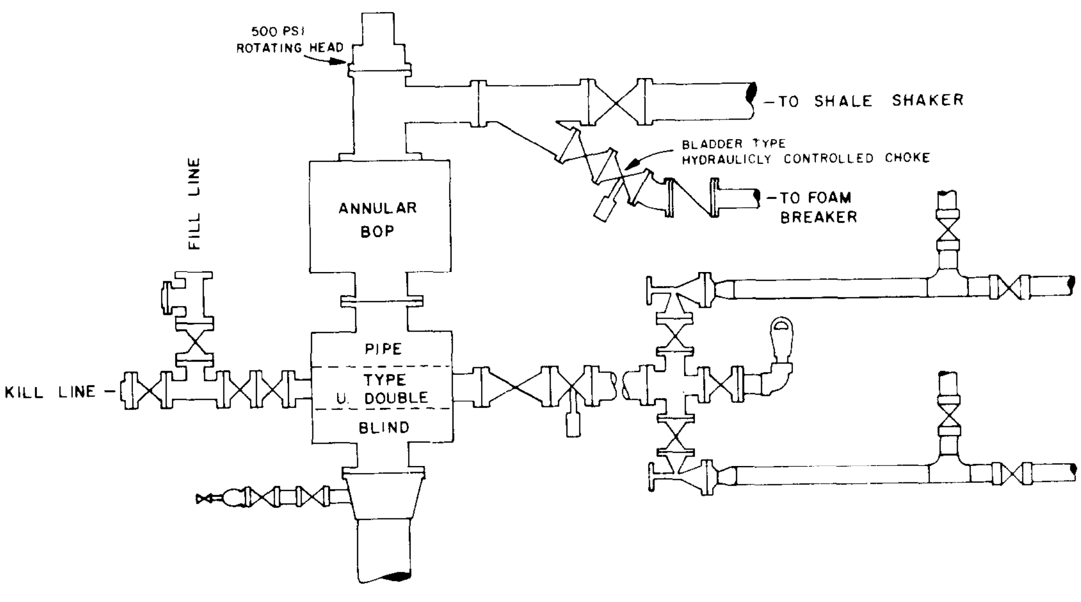

Fig. 2 – Rotating head & blowout preventer design for foam coring

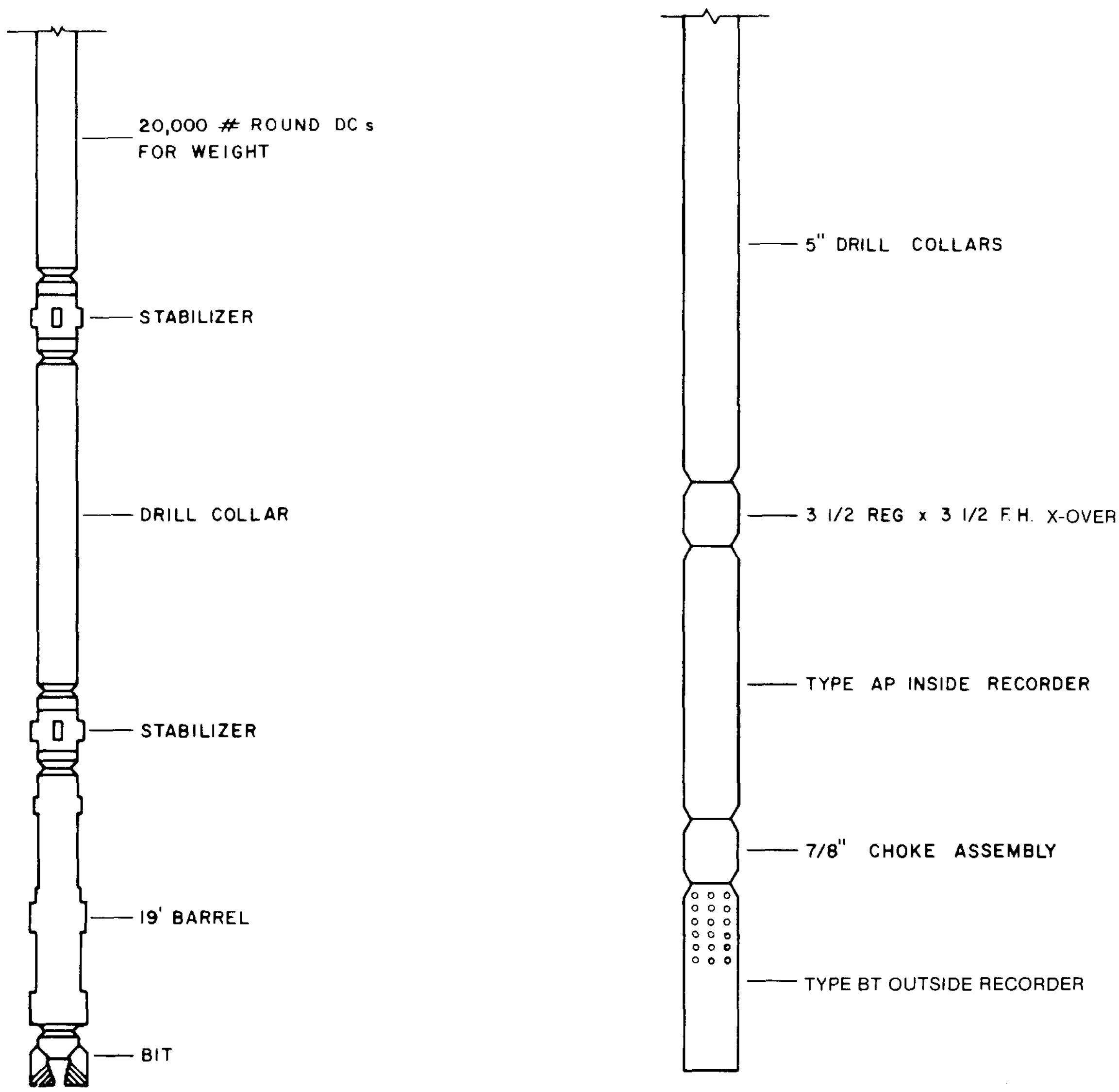

Fig. 3 – A. Bottom hole assembly for pressure coring B. Foam pressure test equipment

