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Development of Self-Expanding
Idealflotm Sandcontrol Technology

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-- DISCLAIMER --

-- ABSTRACT --

Development of Self-Expanding ***Idealflo***tm Sandscreen Technology was a successfully executed design-by-analysis through field demonstration project. This final report is presented as a two-part progression of concept development and manufacturing activities. The first part, conceptual development activities, discusses novel specifications creation and non-linear analytical design generation. The second part, manufacturing, contains achievement related information for detailed-design, fabrication, mechanical testing, and field demonstration activities.

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Executive Summary

The Development of Self-Expanding ***Idealflo***tm Sandscreen Technology introduced and demonstrated new performance expectations for the expandable sandscreen industry. Commenced as a design-by-analysis through field demonstration program, idealized specifications criteria were provided to the project by industry. These ideal performance characteristics included four major criteria, not remotely obtainable in the conventional oil service industry, which were each met or exceeded by orders of magnitude.

The Self-Expanding ***Idealflo***tm project was performed under two major phases: Concept Development and Manufacturing. Significant accomplishments occurring under each are provided.

Concept Development Phase

Industry provided major needs criteria for expandable sandscreens included the following.

- Development of ultimate collapse properties in excess of 13.8 MPa (2,000-psi)
- Development of elastic rock support energy in excess of 1.4 MPa (200-psi)
- Development of expandable sandscreen technology which covers the industry spectrum for sand particle sizes, from 50µ - 250µ.
- Provision of high flow-through percentage of an expandable sandscreen, even when supplied in its pre-expanded diametric condition.

Conceptual and design development efforts resulted in robust, non-linear computational models which provided full functionality of both the sandscreen device and its interactions with various borehole geometry. The designs are tunable and scalable in all respects

Manufacturing Phase

The second-half phase included engineering design refinements, manufacturing, laboratory testing, and demonstration activities. Each area was successfully performed, resulting in constructed and tested performance, including:

- Development of ultimate collapse properties in excess of 55 MPa (8,000-psi)
- Ovalized borehole performance at 120% providing 13.1 MPa (1900-psi) resistance
- Development of elastic rock support energy in excess of .55 MPa (800-psi)
- Development of expandable sandscreen technology which covers the industry spectrum for sand particle sizes, from 50µ - 250µ.
- Provision of high flow-through percentage of an expandable sandscreen, even when supplied in its pre-expanded diametric condition: 20%.
- Expansion ratio to 170%
- Open, flow area to 60%
- Manufacturability including construction by any type of materials with minimal weight requirements.
- Met and exceeded all industry specifications for expandable sandscreens
- Deployed a prototype sandscreen as an actual monodiameter test well operation

I. Conceptual Development

The concept development stage marks the beginning of the sandscreen technology project. Originally, the project was scoped to refine an elastic-cell, sandscreen-tubular geometry by design-by-analysis methods. The original basic problem for this section was to engineer features for the presumed optimal geometric concept. Through the process of refinement, it was discovered that linear, or two-dimensional analysis would be insufficient towards obtaining the advanced level information required to complete the program and prove the technology. Through the analytical process, it was further discovered that modifications to the primary geometry would be recovered and actually suited the development. These modifications led to enhanced device properties and project results.

Description of Experimental Methods - I

The Conceptual Phase was commenced with the following items:

1. Design By Analysis
    - **Product Design Concept** - creating a thorough product design concept by defining performance requirements.
    - **Feature Design** - defining features from requirements.
    - **Geometry Model Development** - creating an analytical geometry model.
    - **Design Feature Parameters** - parameterizing product design features for potential optimization.
    - **Analysis Model** - preparing parameterized analysis models utilizing geometric symmetry.
    - **Performance Evaluation** - evaluating design feature performance metrics against standards.
    - **Continued Evaluation** - repeating preparation and evaluation steps until performance is met.
    - **Geometry Modeler** - translating optimized geometry to the geometry modeler.
2. Sandscreen Coupon Construction
3. Test Verification of Coupons
4. Concept Development for Performance in Ovalized Borehole
5. Construct Panels
6. Pretest Panels

Design by analysis experimental details follow:

Product Design – Specifications Development

Three sets of specifications or user preferences were used. The first set is as proposed and was based on rigid structural theory:

Proposal Specifications:	**Proposed Pre-Expand**	**Proposed Expanded**
Outside diameter (OD, d)	7.6 cm. (3.00”)	7.36 – 9.14 cm. (2.9” – 3.6”)
Inside diameter (ID)	6.35 cm. (2.50”)	6.35 – 7.62 cm. (2.50” – 3.00”)
Wall thickness (T)	.65 cm. (.255”)	.64 cm. (.250”)
Tensile rating	52.9 tonnes (116,655-lbs.)	--
Theoretical collapse	--	40.4 MPa (5,859.35-psi)
Torsion	--	11,396 nM (8398.4 ft./lb.)
Maximum outward force device	49.4 MPa (7165.89-psi)	--
Operating strain energy at expansion		35.3 MPa (5118.49-psi)
Strainer width at OD (W)		.18 mm (.007”)
Strainer width at ID (WI)		.20 mm (.008”)
Slot size (S)		.18 mm (.007”)
Open area percentage		50%
Spacing arrangement / scheme / frequency		.32 cm. (.125”), staggered
Spacer geometry (SPgeom)		.094 X .225 X .0625
Spacer attitude, rotation towards surface		30°
Material		4140 ASTM/6061 Al
Modulus of elasticity (E)		30,000,000 (material)

A second set of standards, however for standard 21.6 cm. (8.5”) hole sizes, was also utilized and scaled:

DIMENSIONS	*Required*	*Preferred*
Maximum running OD (inches)	7.4	<7.0
Minimum running ID (inches)	5.0	>5.5
Minimum joint length (feet)	30	30-40
Available pup joint length	¼ and ½ joint lengths	
Liner hanger OD for 9-5/8”, 53.3 lb. / ft. (inches)	<8.35	<7.625
Liner hanger – positive hydraulic seal post setting	Optional	Yes

CONNECTIONS	*Required*	*Preferred*
Pre-expansion tensile yield (lbs)	>100,000	>125,000
Post-expansion tensile yield (lbs)	>100,000	>125,000
Torsion Yield, un-expanded (ft-lbs)	> 5,000	> 20,000
Maximum no-flow length, made-up connections (feet)	<6.0	<1.0
Able to make-break-remake connections (#)	Twice	Repeatedly
Compatibility with automated make-up systems	Adaptable	Yes
Connection make-up time (# per hour)	>5	>10

INSTALLATION / EXPANSION	*Required*	*Preferred*
Installation efficiency must equal or surpass conventional sand-control completions:		
Trips for installation, expansion and isolation(footnote) (#)	<3	1
Installation dog-leg severity tolerance	>10° / 100ft	>20° / 100ft
Expansion dog-leg severity tolerance	> 7° / 100ft	>15° / 100ft
Ability to run through milled window	Yes	Yes
Ability to run through level-6 multilateral junctions	No	Yes
Maximum allowable running set-down weight, (lbs)	>20,000	>50,000
Required set-down weight for expansion, on bottom (lbs)	40,000	<20,000
Surface pump pressure during expansion(footnote) (psi)	<4500	<2000
Surface pressure bleed-off cycles during expansion (#)	Minimal	? 1
Total system expansion speed(footnote) (feet/hr)	>300	>600
Minimum OD at full expansion (inches)	9.25	>10
Range of compliant expansion(footnote) (inches)	7.4 to 9.25	<7 to >10
Rate of OD change per foot of screen (inches/foot)	>1	>2.5
Minimum compliancy in oval hole(footnote) (Max D / Min D)	>1.1	>1.2
Force transferred to formation, post-expansion(footnote)	0	>0

COMPLETION INTEGRITY	*Required*	*Preferred*
Effective retention(footnote) for range of D_{50} sand sizes (μ)	100-300	50-500
Effective retention(footnote), sand uniformity coefficient ($D_{40/90}$)	1-15	1-40
Maximum sand bleed-through rate (lbs / mboepd)	1	0.01
Base pipe open-flow area, gauge hole (in^2 / ft)	>15	>40
Maximum sand face drawdown (psi)	>1500	>2500
Maximum reservoir depletion (psi)	>5000	>7000
ID reduction at maximum drawdown(footnote)	<10%	<5%
ID reduction at maximum depletion and drawdown(footnote)	<20%	<10%
Maximum reservoir compaction(footnote) (%)	>0.33	>1.0
Unsupported hydraulic collapse pressure(footnote) (psi)	>250	>1250
Acceptable flux rate across screen, gauge hole (boepd/ft)	>750	>1500
Annular flow area, shroud-sand control layer(footnote) (in^2)	<3	<0.5
Planned completion life	10	20

*Footnotes are undisclosed. Specifications presented as published.

Other Industry Specification Proposals and Preferences Applicable to the Project Technology

1. A major design objective is to provide detailed sand support, thus avoiding channels and voids behind the screen, which otherwise lead to erosion hotspots, plugging, and reduced collapse resistance.

2. It is highly important for the device to comply to the wellbore to achieve higher-level constrained mechanical properties, thereby transferring hoop stresses and extending rupture values.

3. Crushing resistance includes collapse against wellbore compression.

4. Screen collapse is largely an issue of external hydraulic pressure occurring following plugging of the screen, where it is then exposed to full drawdown values of the well.

5. Plugging prevention is important as a major collapse prevention approach; the plug-resistant keystone strainer geometry is a positive feature.

6. Collapse is defined in two-orders, a flexible compliance rate and an ultimate failure value. These definitions are further characterized as constrained and unconstrained as the screen contacts the well.

7. There is high importance for certainty that the device reverts to compressed state rather than fail prematurely.

8. Collapse behavior beyond the compressed state will define ultimate limits.

9. Ultimate collapse strength >1000-psi is required, 2000-psi is ideal.

10. Stress relief occurs with initial strain due to stress transfer into formation.

11. Expansion & recompression is important as it determines screen behavior for the above.

12. Borehole strengthening against collapse will occur by delivery of a few hundred psi of flexible support, known as the ‘chicken wire’ or ‘cigarette paper’ effect.

13. Flexible support means sand will be prevented from leaving compression wedges, it will stay in place and absorb load.

14. Flexible support helps create hoop stresses in surrounding rock.

15. Time is of the essence for similar shale stabilization applications.

16. Spring behavior ideally is one which only eventually becomes very stiff in order to prevent ultimate collapse.

17. A high expansion ratio, or recompression ratio with good flow-through and maintenance of a basic intervention diameter are highly sought after properties.

18. Inducing helical flow paths is worth investigating and may become a mechanical parameter to balance strength and formation compliance; local torsion may provide beneficial mechanical properties.

19. A high degree of axial elasticity is desired to make completions more compaction resilient for depletion related compaction situations.

20. Detailed axial buckling of members could prevent failure of overall pipe, implying Euler buckling of elements as a preferred failure mode.

21. An axial strain of 5%, ideally 7% or possibly 10%.

22. Bending failure due to tension/compression in outer fibers is a basic design issue to and potential advantage in high-bend applications.

23. Slot width to hold back sand in 50-250 micron range, but let fines pass.

Feature Design & Geometry Model Development

These steps were performed of first-order basis, as two-dimension analyses and were later initiated as three-dimensional models for the originally proposed structure. Because the original structure did not efficiently yield the preferred properties expressed by industry, the structure was modified to suit the numerous preferred criteria. The modification was an advanced structural form qualitatively prepared by the contractor which provided the preferred flexural approach. The engineering task was clearly non-linear.

Non-linear Modeling of Advanced Screen Geometries

The following discusses the Design/Analysis Phase of the Self-Expanding Sandscreen Technology Development (SESTD) Program. The primary goal of the phase of the program was to establish, via a nonlinear finite element design by analysis process, a viable candidate Self-Expanding Sandscreen configuration that, to the fullest extent possible, meet available field requirements for compliance, collapse and crushing resistance, borehole support, axial and bending response, etc.

Prototype Sandscreen Section at 150% Elastically Recovered Expansion

Fundamentally, the SESTD Design/Analysis study involved subjecting candidate sandscreen configurations to rigorous nonlinear finite element analysis with the goal of obtaining the load-deformation history of the system under a complete cycle of loading; i.e. compression followed by expansion, and then subsequent re-loading. Post processing of such an analysis would include, beyond observation of standard stress and deformation field variable quantities, examination of expanded sandscreen/formation contact force distributions as well.

With regard to execution of the SESTD finite element Design/Analysis process, the initial accomplishment was the establishment of a robust, stable, computationally efficient, nonlinear analysis solution scheme for evaluating candidate Self-Expanding Sandscreen configurations.

Challenges Posed by the Self-Expanding Sandscreen Modeling Effort

Fundamentally, the SESTD Design/Analysis (i.e. Numerical Experimentation or Virtual Testing) process involves subjecting candidate sandscreen configurations to rigorous nonlinear finite element analysis with the goal of obtaining the load-deformation history of the system under a complete cycle of loading; i.e. compression followed by expansion, and then subsequent re-loading. Post processing of such an analysis includes, beyond observation of standard stress and deformation field variable quantities, examination of expanded sandscreen/formation contact force distributions, as well.)

Obvious complexities involved in the nonlinear modeling of a Self-Expanding Sandscreen configuration include a structural response under load characterized by large deformation (both strain and displacement), nonlinear contact, and elastic-plastic material behavior.

The presence of significant compressive stress fields during both the compression and expansion phases lead to the necessity of dealing with transient instability states (i.e. limit or bifurcation critical point instabilities) when attempting analysis of a Self-Expanding Sandscreen system as a quasi-static process. Quasi-static analysis is preferred over transient dynamic analysis in this case because it can be used to precisely locate critical points in the load path that would otherwise be masked by dynamic snap through and other mechanisms in transient dynamic solutions. If it can be made to deal with the aforementioned critical point instability phenomena, a quasi-static nonlinear analysis solution also has the benefit of being computationally more efficient and economical (e.g. faster) than a full transient dynamic solution.

