Use of Pressure Activated Sealant Technology to Cure Pipelines Leaks
Final Technical Report

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ABSTRACT

The objective of this 1 year, $436,828.53 project was to develop new, efficient, cost effective methods of internally sealing natural gas pipeline leaks through the application of differential pressure activated sealants.[i] This objective was to be accomplished through four research phases: Collection and Analysis of Current Field Data, Development of Sealant Formulas and Procedures, Laboratory Testing, and Field Test of Sealant Formulas and Procedures. During the later stages of the project it was agreed to exclude field testing in lieu of extending laboratory testing.

In terms of sealing leaks identified, the project was 100% successful. In regards to maintaining seal integrity after pigging operations we achieved varying degrees of success. Internal Corrosion defects proved to be the most resistant to the effects of pigging while External Corrosion proved to be the least resistant. Overall, under the right circumstances, pressure activated sealant technology was found to be a viable option for pipeline repair.

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EXECUTIVE SUMMARY

The objective of this project was to develop new, efficient, cost effective methods of internally sealing natural gas pipeline leaks through the application of differential pressure activated sealants. This objective was to be accomplished through seven major tasks:

- Technology Assessment
- Collection of Current Field Data
- Analysis of Current Field Data
- Creation of Simulated Leaks
- Development of Sealant Formulas and Procedures
- Sealing Simulated Leaks
- Field Test of Sealant Formulas and Procedures

In the Technology Status Assessment[ii] we reported on the current state of the art for gas pipeline sealing technologies, providing pros and cons for those methods, and concluded that if the project was successful, pressure activated sealant technology would provide a cost effective alternative to existing pipeline repair technology.

In collecting current field data we chose a 13-year period (1985 – 1997), starting with "Analysis of DOT Reportable Incidents for Gas Transmission and Gathering System Pipelines, 1985 through 1997"[iii] and adding additional data from the Office of Pipeline Safety reports as well as operator and service company input. From the analysis of this data we were able to identify 205 incidents from a possible 1,084 that would have been candidates for pressure activated sealant technology, affirming that pressure activated sealant technology is a viable option to traditional external leak repairs. The data collected included types of defects, areas of defects, pipe sizes and materials, incident and operating pressures, ability of pipeline to be pigged and corrosion states. This data, and subsequent analysis, was utilized as a basis for constructing applicable sealant test modeling.

Liquid and gas leak rates were established in the test model defect sections to afford a point of reference for development of applicable sealant formulations and delivery procedures. Different formulations and delivery procedures were tested during the laboratory testing phase. The testing resulted in 100% success in the initial repair of leaks types identified during the Analysis of Current Field Data; however, subsequent line pigging resulted in varying degrees of seal integrity. Internal Corrosion and Weld leaks proved to be the most resistant to the effects of pigging, while External Corrosion proved to be the least resistant.

The field testing phase was excluded to allow more time for laboratory testing. It was felt that additional lab testing utilizing field-scale equipment would provide equivalent data.

Overall, under the right circumstances, pressure activated sealant technology was found to be a viable option for pipeline repair. The optimum chance of long-term sealant success lies in pipelines which exhibit relatively high differential pressure and are not subjected to a rigorous pigging program.

EXPERIMENTAL AND OPERATING DATA

Research Management Plan

With the Research Management Plan[iv] we defined the objective of the project, "… to develop new, efficient, cost effective methods of internally sealing natural gas pipeline leaks through the application of differential pressure activated sealants" and detailed how this objective would be accomplished. As previously described we divided the project into 4 research phases. Where applicable, Milestones and Deliverables were identified within each phase with deadlines assigned. The project budget (80% DOE / 20% STI) was broken down into projected monthly expenditures. We are happy to report that the project came in on schedule and under budget.

Technology Status Assessment

We researched the current state of the art for gas pipeline sealing technologies and provided pros and cons for those methods. This was submitted in our Technology Status Assessment[v]. We concluded that if the project was successful, pressure activated sealant technology would provide a cost effective alternative to existing pipeline repair technology. A summary of the benefits of pressure activated sealant technology along with a comparison of the sealing methods (Table 1) that was included in the original report is reproduced below.

The Potential Benefits of Developing Pressure Activated Sealant Technology

- Repair of inaccessible pipeline leaks
- Repair of pipeline leaks without a need to excavate
- Significant reduction in pipeline downtime
- Elimination of environmental problems caused by pipeline leakage and excavation
- Significant reduction in the cost of pipeline leak repairs
- Internal repair of pipeline leaks without restricting the host pipe ID

Table 1 - Comparison of Pipeline Sealing Methods

Repair Method	Advantages	Disadvantages
External	Restores Pipe Strength In-Service Pipeline Repair No Pipe ID Reduction	Excavation Risks & Costs
Remote/Robotic Welding	Internal, No Excavation No Pipe ID Reduction Can Restore Pipe Strength	Short Working Ranges &/or Unable to Transverse Bends Out-of-Service Repair
Fiber Reinforced Composite	Internal, No Excavation No Welding	Short Repair Sections Reduced Host Pipe ID Low Pressure Rating Out-of-Service Repair Time Consuming

Expandable Metal Patch	Internal, No Excavation No Welding High Pressure Rating	Reduced Host Pipe ID Coiled Tubing Deployed Limited Working Range Short Repair Sections Out-of-Service Repair
Internal Repair Sleeve	Internal, No Excavation No Welding	Reduced Host Pipe ID Low Pressure Rating Out-of-Service Repair Time Consuming
Pressure Activated Sealant	Internal, No Excavation No Welding Unlimited Working Range High Pressure Rating No Pipe ID Reduction Short Job Duration	Dependent on leak size /rate Min. Pressure Requirements Out-of-Service Repair

Collection of Current Field Data

We started with the report titled "Analysis of DOT Reportable Incidents for Gas Transmission and Gathering System Pipelines, 1985 through 1997"[vi]. This 13-year period was chosen because this was the time frame with the most complete data available. Additional data from the Office of Pipeline Safety reports as well as operator and service company input was added to aid in identifying 205 incidents from a possible 1,084 that would have been candidates for pressure activated sealant technology. This number affirmed that pressure activated sealant technology is a viable option to traditional external leak repairs.

In identifying these candidates we not only focused on incidents where Seal-Tite's technology could have been utilized, but where it would have been the optimum repair method. A database of the 205 incidents and the leak characteristics that defined them as applicable candidates for sealant technology was submitted. This data included types of defects, areas of defects, pipe sizes and materials, incident and operating pressures, ability of pipeline to be pigged and corrosion states.

During this stage of the project we made several good operator contacts by our participation in seminars, industry conferences and exhibitions and customer demos and presentations in the Gulf of Mexico and California. Although we were disappointed with operators' willingness to share information regarding leak rates, one operator in particular was extremely forthcoming with most of the other requested information. Some of the contacts made were targeted for the field test of sealant formulas and procedures.

Analysis of Current Field Data

The database[vii] constructed during Collection of Current Field Data was used as a basis in constructing applicable sealant test modeling.

For ease of reference, excerpts from the original Technical Topical Report, "Analysis of Current Field Data"[viii] is included below.

Candidates for pressure activated sealant technology were identified on the basis of several criteria, including: Accessibility/Economic Advantage, Leak Severity, Leak Geometry, Minimum Operating Pressure, and Leak Cause.

Accessibility/Economic Advantage: The more inaccessible the leak site, the greater the economic advantage. Our database focused on leaks where accessibility is difficult, time-consuming and costly. 198 incidents (96.6% of our 205 incident base) were either underground, under pavement or underwater.

Leak Severity and Geometry: While no actual leak rates were collected, we knew through previous field experience and testing that we can cure leaks in the range of 2.83 – 8.50 cubic meters per minute (100 – 300 scf per minute). Our incident base focused on cracks & pinholes, not ruptures, punctures or tears, which may be out of the range for sealant technology. Narrow leaks, which have more surface area to open area, are easier to seal and have longer seal longevity than circular leaks.

Minimum Operating Pressure: MAOP less hydrostatic (or atmosphere) needs to be near or greater than 200 psi for pressure activated sealant technology to be successful. Our testing focused on curing leaks with differentials from 1.28 MPa (185 psi) to 9.93 MPa (1440 psi).

Leak Cause: Weld and corrosion leaks accounted for 75.6% of our incident base and 43.8% of all 354 leaks. By focusing our testing on weld and corrosion leaks we were able to test a representative sampling of the majority of leaks that are applicable candidates for pressure activated sealant technology. Table 2 shows a breakdown by cause of the 354 incidents classified as leaks.

Table 2 – Leaks By Cause

	Number of Leaks by Cause	% of 205 Incident Base	% of All 354 Leaks
Defective Fabrication Weld	9	4.4%	2.5%
Defective Girth Weld	16	7.8%	4.5%
Defective Pipe Seam	12	5.9%	3.4%
External Corrosion	41	20.0%	11.6%
Internal Corrosion	77	37.6%	21.8%
	155	75.6%	43.8%

Creation of Simulated Leaks[ix]

The test model was constructed using 168.28 mm (6-5/8"), schedule 80 XS steel pipe with a wall thickness of 11 mm (0.432"), an internal diameter of 146 mm (5.761") and a Maximum Operating Pressure of 12.36 MPa (1,793 psi) MAOP.

