Draft Report

On

DOT SBIR PHASE II CONTRACT DTRT57-09-C-10031

Development, Design and Testing of Optimized Soft Crack Arrestors

Emc^2 Project Number 09-G78-01

to

US DOT- SBIR Office

Volpe Center

Cambridge, MA

USA

by

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December 2012

EXECUTIVE SUMMARY

The purpose of the Phase II Small Business Innovative Research project was to evaluate the design and ability of a “Soft Crack Arrestor” (SCA) device to stop unstable ductile crack propagation in large-diameter gas pipelines. If the crack-driving force is high enough, mechanical crack arrestors are a viable alternative to crack arrest by toughness of the pipe body and are allowed by ASME B31.8 code.

The unique nature of the SCA device lies in its design which utilizes both strength and ductility of the composite arrestor material to stop unstable ductile axial crack growth and also prevent a pipe ring-off failure mode.

The research during this Phase II project included development of a fiber that possessed the requisite strength and ductility properties to perform as needed for the SCA application and also be low enough in cost to be competitive and attractive for industry use. Additionally due to the high costs associated with performing full-scale burst testing needed to prove concept and design of the SCA, industry pipeline members were petitioned to contribute materials and other resources to complement government funding available to carry out the project but in particular to help pay the costs of the testing activities. We were able to secure donated pipe materials from a member of the pipeline community but other contributions (welding, end caps, transportation of test items, wrap SCA onto test pipes, etc.) were not achieved. Therefore, the funds to cover these items were extracted from project funds which resulted in a major change in full-scale testing.

Pretest analyses were performed to aid in the design and location of the SCA array along the test pipe. Wrapping of the fiber onto the pipe to form the SCA array was performed by our selected composite wrap contractor. Finally, full-scale testing was performed at our Mojave, CA site by a cadre of subcontractors (most of whom had been used by us in previous testing) to aid in the significantly difficult tasks involved in performing full-scale testing.

The first full-scale burst test was conducted in mid-April 2012 at the Mojave site a “Soft Crack Arrest” was achieved, i.e., there was no ring-off fracture of the pipe material at the edge of the arrestor as occurs with steel or fiberglass arrestors. The test temperatures were higher than desired, which affected the fiber strength so that only the longest SCA worked. Nevertheless, even this arrestor was shorter than steel or fiberglass-based arrestors used in past full-scale validation tests. The efficiency of the “Soft Crack Arrestor” comes from the fact that the ductile fiber used and developed for this application allows the crack to propagate under the arrestor and more of the crack-driving force is taken up by the entire arrestor rather than just the front edge of the arrestor.

Subsequent full-scale testing is highly recommended to further validate the SCA design process and provide encouragement for use in construction projects by the pipeline industry.

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1 INTRODUCTION

High-energy pipelines are susceptible to unstable axial ductile crack propagation if the crack-driving force is larger than the material ductile fracture resistance. The potential for axial crack propagation is greater for large-diameter gas pipelines, pipelines operating at higher stress levels, i.e., 80% SMYS, and pipelines transporting rich natural gas, high vapor-pressure liquids such as Y-grade and liquid CO2 pipelines. If the crack-driving force is high enough, mechanical crack arrestors are a viable alternative to crack arrest by the toughness of the pipe body and are allowed by the ASME B31.8 code.

As discussed in our Phase II proposal for the Soft Crack Arrestor Project, the need for this particular type of device lies in the fact that other arrestor types, e.g., steel sleeves, fiberglass wrapped products, etc., do not possess sufficient ductility to prevent a pipe ring-off failure mode when subjected to a propagating unstable axial crack. Hence, the need for an arrestor device that possesses both strength and ductility to stop an unstable propagating axial pipe crack.

2 OBJECTIVE

The objectives of this Phase II SBIR Project were to:

1) Design the SCA for conditions of proposed full-scale burst testing, and
2) Evaluate and verify the SCA design through full scale testing.

3 PROJECT ISSUES

Critical for successful conduct of Phase II were contributions solicited from pipeline industry members. These contributions included the need for:

- Sufficient number of pipe joints (a minimum of three, 10-meter pipe sections),
- End caps (minimum of two),
- Cost of transportation of pipe sections from storage to SCA composite wrap contractor, and onto the Mojave test site,
- Winding of the SCA array onto the pipe test sections, and
- Cost of welding the pipe sections and end caps to form the final test specimen.

The costs associated with the (solicited) contributions from industry to support the testing activity as originally planned in the Phase II proposal were originally equal to the amount of funds provided by the government. As it turned out, the actual contributions provided by industry consisted of three 10-meter pipe sections and two 3-meter rings (pups) of X80-grade material, 48-inch diameter, and ~ 1 inch nominal thickness. Additionally, our industry partner agreed to pay for shipment of pipe sections and rings from storage to our selected composite wrap winder. However this meant that the other solicited costs (contributions noted above) would need to be covered by project funds. In order to conduct the full -scale burst test activity and remain within overall project funds, the following alternate testing activity was performed which consisted of conducting one ambient temperature test as a first test event as opposed to the two tests under temperature controlled conditions originally planned and proposed. Further, we planned to analyze the resulting experimental data, optimize the arrestor design further, and determine the affordable testing efforts that could be conducted in a second test activity. This alternate plan emphasized the need to conduct at least one successful full- scale burst test to verify the SCA concept and design process.

The following sections of this report are constructed according to the tasks described and proposed for Phase II but include the effects of our alternate plans for Phase II as necessitated by the lack of (needed) contributions from the pipeline community.

4 SUMMARY OF PHASE II TECHNICAL WORK

4.1 Task 1 - Optimize Selection of Fiber

In Phase I of this SBIR project, Emc² demonstrated that fibers existed that showed promise for having the requisite performance characteristics (strength and ductility) to satisfy the requirements of a Soft Crack Arrestor (SCA) device. That is, the arrestor device must be able to accommodate the radial load transmitted by a running axial crack in the pipeline and also stretch circumferentially sufficiently to avoid pipe ring off. The tradeoff between strength and ductility are the key items for a successful SCA design.

The challenge in Task 1 was to find a fiber manufacturer that could produce a fiber with the desired performance characteristics (strength and ductility properties) but also make a fiber at a low enough cost to be competitive and possess geometry desirable for the SCA application. The fiber of note in the Phase I work was no longer available (out of production and its replacement fiber was cost-prohibitive) so another fiber needed to be identified for the Phase II work. Working with a range of fiber manufacturers, we were able to find a manufacturer who was willing to develop a fiber that would meet the requirements for the SCA application. These development activities began in the spring of 2010 and culminated with delivery of about 1,500 pounds of production fiber in December 2012. From the Phase I fiber testing results, similar material characteristics of the fiber selected in Phase II compared well to those of Phase I. From our experience with thermoplastic based fiber materials, the response/behavior of the selected Phase II fibers would not be adversely affected by high strain rate loading conditions. Additionally, as discussed in Section 3.0 of this report regarding our alternate burst test activity, the selected fibers for the SCA would not be temperature sensitive for the ambient temperature conditions (+20C to +40C) planned for the full-scale burst test activity, and may have even higher strength properties for arctic applications without the loss of required ductility.

The production run of fiber for the SCA application was wound on 69 spools and each spool weighed ~ 25 lbs. Small quantities of fiber from each of the 69 spools were sent to the Emc² laboratory for testing to verify consistency of fiber performance measures (diameter, strength, ductility). The results of the laboratory testing at Emc² revealed that all but one of the 69 fiber wrapped spools satisfied the requirements for the SCA application.

The 69 spools of fiber were delivered to our selected composite wrap contractor in mid-December 2011. The one spool that was identified as not useful was sent back immediately to Emc² so that it would not be used to wrap any of the arrestors on the test pipe.

The fiber manufacturer absorbed all development costs for the final fiber product for the SCA application. The only costs to the project were for production of the fiber for the SCA application and its transportation (69 spools) to our composite wrap contractor.

4.2 Task 2 - Obtain Pipe Materials and Other Assets Needed for Full-Scale Burst Testing

A member of the pipeline community agreed to provide pipe material for a full-scale burst test activity and transportation of that pipe from storage to our selected composite wrap contractor. Discussions and efforts to obtain this pipe material from industry began in late 2009 and we finally were informed about the decision to provide the pipe material in January 2011. As such, this effort took about 15 months of calendar time and resulted in a significant delay in other previously planned project activities. Since the original Phase II effort was contracted to be a 24-month effort (June 2009 – June 2011), there was no way that we would be able to perform all necessary work to complete the project in less than 6 months, the time remaining after obtaining the pipe material via the industry contributor. Therefore, we petitioned the U.S.DOT PHMSA COTR in conjunction with the SBIR Volpe Contracts Office for a no cost, 18-month time extension (change the completion date to December 2012). This extension was granted in December 2010 and the project then had a 42-month (total time) duration.