In a visual sense, a typical Self-Expanding Sandscreen volume geometry was viewed on the continuum level as a lattice type structure composed of a regular, periodic configuration of identical sub-volumes much as, on the micro-mechanics level, ions or molecules are arranged in a crystalline solid.

Given the geometric complexity of a potential Self-Expanding Sandscreen configuration, the refined finite element meshing of an entire component would not seem to be an approach that would easily lead to the posing of a tractable analytical problem or, finally, the generation of a solvable numerical model. The more practical approach is to implement a finite element *sub-modeling* concept where a typical sub-volume of the Self-Expanding Sandscreen configuration is carefully meshed, implementing adequate refinement, and where imposed boundary and constraint conditions are applied to force the sub-volume finite element model to deform, under load, in such a manner as if it were still embedded in the total structure (i.e. lattice).

A final problem that complicated the Self-Expanding Sandscreen modeling effort was a visualization issue. Simply put, the ratio of characteristic axial to circumferential dimensions is so large that the sub-model geometry appears graphically as nothing more than a slit in any standard visualization. This problem was dealt with (at times) in this development effort by scaling (i.e. mapping), for post-processing purposes, the true geometry in such a way as to artificially thicken the component circumferentially thereby making the sub-model geometry easier to visualize. A difficulty associated with this remedy is the fact that in-plane radii are distorted considerably as a consequence of the mapping. During the development of the Self-Expanding Sandscreen solution scheme, a more practical solution was to parameterize the solid geometry and finite element models in such a way that the solution scheme could be tested and de-bugged using easy to visualize configurations. Once the final solution scheme was established, only a resetting of the parameter values was required to put candidate configuration geometry back into its correct form.

The Self-Expanding Sandscreen Nonlinear Finite Element Analysis Solution Scheme

The metal solid sub-volume characterizing the Self-Expanding Sandscreen configuration was modeled using the SOLID185 element, a three-dimensional, hexahedral eight node finite element that has 3 degrees of freedom at each node (translations in the x-, y- and z- coordinate directions) and possesses plasticity, stress stiffening, large deflection, and large strain capabilities.

Contact between a) the interior surfaces of the sandscreen sub-volume, and b) between the outer surface of the sub-volume and the face of the formation was modeled using contact elements CONTA173 and TARGE170. CONTA173 is used to represent contact and sliding between 3-D "target" surfaces (TARGE170) and a deformable surface, defined by this element. The element is applicable to 3-D structural and coupled field contact analyses and is located on the surfaces of 3-D solid or shell elements without midside nodes.

The structural interaction of the solid sub-volume being modeled with sub-volumes above and below it is modeled using an elastic foundation element SURF154, a surface finite element defined by four to eight nodes, and by a stiffness matrix calculation that uses an in-plane force per unit length (input as real constant SURT) and an elastic foundation stiffness (input as real constant EFS).

In *ANSYS,* the CP Command capability, which defines (or modifies) a set of coupled degrees of freedom, was utilized to impose constraint conditions in order to force the sub-volume finite element model to deform, under load, in a manner as if it were still embedded in the total structure. Coupling degrees of freedom into a set in this manner causes the results calculated for one member of the set to be the same for all members of the set.

Another important *ANSYS* feature that was incorporated in this study was the program's BIRTH and DEATH feature that allows elements, at the beginning of a new load step, to be deactivated (with the EKILL Command) or activated (with the EALIVE Command). This feature was utilized to turn off the contact model between the outer surface of the sub-volume finite element model and the face of the formation finite element model during the compression phase of the analysis.

After model generation and assembly, the actual solution was specified and executed in a Cylindrical Coordinate System with X as the radial coordinate, Y as the circumferential coordinate, and Z as the axis of rotation. *ANSYS* Analysis Options included the implementation of a Bi-Linear Isotropic Plasticity Model for modeling the Sandscreen material behavior, large strain and displacement deformation response, nonlinear contact, and a full static Newton-Raphson nonlinear equation solution process with Line Search.

In the *Nonlinear Finite Element Analysis Solution Scheme* developed during the last quarter's work effort, the Self-Expanding Sandscreen is first compressed, and then released for expansion in three distinct load steps; i.e. stages of loading.

In Load Step #1, the Sandscreen model is compressed from its unstressed nominal initial state (diameter) to its reduced final diameter by an imposed radial displacement field applied to its outer surface, or face. The contact model between the outer surface of the sub-volume finite element model and the face of the formation finite element model is deactivated (via the EKILL Command) during this load step. The implementation of an imposed displacement scheme to compress the model acts as a stabilization effect as far as suppressing buckling and other critical point instability phenomena during the compression/contraction process.

Load Step #2 encompasses swapping out of imposed radial displacement field constraints imposed in LS1 for applied forces derived from the reaction forces from the LStep #1 solution.

Finally, in Load Step # 3 the contact model between the outer surface of the sub-volume finite element model and the face of the formation finite element model is reactivated (via the EALIVE Command) and the applied reaction force system on the front face of the Sandscreen model is ramped off to zero value. As a consequence of ramping off the reaction forces, the compressed Sandcreen model is allowed to expand until it contacts the front face of the formation finite element model. The interaction of the emerging Sandscreen component/formation contact stiffness is a stabilizing factor as far as suppressing buckling and other critical point instability phenomena during the expansion process.

The expanding Sandcreen model thus applies increasing pressure against the formation model until the radial reaction forces are completely ramped off. Elastic strain energy, which is contained in the compressed Sandscreen finite element model, is the force behind the expansion of the Sandscreen model after ramping off (i.e. release) of the reaction forces. It should be noted that, if the formation model were not present, the Self-Expanding Sandscreen model would not return completely to its initial unstressed configuration due to significant plastic deformation occurring during the original compression process.

The Nonlinear Finite Element Analysis Solution Scheme was implemented in succession, of the following three input files (i.e. scripts).

geom.inp: used to create the solid geometry of the Self-Expanding Sandscreen Configuration in Rectangular Cartesian Space

stretch_geom.inp: used to map the Sandscreen solid geometry into a Cylindrical Coordinate System

stretch_model.inp: following the meshing of the Sandscreen solid model geometry created by input file stretch_geom.inp, this input file is used to complete set up and execution of the three load steps comprising the final Self-Expanding Sandscreen Nonlinear Finite Element Analysis Solution Scheme

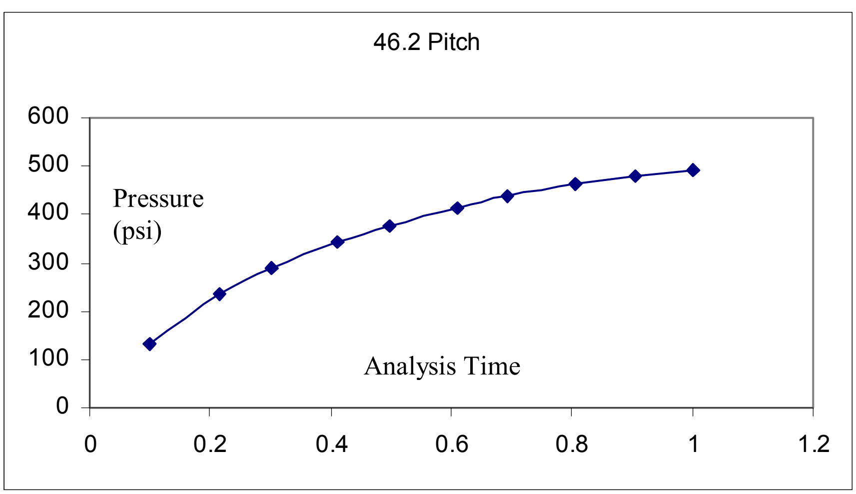
The *Parameterized Stretched Finite Element Model Used to Develop and De-Bug the Self-Expanding Sandscreen Nonlinear Finite Element Analysis Solution Scheme* during the development of the Self-Expanding Sandscreen Solution Scheme the geom.inp input file was parameterized so that the proposed Sandscreen configuration solid geometry could be stretched in order to help mitigate the visualization issues discussed above, and thereby enhance the testing and de-bugging of the new protocol.

In its stretched configuration, the Sandscreen sub-volume is nominally an 8.4° cylindrical wedge of 10.8 cm. (4.25″) internal radius, 13.4 cm. (5.25″) outer radius, and 21.4 cm. (8.40″) height. Nominally, the formation model is a 15.0° cylindrical wedge of 12.1 cm. (4.75″) inner radius, 15.9 cm. (6.25″) outer radius, and 25.4 cm. (10.0″) height. During the compression phase, the Sandscreen sub-volume finite element model is squeezed radially inward 3.8 cm. (1.50") for a ratio of compressed final outer radius to original unstressed outer radius of $(1.5/4.25) = 0.286$.

In order to deal with the structural incompatibility between the stretched Sandscreen sub-volume geometry and the extreme deformation field that was to be imposed on it, an idealized (hypothetical) material model was implemented that minimized but didn't eliminate the plastic field that was generated during loading. This idealized model was developed by modifying material properties for ASTM 4140 Steel to implement an increased value of Tangent Modulus.

Dynamic Formation Support

A numerical study associated with the above described nonlinear finite element analysis solution scheme was applied subsequently to two different Complete Self-Expanding Sandscreen configurations both exhibiting identical slot geometries but different helical pitches; i.e. one had a 92.4 Pitch Configuration and the other a 46.2 Pitch Configuration.



(Convert PSI to MPa: ÷ 145)

As in the case of the Micro-Wedge model, the slot dimensions characterizing the geometry of the strainer volumes comprising the Complete Sandscreen model are those given in the above plot. The pattern shown in the plot basically defines a slot geometry characterized by top and bottom radii of .076 mm (0.003 inches), a center gap thickness of .18 mm (.007 inches), a slot center spacing of .25mm (.010 inches) and a 6.35 cm. (2.5 inch) slot length. In the case of the Micro-Wedge model, the helical distribution of slots (or strainer volumes) structurally reduces the assembly of a complete section of Self-Expanding Sandscreen to a system of helical springs coupled together by a corresponding set of vertical links.

These plot points present Average Pressure (for a 0.10 degree sector of the Complete Sandscreen Model) vs. Analysis Time for the compression phase (analysis time $0 \rightarrow 1$) of the analysis. By comparing with other plots, it can be seen that reducing the helical pitch of the configuration from 92.4 to 46.2 (i.e. cutting it in half) resulted in a 15 fold increase in pressure necessary to compress the Complete Sandscreen model down to its Run In Hole diameter. This of course implies a corresponding increase of stiffness of the system as well.

Clearly, and most importantly, the variation of the helical pitch in this configuration is a powerful tool for tuning the stiffness response of the Self-Expanding Sandscreen Prototype.

Results and Discussion - I

By comprehensive design-by-analysis iteration processes, the following fundamental properties were initially produced utilizing baseline-conventional expandable sandscreen specifications of 17.8 cm. (7”) expandable to 25.4 cm. (10”) diameter, as compared with current product and preferred capabilities:

	E&P Ideals	*Current Service Ind.*	*Current Project*
Ultimate Collapse Rating	>13.8MPa (2ksi)	1.4-8.3MPa (270–1.2ksi)	>28MPa (4ksi*)
Flexible Formation Contact	1.4MPa (200psi)	0–.7MPa (<100psi)	2.8-5.5MPa(.4–.8ksi)
Particle Size Retention	25µ – 250µ	125µ – 250µ	80µ, range 25–250
Expansion Ratio	125% – 150%	115% – 150%	150%
Tensile	--	64.6tonnes (142,500/lbf.est.)	>1,000,000/lbs.
Torsional Yield	--	8656nM (6365ft/lb est)	14874nM(10937ft/lb)
Axial Compressive Load	--	85.3tonnes 188,000/lbf. (est.)	163tonnes (360klb)

**This ultimate collapse figure is only the force required to fully compress the device. Actual plastically deformed collapse is estimated to significantly greater in these dimensions.*

Converting the model to the project MHT dimensions shows the following properties:

Ultimate Collapse Rating	>28MPa (4,000-psi)
Flexible Formation Contact-Bias	2.8-3.5MPa(.4–.5ksi)
Selected Particle Size Retention	180µ
Expansion Ratio	125%
Tensile	>45tonnes (100,000 lbs.)
Torsional Yield	3264nM (2400 ft./lb.)
Axial Compressive Load	39.3tonnes (86,555 lbs.)

Sandscreen Coupon Construction & Test Verification

Due to changes in the program, initial testing tasks were substituted with computational validity. The validity of substituting numerical experimentation for physical testing was based upon the following four points:

First, the fidelity of the sophisticated nonlinear finite element models incorporated in the Self-Expanding Sandscreen development program to date is more than sufficient for carrying out a numerical experimentation process.

Second, numerical finite element models, by the nature as to how they are constructed and executed, produce a wealth of nonlinear load-deformation data for a numerical experiment not easily recoverable from physical testing.

Third, it is much easier to impose realistic load and constraint states on virtual screen Strainer coupons, in a numerical experiment, than it is to impose realistic loading and fixturing conditions on a real coupon in a physical test.

