Battelle

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Final Report

Effectiveness of Hydrostatic Testing for Assessing the Integrity of ERW and Flash-weld Pipe Seams

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January 15, 2013

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on

EFFECTIVENESS OF HYDROSTATIC TESTING FOR ASSESSING THE INTEGRITY OF ERW AND FLASH-WELD PIPE SEAMS

to

BATTELLE

AS THE DELIVERABLE OF SUBTASK 1.2 ON
U.S. DEPARTMENT OF TRANSPORTATION
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January 15, 2013

by

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EXECUTIVE SUMMARY

Six case studies involving extensive, repeated hydrostatic testing to assure electric resistance welded (ERW) and flash-weld seam-integrity are presented and analyzed in this document. These six cases represent 2,096 miles of pipelines in hazardous liquid service. The purpose of this study was to evaluate the effectiveness of hydrostatic testing as a means of assuring the integrity of ERW and flash-weld pipe seams.

The effectiveness of hydrostatic testing is probably best demonstrated when defects that were enlarging in-service fail during the test. In these cases, the test failures can be considered prevented in-service failures. Numerous examples of test failures examined herein fit in this category. Furthermore, when repeated tests have resulted in decreasing numbers of subsequent test failures and in-service failures, then one can conclude that testing has improved the integrity of the pipeline by eliminating potentially injurious flaws.

On the other hand, a significant limitation of hydrostatic testing is demonstrated when an in-service failure occurs shortly after the test. When this has occurred, and an operational pressure excursion can be completely ruled out, the ineffectiveness of the test has been attributed to a combination of circumstances and features resulting in accelerated defect growth rates. Two such examples of test failures examined herein fit in this category. In these circumstances, a combination of in-line inspection (ILI) and hydrostatic testing could possibly outperform either assessment method conducted individually if the ILI is able to detect and classify the features that led to increased growth rates, and the hydrostatic test is able to confirm that no injurious features were missed by ILI.

With regard to small leaks such as from penetrators or pinholes in ERW and flash-weld seams, these leaks might not be prevented by either hydrostatic testing or ILI. The reason is the features are too short to be reliably detected by ILI and they may not leak during a pressure test.

The effectiveness of hydrostatic testing is sometimes shadowed by the notion that the test itself could cause damage to subcritical flaws. The pressure reversal phenomenon observed during some hydrostatic tests is proof that subcritical flaw extension can occur during the test. A pressure reversal is said to occur when a test break occurs at a lower pressure than the test segment experienced on a previous pressurization attempt. Fortunately, the likelihood of a pressure reversal occurring that could affect the integrity of a pipeline has been shown to be extremely small, and the likelihood is minimized by increasing the margin between the test pressure and the operating pressure.

In summary, hydrostatic testing for assuring the integrity of ERW and flash-weld pipe seams can be an effective assessment method provided that:

- The test intervals are short enough to prevent in-service failures between tests in pipelines where a time-dependent seam-integrity-degradation mechanism exists such as pressure-cycle-induced fatigue. This requires a reliable model for predicting defect growth.

- No features exist that could cause faster growth rates than those that the test intervals are based on. Features such as dents or large cracks in unusually tough or strong materials can result in faster growth rates than one might anticipate in the absence of dents and when the properties of the material are close to the expected values. These features can possibly be detected by the combined usage of ILI and hydrostatic tests; ILI to detect stress-concentrating features or large cracks in resilient materials and hydrostatic testing to prove that no injurious features were missed.

- The test-pressure-to-operating-pressure ratio is as high as possible to increase the safety margin and reduce the possibility of a pressure reversal occurring following the test.

- The possibility of a small leak occurring after the test is recognized and mitigated by other means since short, through-wall seam flaws may not leak during a test, nor can they be reliably detected by ILI.

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K. M. Kolovich and J. F. Kiefner

INTRODUCTION

Six case studies involving extensive, repeated hydrostatic testing to assure ERW and flash-weld seam-integrity are presented and analyzed in this document. These six cases represent 2,096 miles of pipelines in hazardous liquid service. The purpose of examining these test experiences is to show the effectiveness of such testing with respect to preventing in-service failures from ERW and flash-weld seam defects. The historical information evaluated herein, where it is was available, includes the mill hydrostatic test and mill non-destructive examination, the pre-service hydrostatic test, the chronology of in-service and hydrostatic test failures, and the nature and causes of the failures.