Two gate valves along with twelve 25.4 mm (1") nipples were incorporated into the test model to achieve varied manipulations of pressure and isolation of sections and to allow for placement of pressure gauges, bleed-off valves, pressure pop-off valves, and ball valves for the injection and discharge of nitrogen, air, water and sealant. An overview of the test fixture is seen below in Drawing 1 with dimensions in Table 3.

Drawing 1: Test Fixture

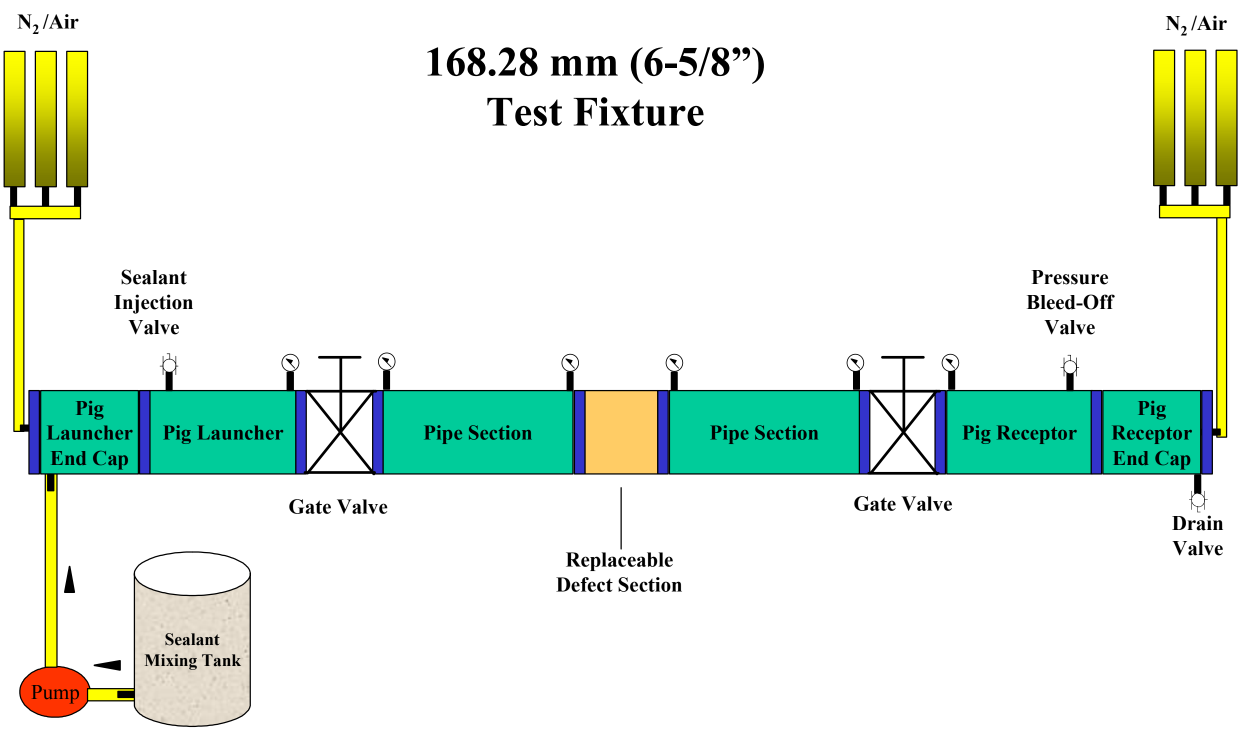


Table 3: Test Fixture Dimensions

	OD, mm	OD, in.
	168.280	6.625

	ID, mm	ID, in.
	146.000	5.761

	Length, mm	Length, in.
Launcher End Cap	543.000	21.375
Pig Launcher	1780.000	70.125
Gate Valve	565.000	22.250
Pipe Section	2530.000	99.500
Defect Section	1003.000	39.500
Pipe Section	2530.000	99.500
Gate Valve	565.000	22.250
Pig Receptor	1780.000	70.125
Receptor End Cap	543.000	21.375
Total Fixture Length	11,839.000	466.000
	11.8 meters	38 ft 10 in.

The test model included replaceable 3 foot defect sections. Each defect section simulated a type of defect identified during the analysis stage; Defective Fabrication Weld (DFW), Defective Girth Weld (DGW), Defective Pipe Seam (DPS), External Corrosion (EC) and Internal Corrosion (IC). As previously reported, these defects accounted for 75.6% of the incidents in our 205 incident base.

The DFW, DGW and DPS defects were represented by a single Weld Defect Section (Photo 1, page 8) that simulated common irregularities associated with welds including cracks and wormholes. Since 68.3% of the externally corroded pipe and 64.1% of the internally corroded pipe was described as either "localized pitting", "pinhole" or "pinhole with localized pitting", the EC and IC defects (Photo 2, page 8 and Photo 3, page 9 respectively) simulated localized pitting with pinholes. The defect section with two (2) pinholes (Photo 4 and Photo 5, page 9) represented defects with higher leak rates. The dimensions of the 100 cm (3.29 ft) defect sections are summarized in SI units in Table 4 and inches in Table 5 on page 7.

Table 4:

168.28 mm OD / 146 mm ID
Defect Dimensions
(mm)

Defect Section	Corrosion			Pinhole 1		***Pinhole 2***	
	Length	Width	Depth	OD	Depth	OD	Depth
External Corrosion							
Defect 1	102.00	50.80	8.00	1.60	11.00	na	na
Defect 2	82.50	31.80	8.00	na	na	na	na
Internal Corrosion							
Defect 1	102.00	76.20	3.05	1.60	11.00	na	na
Defect 2	82.50	76.20	3.05	1.60	11.00	na	na
Pinhole Defect (2)	na	na	Na	1.60	11.00	1.60	11.00
Weld Defect							
Crack	50.80	1.60	11.00	na	na	na	na
Wormhole	xx	xx	11.00	na	na	na	na

Table 5:

6-5/8" OD / 5.761" ID
Defect Dimensions
(inches)

Defect Section	Corrosion			Pinhole 1		***Pinhole 2***	
	Length	Width	Depth	OD	Depth	OD	Depth
External Corrosion							
Defect 1	4.00	2.00	0.315	0.063	0.432	na	na
Defect 2	3.25	1.25	0.315	na	na	na	na
Internal Corrosion							
Defect 1	4.00	3.00	0.120	0.063	0.432	na	na
Defect 2	3.50	3.00	0.120	0.063	0.432	na	na
Pinhole Defect (2)	na	na	na	0.063	0.432	0.063	0.432
Weld Defect							
Crack	2.00	0.063	0.432	na	na	na	na
Wormhole	xx	xx	0.432	na	na	na	na