Fourth, subjecting a virtual screen Strainer concept to numerical experimentation prior to actually manufacturing prototype Strainer elements and coupons yields the opportunity of finding flaws, or weaknesses in a design concept, before considerable resources are expended in the manufacture of the actual physical Strainer elements

Compliance and Loading in Ovalized Borehole - Concept Development

Development of a Robust, Stable, Computationally Efficient, Nonlinear Analysis Solution Scheme for Carrying Out the Structural Analysis of a Complete Three-Dimensional Nonlinear Beam Element Model of a Five Foot Section of Self-Expanding Sandscreen Expanding Against an Elliptical Wellbore:

The majority of the nonlinear finite element analyses first undertaken were carried out as a nonlinear solution scheme (or protocol) developed as locally occurring mechanisms. This solution scheme reduced the three dimensional structural system comprising a complete five-foot section of screen to a Micro-Wedge model encompassing a relative few strainer volume elements. While such a micro-model is extremely capable of answering the question as to the nature of the detailed stress and strain distributions in a Self-Expanding Sandscreen element during a complete compression and then expansion cycle; it was not, however, capable of answering two other important questions.

First, the original Micro-Wedge solution scheme did not provide an accurate estimate, with regard to its implementation in a detailed design process concerned with evaluating candidate Self-Expanding Sandscreen configurations against available field requirements, of the force vs. displacement history for either the compression or expansion cycles of the component load process. Second, the original solution protocol did not predict the effect of releasing a compressed circular screen (in Run In Hole configuration) to expand against an elliptical wellbore cross-section.

Therefore, the subsequent accomplishment was establishment of a robust, stable, computationally efficient, nonlinear analysis solution scheme (protocol) for carrying out the nonlinear finite element analysis of a complete three-dimensional nonlinear beam element model of a five-foot section of Self-Expanding Sandscreen expanding against an elliptical wellbore.

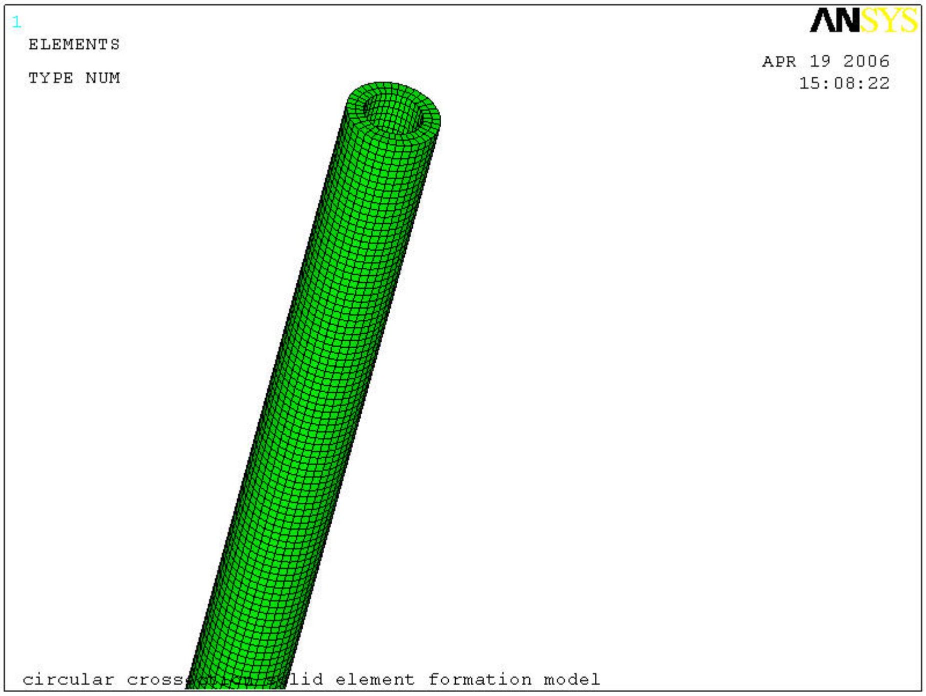
The complexities involved in developing a nonlinear analysis solution scheme for modeling a Complete Screen model are many of the same as those that complicated the development of the Micro-Wedge model; i.e. a structural response under load characterized by large deformation, nonlinear contact, and elastic-plastic material behavior, the incredible geometric complexity of a five foot prototype Self-Expanding Sandscreen component composed of upwards of 15,000 strainer sub-volumes, and the visualization issue deriving from a ratio of characteristic axial to circumferential dimensions so large that the strainer sub-volume geometry appears graphically as nothing more than a slit in any standard visualization. The challenge then in developing a Complete Screen model lies in dealing with all the issues plaguing the development of the Micro-Wedge model solution scheme, but also confronting the fact here that one is attempting to develop a protocol for modeling an entire device and not just a small grouping of sub-volumes.

Clearly, given the fact that the five strainer sub-volume Micro-Wedge model reviewed in the previous discussion was defined by a total of 52,960 nodes, one would expect to need (assuming the implementation of a three-dimensional finite element model incorporating the same level of refinement) on the order of 1×10^8 nodes (or 3×10^8 degrees of freedom) to characterize a complete five-foot section of Sandscreen. This of course leads to a ridiculously large problem and is not a path that would lead to the generation of a tractable or solvable numerical model. The solution to this dilemma was, as indicated above, to continue to rely on the three dimensional Micro-Wedge model to answer the question of the nature of the detailed stress and strain distributions in a compressing or expanding Sandscreen element; and then go on to find a means of implementing a less refined model to address the issue of the deformation of a Complete model.

Accordingly, the development of the Complete Self-Expanding model Nonlinear Solution Scheme during the last Quarter's work effort was based upon the *ANSYS* BEAM188 nonlinear beam finite element rather than a solid element. Though such a model is not capable of predicting the detailed stress and strain distribution surrounding each strainer element (or sub-volume), it is more than capable of predicting the overall global nonlinear force-displacement (i.e. stiffness) response of the entire structural system comprising a five-foot screen section.

The BEAM188 nonlinear beam element is suitable for analyzing slender to moderately stubby/thick beam structures. This element is based on Timoshenko beam theory. Shear deformation effects are included. BEAM188 is a linear (2-node) or a quadratic beam element in 3-D. In the implementation described here, BEAM188 has six degrees of freedom at each node. These include translations in the x, y, and z directions and rotations about the x, y, and z directions. This element is well-suited for linear, large rotation, and/or large strain nonlinear applications.

BEAM188 includes stress stiffness terms, by default, in any analysis with NLGEOM,ON. The provided stress stiffness terms enable the elements to analyze flexural, lateral, and torsional stability problems (using eigenvalue buckling or collapse studies with arc length methods). BEAM188 can be used with any beam cross-section defined via *ANSYS* SECTYPE, SECDATA, SECOFFSET, SECWRITE, and SECREAD options. The cross-section associated with the beam may be linearly tapered. Elasticity, creep, and plasticity models are supported (irrespective of cross-section subtype). A cross-section associated with this element type can be a built-up section referencing more than one material.



The Nonlinear Finite Element Analysis Solution Scheme for the Complete Self-Expanding Sandscreen model was implemented via utilization, in succession, of the following three input files (i.e. scripts).

helix.inp: used to create the solid geometry (i.e. detailed helical line model) of the Complete Self-Expanding Sandscreen Configuration in Rectangular Cartesian Space

hlxproto.inp: used to mesh the helical line model built by helix.inp

proto.inp: following the meshing of the Complete Sandscreen finite element model created by input file hlxproto.inp, this input file is used to complete set up and execution of the three load steps comprising the final Complete Self-Expanding Sandscreen model Nonlinear Finite Element Analysis Solution Scheme

helix.inp

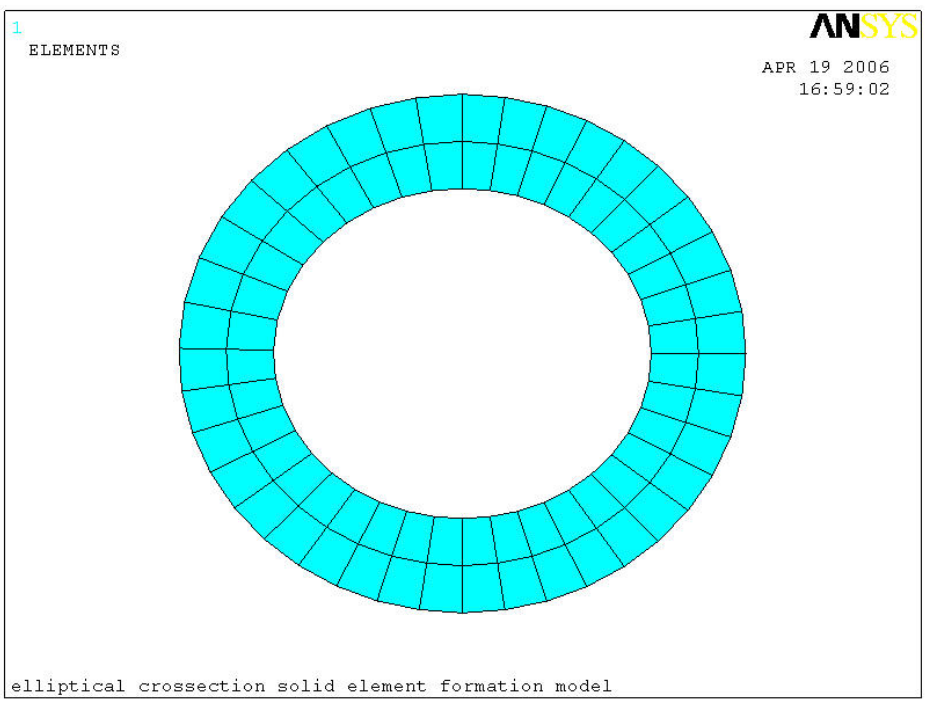
Input file helix.inp builds the solid helical line model of the Complete Sandscreen geometry by first generating a number of regularly spaced, circumferentially distributed helices, and then going through the complex process of slicing them, again in a regularly spaced circumferentially distributed pattern, to provide the vertical lines intersecting and linking the helices. The end product of this process is contained in the database *helix.db*. With respect to computational time, for the 46.2 Pitch Complete Sandscreen model described below, this process consumed 54 hours (clock time) on a fully dedicated Dell Precision PWS670 3.59GHz Intel Xeon Computer with 5.93 GB of RAM.

hlxproto.inp

The script contained in input file hlxproto.inp proceeds to mesh the helical line model contained in database helix.db using ANSYS nonlinear beam element BEAM188. The end product of this process is contained in the database *hlxproto.db*.

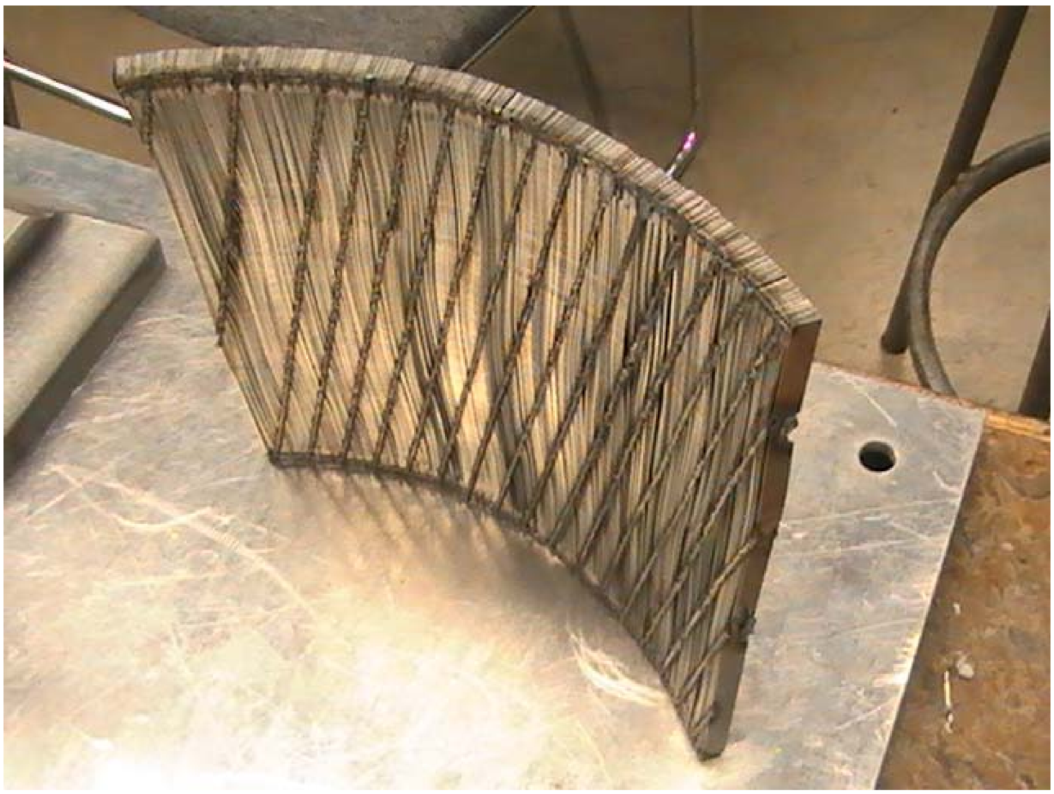
proto.inp

Following the meshing of the helical line model by hlxproto.inp, input file proto.inp resumes database hlxproto.db and goes on to first add an elliptical formation model and the associated external contact model, and then proceed to complete execution of the three load steps comprising the final Complete Self-Expanding Sandscreen model. In the nonlinear finite element analysis solution scheme carried out by input file proto.inp, the Complete Sandscreen model is first compressed, and then released for expansion in three distinct load steps; i.e. stages of loading. The load steps were designed to represent, in order, (i) compression of the device down to its specified compressed outer diameter by an imposed radial deformation field applied to the outer surface of the device, (ii) the replacement of the imposed boundary displacement field by reaction forces, and (iii) the ramping off (or release) of the restraining reaction forces to allow the device to expand against the formation.