Having obtained the most critical item (pipe material) from industry, we began to plan other necessary steps to conduct the full-scale burst test activity. The fiber to be selected for the SCA application was still in development in January 2011, so there was significant work remaining to complete that effort. As stated previously, the other items solicited as contributions from industry (welding of pipe sections, transportation of pipe sections, end caps, wrap of SCA arrays onto the pipe sections) were not obtained and the probability of getting all or any of these needed items seemed not high. We therefore had to restructure our Phase II activities to be able to meet the overall goals of the project within the (extended) time period and project funds.

As also discussed in Section 3.0 of this report, the lack of industry contributions set in motion the effort to estimate all unplanned costs to determine whether or not sufficient funds were available to cover the unplanned (additional project) costs and have funds to be able to conduct (at least) one successful full-scale burst test to validate SCA concept and SCA design process. Efforts over the next few months consisted of working with vendors and potential project subcontractors to estimate the unplanned costs and also understand timing of activities so that full-scale testing at the Mojave, CA site could be performed in the spring of 2012. As it turned out, the unplanned costs were estimated to be about $130,000 per test which allowed us sufficient funds to plan for (at least) a first full-scale burst test. However, this decision was based on our past experience and data from performing testing activities at the Mojave, CA site in the 2005 time frame. Therefore, we did work with vendors and subcontractors to begin generating the necessary assets (materials) for full-scale testing:

1. End cap contractor; Prepare two end caps and transport to wrap contractor
2. Composite wrap contractor;
    a. Receive, unload and store pipe material (as directed),
    b. Wrap SCA arrays on 2 pipe pieces (as directed),
    c. Weld one end cap to one ring, then weld this to one pipe piece,
    d. Repeat "c" for 2nd pipe piece,
    e. Assist in placement of thermocouples through SCA thicknesses (as directed),
    f. Prepare locations for pressure ports on pipe pieces (as directed), and
    g. Load and prepare wrapped pipe pieces for transport to Mojave.

3. Fiber Manufacturer;
    a. Fabricate 1,500 pounds of production fiber and transport to composite wrap contractor.
4. Emc^2; Prepare SOW'S for contractors to support testing at Mojave site.

Working from the spring through the late fall of 2011, we were able to provide the necessary materials to our composite wrap contractor to begin fabrication of the full-scale pipe test sections and wrap the SCA arrays onto the pipes beginning in January 2012.

Also, we worked through our selected subcontractors (most of whom we had previously used for testing support) who were in proximity to the Mojave, CA test site to prepare the site for an initial full-scale burst test for the mid-April 2012 time frame.

4.3 Task 3 - Pretest Design Analyses

4.3.1 Preliminary Analysis

Some basic information/data pertaining to the pipe material to be used in the full-scale testing activities was needed so that the design of SCA array for this testing activity could be established. One of these data points is the estimated fracture speed of the pipe material. As pointed out in Task 2 discussions, an industry member donated pipe material to be used for our (at least one) burst test at Mojave. In order to estimate the fracture speed in the donated pipe material, we needed to perform drop weight tear test (DWTT) activity on this donated pipe material. Since we did not have possession of this pipe material at the time, we elected use pieces of the same donated pipe material left over from a previous project performed by Emc^2. We fabricated DWTT specimens from the material pieces on hand (from the previous project) that matched the donated pipe pieces. The DWTT activity was to determine if the donated pipe material would sustain unstable crack growth at the temperature (ambient) conditions planned for the Mojave site. If the donated pipe material would not sustain crack growth at ambient conditions then the strategy of the alternate test plan would be flawed. The DWTT activity was conducted at temperatures from +20C to +40C, the likely temperature range at Mojave during a typical spring time period. Based on fracture energy values obtained from DWTT activity, the donated pipe sections were determined to be able to sustain unstable crack growth at ambient temperatures and the full-scale test could be employed to evaluate the effectiveness of the SCA. Table 1 shows the calculated values of fracture speed per the DWTT activity.

Table 1 Predicted fractures speeds for Pipes 687 and 731

Pipe Material	Temperature, C	AVG SPC-DWTT Energy, ft-lb	AVG PN-DWTT Energy, ft-lb	SPC-DWTT BTC predicted V_f, fps	PN-DWTT BTC predicted V_f, fps	Avg predicted V_f, fps
687	20	4,310	6,975	840	647	744
	30	5,273	8,829	689	555	622
	40	4,698	7,402	770	622	696
	Average of three temperatures			**766**	**608**	**687**
731	20	6,267	10,752	579	485	532
	30	6,679	11,711	541	455	498
	40	7,301	10,917	489	481	485
	Average of three temperatures			**536**	**474**	**505**

Knowing the approximate fracture speed values for the test pipe pieces, we were able to begin the design of the SCA array to be evaluated via the full-scale test activity. Based on experience in design of steel arrestors [1], we were able to determine the length of each arrestor in a five arrestor array (per side) of the test specimen assuming that the symmetrically placed crack initiation location would be at the test pipe centerline. Our experience in steel arrestor design is based on the premise that the thickness and ultimate strength of the arrestor rings are the same as the test pipe. This translates to the thickness of the arrestor being constant but length variable along the longitudinal direction of the pipe [1]. The results of the work from [1] showed a linear relationship of the arrest-propagate boundary in the form of fracture speeds versus normalized arrestor length (arrestor length/pipe diameter, L/D). Using the average fracture speeds shown in Table 1, arrestor lengths were determined that bracketed the "loose and tight" sleeve lengths. The lengths of the arrestors on each of the pipe sections (#687 and #731) are tabulated in Table 2.

Table 2 Crack arrestor lengths

Arrestor dimensions, L/D						
		Arrestor 1	Arrestor 2	Arrestor 3	Arrestor 4	Arrestor 5
Test 1	687 side	0.035	0.065	0.165	0.250	0.50
Test 1	731 side	0.0125	0.035	0.065	0.120	0.24
Arrestor dimensions, inch						
		Arrestor 1	Arrestor 2	Arrestor 3	Arrestor 4	Arrestor 5
Test 1	687 side	1.68	3.12	7.92	12.0	24.0
Test 1	731 side	0.60	1.68	3.12	5.76	11.4

Additionally, since the composite arrestor thickness is assessed to be equal to that of the steel sleeve, then accounting for the fiber packing density (we assumed a 0.70 pack density) we have a constant arrestor thickness that is 40-percent larger. The arrestor lengths listed in Table 2 are the "minimum" lengths which occur at the "pipe + arrestor thickness" OD.

After discussions with our composite wrap contractor, it was determined that wrapping of the fiber onto the pipe to form an arrestor should be laid out so that the side slope of each arrestor would be 45° with respect to the outer normal to the pipe surface. The 45° slope was selected so that a relatively high fiber packing density could be achieved to "optimize" the amount of fiber material required for an arrestor. Figure 1 illustrates the through thickness design of the arrestor.

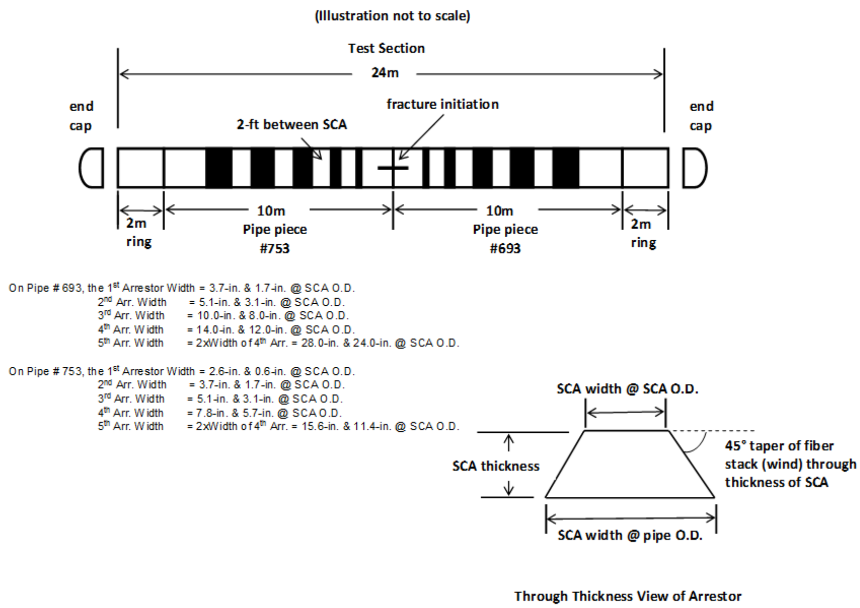


Figure 1 Schematic of test pipe and SCA through thickness design

Finally and after determining the physical size of the arrestors per the preceding discussion, placement of arrestors along the test pipe length (along the longitudinal surface) was the next decision. Our intentions included not only attempting to validate the concept of the SCA (i.e., stop a propagating crack without creating a ring off failure mode) but also we wished to generate as much information/data as possible with the first burst test. The fact that the test section was made up of two distinct pipes with distinct (predicted) average fracture speeds (687 fps and 505 fps, respectively) provided the potential for establishing SCA design performance as a function of fracture speed. Again our past experience with "arrestors" suggested that each arrestor (in an array) be separated by ½ D (pipe diameter, D) which for this case is 24 inches or 2 feet between adjacent arrestors. Test strategy also considered placing five arrestors longitudinally from the centerline of the test pipe. The crack initiation location was at the test section centerline with allowance for an initial 1-foot crack length. For design purposes, we assumed the crack and gas decompression began at the end of crack initiation location, 6 inch from the pipe centerline for each of the two pipe sections. Location of the first arrestor was 4 feet from the pipe centerline.

