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Advances in 3D Wellbore Visualization and Their Impact on Drilling and Completion Optimization

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Abstract

Numerous opportunities have spawned from the recent, successful introduction of 3D visualization of downhole drilling hydraulics. In addition to powerful transient and real-time enhancements, visualization applications are being integrated into advanced engineering software to help optimize other well construction and workover operations. The primary objective of this paper is to discuss the new technical developments, along with their current and expected impact on related work-flow processes. Also presented are possibilities to further expand this technology and opportunities to help take full advantage of the concept.

The initial drilling hydraulics application is now standard-issue for wellsite, office, and drilling-center use on Windows-class PCs. It creates a virtual wellbore from snapshot-style data and allows interactive navigation of the well using a virtual camera controlled by a gamepad or the keyboard. Step improvements in modeling, data interface, and graphics design now permit creation and interactive display of dynamic images based on real-time and simulated transient data for varied drilling, tripping, displacement, and other operations. Powerful graphics software from the computer gaming industry continues to play a key role in the application of this technology.

Advent of 3D wellbore visualization has had a positive impact on business and work-flow issues. It systematically is changing perception of the downhole environment for many people, including non-drillers, experienced drillers, students, and especially those generally unfamiliar with the oilfield. Multi-disciplinary collaboration is a natural consequence. Major reevaluation of existing analytical and empirical models is another.

Introduction

It is not uncommon for technology developed by one industry to be subsequently ported to another, sometimes with greater technical and financial success. PDC cutters, solid-control and waste-management equipment, ground barite, biopolymers, viscometers, and the rotary drilling rig itself are but a few notable examples of technology successfully transferred to the drilling industry. Moreover, concepts and technologies from different sources often are combined synergistically to create new advancements. Such is the case when 3D wellbore visualization was applied for the first time to downhole drilling hydraulics.[1] The six key technologies that contributed to its development, in one form or another, are illustrated in **Fig. 1** and summarized below:

1. *3D Reservoir Visualization*[2] is a proven technology to interpret seismic data, 3D logs, geocellular models, grids, and horizons. Drilling applications include well placement in complex reservoirs, avoidance of well collisions, and correlation of drilling data to earth models.[3]
2. *Downhole Video*[4] systems provide spectacular downhole wellbore views for mechanical inspection, fishing operations, and problem investigation in transparent fluids where internal drill/work strings do not interfere with camera operations.
3. *Flow-Loop Video*[5] taken of simulated wellbore studies in the laboratory have captured invaluable, though artificial, views of downhole processes such as hole cleaning and barite sag.
4. *Non-Invasive Medicine*[6] procedures provide the ideal analogy for creating downhole images without the need to insert video cameras into the wellbore. The "virtual" colonoscopy, which constructs 3D digital images from 2D x-ray measurements assembled like slices in a loaf of bread, is a notable example.
5. *Engineering Modeling*[7] used in some advanced drilling and completions programs are based on finite-difference methods for improved simulation quality. The natural data output from these models is fully compatible with graphics techniques used for 3D visualization, as well as the loaf-of-bread analogy used to describe the virtual colonoscopy.
6. *Interactive Computer Games*[8] use remarkable 3D graphics engines, video cards, computer hardware, and techniques fully adaptable for creating credible, virtual wellbores that are true to the data sets provided by the engineering modeling.

The ultimate goal was to develop innovative software for interactive navigation of the inside of a virtual wellbore using a gamepad or keyboard on Windows-class computers. Conveyance of the right message took priority over attempts to provide imagined realism. The initial application targeted downhole hydraulics. It was integrated into an advanced drilling hydraulics software suite and formally released to the field in 2005. The combined software technologies are now standard issue for wellsite, office, and drilling-center use.

Application of wellbore visualization technology has continued to evolve at a rapid pace. Its use is being extended to transient hydraulics models and other well construction and workover operations. The primary objective of this paper is to discuss these new developments, along with their impact on related work-flow issues. The discussion starts with the key wellbore visualization components because of their relationships to the new applications. Also presented are possibilities to further expand this technology and opportunities to help take full advantage of the overall concept.

Wellbore Visualization Components

Engineering modeling and computer-game graphics are the two supporting technologies that also are key pillars of the wellbore visualization system. Both offer considerable challenges in their own right. Engineering modeling is complicated by the lack of complete understanding of many downhole processes, particularly under transient conditions. The 3D graphics engines used for computer games, on the other hand, are inherently complex and evolving at a very rapid rate. Keeping current with continual step improvements in software, hardware, and artistic techniques is a major challenge in itself.

Data input, data interface, and interactive navigation are three additional components that play crucial supporting roles to link the modeling and graphics, and complete the wellbore visualization process. The simplest version of the flow diagram is illustrated in **Fig. 2**. Responsibilities and interaction among the five components depend on the application. A more complex diagram for network environments is presented later.

The original wellbore visualization system was designed to run on single desktop and laptop computers. In this configuration, data input and the engineering modeling are completed first and the results are then passed to the graphics and navigation components through the data interface. In real-time and network environments, all components are concurrently active. Necessity and processor constraints may require that heavy engineering calculations and graphics processing be conducted on separate computers.

The *data input* module accepts data from different sources and transfers them to the engineering models. Data manually input via the keyboard are the norm for planning and typical analysis sessions involving steady state, semi-steady state, and simulated transient engineering models. True real-time applications also receive continuous, measured data provided electronically by surface and downhole sensors.