Cell-Coupon Compression Pre-Testing – Coupon Development and Related Nonlinear Plane Stress Finite Element Analysis Activities

Analytical and coupon manufacturing activities were coupled towards optimization of the Sandscreen strainer slot pattern geometry and the specifications, by way of testing, of adhesive bonding systems for retaining the compressed form of the Self-Expanding Sandscreen device at the Run-In-Hole radius value. Construction of panel sections and basic elastic functionality testing were performed.



Development of a Parametric Finite Element Model for Analyzing the Prototype Strainer Slot Configuration Deformation Response Under Plane Stress Conditions

The parametric Plane Stress Coupon model, developed under this task, is basically a two dimensional version of the Micro-Wedge model addressed in previous discussion. The Plane Stress Coupon model uses the same basic solution scheme as the Micro-Wedge model but is based on a two-dimensional displacement field instead of a three-dimensional field.

The loss in completeness of the deformation field response, for three-dimensional stress states, does not negate the fact that the Plane Stress Coupon model retains considerable fidelity as far as predicting the ($z-\theta$) plane load-deformation response of a given strainer slot configuration, under compression and expansion loadings, is concerned. A big advantage that the Plane Stress model has over the Micro-Wedge model is that it is much easier to set up, run and post-analyze for a given strainer slot pattern geometry.

The Plane Stress Coupon model was developed by modifying the Micro-Wedge model nonlinear solution scheme by replacing the 3-D Solid Elements and Contact Models by their 2-D counterparts; i.e. the PLANE182 Solid Element and the CONTA171 and TARGE169 contact and target elements.

PLANE182 is a two dimensional 4-Node Structural Solid element that is used for 2-D modeling of solid structures. The element can be used as either a plane element (plane stress, plane strain or generalized plane strain) or an axisymmetric element. It is defined by four nodes having two degrees of freedom at each node: translations in the nodal x and y directions. The element has plasticity, hyperelasticity, stress stiffening, large deflection, and large strain capabilities. In this application the element is implemented as a plane stress with thickness element using the BISO (Bi-Linear Isotropic) Plasticity Model and material properties established for the Micro-Wedge model.

CONTA171 is used to represent contact and sliding between 2-D "target" surfaces (TARGE169) and a deformable surface, defined by this element. The element is applicable to 2-D structural and coupled field contact analyses. This element is located on the surfaces of 2-D solid, shell, or beam elements without midside nodes. It has the same geometric characteristics as the solid, shell, or beam element face with which it is connected. Contact occurs when the element surface penetrates one of the target segment elements (TARGE169) on a specified target surface. Coulomb and shear stress friction is allowed.

Within the context of the Self-Expanding Sandscreen Prototype device development, the Planar Coupon model has three basic uses.

First, because it is a much smaller model, once its behavior has been correlated against a corresponding Micro-Wedge solution, it can be used in a multi-analysis numerical study in order to optimize the design of the given Pitch and Slot Geometry for the Sandscreen Prototype.

Second, the Plane Stress Coupon model can be used to generate an actual physical metal coupon, for load-displacement testing, to be implemented in evaluating the accuracy of the nonlinear finite element models implemented in this development program by comparing their results against experimental data obtained from a laboratory test.

Third, linking the modeling effort with the Normal Bonding Testing Program (see discussion below), results obtained from exercising the Plane Stress Coupon model can be used to characterize the relationship between shear stress adhesive bond requirements and both Pitch and strainer slot geometry

Example illustrations of the implementation of this model in the execution of a nonlinear Plane Stress finite element analysis of an oversized Coupon were extensively made. Dimensions of the coupon were specified while the finite element mesh were pictured separately. Von Mises stress distributions for the end of compression phase (TIME=1.0) and the end of unloading (TIME=3.0, after removal of the compressing load) were presented, respectively. One point to note on reviewing the results is the total recovery of the Coupon after unloading.

Design and Fabrication of Bond-Joint Coupons to Carry-Out a Sandscreen Normal Bonding Testing

The approach for bond-testing is to have the screen held in its compressed diameter state by infiltrating the slots with a thermosetting adhesive. In order to model the security of the closure it is necessary to measure the normal bond strength of candidate adhesives. For this purpose an adjustable distance, tensile test coupon was designed and manufactured with identical halves.

A description of the coupon is as two half-hole cut-outs on the surface to be bonded (following final milling across x_x) separate a center length of 2.54 cm. (1.00 inch). This corresponds to the intended slot lengths in the screen design. The specimen is made from .64 cm. thick 4140 steel plate so that the bonded area will be equivalent to a bonded screen slot.

The distance between the cylindrical slots on the bonding surface is 2.54 cm. (1.00 inches) to give a bonded surface of 1.6 cm^2 (0.25 $in^{2)}$. The purpose of the cylindrical slots is to define/limit the bonded area. The extensions at each side of the bonding surface are intended to enclose spacer shims in order to control the thickness of the bond. Tests were then able to be carried out with a series of layer thicknesses for any particular adhesive .025mm, .050mm, .075mm (0.001, 0.002, 0.003 inches say) in order to obtain relationships of bond strength against thickness for FEA modeling. The end sections of the specimens were hardened prior to final surface grinding in order to allow adhesive removal without damaging the bonding surfaces.

Test Procedure, Self-Expanding Sandscreen Normal Bond Test

A test procedure was established for the proposed adhesive locking of collapsible sand screens. The design of the sandscreen cell-coupon involves cutting of .20mm (0.008 inch) wide slots into .0635 cm. (0.25 inch) wall thickness 4140 steel tubing. The slots are to be arranged in a helical pattern, which provided the property of diameter reduction under radial pressure, also with control over length or other needed changes. The proposal was to infuse the slots with adhesive which would be allowed to set with the tubing in its compressed state. After installation down hole the adhesive would be released with chemical solvents, electro-chemical activity, heat or other activity. In order to carry out modeling of this behavior it was necessary to obtain data on the normal bond test of candidate adhesives. The set-up described below was established for this purpose.

The initial tensile test specimen was clamped and bonded with 2-part liquid epoxy. After thoroughly cleaning the hardened test surfaces, adhesive was applied and the test specimen clamped with pieces of shim stock between the extensions to experimentally control the various adhesive film thickness.

Even though various bonding and disintegration data was available, the specific requirements for the structure would only be determinable after actual construction. At the point of prototype construction it was found that the screen properties were substantially higher than predicted due to materials substitution and manufacturing processes.

Conclusion - I

Conceptual Design Phase Conclusions

On reviewing the results of the nonlinear finite element analyses of both the Three-Dimensional Micro-Wedge Model and the Complete Three-Dimensional Nonlinear Beam Element Model of the proposed configuration for the Self-Expanding Sandscreen prototype, four significant conclusions are made:

1. The proposed prototype Self-Expanding Sandscreen configuration is predicted by nonlinear finite element analysis to be fully elastic in all regions of deformation; which implies significant recovery of strain energy on expansion of an actual device.
2. Control of pitch in the prototype geometry is a powerful tool for tuning the stiffness response of the system.
3. The numerical modeling results have, to date, shown that the geometric configuration chosen for the Self-Expanding Sandscreen prototype is an extremely efficient structural form. This conclusion is supported by the fact that this form is found in certain natural structures which has helical constituents, giving needed torsional and axial stiffness, as well as the ability to expand radially with fluid intake.
4. The numerical modeling results have, to date, shown that the geometric configuration chosen for the Self-Expanding Sandscreen prototype is an extremely efficient structural form. This conclusion is supported by the fact that this form is found in nature in such places as the skeleton of the certain flora which has a helical structure giving the plant the needed torsional as well as axial stiffness, as well as the ability to expand radially with water intake.

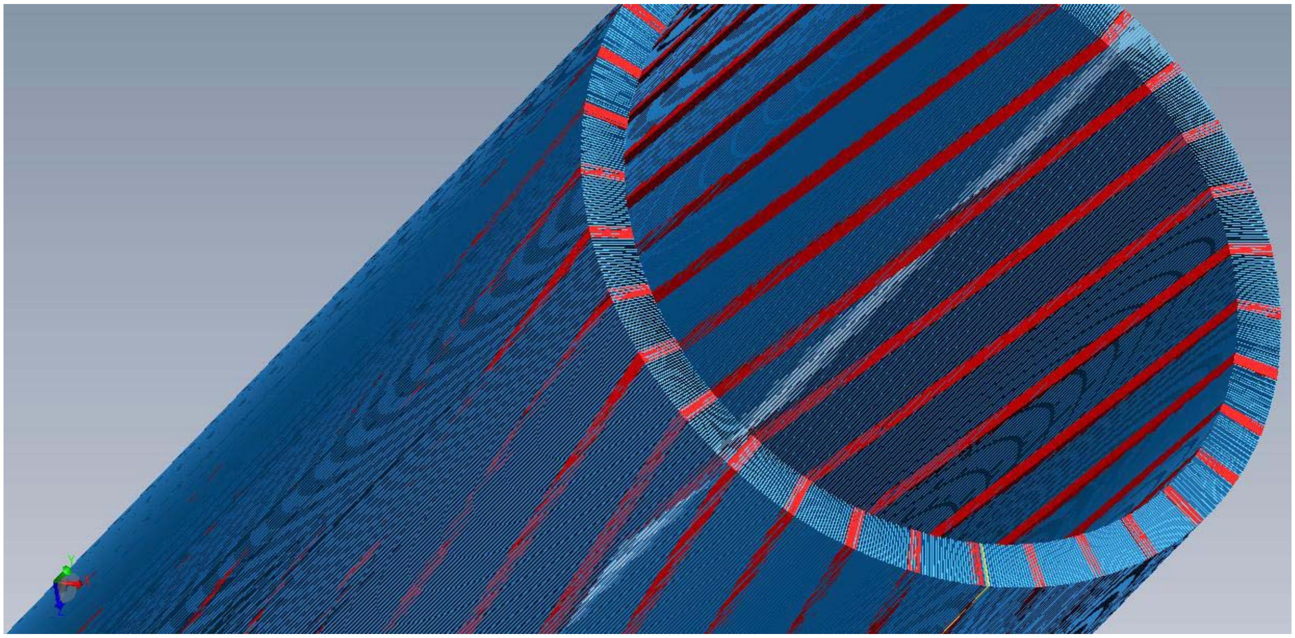
II. **Manufacturing Phase**

In the second major phase, major areas include engineering-design advances, fabrication and testing of prototypes, and demonstration and technology transfer activities.

Detailed Engineering Refinements

The work, '*Concept Development and Coupon Construction of Representative Pre-Prototype for 8.9 cm (3.5") Diameter*' is discussed. Fundamentally, the Self-Expanding Sandscreen Design/Analysis detailed process involves subjecting candidate Sandscreen configurations to rigorous nonlinear finite element analysis with the goal of obtaining the load-deformation history of the system under a complete cycle of loading; i.e. compression followed by expansion, and then subsequent relaxation against the formation. Post processing of such an analysis includes, beyond observation of standard stress and deformation field variable quantities, examination of expanded Sandscreen/formation contact force distributions as well.

The work was accomplished in three tasks. First, a nonlinear finite element analysis of a three-dimensional Micro-Wedge model of a candidate Sandscreen configuration was carried out in order to observe the detailed nature of the elastic response of the system in both compression and expansion phases. Second, the development of a robust, stable, computationally efficient, nonlinear analysis solution scheme for carrying out the structural analysis of a complete three-



3D Solid Model of 152 cm. (5') Prototype

dimensional nonlinear beam element model of a 152 cm. (five-foot) section of Self-Expanding Sandscreen expanding against an elliptical wellbore. Following the development of this nonlinear solution scheme, the initiation of the analysis of a 152 cm. (five-foot) section of screen for the dual purpose of obtaining an accurate estimate of the compressive force required to compress the sandscreen to its desired reduced volume and to also obtain insight into the predicted response of the prototype sandscreen component when it is released from its circular form against an arbitrary elliptical (e.g. egg shaped) wellbore cross-section. The third and final task was to design and fabricate coupons for carrying out a screen normal bond testing program.

A Nonlinear Finite Element Analysis of a Three-Dimensional Micro-Wedge Model of a Candidate Sandscreen Configuration

In this phase of the work effort a nonlinear finite element analysis of a three-dimensional Micro-Wedge model of a candidate Sandscreen configuration was carried out in order to observe the detailed nature of the elastic response of the system in compression and expansion phases.

Complexities involved in the nonlinear modeling of a Self-Expanding Sandscreen configuration include a structural response under load characterized by large deformation (both strain and displacement), nonlinear contact, and elastic-plastic material behavior. The presence of significant compressive stress fields during both the compression and expansion phases lead to the necessity of dealing with transient instability states (i.e. limit or bifurcation critical point instabilities) when attempting analysis of this device as a quasi-static process.

In an abstract sense, a typical Self-Expanding Sandscreen Strainer volume geometry can be viewed on the continuum level as a lattice type structure composed of a regular, periodic configuration of identical sub-volumes much as, on the micro-mechanics level, ions or molecules are arranged in a crystalline solid. Given the incredible geometric complexity of a potential

Strainer Volume configuration, the refined finite element meshing of an entire component is not an approach that easily leads to the posing of a tractable analytical problem or, finally, the generation of a solvable numerical model.

Accordingly, an alternative approach was implemented.. The alternative approach involved implementing, in the Micro-Wedge model analysis, an assembly of five Strainer elements (or sub-volumes) and then applying appropriate boundary conditions to the sides of the assembly and interior contact models to the interior surfaces of the sub-volumes in order to constrain deformation of the interior surfaces during loading.

A final problem that complicates the Self-Expanding Sandscreen modeling effort is a visualization issue. Simply put, the ratio of characteristic axial to circumferential dimensions is so large that the sub-model geometry appears graphically as nothing more than a slit in any standard visualization. As in past modeling efforts in this program, this problem was dealt with by scaling (i.e. mapping), for modeling, meshing and post-processing purposes, the true geometry in such a way as to artificially thicken the component circumferentially thereby making the sub-model geometry easier to visualize. A difficulty associated with this remedy is the fact that in-plane radii are distorted considerably as a consequence of the mapping and the resulting geometry is distorted in such a way that some features of the geometry can either be under or over emphasized.