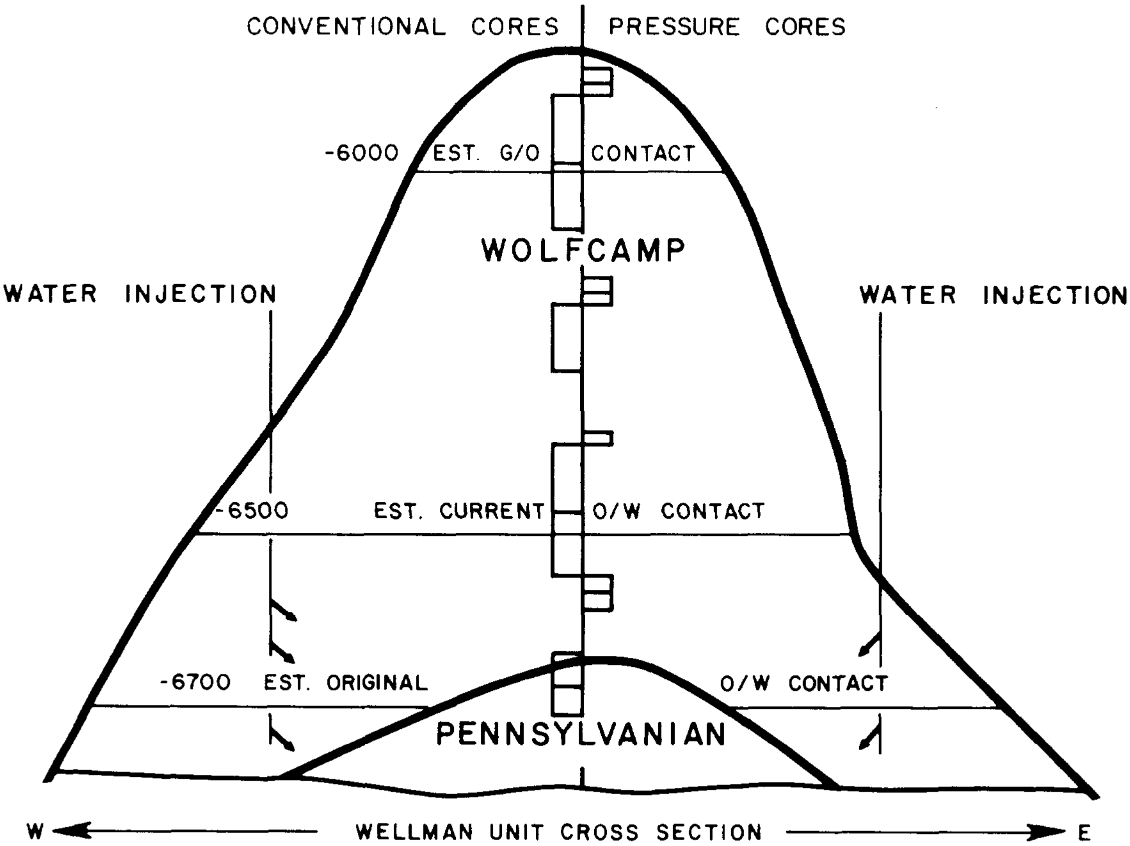

Fig. 4 – Wellman unit crossection and coring program