In most cases, input data are subsequently processed by the modeling component to yield desired results. In real-time applications, however, it is best if measurements can be passed directly to the graphics component with no or minimal manipulation. While very few real-time measurements currently are available along the complete well profile, research in this important area is ongoing.

Primary responsibility of the *engineering modeling* component is to define the downhole wellbore, using appropriate engineering models and data sets whenever direct measurements are unavailable. Different model types include predefined (such as for downhole tools), steady state, and transient. Steady state models typically produce static results, while transient models used for look-ahead/reconnaissance and real-time applications can continually display intermediate values using a variety of dynamic and animated objects.

Differences between steady state and transient applications are magnified in a wellbore visualization system. Firstly, transient models typically are more complex and demand significantly more calculation and graphical processing time. Secondly, back-and-forth data transfer activity among the different components is greatly elevated for transient modeling. Finally, a real-time, transient visualization system can be somewhat unnerving for users when important downhole events occur simultaneously along the well profile, beyond the virtual camera view. Special navigation aids have been developed to assist with this issue.

The final task of the engineering modeling component is to ensure that each object that is to be graphically represented is properly characterized with regard to data and associated structure. It is fortuitous that the finite-difference method used by existing engineering software creates a suitable underlying structure defined around wellbore segments that can be further divided as necessary for increased graphical resolution.

The *data interface* accepts engineering data sets and transfers them to the graphics component in a format suitable for rendering. Communication can be a one-time occurrence for fixed and steady-state data, or a continual transfer for transient engineering data at a frequency corresponding with key changes in input, measured, calculated, and image data. The latter process must be quick and concise to mitigate bottlenecks. Data volume, format, frequency, speed, and transfer method are among the critical details associated with the data interface. Compromises often are necessary among these parameters to achieve quality visualization performance.

Shared memory and file streams are two primary methods to implement the data interface. While both are suitable and equally fast, there are differences in storage requirements, integrity, and complexity. For shared memory, the operating system allocates a portion of computer memory that multiple, threaded processes can alternate access and transfer of large amounts of data at near instantaneous speeds. For file streams, the data are stored on the hard drive. This method is particularly suited to real-time applications involving network traffic, such as those in onshore drilling centers.

The *3D graphics* component generates and displays graphic images on the computer screen. It is important to appreciate that the graphics component is highly dynamic, regardless of whether the underlying engineering application is static, steady state, or fully transient. Furthermore, this component can serve as an excellent check-and-balance system for the modeling process when rendering produces unexpected or unforeseen results.

Most rendering details are handled by a graphics API (application programming interface). The evolution of principal 3D APIs (Microsoft's DirectX and OpenGL whose open specifications are maintained by Silicon Graphics) have paralleled extraordinary developments in graphics hardware. While both graphics APIs are equally capable, DirectX has been used for the vast majority of computer games, and its capabilities have proven quite suitable for visualization on Windows-class computers.

The main graphics primitive for the current virtual wellbore implementation is a *mesh* that consists of a list of vertices and a list of edges that connect these vertices to form primitive geometric polygons (triangles). The DirectX engine features a sophisticated graphics pipeline consisting of stages that (a) process static mesh data in a canonical form, (b) use a *vertex shader* function to manipulate lighting and transformation of every vertex, (c) cull and clip faces and vertices not visible to the user, (d) use a *pixel shader* to color pixels contained in each triangle with gradient colors, solid colors, texture maps, and other techniques, (e) further process pixels to apply various effects such as alpha blending, fog, etc., and (f) finally, render the pixels to the screen. To help illustrate this process using the lower part of the drill string, **Fig. 3** displays both the mesh and the final rendered images.

The above description shows how to render one scene. In an animation, a graphics card renders several scenes per a second. Literally millions of triangles can be rendered within microseconds on today's hardware-accelerated graphics cards. Highly efficient scene, mesh, and texture management is among the many concerns that need to be addressed to ensure that frame rates are sufficient to create the effects of full motion.

Static and steady-state data are easier to represent then transient data in a 3D system because they can be created in one frame and rendered repeatedly without requiring work by the graphics engine. Transient data, however, require the graphics engine to smoothly update old data to the new state over a set time period.

The *interactive navigation* component accepts commands from the user via a keyboard, joystick, or gamepad to manipulate the virtual downhole camera so that the user sees what the camera sees. Action mapping synchronizes the input device and camera movements including down/up, side-to-side, and telescoping during internal and side projections. Internal projections simulate the downhole video and colonoscopy examples mentioned previously. Side projections provide a perspective that especially illustrates the skewed aspect ratios involved in well construction. Combined navigation along the well path, zoom, and complete rotation provide maximum ability to critically examine the virtual wellbore in this mode.

Real-time and network configurations are designed to separate the engineering modeling and graphics processes. The enhanced flow diagram shown in **Fig. 4** illustrates how three graphics stations could be supported by a single engineering computer or network server. The same data provided concurrently could be visualized at will at the three stations. This approach also is possible over the internet, even though some delays and interruptions could be expected depending on communications quality.