In the *Nonlinear Finite Element Analysis Solution Scheme* implemented during this study, the Micro-Wedge model is first compressed, and then released for expansion in three distinct load steps; i.e. stages of loading. The load steps were designed to represent, in order, (i) compression of the device down to its specified compressed outer diameter by an imposed radial deformation field applied to the outside of the outer surface of the device, (ii) the replacement of the imposed boundary displacement field by reaction forces, and (iii) the ramping off (or release) of the restraining reaction forces to allow the device to expand against the formation.

The slot dimensions, characterizing the geometry of the strainer volumes comprise the Micro-Wedge model The pattern basically defines a slot geometry characterized by top and bottom radii of .075mm (0.003) inches, a center gap thickness of .18mm (0.007 inches), a slot center spacing of .254mm (0.010 inches), a 6.35 cm. (2.5 inch) slot length and a helical pitch of 92.4 units. The helical distribution of slots (or strainer volumes) structurally reduces the assembly of a complete section of Self-Expanding Sandscreen to a system of helical springs coupled together by a corresponding set of vertical links.

Modification of the Unloading Procedure for the Robust, Stable, Computationally Efficient, Nonlinear Analysis Solution Scheme for Carrying Out the Structural Analysis of a 152 cm. (Five Foot) Section of Self-Expanding Sandscreen Expanding Against an Elliptical Wellbore.

An accomplished unloading procedure for the described nonlinear analysis solution scheme for carrying out the structural analysis of a complete three-dimensional, nonlinear beam element model of a five-foot section of Self-Expanding Sandscreen expanding against an elliptical wellbore. The modification of the Self-Expanding model Nonlinear Solution Scheme was necessitated by the need to introduce more reliability, with respect to solution convergence behavior, into the unloading process than currently evidenced by the procedure originally implemented in the algorithm; i.e. the original unloading procedure exhibited excessive convergence problems when attempting to ramp off the compressive force system.

It should be recalled that in the original loading scheme implemented in the Self-Expanding Sandscreen Development Program, the Complete Sandscreen model is first compressed and then released for expansion in three distinct stages of loading (**Table 1**).

Load Stage #	Analysis Time Start Time	 End Time	Action
1	0.0	1.0	Impose compressive radial displacement of –0.50 in on the outer surface of the Complete Screen model while killing the external contact and the formation contact models
2	1.0	2.0	Delete all ux boundary conditions on the front face and replace them with reaction forces
3	2.0	3.0	Restore the external contact formation models to life while ramping the reaction forces to zero thus allowing the compressed device to expand and come to rest against the formation

Table 1 (Convert to Centimeter: X 2.54)

In Stage #1, which occupies analysis time $0 \rightarrow 1$, the Complete Screen model is compressed from its unstressed nominal initial outer radius of 4.8 cm. (1.875 inches) to its reduced final outer radius of 3.5 cm. (1.375) inches by an imposed radial displacement field applied to its outer face. Both the contact model between the Complete Screen model and the formation finite element model, and the formation model itself, are deactivated (via the EKILL Command) during this load step.

Stage #2, which occupies analysis time $1 \rightarrow 2$, encompasses the swapping out of the imposed radial displacement field constraints imposed in Stage #1 for applied forces derived from the reaction forces from the Stage #1 solution.

Stage # 3, which occupies analysis time $2 \rightarrow 3$, encompasses the expansion phase of the nonlinear analysis. During this stage, the contact model between the device's outer surface and the face of the formation finite element model, and the formation finite element model itself are both reactivated (via the EALIVE Command) and the applied reaction force system on the front face of the Complete Screen model is ramped off to zero value. As a consequence of ramping off the reaction forces, the compressed Complete Screen model is allowed to expand until it contacts the front face of the formation finite element model. At this point further expansion of the Complete Screen model is restrained and a contact pressure (i.e. force distribution) is generated.

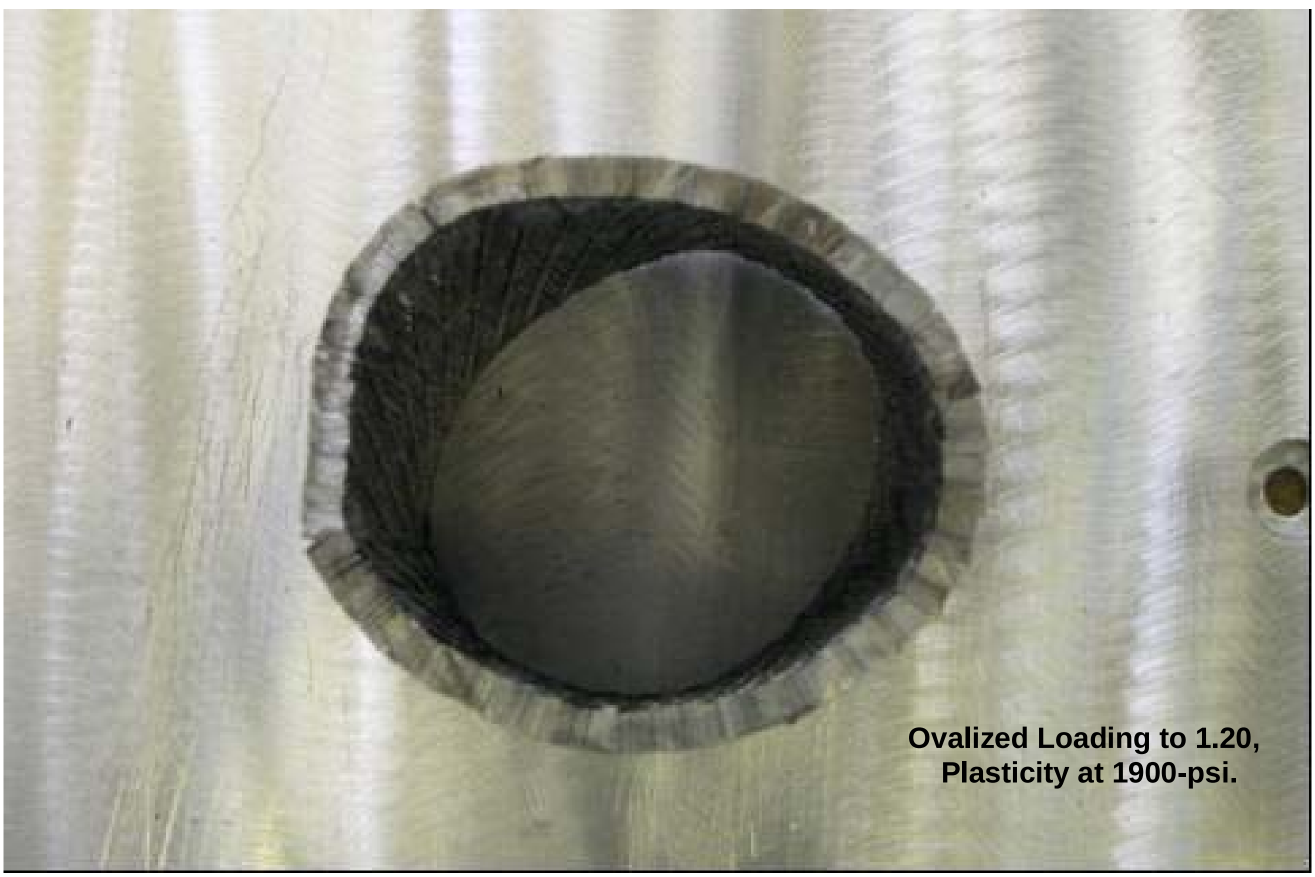
Load Stage #	Analysis Time Start Time	 End Time	Action
1	0.0	1.0	Impose compressive radial displacement of –0.50 in on the outer surface of the Load-Transfer Model while killing the external contact and the formation contact models

2	1.0	2.0	Restore the external contact formation models to life while ramping the imposed compressive radial displacement on the outside of the Load-Transfer Model to zero thus allowing the compressed Sandscreen device to expand and come to rest against the formation

Table 2 (Convert to Centimeter: X 2.54)

The expanding Complete Screen model thus applies increasing pressure against the formation model until the radial reaction forces are completely ramped off. Elastic strain energy, which is contained in the compressed Complete Screen model, is the force behind the expansion of the model after ramping off (i.e. release) of the reaction forces.

The modified unloading procedure incorporates a cylindrical, linear elastic, Load-Transfer solid finite element model to surround and compress the complex nonlinear *ANSYS* BEAM188 nonlinear beam model of the five foot section of Sandscreen; i.e. a contact model being used to effect structural interaction between the cylindrical Load-Transfer model and the beam model of the Sandscreen. On the other hand, it should be noted that no contact mechanism is provided in order to cause the Load-Transfer model and the Formation model to interact. The modified Sandscreen loading scheme can be represented as shown in **Table 2**.



In Stage #1, which occupies analysis time $0 \rightarrow 1$, the Complete Screen model is compressed from its unstressed nominal initial outer radius of 4.76 cm. (1.875 inches) to its reduced final outer radius of 3.5 cm. (1.375 inches) by an imposed radial displacement field applied to the outer face of the Load-Transfer Model. Both the contact model between the Complete Screen model and the formation finite element model, and the formation model itself, are deactivated (via the EKILL Command) during this load step.

Stage # 2, which occupies analysis time $1 \rightarrow 2$, encompasses the expansion phase of the nonlinear analysis. During this stage, the contact model between the device's outer surface and the face of the formation finite element model, and the formation finite element model itself are both reactivated (via the EALIVE Command) and the imposed radial displacement field applied to the outer face of the Load-Transfer Model is ramped off to zero value. As a consequence of ramping off the imposed radial displacement field, the compressed Complete Screen model is allowed to expand until it contacts the front face of the formation finite element model. At this point further expansion of the Complete Screen model is restrained and a contact pressure (i.e. force distribution) is generated.

The solution scheme was implemented in order to re-visit the 152 cm. (five-foot) section Self-Expanding Sandscreen analysis in order to continue to investigate the ability of the Sand screen configuration to expand against a non-circular wellbore and to obtain an estimate of the strainer gap size under operational conditions.

Strainer Assembly Fixturing – Device Construction

Two fixturing related manufacturing refinements were achieved in order to enable manufacturing. The first was development of new assembly hardware The second was application of integration materials to the longitudinal ends of the pre-deposited assembly.

The fixture designed and fabricated for assembly and laser deposition, scalable to any length, was first capable of producing a 15.2 cm. (6") long sandscreen tubes. A pi-shaped cover is removable in order to load strainer wires. It is held in place be machine screws. Partial ovals running obliquely throughout the cover's surface are seen milled into the thickness of the piece. These served as guides for the application of joining materials.

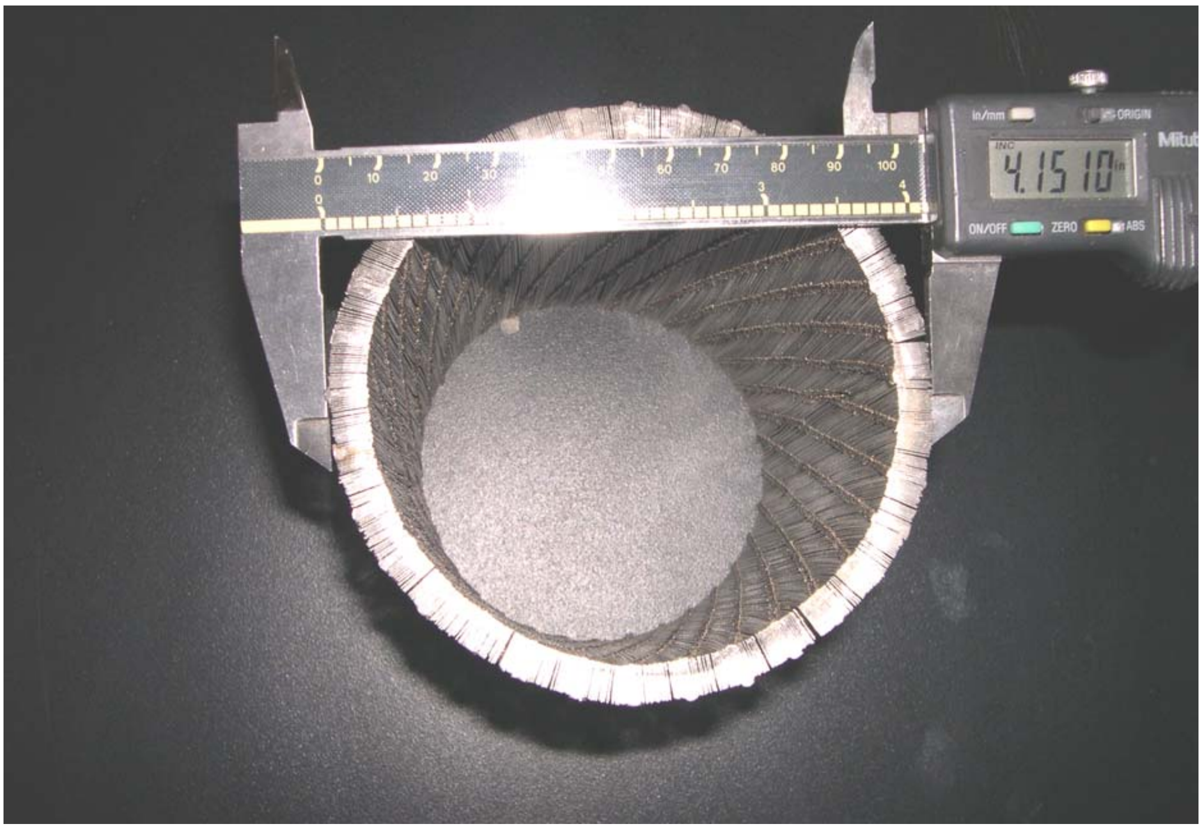
Application of the second fixturing improvement required joining the specimen to the fixture. By welding the fixture assembly, it is stiffened and the amount of waviness caused by distortion through the aperture sections experienced previously is lessened. Without solid fixturing effects, there previously were burn-through problems and regular areas with excessive distortion. The additional fixturing method is an efficient means of improving overall structural and joint quality in the absence of advanced spacing and stabilization manufacturing machinery. The ending-assembly effectively becomes a solid component which is stable for manufacturing treatments and the solid ends later serve to couple to laboratory testing equipment.