BACKGROUND

Hydrostatic testing is a well-established procedure for assessing the pressure-carrying capacity of a pipeline. The principle of testing is that a pipeline that survives a given pressure level without failing can be operated safely at a lower pressure level. The ratio of test pressure to operating pressure establishes the degree of safety achieved by a pressure test. The higher the ratio, the more confidence one can have that the pipeline is safe to operate.

The above-described principle of testing represents the ideal case. In reality, things are not always that simple. The actual integrity of a pipeline (from the standpoint of its pressure-carrying capacity) depends on whether or not it contains injurious defects that could cause failure of the pipeline in service. Ostensibly, a hydrostatic test either causes such defects to fail or it proves that none with failure pressures below the test pressure existed. However, the margin of safety following a hydrostatic test may not be as large as the ratio of test pressure to operating pressure. First, defects large enough to be on the verge of failure at the target test pressure may begin to grow during the test as the target test pressure level is approached. If they do not fail before the test is terminated, they may be further degraded as the pressure is released such that their failure pressure upon subsequent pressurization may be less than the level of pressure reached during the test. This phenomenon is referred to as a “pressure reversal”. Small pressure reversals (in terms of the margin between their failure pressures and the previous test pressure) are often seen in repeated cycles of hydrostatic testing of a particular segment of pipe, but, fortunately, the probability of a pressure reversal being large enough to cause the pipeline to fail at its operating pressure is extremely small.

A second phenomenon may erode the effectiveness of a hydrostatic test with the passage of time if defects that survive the test grow during the service life of the pipeline from pressure-cycle-induced fatigue. Alternatively, defects arising from corrosion or stress corrosion cracking may grow large enough after a test to cause an in-service failure. The possibility of the growth of defects after a hydrostatic test means that in order to assure continued pipeline integrity, the test will have to be repeated at some time in the future before the growing defects become large enough to fail in service.

Another aspect of hydrostatic testing that affects its effectiveness relates to the fact the “short” defects tend to survive hydrostatic tests because they may have failure pressures higher than the test pressure even if they penetrate most of the way through the pipe wall thickness. Short, deep defects have been known to exhibit leakage almost immediately after a tested pipeline has been restored to service. Pipeline operators who rely on hydrostatic testing for pipeline integrity assessment should be aware of this possibility.

The cases of hydrostatic testing examined herein provide examples of all of the non-ideal aspects of hydrostatic testing. However, they also show that in spite of these limitations, hydrostatic testing at appropriate times can be an effective means of verifying pipeline integrity.

CASE STUDY 1

The first case study involves a 12.75-inch diameter liquid pipeline comprised of 0.250-inch wall thickness, API 5LX Grade X46 pipe installed prior to 1960. The maximum operating pressure corresponds to more than 60% SMYS. The pipe was manufactured by Republic Steel using a low-frequency ERW process. The minimum mill hydrostatic test pressure required by API Specification 5LX was 85% of SMYS. Non-destructive examination of the ERW seam was not required by API Specification 5LX at the time this pipe was manufactured.[1] Table 1 lists the sequence of seam-integrity events that are described in the following paragraphs. Note that the target test pressures are given in terms of % SMYS. The pressure levels at which in-service failures occurred where not always available, but it is reasonable to assume that they could have been in the neighborhood of the maximum operating pressure (about 64% of SMYS).

[1] API 5L/5LX required non-destructive examination (NDE) of seam welds beginning with the 1963 editions. Pipe manufacturers were likely employing NDE techniques prior to 1963, although usage may not have been uniform.