Drilling Hydraulics Visualization

Drilling fluids hydraulics was selected as the target discipline for the initial wellbore visualization system for several reasons, including the following:

- Hydraulics is a critical issue on all wells, especially deepwater, HTHP, and extended-reach well-construction projects.
- Hydraulics is central to most common downhole problems and solutions.
- Flow-loop videos on hole cleaning and barite sag suggest hydraulics interactions, but downhole fluid behavior has been left to individual imaginations.
- Step improvements in simulation software have been realized in recent years.
- Results from some of these advanced hydraulics programs are already in a format compatible with current 3D graphics engines.
- Many, but not all, hydraulic parameters are highly visual and lend themselves to 3D visualization.
- This technical subject choice is ideal to help launch visualization ventures in several other well-construction areas.

Three different drilling hydraulics visualization "versions" have been created, distinguished by subtle and major variations in one or more of the components discussed in the previous section. The steady state version has been widely distributed to the field; the transient and real-time versions are functional, but have not yet been formally released.

Steady State Version. This wellbore visualization version was introduced previously.[1] It was based on advanced software that used the method of finite differences to consider, among other details, the effects of temperature and pressure on density and rheology. For simulation purposes, wells are subdivided into cells less than 100 ft in length that are reminiscent of the slices in the loaf-of-bread analogy described earlier. Each cell contains key parameters including fluid rheological and physical properties, cuttings-bed characteristics, drill-string configuration and eccentricity, and wellbore geometry, inclination, azimuth, and lithology. Graphical plots of the cell data result in profiles such as those illustrated in the upper right-hand corner of **Fig. 1**.

The visualization is available immediately thereafter, or can be saved to file for later viewing and comparison. Among other advantages, the visualization process provides means to critically examine the large data set in an intuitive manner. In this steady state version, the dataset and 3D wellbore images are effectively frozen at a single point in time and stored in computer and video-card memories. The virtual camera is then free to move up/down, in/out, and around the wellbore at will under user control.

Numerous visualization refinements have been implemented since the original release, including improved solids modeling of downhole tools, optimized programming to maintain high frame rates, and integration of the latest graphics engine technologies such as shaders. The additional drill-string eccentricity dimension required to handle helical buckling in coiled-tubing drilling also called for overhaul of the annular velocity profile and hole-cleaning procedures (see **Fig. 5**). Finally, major revisions have been incorporated so that the steady state version is simply a special case in a system also capable of handling transient and real-time applications.

Transient Version. After being an integral part of a real-time ECD management system for some time, a reconnaissance optimization module now provides transient, look-ahead capabilities to the advanced hydraulics program. The screen capture in **Fig. 6** illustrates how different options can be evaluated from a file stream of data for varied drilling, tripping, and multiple-fluid displacement scenarios. Wellbore visualization capable of handling this transient engineering-modeling and data environment is pivotal because of the close similarities to requirements for real-time use.

Transient visualization applications create numerous, challenges, even beyond the need for enhanced transient engineering models. New complications exist for the user as well as the developer. As in a real well, important events occur simultaneously along the complete well path. The user must make decisions on which interval to focus. VCR-type controls linked to the file stream are particularly helpful in this regard. Another useful aid is the ability for the software to automatically seek and concentrate on problem areas interactively selected by the user.

On the program development side, major object collections (drill string, bit, cuttings bed, wellbore, etc.) need to be decoupled and manipulated independently. **Fig. 7** is a screen capture that shows the drill string on its way out of the hole during a short trip operation. Unlike the steady state case where the drill string is always on bottom, a substantial number of engineering calculations must be included in the visualization software for interpolation, to fill in gaps in the discrete data sets, and to handle dynamic objects such as moveable cuttings beds. Failure to do so smoothly and efficiently would diminish the full motion experience for discriminating users.

Real-Time Version. The move from transient to real-time version has been facilitated by the proven success of a wellsite ECD management system[9] that can provide in real time hydraulics profiles similar to those shown in **Fig. 1**. While it would seem, then, that the two versions are otherwise functionally equivalent, the real-time version requires concurrent execution of all five basic wellbore visualization components illustrated in **Fig. 2**. The resulting high demands on computer time to synchronize and process continual interactions among the components become a major concern.

As such, the current real-time application is designed to handle graphics and interactive navigation on a different computer than the combined data input and engineering modeling. The bi-directional data interface linking the computers is best handled by file streams.

Distribution of responsibilities on different computers, however, is not without its advantages. The flow chart in **Fig. 4** shows how this architecture is well suited for drilling-center and internet applications. The use of multiple computers for graphics and interactive navigation is a definite advantage, especially if several critical events worthy of visualization by different personnel occur simultaneously in different intervals of the well.

Completion Operations Visualization

Hydraulics and other fluid-related processes also are important to downhole completion and workover operations. Displacement mechanics and wellbore cleaning are among those issues that are particularly suited for 3D wellbore visualization. Functional requirements are the same as for the drilling hydraulics case; however, engineering modeling requirements and technical focus are somewhat different. For maximum benefit, it clearly is important to design the visualization application to fit specific user needs as much as possible.

Displacement from drilling mud to clear-brine completion fluid is a critical, initial step in the completion process. The objective of this dynamic operation is to provide a water-wet wellbore full of clean brine and without the presence of any whole mud or mud film on tubular surfaces. This can be challenging if synthetic or oil-based fluids are involved.