Our test strategy also included placement of the smallest/weakest arrestor first in the SCA array followed by adjacent arrestors of increasing strength with the intent of arresting the crack somewhere between the second and third arrestors within the array as in Reference [1]. Modeling the influence of the propagating crack and crack initiation wave allowed us to judge the needed pipe length to avoid interference of reflected wave and crack/arrestor interactions. Figure 2 shows the location of the SCA array for each of the test pipe pieces, estimations of crack fracture along the pipe length and the location (timing) of the reflected wave. From these estimations we determined that a fifth (~ 2-foot long arrestor) could be placed 2 feet from the fourth arrestor on each SCA array.

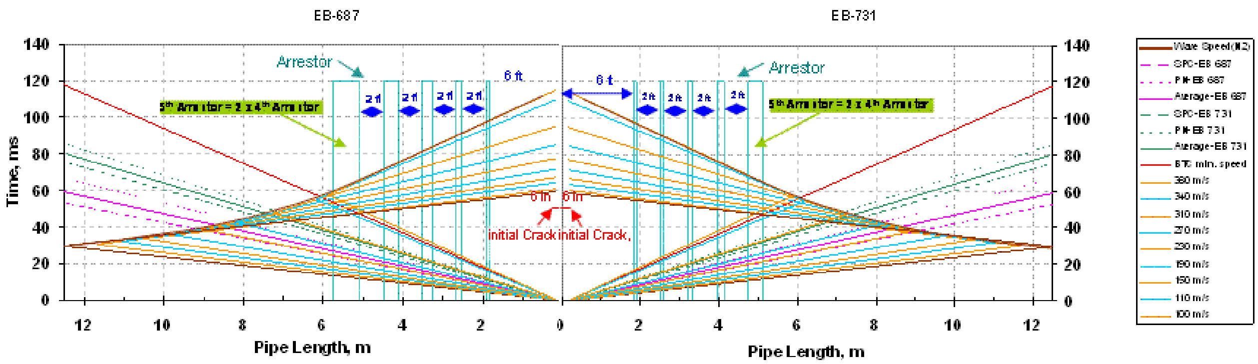


Figure 2 SCA array locations on test pipes

4.3.2 Finite Element Method (F.E.M.) Analyses

4.3.2.1 Pipe FEA model

Finite element-based methods were used to assist in the pretest design of the arrestor system for the SCA application. Emc² staff members are experienced in the use of the commercial FE code ABAQUS to model the pipeline crack propagation class of problems. During the DOT/PRCI "Backfill" project, an ABAQUS explicit FE model was created to simulate a crack propagating in a pipe without backfill [2,3]. An ABAQUS dynamic ductile fracture model was developed based on cohesive-zone modeling for the fracture process in pipeline steel. The cohesive parameters were calibrated using measured fracture speed values from a full-scale pipe test. Additionally, a simplified three-dimensional pressure decay based on experimental data for an ideal gas was used to model the gas-decompression behavior.

The intent for this task was to use a similar approach to model the pipe fracture process for the donated pipe material. This included the same modeling technique for the crack-driving force model (gas decompression scheme) and the effects of including a FE model for the arrestor. The inputs needed for models of the fracture process (donated material characteristics, estimated fracture speeds based on DWTT data, fiber material characteristics including damage metrics) were mostly available from previous/ongoing project tasks and previously performed experimental work.

A finite element analysis was conducted for one of the pipes (Pipe #687) contributed for the actual Mojave full-scale burst test. Figure 3 shows the stress-strain curve of the pipe material used in the FE analysis. The data for the stress-strain curve shown in Figure 3 were provided by the industry member who supplied the pipe material for this project. The expected fracture speeds were presented previously (Table 1) and the predicted speed for Pipe #687 was used in this analysis. Table 1 shows the predicted fracture speed at three different temperatures, with the predicted fracture speeds depending on which DWTT (i.e., SPC or PN) data were used. The average value was used as the final predicted fracture speed. Table 3 shows data for Pipe #687 only.

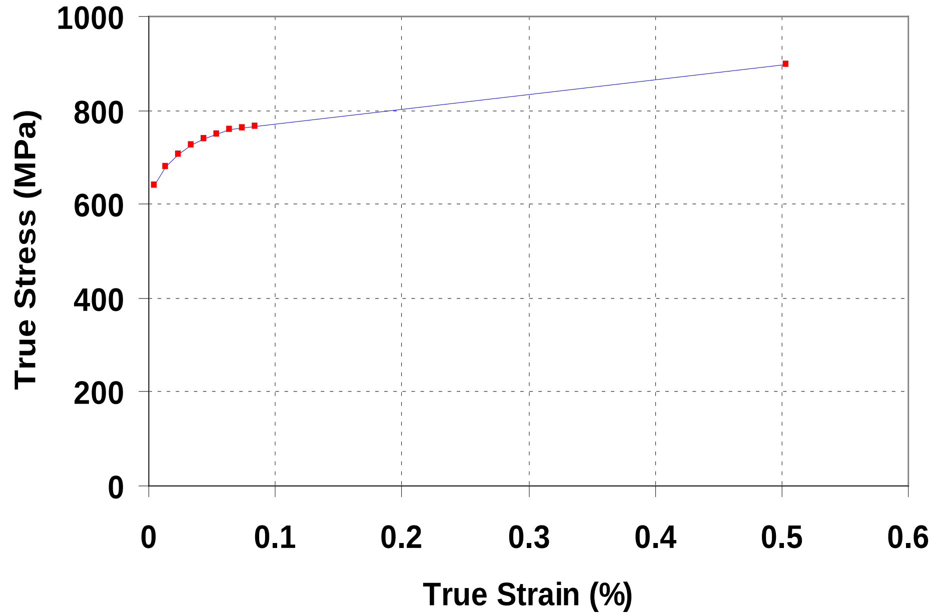


Figure 3 Stress-strain curve used in the finite element analysis of Pipe #687

Table 3 Predicted fracture speed for Pipe #687

Pipe Material	Temperature, C	AVG SPC-DWTT Energy, ft-lb	AVG PN-DWTT Energy, ft-lb	SPC-DWTT PipeDFrac Vf, fps	PN-DWTT PipeDFrac Vf, fps	Average predicted Vf	
						fps	m/s
687	20	4310	6975	840	647	744	227
	30	5273	8829	689	555	622	190
	40	4698	7402	770	622	696	212
Average of three temperatures				**766**	**608**	**687**	**209**

The ductile crack propagation scheme discussed above and used in previous studies was also used for this analysis. A slight modification was made to the model. The model was modified so that the pipe was pressurized in a quasi-static, two-step approach, 1) using an implicit FE analysis prior to growing the crack, and then 2) performing a dynamic analysis (explicit FE analysis). Figure 4 shows how the internal pressure was simulated in this 'two-step approach' model. As shown in this figure, the uncracked pipe was pressurized to the initial test pressure. Then, the crack was introduced in the model and the decompression model (used in previous studies) was used to propagate the crack. This method eliminates dynamic ringing of the entire pipe which occurs when pressure is suddenly taken up to an initial test pressure which happens when using a one-step dynamic analysis.

