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Development and First Application of Bistable Expandable Sand Screen

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Abstract

Sand control in an open hole typically results in risky completions, especially in weak or unconsolidated formations. Stand-alone screen completions present the risk of wellbore collapse and screen erosion, while gravel packing involves time-consuming and complicated pumping operations. Although expandable sand screens have recently become available to provide the best of both worlds, fast installation and wellbore support, design constraints limit their application. Wellbore conformance, expansion loads, and connection integrity have been critical issues with these types of screens. Where successful applications have been found, improved production with lowered drawdown have been typical.

Extensive research and finite element analysis have led to the development of bistable expansion cells. These cells have minimal plastic deformation during expansion and exhibit a hysteresis-like behavior. The specific cut pattern can open with relatively low expansion force, and then resist higher-level collapse loads. Due to the low plastic strain levels, bistable cells are compatible with any common oilfield material, achieving expansion ratios as high as 1.6 times the original screen diameter. This paper will cover the design, development, and testing of an expandable sand screen using bistable cell technology. In addition, the design and development of the proprietary expandable connection will be presented. The testing presented covers a wide range of structural integrity, expansion, sand retention, mudflow, and geomechanical tests performed on the screen, base pipe, and connection.

In late 2002, the first bistable expandable sand screen was deployed in a 4,400-ft water injection well in west Texas. The

compliant expansion tool deployed the screen in one trip at speeds exceeding 1,800 feet per hour with set-down loads of less than 20,000 pounds.

Introduction

The open hole performance of sand control screens depends on preventing sand grain migration through the screen's filtration media. In order to achieve this rather simplified objective, rapid annular flow along the outside of the screen must be eliminated. Annular flow can lead to localized erosion and failure of the filtration layers over a relatively short time period. For this reason, operators have not widely adopted traditional stand-alone sand screen as a low risk solution for high-value open hole completions. Instead, the reliability of this screen type, when in-situ, is improved through the application of a gravel pack that introduces a secondary filtration layer around the screen. Although placing a gravel pack around a sand control screen eliminates the annular gap, it can involve significant additional cost and can introduce additional risks if the gravel pack pumping operations are not performed correctly.

Emerging expandable screen systems, available today, have demonstrated the potential for a reliable sand control solution by expanding screen into the wellbore annulus. Closing the open hole annulus not only eliminates the need for gravel packing operations but is also proven to increase reservoir productivity due to the higher screen area in contact with the formation. Greater access for intervention and the ability to reduce the number of completion casing sizes are other observed benefits of expandable screens over existing sand control screens.

When choosing a sand control solution, expandable screens bring many new benefits to the completion engineer; nevertheless, successfully installing and expanding this type of screen brings its own unique problems. Current expandable screens rely on increasing their diameters by significant plastic deformation of an expandable tubular. Such high plastic deformation levels require a deployment tool to exert considerable energy, typically achieved by high set down weight or via hydraulic power transferred through the drill string.

An even greater problem, caused by the plastic deformation of expandable steel tubular structures, is the inevitable elastic

strain relaxation once the expansion stress is removed. Due to this phenomenon, an annulus can be created around the expandable screen, even after the screen is initially expanded to the wellbore wall. This relaxation gap can lead to annular flow around and along the expandable screen completion, exposing the screen to the same failure mechanisms as a stand-alone screen.

Plastic material deformation, as a means of expanding a steel tubular structure, also gives rise to the tubular shrinking in axial length. This length reduction is a function of the material Poisson's ratio, the expanded diameter, and cut pattern. Regardless of the reason, axial shrinkage must be accounted for when planning an expandable screen completion's length.

While developing an expandable screen, the project team was given four primary goals to achieve a successful expandable screen:

1. Low radial deployment force
2. High circumferential compliance
3. No relaxation of the post-expanded diameter
4. Constant axial length during expansion

These project goals were achieved through the development of a unique bistable cell design. The bistable design allows the base tubular expansion to be dominated by the behavior of the bistable cell geometry rather than the properties of the base structure tubular material.

Application of Bistable Cells

The concept of the bistable cell has been used successfully in the development of medical stents. Stents are small expandable tubulars placed in blood vessels for many medical conditions, including support. In most procedures the stent is expanded in place by a balloon, but for the bistable configuration, the stent can be deployed with a very small force. In this situation, bistable technology has an added benefit of maintaining a constant length, minimizing stent migration.

To date, expandable screens all require very large deployment forces. An alternative approach makes use of a system long known in mechanical design, the toggle or over-center mechanism. In the application to expandable screens, this toggle device is referred to as a bistable cell. Like all over-center devices, the bistable cell exhibits a unique force displacement curve, shown in Figure 1. As force is applied to open a cell, a point is reached where the force input becomes a force output and the cell opens spontaneously to its second stable position. To illustrate the principal, consider a rod held between two rigid buttresses as shown in Figure 2. If the buttresses are moved inward the Euler buckling limit will be exceeded and the rod will deflect, first to a sine wave and then to a full curve at any direction. If the buttresses are held in the position where buckling has taken place, a lateral force on the rod will cause the rod to move to a second stable position and the force deflection will be as shown in Figure 1. The simplest bistable cell consists of two sinusoidal leaves,

connected at their ends. Three versions of this geometry are illustrated in Figure 3, one with leaves of the same thickness and two with different thickness ratios. With equal thickness leaves, both leaves will move when subjected to a vertical force and the length of the cell will decrease. For leaf ratios of two and three, the force deflection curve is the bistable curve in Figure 1 and, when in either of the cell's stable positions, the length of the cell is unchanged.

An expandable pipe using the bistable principal is created by cutting a circumferential pattern of cells where the thin strut of one cell is connected to the thick strut of the next cell. This pattern is continued down the length of the pipe. The cells illustrated above are ideal in that no plastic deformation takes place. For the case of a thick wall steel pipe some plastic deformation will take place, particularly at the end joints of the thick and thin struts and the cell design must be modified so that the bistable action takes place without exceeding the fracture strength of the steel. A pipe with the bistable cell pattern has another unique feature, once an expansion tool opens the first cell, the next ring of cells will begin opening due to the transfer of stress. This opening will propagate down the length of the pipe. With the negative force deflection characteristics of the bistable cell, this self-opening feature contributes to the reduced force to expand a screen based on the bistable cell configuration.

Bistable Cell Design

Bistable systems have long been used for small-scale applications, such as medical stents, where superelastic materials can be employed. However, a simple bistable cell typically used in medical applications, shown in Figure 4, will not achieve the same bistable force/deflection behaviour when standard oilfield tubular steels are employed. This behaviour will not be achieved because plastic hinges developed at the thin strut ends. In order to obtain a comparative bistable effect in oilfield steels, development of dramatically different geometry would be required.

To understand how to achieve bistable behaviour in a cell, it is necessary to review how the forces in the system combine to provide the vertical force characteristic during deployment (Figure 4). In the elementary cell, the thin struts bend as the load application point moves through the neutral position (A) and the curvature is reversed at full deployment. The work required to bend the struts is stored as elastic strain energy, which is then released later in the deployment. However, if the forces are sufficient to yield the material at any point along the length of the thin struts, most of this energy is converted to irrecoverable strain energy due to plastic deformation. The design problem therefore became one of finding another mechanism for storing and releasing elastic energy during deployment. Instead of relying on bending of the thin struts, inclusion of end 'horns' was proposed (Figure 5). These features would rock backwards and then spring forwards during deployment to provide the thrust force.