Engineering software that targets key hydrodynamic and chemical factors has been developed to help design and manage this process.[10-11] Pressures, volumes, flow rates, fluid-fluid interfaces, film thicknesses, cleaning efficiency, and flow-back characteristics are among the key transient parameters considered during the operation (see **Fig. 8**).

One part of the visualization focuses on the different fluids and the spacer train, tracking positions and interfaces as shown in the screen capture in **Fig. 9**. Work-string reciprocation requires special care because of its impact on fluid heights and mixing. Another part of the visualization is concerned with mud film on tubulars. Interactive navigation is particularly helpful for monitoring this process, because the requisite transient models are somewhat involved and conditions are continually changing along the well path. Special digital mixing and blending schemes for color highlighting used in both parts can be selectively activated. VCR-type controls also are available to allow the user to target selected intervals in the well and focus on key displacement sequences.

Influence of Visualization on Work Flows

Without a doubt, the initial 3D wellbore visualization offering (based on steady state modeling of drilling fluid hydraulics) has made an impact on technical users in the field and in the office. Released as an integrated module of a major upgrade to the advanced hydraulics software, the visualization is helping users to appreciate intricacies of the engineering models and to explain results to interested parties. In particular, field personnel are benefiting from visualizing the effects of eccentricity and rheology on annular velocity profiles, and the combination of different parameters on hole cleaning. The ability to run on standard computers has widened the distribution and clearly is accelerating overall acceptance.

Influence on work flows involving asset teams is facilitating multi-disciplinary collaboration, especially in operations-center environments. Visualization is helping with downhole drilling processes that previously had not been well understood by non-drillers. The same should be expected with other well-construction areas.

Visualization by default is forcing critical examination of engineering models and overall simulation procedures to the point where assumed, uncertain, and ignored parameters invariably standout. Additional analytical and experimental development needs for certain downhole processes also have become evident. Clearly, models will be improved with additional measured downhole data and related laboratory studies.

Business proposal and training are two other areas where visualization will influence work flows. One example is associated with the special tools and operations used for mechanical clean-up of cased hole and marine risers. The ability to present a proposal in full motion using engineering simulations (as opposed to animations or hardcopy images) could be dramatic. The same sequences also could be used for training in general and preparation of the job in the field.

Perhaps the most interesting impact of 3D wellbore visualization is the systematic change in perception experienced by a wide range of people of the downhole environment. It is an effective way to expose students and those generally unfamiliar with the oilfield to the complexities involved with drilling and completing oil and gas wells. Even some experienced field and staff personnel have come to appreciate differences between well prognoses on letter-sized paper and the more realistic aspect ratios visible in the 3D images.

Conclusions

1. Integration of 3D wellbore visualization technology into advanced well-construction and workover software has notably improved the understanding, analysis, and optimization of a range of downhole processes.
2. Step improvements in modeling and graphics technology have made it possible to use real-time and simulated transient data to create and interactively display dynamic images.
3. Simulation of the downhole environment is still the most challenging component of the wellbore visualization process, even though "realism" remains a lower priority than communicating the right message.
4. 3D wellbore visualization is impacting wellsite, office, and operation-center work-flow processes, and changing downhole environment perceptions for personnel of all experience levels.
5. Success of this software has proven that cutting-edge graphics engines and technology from the computer games industry can be used effectively for industrial applications on standard-issue, oilfield personal computers.
6. More opportunities still exist for 3D visualization – perhaps the most intriguing are related to real-time operations at the wellsite and from within onshore drilling and operations centers.