Photo 1: Weld Defect

Photo 2: External Corrosion Defect

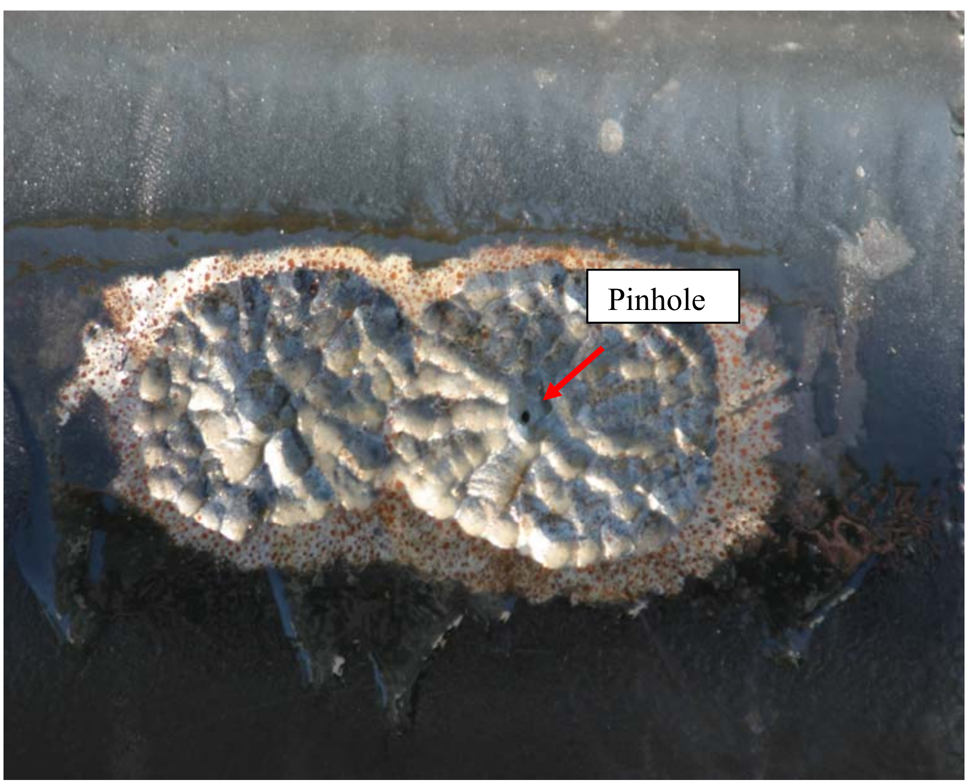


Photo 3: Internal Corrosion Defect

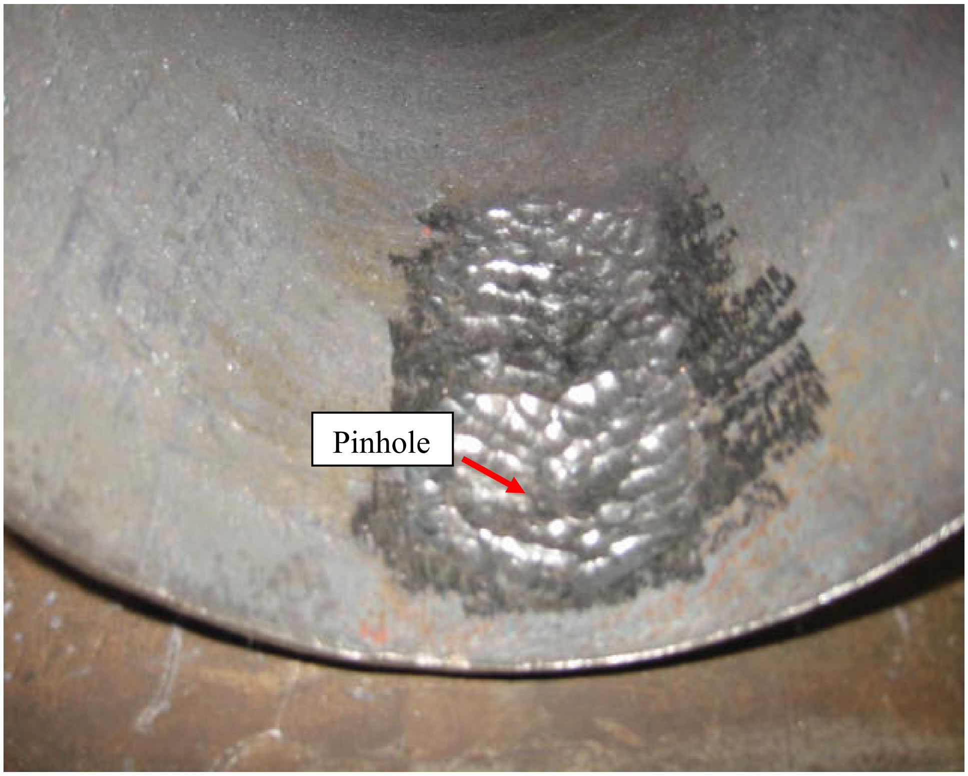


Photo 4: Pinhole Defect

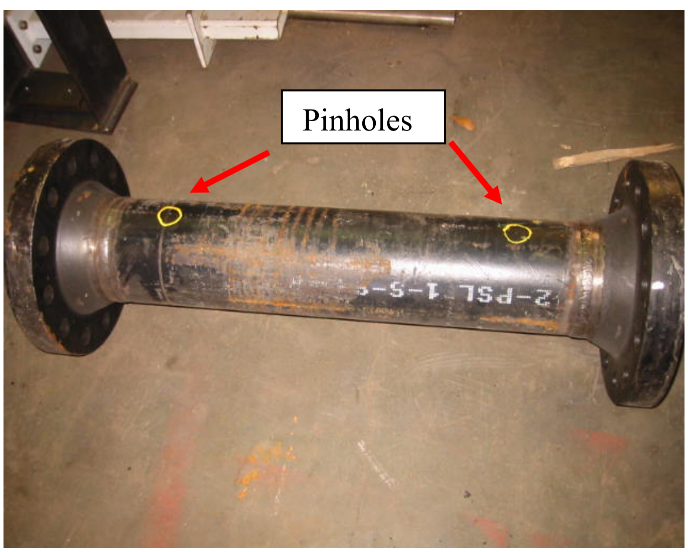


Photo 5: Pinhole Defect

Development of Sealant Formulas and Procedures[x]

In order to expand or enhance the capabilities of our pressure activated sealant technology to cure the leaks experienced in natural gas transmission pipelines, we needed to compare existing formulas and delivery methods to the types of leaks identified during the analysis stage of the project.

Since our experience in curing leaks in downhole applications has centered on liquid leak rates and not actual defect size we first needed to establish leak rates for each defect. We established leak rates with water, as well as nitrogen, providing a basis to correlate to past testing and operations. This data was then used to modify existing as well as develop new sealant formulations.

Liquid leak rates were established by first filling the test model with water and continuing pumping from a marked drum. Maximum rate was determined either by maximum pressure allowed or maximum output of pump and recorded at X psi. The pumping rate was then reduced and once stabilized, the appropriate pressure and rate was recorded. We continued this process until a representative amount of data points was collected. The Weld Defect only had 2 data points due to the extremely small leak rate.

Nitrogen leak rates were established by pressuring the test model to maximum psi (limited either by pipe strength or nitrogen tanks) and recording the pressure drop over time. The leak rate was then calculated by first solving for the volume of nitrogen needed to pressure the test model at initial pressure by utilizing:

$$P1*V1*Z1 = P2*V2*Z2$$
$$V1 = (P2*V2*Z2) / (P1*Z1)$$

We then solved for the change in nitrogen volume due to pressure drop over time by utilizing the same formula at the final pressure. The leak rate was then calculated as the difference between Initial Nitrogen Volume and Final Nitrogen Volume over Time.

The compressibility factors used in the calculations were derived from the Beattie-Bridgeman equation of state for real gases at 20°C as shown in Table 6.

Table 6
Compressibility of Nitrogen
at 293°K (20°C)

Pressure (MPa)	Pressure (psi)	Z-Factor
0.690	100	0.998
1.379	200	0.997
2.068	300	0.995
2.758	400	0.994
3.447	500	0.993
4.137	600	0.993
4.826	700	0.993

5.516	800	0.993
6.205	900	0.993
6.895	1,000	0.994
7.584	1,100	0.995
8.274	1,200	0.996
8.963	1,300	0.997
9.653	1,400	0.999
10.342	1,500	1.001

The results of the leak rate testing is summarized below in tables and charts for each defect type, showing liquid and gas leak rates in both SI and English units. Examples of the leak rate tests are shown below in Photo 6 and 7.

Photo 6:
Internal Corrosion Leak Rate Testing

Photo 7:
Pinhole Leak Rate Testing

Table 7: External Corrosion Leak Rates

Nitrogen					Water			
scf/min	scm/min	ΔP MPa	ΔP psi		l/min	gpm	ΔP MPa	ΔP psi
66	1.870	8.320	1,206		10	2.64	9.960	1,445
48	1.360	7.490	1,087		8	2.11	6.790	985
48	1.360	6.810	987		6	1.59	4.650	675
40	1.130	6.170	895		4	1.06	1.900	275
36	1.020	5.620	815					
33	0.934	5.120	743					
30	0.850	4.660	676					
26	0.736	4.070	590					
23	0.651	3.520	511					
20	0.566	3.210	465					
19	0.538	2.920	423					
18	0.510	2.650	385					
16	0.453	2.410	350					
15	0.425	2.190	318					
13	0.368	1.990	289					
12	0.340	1.810	262					
11	0.311	1.630	237					
10	0.283	1.480	215					
9	0.255	1.340	194					
9	0.255	1.210	175					
8	0.227	1.090	158					

