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Horizontal Radial Drilling System

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ABSTRACT:

A high pressure, water jet drilling system has been developed using a new force system to concurrently drill a bore hole and place a metal tube in the bore hole.

The first commercial application has been horizontal radials for shallow heavy oil reservoirs. Many radials may be placed at the same elevation. Logging, and completion techniques have been developed.

I. Introduction

Over the past five years Bechtel Investments Inc & Petrolphysics Ltd. have been developing a new drilling system. The initial goal of the work has been to provide multiple horizontal drain holes or injection radials in unconsolidated heavy oil reservoirs via existing wells. In this paper we shall discuss the technology which has been developed to achieve that goal. We will also comment on other applications of this technology.

In this paper the term "radial" refers to the approximately 4 inch radial bore drilled into the formation. The term "production tube" refers to the 1¼ inch metal ERW tube placed in that bore.

A. System Technical Objectives

The following Project Technical objectives evolved from the primary goal:

1. Provide multiple, generally horizontal radials of predetermined direction, 100 to 200 feet in length from a single existing oil well, all from the same depth.
2. Drill a 100-200 foot hole rapidly, approximately 4 inches in diameter, through an unconsolidated formation.
3. Place a 1¼ inch OD production tube within the 4 inch diameter bore hole in the formation while drilling is in progress.
4. Cutoff the production tube, as required, downhole.
5. Log the individual production tube in three dimensions.
6. Provide perforations and sand control, if desired.

B. System Technology Summary

Early in the system development, a decision was made to employ a 10 to 12 inch radius turn from the vertical to the horizontal so as to be able to penetrate shallow or thin formations and to minimize underreaming. An erectable whipstock containing a combination of slides and rollers has been developed to effect this bending and straightening process.

The drill system uses 8,000-10,000 psi water for water jet drilling and can be adapted to commonly used additives. The drill bores an approximately 4-inch diameter radial within which it progressively places a 1¼ inch OD carbon steel production tube as it proceeds through the formation. The jet drill head does not rotate and delivers in excess of 1,000 hydraulic horsepower to the formation.

For drill propulsion, a totally new push-pull process has been developed. Specifically, the drill penetrates the formation in self-regulated movements propelled by internal static fluid pressure. Forward velocities can be controlled from a low of 6 feet per minute to a high of 120 feet per minute. As the drill moves through the formation, the anterior portion of the 1¼ inch tube is

References and illustrations at end of paper.

maintained in tension. The internal static pressure provides a pulling force of 4000-8000 pounds. This tension force tends to keep the production tube straight which aids directivity for the system.

Methods have been developed to provide regulation of the forward speed of the drill which in turn tends to control drill inclination or vertical trajectory. Among these are a cable tail restraint attached to the tail of the radial.

The drill system has been principally tested in unconsolidated California reservoirs of 500 to 2,600 feet depth, such as Bakersfield (Kern River), Taft, and Brea (Olinda). The drill has penetrated through cobbles of hard crystalline rocks for short distances, as confirmed by experiments down shallow caissons where drilling progress can be seen directly. No work has yet been done in continuous consolidated formations. The system has effectively penetrated thick cement. An important part of the system is to log the drill trajectory. Normal logging equipment will not bend around a 12 inch radius. Hence, entirely new flexible logging and electronic packaging systems suitable for downhole application have been developed and are being applied. This technology is being extended to provide three-dimentional trajectory maps of the radial location.

For sand control of highly deviated or horizontal wells in unconsolidated formations, an integrated technology of radial completion is being developed. Operational applications examined for the system involve either production, injection, or both. The initial economic objective for the system was to provide a capability to get a quick production response. Hence, a huff-and-puff approach was initially applied. The technology is applicable also to steam drive or injection.

II. Systems Theory and Functioning

A. Drilling and Propulsion

The basic cutting, drilling and propulsion systems uses hydraulic forces. These forces concurrently (a) cut the formation, (b) pull forward the drill head attached to the production tube and (c) push forward the tail of the production tube. These forces and functions will be separately discussed.

1. Cutting

The basic cutting mechanism is an array of nozzles in the drill head. Each nozzle in the array achieves about 900-1000 feet per second exit velocity. The combination of water jets cuts a cavity of about 4 inches diameter in unconsolidated formations.

In consolidated formation materials the array of nozzles creates an alternating pattern of compressive and tensile forces in the rock such that spalling occurs continuously, even in very highly consolidated cobbles and rocks as are often found bedded in oil formations near Bakersfield. The combined jets also wash away cuttings from the area around the drill head. The measured nozzle velocity coefficient of the drill head is in excess of 80 percent.