The design of the horn geometry itself was reduced to an elastic optimisation problem where the geometry was varied to

keep the horn stress below yield for a given deflection. A first prototype cell geometry (see Figure 5) was developed using an automatic finite element based design optimisation process. The deployment curve (Figure 6) clearly demonstrates the bistable behaviour. The advantages of the system as a whole are inherent in this deployment curve. Firstly, the energy (area under the deployment curve) required to deploy the system is quite low. Secondly, since the plastic strain is localized, springback forces are very low, resulting in no annular gap for the full range of deployment diameters. Traditional expandable systems, including slotted and solid pipe designs, both undergo widespread plastic deformations during deployment and the resulting residual stresses lead to contraction after the deployment tool has passed.

With the general geometry defined to generate a positive bistable effect using typical oilfield materials, the cell design needed optimization for down hole service. A different type of design optimization well suited to solving non-linear optimization problems was employed for this purpose. Response surface optimization techniques are widely used in the automotive industry for the design of crash resistant and energy absorbing systems. This same technology was employed to automatically define the key dimensions of the cell to meet pre-defined design targets detailed in Figure 7. A flow diagram summarizing the design optimization process is provided in Figure 8. Initially, a set of design variables is defined for the cell. These are user defined controlled perturbations of the design geometry. In the first phase of the design optimization process, an approximation is made of the response surface by sampling points within the design space. Once an approximate response surface is available, an approximation to the optimum can be made. In the second phase, this approximate optimum is used to start an automatic non-linear response surface optimization procedure to find the true optimum solution. To set up the optimization problem, it is necessary to define a global objective and constraints on design responses. The objective and constraints can be any of the deployment curve features in Figure 7. The process provides a highly automated method for design engineers to tune the system for a wide variety of applications.

To complete the design of the base structure, it was necessary to develop a full understanding of how the cells would behave when stacked in a cylindrical array. To investigate this, a complete deployment simulation environment was developed (shown in Figure 9). By modelling how the load is transferred from the deployment tool to the cylindrical array, it was possible to gain early insight of exactly how the system would deploy. Deployment expansion arms were modelled as well as the main structural components of the sand screen and a constraining bore hole. This deployment simulation was used to capture stresses in the sand screen and expansion tool for a variety of expansion situations including one referred to as bubble expansion. Here, the tool expands in collapsed screen, pushing the screen out to the bore hole diameter (demonstrated in Figure 10). This results in the most severe loading case for the expansion tool, requiring the maximum radial force. In this expansion situation, the radial load to open the screen is

resisted by the adjacent row of cells and a number of rows of cells either side due to the load carrying capacity of the thick struts. This non-linear effect can only be captured fully by modelling the system in this way.

The detail available in the deployment simulation models also allowed investigation of bore hole expansion scenarios and deployed screen performance. It was demonstrated that the system could be deployed through restrictions, curved, and helical bore hole geometries without adversely affecting the structural integrity or deployment loads as seen Figure 11. Further simulations to understand how the system behaves during installation and operation included: torsion, axial compression, bending, and external pressure. Results from the axial compression load case are shown in Figure 12. It can be seen from the force-deflection data that the system can resist high levels of compressive load (greater than 90,000 pounds). The ability of the simulation environment to capture the post yield response is also clear from the graph and demonstrates significant redundant strength.

Bistable Expandable Screen Design

As is the case with any other sand screen, expandable or not, the base pipe forms the primary structural element. For the 8-1/2 inch completion, the base pipe begins as a standard 5-1/2 inch 17 pound-per-foot oilfield tubular. The ends have the outer and inner diameter finished to accommodate the connection, whose profile is cut during the same operation as the bistable cells, while the rest of the tube is left as received. The bistable cell pattern repeats along the entire length of the base pipe. Base pipe features include a number of mechanical fasteners clearance holes to attach connection hardware, discussed later in this section, and the backing strip. The backing strip, typically 316L stainless steel, allows the shroud to be attached to the base pipe. Figure 13 shows the bistable cut pattern in the base pipe.

The shroud and filter subassembly is made offline in a separate process. The subassembly is made flat and consists of the shroud, high expansion filter layer (HEFL), and woven wire cloth sheets, in that order. The shroud's optimized design maintains a constant length while providing a very small compressive stress on the filter layers after expansion. This gives the best possible sand exclusion. The design of the high expansion filter layer provides filtration protection from wellbore fluids and mud cake, for the woven filter sheets, during run-in-hole and the screen expansion process. The woven filter material has a weave designed to the sand grain size of the application according to industry standards. Figure 14 shows a sectional view of a finished bistable expandable sand screen.

Requirements to maintain full tensile capacity during expansion make the design of an expandable connection inherently difficult. Fortunately, the absence of any deformation in the thick strut of a bistable cell provides the perfect basis of an expandable connection. Because the thick struts in a bistable tube do not deform in either the longitudinal or transverse directions, simply connecting the

thick struts on one joint to the thick struts on another form the necessary coupling to transmit the string's entire weight. During expansion, these coupled thick struts simply translate radially, as if a single joint. An interlocking profile, cut during the base pipe manufacturing process, connects the thick struts. Immobilized by a sliding cover, these interlocking profiles become very rigid after make-up. In order to maintain the screen's sand integrity around this connection, a secondary sand screen spans the connection region. The connection sand barrier is swaged against the inside of the screen during the expansion process to form a sand-tight seal. Figure 15 shows the two mating ends of the connection while Figure 16 shows the progression of the connection make-up.

The profile design not only must take the tensile transfer from joint to joint, but the need to quickly make or break the connections. The structural integrity of this connection has been tested extensively by either a coupon test to check the validity of a single interlocking profile and by full-scale destructive test of a screen's made-up connection. Testing has verified the screen connection to have a tensile yield of 112,000 pounds and a torsional yield of 5,000 foot pounds. Experimental and design verification of the connection make-and-break cycle have shown the connection can be remade multiple times without any adverse effects on performance. Current recommendations allow the connection to be made and broken up to 8 times without compromising integrity of the mechanical joint.

To make this connection, a snap together force of approximately 2,000 pounds is required to engage the locking profiles. This load (joint weight plus approximately 1,000 pounds from external source) is applied by a hydraulic crosshead attached just above a hydraulic spider, used to hang the screen above the well. The assembly tool not only assembles the screen, but in case the screen must be removed from the well, it is required to disconnect the connection as well. To further reduce the amount of manual labor involved in the connection process, the assembly tool moves all the connection locking covers into place in a single operation, resulting in a very efficient connection time.

Because full and compliant expansion is key to the successful application of expandable sand screens, exhaustive tests have been performed on the base structure, entire screen assembly, and the connection to ensure it expands to the correct diameter every time. Trial expansion tests were typically performed horizontally in a laboratory environment where a measured axial load from a hydraulic ram can be applied to the expansion tool. These tests allowed screen and connection construction techniques to be assessed as well as evaluation of the deployment tools. Typical samples used for laboratory testing comprised of two 12 foot joints of expandable screen joined by one connection. This entire sample is then expanded and checked for structural and sanding integrity.

