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Final Report

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Submitted by:
Dynamic Tubular Systems, Inc.
12755 Ashford Hills Drive
Houston, TX 77077

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8. **Name and Address of Submitting Organization**:

Dynamic Tubular Systems, Inc. and Confluent Filtration Systems, LLC
12755 Ashford Hills Drive
Houston, TX 77077

AMET, Inc.
35N 1E
Rexburg, ID 83440

-- DISCLAIMER --

-- ABSTRACT --

The Advanced Monobore Concept – **CFEX©** Self-Expanding Tubular Technology Development was a successfully executed fundamental research through field demonstration project. This final report is presented as a progression, according to basic technology development steps. For this project, the research and development steps used were: concept development, engineering analysis, manufacturing, testing, demonstration, and technology transfer.

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4. Executive Summary

The **CFEX©** Technology Development – Advanced Monobore Concept Project successfully completed all of the steps for technology development, covering fundamental research, conceptual development, engineering design, advanced-level prototype construction, mechanical testing, and downhole demonstration. Within an approximately two year period, a partially defined, broad concept was evolved into a substantial new technological area for drilling and production engineering applicable a variety of extractive industries – which was also successfully demonstrated in a test well. The demonstration achievement included an actual mono-diameter placement of two self-expanding tubulars. The fundamental result is that an economical and technically proficient means of casing any size of drilling or production well or borehole is indicated as feasible based on the results of the project.

Highlighted major accomplishments during the project's Concept, Engineering, Manufacturing, Demonstration, and Technology Transfer phases, are as follows:

Conceptual and Engineering Development Phases

Basic research for the project included literature review and ideal specifications development for the new and undefined technical area. The latter was established with the assistance of a major producer familiar with expandable system developments. A detailed, qualitative study, intended to elucidate tubular geometries that potentially provide the mechanical characteristics required to comply with the new specifications was performed. The results of the concept development led to categorization of approximately 15 basic geometries with varying commercial abilities, and based on in-excess of 100 geometric approaches.

The selected conceptual approaches were demonstrated during the engineering analysis phase and subsequent phases to provide numerous novel capabilities, including:

- Solid tubular expansion ratios in excess of 200%
- High-pressure capabilities in excess of 70 MPa (10-ksi)
- Expansion with suitability for ultra-deep drilling
- Limitless applicability of materials yield and quality
- Self-sealing for most applications in order to eliminate needs for cement in wells
- Elimination of conventional longitudinal shrinkage issues
- Indicated elimination of conventional expandables connection failures
- Development of dry expansion processes

Manufacturing Phase

The manufacturing phase included all prototype and appurtenant construction, mechanical testing, and a special study proving commercial manufacturing feasibility. Construction of long-length, high-strength specimens was accomplished, requiring coordination and execution by several specialized manufacturers not widely available. One prototype appurtenance successfully constructed included design through testing of the pre-load sealing sleeve component for the tubular device, which showed capability to 110 MPa (16-ksi) pressure integrity. The two-phase manufacturing analysis revealed commercial viability for the technology at approximately 200% - 250% differential over standard pipe. The cost is less than selling prices for standard expandable casings and liners. The study also detailed individual processes, plant layout, capital requirements, and product type and volume sensitivities.

Demonstration Phase

The as-proposed length field prototype was successfully deployed in a test well, also constructed by the contractor. The deployed casing also demonstrated basic properties of the technology's ideals, including integrity of the set condition and annular sealing functions. Field demonstration of the Advanced Monobore Technology constituted the first known deployment for solid expandables featuring expansion capabilities in excess of 130%. The demonstrated expansion ratio was 133%. The set casing was also used to demonstrate the contractor's other self-expanding tubular developed for the MHT program. Successfully passing and expanding underneath the original tube thereby demonstrated a single-diameter system.

Technology Transfer Phase

Tech-transfer activities were carried-out continuously throughout the duration of the program. These included efforts with multiple major oil producers, service companies, manufacturers, government agencies, industry associations, and investment concerns. Numerous novel applications for the technology were identified through the task. The major accomplishment, however, is the contractor's developing and receiving three RFP's from a major energy producer towards interests in furthering the technology.

Other Comments and Conclusion

The **CFEX©** project was completed without major issues and with results exceeding those originally proposed. It was completed on schedule and on budget. The contractor substantially augmented its cost-share contribution in order to further discoveries made during the course of the program. The contractor also performed several additional tests in excess of the contracted commitments.

I. Conceptual Development

The concept development stage marks the beginning of the technology development project. Although multiple approaches to obtain the objectives of self-expanding tubulars were proposed, and even more were under consideration, a process allowing full understanding and optimization of many complex operational needs the overall concept was required to be employed by for the project. The basic problem for this section is to determine the geometric basis for potentially to most optimal tubular design.

Description of Experimental Methods - I

The first project stage did not consist of experimentation per se. The first stage was a qualitative, pipe-geometry, concept elucidating operation, or brainstorming process. The project was treated as fundamental research. This fundamental research commenced with technical literature research and extensive efforts towards creating complex definitions and technical requirements to be used for the purpose of establishing specifications and specific project performance goals.

The basic specification is as follows:

The device' performance criteria are provided in two-tiers, under 'Critical' and 'General' items. The performance values are, in turn, requested in three levels approaching the properties of higher-end, conventional, correspondingly-sized API tubulars, as follows:

Critical Areas

Item	Measure	Minimum	Expected	Exceptional
Device diameters:	4.00" OD ± .25" 2.125" ID ± .125"			
Expansion ratio Thru expanded self		~125%	140%	>150%
Burst rating	psi	2000	6000	10810
Collapse rating	psi	1500	6000	13830
Sealing	psi	1500	6000	13830
Tensile strength	3000' length self-supporting plus 25,000 lbs. safety factor.			
Buckling, 10,000#	Compressed/in. - δ	0.5"	1.00"	open-hole
Torsion compliance	Compressed - ft./lb.	1500	3000	>4500
Production cost target	$ / ft.	<$50	--	$15>

General Parameters

Item	Measure	Minimum	Expected	Exceptional
Corrosion	CO_2, partial psi	<3	3-200	any
	H_2S, ppm	<5	<5	.05
	Chloride, %	<2	>2	any
Materials types & grades:	Unlimited.			

(Convert Inches to centimeter: multiply by 2.54; PSI to MPa: divide by 145; foot-pounds to Meter-Newtons: multiply by .737)

Specifically, a sub-award was granted to a consultant calling for development of at least two design concepts for self-expanding casing to occur through a detailed user-preference, design-feature trade-off study process. The project began with a conceptual design stage consisting of basic research performed for the purpose of detailing the nature of a technical problem and its potential solutions. Components of basic research include:

- Detailed problem definition – where design requirements and constraints are identified and prioritized and technical specifications are formed and continually refined.

- Technical and patent literature research – where any pertinent information might be uncovered to assist progress.

- Brainstorm meeting – to generally develop design possibilities for the technology which satisfy the set of standards.

The goal of the brainstorming process is to develop design options that can be carried into more advanced stages. Once exact definitions and goals are determined, the process matches detailed problem-definition-characterization and evolved design criteria observation and relatively ranks them against the technology's objectives and characterization.

Generated concepts are then qualitatively assessed relative to the problem definition. The outcome of this 'trade-off' study allows a ranking of concepts. The variables are placed into a matrix where the outcome for the process can be viewed. Scientific methods for the early stages of the project were objective observation and detailed review towards conceptual design generation.

Results and Discussion - I

A brainstorm effort resulted in generation and illustrations for, overall, in excess of 100 new conceptual ideas relating to self-expanding tubular technologies. The new items were added to numerous existing concepts, totaling then well over 100. The concepts were later grouped into approximately 15 categories based on their distinct geometry or features. Two excellent rated geometries were generated.

Definition and selection of criteria for determining best conceptual designs – eight criteria factors were generated and were provided with definitions of excellent-poor ratings for each:

- Technical performance
- Differentiation from competition.
- Installed cost
- Compatibility with oilfield
- Development effort
- Reliability during deployment.
- Durability
- Health, safety & environment

Data generated during the process consisted of votes made for each geometry against the performance. The process is described:

Trade off study – development of a range of conceptual designs for an expandable casing. The process was preceded by refining fifteen potential device geometry categories to nine.

Based on performance criteria and operating preferences, a qualitative design parameter ranking process was then performed. Basic engineering calculations were used to verify the qualitative suppositions. The trade-off study yielded two initial design types, acceptable to project design review. Decision and math CAD software is used in experimental and analytical modeling activities were used. The favored potential embodiment is confidentially termed 'split-tube'. It consists of layers of novel geometry, split-spring forms and is estimated to eventually outperform all previous expectations, including expansions ratios of some 200%.

The definitions, brainstorming, and ranking processes led to the generation and careful ranking and elimination of numerous conceptual possibilities, thought to effectively exhaust the area for the particular monobore application. The addition of initial numerical analyses confirmed the qualitative selection as an excellent design candidate to be taken forward.

Conclusion - I

To conclude this section, a basic research process which produced excellent results for design candidates has been presented. Based on the ranking of the abilities of each geometric type, several types of microhole casing could be developed, but only very few meet all technical and commercial requirements, so as to succeed in assisting development of a microhole industry. Excessively small device diameters pose difficulties to the technology's design efforts and even possibly to general feasibility issues for some prospective embodiments of self-expansion technology.