Utilization of the developed manufacturing techniques led to building numerous, progressively refined test specimens. The first acceptable specimen slated for testing was subjected to elastic response testing. The amount of plastic deformation during compression is .28 cm. (0.11") in diameter. The loss in expansion capability due to plastic deformation is:

$$\frac{\frac{(4.26-3.14)}{4.26}-\frac{(4.15-3.14)}{4.15}}{\frac{(4.26-3.14)}{4.26}}=6.73\%$$

(Convert to Centimeter: X 2.54)

Given minor losses to plasticity in the prototype-level construction after maximum compression, this particular sandscreen specimen will always retain an elastic expansion capability of 133%.



Elastically Recovered Sample

Sand Retention, Hydraulic conductivity, and Plug Prevention Testing

Basic Sand-Control Testing was performed to a representative coupon section. The coupon section (Shown Below) provided 45% flow-area and profile shaping to the straining area.

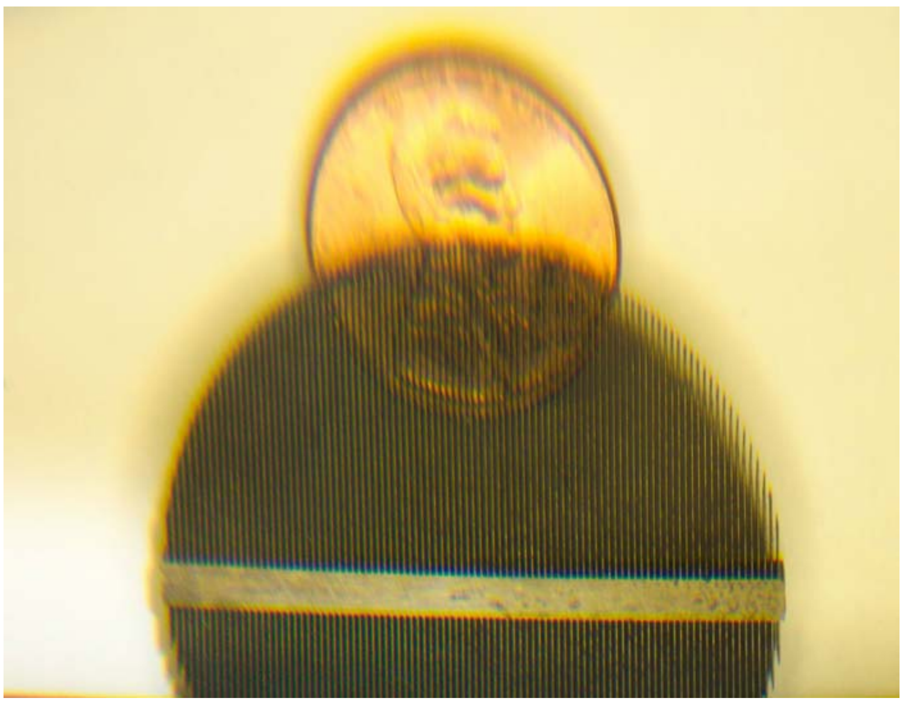
The below example slurry procedure allows observation and evaluation of retention, plug-resistance, and certain flow characteristics simultaneously. The procedures are altered by the consulting laboratory to fit specific project needs.

EXPERIMENTAL PROCEDURES

Slurry Test

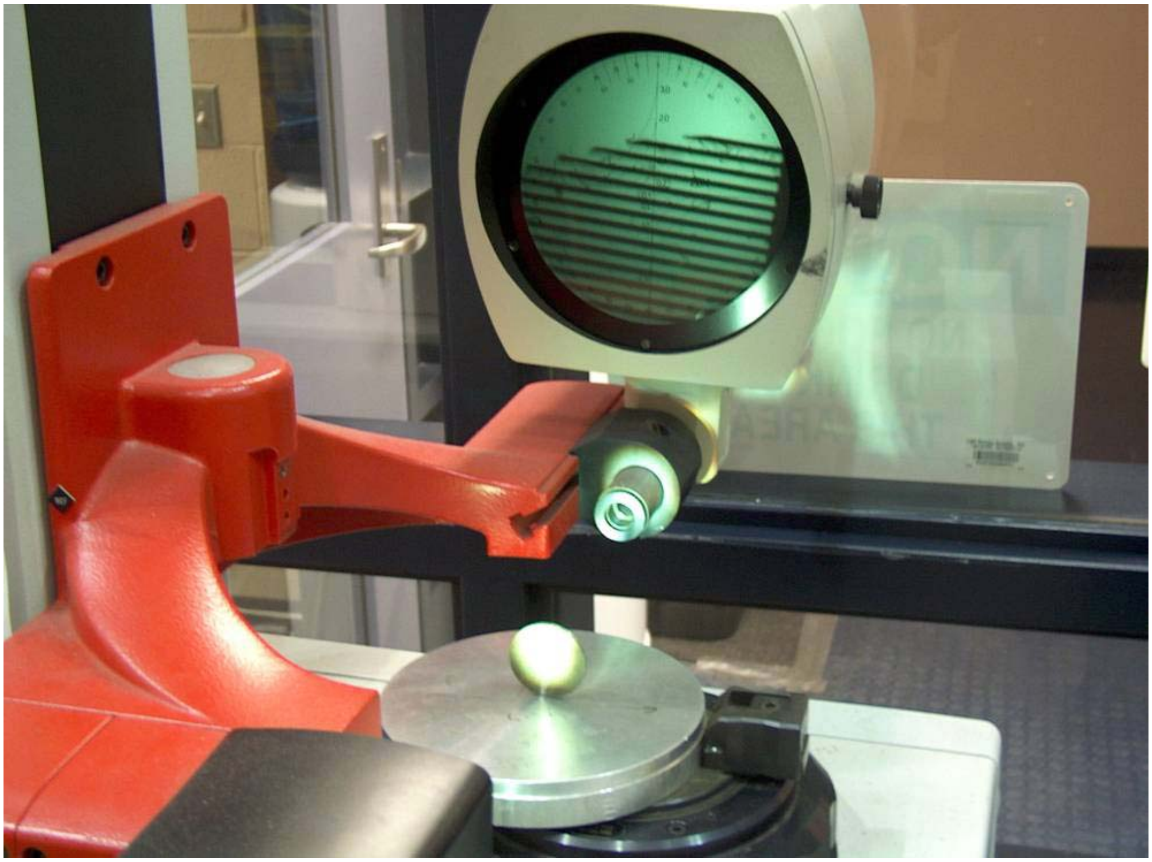
1. The specified sand interval was disaggregated to grain size, cleaned using a chloroform/methanol azeotrope, and dried in a vacuum oven.

2. The core material was homogenized and a laser grain size measurement (LGSA) performed on the whole sand fraction.
3. A one-percent (by volume) slurry of sand in heavy completion brine was prepared for testing.
4. A stainless steel sandpack tube having an internal diameter of 1-1/4 inches was assembled in a vertical orientation. The assembly consisted from bottom to top of a conical downstream endpiece, the test screen, a 3-inch tall void space, and an upstream endpiece.
5. The assembly was pre-filled with the heavy completion brine then the sand slurry injected into the top of the tube using a peristaltic pump while monitoring differential pressure across the overall sample. The slurry was injected at a flow rate of 50 cc/min for a period of 32 minutes or until a maximum differential pressure of approximately 100 psi was obtained. Test parameters were selected to yield a layer of deposited sand at least 1-inch high.
6. Effluent samples were collected throughout the test. Laser grain size and total suspended solids analyses were performed on selected effluent samples.



Result and Discussion

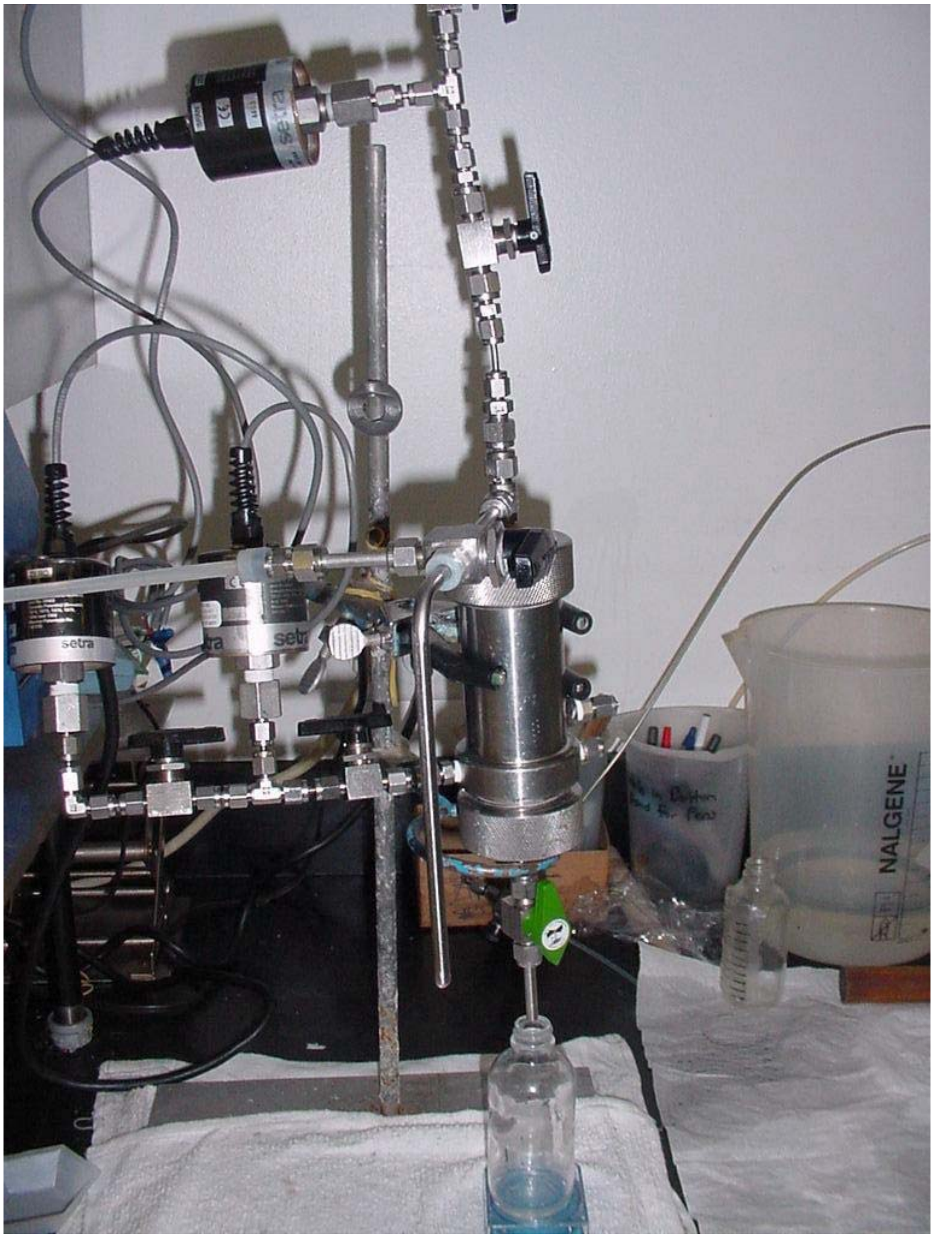
The lab testing work was performed a standard, simultaneous flow, plug, and particle-retention process. The standardized industry testing operation emphasizes sieve-particle passing and related results which are regimented by standard flow times. Also standard to the testing is technician practice of manually sizing slot sizes of test specimens. Accordingly, an undersized analog sand was used in the test since the presence of machining residues lead to an under-sizing conclusion. Further to standard laboratory practice is the taping of sample edges, so as to effect a minor seal between test vessel and sample piece. This lead to a reduction in open flow-area from 45.7% as constructed to approximately 31.6%. From efficient flow and non-plugging perspectives the performance was excellent since the reduction of the technology's characteristic high-flow area still resulted in a 2-3 or more orders of magnitude improvement over conventional test specimens. Although by no means representative of an exhaustive conventional sand-control development, the basic level test lead to four conclusions and results ranging from expected to better than expected performance.



Sand test coupon detail as viewed through comparator magnification>

The correct sizing of the screen openings is 210µ. The laboratory supplied material D50 = 134µ and ranged from <4µ - >367µ. Based on correct sizing, retention was 99.1%, which is better than expected, potentially given to the distorted open areas present in the construction. Tested on a basis of undersized material for any straining device, the retention level was expectedly not at high levels, but was still better than similarly disadvantaged legacy designs.

Screen-sample flow and anti-plug characteristics were both excellent, but should be discounted slightly due to analog material sizing. Very low pressure loss was recorded across the screen due to high open area. Screen pressure loss was negligible, ranging .007 – .021 bar (<0.1-psi – 0.30-psi.) The high-pressure side of the test flow was <.55 bar (8-psi) compared with 6.9 bar (100-psi) typical apparatus capability. Increases in pressure began approximately half-way through the test, as is normal, but this pressure was still negligible in magnitude.