Table 1. Case Study 1 Seam Integrity Timeline (Year 0 refers to the year the pipelines was commissioned)

Year	Segment	Event
0	1	Pre-service test (69% SMYS), 4 failures
0	2	Pre-service test (69% SMYS), 1 failure
0	3	Pre-service test (69% SMYS), No failures
6	1	Field test (80% SMYS), No failures
6	2	Field test (80% SMYS), No failures
6	3	Field test (80% SMYS), 2 test failures
13	2	**Service failure, seam split**
13	2	Field test (90% SMYS), 4 failures
13	2	**Service failure, seam split**
14	3	Field test (90% SMYS), 21 test failures
16	1	Field test (90% SMYS), 2 failures
16	3	Field test (90% SMYS), cont. of Year 14 test
17	2	**Service failure, seam split**
17	3	**Service failures, 2 seam splits**
21	1	**Service leak, pinhole**
28	3	**Service failure, seam split**
29	1	Field test (90% SMYS), 3 failures
29	2	Field test (90% SMYS), 4 failures
29	3	Field test (90% SMYS), 3 failures
31	2	**Service failure, seam split**
35	1	**Service failure, seam split (fatigue)**
37	1	Field test (90% SMYS), 2 failures
37	2	Field test (90% SMYS), 1 failure
37	3	Field test (90% SMYS), 4 failures
41	1	Field test (90% SMYS), 5 failures
41	2	Field test (90% SMYS), 1 failure
41	3	Field test (90% SMYS), 7 failures
45	2	Field test (90% SMYS), 1 failure
46	1	Field test (90% SMYS), 4 failures
46	3	Field test (90% SMYS), 5 failures
47	2	**Service leak, pinhole**
50	2	Field test (90% SMYS), No failures
50	3	**Service failure, dent on seam**
51	1	Field test (90% SMYS), No failures
51	3	Field test (90% SMYS), 3 failures
52	3	**Service leak, pinhole**

During the commissioning hydrostatic test (represented as having occurred in Year 0), at least five seam failures occurred. The details of these failures are unknown, but they occurred at pressures corresponding to about 69% SMYS which was much less than the mill test pressure (85% SMYS). The implications could be that the mill test was not long enough to cause the defects to fail, or the mill test was not adequately performed on every pipe joint. Whatever the causes may have been, it suffices to say that at least some significant seam-weld manufacturing defects were not detected in the pipe mill.

The pipeline was operated with a maximum operating pressure (MOP) corresponding to 65% SMYS for six years without a seam failure. The pipeline was then re-tested in three segments to about 80% SMYS. No seam failures occurred on two of the segments and two seam failures occurred on one of the segments. The pipeline continued to operate for another seven years until a seam split occurred (Year 13). The pipeline was tested to about 90% SMYS (the highest level it had been tested to yet) over a two-year period which produced a total of 27 seam failures. One month after the test in Year 13 another seam split occurred on the same segment, followed by another four years later (year 17).

A pinhole leak occurred in a seam four years later (Year 21). The pipeline operated without incident for another seven years when another seam split occurred (Year 28). The entire pipeline was re-tested to about 90% SMYS (Year 29) producing ten seam failures. Two years after this test a seam split occurred (Year 31), followed by another four years later (Year 35).

In Year 37 the pipeline was tested again to about 90% SMYS producing seven seam failures. No in-service seam failure occurred over the next four years and the pipeline was tested again in Year 41. The Year 41 test was conducted at pressures equal to or greater than the Year 37 test. The test pressures ranged from a minimum of 90% SMYS to a maximum of 98% SMYS. Thirteen test failures occurred and all but four were attributed to lack-of-fusion defects without any evidence of their having been enlarged in-service. Four hook crack failures occurred, two of which showed evidence of fatigue crack growth.

No in-service seam failures occurred over the next four years and the pipeline was tested again in Years 45 and 46. Ten seam failures occurred at pressures of 93% SMYS or more. Four of the test failures were leaks and six were ruptures. Three of the leaks were caused by lack-of-fusion defects and one was caused by a combination of a hook crack, lamination, and lack-of-fusion. Two ruptures were caused by lack-of-fusion defects. One rupture was caused by a hook crack and another was caused by a hook crack and lack-of-fusion defect combination. Only one failure showed evidence of fatigue crack growth, a hook crack in the vicinity of a lamination.

Over the next 4 years, two service failures occurred. One was a leak caused by a pinhole. The second was a rupture caused by a dent associated with the pipe seam which occurred 4 years after a hydrostatic test.