II. Engineering Design

Arrival at the numerical analysis, preliminary design selection project stage signified completion of the conceptual design phase of the project. The next stage is more analytically detailed, consisting of Preliminary Design and Detailed Design phases, but also adds basic-level testing in between, so as to test the analytical predictions. The basic problem solved in the section is the need to analytically verify performance predictions for design candidates at expected operationally detailed levels.

The preliminary design phase serves to:

- further quantify the practicality of the design
- divide the concept into subsystems & define detailed design requirements for each
- lead to an overall integrated tradeoff to select best combination of subsystems & effects

Detailed Design is the subsequent stages of the development, which further refine detail features after preliminary testing has occurred. The stages and phases are presented as a progression:

Experimental Methods - II

Preliminary Design – Early Configurations

Analysis of the preferred pipe configuration originally focused on three areas: compression and expansion of pipe, strength properties of assembly, and simple joining requirements. Both hand calculations and finite element analysis (FEA) were used to study how much a self-expanding pipe can be compressed without plastically yielding the material. These calculations have provided guidelines with regards to the number of required layers and each layer's wall thickness. Simple mechanics were first used to analyze the design in regards to the compression and subsequent expansion of individual layers. The strength of the assembly also involved relatively straightforward calculations. The device cross-sections were treated as a curved beam. Two-dimensional analysis was initially used for all calculations as the strength and bending properties were assumed not to vary axially. A moment is applied to the beam to change its angle of rotation and, hence, its radius of curvature. The equations used were considered valid for beams in which the radius is more than ten times the wall thickness. The deflection of a curved beam can be analyzed by studying the strain energy of the system, which is the amount of potential energy stored in a body as a result of elastic deformation. The strain energy, U, is related to the applied moment, material properties, and beam geometry

Burst, collapse, and tensile loading requirements for the project guided the analysis of various configurations. FEA was used to analyze the structural integrity of pipe configurations with the preliminary assumption that each layer is effectively bonded to all contacting layers. From mechanical standpoints, the compression and subsequent expansion of such assemblies were always shown as highly viable. A critical element of the concept and experimentation was determining materials and effects that re-integrate and seal the tube system

FEA was then used as a check of the analytical calculations. Further analysis of chosen designs was performed using FEA, as the analytical computations did not account for subtleties in geometry. Workbench® 9.0 was used as the FEA tool for this project. Two-dimensional plane strain elements were used since the expansion, burst, and collapse properties of the design were assumed not to vary axially. End effects at segment joints have not been incorporated at this stage of development. The initial analysis of burst and collapse strength of various designs utilized bonded line-to-line contact elements.

First Level Advancing of the Design

Progressing analysis to non-linear states, as the subsequent effort titled: 'Nonlinear Finite Element Analysis of a Simple S-T Expandable Casing Concept for the Purposes of Understanding Inter Layer Structural Interaction During Wrap Up, Release and Subsequent Burst and Collapse Loading', comprised the evolved experimental method, as follows:

Nonlinear FEA in order to develop an understanding, for design and manufacturing purposes, of inter-layer structural interaction during wrap up, release and subsequent burst and collapse loading of a simple two-layer Self-Expanding Tubular. The finite element analysis of the Two-Layer S-T Tubular was executed using the *ANSYS General Purpose Finite Element Program's* nonlinear analysis capabilities.

The model implemented in this study was been parameterized to permit easy modification of the layer dimensions and material properties, and to also facilitate modification of the concept with respect to both the number of layers included in the configuration as well the orientation of each layer in the tubular system. This flexibility allows the finite element model to be used in both a design optimization mode for the purposes of selecting a prototype concept for manufacture and testing, as well as using the model to provide feedback in support of establishing both the means and methods of manufacturing the prototype.

With respect to design considerations, feedback from the nonlinear FEM analyses is useful in gauging a concept's potential for performance in a field application; i.e. the model was useful in estimating such quantities as force requirements for attachment and integrity mechanisms, contact force pressure between the deployed system and the wellbore, response to burst and collapse loading, etc. In the case of laying out the steps of the manufacturing process for a prototype, the nonlinear analysis results provide valuable incite into the path dependent process which constitutes the assembly of such a device; an important consideration when attempting to minimize the stressing and damaging of vulnerable components during the manufacturing process.

Curved layers of steel were modeled using the PLANE182 element, a two-dimensional, quadrilateral four node finite element that has 2 degrees of freedom at each node (translations in the x- and y-coordinate directions) and possesses plasticity, stress stiffening, large deflection, and large strain capabilities. Contact between the steel layers was modeled using contact elements CONTA171 and TARGE169. CONTA171 is a two-dimensional two node surface-to-surface contact element used to represent contact and sliding between 2-D "target" surfaces (TARGE169) and a deformable surface, defined by this element. Large strain and displacement deformation response, nonlinear contact, and a full static Newton-Raphson nonlinear equation solution processes were employed.

The design of the candidate Tubular Form had to result in a device able to (i) exhibit elastic response throughout its range of deformation; (ii) must be able to robustly and smoothly compress and expand with minimal friction effects; (iii) must be automatically self-locating between its leaves (or layers); (iv) must admit to the inclusion of securement mechanisms for both limiting the range of expansion under internal pressure as well as locking to prevent re-compression under external pressure; (v) must permit the inclusion of mechanisms for sealing against both unbalanced internal and external pressure; and, (vi) finally, must satisfy critical expansion ratio, burst, collapse, sealing, tensile strength, buckling, and torsion compliance requirements.

Subsequent experimentation at analytical levels was accomplished in two stages. First, a nonlinear FEA of an interleaved, multi-layer layer scheme was undertaken to gain insight into the large deformation response of a potential device; including the interaction between its layers or leaves during both compression and expansion, its behavior during release or unloading against the formation and finally the nature of its residual stress distribution following the activation of securement operations. Following the identification of key issues and problems identified via the aforementioned nonlinear FEA, a conceptual study was undertaken in order to establish further refined forms for a Prototype Device.

Subsequent phases analyzed large displacement/large strain, elastic-plastic, plane strain, nonlinear FEA of an interleaved tubular form was undertake in order to gain insight into the response of a typical Self Expanding Tubular Device to operating load conditions. In mimicking critical deployment deformation states, the FEM of contemporary device, was subjected to a number of different sequential load cases. The load cases were designed to represent (i) compression of the device down to its specified compressed outer diameter by an imposed radial deformation field applied to the outer layer of the device, (ii) the replacement of the imposed boundary displacement field by reaction forces, (iii) the ramping off (or release) of the restraining reaction forces to allow the device to expand against the formation, (iv) the securement of the device (via activation of a sticky contact model) after it has come to rest against the formation, and (v) the removal of the restraining formation model in order to release the secured device and allow it to develop a residual stress state.

Software solution control features implemented during the nonlinear FEA included options for nonlinear geometry (large deformation/large strain) analysis, full Newton-Raphson solution process, Auto Time Step Control, full Line Search and no Solution Predictor.

Results and Discussion Data

The outcomes for preliminary design and detailed design analyses are shown according to expansive states and various loading conditions.

Casing Diameter Change

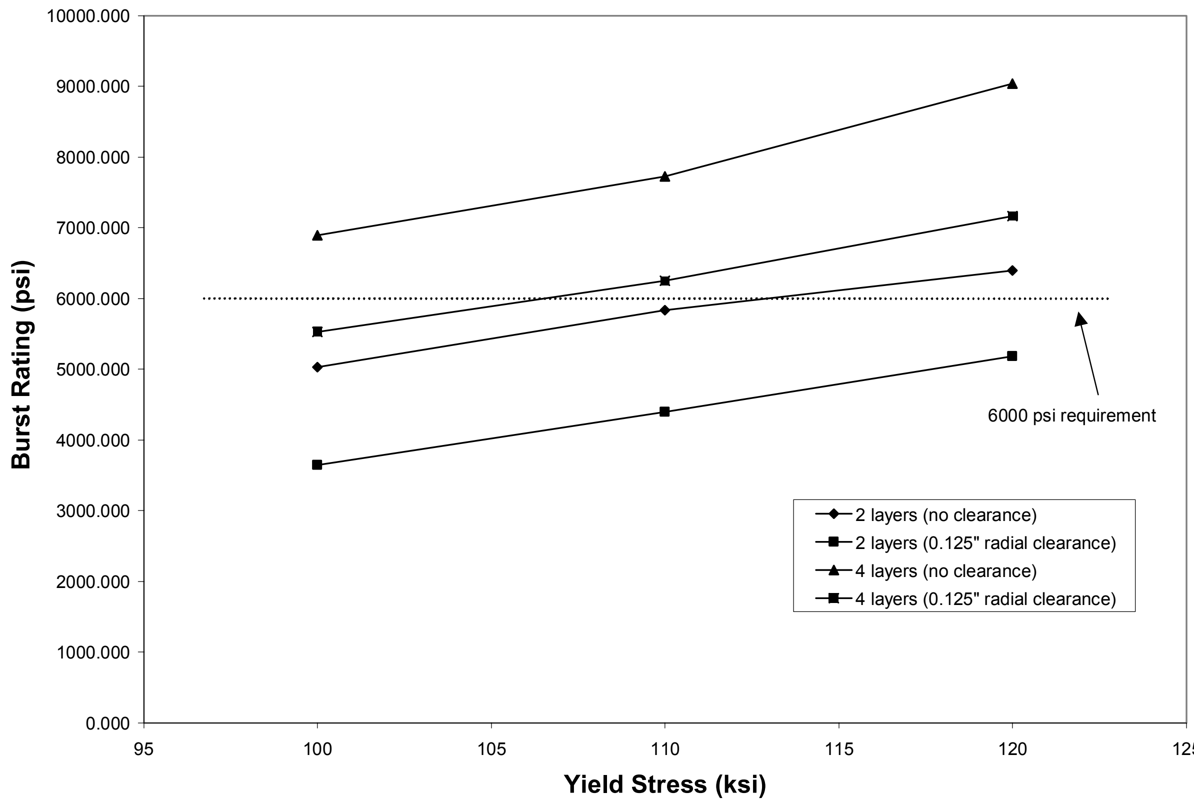
The driving advantage expandable casing is its ability to pass unset casing through casing already set in the well. To accomplish this objective, the OD of the casing being deployed must be reduced by compressing the assembly. The required compression was studied by evaluating the bending of individual layers to produce a change in casing diameter. Basic equations for this bending and FEA were again used to validate the calculations. A moment was applied to both free ends of a particular layer in the FEA simulations. All stage FEA stress results are Von-Mises equivalent stresses. A key design assumption is that the compression of a layer could not result in the plastic deformation of that member. All of the designs presented in this report fulfilled this requirement.