Standard Sand-flow Test Setup

Low pressure loss also indicated non-plugging of the device. Approximately 25% of the sample flow area remained unobstructed. Plugging occurrence was complete in one hemisphere of the specimen, sporadic in the other, presumably due to drainage pathways. Standard regimented pump-time practice did not allow for full plugging.

In summary, many basic performance characteristics were demonstrated as expected or better than expected. The work was not comparative, precise or statistically significant. More work in the area is merited, but was beyond the task's scope.

Post Sand-flow Condition

Laboratory Testing of Mechanical Properties

As related to the original project plans and pragmatic constraints, the nature of the prototype-level construction went forward with testing short length specimens. No single, wholly applicable testing protocol has been made known to detail the novel structure. Testing, acceptance criteria, and QA are not publicly settled in the expandables industry – particularly at prototype, or proof-levels. It was thought at the time of proposal that such accord would be known when required for the project schedule, but recent interviews indicate that is still years away in the expandables industry. Furthermore, since the perfection of this technology's manufacturing processes are well beyond the project scope, even the most precise of tested information would not fully represent the early technology. Consequently, the project used analytically robust predictions along with generally acceptable testing protocol, with all reasonable efforts made to qualify any results where needed. Well known mechanical engineering and, where possible, generally agreed criteria found in tubular industries were utilized. A qualification factor includes conversion for the approximately 60% weld penetration made in the prototype structures are now estimated to be closer to 20% effective penetration for such analytical purposes, plus the protrusions emanating beyond the ID and OD surfaces. The structures also show very rapid stiffening actually as the lengths increase. Accordingly, qualifications were made between the apparent fixed and free end conditions as appropriate. All tests were performed on a 181-tonnes (200-ton) downward rated universal testing press with 152 cm. (60") stroke.

The following tests were performed and are presented in the order:

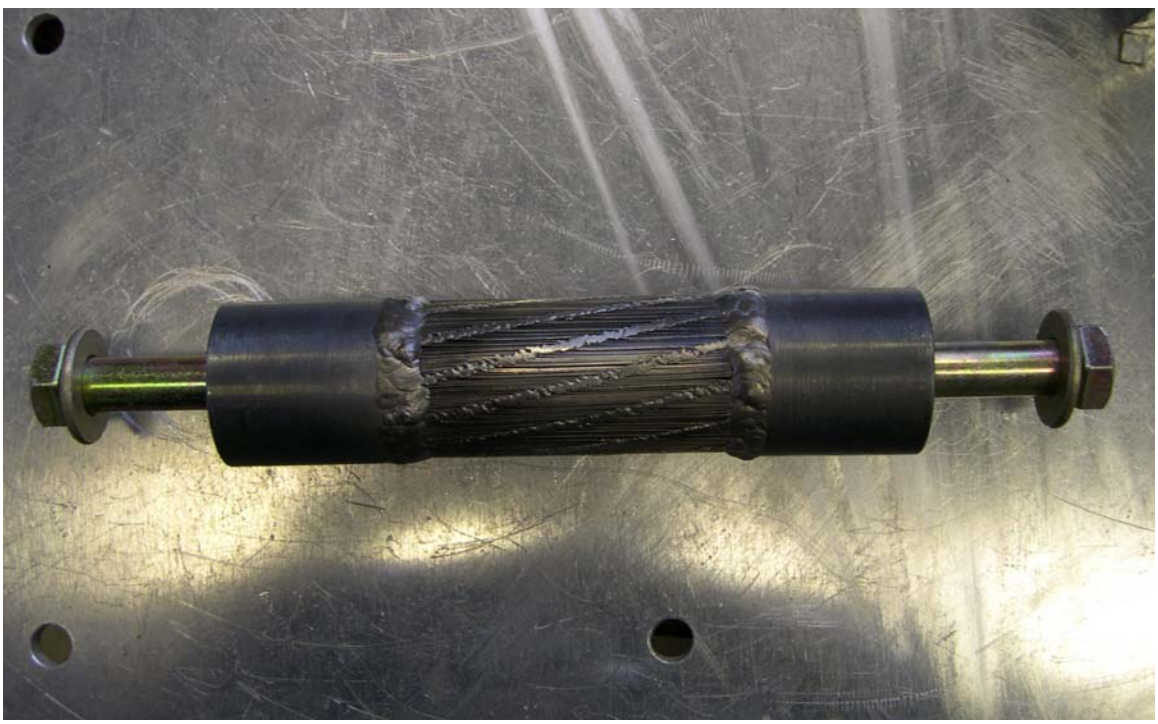
1. Tensile
2. Column Buckling
3. Torsion
4. Flexural Rock Support Elastic Phase Compression & Recovery
5. Ultimate Collapse

Execution and results of the mechanical testing program are as follows:

1. **Tensile testing** – The proposed value for the property was 53 tonnes (116,655-lbs). The resulting values were in excess of 300% greater that proposed.

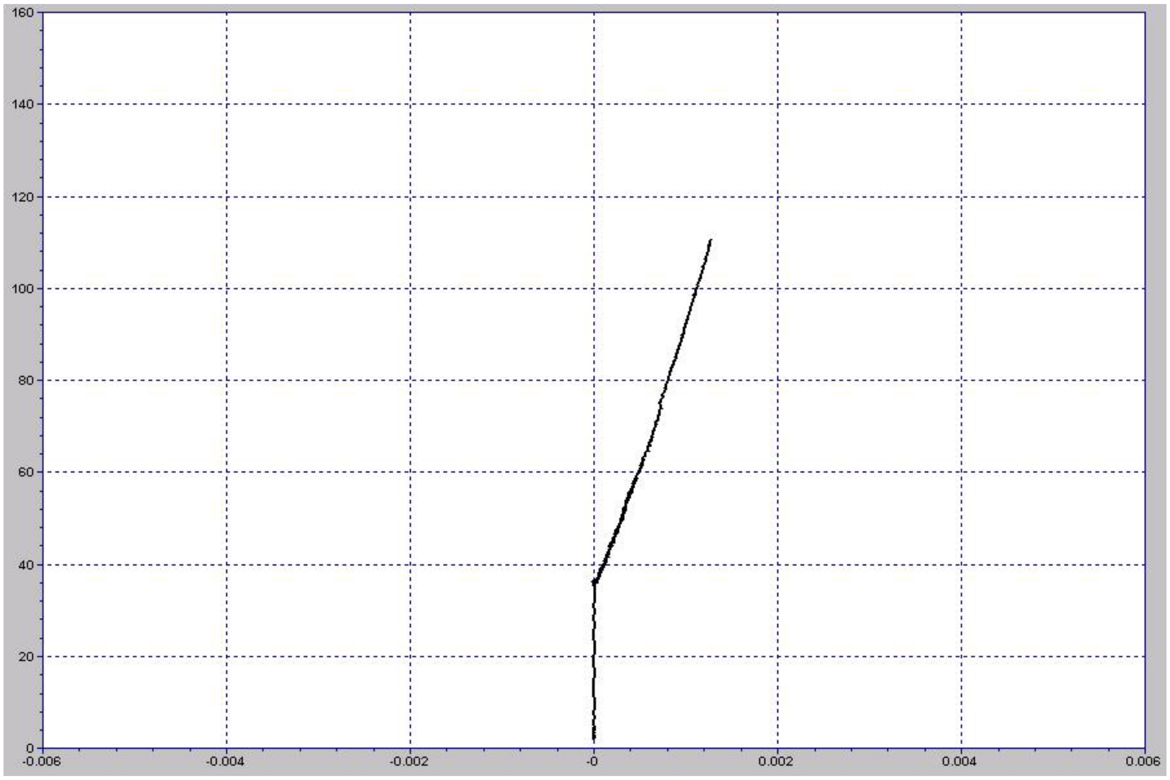
Sand Screen Tensile Test-I

Two tensile tests were performed. First, a 10.7 cm. (4.2”) diameter, .64 cm. (.250”) wall and 15.2 cm. (6”)-length screen constructed from work hardened 308 stainless steel was initially tested by use of 152 cm. (60”) travel, 181 tonnes (400,000-lb.) hydraulic buckling press. The screen was compressed to approximately 7.9 cm. (3.125”) diameter and was fixtured by welding to bolted flanges. Because the 181 tonnes (200-ton) hydraulic press is oriented to perform Euler compression evaluations, its upward, or tensile rating is limited to 159 tonnes (350,000-lbs.)



3.5 cm. (1.375”) natural OD, second tensile sample.

tensile force. The tensile test was performed to maximum pull of the tension machine, but no yielding or other remarkable strain was realized during the operation. Because the 159 tonnes (350,000-lbs.) tension was well in excess of proposed values, the test was accepted and not rerun on a higher capacity machine.



Stress-strain curve from the 3.5/2.54 cm (1.375"/1.00") sand-screen tensile test. The vertical axis for stress (in MPa), and the horizontal axis is for strain. The Young's modulus is calculated as 60 GPa (or 8700 KSI).

Sand Screen Tensile Test - II

However, because of the fundamental interest to obtain axial stress-strain information, a small, 3.5 cm. (1.375") natural outer-diameter sandscreen specimen was fabricated and connected two stainless end cylinders by welding in order to the form a manageable tensile test sample. The compressed state of the micro-micro screen is approximately 2.54 cm. (1.00") OD.

For testing of the reduced diameter sample, an extensometer with 5.1 cm. (2-inch) gage length was attached to the sample and tensile test was conducted. High-tensile bolts were necessarily affixed to the force machinery and specimen. The bolts were expected to fail prior to yield by the screen. As estimated, one bolt fractured at 12.2 tonnes (27,000 lbs.) tension, while the sandscreen remained, again, unaffected, still in elastic range as recorded by the extensometer. There was no sign of yielding of the sandscreen when the bolt failed.

2. **Euler Buckling** – The proposed column bucking value was 4.5 tonnes (9861-lbs.), based on 355 cm. (120") sample length with 8.9 cm. (3.5") OD. Two tests with differing dimensions showed 22.7 tonnes (50,000-lbs.) capability for a fixed-end condition and 9.1 tonnes (20,000-lbs.) as free-end, non-coupled condition value.

Sandscreen following non-coupled compression test at 22.8 tonnes (50,000 lbs.)
The sample remained functional after plastic deformation.

Sand Screen Column Bucking Test

Two sets of Euler buckling tests were performed for fixed and free end conditions to a short laboratory specimen. A 10.7 cm. (4.2-inch) diameter and 5.1 cm. (2-inch) high sand screen was dipped into liquid epoxy, and compressed and clamped to a 8.9 cm. (3.5-inch) OD. After the hardening of epoxy overnight, the clamps were removed, and the sample remained at 7.62 (3-inch) OD. The tube was put into a pair of tube ends for testing. The tube could withstand 22.7 tonnes (50,000 lbs.) before it buckled. The compressive strength for buckling (with end-clamping) is therefore 51-ksi. The end-clamps were removed and the tube tested again. The tube could withstand 9.1 tonnes (20,000 lbs.) before it buckled (at 20.7-ksi). The laser deposits did not break, nor the wires. Upon unloading, the sample elastically recovered some of its original dimensions, but with apparent plastic (permanent) deformation.

3. **Torsion** – The proposed value for the original staggered-cell, 4140/aluminum epoxy structure was 11,428nM (8398-ft./lbs.) An, as fabricated, adjusted value of 3794nM (2790-ft./lbs.) resulted, and 15,178nM – 18972nM (11,160 – 13950 ft./lbs.) estimated were made based on full manufacturing joining development.

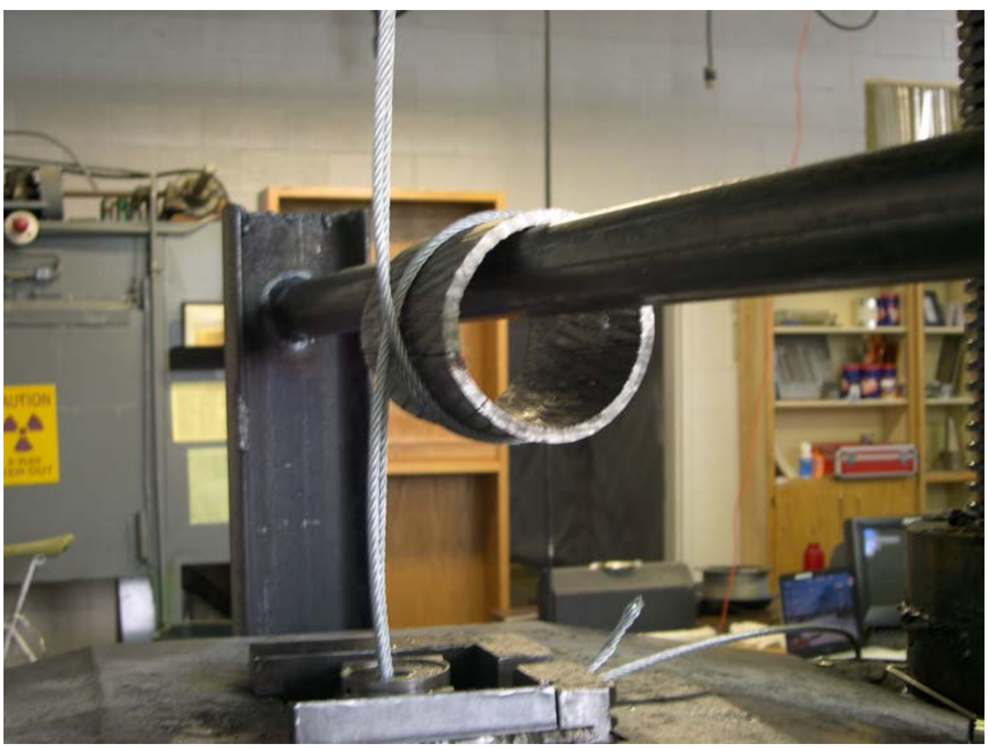
The torsion test was conducted with the following setup on a 2.5 cm. (1.00") OD sandscreen glued with epoxy. Testing was also conducted on the universal tensile machine. The torque to cause yielding and plastic deformation in the screen is a converted 3794nM (2790-ft./lbs.).