2. Pulling Force

The production tube is 1¼ inch OD, 1.03 inch ID A-606 carbon steel, electric resistance welded reeled tubing (ERW). When the area of the nozzles is subtracted, the net internal cross sections of the drill head is about .8 square inch. Hence, excluding the jet reaction force, at 8000 psi net drill head pressure, the gross force from fluid static pressure on the backside of the drill head is about 6000 pounds. This force literally pulls the radial through the formation. This force also initially aids in moving the 1¼ inch tube through the whipstock.

To understand why this pulling force exists, consider a simple elongated vessel with closed ends, which is filled with a pressurized fluid. The axial forces on the closed ends balance out, so there is no reaction force on the vessel. Now if a hole is cut in one end of the vessel, the pressurized fluid exits through the hole and exerts a reaction force on the vessel. Next, consider that a tube with one end closed is placed in that hole and that a seal is provided in the hole so the tube will slide with respect to the vessel. The result is that the tube will be ejected much like a projectile by the static force on its closed end. This is the principle which has been applied to provide a pulling force on the production tube.

By placing suitable nozzles or holes in the closed end of the tube, or drill head, the water jet cutting system just described is provided. Thus for this drilling system, both the static and dynamic properties of the pressurized water jet cutting fluid are concurrently applied.

In our drilling system, the production tube begins vertically, proceeds around a 90° whipstock turn and enters the formation horizontally. As later described these same fluid pressure forces are further exploited to control the system. The overall drilling system configuration is shown in Figure 1.

3. Pushing Force

The production tube wall is .109 inches

thick. A simple configuration of the system is shown in Figure 1 - Overall Drilling System. Therein the posterior of the production tube is vertical and contained in a sealed chamber made up of the string of drill pipe down to the whipstock. This string operationally terminates in a high pressure, sliding seal system riding against the OD of the 1¼ inch production tube.

Within the vertical tubing string holding the whipstock and containing the production tube, the high pressure water is at 9000-10000 psi. The water exerts a force on the cross-section of the tail of the .109 inch thick production tube of about 3500 pounds. This force helps push it through the seal/whipstock system. This force is reduced by any net cable restraint forces. The result is a total push/pull forward gross force on the projection tube of about 9500 pounds less net cable restraint forces. As later discussed, other restraint or pushing force systems can be applied to control or enhance the gross forward directed force.

B. Whipstock

The next major component of the system is the whipstock. The whipstock provided two separate capabilities or functions that are totally integrated into one tool. The first set of components consists of the slides and wheels which enable the production tube to move initially from the vertical, around the 90° whipstock turn, through the straightener and out horizontally into the formation. The second set of components functions only during the passage of the tube through the formation. While moving out into the formation the production tube automatically lifts itself off the bending wheels and slides, which reduces friction.

In this process the metal production tube moves through a 12 inch radius, 90° turn very rapidly. The reason for the sharp turn radius is threefold.

1. To assure suitable placement in thin formations

2. To minimize the diameter of an underreamed hole or a slot for whipstock erection.

3. To keep the metal tube at high stress under the combination of pushing, pulling, and bending forces, plus internal fluid pressure.

The result is that the electric resistance welded production tube is highly stressed and is in a plastic state. Hence, large deformation of the tube can be accomplished at low incremental stress. To provide a space into which the whipstock can be erected, a series of high pressure hydraulic underreaming tools has been developed. These create a space of up to four feet in diameter. Such a large underreamed hole diameter is not possible with conventional mechanical underreamers within the constraints of the casing sizes characteristic of the typical older existing wells in California.

Two of the most time consuming tasks in placing radials involve the large diameter (48 inch) underreaming and repeatedly tripping of the whipstock to the surface to provide the mulitple radials. The second-generation whipstock, which is just coming out of research, requires only one-half that diameter of underreaming. These new tools also permit placing multiple radials without tripping to the surface between radials. The new tool is a repeater, rather than a single shot.

C. Control of Direction

The jet drilling system creates a generally round radial bore in the formation of about 4 inches diameter. Of course, consolidated areas or formation inhomogeneities affect the radial section. But, because the production tube is under tension as it enters the formation, it has a natural tendency to go straight, as does the resulting bore hole.