Chart 1: External Corrosion Leak Rates

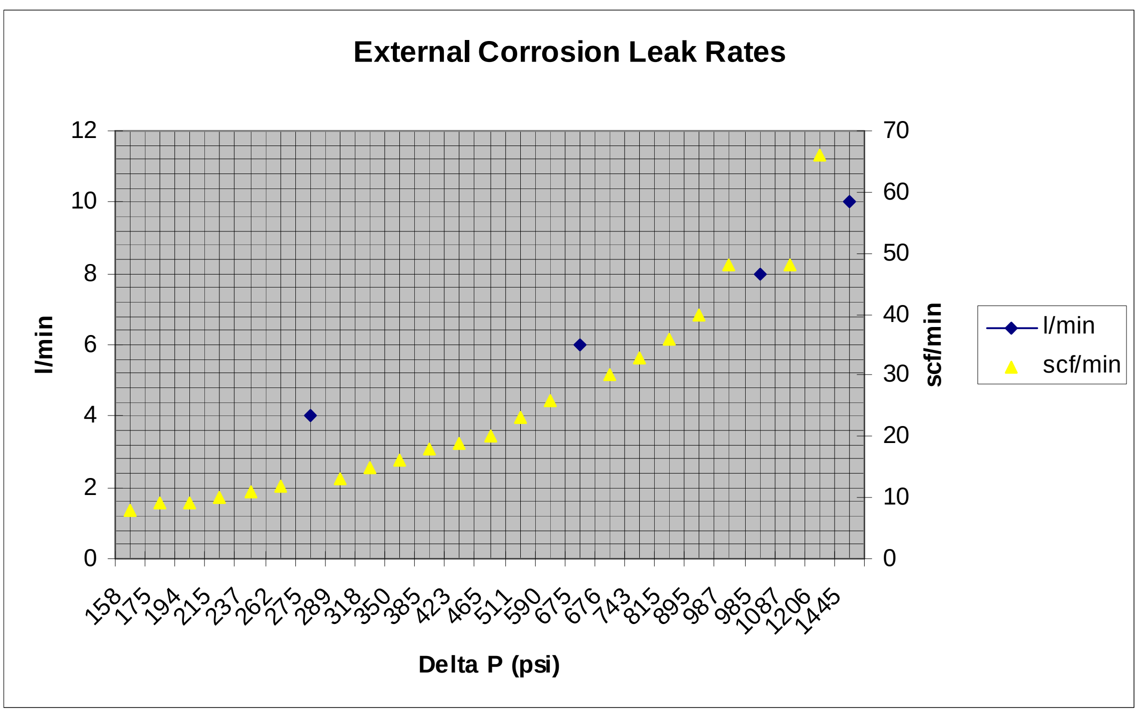


Table 8: Internal Corrosion Leak Rates

Nitrogen					Water			
scf/min	scm/min	ΔP MPa	ΔP psi		l/min	gpm	ΔP MPa	ΔP psi
79	2.240	8.230	1,193		10	2.64	9.550	1,385
56	1.590	7.250	1,052		9	2.38	6.930	1,005
47	1.330	6.510	944		6	1.59	4.520	655
42	1.190	5.870	851		5	1.32	2.550	370
35	0.991	5.050	733		4	1.06	1.620	235
30	0.850	4.320	627					
27	0.765	3.910	567					
25	0.708	3.530	512					
23	0.651	3.180	461					
20	0.566	2.870	416					
18	0.510	2.590	376					
17	0.481	2.340	339					
15	0.425	2.100	305					
13	0.368	1.800	261					
11	0.311	1.530	222					
10	0.283	1.370	199					
9	0.255	1.230	178					
9	0.255	1.100	159					

Chart 2: Internal Corrosion Leak Rates

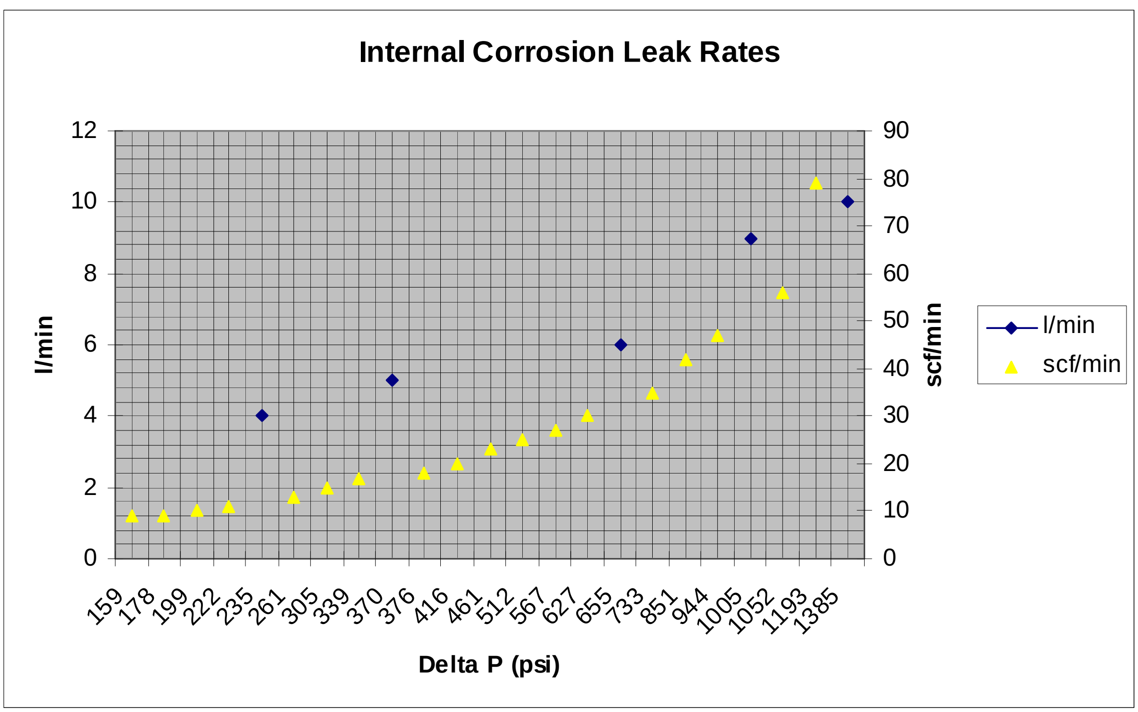


Table 9: Pinhole Leak Rates

Nitrogen					Water			
scf/min	scm/min	ΔP MPa	ΔP psi		l/min	gpm	ΔP MPa	ΔP psi
96	2.720	6.460	937		13	3.43	3.140	455
71	2.010	5.250	761		12	3.17	2.650	385
57	1.610	4.320	626		10	2.64	1.970	285
47	1.330	3.560	516		10	2.64	1.900	275
39	1.100	2.930	425		9	2.38	1.340	195
32	0.906	2.410	349		9	2.38	1.280	185
27	0.765	1.980	287					
23	0.651	1.610	234					
19	0.538	1.310	190					
16	0.453	1.060	154					
13	0.368	0.848	123					

Chart 3: Pinhole Leak Rates

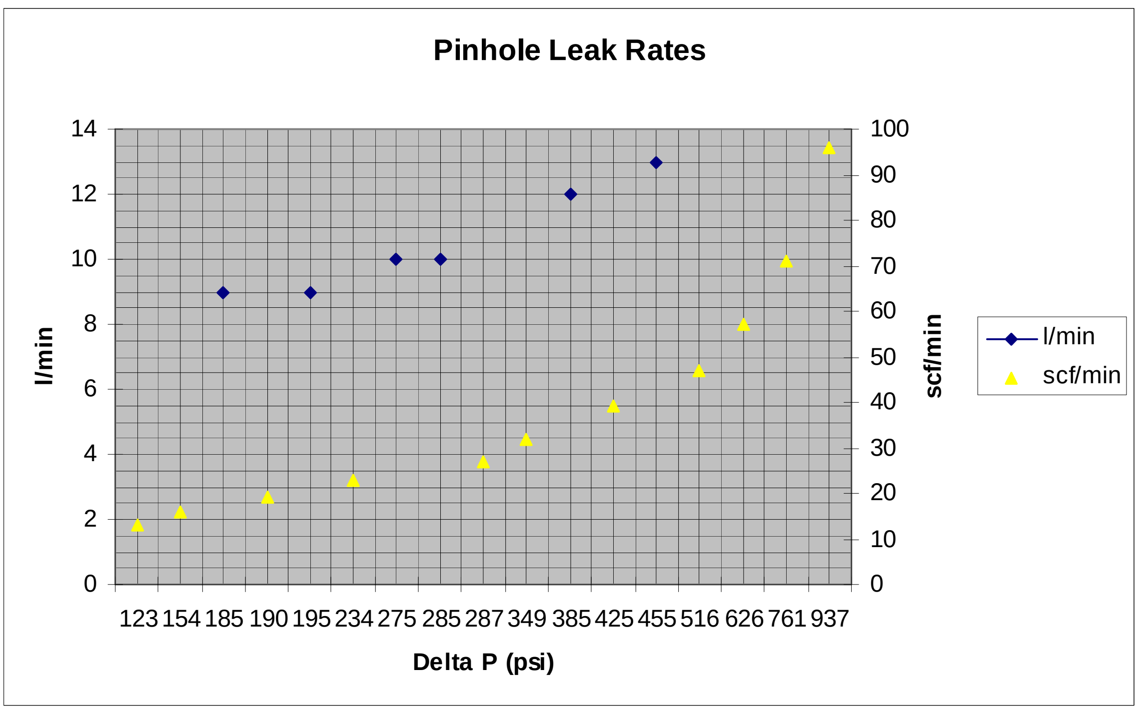
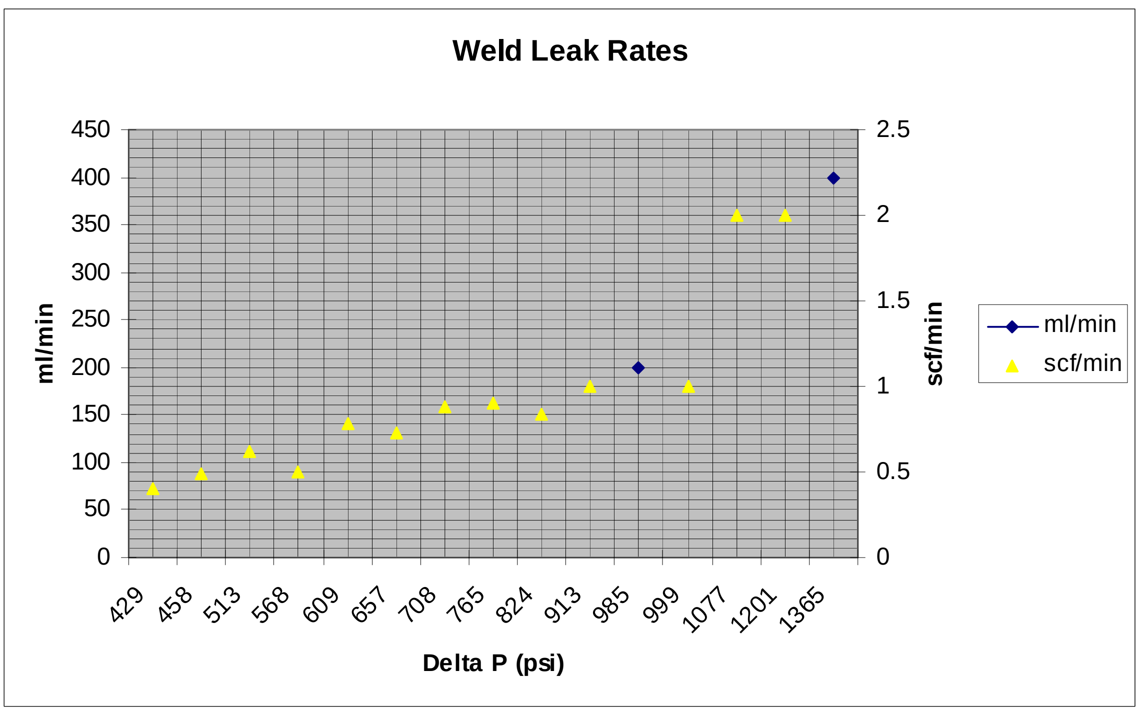