After a successful expansion test, one of the ways the structural integrity of the base pipe is accessed was a corrosion test on the expanded bistable cell. With the hinge being both

the minimum dimension in the entire structure and the only location where plastic material deformation occurs, the hinge was typically the focal point of any corrosion test. In one test, an expanded bistable cell cut from standard L-80 tubing was subjected to a 720 hour corrosion test. The environment was 5% sodium chloride, 0.5% acetic acid, and 100% H₂S in a deaerated, sealed vessel. Post-test metallurgical inspection showed no signs of environmentally assisted cracking.

An equally important performance parameter of an expandable sand screen is the collapse resistance. Using the multiple design parameters available in a bistable cell (horn stiffness, hinge thickness, etc.) the stiffness of the structure can be adjusted to achieve a variety of different collapse ratings. Modifying the cell geometry can also influence compliant expansion range, deployment force, and inflow area. Figure 17 shows typical collapse data for different bistable cell designs.

Extensive testing has been performed on the screen to measure sand retention and mudcake flowback characteristics, both critical features of any sand screen. To address the question of sand retention, both large and small scale testing were conducted. For the small-scale tests, fluid was pumped through a sand pack and a 5 inch screen coupon (shroud, filter layer, and base pipe). Due to the large opening of expanded base pipe and shroud, 48% compared with the conventional base pipe opening of approximately 10%, the pressure drop across the expandable screen was much lower than conventional screens. Another result of this large open area was revealed when the gap between the screen and the formation was eliminated, sand did not plug the screen. This allows an expandable screen to utilize mesh with optimized pore size, resulting in the lowest rate of sand production, shown in Figure 18.

The large scale testing of the bistable expandable screen structure was performed by pumping fluid through a sand pack around a full screen section 2 feet long. The experimental set-up, shown in Figure 19, enabled measurement of sand production on the entire screen assembly, especially the filter media. The effluent sand measured less than 1.0 lbs/mbpd. This test was duplicated for the region of the expandable sand free connection. Sand production was once again less than 1.0 lbs/mbpd.

The expansion method of a bistable expandable sand screen results in the shroud being forcefully pushed against the wellbore. This action requires two things: 1) mud is capable of flowing through the sand screen without plugging and 2) the sand screen is capable of producing the filter cake once production begins. An expandable sand screen that cannot meet both of these criteria, will plug and fail immediately upon production. To ensure the bistable screen filters were designed appropriately, two types of mud flow experiments were performed. First, mud was simply flowed through a screen coupon (shroud, filter layer, and base pipe) to ensure it would not plug the filter assembly. The results of these experiments showed that certain muds were more prone to

plugging, regardless of particle size (Figure 20). Second, filter cake flow-back tests were performed by dynamically building up a mud cake on rock core's surface. Then fluid was pumped in the production mode to compare the lift-off pressure with and without an expandable screen on the filter cake. The results showed the expandable screen did not inhibit the clean up of the filter cake by flow-back, as shown in Figure 21 and Figure 22.

Deployment Tool Design

The deployment tool was designed to compliantly expand the bistable expandable sand screen in a single trip. In order to achieve this goal, the following requirements were set forth for the design:

- Maximum Collapsed OD = 4.8 inches
- Nominal Expanded OD = 7.6 inches
- Maximum Expanded OD = 8.5 inches
- Compliant screen outer diameter expansion range of 7.0 to 9.5 inches

Other design constraints included robust design, length not exceeding 40 feet, and ease of use – to minimize operator intervention. The tool consists of an expansion head, an activation system, and a locating system.

Rollers, pistons, inclined surfaces, and linkages were all examined as basic mechanical principles for the expansion head design. In order to get a high expansion ratio (177%) along with the required expansion force, a concept utilizing a combination of a linkage and an inclined plane was chosen. The linkage and inclined plane concepts both take advantage of the large amount of space available along the axis of a well bore. The expansion head consists of a set of slider/crank linkages arranged in a polar array about a central support shaft (see Figure 23). Each expansion arm is pushed radially outwards via a link connected to a slider riding along the central support shaft. Since the mechanical advantage of the slider/crank is relatively low at small diameters, at the lower end of the expansion range the expansion arms are forced outwards via a separate slider. This slider contacts an inclined surface on the underside of each expansion arm, resulting in the required force over a specified diameter range. Several versions of the tool have been successfully tested.

Internal pressure activates the tool by pumping fluid from the tool interior to the exterior through sized orifices. The pressure differential required to set the tool varies from 2,500 to 3,000 psi depending on whether the tool is expanding screen. This pressure creates the force necessary to compress a large spring stack, storing the energy needed for screen expansion. Storing energy in a spring stack allows the expansion arms to comply with variations in the well bore diameter as the tool expands the screen – at larger diameters, the spring stack is less compressed, and smaller diameters compress the stack more.

The spring stack, and thus expansion tool, is held in the

expanded position with an indexing mandrel that operates similarly to one in a ballpoint pen. By applying pressure to the tool, the springs are compressed and the indexing mandrel is locked. To collapse the tool, pressure is applied again the indexing mandrel is unlocked, releasing all the energy stored in the spring stack. The tool can be expanded and collapsed an indefinite number of times in order to pass through small restrictions such as collapsed sections in the well bore or completion hardware. Initial field tests have shown that the force required to move the tool through the screen ranges from 15,000 to 30,000 pounds. During the same tests, the tool was able to move through, and expand, the screen at a rate exceeding 1,800 feet per hour.

Geomechanics

Full-scale experiments investigated the interaction between a bistable expandable sand screen and borehole failure with the aim of verifying the borehole support capabilities of the bistable sand screen. Another goal of the research program was to investigate the interaction between screen, rock and borehole shape. This interaction forms the basis of an expandable screen's design.

The experimental setup simulated the relevant downhole conditions, which occur during oil production. A large pressure vessel was used, which holds rock samples approx. 2 feet in diameter and 3 feet long with an approximately 8-1/2 inch borehole drilled along the cylinder axis. All experiments were done on Castlegate Sandstone, a weakly consolidated sandstone from the Upper Cretaceous of Utah (USA), which is often used as a reservoir equivalent rock. It has a uniaxial strength of about 15 MPa (2,200 psi) and a porosity of 25% - 27%. To increase the depletion-induced effective stress acting on the outside of the sample, the confining pressure was raised in the testing vessel. Oil production was simulated by kerosene flowing along the borehole. Previous work has shown that for consolidated sandstones, borehole failure is determined by the state of stress and the fluid flow along the borehole; fluid flow through the rock into the borehole has a negligible effect. During the experiment a camera inside the borehole recorded the deformation and failure process.

The first experiment was done on a sample with an 8 inch open hole in order to determine the failure strength of an unsupported borehole in this rock and geometry and to describe the process of borehole failure and sand production in weakly consolidated sandstone. The failure strength of the borehole was reached at 170 bar (2,500 psi, see Figure 24), when cracks formed at four points evenly distributed around the circumference of the borehole. The increase of confining pressure was stopped at this point and the following failure evolution took place at constant confining pressure. The cracks grew rapidly and merged to form two zones of failure, from which thin, long pieces of rock were pushed into the borehole and transported away by the fluid flow. This process of spalling and immediate removal by the fluid flow gave way to further failure, which continued until the stress concentrations around the borehole were redistributed and a new borehole shape developed, which was stable under the

applied stress conditions (Figure 25). The material produced during the failure process consisted of long and thin sandstone flakes with sand grains and small rock pieces in between. In total a large volume of material was produced over a short period of time. After the failure process had stabilized and as long as the confining pressure was kept constant, the sand production decreased to nearly imperceptible quantities.