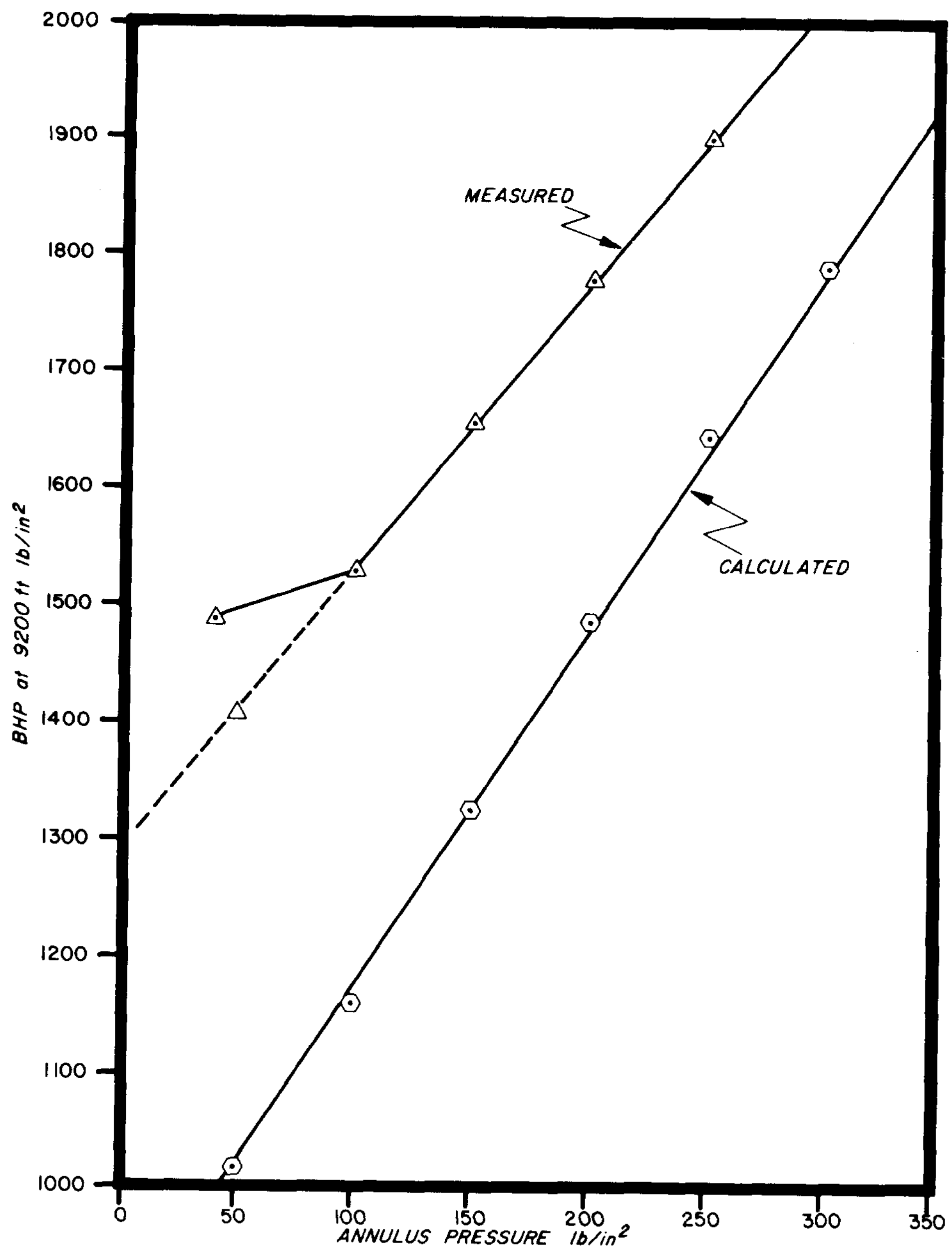

Fig. 5 – Annular pressure (surface) versus bottom hole pressure (measured & calculated)