The velocity of the production tube and the volumetric flow rate of the high pressure water both have a strong bearing on radial pitch or inclination. Typical velocities of 20-120 feet per minute cause the radial to rise. Conversely, lower velocities cause the trajectory to droop downward. The precise downhole effects are not experimentally known. But one model is that at higher velocities the larger cuttings are probably not slurrified out of the way fast enough and may pile up ahead of, or under the drill head, causing it to rise. Conversely, at lower velocities the sorted cuttings may be more thoroughly washed out so that the drill would tend to droop as a cantilever beam, and move progressively downward.

For actual operations, the drill is started at lower velocities and the velocity is progressively increased as the radial progresses outward.

D. Velocity Control

To provide control of velocity, especially during progress through the whipstock and during initial entry into the formation, a cable restraint is applied. This consists of a cable truck, a wellhead high pressure grease seal and a removable plug at a tail of the production tube. The plug is removed after a run to permit the entry of logging tools. Of course, the restraining cable instrumentation gives a real-time indication of production tube movement.

E. Instrumentation and Logging Equipment

1. Drilling Instrumentation

To control the production tube during drilling, two variables are monitored in real time.

a) High pressure water pressure and flow

b) Production tube displacement and velocity in terms of cable movement

2. Logging

Because of the 12 inch radius turn through the whipstock, the logging instrumentation must pass through this 1 inch internal diameter production tube at a 12 inch turn radius. Rigid conventional instruments won't pass and no gyroscopes are available which are small enough to pass through the tube. Hence, completely new types of mechanical sensor instruments and packaging have been developed.

The key to these new logging systems is a packaging concept which combines several conflicting properties. The packaging must be soft and yielding, yet supportive around the electronics and sensors. The package must be sufficiently tough and strong to take external abrasion, pressure and shock. These resulting flexible logging systems currently provide a reliable and reproducible printout of inclination or pitch accurate to 1^{o}. Instruments in test are expected to do the same in yaw or azimuth in the field.

F. Sand Control and Downhole Completion

The requirements of a 12 inch radius whipstock turn and a thin ERW production tube created a need for a new procedure of tube in-situ cutoff, in-situ perforation, gravel packing and flexible lining of the production tube. These technologies are in commercial usage or on test.

G. Well Head and Surface Equipment

Throughout the system development program, standard oil field equipment has been used where possible. Hence, the surface equipment is conventional. Pump power is supplied by a 1600hp/10000 psi frac pump. The rigs used are generally double stand, work-over rigs. Logging trucks are conventional.

Equipment for measuring production tube movement, instrumentation for fluid pressures, flows, cable tension, etc. are all conventional oil field hardware and function well in this application.

III. System Applications

The initial application of the drilling system is in shallow, heavy oil reservoirs in the San Joaquin Valley and the Los Angeles basin. Both huff and puff and pure injection commercial applications have been done.

For these reservoirs the system has been applied to provide more than three hundred radials in many wells. In general, four radials are provided in each well. All are at the same depth, as shown in Figure 2 - Typical Vertical Radial Patterns. But, if desired, many more than four radials can be placed at the same elevation as shown in Figure 3 - Typical Aerial Radial Patterns.

The drilling system is not limited to horizontal shallow, 100-200 foot radials, nor is it limited to a 1¼ inch production tube nor a 4 inch radial bore. The system can work vertically and we believe it can place very long and large tubes. Hence, among the applications other than the initial one which may have potential value are:

a) Offshore reservoirs
b) Consolidated formations and long radials
c) In-situ coal gasification or gas drainage radials
d) Waste disposal
e) Mineral recovery by solution mining

Conclusion:

A new concept of drilling a bore and placing a tube within that bore has been developed and applied in existing California oil wells. The technology has been successfully applied to providing multiple horizontal radials at the same level in a single well. Suitable logging, and completion techniques are in hand. The technology has potentially broad application to many petroleum and other resource drilling needs.

Acknowledgment:

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Reference:

1. Based upon reservoir studies undertaken for Bechtel by Scientific Software Intercomp, a 100 foot, or at most a 200 foot radial, is all that is required for heavy oil production or steam injection. Longer radials are not useful in these typically low pressure reservoirs. This is more fully discussed in the paper: "An Innovative Methods of Drilling Horizontal Boreholes," by Larry E. Pendleton and A. Behrooz Ramesh on February 20, 1985 at the Heavy Oil and Oil Sands Technical Symposium,

University of Calgary, Calgary, Alberta CN 2500 University Dr., N.W., Calgary, ALBT T2N1N4. A copy of this paper may be obtained from the University of Calgary or from the authors.