Axial Loading

One of the specification requirement was that the pipe must at least be able to axially support the weight of a 915 meter (3000’ length) plus 11,340 kilograms (25,000-lbs.) This requirement is to ensure that the casing will not yield during deployment while long lengths of pipe are suspended in the well bore. The results showed, the requirement of pipe weight plus 25,000 pounds to be easily fulfilled easily fulfilled since each layer complies with the criteria. For concept selections presented in this report, axial loading was not considered a critical evaluation requirement due to all designs fulfilling the project goal.

Burst and Collapse Strength

The burst strength for various tubular configurations. Data are presented for the case designed to have .3175 centimeter (0.125 inches) of radial clearance during deployment as well as a design with no such clearance. For each given number of layers and material yield stress, the design was optimized to provide the maximum burst and collapse pressure rating while fulfilling all of the design requirements. The burst ratings presented in the plot represent the lowest pressure at which yielding of one layer of material may occur. FEA test cases showed reasonable correlation with hand calculations in determining the strength properties of the evaluated assembly. No two-layer cases for the design goal of a 3175 cm. (0.125-inch) radial clearance were found to meet burst and collapse requirements for the range of yield stresses tested.



Maximum Burst Strength for Various Designs as a Function of Material Yield Stress (Metric, MPa Equivalent = PSI ÷ 145).

Successful Execution of Basic Testing

Based on acceptable analytical predictions, coupon-level construction and testing was performed. A specialized matrix was made in order to perform basic testing program. (Measurement conversions are previously supplied).

Test Matrix for Self-Expanding Tubulars Prototype Development

Test Description	Orientation	Temperature RT	tbd	Total	Notes
Tension	Axial	6	3	9	Multi-layer strength confirmation
CFS Compression	Axial	6	3	9	Multi-layer strength confirmation
Ring Tension	Hoop	12		12	Deployment force verification
Ring Compression	Hoop	12		12	Closing force verification
Lap Shear	Circumferential	6	6	12	Sealing mechanisms
			Total	**54**	

Coupon Testing Results

Nested C Column-Buckle Data

		Un-Nested					Nested				
		Average Dimensions					Average Dimensions			Buckling Load	
Part		Length, inches	OD, inches	Wall, inches	ID, inches	~Interference, inches	OD, inches	Wall, inches	ID, inches	*Calculated, pounds	Measured, Pounds
Column-Buckle #1	Outer C	36.0	4.090	0.140	3.810	-0.021	4.092	0.278	3.536	1,391,118	>92,120
	Inner C	36.0	3.789	0.126	3.537						

Notes: * - assumes Euler buckling of continuous steel pipe of nested dimensions with pin-ended conditions

Single C Column Buckle Data

		Un-Nested					Buckling Load		
		Average Dimensions							
Part		Length, inches	OD, inches	Wall, inches	ID, inches	~Interference, inches	*Calculated, pounds	Measured, Pounds	% Reduction in Load-Carrying Capability
Column-Buckle #1	Inner C	36.0	3.789	0.126	3.537	NA	556,251	71,260	87%
	Outer C	36.0	4.090	0.140	3.810	NA	775,069	90,175	88%

Notes: * - assumes Euler buckling of continuous steel pipe of nested dimensions with pin-ended conditions

Table 1. Column-Buckle Data

Nested C Mechanical Collapse Data

		Un-Nested					Nested			
		Average Dimensions					Average Dimensions			
Part		Length, inches	OD, inches	Wall, inches	ID, inches	~Interference, inches	OD, inches	Wall, inches	ID, inches	Max. Load, pounds
Collapse #1	Outer C	2.0	4.080	0.140	3.799	0.014	4.093	0.268	3.557	1,730
	Inner C	2.0	3.814	0.126	3.562					
Collapse #2	Outer C	2.0	4.079	0.140	3.799	0.006	4.086	0.269	3.548	2,607
	Inner C	2.0	3.805	0.125	3.554					
Collapse #3	Outer C	2.0	4.079	0.140	3.799	0.025	4.093	0.267	3.559	1,356
	Inner C	2.0	3.824	0.126	3.573					
									Average	1,898

Clock Spring Data

	Average Dimensions					
Part	Length, inches	OD, inches	~Wall, inches	ID, inches	~Interference, inches	Max. Load, pounds
Spring #1	2.0	3.838	0.200	3.438	NA	19,396

Table 2. Mechanical Collapse Data

Un-Nested Data						Post-Test Nested			
		Average Dimensions				Average Dimensions			
		OD,	Wall,	ID,	~Interference,	OD,	Wall,	ID,	Max. Load,
Part		inches	inches	inches	inches	inches	inches	inches	pounds
INT #1	Outer C	4.005	0.141	3.723	0.033	4.032	0.271	3.490	85
	Inner C	3.756	0.125	3.506					
INT #2	Outer C	4.013	0.141	3.731	0.020	4.033	0.275	3.483	48
	Inner C	3.751	0.126	3.499					

Table 3. Interference Fit Data

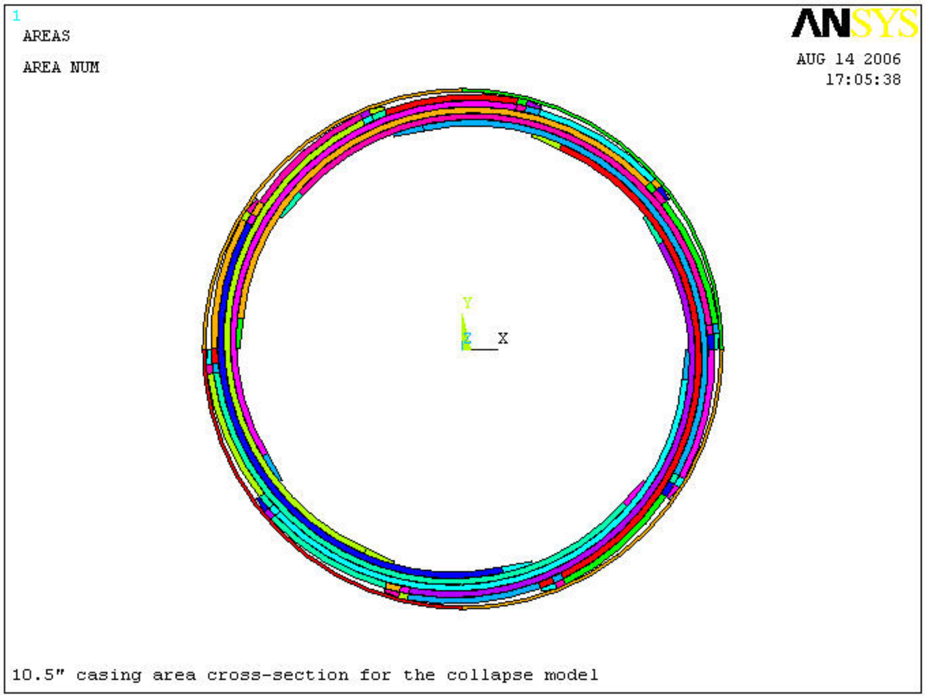
Detailed Design Phase

Even though various concentric configurations analysis and coupon testing performed well, more technically elegant spiral and combination forms were developed as detailed designs.

Detailed design work first established an appropriate robust, stable, computationally efficient, nonlinear analysis solution scheme for carrying out the structural analysis of a two-dimensional plane strain nonlinear finite element model of a generic interleave casing configuration. The detailed design again must result in a device that is able to (i) exhibit elastic response through out its range of deformation; (ii) must be able to robustly and smoothly compress and expand with minimal friction effects; (iii) must be automatically self-locating between its leaves (or layers); (iv) must admit to the inclusion of securement mechanisms for both limiting the range of expansion under internal pressure as well as locking to prevent re-compression under external pressure; (v) must permit the inclusion of mechanisms for sealing against both unbalanced internal and external pressure; and, (vi) finally, must satisfy critical expansion ratio, burst, collapse, sealing, tensile strength, buckling, and torsion compliance requirements. The solution scheme developed and tested during this work effort implemented a different procedure for release of a compressed Self-Expanding Tubular device and introduced the effect of friction in the solution process.

In the work, 'Nonlinear Finite Element Analysis of an Eight Leaved Iris-Type Interleave/Leaf Spring Self-Expanding Casing Concept Using a Modified Procedure for the Release of the Compressed Device', a large displacement/large strain, elastic-plastic, contact with friction, plane strain, nonlinear finite element analysis of an interleaved Tubular Form was undertaken, using the *ANSYS General Purpose Finite Element Program*, in order to gain incite into the response of this class of Self Expanding Tubular Device to compressive and expansive load conditions.