The next experiment tested the effect on the failure strength and failure process of a bistable basepipe, compliantly expanded inside the sandstone core and perfectly fitting the ID of the borehole. The rock around the borehole started to fail at the same pressure as the previous open hole experiment, which should be expected, because an expandable sand screen is a passive support element and so is not able to alter the mechanical properties of the rock. Nevertheless, even a plain, expanded basepipe had a tremendous effect on borehole stability, as it was able to hold the failed material in place and thus allowed the confining pressure to be increased considerably beyond initial rock failure. At about 340 bar (5,000 psi, twice the open hole failure stress) the failed zones extended to the outer boundary of the sample, large deformations occurred and the experiment had to be terminated. The reduction in borehole area was about 10% until sample failure and reached 20% at the end of the experiment (see Figure 24). As the basepipe had no filter element, sand and small rock particles could enter the borehole and some sand production took place during the experiment.

An experiment with a full prototype bistable screen showed that by using a properly designed filter medium and thus avoiding any sand transport, the system performance can be further improved. In this experiment a prototype of a bistable expandable sand screen, which was again expanded to fully conform to the borehole, was tested with the procedure described above. The pressure – deformation curve in Figure 24 shows an increase in deformation rate from about 150 bar onwards suggesting that rock failure had started. Up to about 320 bar the curve follows the curve of the previous experiment and from 320 bar onwards the deformation rate increases again and the curve becomes fairly linear. In this experiment the confining pressure could be increased beyond the point where the previous sample had failed, which was at about 340 bar. At 500 bar (7,200 psi) the experiment was stopped and the sample removed from the pressure vessel for visual inspection. Although the reduction in borehole area eventually reached more than 30% of the original diameter, the integrity of the sand screen was maintained and no sand was produced during the experiment. Figure 26 shows a cross section of the failed sample after the experiment. The rock in the breakout areas (Figure 26) are heavily crushed and consists of a few pieces of sandstone in a matrix of loose sand. The shear surfaces (Figure 26) that developed when the failure reached the outer boundary of the sample, and are artifacts of the experiment geometry.

From the geomechanical analysis it can be concluded that the main function of a bistable expandable sand screen is to hold

the failed material in place, thus activating the self-support capabilities of the rock surrounding the borehole. The negative effect of removal of failed material from the breakout zones can be seen from the pressure deformation curves in Figure 24.

The plain basepipe test allowed material to enter the wellbore and be removed by the fluid flow. In this experiment it was not possible to increase the confining pressure beyond the failure of the sample, because the amount of removed material caused large deformations. In the experiment with the prototype bistable sand screen no material was removed and although the sample was heavily crushed, the confining pressure could be increased well beyond sample failure.

A large annular gap behind a sand screen would provide enough space for sand movement, which could possibly have a deleterious effect on the completions performance. Therefore, the mechanical strength of the bistable expandable sand screen is much less importance for systems performance than the minimization of the annular gap and the avoidance of sand transport.

Full-scale Yard Testing

The first test of how all the components operated as a complete system was performed at a Schlumberger test rig during the second half of 2002. A string of 9-5/8 inch casing was hung inside the test well's 13-3/8 inch casing to simulate an 8-1/2 inch open hole. An expandable completion 100 feet long was run into the hole containing a lower crossover, two joints of bistable expandable screen, and a top crossover. The three expandable connections were made-up using the specialized assembly equipment. The screen completion was anchored inside the 9-5/8 inch casing utilizing a commercially available Quantum packer set at a depth of 650 feet (see Figure 27). Next, the deployment tool was run to depth on an appropriate string of drill collars and drill pipe. Once at the proper depth (the expansion head just inside the first section of unexpanded screen – indicated by snapping the tool's locating collet into the locating profile below the packer), the tool was activated using the mud pumps and the expansion head opened. The tool was set with a pump pressure of 2,900 psi at a flow rate of approximately 5 1/4 bbl/min. With the tool energized and disconnected from the pumps, it was able to expand the screen at a rate exceeding 1,800 feet per hour. The set down weight varied from about 12,000 to 15,000 pounds while traveling through the body of the screen and would increase to about 20,000 pounds when passing through a connection. The extra weight indication at the connection serves as a useful feedback system for the operators to verify the tool location and that it is functioning correctly. The end of the expandable screen was located by tallying the drillstring run during the expansion process. The final step in the expansion process was deactivating the tool by applying another pressure cycle and pulling out of the hole.

Of the major findings from this test, some of the most important were verification of the screen's handling and running procedures. This screen had previously never been

handled in 38 foot length, leaving many unknowns as far as how to handle and bring the screen onto the rig without damage. The screen connections went together well but highlighted two areas of concern: 1) difficulty in aligning the connection and 2) engaging the connection slide covers. The alignment problem was corrected by designing a stabbing guide for use during make-up. Further modifications to the connection features and slide cover tolerances also made engagement more efficient.

The major findings regarding the expansion process related to tool position and state. The amount of load indicated by the locating collet below the packer was inadequate to be seen at surface in this purely vertical well. In a well with any amount of deviation, the load would need to be much higher. A subsequent design change has more than tripled the snapping load of the collet. To determine the tool state, a weight indication was visible at surface when slacking off the energized expansion string. Once again, this works in a vertical application, but would be much more difficult in a horizontal application. Modifications to the expansion tool activation system now allow for a flow test to determine tool state.

After the expansion was completed, the casing, with the screen expanded inside, was pulled from the well, cut into sections, and expansion verified. Figure 28 shows the expanded screen interior. Figure 29 shows the measured OD of the screen after it was removed from the confining casing.

First Field application

The well selected for the first field test of the Schlumberger expandable screen was a Grayburg formation injection well located in Ector County, Texas. Pertinent well data is presented in Table 1. The test took place in late 2002 with the following primary objectives:

- Evaluate running procedures and equipment
- Evaluate expansion tool and level of compliant expansion
- Benchmark deployment times (make-up, running, expansion rate)
- Determine plugging tendency in injection applications

After the 8-1/2 inch section had been drilled, open hole logs, including a 2-arm caliper intended as a baseline to gage post-expansion screen compliancy, were run. Screen make-up and all assembly equipment worked as designed, and good benchmark data on make up time was obtained. The screen was run to setting depth and the packer set inside the 9-5/8 inch casing shoe without incident. With the screen located and anchored in the well, the expansion tool, twelve 4-1/8 inch drill collars, and twelve 6-1/4 inch drill collars were run in hole on 4-1/2 inch drillpipe to the top of the screen. Once positive depth confirmation was made with the locator collet, the expansion tool was indexed into the open position by applying the required pressure cycle. The screen was

expanded by tripping pipe to the predetermined stop depth at the end of the screen. Finally, the expansion tool was indexed into the closed position by repeating the previous pressure cycle, and retrieved.

Results from the field trial showed the system could be handled and used in a field environment successfully. The connection proved to be robust and viable; however, even with assembly equipment working well, the benchmark data showed slow connection times throughout the screen make-up phase. The largest contributors to the slow connection times were inexperience with the connection and the sensitivity of the "box pin" to alignment during make-up. The lessons learnt have enabled design improvements to surface equipment that will reduce connection times on future installations by nearly 50% (see Figure 30). There was also new emphasis on making the connection procedure more "rig friendly" in case of leveling inadequacy.