The pipelines were tested in Years 50 and 51 to similar pressures as the previous test. Only three test failures occurred. One was caused by corrosion in combination with a hook crack. The second failure was caused by a hook crack and lack-of-fusion defect combination with no evidence of in-service growth. The third failure was caused by a hook crack with no evidence of fatigue.

One year after the hydrostatic test (Year 52), a seam leak occurred which was caused by a pinhole.

Case Study 1 Discussion

The early service history of this pipeline indicates that significant seam defects were not detected in the pipe mill, and that these defects were apparently capable of enlarging in-service by fatigue. Metallurgical investigations of the more-recent test failures indicated that the majority of causes were cold welds with no evidence of in-service growth, but at least three were caused by a hook crack that had been enlarged by fatigue. One could speculate that the early service failures were caused by fatigue (at least one reportedly was), or perhaps upset operational conditions that resulted in overpressure events causing otherwise stable flaws to fail.

Figure 1 through Figure 3 show the cumulative number of seam test failures over time for Segments 1 through 3, respectively. Also shown on the timelines are the occurrences of in-service seam failures with the exception of the three pinhole leaks. As discussed in the Subtask 1.4 report[2], pinholes (also described as penetrators, the two terms having effectively the same meaning) might not be detected by either hydrostatic testing or in-line inspection and such defects are analogous to pinholes in girth welds in that respect. Both pinholes in seam welds and girth welds may result in small leaks, but none has ever caused an in-service rupture.

Figure 4 shows the cumulative failure history for all three segments combined. While the number of test failures over time appears somewhat steady after the pipeline was tested to levels of around 90% SMYS, the number of service failures over time appears to be flattening out.

[2] Kiefner, J.F., and Kolovich, K.M., "ERW and Flash Weld Seam Failures" Subtask 1.4 of U.S. Department of Transportation Other Transaction Agreement No. DTPH56-11-T-000003, May 30, 2012.