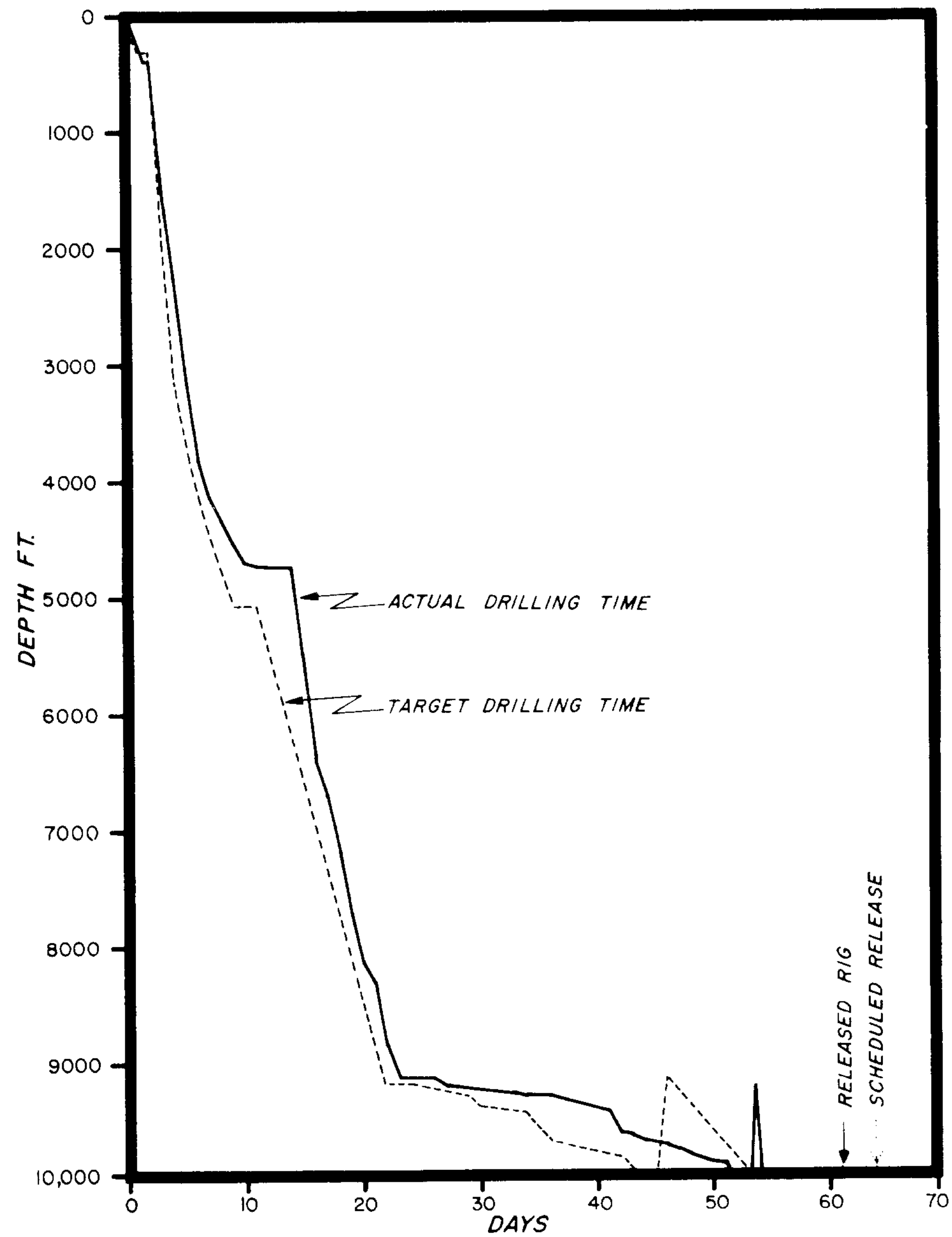

Fig. 6 – Depth versus drilling days – target and actual