The finite element model of the Eight-Leaved device, which is described below, was subjected to two different sequential load cases. The load cases were designed to represent, first, (i) compression of the device down to its specified compressed outer diameter by an imposed radial deformation field applied to the outside of a cylindrical, linear elastic, Load-Transfer Model surrounding the device, followed by (ii) expansion of the Eight-Leaved device induced by ramping the imposed outer radial deformation on the outside of the Load-Transfer Model to zero; i.e. a contact model being used to effect structural interaction between the cylindrical Load-Transfer model and the solid model of the Eight-Leaved device.



Basic Spiral Casing form

In Stage #1, which is comprised of Load Steps 1 through 9, the Eight-Leaved device is compressed from its unstressed nominal initial outer radius of 5.715 centimeter (2.25 inches) (4.5 inch diameter) to its reduced final outer radius of 4.763 centimeters (1.875 inches) (3.75 inch diameter) by an imposed radial displacement field applied to the outer surface of the Load-Transfer Model. 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.

Stage #2, which is comprised of Load Step #10, encompasses the expansion of the Eight-Leaved device induced by ramping the imposed outer radial deformation on the outside of the Load-Transfer Model to zero.

Results for the nonlinear analysis were generated: 16. Stage #1, which occupies analysis TIME $0 \rightarrow 9$ (see Table 2), encompasses the compression phase of the analysis. Deformed configuration plots, taken with the surrounding Load-Transfer Model removed, were calculated for, respectively, .0762 cm. (0.03"), .254 cm. (0.10"), .635 cm. (0.25") and .953 cm. values of radial compression. A Von Mises Stress plot for the Eight-Leaved device at 0.375" radial compression was made. Stage #2 results, which represent the expansion phase of the analysis occurring over analysis TIME $1 \rightarrow 10$, were also calculated for, respectively, 10%, 15%, 20%, 25%, 35%, 50%, 70%, 85% and 99% expansion states.

It is important to note here that the primary purpose of executing the foregoing analysis was the verification of the solution procedure developed previously. Though further design/analysis work was to be undertaken, a final configuration was enabled for selection for manufacture of the prototype.

Machining of Spiral Casing Coupons

Subsequent work emphasized higher-pressure objectives for design and fabrication of a high-pressure section specimen, Self-Expanding configuration equivalent to standard 24.45 cm. casing size for compliance with burst and collapse loads which properties exceed 68.95 MPa.

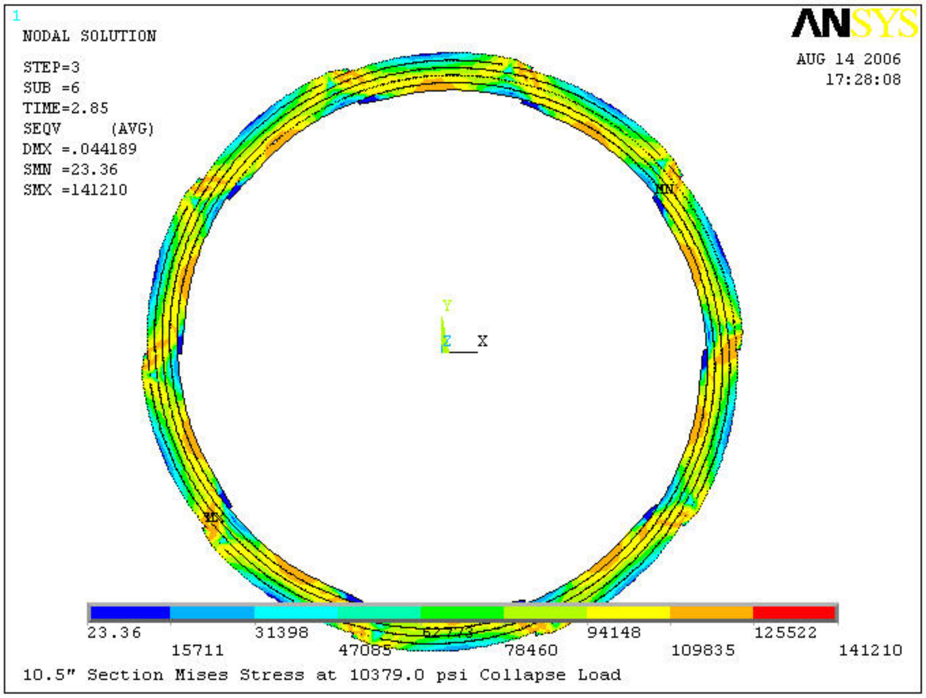
The standard diameter specimen for the Self-Expanding casing configuration, pictured in Figures 1 and 2 below, was characterized by a maximum outer diameter of 26.67cm. and minimum inner diameter of 22.94 cm. in its stress-free as manufactured condition. Its effective outer diameter of 26.09 cm. and the effective inner diameter of 23.57 cm. yield an effective structural thickness of 1.27 cm. for the coupon. The height of the coupon, measured normal to the X-Y Plane (i.e. in the Z-direction) of Figures 1 and 2 was set at 1.27 cm. The coupon was proposed as being manufactured from 4140 steel and specified to be cut with a .0127 cm. kerf.

Discussion With Regards To Solving the Section-II Problem

There are several conclusions that can be drawn at this point with respect to the structural performance of this class of device (i.e. interleaved Horse Shoe type cross-section) in a Self Expanding Tubular application.

1. As would be expected, all configurations exhibited predominately elastic response throughout its range of deformation.

2. The compression and expansion of the device occurs in such a manner that its deformation is largely self-locating between leaves (or layers).



Sample Modeling Printout of High-Pressure Collapse Stress

3. The nonlinear analysis demonstrated *theoretically* and *structurally* that no reason prevents a variety of securement and sealing mechanisms to be incorporated in designs of this class.

4. Due to the large amount of sliding inherent in this system, friction effects can be expected as factors in any binding occurring on opening of the device. This is a serious issue since it is paramount that this-type device exhibits a stable and reliable tendency to open.

5. As would be expected as a limitation of the design concept, the geometric discontinuities (i.e. gaps) provide for the development of stress concentrations that can lead to the development of plastic hinges on further loading, a factor that can potentially inhibit the structural performance of this system if not properly accounted for.

6. High-pressure uses can be applied to the technology.

7. The technology is directly scalable by diameter.

Conclusion

Presented in Section-II is an evolution of analytical design work and rapidly progressed design capabilities. As occurred regularly during design phases, significant leaps in operating refinements and technical capabilities led to performance which was better than originally proposed. Continually higher standards became expected, culminating in 69 MPa (10-ksi) predictions. It was also clear that the continually improving design would require that the project be altered in order to accommodate both those benefits, while remaining on schedule in terms of subsequent deliverables. Accordingly, the slight change was presented to DOE, which simply did not seek terminus to design and materials development tasks.

Detailed Design of the Initial Laboratory Test and Field Prototypes

The design of the casing prototypes was then based on theoretical and basic testing and considerations generated by the primary design stages. Additional design details included anti-collapse details; anti-burst; over-expansion limiters; anti-spring-back features; longitudinal alignment geometry; controlled securement, shear-pin sub-systems; and various sealing methods and mediums.

III. **Fabrication & Testing**

Section-III discusses two major deliverables for the project – fabrication of various Prototypes and their deployment system to be used for formal testing and field deployment purposes, and for the actual mechanical testing operations. Construction of the delivery and expansion initiation system are included in these activities. The research questions involved for this section, first, are centered around discovering and adapting feasible machining processes which are applicable to the high-yield materials, high-tolerances, and other requirements in order to manufacture the technology. A parallel study regarding commercial manufacturability was also performed.

Experimental Methods

Because the section activities were construction and straightforward laboratory testing operations which, by their nature are minimal with regards to experimentation, the corresponding comments are limited. Basic data in the form of testing result points are provided. For construction purposes, tolerances were established to simply confirm that the final tubular structure dimensions were within a few percent of designed dimensions. Testing related experimental methods simply incorporate the best of available standards and practices for mechanical testing and downhole tubular development. There are few directly established testing standards applicable to conventional expandable tubulars. There are no directly established standards for self-expansion.

The two major activities, construction and testing are presented, as follows:

Fabrication

Overall fabrication activities consisted of three types: coupon, full-laboratory specimens, and field prototypes. Because many aspects of higher-level coupon samples, the lab specimens, and the field prototype are identical, differing only by length, each major construction phase is presented here in one section.

Fabrication of the technology consists of five steps:

- Forming
- Assembling

- Joining
- Compressing
- Sleeving, also packaging

The manufacturing development can be viewed as adapting specialty applications for forming, cutting, joining, etc. For project execution purposes, and in order to reconcile the fabrication processes with the structure of the commercial manufacturing feasibility studies, a detailed manufacturing plan was generated and continually updated.

Although subjected to evolving designs and dimensions, the basic structural and operating dimensions built were as follows:

Dimension	**Min.**	**Max.**
OD (relaxed)		4.180" / 4.300"
OD (operating)	3.920"	4.170"
OD (operating with elastomer)	4.0"	4.25"
OD (collapsed) nom.		3.034"
OD (collapsed w/ elastomer) nom.		3.154"
Wall thickness (single leaf)	.036"	.036"
Wall thickness (operating state)	.184" (5 leaves)	.258" (6 leaves)
Thru bore diameter(operating)	3.404"	3.654"
Specified clearance between collapsed and operating ID.	.25"	
Internal drift diameter	3.284"	
Overall casing length		10 ft.