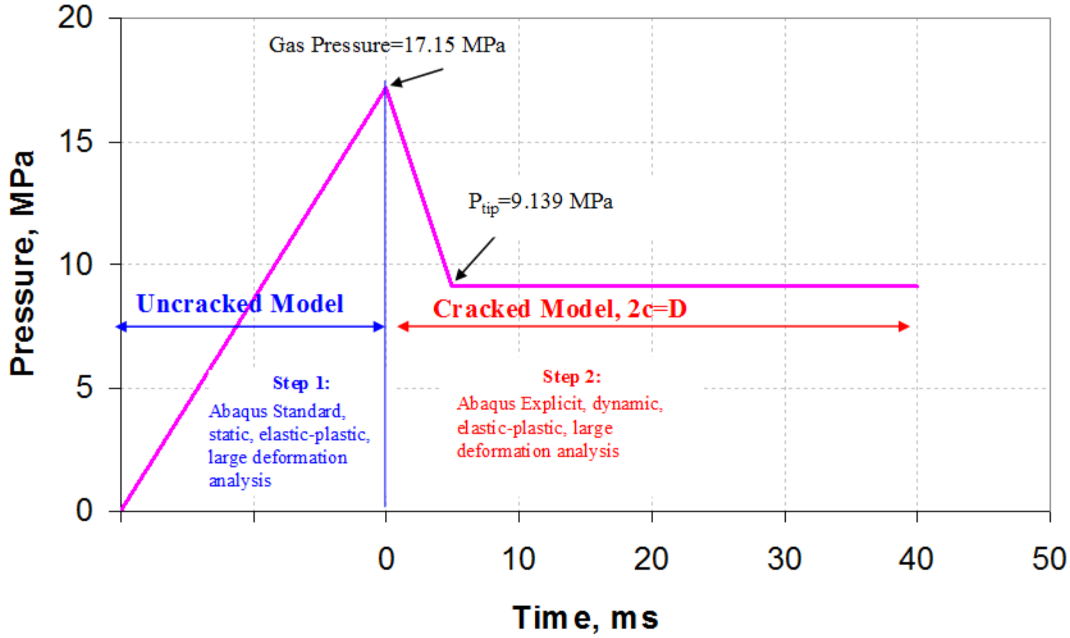


Figure 4 Variation of internal pressure in the two-step analysis approach – radial pressure profiles behind the crack tip not shown

Figure 5 shows the predicted crack growth as a function of time for Pipe #687. As shown in this figure the predicted fracture speed from the FE analysis was 228 m/s, which is approximately 8.5% higher than that predicted from the BTC model. Since scatter in BTC predictions compared to some past full-scale burst tests were shown to be greater than 8.5% (as previously reported), this finite element analysis was not further fine-tuned to exactly match the BTC results. Figure 6 shows snap shot of a crack propagating in Pipe #687.

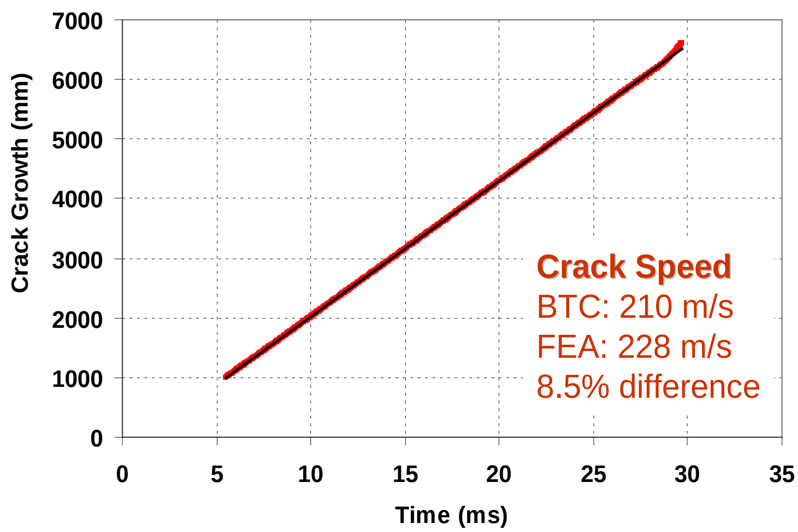


Figure 5 Variation of internal pressure in the two-step analysis approach

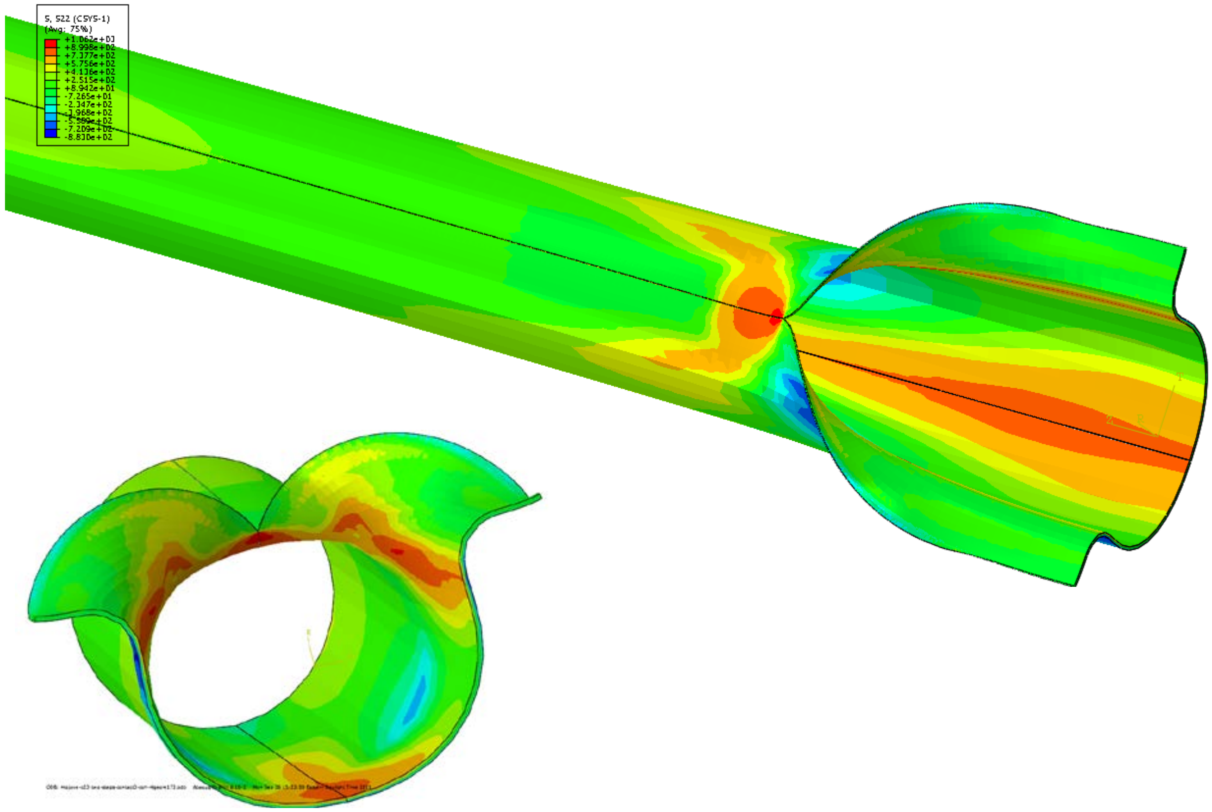


Figure 6 Snap shot of crack propagating in Pipe #687

4.3.2.2 Fiber FEA model

A finite element analysis was conducted to simulate a single fiber tensile test in order to validate the fiber material model. The validated fiber material model was to be incorporated in ductile axial crack growth analyses to model arrestor material behavior. In this single fiber model, the fiber is modeled with symmetric boundary conditions as shown in Figure 7. The fiber was then loaded in displacement control at the other end.

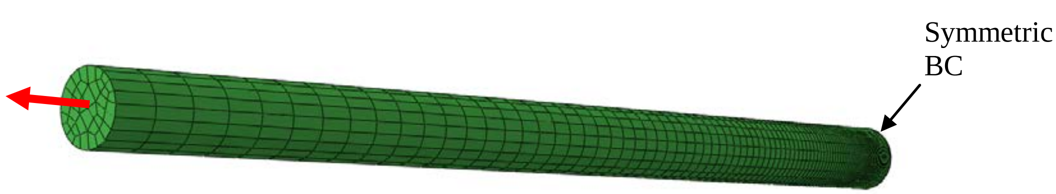


Figure 7 Single fiber tensile test model

A hyper-elastic material model was employed for this analysis using Marlow strain-energy potential. Single fiber uniaxial tensile test results were available to validate the material model. The Marlow hyper-elastic material model was used as one set of test data (uniaxial tensile test) to compute model material constants. This material model was to be used in the ductile crack growth pipe FE model which was analyzed in two steps as discussed in the preceding paragraph. The current material model was to be validated under both ABAQUS standard and ABAQUS explicit. Crack propagation speeds can vary depending upon pipe material. Different crack speeds will cause different loading rates on the arrestor materials.

A single element finite element analysis with a damage model was conducted to establish the fiber material model using single fiber tensile test results. A strain-based damage model was used to simulate the failure of a single fiber in tension.

Figure 9 shows the comparison of load-displacement curves for the experimental result of a single fiber tensile test and ABAQUS explicit analyses with and with without the damage model. As seen in Figure 9, the FE analyses match very well with the experimental load-displacement results. FE material model also followed the strain based damage model which, in this case, occurred at displacement of 4 mm.