Acknowledgments

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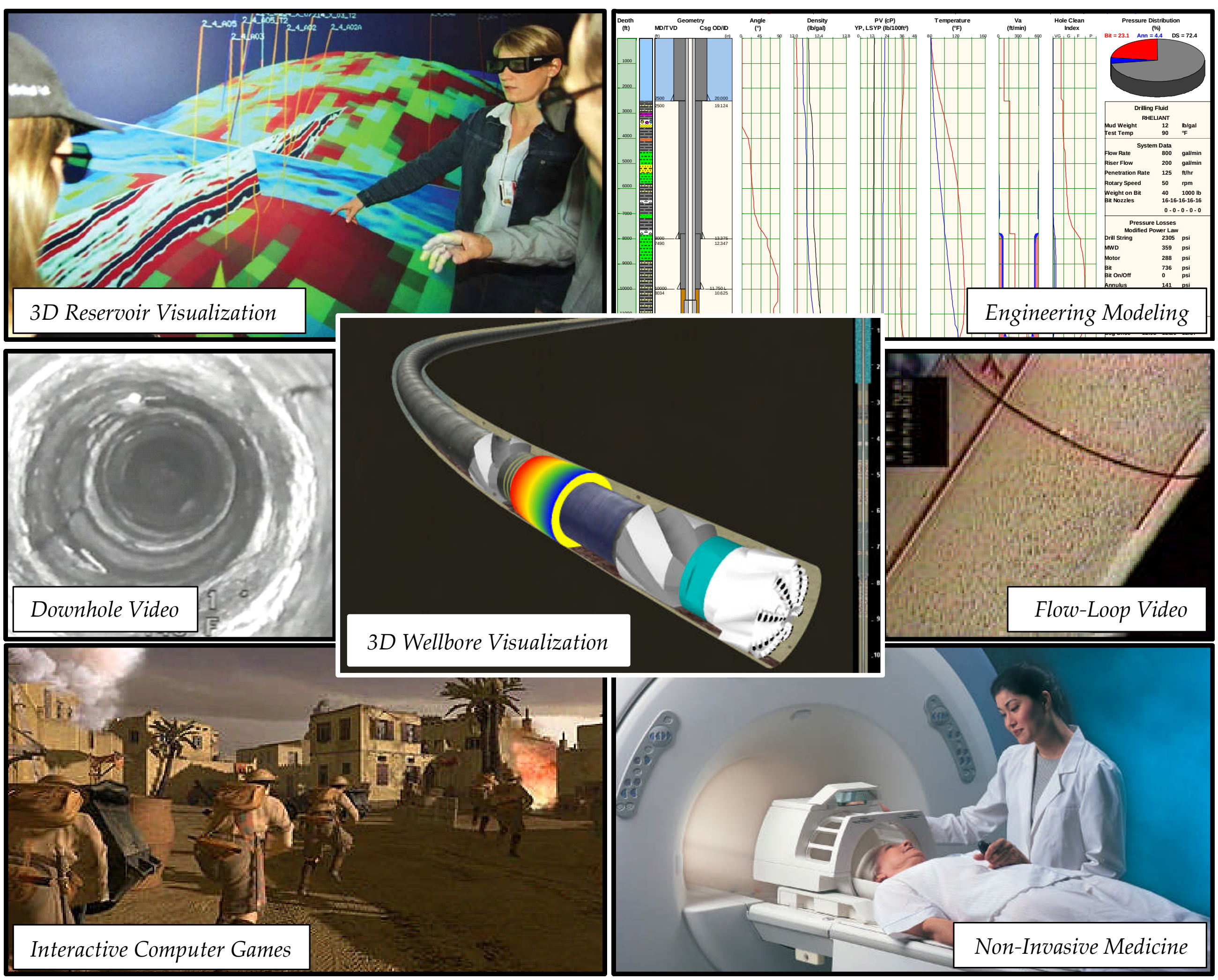

Fig. 1– Key contributing technologies to 3D wellbore visualization applications.

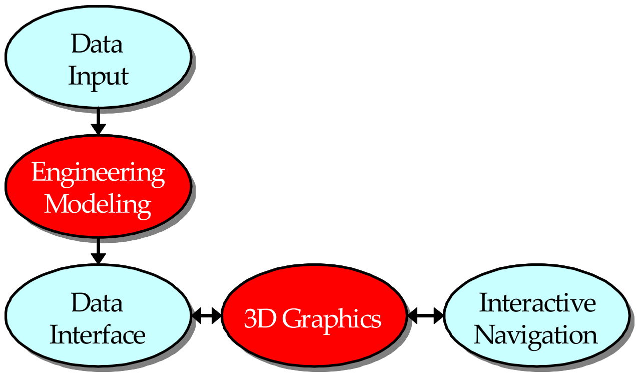

Fig. 2- Basic wellbore-visualization flow chart highlighting relationships among the 5 primary components.

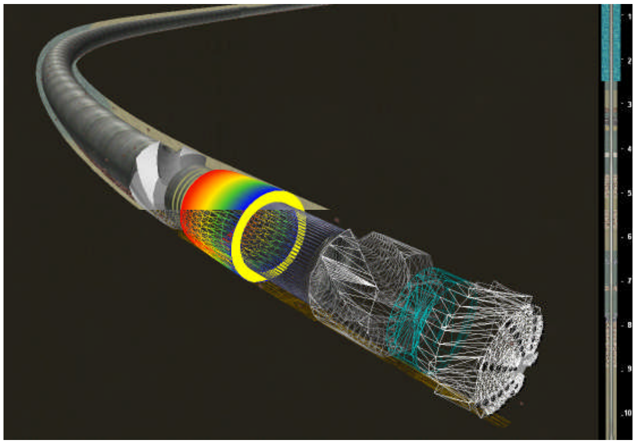

Fig. 3- 3D graphics of the drill string showing mesh primitives and fully rendered images.

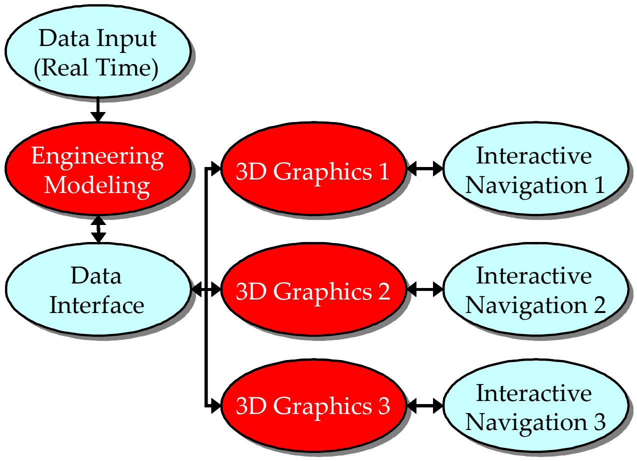

Fig. 4- Enhanced flow chart showing multiple graphics stations supported by single engineering computer.