General dimensions of the casing prototypes. (Convert Inches to Cm.: multiply by 2.54)

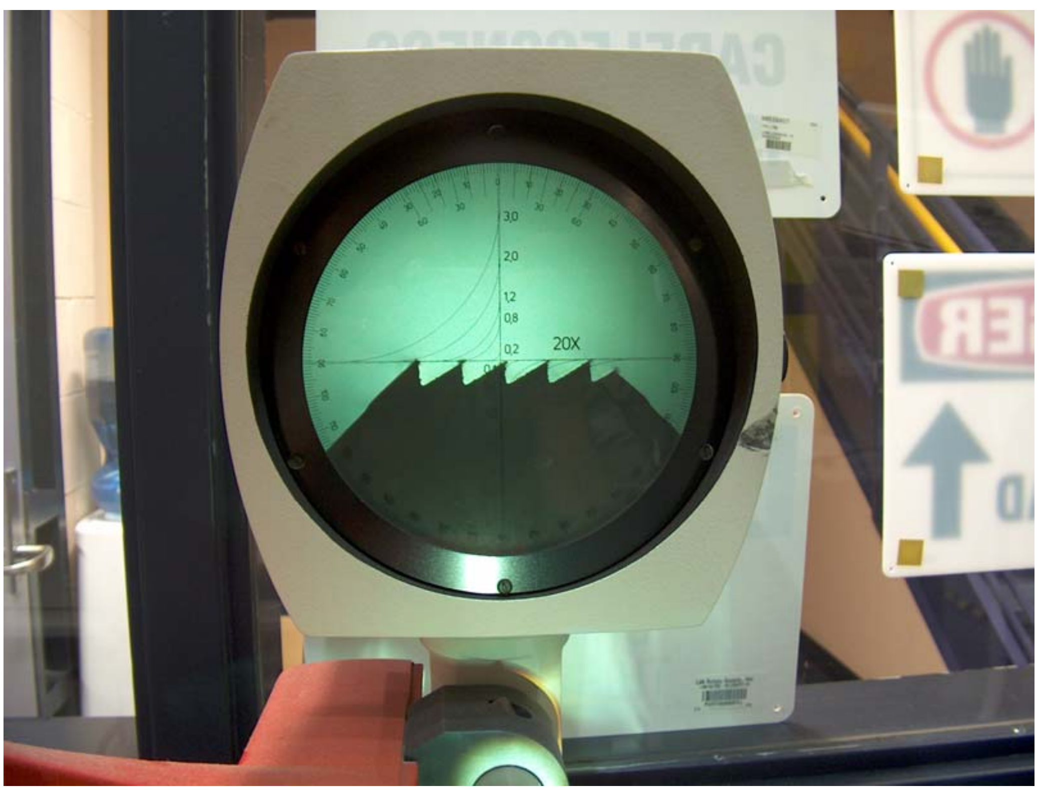
Descriptions and images of each fabrication step are discussed:

Forming

Shaping of the casing leaves' irregular symmetry in a high-yield material was performed by use of high-tonnage stamping press, or break-forming process, as shown below. Because of the varying leaf shape and span in excess of 180◦, a standard shaping die could only be partially useful. The leaf shaping process then became three steps: general shaping by use of the die and press; local shaping by use of discrete press-hammer which would fit within the >180◦ shell; and general, final reshaping by use of the primary shaping dies.

The forming activities also included application of early-form surface texturing, so as to assist with various aspects of the device integrity. A tungsten carbide die cross-section is shown as viewed through a comparator magnification device. Application of approximately 36.29 Tonnes (40-tons) force across 1.29 cm^2 will cause formation of uni-directional surface features, on .0365 cm. (.025") centers.

Original 152 cm. (5-foot) Shaping Dies and 122-tonne Press.



Tungsten Surface Tooth Detail.

Assembly

Handling and assembly of the long casing members into a close-tolerance mechanism proved a difficult process in the absence of precise jigs' particularly as temperature changes occurred during manufacture. An initially complex fixturing scheme became a simple alignment of holes precisely placed into leaf members. The alignment holes were then temporarily secured by use of steel dowels and spot welds.

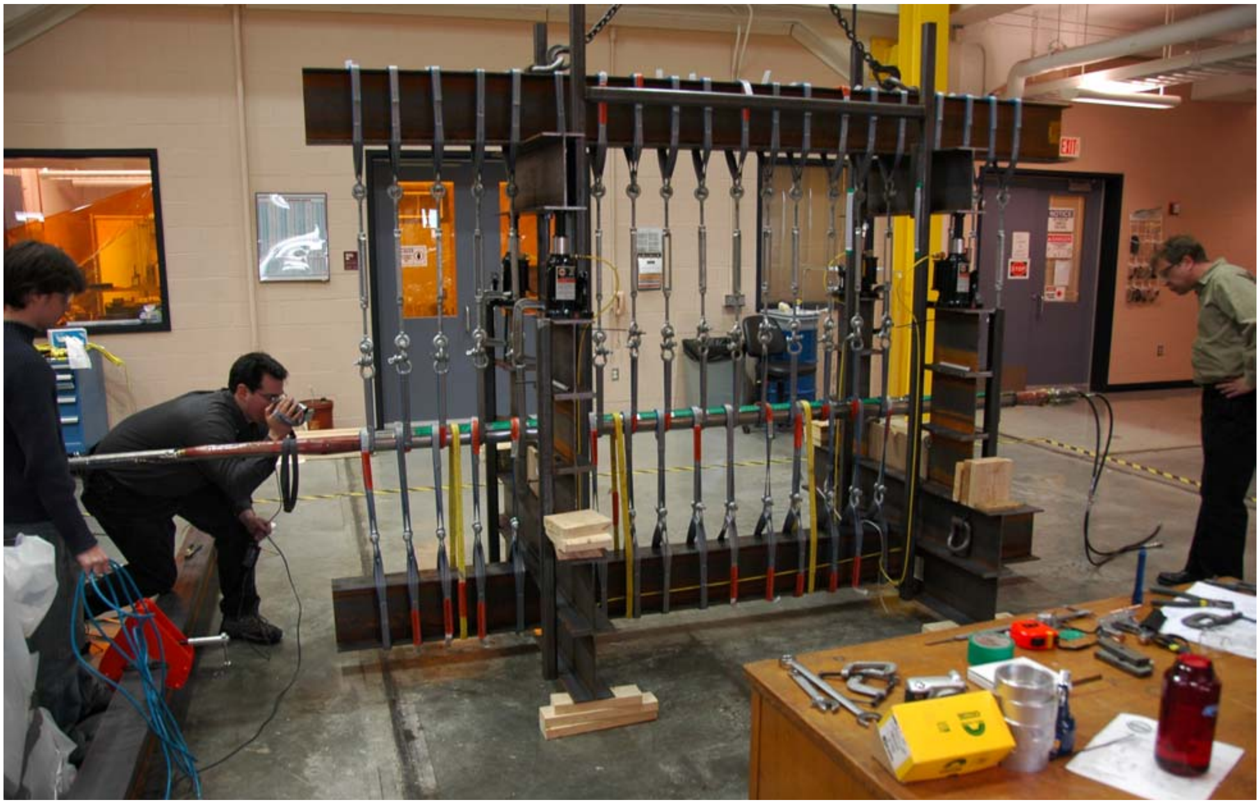
Joining

Most prototype specimens only required limited amounts of final joined condition. Accordingly, a basic, non-feed TIG weld in stitch form was used. With appropriate spacing and quantity of welds, only torsion and collapse related stresses indicated needs for anything further.

Stitch welding of prototype by TIG.

Compressing Casing Prototypes

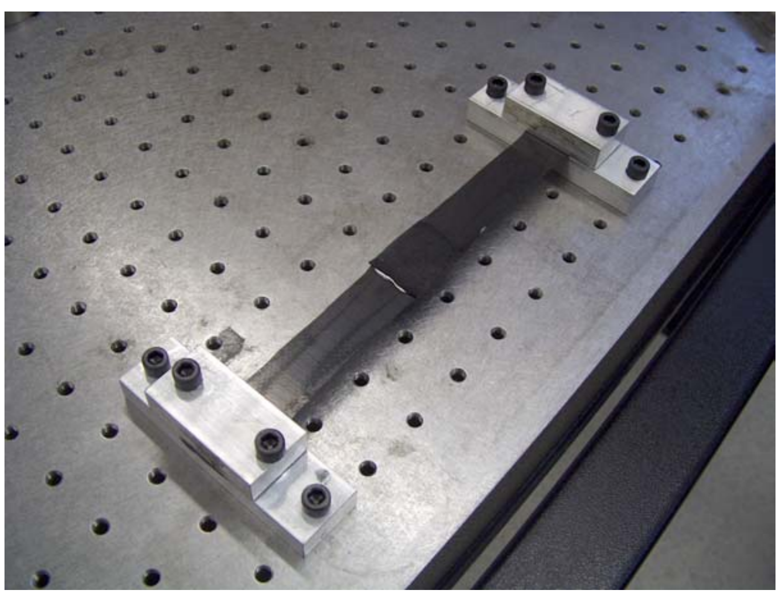
Because the casings were constructed in their expanded diameter form, a custom-built, high-force hoisting device was designed and constructed for the project. As shown below, an I-beam, frame construction is raised, causing tension to the looped lifting straps. The system was built to 72.5 tonnes force capability. The frequently placed straps are each adjustable for tension by use of simple turnbuckle. This allows for even compression of the casing device. Once compressed, the casing securement features are welded thereby stabilizing the RIH diameter.