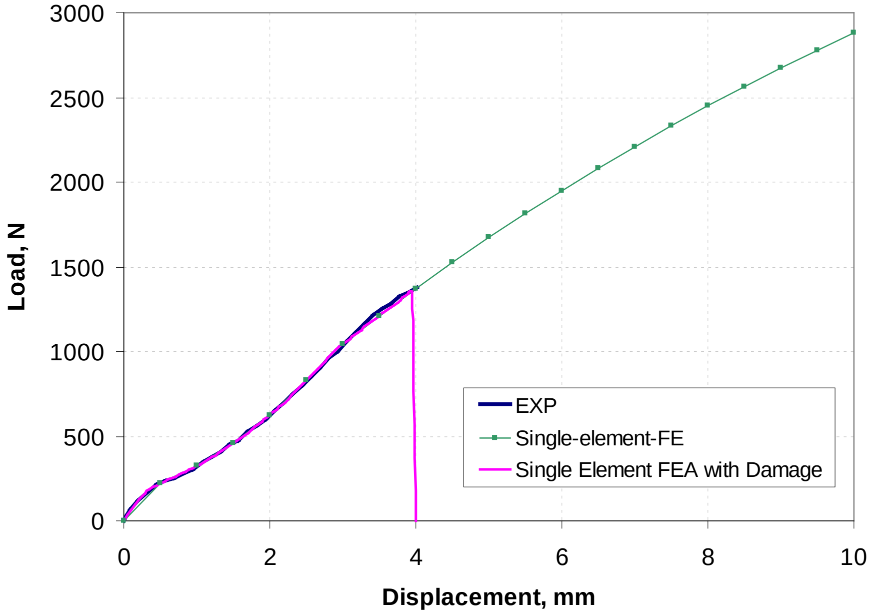


Figure 8 Comparison of stress-strain curves for experimental and FE results with strain-based damage model

An arrestor was incorporated in the existing pipe model as shown in Figure 10. The arrestor was 40-mm wide and was placed 1.22 m away from the initial crack tip. There was no radial clearance between the pipe outside surface and arrestor inside surface. The arrestor was modeled using the hyper-elastic material model developed and validated as discussed in the preceding paragraphs. The simulation (with arrestor) was then run with the same cohesive parameters that were tuned in the pipe model (without arrestor) to get the desired crack speed. There were some variations in the results between the pipe models with and without arrestor events though the same cohesive parameters were used in both models.

Note that in this modeling approach, it is assumed that the resin matrix shatters and offers no load-carrying capacity, so only the strength of the fiber is available for arrest. This assumption was validated in the full-scale test results that are shown later.

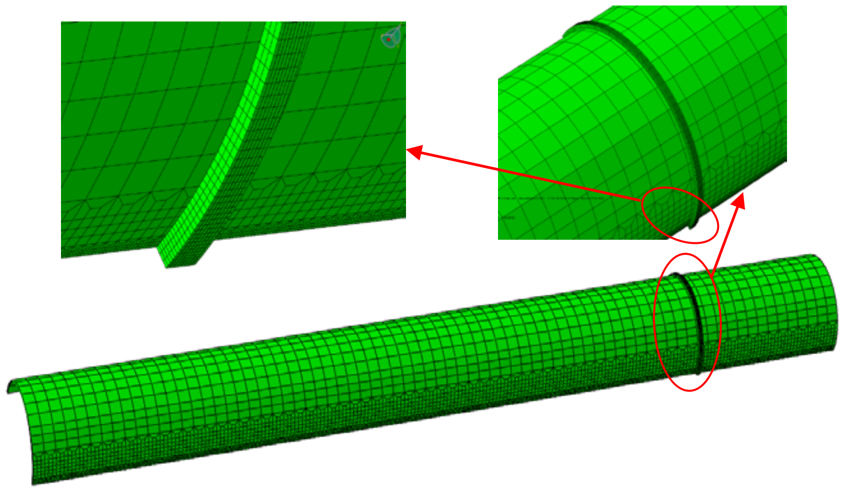


Figure 9 FE pipe model with arrestor

4.4 Task 4 - Fabricate SCA Array onto Test Pipes

In our Phase II proposal, we identified two potential subcontractors to wind the SCA array onto the test pipe sections. The subcontractor selected could receive and unload the project materials (end caps, rings/pups, pipe sections, fiber material), store those materials not needed for a first burst test activity, weld pipe pieces together (qualified welders on hand), wrap the arrestors, prepare specified locations on pipes for pressure ports, assist placement of thermocouples on arrestors, and arrange for transport of arrestor wrapped pipe pieces to the Mojave test site. Thus, our selected composite wrap contractor provided "one stop shopping" for the needs of the project. A statement of work (SOW) was sent to the selected composite wrap subcontractor in June 2011 to perform the following activities:

Subcontractor Statement of Work

Materials to be sent/delivered to selected contractor:

- X80 grade pipe, 48-inch diameter, ~1-inch thickness,
  - 3 pipe pieces, each 10-meters long,
  - 2 pipe rings, each 2-meters long, and
  - 2 end caps.
- Fiber material, placed on spools for transport from fiber manufacturer to composite wrap contractor location.

Step 1. Preparation:

Receive, unload and store the material pieces; pipe pieces and rings will arrive from one source and the end caps will arrive from a second source. (Each of the parts will be marked for identification). Receive fiber material from fiber manufacturer.

Emc^2 will identify which 10-meter pipe piece will not be used in the first test at our Mojave test site. This 10-meter pipe piece will be stored until/if further testing is performed.

Step 2. Welding of pieces:

- One ring to be welded to one of the 10-meter pipe pieces to form a 12-meter piece to be used in burst tests at Mojave.

- One end cap to be welded to the 12-meter piece. This will result in a 12-meter pipe section with end cap attached.

Repeat the two steps immediately above with the other 2-meter ring, other 10-meter pipe piece and end cap.

Step 3. Wrap SCA arrays onto pipe pieces:
Guidelines/instructions will be sent to contractor regarding wrapping SCA arrays onto pipe pieces using fiber material received from fiber manufacturer and assist in installing thermo-couples into SCA arrays.

NOTE: The contractor will employ certified welders with approved Weld Procedure Specification (WPS) as a guideline to perform all welds. Also, contractor will prepare all joints to be welded (via end facing machine or other means) as necessary to ensure/achieve proper weldments.

Weld rods to be compatible with X80 grade pipe material and end caps (end cap material will be identified so that other weld rods can be employed if necessary when joining end caps to ring pieces).

Weld process (e.g., MIG, etc.) will be suggested by contractor and consistent with the WPS. Emc^2 will provide a weld procedure that could be used for this X80 pipe material, which has been used successfully in actual pipeline construction projects. We will then decide which procedure is best to use.

Contractor will identify a transport company to transport the pipe pieces to the Mojave test site. Emc^2 will work with that company to perform the following:

- Load two pipe pieces (12-meter test piece plus end cap, each) that will be at contractor facility after SCA has been applied to each 12-meter test pipe piece.
- Transport two pipe pieces from contractor facility to the Mojave test site.
- Unload pipe pieces at specified location at Mojave.

Welding the two pipe pieces together to form the final test pipe configuration would be performed at the Mojave site during pre-test set up operations.

Our plans called for delivery of all materials needed to perform the tasks in this SOW by mid-December 2011 so that these tasks would be completed by our selected composite wrap contractor no later than late March 2011 in order that the first full-scale burst could be conducted by mid-April 2011.

As it turned out, all materials (noted above) needed by our wrap contractor did arrive by mid-December 2011 and plans were made to begin work immediately after the New Year (January 2012) to accommodate the planned burst test date.

Our selected composite wrap contractor began work on preparing the pipe materials during January 2012 for the testing activity planned for the April 2012 time period. The expected sequence of that preparatory work included welding an end cap to one of the 2-meter rings then welding this end cap-ring piece to a 10-meter pipe section to form a (approximately) 12.5-meter section which would form one half of the test pipe configuration. Repeat of this welding activity with the other end cap, ring and 10-meter pipe section would form the other half of the test pipe configuration. Welding of these pieces was completed in mid-March 2012 and then wrap of the SCA arrays onto each of the test pipe pieces began. A member of the Emc^2 technical staff arrived at the composite wrap contractor's facility the week of March 19, 2012 and participated in the SCA wrapping activity and led the effort to place thermocouples within each arrestor (SCA ID, SCA mid-thickness, and SCA OD) which were used to monitor temperature profiles prior to and at test crack initiation. The Emc^2 staff member remained for the rest of that week to assist in wrapping the SCA arrays, installing thermocouples and ensuring test pipe configuration needs. The Emc^2 staff member also observed application of a covering resin to each SCA for protection and SCA shape and packing integrity. Figure 12 (a repeat of Figure 2) illustrates placement of the actual SCA array on one of the test pipe sections. Also, note that each arrestor is covered with plastic wrap (same material used with shipped goods on pallets) for protection during transport and the 45-degree fiber profile of each arrestor (at the axial end of each arrestor) is covered with duct tape also for protection. The length of each arrestor is listed in the guidelines sent to the composite wrap contractor and denoted in Figure 12.

Figure 10 Wrapped SCA array onto test pipe

Guidelines for Materials Received for SCA Project

Pipe material delivered was 48-inch diameter, ~1-inch thick, X80 grade.