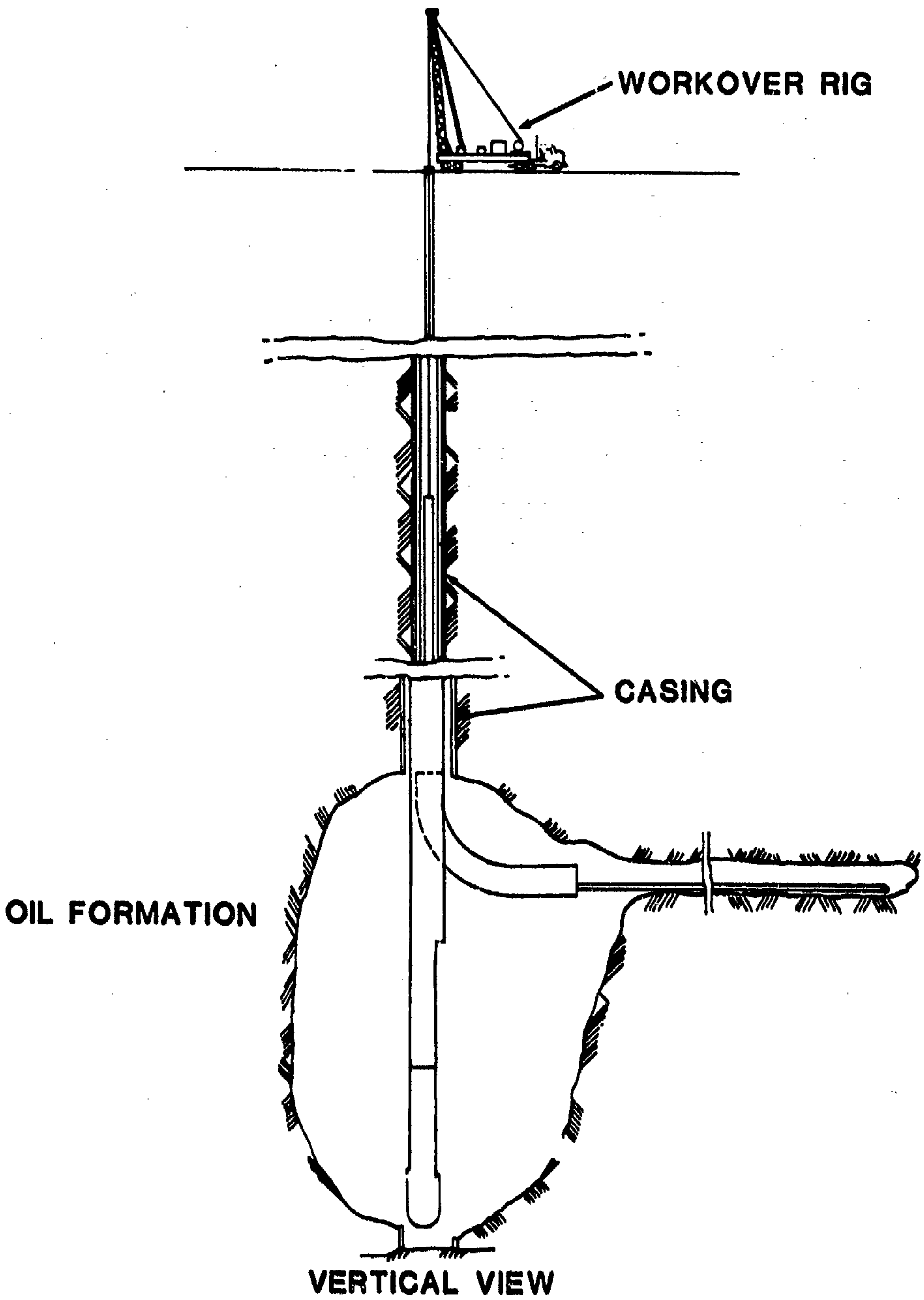

Fig. 1—Overall drilling system.