Compression apparatus reducing the 10.92 cm. (4.30") casing to approximately 7.62 cm. (3.00").

Sleeving

The final construction step was application the external pre-load/sealing material.



Long-term testing of elastomer material and joint while subject to 300% strain.

For prototype purposes, the elastomer sleeve was a thin layer .081 cm. (.032") of ester-based polyurethane while in the unstressed state; the average stretched thickness was estimated at .0635 (.025") when the casing the 10.16 cm. (4.00") operating expanded state. There were two possibilities towards applying the sleeve. First, commercially available tubing with an ID of 8.255 cm. (3.25") can be fit over the collapsed casing. Alternatively, the sleeve can be applied in a sheet that is wrapped around the outside and adhered to the casing using a polyurethane based adhesive. The latter approach was taken, as shown in the following three photos:

Joining elastomer sealing material and metallic casing.

304 cm. (10’) Field Prototype with elastomer material applied.

Manufacturing Studies

A fundamental commercialization criteria for the new technology is its ability to be technically and economically manufactured. As a completely new technology, the issue was made significant to the extent so as to require a deliverable for the project. A single deliverable to demonstrate viability was proposed. The actual progression of the project lead to a two-phased delivery for the study. The first stage analyzed major manufacturing components, the second added detailed design features. For both phases, conventional pipe diameters were used which represented median industry usage. The study and manufacturing systems are each scalable for microhole diameters.

Summary of Topics for Manufacturing Analyses – Phase - 1

- Major Processes
- Fundamental Components
  - Tube
  - Surface engineering
  - Connectors
  - External sleeve
  - Packaging & storage
- Equipment
- Plant Layout
- QC
- Capital Requirements
- Unit Costs
- Sensitivities
  - Footage volume
  - Tube length variations
  - Changes in leaf thickness
  - Alternative joining

The factory design is capable of 73,152 meters – 109,728 meters (240,000' – 360-000') annual output of heavy-wall 24.45 cm. (9-5/8") casing. Output for microhole size casing would be approximately double. The preliminary phase showed excellent manufacturing feasibility at less than 200% over standard, non-expanding casing. The projected accuracy of cost estimates was 75% - 80%.

Augmented Details for Manufacturing Analyses – Phase - 2

Refinements to the technology's design provided substance towards manufacturing items previously only estimated. The refinements considered applications properties substantially higher than originally contemplated for microhole purposes. Several evolved inputs were added to the second-phase study, as follows:

- Substantially higher alloy materials
- Profile shaping of materials
- Surface engineering, with multiple options
- 110 MPa (16-ksi) carbon composite sleeve layers
- Additional personnel and facilities for sleeve manufacturing
- Details as to device leading edges

The impact of improved design features increased the costs, adding some 40% to costs, or estimated total of 200% - 250% over standard pipe. Costs are less than standard expandable pipe.

Results, Discussion, and Conclusions of Manufacturing

The study utilized the expertise of a manufacturing and related process control development specialist. The study approach process was by industry survey for costs; application of known process rates; and application of surveyed and known capital costs and, expert plant layout. Because the processes to manufacture the new technology are very similar to standard methods, the technical feasibility for all aspects of the self-expanding tubular is considered quite viable. The feasibility includes numerous options for each major technical step. Further, any length or diameter of tubular can be economically manufactured due to scalability.

Deployment Mechanism

In order to deliver the casing device into a test well and actuate it once in place, a pressurized-friction system was designed and constructed. The original design criteria provided for the ability to activate a casing device at while at maximum MHT depth and column of brine fluid. The parameters were later changed to reflect normal test facility well conditions.

The constructed design of the delivery deployment mechanism is shown below. The basic functions of the deployment mechanism are to a) deliver the casing in the collapsed state to the specified depth; b) assist expansion of the casing once located; and, c) controllably release from the expanded tubular. The main features of the design are:

- Lay-flat hose design surrounding a central pipe. The lay-flat hoses enable the device to be inserted into a collapsed casing and then expanded as fluid enters the tubes from the manifold at the top of the device.

- An auxiliary line is required to pressurize the device to ensure clean fluid is entering and provide better pressure control.
- The design allows for the use of a rupture disc on the bottom of the device or a second auxiliary line to the surface with a shut off valve to relieve the pressure.
- A check valve is incorporated into the system to maintain pressure at the bladder regardless of any surface conditions (malfunctioning pump, break in the auxiliary line, etc.).
- The primary means of relieving internal pressure after casing expansion is to purge the system of water through a secondary auxiliary line.
- The secondary means is with a safety rupture disc at the bottom of the device.

304 cm. (10') Inflated Bladder Arrangement.

Results and Discussion

Development of the initiating equipment was limited by the tight clearances and obviously small parts required for use inside of a compressed microhole casing. Verifying acceptable performance of manufacturers' claimed pressure ratings required several experimental constructions. Service life for the selected material, while relatively low grade in comparison with materials under development at later phases of the project, was in dozens of cycles. The initiating system proved a reliable tool for each of its intended functions and performed without issue during lab tests, pre-field testing, and actual field testing.

Pre-Testing Operations

Functionality of the delivery-initiator was established by repeated operations in the lab while simulating full field deployments for 152 cm. length prototypes. The expansion forces showed highly-energetic, loud and violent initiation while subjected to only fractions MPa bias. Even though some specimens were repeatedly compressed and expanded, all expansion was to full drift. Films were made of the process during many stages of in the development. The pre- and post-expanded conditions of casing and bladder tubings can be seen following:

152 cm. (5') Pre-Expanded Casing Affixed Over Initiator.

Expanded Casing Condition With Deflated Bladders.

Laboratory Testing

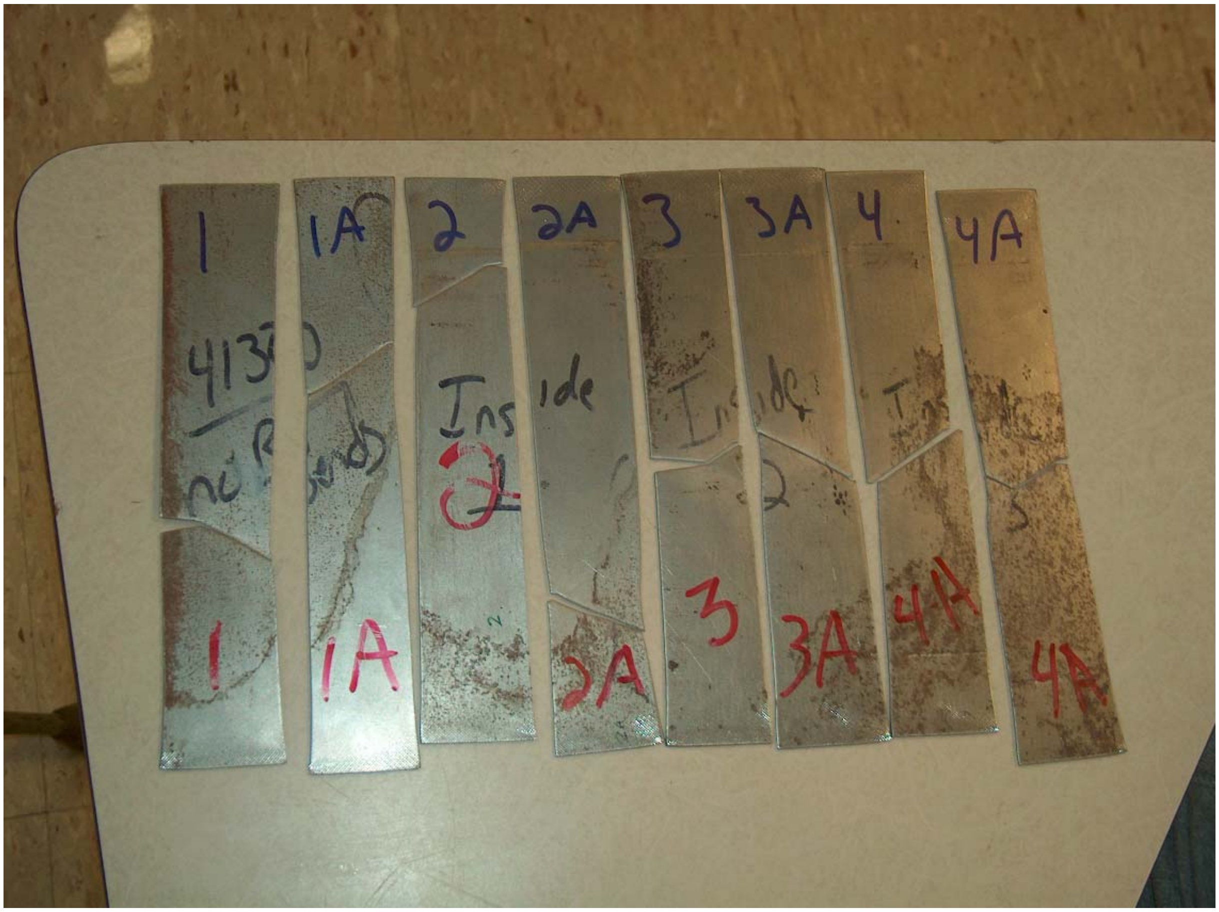
Mechanical testing was performed at four different levels. These were as basic materials testing; coupon testing; and formal, full-length laboratory testing. The fourth testing type was the system pre-test just discussed above.

Baseline Materials Testing

Standard tension tests were applied to specified thicknesses an early material selection. An example operation is shown below:

Standard Tension Testing.