1) Receive three 10-meter pipe pieces and two 2-meter rings in one delivery**.**
    i) Pipe number #693, 10-meter pipe piece; and two 10-meter pipe pieces #753 & #719
    b) Pipe pieces to be used in testing, 10-meter piece of Pipe #693 & #753 plus two 2-meter rings supplied.
    c) Pipe piece to be stored, one 10-meter pipe piece #719.
2) Receive end caps – two each, 48-inch diameter.
3) Receive fiber – 1,500 lb on 25-lb spools (69-spools used).
4) Welding*:
    a) Weld <u>one</u> 2-meter ring to <u>one</u> 10-meter pipe (#693),
    b) Weld <u>one</u> end cap to the 12-meter pipe constructed in Step 4a. End cap goes on the 2-meter pipe side (see Figure 12),
    c) Weld remaining 2-meter ring to 10-meter pipe (#753), and

d) Weld remaining end cap to the 12-meter pipe constructed in Step 4c. End cap goes on the 2-meter pipe side. The center weld for the final test configuration will be performed at the Mojave site.
 * Use of approved Weld Procedure Specification (WPS) required.

5) Wrap SCA on pipe sections. Per 4) above, two pipe sections will result; each 12-meters long with end cap attached at each end. These two separate pipe sections will be wrapped with SCA.
   a) Each SCA has different width (distance along axis of pipe), separated by 2 feet between adjacent SCA's.
   b) Three (3) thermocouples (TC) will be placed in each SCA (except the last/widest SCA), about 1 inch from the SCA leading edge; one TC at top of pipe surface, one at top of SCA and one at SCA mid-thickness. Emc^2 staff member will be present at SCC to assist.
   c) Approximate geometry for side shape of SCA (~45 degree slope w.r.t. to vertical so that largest SCA width is at pipe surface, see Figure 12).
   d) The nominal design thickness determined by Emc^2 staff design.

The first SCA (one closest to the test pipe center) will be 4 feet from the test pipe center (both right and left of center).

The width schedule for the SCA along the length of the pipe axis (at the pipe surface with tapers accounted for) and the constant thickness lengths will be as follows (see Figure 12):

On Pipe #693, the 1st arrestor width = 4.5-inch (on pipe surface including taper lengths) & 1.7-inch (constant thickness length) at SCA O.D.
2nd Arr. Width = 5.9-in. & 3.1-in. at SCA O.D.
3rd Arr. Width = 10.8-in. & 8.0-in. at SCA O.D.
4th Arr. Width = 14.8-in. & 12.0-in. at SCA O.D.
5th Arr. Width = twice width of 4th Arr. = 29.6-in. & 24.0-in. at SCA O.D.

On Pipe #753, the 1st Arrestor Width = 3.4-in. & 0.6-in. at SCA O.D.
2nd Arr. Width = 4.5-in. & 1.7-in. at SCA O.D.
3rd Arr. Width = 5.9-in. & 3.1-in. at SCA O.D.
4th Arr. Width = 8.6-in. & 5.7-in. at SCA O.D.
5th Arr. Width = twice width of 4th Arr. = 17.2-in. & 11.4-in. at SCA O.D.

6) Other activities:
   a) Welds will be performed prior to wrap of SCA onto the pipe sections.
   b) Install nipples on end caps to receive test gas/fluid; nipple location and other information will be provided by Emc^2.
   c) Install pressure nipples after last SCA on both right & left sections (for symmetry). Instructions and all miscellaneous hardware will be provided by Emc^2 upon arrival (prior to SCA wrap activities). Pressure transducers will be installed at Mojave.
   d) Make a nipple for a sheath thermocouple on both ends in the 2-meter pipe sections. (Sheath thermocouples to be installed at Mojave).

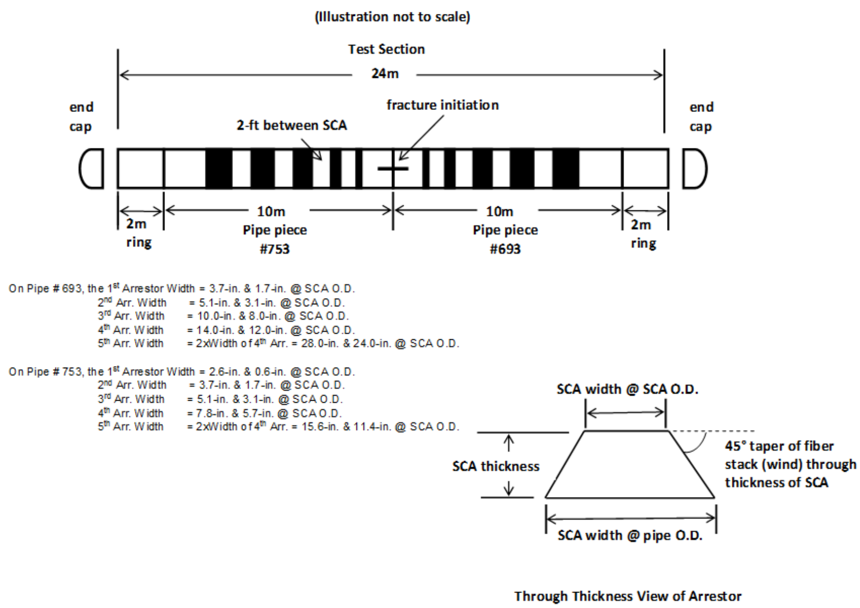


Figure 11 Layout of arrestors for subcontractor

Emc^2 prescribed pressure port locations so that each test pipe section was prepared to have pressure transducers inserted at the Mojave site prior to the test. We were concerned about potential damage to transducers during transport from the composite wrap contractor's facility to Mojave so the pressure transducers were not inserted into the test pipe sections until after arrival at the test site. Wrapping of the SCA arrays on both pipe pieces, creating the pressure transducer ports and other test pipe preparation related items were completed at the composite wrap contractor's facility by the 1st week of April 2012 and plans were made to transport the test pipe sections for arrival at Mojave on April 9, 2012.

4.5 Task 5 - Validation of SCA Design through Full-Scale Burst Test

4.5.1 Initial Comments about the Burst Test

The full-scale test was a rather large demonstration and validation test that was also intended for further design optimization. This test was on a 48-inch (1,219-mm) diameter, 0.935-inch (23.75-mm) thick X80 pipe at ~80-percent SMYS. The test specimen was about 84-feet (25.6 m) long with different pipe materials on either side of the center girth weld having significantly different toughness values. The test pipe was pressurized with nitrogen at ~2,500 psig (17.24 MPa) and was in the unbackfilled condition to promote unstable ductile fracture propagation. The particular material being used was controlled-rolled steel that at the anticipated test temperatures of 69 to 104F (20 to 40C) exhibits a significant number of separations on the fracture surface that would result in unstable ductile fracture speeds of 500 to 675 feet (152 to 198 m) per second in the two different pipe steels. A series of five crack arrestors with different sizes were on each side of the center of the pipe as previously explained where a supercritical axial through-wall flaw was initiated with an explosive cutter. Normal and high-speed video of the event were taken.

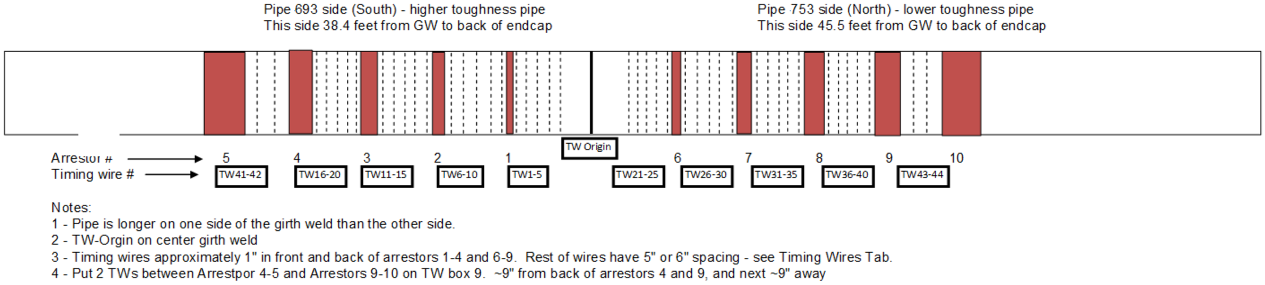
The instrumentation layout of the test specimen with the timing wires (TW) and thermocouples (TC) is shown in Figure 13. The timing wires are generally arranged in banks of five and allow the fracture speed to be determined before each arrestor. In crack arrestor tests, it is necessary to know the fracture speeds for design purposes, and these speeds may be slightly higher near the origin of the fracture event than those that will develop under steady-state conditions. Hence having the arrestors close to the origin gives higher speed and crack-driving force. From past steel sleeve arrestor work, the higher the fracture speed the larger the arrestor needs to be. Hence we used pipes with two different toughness levels to help confirm the fracture speed dependence on the optimal arrestor size as previously explained.

The arrestors on the pipes were sized so that the closest to the center girth weld should definitely fail. The second position would have marginal failures, and the third position should arrest the crack. The fourth SCA from the center were there in case a problem occurred, and the fifth SCAs were for added safety and to protect the rest of the pipe and end caps for potential future testing.