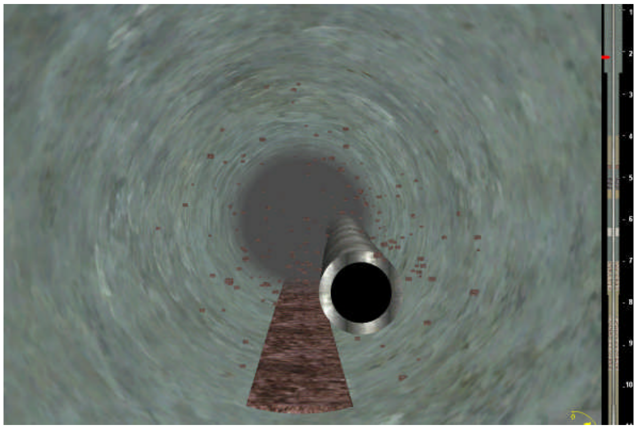

Fig. 5- Inside wellbore view showing cuttings bed, drilled cuttings, and effects of coiled tubing helical buckling on eccentricity.

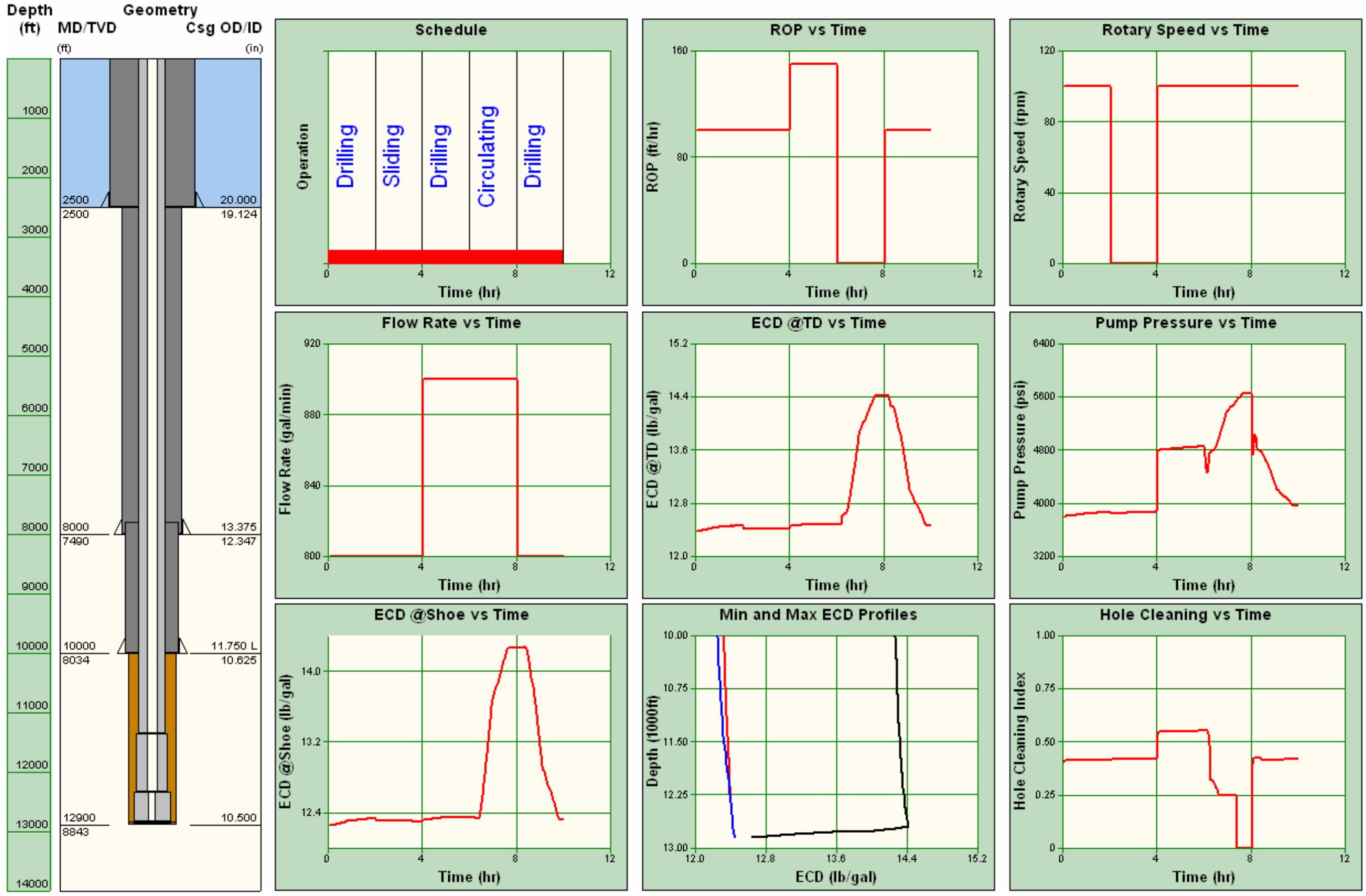

Fig. 6- Transient reconnaissance simulations displaying key parameter results for a predefined, 10-hr operations sequence.