Although the properties of the material are well known and published, the purpose was also intended to impart various bending and irregular stresses against the material. Various parallel and triangular stresses were applied in addition to the tension which simulated various in-hole at different states of expansion. The ruptured results are shown:



Shear Planes at Varying Combined Loading.

Full-Laboratory Testing

Formal testing of the prototype expandable casing design developed in a previous phase. The consultant fabricated seven – 91 cm. length test specimen assemblies. With regards to any influence by end effects, for expanded state test purposes, the L:D was 9:1, for compressed state tests, the L:D was 11.6. A seperate test article was used for each test. The test articles were manufactured using the same materials, processes and design used for the final field prototype. Each test article measured 8.128 cm.(3.20 in) diameter when compressed and is 10.16 – 10.8cm. diameter after expansion. Three tests were performed to evaluate the strength of the test articles in the compressed state (tension, buckling, and torsion). Three other tests were performed to evaluate the expanded state (collapse, burst, and annular sealing). Primarily, only single data points were taken as a budgeted limitation. Testing was performed generally only as incomplete systems, without the external sleeve component and other details in some cases.

Because testing protocol for expandables is unsettled in the industry, only the highest or most appropriate of various mechanical and drilling engineering practices could be employed. Additionally, specifications and some of their testing basis were provided by a major energy producer highly familiar with expandable tubulars development. Some example predictive formulae are shown for the more important radial strength properties. Generally, the most conservative of these and other were used in order to provide measures of testing objectives. Sample formulae are:

Equation 1 - Hoop Stress

$$\frac{\sigma_{Y.S.}}{F.o.S.} = \frac{p \times r}{t}$$

Equation 2 - Timoshenko

$$P_e^2 - P_e * \{\frac{2\sigma_{Y.S.}}{[\frac{D_0}{t}-1]} + P_{CR} * (1 + 3e * [\frac{D_0}{t} - 1])\} + \{\frac{2\sigma_{Y.S.}P_{CR}}{[\frac{D_0}{t}-1]}\} = 0$$

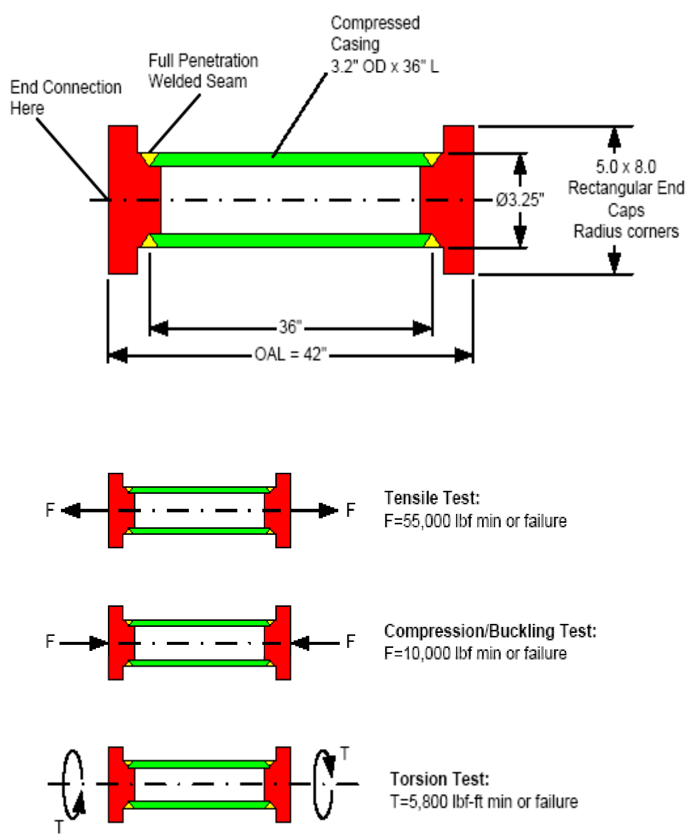
$$P_{CR} = (\frac{2E}{1-\mu^2}) * \{\frac{1}{(\frac{D_0}{t}-1)}\}^3$$

Equation 3 - Tamano

$$P_c\,ult = (p_e + p_y) / 2 - \{(p_e - p_y)^2 / 4 + p_e p_y H\}^{1/2}$$

A simple schematic of compressed state testing with generalized depiction of test fixturing hardware follows (conversion equations provided previously):

Test Descriptions



Further test descriptions and results are presented:

1. **Tensile strength** criteria - industry supplied performance for MHT casing recommended a minimal ability to suspend a 914 meters (3,000') assembly, with 11.34 tonnes (25,000-lbs.) safety margin, or a total of 22.68 tonnes (50,000-lbs).

Tensile testing of the casing comprised one 91.44 cm. (3- ft.) long casing in the compressed 8.153 cm. (3.21- in.) OD state. To enable tension testing, the end-caps were welded, beveled casing ends. The test article was attached at one end to the bottom of the steel frame of the testing apparatus. The other end was attached to a Baldwin type L-100, 34 tonnes (75,000 lbf.) capable load cell. The load cell was connected to a Vishay 2120A strain gage conditioner and 2110 power supply. The output was recorded on an HP7090A Measurement Plotting System. The load cell was mounted above a 27.22 tonnes (60,000 lbf.) hydraulic piston which was located above the top frame member of the structure. Attached to the ends of the casing was a measuring tape used to monitor length change in the casing. The hydraulic piston was pumped up to 27.22 tonnes (60,000 lbf.) The tests were recorded using a standard resolution camcorder system, during which no significant change was noticed in the casing diameter or the overall length.

Result - Sustained acceptable tensile load without recordable change.

2. **Compression/Column Buckling** criteria - industry supplied performance for MHT casing recommended column loading to 4.54 tonnes (10,000-lbs.) An auxiliary recomended loading scheme adds compliance while deflected laterally to upwards of 1%.

Buckling/Axial Compression testing of the casing comprised one 91.44 cm. (3-ft.) long casing in the compressed 8.153 cm.(3.21- in.) OD state. To enable column testing, the end-caps were welded to beveled casing ends. The test article was attached at one end to the bottom of the steel frame of the testing apparatus. The other end was attached to a Baldwin type L-100, 34 tonnes (75,000 lbf.) capable load cell. The load cell was connected to a Vishay 2120A strain gage conditioner and 2110 power supply. The output was recorded on an HP7090A Measurement Plotting System. The load cell was mounted above a 27 tonnes (60,000 lbf.) hydraulic piston which was located above the top frame member of the structure. Attached to the ends of the casing was a measuring tape used to monitor length change in the casing. The hydraulic piston was pumped up to 20.4 tonnes (45,000 lbf.) The tests were recorded using a standard resolution camcorder system, during which no significant change was noticed in the casing length or lateral deflection.

Result - Sustained acceptable column load without failure or recordable change.

3. **Torsion testing** criteria - industry supplied performance for MHT casing recommended a range of compliance of 2035.5 nM (1500-ft/lbs.) as a minimum; 4071 nM (3000-ft.lbs.), as an artificially high median value; and >6107 nM (4500 ft.-lbs.), as an exceptional torque rating.

Torsion testing of the casing comprised one 91.44 cm. (3-ft.). long casing in the compressed 8.153 cm.(3.21- in.) OD state. To enable testing, the end-caps were welded to beveled casing ends. The test article was rigidly attached at one end to a steel right angle plate secured to a table.

The other end of the test article was secured to the mounting plate of an 8142 nM (6,000 ft-lb) rotational load cell that was mounted to a Parker Rotary Actuator that is controlled by an MTS 442 Controller. The output from the load cell was recorded using an HP7090A Measurement Plotting System. The hydraulic pressure was increased to the unit slowly increasing the torsion stress seen by the casing. A standard resolution video recording device taped the event.

Result – a premature fixture-weld failure occurred when torque reached 3379 nM (2490 ft-lbs.) The failure lead to the external leading edge fully releasing and allowing the rotary stage applying the torque to the casing to rotate throughout its full travel of 270°. Since the failure was actually premature due to fixturing practices, post-testing summaries included performance estimates attributable to improved welding practices at the fixture ranging between 10% and 30%. Extracting a mean improvement of 20%, the presumed torsion compliance value to at least 4342 nM (3200-ft./lbs), or above the high-median expectation.

4. **Burst testing criteria** - industry supplied performance for MHT casing recommended a range of compliance of a minimum, 13.78 MPa (2000-psi) to > 68.95 MPa (10,000-psi) as an exceptional rating.

Burst testing by hydraulic and mechanical methods of a 91.44 cm. (3-ft.) long casing began as compressed to a diameter of 8.153 cm.(3.21- in.). The casing was expanded to 10.24 cm. (4.03-in.) diameter using the field inflation unit. The test purpose was to evaluate and improve early and only partly constructed design features of the metallic components only. Design and construction of a substantial composite sleeve component was ongoing. In the absence of a substantial pre-load sleeve, a series of aluminum rings was used to constrain the expansive force, preventing over-expansion. The rings located at each end of the specimen were made of stainless steel and welded to the ends of the leafs of the casing. The rings located at each end of the specimen were made of stainless steel and welded to the ends of the leafs of the casing. Packers, rated to 34.47 Mpa (5,000-psi), and placed at each end and inside the casing were slowly pressurized.

Result – the pre-load sleeve not available at the time of the metallic tube test was tested to 110 MPa (16-ksi). The incomplete, basic-only feature to resist burst stress yielded at an acceptable load, while the supported sections remained unaffected.

5. **Collapse testing** criteria - industry supplied performance for MHT casing recommended a range of compliance of a minimum, 10.34 MPa (1500-psi) to nearly 96 MPa (14,000-psi) as an exceptional rating. The lower value is a frequently used expectation for CT or MHT applications.