Table 10: Weld Leak Rates

Nitrogen					Water			
scf/min	scm/min	ΔP MPa	ΔP psi		l/min	gpm	ΔP MPa	ΔP psi
2.000	0.0566	8.280	1,201		0.4	0.11	9.410	1,365
2.000	0.0566	7.430	1,077		0.2	0.05	6.790	985
1.000	0.0283	6.890	999					
1.000	0.0283	6.290	913					
0.838	0.0237	5.680	824					
0.898	0.0254	5.270	765					
0.883	0.0250	4.880	708					
0.725	0.0205	4.530	657					
0.788	0.0223	4.200	609					
0.504	0.0143	3.920	568					
0.623	0.0176	3.540	513					
0.489	0.0138	3.160	458					
0.403	0.0114	2.960	429					

Chart 4: Weld Leak Rates



The leaks rates, though large, were not considered to be beyond Seal-Tite’s capabilities. Seal-Tite has previously cured downhole leaks in the 37.85 L (10 gal) per minute range. The critical factor was determined to be generating and maintaining a seal in a circular defect, as opposed to a split or crack. Circular defects are more difficult to seal since there is more open area than surface area. Also, the effect of pigging on seal integrity was unknown and needed to be explored in the full scale pipeline testing phase.

Sealing Simulated Leaks[xi]

Full Scale Pipeline Testing

There were three objectives for the full scale pipeline testing: First, to test the feasibility of transporting the sealant between two pigs; secondly, to test sealant formulations necessary to seal the leak(s); and finally, to test the ability of the newly formed seal to withstand the effects of pigging. Based on operator and service company input, two different wire brush pigs were utilized in the testing: the Crisscross Wire Brush (Photo 10, page 18) for use in coated pipe and the Super Javelina Brush (Photo 11, page 18) for aggressive scraping in non-coated pipe.

In addition to the apparatus as described under Creation of Simulated Leaks, each end-cap was fitted with a manifold for the injection and regulation of nitrogen.

Testing Procedure:

1. With test model pressure bled to zero remove the launcher end-cap.
2. Close launcher gate valve and insert lead pig to gate valve.
3. Insert trailing pig into pipe, ensuring that pig does not cross sealant injection valve. Reinstall launcher cap.
4. Inject sealant volume between pigs in launcher section by pumping sealant into sealant injection ball valve.
5. Close sealant injection valve.
6. Pressure pipeline system to 200 psi with nitrogen from both receptor and launcher ends simultaneously.
7. Open launcher gate valve.
8. Move pigs & sealant train by regulating nitrogen pressure on receptor side through needle valve. Approximately 20 psi less on receptor side than launcher side moves pigs/sealant train to receptor.
9. When lead pig is across leak site (indicated by sealant extruding from defect in early tests – indicated by electronic pig indicator on latter tests) open receptor needle valve fully to maintain equal pressure on upstream and downstream side of pigs.
10. Increase pressure until initial seal is formed. Shut in both receptor and launcher end-cap ball valves simultaneously to keep sealant train from moving pass leak site. Hold pressure for X minutes.
11. Open both receptor and launcher ball valves simultaneously and utilize needle valves to incrementally increase pressure. Continue the pressure and hold cycles until final 9.65 MPa (1440 psi) seal is achieved.
12. Shut-in for cure cycle. Note initial shut-in pressure.
13. After designated curing time note final shut-in pressure. If final pressure is less than initial shut-in pressure retest seal by re-pressuring system to initial shut-in pressure from both receptor and launcher sides simultaneously. If seal maintained integrity proceed to Step 14. If seal broke then End Test.
14. Open drain valve and needle valves on receptor end and bleed pressure down to move pigs and sealant to receptor.
15. When pigs are in receptor (indicated by a reduction or elimination of pressure & fluid bleed-off) close drain and needle valves.

16. Re-pressure system from launcher side to final shut-in pressure to confirm trailing wiper pig did not destroy seal integrity. If seal maintained integrity proceed to Step 17. If seal broke then End Test.
17. Bleed pressure off test model through receptor side pressure bleed-off valve. Remove launcher cap and insert wiper assembly. Reinstall launcher cap.
18. Leave pressure bleed-off valve open (upstream of defect section).
19. Pressure launcher end and move pigs pass defect section.
20. Close pressure bleed-off valve and re-pressure system to final shut-in pressure. If seal maintained integrity proceed to Step 21. If seal broke then End Test.
21. Bleed pressure off test model. Remove launcher cap and insert scraper assembly.
22. Leaving a receptor side pressure bleed-off valve open, pressure launcher end and move pigs pass defect section.
23. Close pressure bleed-off valve and re-pressure system to final shut-in pressure. Record if seal maintained integrity or if seal broke. End Test.

The 32 kg/m^3 (2 lbm/ft^3) density yellow swab pig (Photo 8) was tested for use in multi-diameter pipelines where more rigid pigs are not as easily transported. During preliminary testing, it was noted that while straddling the liquid sealant the swab pig acted like a sponge and became saturated, resulting in the nitrogen creating channels around the pigs and subsequently not allowing the nitrogen to move the sealant train. Higher gas rates that are experienced in the field most likely would have moved the sealant train.

The 80 kg/m^3 (5 lbm/ft^3) density foam disc pigs (Photo 9) on the other hand formed a tight seal against the pipe internal diameter and were very easily moved by nitrogen with only a 20 psi differential.

Photo 8
2 lbm/ft^3 Yellow Swab Pig with Nose

Photo 9
5 lbm/ft^3 Foam Disc Pig with Nose

Initial tests were performed by gauging when the sealant train crossed the defect area by observation of sealant extruding through the leak site. Later tests were performed utilizing electronic pig detectors. Both methods were effective in aligning the sealant train across the defect.

We were successful in obtaining a 9.93 MPa (1440 psi) seal in all seven tests conducted, with leak rates ranging from a low of 0.0114 scm/min (0.403 scf/min) to a high of 2.720

scm/min (96 scf/min) at 2.96 MPa (429 psi) and 6.46 MPa (937 psi) respectively, and with leak orientation varying from 6 o'clock low side to 12 o'clock high side.

Referring to Table 11, we concluded that the effects of additional wiping and/or scraping were directly related to defect geometry. External Corrosion (EC) leaks with a large amount of external wall loss and an inverted funnel configuration were the least resistant to the effects of pigging; Pinhole and Weld leaks, with no loss of wall thickness were more resistant; and Internal Corrosion (IC) leaks, with a funnel configuration and an internal "valley" for sealant reserve were the most resistant.

Table 11: Results of Seal Integrity after Pigging

	Trailing Sealant Pig	Wiper Assembly	Scraper Assembly
Test 5: EC I	Passed	Not Run	Failed[1]
Test 6: EC II	Passed	Failed[2]	NA
Test 7: EC III	Failed	NA	NA
Test 4: IC I	Passed	Not Run	Passed
Test 3: Pinhole I	Failed[3]	NA	NA
Test 8: Pinhole II	Passed	Passed[4]	Not Run[5]
Test 9: Weld I	Passed	Passed[6]	Failed[7]

[1]wiper/Crisscross wire-brush scraper (Photo 10)/wiper
[2,4,6] (2) wipers
[3] Low pressure seal 5.52 MPa (800 psi) and short curing time (18 minutes)
[5]At 10 MPa (1450 psi) leak started to bubble. Most likely seal would not have withstood effects of scraping
[7]wiper/Super Javelina wire-brush scraper (Photo 11)

Note: The first two tests, which are not displayed in Table 11 were preliminary tests to determine the volume of sealant needed to compensate for loss of sealant volume due to hoses and pump and to determine the optimum pig type to minimize sealant bypass.