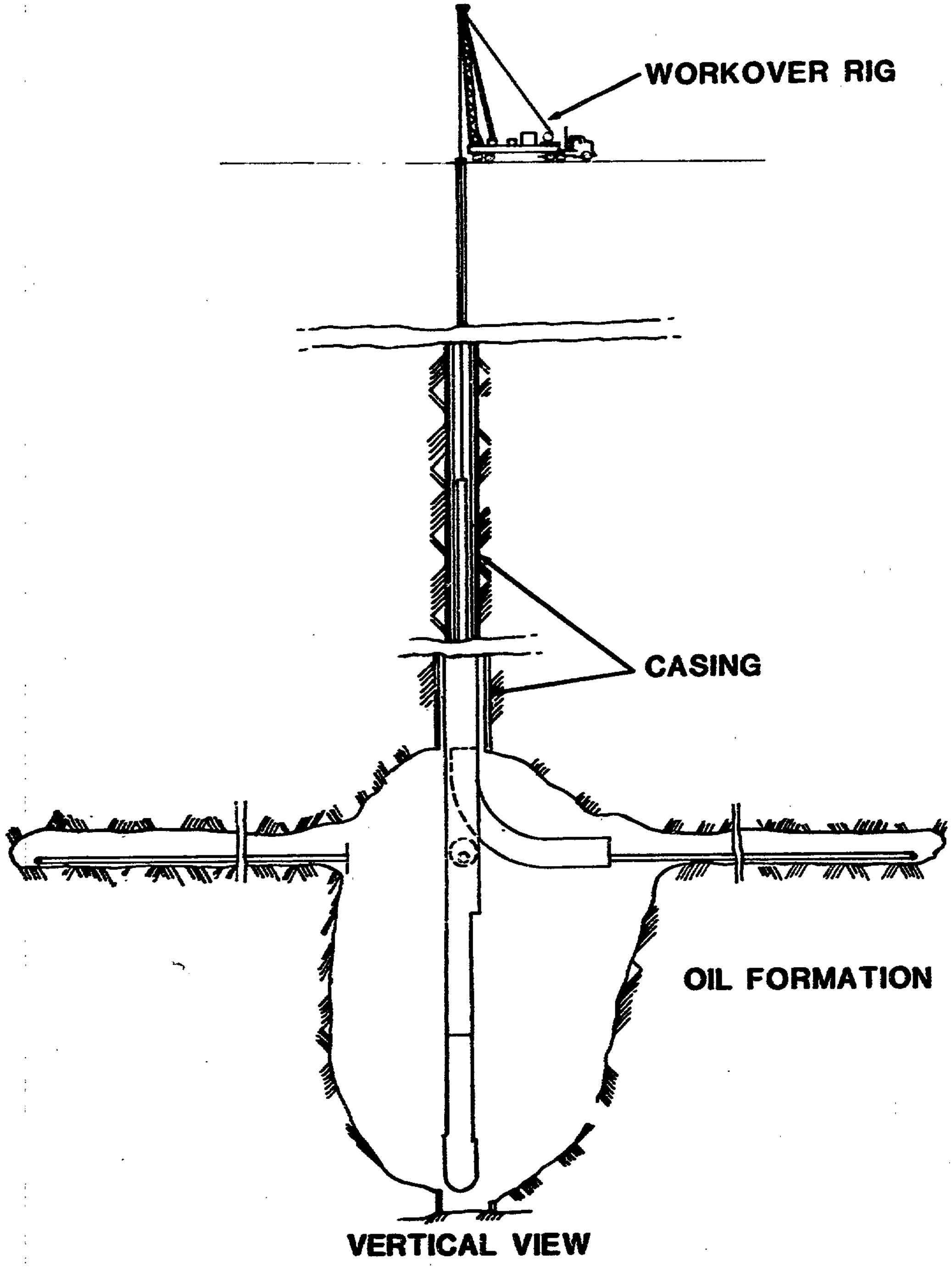

Fig. 2—Typical vertical radial patterns.