Expansion tool pressure signatures during the indexing process were not as apparent as they had been in previous shallow engineering tests. The lack of pronounced signatures made it difficult at times to determine the tool state (energized or closed). A redesign of the flow orifices and tool activation system has resulted in more pronounced signatures. Expansion rates during the test were very good, between 1,800 to 3,600 feet per hour. Screen compliancy was initially demonstrated as seen in the post-expansion caliper log results versus base-log. The expected hook loads of approximately 20,000 pounds were seen during expansion of the first three joints; however, subsequent expansion indicated a problem as the hook load steadily decreased. The reason for this load reduction was evident upon retrieving the expansion tool, as several expansion linkages were subject to fracture related failures. The linkage components had been surface hardened to improve wear resistance, and subsequent metallurgical testing revealed that hydrogen sulfide stress cracking caused the expansion linkage failures whilst in the well environment. Prior to this test, it was known that high H₂S concentrations could be present, but the risk was underestimated. Following the field test, the deployment tool material was changed to remove the need for surface hardening of load bearing components.

The early field trial, in a low risk well, was valuable - it successfully demonstrated an alternative expandable screen design, and identified areas for system improvement. The operational lessons learnt have directly impacted system improvements. As of May 2003, the completion is operating effectively with no evidence of screen plugging.

Conclusions

- An expandable screen, based on bistable technology, results in a compliant system that eliminates a wellbore annular gap, maintains axial length, and requires low expansion loads.

- Expandable screens do not prevent the failure of a reservoir formation under stress. Rather, they stabilize the formation by preventing the failed breakout regions from collapsing into an annulus, where they could be transported along the wellbore.
- The bistable expandable screen filter layer configuration provides better formation filtration than traditional non-expandable screens due to its large flow area and low-pressure drop characteristics. Mudcake clean up is not inhibited by compliant expansion of the expandable screen to the face of the wellbore.
- The bistable expandable sand screen system has been successfully proven by one full-scale yard test and one field trial.

Acknowledgements

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SI Metric Conversion Factors

feet × 3.048*	E-01	= m
in. × 2.54*	E+00	= cm
lbf × 4.448 222	E+00	= N
lbm × 4.535 924	E-01	= kg
psi × 6.894 757	E+00	= kPa
psi × 6.894 757	E-03	= N/mm ²

*Conversion factor is exact

Tables

Table 1. Well Characteristics for First Field Trial

Well Depth	4676' MD
Trajectory type	Vertical
Casing	9-5/8" 36 ppf @4279' MD
OH Interval	4279' MD – 4676' MD
OH Size	8-1/2"
Screen Size	6" OD expandable to 9.5"
Mesh	140µm
Hanger	9-5/8" QHS packer
Drilling Fluid	8.6 ppg field brine
H ₂ S concentration	14.15 mol %

Figures

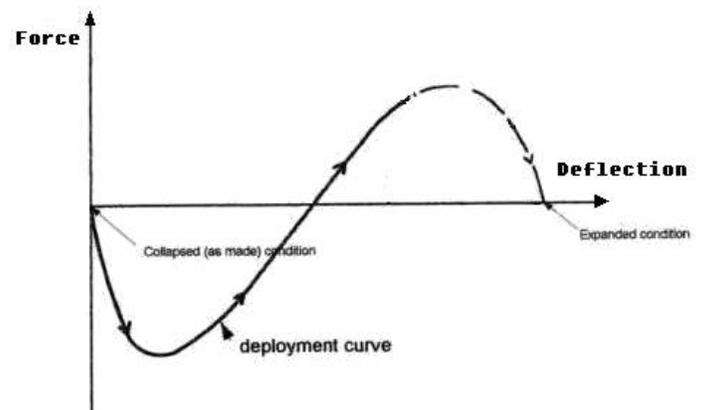


Figure 1 - Force Deflection Behavior of a Bistable Cell

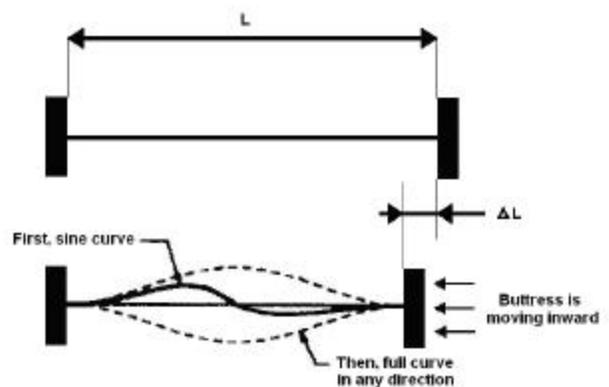


Figure 2 - Buckling Formation of a Bistable Cell

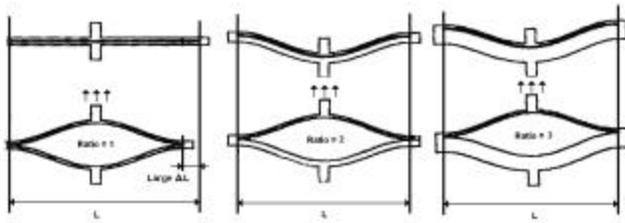


Figure 3 - Thickness Ratios in Bistable Cells

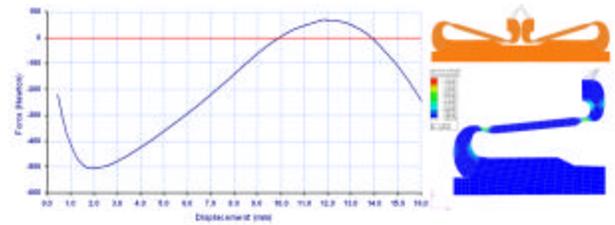


Figure 6 - Horn Force/Deflection Behaviour With Positive Thrust Force

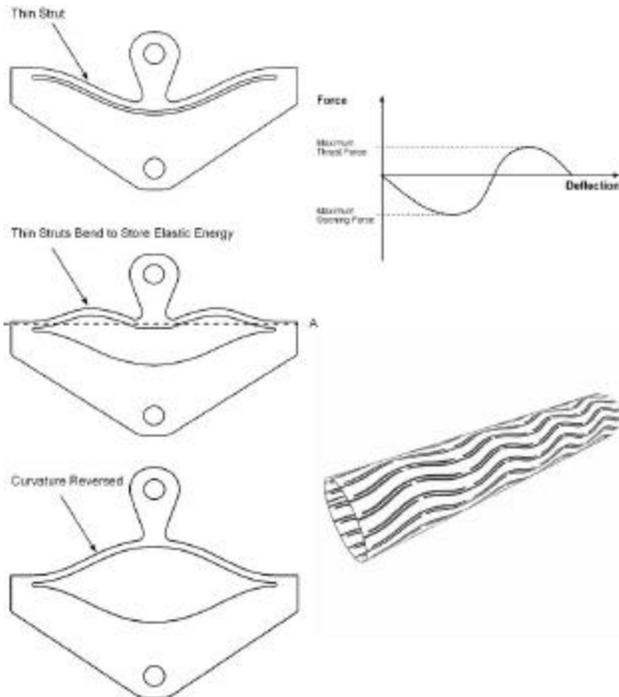
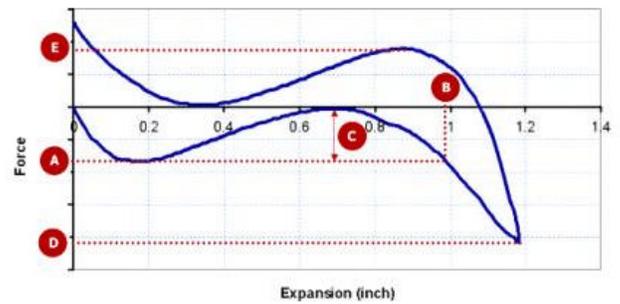