Photo 10: 5 lbm/ft^3 Foam Crisscross Wire Brush Pig with Nose

Photo 11: 5 lbm/ft^3 Foam Super Javelina Brush Pig with Nose

From the data collected during this testing stage the following conclusions were made:

1. Foam Disc pigs are the preferred pigs for isolation and transporting sealant to the leak site.
2. All leaks were successfully sealed to 9.93 MPa (1440 psi).
3. Leak orientation had no effect on quality of seal generated.
4. At the low curing pressure of 9.93 MPa (1440 psi) pigging did affect seal integrity.
5. Leak geometry played a large role in maintaining seal integrity after pigging operations.
6. The effect of curing time on seal quality of a low pressure seal was still unknown.

Lab Tests to Determine the Effect of Curing Time on Seal Quality

The objective of these tests was to determine if length of curing time had a favorable effect on a seal generated at 9.93 MPa (1440 psi). By conducting these tests in a controlled environment, pressure fluctuations due to temperature effects were minimized. In order to minimize the effect that "additional" curing time may have had, we reduced the amount of pressure stages or cycles by immediately bringing the pressure up to 9.93 MPa (1440 psi).

The defect sections utilized were the same as previously described under Creation of Simulated Leaks. In addition, as seen in Photo 12 and Photo 13 below, the defect sections were fitted with a blind flange on bottom and a ported flange with a ball valve, needle valve with 6.35 mm (¼") JIC connection for nitrogen injection, and gauge on top.

Photo 12: Full Scale Lab Fixture

Photo 13: Full Scale Lab Fixture

Testing Procedure:

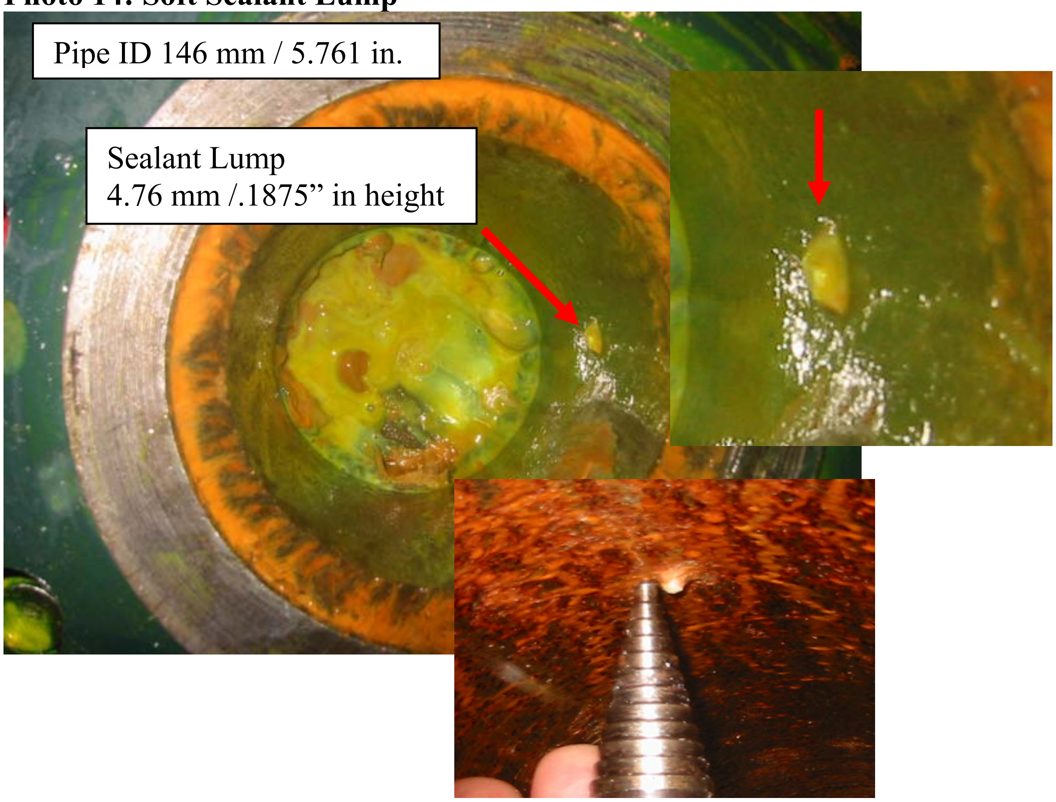
1. Install blind flange on bottom of defect section (bottom is end with defect, except for pinhole defect which had defects at each end).
2. Stand defect section vertical and fill to top with sealant formulation.
3. Install flange with ball valve, needle valve with nitrogen connection and gauge on top.
4. Inject nitrogen until pressure reaches 9.93 MPa (1440 psi).
5. Shut-in and monitor for 30 minutes.
6. Continue steps 4 and 5 until zero bleed-off after 30 minutes.
7. Shut-in for designated time (defects assign alphabetically):
    a. External Corrosion 48 hours
    b. Internal Corrosion 96 hours
    c. Pinholes 144 hours
    d. Weld 192 hours
8. After shut-in period re-pressure system to 9.93 MPa (1440 psi), if needed, to verify seal integrity. If pressure held proceed to step 9. If pressure didn't hold then End Test.

9. Bleed-off pressure and open assembly. Observe and note.

This testing stage indicated that at a sealing pressure of only 9.93 MPa (1440 psi), curing time had no effect on the quality of the seal generated. The sealant formulations necessary to seal the pinhole sizes that were represented in our testing required particulates (bits or flakes) that are forced into the defect and, under pressure, expand to form a bridge that allows the polymers and monomers to create a seal. In the weld leak, sealant penetration is also required to aid in generating a seal that can withstand the effects of scraping.

The soft lump of sealant in the pinhole (Photo 14) indicated that we were not achieving penetration into the leak site with the particulates and the seal that was being generated was a superficial seal across the interior wall. The same was concluded on the weld leak. Although there was not an internal soft lump of sealant on the weld leak due to the low leak rate, there was also no indication of cured sealant extruding through the leak site.

Photo 14: Soft Sealant Lump



For the next stage we branched off our testing in two directions:

1. To test less aggressive, non-particulate formulations in order to achieve deeper penetration in the weld defect.
2. To evaluate our most aggressive non-particulate sealant on pinhole defects to use as a benchmark in developing other formulations.

Lab Tests to Determine Optimum Sealant for Weld Penetration

The objective of these tests was to determine the optimum sealant formulation to penetrate the small leak rate that was exhibited by the weld defect.

The defect sections used were the same as previously described in <u>Lab Tests to Determine the Effect of Curing Time on Seal Quality</u>.

Testing Procedure:

1. Install blind flange on bottom of weld defect section (bottom is end with defect).
2. Stand defect section vertical and fill above defect with sealant formulation.
3. Install flange with ball valve, needle valve with nitrogen connection and gauge on top.
4. Increase pressure until initial seal is formed. Shut in for <u>X</u> minutes
5. Increase pressure and shut-in in increments until final 9.93 MPa (1440 psi) seal is achieved with no bleed-off.

    Note: Atomization procedure injected sealant continuously until final pressure was reached
6. Shut-in for 24 hour cure cycle. Note initial shut-in pressure.
7. After designated curing time note final shut-in pressure. If final shut-in pressure is less than initial shut-in pressure retest seal by re-pressuring system to initial shut-in pressure. If seal maintained integrity proceed to next step. If seal broke then End Test.
8. Bleed-off pressure and open assembly.
9. Observe and note.
10. Pig defect.
11. Observe and note.
12. Reseal test fixture and re-pressure system to 9.93 MPa (1440 psi).
13. If re-pressure test fails record pressure and End Test. If seal retained integrity repeat steps 10, 11 & 12 with a different pig type. Continue steps until re-pressure test fails.
14. Inject Seal-Tite's Valve-Flush into leak to remove any cured sealant.
15. Set-up fixture for next test.

This test utilized six different formulations. The test data showed that only when using Gly-Flo "G" sealant, was enough penetration achieved to withstand the effects of the wiper pigs. The scraper run failed at maximum pressure 9.93 MPa (1440 psi) with the most aggressive wire brush pig available. A run with a lesser aggressive scraper pig may have had better results.

In comparing this test to the weld defect test done on the full scale pipeline model utilizing 9:1 Flo-Seal-P (particulate based) as the sealant, the Gly-Flo "G" sealant had better results after scraping. With no particulates, the Gly-Flo "G" was able to achieve deeper penetration into the weld leak before activation.

It can also be noted that Gly-Flo "G" had a strip of medium consistency, as seen in Photo 15, page 23. The other sealant formulations resulted in either a soft lump, which was wiped off with the swab wiper pig (Photo 16 and Photo 17, page 23), or a hardened strip of sealant, which resulted in the seal being pulled out of the defect by the wiper pig.