Collapse testing of the 91.44 cm. (3-ft.) long casing began as compressed to a diameter of 8.153 cm.(3.21- in.). The casing was expanded into a soft, gum rubber tube with a .3175 cm. (0.125") wall and nominal ID of 10.16 (4.0-in). The rubber tube was provided no auxiliary mechanical integrity to the sample and was used only to assist high-pressure sealing. The device and fixtured assembly was placed inside of a large-volume, 103 Mpa (15,000-psi) rated pressure chamber for testing.

Result - the pressure in the chamber was slowly increased and monitored resulting in a consultant acceptable load value. The assembly was removed from the pressure chamber and inspected for damage. The casing failed at a value approximately, but less than the peak. Related testing and evaluation was also performed as the annular sealing function tests described below. Adjusting for the typically known effects of confinement, a similar acceptable collapse value of was realized as an additional data point.

6. **Annular sealing** criteria - industry supplied performance for MHT casing recommended a range of novel external, self-sealing abilities of a minimum, 10.34 MPa (1500-psi) to nearly 96 MPa (14,000-psi) as an exceptional rating.

Annular sealing testing of the 91.44 cm. (3-ft.) long casing began as compressed to a diameter of 8.153 cm.(3.21- in.). The casing was wrapped with a 1/16 " polyurethane rubber wrap prior to being expanded into the sealing fixture. The sealing fixture was fabricated out of a stainless steel pipe with a nominal ID of 10.16 cm. (4.0"). Elbow fittings were welded to the outside of the pipe to allow a side pressure be applied to the casing and polymer wrap. The flow thru this .635 cm. (¼") fitting was restricted to a .3175 cm. (1/8") port into the stainless pipe. The polymer was affixed to the casing using the same procedure shown in construction of the field specimen. Deployment of the casing occured at a very minor force, approximately 1.9 Mpa (275psi). Six phases of the annular sealing test were conducted. It should be noted that, although passing, all tests were run at a disadvantage due to the presence of a seam void in the sealing material and non-smooth casing surfaces of the prototype casing itself due to cut-in features. Tests were conducted both with and without assistance of internal pressure.

Result – the low initiation force led to an artifically lowered sealing value of 4.83 Mpa (700-psi), with the breach occuring at the seal-seam. A series of pressurization and release activites took place which produced the objective sealing rating. Dynamically imposed, minor amounts of internal force were then performed which led to generating properties that exceeded the 34.47 MPa (5,000-psi) test pump capability. Both the static and dynamic efforts revelated a normal 3.5X – 5.5X seal rating made.

Annular Sealing Test Setup to 34.5 MPa (5,000-psi).

Conclusion

Although the device design that was tested had been superseded at the time of testing, the results ranged from acceptable to excellent. The acceptability was notable in that testing occurred only as an incomplete system, serving to evaluate basic structure, generally with only 60% of components or full details present. Some tests were not specified as high with regards to oil field standards because the microhole and coil-tubing references require lesser values. The properties shown by some tests exceeded the testing equipment capabilities. Consequently, not all failure modes were discovered because no remarkable change occurred to the specimens. Similarly, the ideals contemplated by the technology were shown as not optimized at the early stage, but each such mechanical effect was indicated to be present. Provided full construction, features, and components, the performance of the self-expanding devices can only be correspondingly increased.

IV. 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 same delivery system, initiation processes, and hardware as reported in earlier report sections were duplicated for the field operation. Various in-hole tests were performed during a later period, as discussed below. The in-hole tests were performed in excess of project or contractual requirements. Placement into the well is shown:

10' Field Prototype Set Over Test Well.

Although not contractually required, the demonstration program later provided an actual mono-diameter installation in the form of a further embodiment self-expanding tubular.
The field demonstration consisted of basic steps including:

- Drift testing of demonstration well
- Verification of prototype casing specified compressed diameter
- Caliper and tallying of RIH assembly
- Actuation of casing device at approximately 500-psi
- Retrieval of delivery and actuation equipment
- Post-expansion drift testing
- Downhole video survey

Pre-installation diameter verification is shown:

Field RIH diameter gauge. Noting gap between gauge and device and accounting for elastomer sleeve thickness reveals an actual compressed steel tube diameter of 3.04".

Expansion of the Field Prototype

The pressure in the expansion mechanism was slowly raised until the casing was deployed. At approximately 3.59 MPa (520-psi) a large "POP" was heard from the casing. As reported previously during laboratory pre-testing, the expansive moment occurs at <170 milliseconds. The very quick effects to the delivery pipe assembly, including both longitudinal and torsional movements, are shown occurring over a .270 millisecond period in seven photographs, collectively as the photograph series, and marked with time nomenclature:

Once expanded, the initiating pressure at the gauges dropped to approximately .69 MPa (100-psi). The inflatable delivery system bladders were then purged of all water by use of pressurized air. This reduces the pressure in the system to near atmosphere and the bladders become completely deflated. The expansion mechanism was then hanging freely from the rig and was retrieved, while the casing remained clad to the well.

00:00.47 **00:00.53** **00:00.60**

At :00.67, the pipe assembly twists approximately 5° counter-clockwise and falls slightly. At :00.73, the pipe lunges slightly towards the camera. At :00.80, the noise-concussion felt at the surface causes the camera operator to twist the view slightly counter-clockwise.

00:00.67 **00:00.73** **00:00.80**

At :00.87, the camera operator moves the view up and left, while a vibration propagated through the pipe assembly, causing the pipe to go out of focus. At :00.94, the pipe lunges towards the camera while falling, or bouncing a small amount.

00:00.87 **00:00.94**

Post-Expansion Drift Verification

Two drift related tools were constructed to be used as post-expansion verification. The primary steel drift tool was custom-sized, in excess of API length, and made to the minimum

Steel drift and tapered wax device (Shown upside-down).

Lowering the drift verification tool into the well.

objective. The piece was made in fluted form so as to eliminate hydraulic surging or sticking issues since the drift testing was to occur in a well environment. A second tool, a tapered wax impression device was built in order to obtain the drift dimensions without becoming stuck in the event that the minimum diameter was not achieved during the primary expansion. After the successful casing deployment, a 76.2 cm. (30”) length drift tool was lowered through the casing. The 8.81 cm. (3.46”- 3.48”) diameter tool passed through the casing without incident. The impression device was not used.

Insitu Set Condition

As demonstrated by mechanical drift and video survey (partially shown below), the expansion process was completed in excess of the minimum drift objective. No abnormalities with regards to full-expansion, ovalization or other were visible during the original or subsequent inspections. The transverse, top-section, as-set condition is shown:

Top of Expanded Casing Set Into 4” Demonstration Well.

Post-Demonstration, Insitu Testing and Evaluation

Several basic effect level evaluations were made to the set tubular during a subsequent demonstration which featured setting the contractor’s other MHT technology, later run and expanded through the original expanded casing tubular. The evaluations, performed in excess of contractual requirements, were as follows:

1. **(Re)-Inspection** -A second set verification of correct device expansion and device condition was performed to confirm the observations previously conducted. A follow-on video

recording showing good condition of the device is shown as recorded with downhole video equipment.

2. Drift Verification - Was performed during the original deployment, but re-confirmed visually during a second downhole video survey.

3. Evaluate ID Variations - No variations in the expanded ID were shown by either the original or the subsequent downhole video recordings.

4. Vertical Set Integrity, Secondary Activity – Although not a high design priority, the estimated casing adherence set was estimated to be substantial; no movement of the device occurred during any subsequent validation or RIH operations during the demonstration day. The original demonstration well environment was fluid-less. A force estimated at slightly in excess of 2.268 tonnes (5,000-lbs.) caused axial movement of the set casing.

5,000-lbs force applied to expanded liner by 8.89 cm (3.5") OD flush-joint drill pipe.

5. Internal Yield - A basic Braden-head type of pressure test to 10.34 MPa (1500-psi) was performed with fresh water as the medium. The test was also to act as an evaluation of pressure maintenance, as might be required for use in some casing patch applications.

Conclusion

The demonstration effort was performed with excellent results, serving as the culminating milestone for the project. The fundamental compression and elastic recovery previously demonstrated in the laboratory was repeated in a demonstration well. The objectives for the fundamental drift diameter were achieved. Similarly shown present were basic integrity and set over a short period consisting of months. Because the expansion forces were small by oil field standards, the logical progression would be to substantially increase forces in order to evaluate resultant effects to the casing functionality.

V. Technology Transfer   Experimental methods; Results and discussions; Conclusion

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 two months 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. The nearly exclusive interests in the technology development is from sources outside of the country. 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

Technical Applications:

- Remedial, patches for well repair
- Re-entry operations for Alaska CT
- Extension of deepwater exploratory wells not reaching TD
- Non-microhole applications diameters
- Subsidence compliance
- Water shut-off, squeeze elimination
- Cement elimination
- Through-tubing applications
- Stranded resources applications
- Coil tubing
- Coal bed methane

Conclusion

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.

National Energy Technology Laboratory

626 Cochrans Mill Road
P.O. Box 10940
Pittsburgh, PA 15236-0940

3610 Collins Ferry Road
P.O. Box 880
Morgantown, WV 26507-0880

One West Third Street, Suite 1400
Tulsa, OK 74103-3519

1450 Queen Avenue SW
Albany, OR 97321-2198

2175 University Ave. South
Suite 201
Fairbanks, AK 99709

Visit the NETL website at:
www.netl.doe.gov

Customer Service:
1-800-553-7681