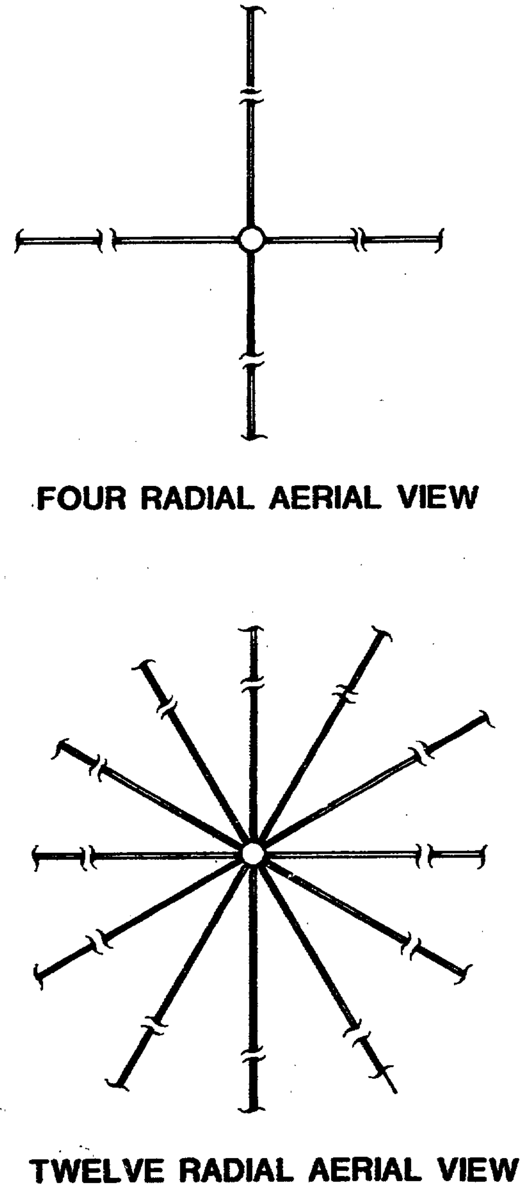

Fig. 3—Typical aerial radial patterns.

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Discussion of Numerical Simulation of CO_2 Flood Performance

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This Discussion addresses Chase and Todd's paper that appeared in the Dec. 1984 *SPEJ* (Pages 597–605). In their recent paper on CO_2 simulation,[1] a stabilized implicit pressure, explicit saturation (IMPES) time discretization was suggested. This method is purported to increase stable timestep sizes for IMPES-like simulators. This technique was suggested by van der Houwen[2,3] for parabolic equations. It also was used in reservoir simulation by Meijerink[4] and Vinsome.[5] However, the maximum timesteps calculated by van der Houwen do not apply to hyperbolic equations if upstream differencing is used. Upstream differencing results in a Jacobian that is defective (not diagonalizable). In fact, for a one-dimensional Buckley-Leverett problem, it is possible to prove that the stabilized IMPES method is never more efficient than ordinary IMPES.[6] Consequently, the claims made by various authors[1,4,5] about increased stable timesteps with the stabilized IMPES method must be regarded as being without theoretical basis.

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4. J.A. Meijerink: "A New Stabilized Method for Use in IMPES-Type Numerical Reservoir Simulators," paper SPE 5247 presented at the 1974 SPE Annual Meeting, Houston, Oct. 6–9.
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Authors' Reply to Discussion of Numerical Simulation of CO_2 Performance

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Sammon and Forsyth[1] are, of course, correct in their claim that the van der Houwen[2] stability limit is too optimistic for the upstream weighted finite difference discretization of the hyperbolic Buckley-Leverett equation, particularly under the positivity requirement of their Eq. 11. Using the linear Buckley-Leverett problem they illustrate that, beginning at time zero with a step change boundary condition, one cannot significantly exceed the single-stage stability limit. Their analysis also helps explain several phenomena we have observed using the m-stage discretization in actual reservoir simulations.

Because of time truncation error, one would never attempt in an actual reservoir simulation problem to use timestep sizes approaching the Euler stability limit after step changes at the boundaries (for example, turning on of water injection wells). Instead, multiple stages are applied only after fronts have moved away from the wells and, because of the divergent nature of the flow field, stability in the well region is limiting rather than time truncation error. For this case, we illustrated in our paper[3] that significant work improvements can be obtained even though, as Sammon and Forsyth have pointed out, we exceeded the strict stability limits imposed by their analysis. This work improvement also can be demonstrated with the linear Buckley-Leverett problem by comparing the amount of work required both with and without multiple staging per timestep to simulate a well into the steady-state region. The key to this comparison, however, is the use of a timestep selector to keep the timestep size below the single-stage stable value when time truncation error is important.

Why the m-stage method works, apparently in violation of the stability limitations pointed out by Sammon and Forsyth, is perhaps a result of the fact that in the quasisteady-state region it may not be necessary to invoke the positivity requirement expressed by Eq. 11 in their paper.[1] Violation of the positivity condition, however, probably causes the oscillatory solutions we often have observed with the m-stage method. Because the single-stage stable timestep size seldom is known exactly in real reservoir simulation problems, but only estimated,[4] a good timestep selector, which can sense the onset of instability and correct the timestep size, is a must.

Finally, we would like to point out that the simulator described in our paper[3] uses a two-point upstream weighting[4] of transmissibilities rather than single-point weighting as analyzed by Sammon and Forsyth. Their analysis applied to two-point upstream hyperbolic systems would, no doubt, lead to very similar conclusions concerning the stability limitations of the m-stage process.

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