Figure 4 - Elementary Bistable Cell and Cylindrical Array



- A: Snap-through load
- B: Symmetry Stroke
- C: Bistable Range
- D: Maximum Opening Load
- E: Maximum Collapse Load

Figure 7 - Bistable Cell Deployment Characteristic Showing Key Design Parameters

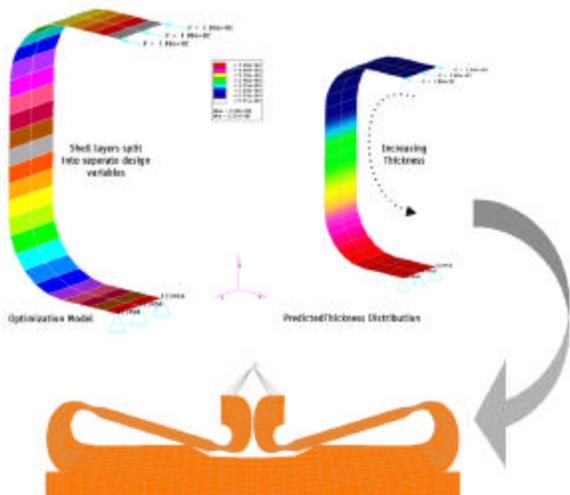


Figure 5 - Horn Size and Shape Optimisation

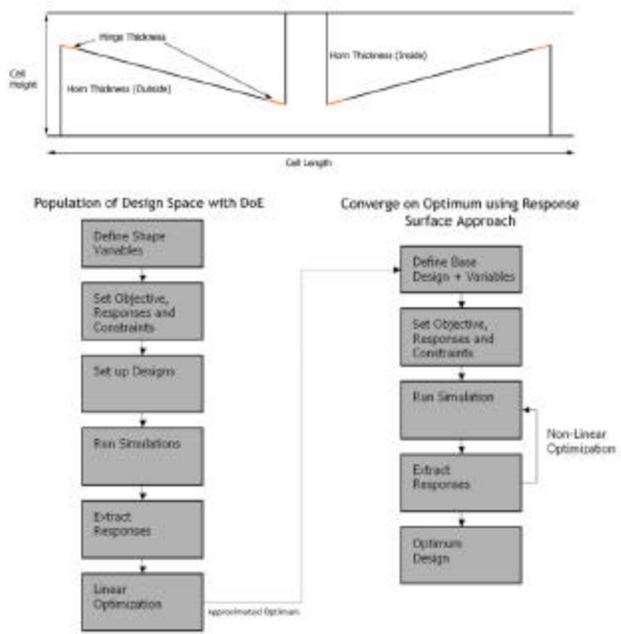


Figure 8 - Optimisation Process for Base Structure Cell

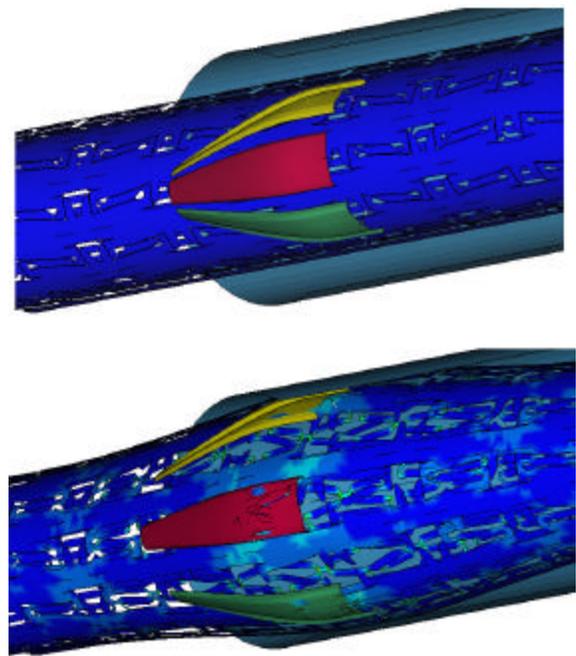


Figure 10 - Bubble Expansion Simulation Including Base Pipe and Outer Shroud

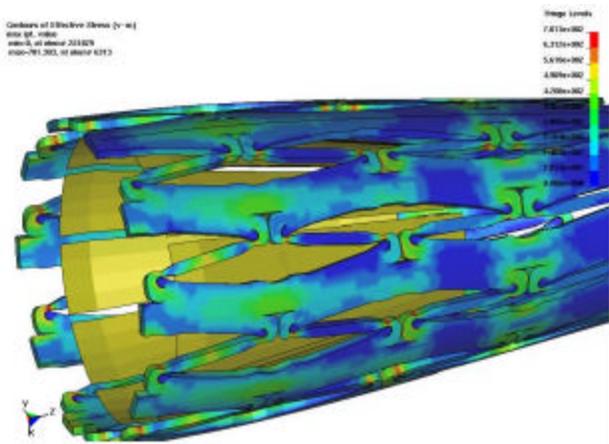


Figure 9 - Full Deployment Simulation Environment

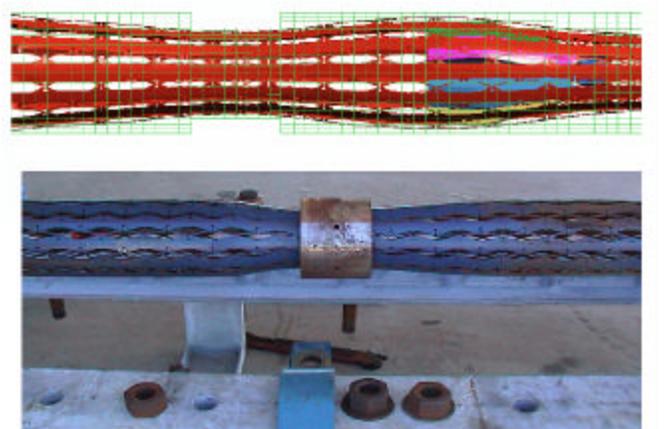


Figure 11 - Simulation and Expansion Test of Bistable Base Structure Expanding through Restriction

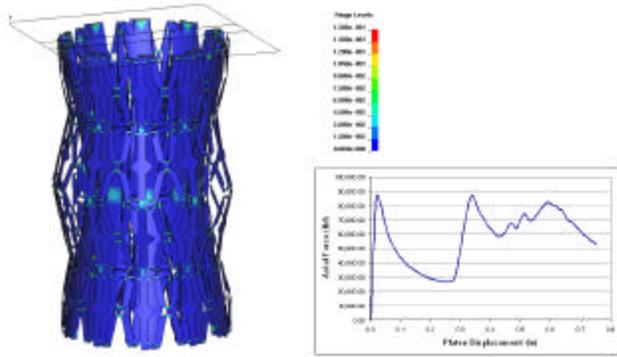


Figure 12 - Collapse Simulation of Base Pipe and Outer Shroud Including Force Versus Axial Displacement Result