Photo 15:
Gly-Flo "G" Sealant Strip

Photo 16:
Soft Sealant Lump

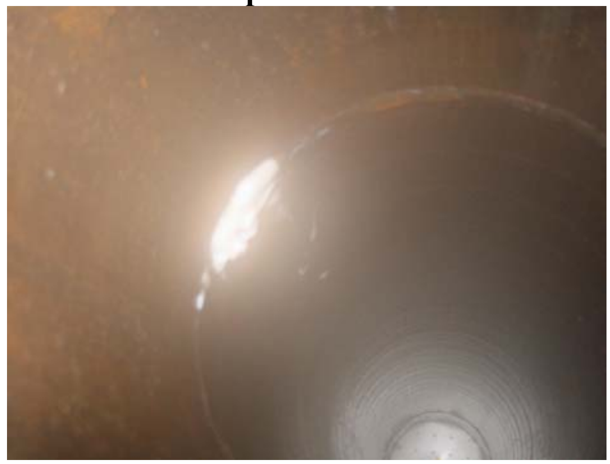


Photo 17: Soft Sealant Lump Removed by Pigging

Flex-Plug Testing

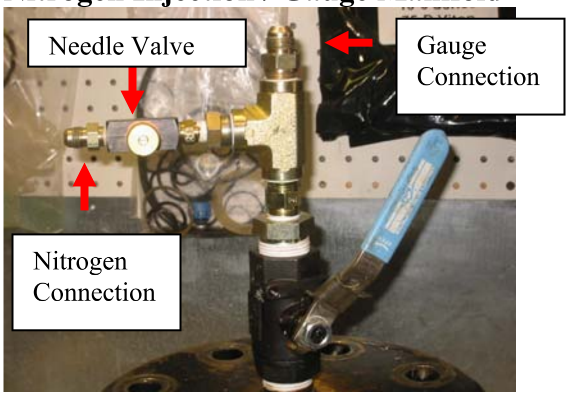
The objective of these tests was to utilize Flex-Plug, our most aggressive, non-particulate sealant, for:

1. Determining if 1.59 mm (1/16”) pinholes were within our capabilities of generating a seal that could withstand the effects of scraping.
2. Establishing the maximum pinhole size that is within our capability for generating a seal that could withstand the effects of scraping if the 1.59 mm (1/16”) pinholes tests failed.
3. Aiding in determining what modifications needed to be made to sealant formulations in order to enhance the ability to seal pinholes in pipe body, pipe welds, and internal corrosion defects.

The internal corrosion defect used in this testing stage was the same described in Creation of Simulated Leaks. For the pinhole defects in varying sizes we made 114.3 mm OD x 97.2 mm ID x 152.4 mm L (4-1/2” OD x 3.826” ID x 6” L) Schedule 80 test fixtures. The fixtures had a steel plate on bottom that would allow the test fixture to stand vertically and a ported flange on top for connection of a nitrogen injection and gauge manifold (Photo 18 and Photo 19). The pinhole defects tested were 1.59 mm (1/16”), 1.19 mm (3/64”), 0.79 mm (1/32”) and 0.40 mm (1/64”) holes in pipe body and 1.59 mm (1/16”) hole in pipe weld.

Photo 18:
114.3 mm (4-1/2”) Test Fixture

Photo 19:
Nitrogen Injection / Gauge Manifold



Testing Procedure:

1. With defect at 6 o’clock inject Flex-Plug sealant into defect hole with syringe.
2. Scrape internally to remove excess sealant.
3. Let stand to atmosphere for 24 hours.
4. Pressure test to 9.93 MPa (1440 psi). If pressure test fails record pressure and End Test. If seal retained integrity proceed to Step 5.
5. Scrape defect. Re-pressure to 9.93 MPa (1440 psi). Note and record results.

The two 1.59 mm (1/16”) pinholes (in pipe body and pipe weld) failed after scraping. The remaining four tests were successful in obtaining a seal that could withstand the effects of scraping. The only 1.59 mm (1/16”) pinhole that maintained integrity was on an internal corrosion defect (Photos 20, 21, 22 and 23). This confirms our conclusion under Full Scale Pipeline Testing that the geometry of internal corrosion defects is advantageous for resisting the effects of pigging.

The possibility of sealing 1.59 mm (1/16”) pinholes in other defect types and having the seal maintain integrity after scraping will require a sealant formulation with particulates and the ability to achieve penetration into the defect before activation. Testing also showed that the 1.19 mm (3/64”), 0.79 mm (1/32”) and 0.40 mm (1/64”) pinholes are within our capability but new less aggressive sealant formulations that can be transported between pigs needed to be developed.

Photo 20:
Internal Corrosion Defect - Bare

Photo 21:
Internal Corrosion Defect with Flex-Plug

Photo 22:
External View before Flex-Plug

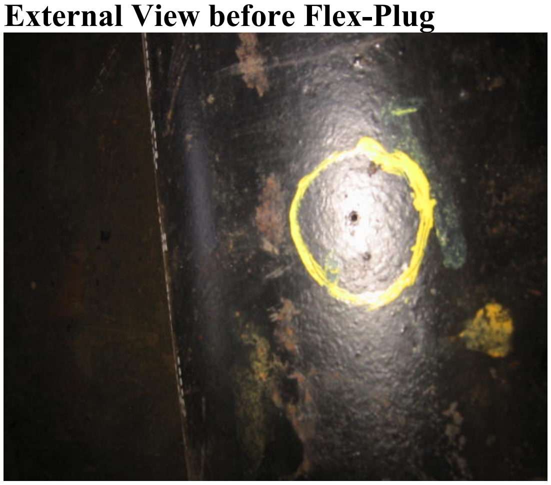
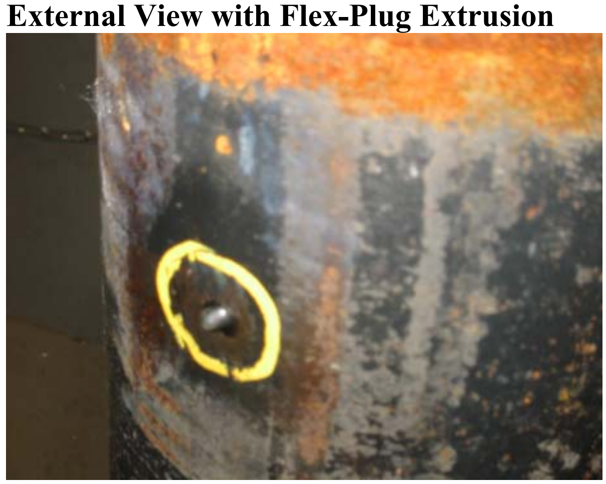


Photo 23:
External View with Flex-Plug Extrusion



Lab Tests to Determine Optimum Sealant for Pinholes

The objective of this stage was to determine the optimum sealant for curing pinholes by utilizing the data collected during the previous tests.

The apparatus utilized during this stage was the same as described under Flex-Plug Testing.

Testing Procedure:

1. Stand test fixture vertical and fill with sealant formulation.
2. Install flange with ball valve, needle valve with nitrogen connection and gauge on top.
3. Increase pressure until initial seal is formed. Shut in for X minutes
4. Increase pressure and shut-in in increments until final 9.93 MPa (1440 psi) seal is achieved with no bleed-off.

   Note: Atomization procedure attempted to inject sealant continuously until maximum pressure is reached
5. Shut-in for cure cycle. Note initial shut-in pressure.
6. After designated curing time note final shut-in pressure. If final shut-in pressure is less than initial shut-in pressure retest seal by re-pressuring system to initial shut-in pressure. If seal maintained integrity proceed to next step. If seal broke then End Test.
7. Bleed-off pressure and open assembly.
8. Observe and note.
9. Pig defect with rubber disc pig (Photo 24).
10. Observe and note.
11. Reseal test fixture and re-pressure system to 9.93 MPa (1440 psi).
12. If re-pressure test fails record pressure and End Test. If seal retained integrity repeat steps 10, 11 & 12 with a different pig type. Continue steps until re-pressure test fails.
13. Inject Seal-Tite's Valve-Flush into leak to remove any cured sealant.
14. Set-up fixture for next test.

Photo 24: Rubber Disc Pig

When we were able to generate a seal with a non-particulate and predominately non-particulate sealant (Gly-Flo "G" and Gly-Flo/Flo-Seal-P Mixture respectively) the results after pigging were not good. The only time we were able to establish a seal that, after pigging, retained some integrity was with Tur-Flo, a particulate based sealant.