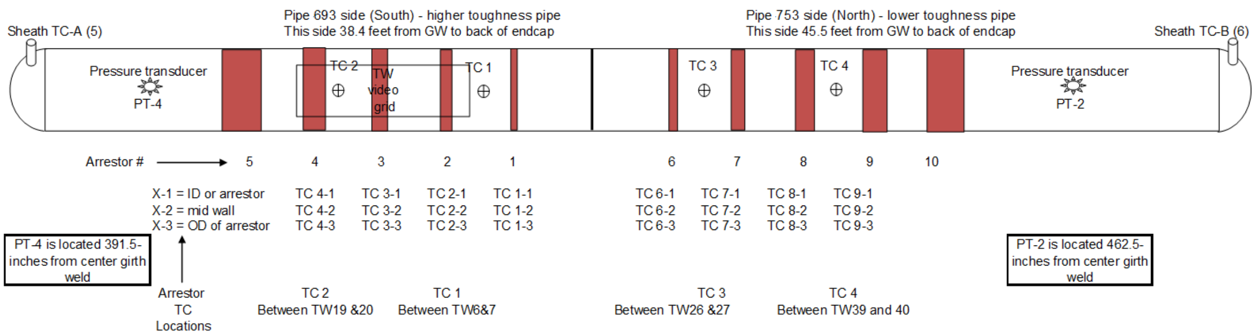
Pressure transducers were placed about 7 feet (~2.1 m) from the end caps on both sides and also in the end caps (see Figure 14). This allowed for the initial pressure wave to be determined and the time that the reflected decompression wave comes back from the end cap. The minimum length of the vessel was based on the time for the slowest possible ductile fracture speed to reach the last arrestor and still not have the reflected wave reach the back of that arrestor, i.e., we did not want the arrest to be affected by the decompression speed as explained in Section 4.3

The vessel was slightly longer on the North end by 7.1 feet (2.17 m). This was done unintentionally by a subcontractor and was not noticed until shipping the pipe to the site, so nothing was done about this discrepancy to prevent significant time delays. The shorter side was still sufficient for avoiding reflected waves from interfering with the test, see Figure 15.

Figure 15 is an enlarged view of that shown in Figure 2 (but for only one/either pipe piece). Again, it can be seen that the cracks with either speed reach the back of the fifth arrestor before the reflected wave reaches the back of the last arrestor. The effect of the longer length of pipe on one side is that the pipe may jump to the north from unbalance decompression at the end of the test. Ring-off should not occur with the “Soft Crack Arrestors”, but the unbalance lengths could cause the whole vessel to move north.



(a) Timing wire layout



(b) Thermocouple wire layout

Figure 12 Instrumentation for the "Soft Crack Arrestor" burst test

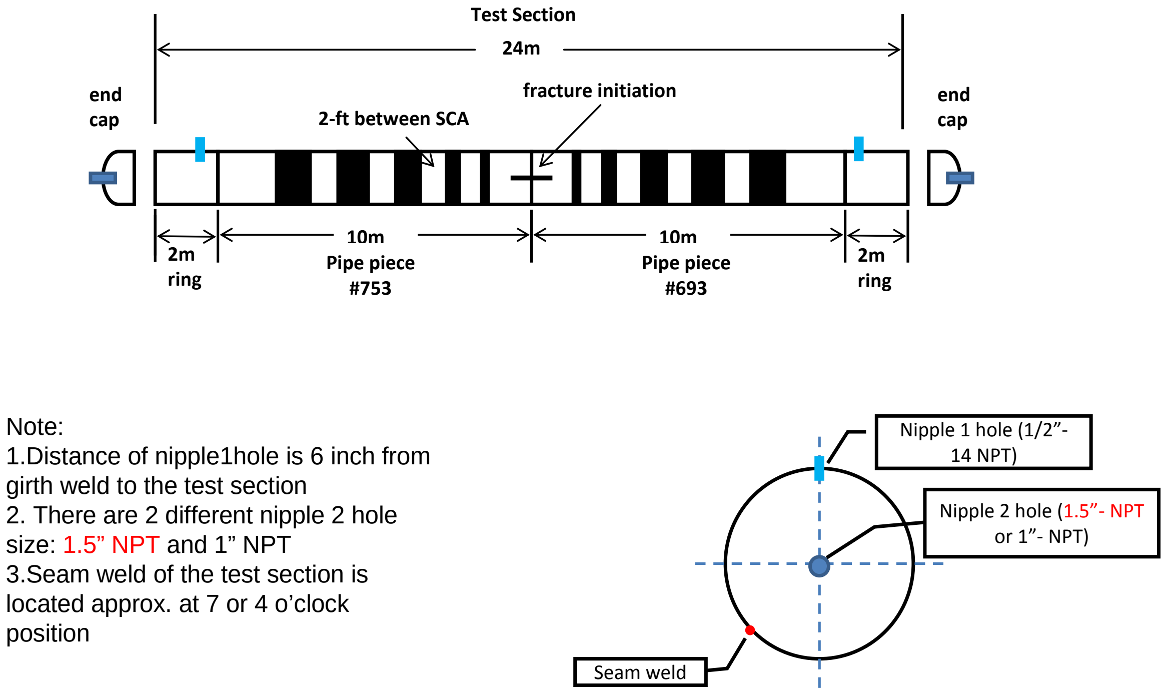


Figure 13 Pressure transducer locations on test pipe

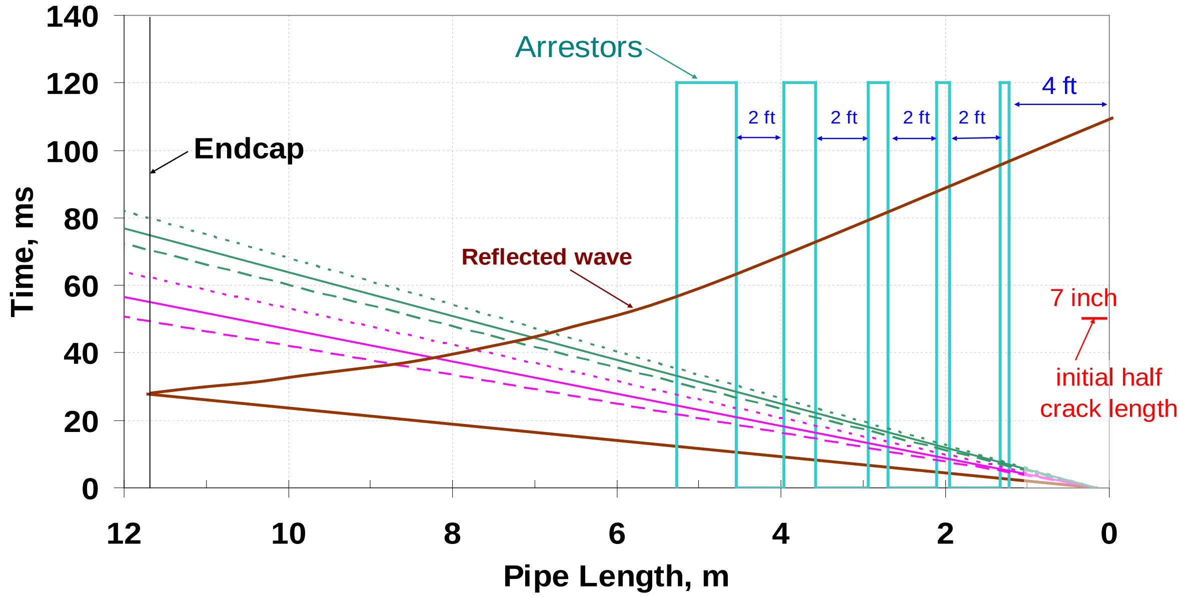


Figure 14 Analysis to determine potential of reflected wave interference with crack arrestor

4.5.2 Preparation for Burst Test

Two Emc^2 staff members travelled to our Mojave, CA storage site in mid-February 2012 to assess status of assets stored from previous testing. A complete inventory of all assets was conducted to ascertain what additional items would be needed to perform the planned testing. Also, our two staff members met with our foreman from previous testing at Mojave and a member of the company that provided assistance/support for full-scale testing. That meeting resulted in locating the buried pressure test supply line at Mojave. Pressure testing of that line was performed in early March 2012 which determined that the line needed to be and was repaired prior to our full-scale testing.

All contractors needed to support test preparations and full-scale test activities were on site at Mojave during the latter part of March 2012 conducting initial tasks. All test equipment necessary to conduct the test, monitor the test events, and acquire test results were packaged by Emc^2 staff and sent to the Mojave area. Local safety, fire, and law enforcement agencies were informed during March 2012 about the Mojave testing to ensure appropriate protocol adherence.