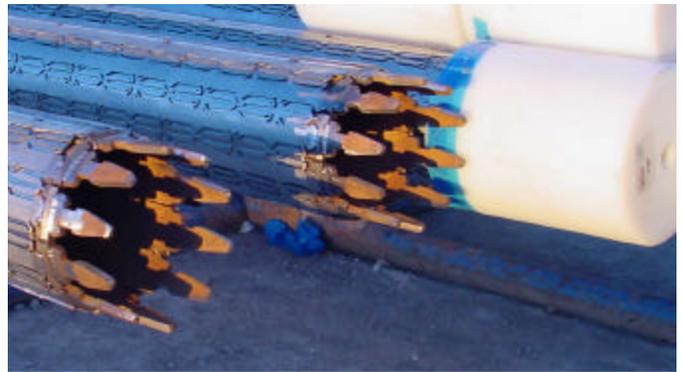


Figure 15 – Expandable Sand Screen Pin Connection (above) and Box Connection (below)



Figure 13 - Bistable Cut Pattern in a Base Pipe

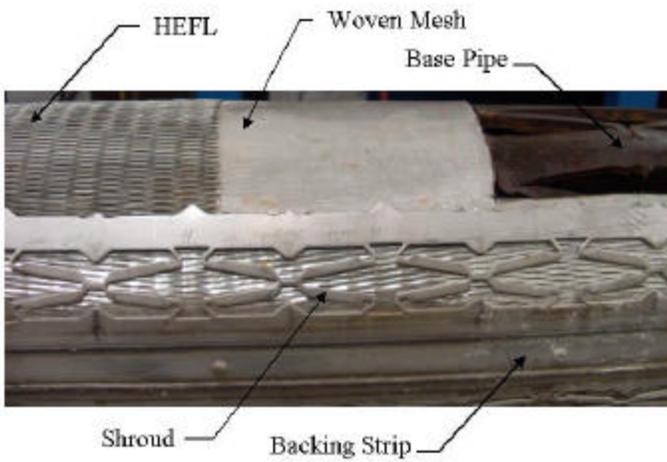


Figure 14 - Layers of Bistable Expandable Screen



Figure 16 - Make-Up Sequence of Expandable Connection

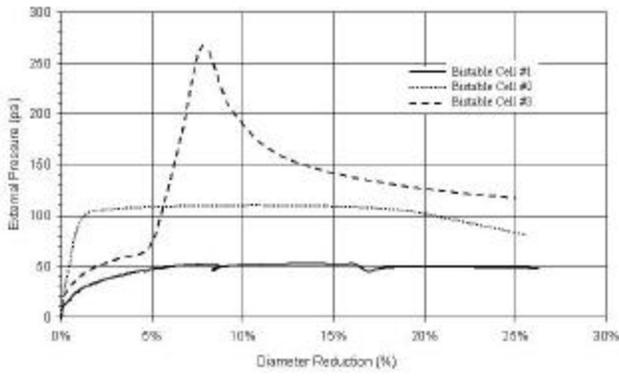


Figure 17 - Collapse Characteristics of Different Bistable Cell Designs

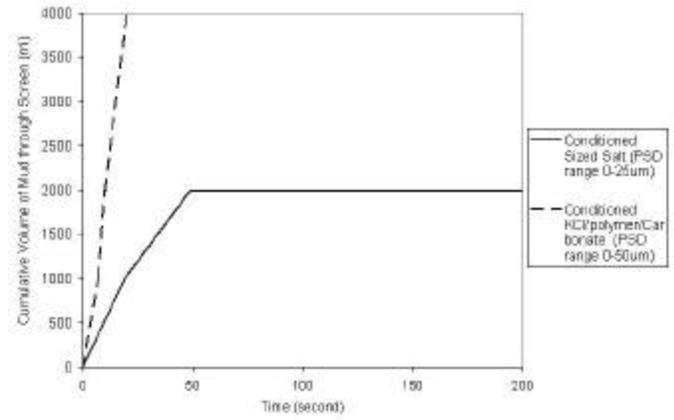


Figure 20 - Mud Flow Tests Through Screen Coupon

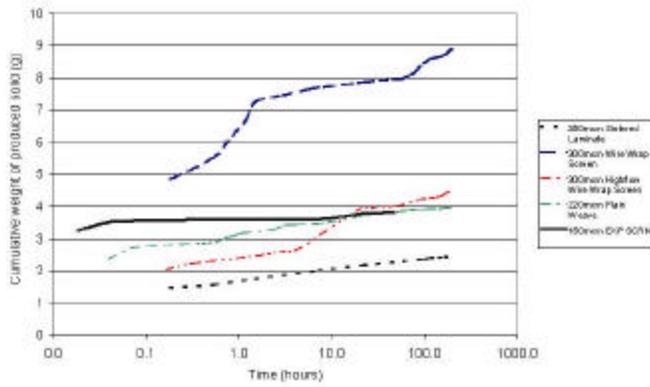


Figure 18 - Sand Production Through Various Filters

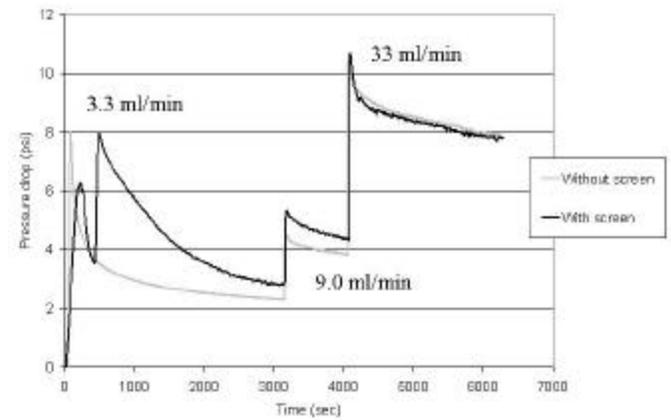


Figure 21 - Filter Cake Lift-Off Test with Sized Salt Mud

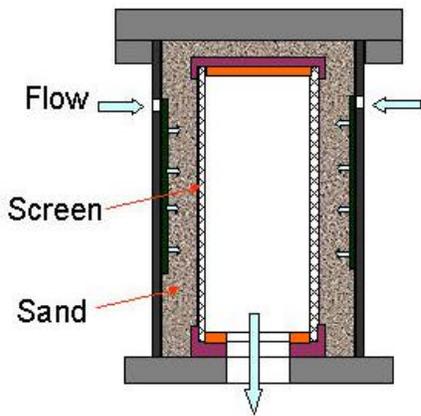


Figure 19 - Testing Apparatus for Large-Scale Sand Retention Test