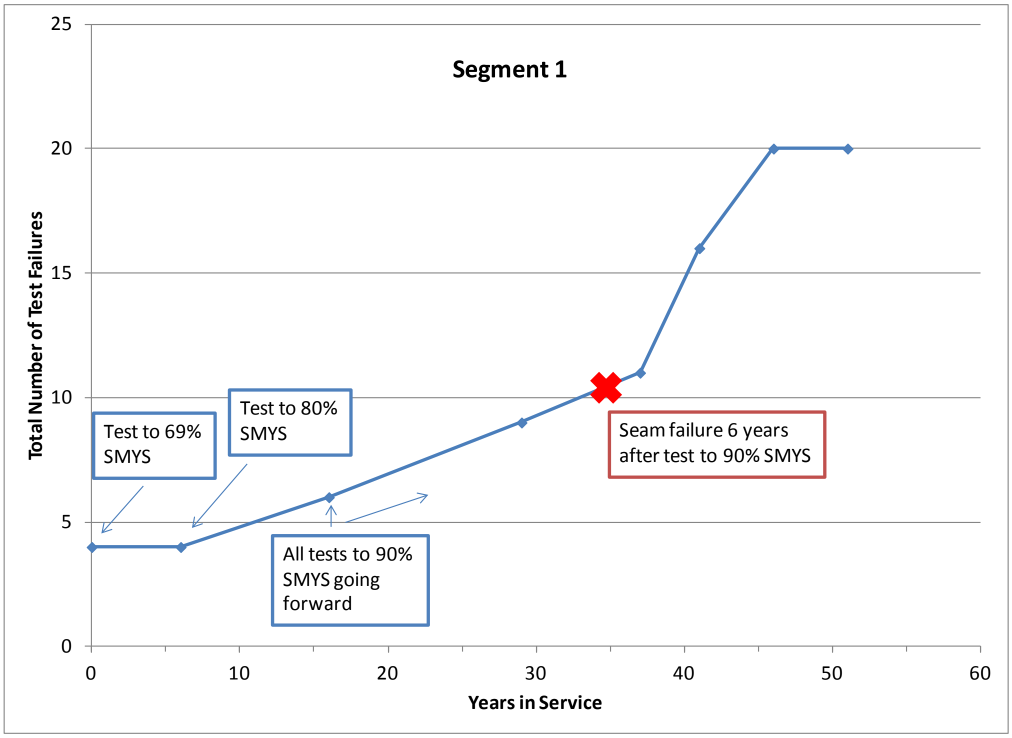

Figure 1. Case Study 1, Segment 1 Hydrostatic Test and Service Failure Timeline

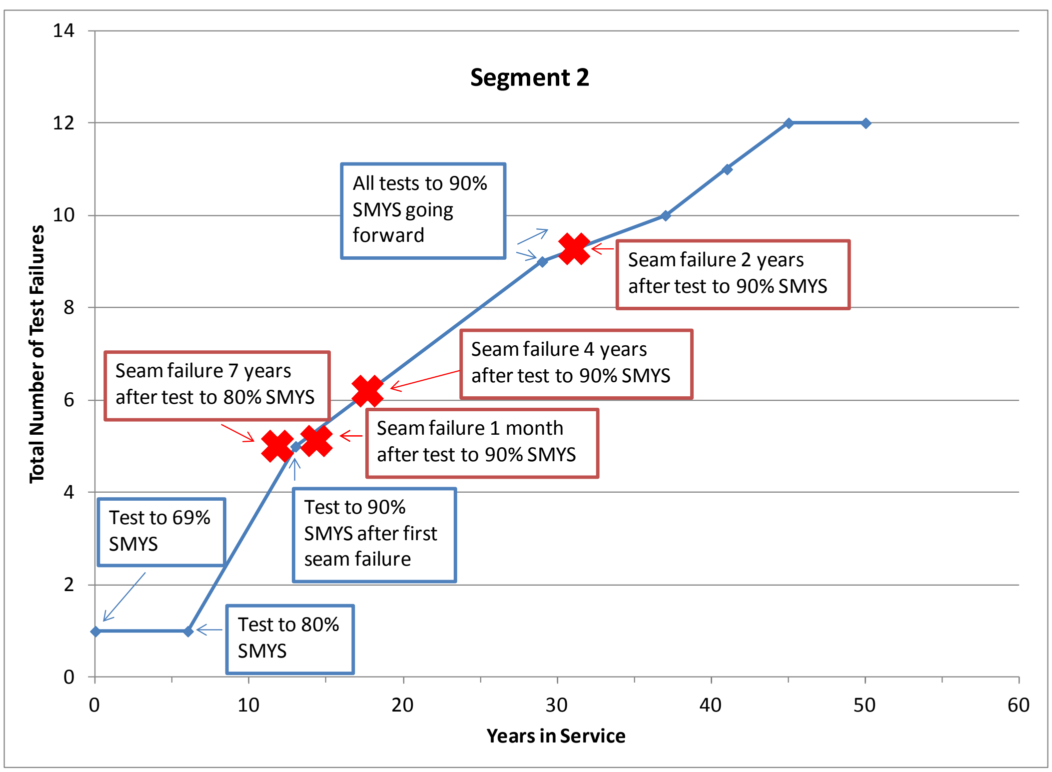

Figure 2. Case Study 1, Segment 2 Hydrostatic Test and Service Failure Timeline