The two pipe sections arrived at the Mojave test site as planned on Monday, April 9, 2012. Five Emc^2 staff members arrived in CA on Sunday, April 8th and were at the test site for arrival of the test pieces on April 9th as planned. Actual pre-test work started with arrival of Emc^2 staff on Monday, April 9th and the pre-test activities continued with completion of those activities on Monday, April 16th.

Also in attendance (by invitation) to observe the full-scale burst test planned for April 17, 2012, were the project COTR, Dr. James Merritt and his supervisor, Mr. Jeff Gilliam (Director of Research for DOT/PHMSA), two members from PRCI, and a technical staff member from the industry partner that donated the pipe material for the burst test activity.

4.5.3 Conduct Full-Scale Burst Test and Post Test Observations

After ten hard days of preparation, the full-scale "Soft Crack Arrestor" test was conducted on Tuesday, April 17, 2012 as planned. (The test pipe was about 84-feet long, 48-inch diameter by 0.935-inch thick, and pressurized with nitrogen to 2,518 psig.) The test resulted in quite a jolt as experienced in the bunker – cracked some roof support beams in the bunker even though there was 6 feet of soil on top of the bunker which was about 100 feet away at the closest point. Soft crack arrest was successfully achieved with a high-speed ductile fracture ~650 fps. However, only one of the 10 arrestors worked. The high-speed digital video was highly instructive and showed how much each arrestor stretched as the crack ran under them; the crack was stopped at the last and longest arrestor. We have also determined that the arrest event in the longest arrestor was accomplished well before the reflected wave from the end cap had a chance to reach the back of the arrestor, almost in perfect agreement with the pretest predictions shown in Figure 15. Figure 16 shows the test pipe just before test start, and Figure 17 and Figure 18 show the post-test pictures of the damaged pipe sections and the arrestor that stopped the crack. The crack actually propagated about 15 inches under the arrestor, and as expected the resin used with the fiber was too brittle and shattered leaving the fiber to arrest the crack.

Figure 15 Test pipe prior to test start

Figure 16 Damaged pipe at the center location and towards Pipe #753 end

Figure 17 Crack Arrest at 5th Arrestor on Pipe #693

The conditions at the Mojave test site on test day (April 17, 2012) were at notably higher temperatures than those anticipated. Values of thermocouple readings (taken one minute prior to the burst test) showed that temperatures ranged from 215F to 116F (102C and 47C) on the North test pipe section SCA arrays and from 247F to 100F (119C and 38C) on the South test pipe section arrays. This indicates that the fibers wrapped per design for the SCA arrays were subjected to temperatures that compromised fiber strength to the level that the SCA did not have the necessary load-carrying capacity to perform as designed. We expected that the SCA arrays would be subjected to temperatures that would not exceed 110F (43C). Laboratory tests conducted later by Emc^2 staff on typical SCA fibers subjected to temperatures at 239F and 190F (115C and 88C) showed a reduction in UTS of about 10% to 30% depending on temperature conditioning strategy. The higher than planned test temperature at the Mojave site reduced the strength of the fiber material in the arrestors, so it took a much longer arrestor to be successful than initially designed. That is why more of the crack arrestors did not work. Nevertheless, the longest/successful arrestor was still shorter than a fiberglass arrestor to be successful, due to the arrestor ability to deform, allow the crack to propagate under it, and have more of the arrestor take the loads needed to arrest the crack.

Finally, Emc^2 performed post-test activities on material samples extracted from scrap pipe pieces from the Mojave test. The intent of these post-test activities were to; 1) ensure that the tested pipe material had similar performance characteristics at ambient temperature compared to the performance characteristics we measured from the re-constituted DWTT specimens tested and reported in Table 1, and 2) since the temperature conditions during the Mojave testing were elevated compared to the expected conditions, we also performed DWTT on specimens (also from Mojave test pipe scrap material) at the temperatures that existed during the Mojave test. (Recall from Figure 13a, that TC's were used to monitor pipe surface temperatures). The temperature readings just prior to test initiation were +71C and +57C on Pipe #753 (North) and +57C and +82C on Pipe #693 (South).

The results from the ambient temperature DWTT on the Mojave scrap pipe material provided proof that the actual pipe sections responded similar to the previous DWTT results described in Section 4.3.1. That is, the decision to use the donated pipe sections for full-scale burst testing was further validated.

Scrap material pipe pieces from the Mojave test were conditioned at the temperatures noted above with two samples each from Pipe #693 conditioned at +57C and +82C and two samples each from Pipe #753 conditioned at +57C and +71C for a total of eight test specimens. Table 3 shows the results from the DWTT and Figure 19 illustrates pipe fracture energy at the elevated temperatures. Examination of the shear surfaces (pictures not presented here) from DWTT activity indicates that at these temperatures, the specimens exhibited 100% shear, full ductile shear fracture with little splitting as anticipated. In other words, the elevated temperatures during the burst test did not unexpectedly affect the test results.

Table 4 Results from DWTT testing

Pipe ID	Specimen ID	Temperature	Energy	AVG Energy	SA, API
		C	Joule	Joule	%
693	1	57	9,643	9,717	100
	2	57	9,792		100
	3	82	11,834	11,185	100
	4	82	10,535		100
753	5	57	11,146	10,957	100
	6	57	10,767		100
	7	71	12,574	11,807	100
	8	71	11,041		100

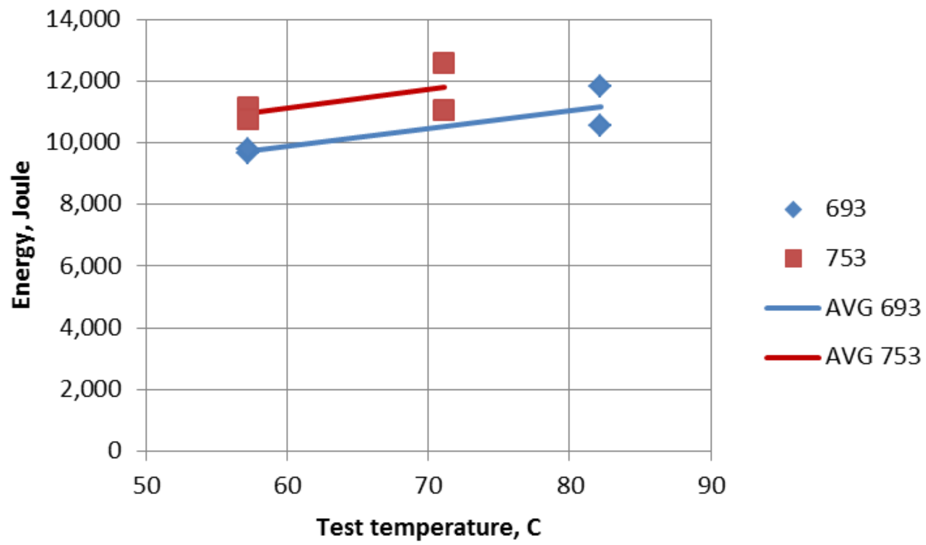


Figure 18 Comparison of fracture energy for Pipes #693 and #753 near burst temperatures

5 CONCLUDING REMARKS AND RECOMMENDATIONS

A Soft Crack Arrest was successfully achieved as desired. Even though only the longest arrestor worked, that arrestor was still shorter than comparable fiberglass arrestors since the ductile fiber used in the SCA allowed the crack to propagate under the arrestor and more fibers took the load.

The members from the project sponsoring agency, U.S. DOT-PHMSA, who attended the test activity, were quite pleased with the execution and results from the full-scale burst test. These representatives requested that Emc^2 plan a second burst test and submit a proposal to perform a this test. The intent was to additionally demonstrate the efficacy of the SCA device to industry through this second test. A proposal was necessary because project funds were practically exhausted after all costs were paid to subcontractors upon completion of the testing and post-test clean-up activities. A proposal to perform this second burst test was submitted on May 24, 2012 with a tentative test date planned for the October-November 2012 time period. However, the costs required to perform a second burst test exceeded the funds available to the U.S. DOT/PHMSA at the time of that proposal. The proposal costs were considered to be accurate and current since Emc^2 had just paid the same subcontractors (whose costs were included in the proposal to aid in a second burst test) for their work on the first burst test activity. The proposed effort for a second test also included another pipe section (~12-meters in length) provided by the same industry partner who donated the pipe material used in the first burst test. Since attempts to secure sufficient funding to perform the second full-scale burst test have not been successful to date, this summary report serves as our Final Project Report.

Emc^2 strongly recommends that the U.S. DOT/PHMSA continue to support these efforts to perform a second full-scale burst test because the need for the SCA device still exists. A major intent of this project is to provide the pipeline industry with a technically robust and cost effective solution to prevent pipeline failures from unstable ductile propagating axial cracks. The SCA device provides an alternative and safe solution for the crack arrest class of problems. For the foreseeable future, the demands for increased energy in the U.S. and international markets necessitates that this device be unquestionably proven to the pipeline community so that use of the SCA device will aid in the transmission of high energy products in an efficient and safe manner.

6 REFERENCE

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