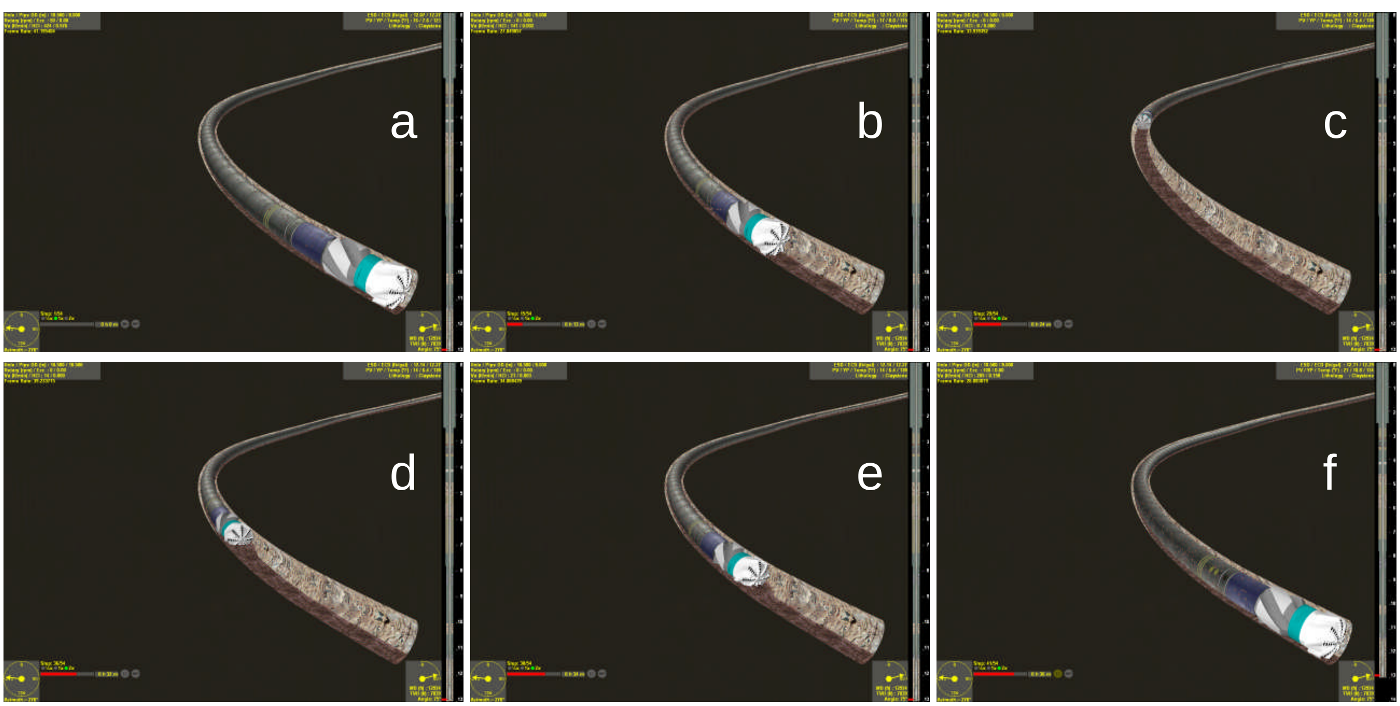

Fig. 7- Transient version screen captures illustrating a short trip (sequentially from frames a-f). The virtual camera is stationary during this sequence. Note the cuttings piles immediately ahead of the bit in frames *d* and *e*.