The relative lack of metallic bonding in the structure itself, consisting of only 1/5 of the wall thickness provided the test result, which was still in excess of conservative predictions. Fuller construction detail will increase the torsional strength proportionally.

4. **Flexural Rock Support Elastic Phase Compression-Recovery** – The property measuring elastic bias exertion against the wellbore rock, ranging from full-expansion to full elastic-phase compressed states, is new to the proposed specifications. Through the course of the project, industry preferences, reported previously suggested a minimum 1.4 MPa (200-psi) value or higher as quite technically beneficial to support wellbore rock. Subsequent reporting of 3D modeling predictions indicated values exceeding 5.5 MPa (800-psi) for a larger diameter and substantially thicker-walled screen structure. The analytical model was limited by not considering full compression of the device, however. The "cigarette paper" test was conducted on the universal tensile machine.

Testing, considering full elastic compression but without end support, revealed approximately 300% actual performance increase over the 5.5 MPa (800-psi) prediction at slightly more than 17 MPa (2400-psi) as shown at highly-concentrated, eccentric load areas of the setup. The eccentric loading is considered 'bonus' information. An extended compressed phase exists due to use of rectangular straining elements, which do not mate perfectly along the circumference was also shown by testing. Despite acceptable results, premature yielding occurs for the same reason.

A single-wrap, double-cable pull test was conducted with the following setup on a 10.16 cm. (4") OD X 15.2 cm. (6") long sand screen in its relaxed state. The load applied on the cable and the corresponding extension were recorded during the test. The test was stopped when an apparent plastic deformation in the sandscreen was observed. The cable extension and load data were processed to get the radial strain and radial stress after testing.



The elastic-energy, coil-test arrangement.

The sand screen was first elastically compressed by configurational changes, i.e., decreasing the gaps between the fins. After compression, thereby simulating a solid tube, i.e., all fins couching each other, the deformation started to be concentrated in the region where the cable was located. There was permanent plastic deformation in the sandscreen following testing. The original shape of the screen was cylindrical. Plasticity occurs at the tube's seam, also near the point of maximum stress from testing.

A stress-strain plot shows configurational compression from the origin to the point of 0.167 radial strain and .91 tonnes (2000-lbs.) radial stress. After that point, the slope of the curve increases. This means the sand screen has become a "solid", with a greater elastic modulus. The yield point is approximately 0.263 (strain) and 5.2 tonnes (11500-lbs.) stress.

Measurement of the 13.1 MPa – 16.6 MPa (1,900-psi – 2,400-psi) yielded specimen non-round condition reveals excellent correlation with the actual ultimate collapse results discussed below, and with theoretical collapse calculations for tubular eccentricity. Use of the formula, Dmin – Dmax divided by the same provides eccentricity of 19.24%. Determination of the actual 55.3 MPa (8,011-psi) ultimate value shown by the device, and adding various eccentricity by formula provides direct relationships between calculated and actual yield.

5. Ultimate Collapse - Radial Compression Test of Sandscreen – The proposed value for the property was 40.4 MPa (5,859-psi). The tested result was 55.3 MPa (8,011-psi) on a partially qualified basis.

Radial compression test setup.

A 7.62 cm. (3.00-inch) long, 10.7 cm. (4.2-inch) diameter sandscreen was put into a tube of 7.62 (3.00-inch) ID. The ends of the sandscreen were loosely supported by two rings (.635 cm./250" thick and 1.27 cm./.500" wide) to simulate the inverse stiffening effects that longer specimens cause for these structures. A special fixture was designed and fabricated to apply a concentrated load at the middle point of the clamped sandscreen. The load geometry was a 1.27 cm. (.500") wide semi-circular die which was also shaped according to a <7.9 cm. (3.1") arc.

Under compression, the sample started to show apparent radial buckling at the 4.5 tonnes (10,000 lbs.) load; with increased loading, the sample continued to buckle. The test was stopped after the load reached 9 tonnes (20,000 lbs). Upon unloading, the sample elastically recovered some of its original dimensions, but with apparent plastic (permanent) deformation. The interpretation of the range of test input values is that the elastic collapse result is minimally 27.6 MPa (4,000-psi) and the plastic collapse result is 55.3 MPa (8,000-psi).

Summary Comparison of Mechanical Performance for the Project Development:

Proposal Specifications:	**Proposed Pre-Expand**	**Proposed Expanded**	**Realized**
Outside diameter (OD, d)	7.6 cm. (3.00")	7.4–9.1cm(2.9–3.6")	2.5–10.9cm (1" - 4.3")
Inside diameter (ID)	6.4 cm. (2.50")	6.4–7.62 cm. (2.50"–3.00")	1.3–9.7 cm .5 – 3.8"
Wall thickness (T)	.65 cm. (.255")	.64 cm. (.250")	.65cm (.255")
Tensile rating	52.9 tonnes (116,655-lbs.)	--	159tonne(350klbs)
Theoretical collapse	--	40.4 MPa (5859psi)	55.3MPa(8011psi)
Torsion	--	11419nM (8398ft/lb)	3794 – 15178nM (2790–11160ft/lb)
Maximum outward force device	49.4 MPa (7166psi)	--	16.9 MPa(2447psi)*
Operating strain energy at expansion		35.3MPa (5118psi)	0
Strainer width at OD (W)		.18 mm (.007")	.20 mm (.008")
Strainer width at ID (WI)		.18 mm (.007")	.20 mm (.008")
Slot size (S)		.18 mm (.007")	.20 mm (.008")
Open area percentage		50%	36% - 60%
Spacing arrangement / scheme / frequency		.64 cm.(125"), staggered	.64 (1.3") helical
Spacer geometry (SPgeom)		.094 X .225 X .0625	---
Spacer attitude, rotation towards surface		30°	20°
Material		4140 ASTM/6061 Al	302/8 Stainless
Modulus of elasticity (E)		20.7 GPa30,000,000 (mat'l.)	8,700ksi (device)

**As demonstrated. Value is tunable, higher or lower.*

Construction of Field Prototype

A 152 cm. (5-foot) length prototype was constructed utilizing fabrication approaches identical to those used for laboratory test specimen construction. Although completely scalable as to length, project constraints limited the construction to a joined series of 30.5 cm. (one-foot) length pieces.

5' Field Prototype Lowered into Demonstration Well

Field Demonstration - Deployment Test

The deployment took place at the former government facility. The test well was constructed by the contractor and consisted of a top section of nominal 10.48 cm. (4.125”) ID casing. Below this was standard 11.43 cm. (4.5” 9.50# J55) casing with nominal 10.29 cm. (4.052”) ID. The delivery system utilized a simple threaded rod and back-off mechanism. As the sandscreen tubular was set through a previously set self-expanding tubular of the same diameter, a mono-diameter demonstration was provided by the project. Placement into the well is shown:

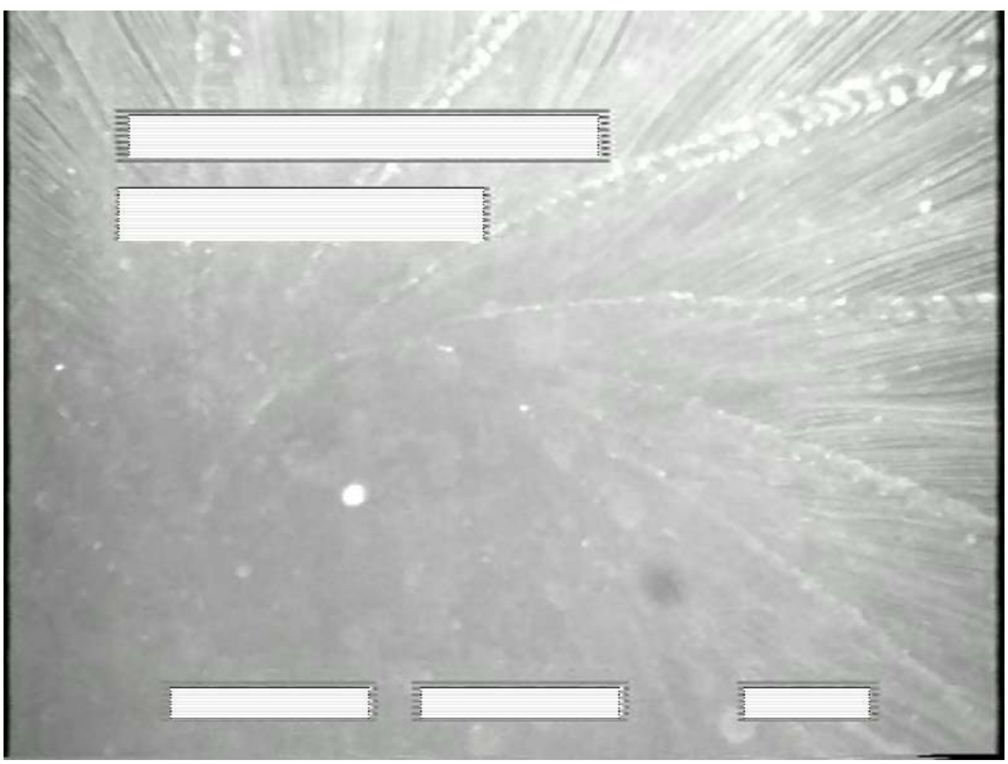
Field Demonstration

The demonstration well was inspected, drift-tested, video and caliper-logged previously. Construction of the well occurred in excess of proposal requirements, but did not include production related or other testing.

The field demonstration consisted of basic steps including:

- Drift testing of the demonstration well
- Caliper log of demonstration well
- Verification of prototype sandscreen compressed diameter, also realized by passing through expanded casing ID.
- Caliper and tallying of RIH assembly
- Actuation of sandscreen device by mechanical release
- Retrieval of delivery and actuation equipment
- Post-expansion inspection by downhole video survey

Insitu Set Condition



As demonstrated by video survey (partially shown above), the expansion process was completed. No abnormalities with regards to full-expansion, ovalization or other were visible during the original or subsequent inspections. A section towards the bottom, revealing typical screen condition and the bottom shoe area

Conclusion of Manufacturing Phase

Each aspect of the manufacturing phase of the project, including detailed design, manufacturing, testing, and deployment was successfully performed. Each is further detailed:

Detailed Engineering – demonstrated both discrete area and global functionality. The predicted specifications were in some cases well over quite high goals. The system showed its ability to be tuned, by altering any of the pitch, quantity, thickness or materials inputs. If any one conclusion related to the engineering applies, it is that the robust analyses were conservative and that actual performance was favorably higher

Manufacturing – the device was shown to be highly manufacturable and exhibited remarkable mechanical integrity even at relatively crude prototype levels. Manufacturing scalability was also demonstrated. Although not perfected, the quality of product improved rapidly during the course of the project to where regular aperture sizing was produced.

Testing – showed commercial scale sand-retention properties. Also demonstrated were better than commercial functions for plug-resistance and hydraulic differential across the screen. Mechanically, radial properties were demonstrably in a class all their own, as numerous orders-of-magnitude in excess of conventional technologies. Other properties were similarly demonstrated even at partial construction quality or provided plausibility towards outstanding performance levels.

Demonstration – was successfully passed as a monobore effort, in excess of proposed obligations.

V. Technology Transfer

The final area of the project is the technology transfer function. Performance of the tech-transfer, or commercialization related activities was nominally scheduled to occur during only the last month of an approximately 30 month schedule. The function was actually carried-out by the contractor on an ongoing basis throughout the program schedule.

The tech-transfer activities have covered numerous types of entities, technology applications and even four foreign countries. Some conferences presentations, business activities, or articles published were not directly related to MHT-II, but the program was referenced wherever applicable. An outline of effort types and entities is presented:

Oil Producers and Service Companies

- Major producers – 5
- Independent producers

- Small producers
- Four major service companies
    - Each attempted at least four times with no interest in any technology not readied for immediate exploitation.
- Non-major service and manufacturing companies – 4

Investment Areas

- Private investors
- Institutional investors
- Investment forums

Associations and Government

- DEA
- DEAe
- PTTC
- RPSEA
- Department of Commerce
- DOE - Geothermal

Media

- Three articles in industry publications
- Company website
- Printed promotional materials

Conclusion

While the self-expanding sandscreen development indicated significant solutions for four major performance issues in the expandable screen industry, there currently is no expressed interest by US oil companies and none whatsoever by major service companies despite numerous attempts. Interest is indicated internationally. Further technology transfer efforts will continue beyond the project schedule.

There was wide awareness of Microhole indicated throughout the US drilling industry, as observed during numerous meetings. The contractor traveled to three other countries where little or no knowledge of the program existed. Domestically, personnel shortages in the industry only serve to inhibit industry participation and uptake of MHT technologies. Expectations by industry are that the technologies are fully developed and ready for exploitation when presented.

-- GRAPHICAL MATERIALS LIST --

Section is not applicable.

-- REFERENCES --

Section is not applicable.

-- BIBLIOGRAPHY --

Section is not applicable.

-- LIST OF ACRONYMS AND ABBREVIATIONS --

CT	Coil-Tubing
FEA	Finite Element Analysis
FEM	Finite Element Model
ID	Inner-Diameter
L:D	Length-Diameter Ratio
OD	Outer Diameter
RIH	Run-In-Hole
S-T	Split-Tube
TIG	Tungsten Inert Gas

-- APPENDICES --

Section is not applicable.

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