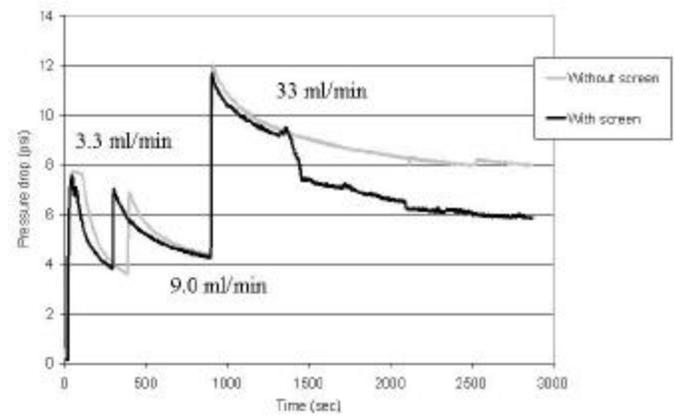


Figure 22 - Filter Cake Lift-Off Test with KCL/Polymer/Carbonate Mud

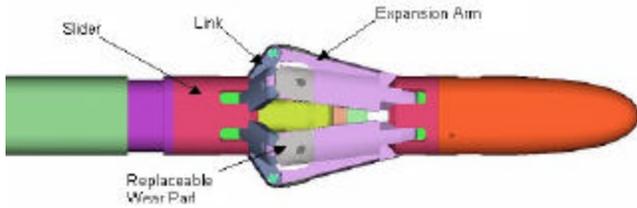


Figure 23 – Energized Expansion Head

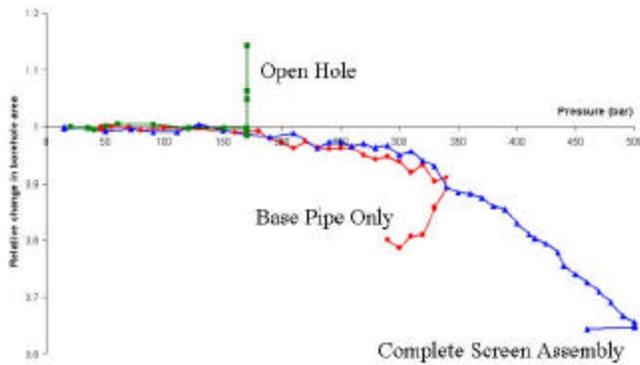


Figure 24 - Results of Castlegate Sandstone Tests



Figure 25 - Stages of Open Hole Collapse

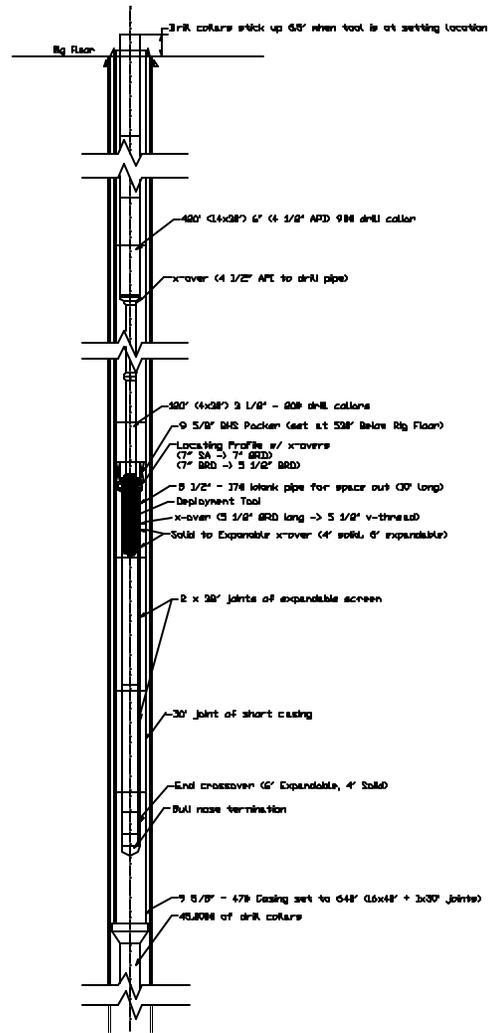


Figure 27 - Completion Diagram of Full-Scale Yard Test

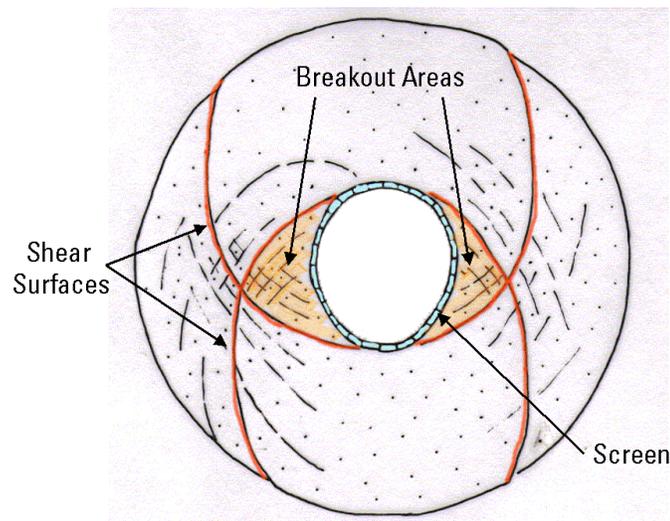


Figure 26 - Schematic of Rock Core Failure



Figure 28 - Casing and Screen Removed after Yard Test

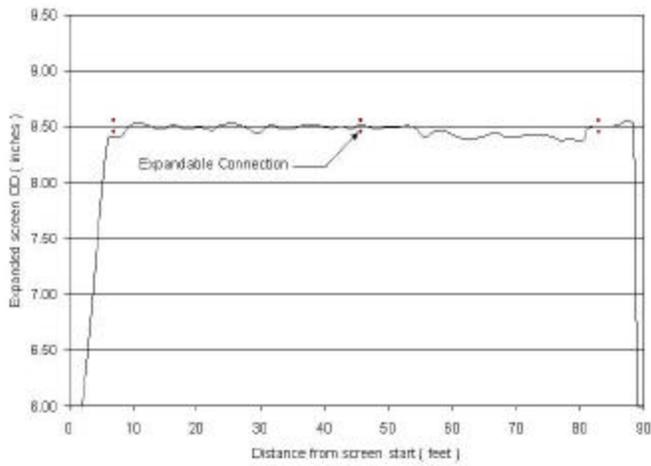


Figure 29 - Measured Post-Expansion Screen OD Along Completion

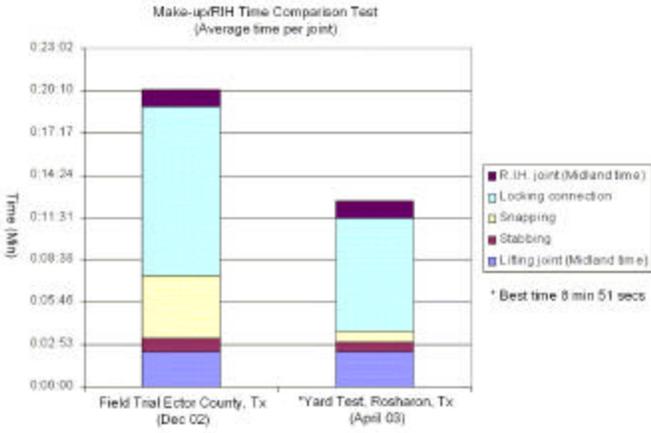


Figure 30 - Average Screen Joint Make-up Time Comparison