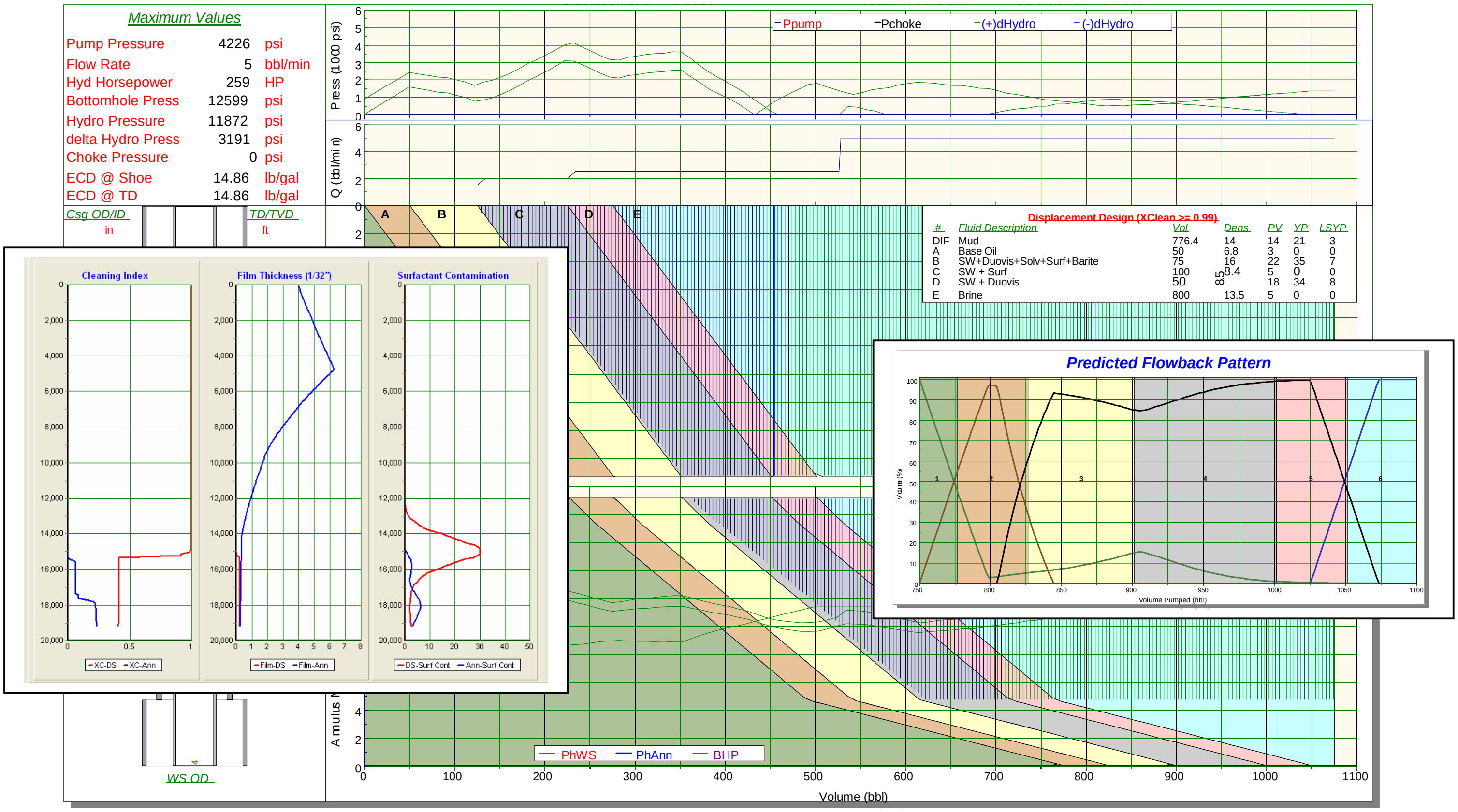

Fig. 8- Transient cleaning profiles and flowback predictions superimposed over the corresponding rainbow chart where the cross-hatching indicates wellbore cleaning efficiencies greater than 99%.

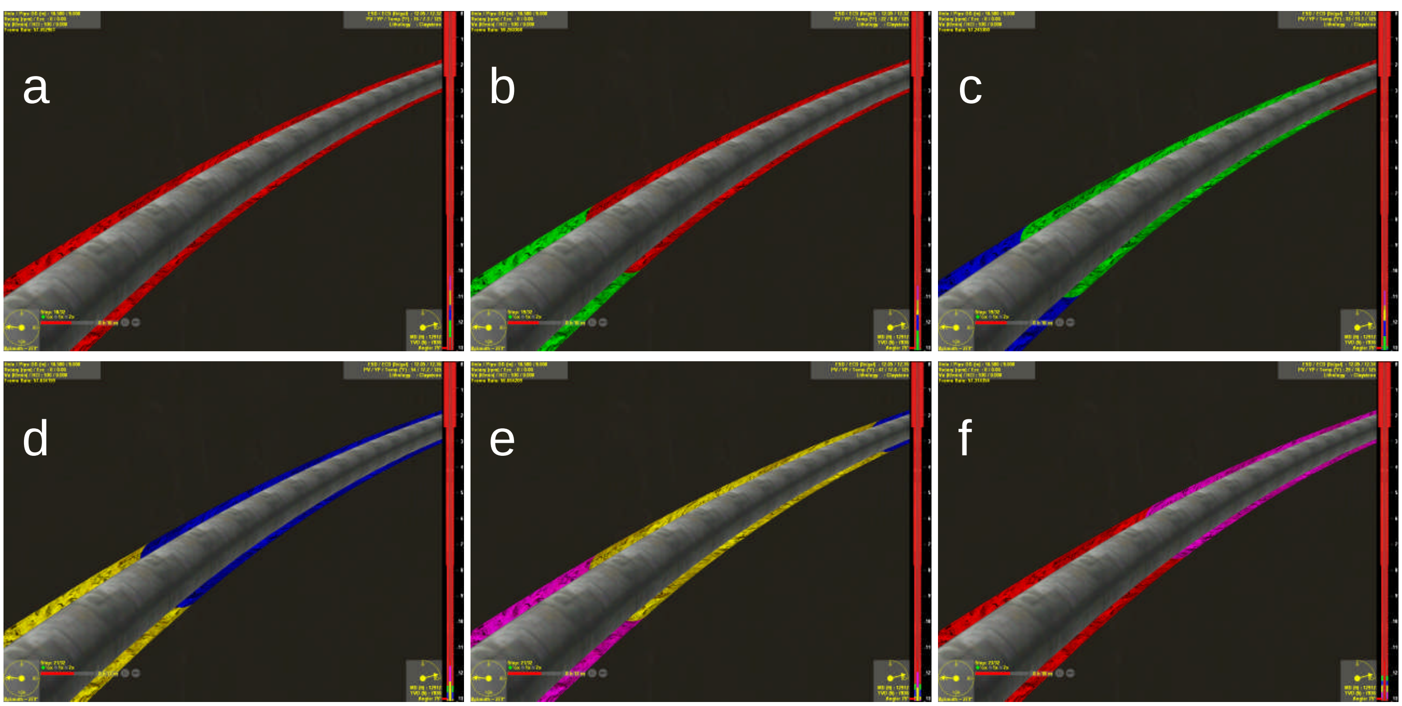

Fig. 9- Screen captures for a displacement (sequentially from frames a-f) where different fluids and spacer are highlighted by color.