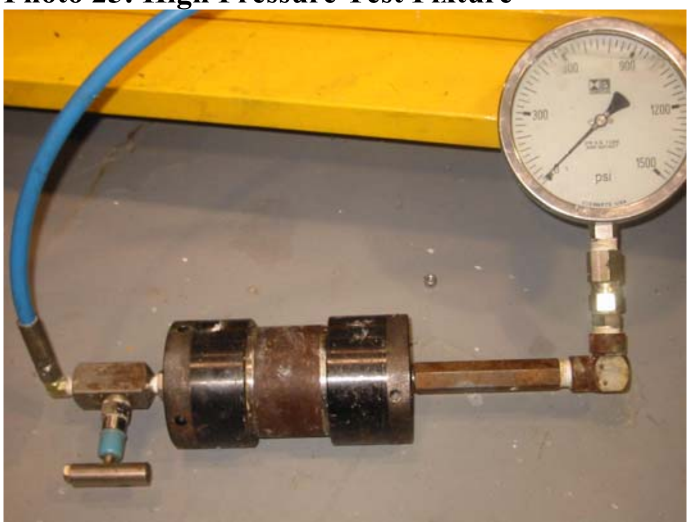
The next testing stage tested the theory that Flo-Seal-P, at higher curing pressures, would seal the 1.59 mm (1/16") pinholes, and retain integrity after pigging. If this theory proved out then we would attempt to modify the Flo-Seal-P formula to achieve the same results at pipeline pressures.

High Pressure Testing

The objective of this testing stage was to confirm or refute our theory that a seal establish in 1.59 mm (1/16”) pinholes with Flo-Seal-P at pressures indicative of downhole petroleum applications would withstand the effects of pigging; and if this theory was proven then proceed with modifying sealant formulation to achieve the same results at pipeline pressures.

An 88.9 mm OD x 73.7 mm ID x 177.8 mm L (3-1/2” x 2.90” x 7”) 4140 carbon steel test fixture was made with a 1.59 mm (1/16”) pinhole in pipe body. End caps (57.2 mm long) were threaded on each end for an overall length of 190.5 mm (7-1/2”). Each end cap was threaded to accept a gauge on one end and a needle valve with a connection for nitrogen injection on the opposing end, as seen in Photo 25.

Photo 25: High Pressure Test Fixture



Testing Procedure:

1. With injection side end cap removed and pinhole at 6 o’clock fill cylinder with sealant.
2. Install nitrogen injection end cap and begin injecting nitrogen.
3. Increase pressure in increments and hold for X minutes.
4. Continue pressure cycles until seal holds at 34.47 MPa (5,000 psi).
5. Bleed pressure from cylinder and open.
6. Drain remaining liquid sealant and observe and note seal.
7. Remove approximately ½ of seal height and re-pressure assembly to 34.47 MPa (5,000 psi). If fails then End Test. If pressure held proceed to Step 8.
8. Remove ½ of remaining seal and re-pressure cylinder to 34.47 MPA. If fails then End Test. If pressure held proceed to Step 9.
9. Remove all of remaining seal on interior wall and observe. Re-pressure cylinder to 34.47 MPa. If fails then End Test. If pressure held proceed to Step 10.
10. Run wire brush across defect 8 times to simulate a wire brush pig run. Observe and note. Re-pressure cylinder to 34.47 MPa. If fails then End Test. If pressure held proceed to Step 11.

11. Repeat the above steps with different sealant formulations to achieve the same results at pipeline pressures 9.93 MPa (1440 psi).

The first test proved that the sealant formulation used during the Full Scale Pipeline Testing was adequate for sealing 1.59 mm (1/16") pinhole leaks and generating a seal that could maintain integrity after pigging when higher sealing pressures were applied. The higher pressure of 34.47 MPa (5,000 psi) forced a particulate unit that, under pressure, expanded and formed a platform for the sealant to bridge across.

The last four seven tests were unsuccessful in finding the right combination of particulate size and sealant formula to achieve the same results with pipeline pressures of 9.93 MPa (1440 psi).

We believe that development of such a combination was possible but beyond the scope of this project.

CONCLUSION

Through research of current state of the art pipeline repair methods and the collection of current field data we conservatively concluded that there is a need and an opportunity for sealant repair technology. Through analysis of the data collected we identified a representative sampling of the type of leaks and their characteristics that are experienced in gas transmission pipelines.

Starting with 354 leaks out of 1,084 incidents in a 13 year period we identified 205 leaks that were candidates for our sealant technology. This number affirmed that pressure activated sealant technology is a viable option to traditional external leak repairs.

Candidates identified for pressure activated sealant technology were based on several criteria: Accessibility/Economic Advantage, Leak Severity, Leak Geometry, Minimum Operating Pressure, and Leak Cause.

Accessibility/Economic Advantage: The more inaccessible the leak site, the greater the economic advantage. Our database focused on leaks where accessibility was difficult, time-consuming and costly. 198 incidents (96.6% of the 205 incident base) were either underground, under pavement or underwater.

Leak Severity and Geometry: While no actual leak rates were collected, we know through previous field experience and testing that we could cure leaks in the range of 2.83 – 8.50 cubic meters per minute (100 – 300 scf per minute). Our incident base focused on cracks & pinholes, not ruptures, punctures or tears, which may have been out of the range for sealant technology. Narrow leaks, which have more surface area to open area, are easier to seal and have longer seal longevity than circular leaks.

Minimum Operating Pressure: MAOP less hydrostatic (or atmosphere) needs to be near or greater than 200 psi for pressure activated sealant technology to be successful. Our testing focused on curing leaks with differentials from 1.28 MPa (185 psi) to 9.93 MPa (1440 psi).

Leak Cause: Weld and corrosion leaks accounted for 75.6% of the incident base and 43.8% of all 354 leaks. By focusing our testing on weld and corrosion leaks we would be testing a representative sampling of the majority of leaks that were applicable candidates for pressure activated sealant technology.

This representative sampling was the basis for our test modeling.

In order to expand or enhance the capabilities of our pressure activated sealant technology to cure the leaks experienced in natural gas transmission pipelines, we needed to compare existing formulas and delivery methods to the types of leaks identified during the analysis stage of the project.

Since our experience in curing leaks in downhole applications has centered on liquid leak rates and not actual defect size we first needed to establish leak rates for each defect. We established leak rates with water, as well as nitrogen, providing a basis to correlate to past testing and operations. This data was then used to modify existing as well as develop new sealant formulations.

The leaks rates, though large, were not beyond our capabilities. We successfully sealed every defect to 9.93 MPa (1440 psi) both on the full scale pipeline test model between two pigs and in the lab utilizing test fixtures of different configurations. The difficulty was achieving a seal that could resists the effects of wiper and scraping pigs for all defects.

By testing the defects in a controlled environment, at different sealant curing times, it was shown that curing time had no effect on improving seal quality at pipeline pressures; the sealant was still not penetrating the defect properly prior to activation. The testing needed to split into two directions: one, for the weld defect that exhibits a very low leak rate and another for the pinhole based defects where larger leak rates were exhibited.

With the weld defect a lesser aggressive sealant formulation was developed, Gly-Flo "G", which yielded better results than the earlier 9:1 Flo-Seal-P that was utilized on the full scale pipeline testing.

On the pinhole based leaks our most aggressive non-particulate sealant, Flex-Plug, could not maintain a seal to 9.93 MPa (1440 psi) on a 1.59 mm (1/16") pinhole, except on an Internal Corrosion defect. Flex-Plug was able to successfully seal 1.19 mm (3/64"), 0.79mm (1/32") and 0.40 mm (1/64") pinholes to 9.93 MPa (1440 psi).

During the next test stage we tried different sealant formulations of non-particulate and non-particulate / particulate combinations with little success.

Then, going back to our past experience in sealing downhole leaks we tested our original formulation of 7:1 Flo-Seal-P at a higher pressure of 34.47 MPa (5,000 psi) with outstanding results. From this data we knew that to accomplish the same results we needed to inject a pressure expandable particle into the defect hole at pipeline pressures to act as a platform for the sealant to bridge across. To date, we have not been successful in modifying sealant formulas and particulate sizing to achieve the same results at typical pipeline pressures of 9.93 MPa (1440 psi) or less.

In summary, pressure activated sealant technology can be considered a viable option for pipeline leak repairs under the right circumstances of pressure, leak type and pigging requirements, with the optimum chance of long-term sealant success in pipelines which exhibit relatively high differential pressure and are not subjected to a rigorous pigging program.

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LIST OF ACRONYMS AND ABBREVIATIONS

Note: SI is an abbreviation for Le Systeme International d'Unites.

ºC	Degrees Celsius
cm	Centimeters
DFW	Defective Fabrication Weld
DGW	Defective Girth Weld
DOT	Department of Transportation
DPS	Defective Pipe Seam
EC	External Corrosion
ºF	Degrees Fahrenheit
ft	Foot
gal	Gallon
gpm	Gallons per Minute
IC	Internal Corrosion
ID	Internal Diameter
in	Inch
ºK	Degrees Kelvin
kg/m^3	Kilograms per Cubic Meter
L, l	Liter
lbm/ft^3	Pounds per Cubic Foot
lbs	Pounds
l/min	Liters per Minute
M	Meter
MAOP	Maximum Allowable Operating Pressure
mm	Millimeter
MPa	Megapascal
ml/min	Millimeter per Minute
N_2	Nitrogen
OD	Outside Diameter
ΔP	Pressure Differential
P_1, P_2	Initial Pressure and Final Pressure
Psi	Pounds per Square Inch
Scf	Standard Cubic Feet
scf/min	Standard Cubic Feet per Minute
scm/min	Standard Cubic Meter per Minute
V_1, V_2	Initial Volume and Final Volume
Z_1, Z_2	Initial and Final Compressibility Coefficient