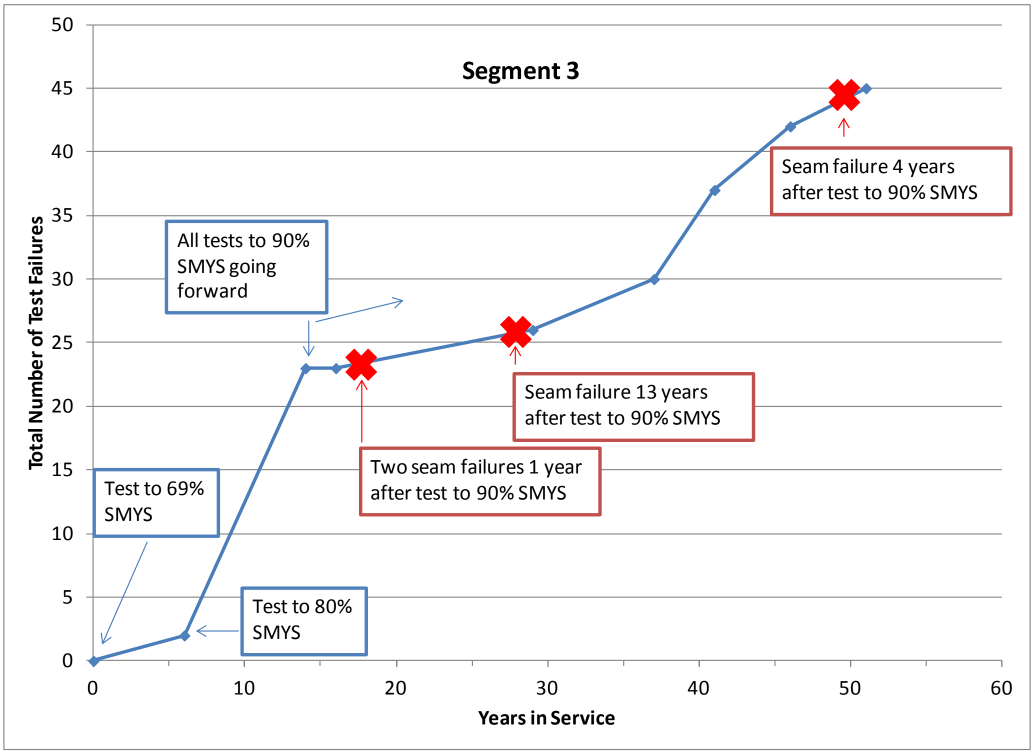

Figure 3. Case Study 1, Segment 3 Hydrostatic Test and Service Failure Timeline

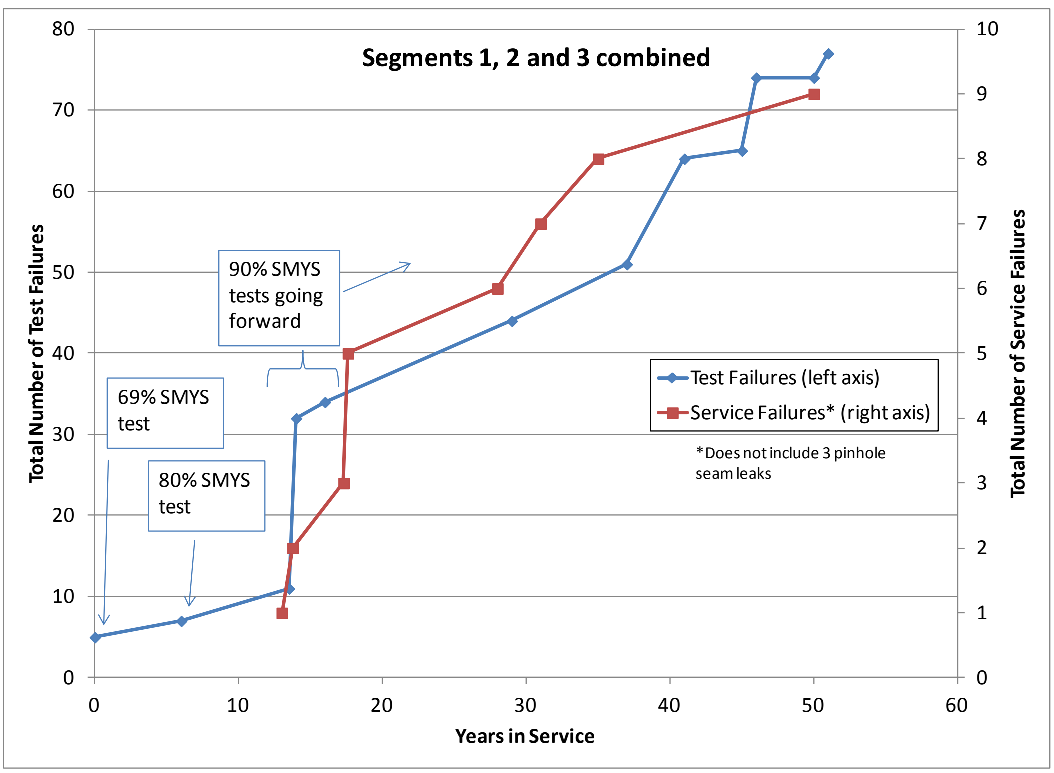

Figure 4. Case Study 1, Segments 1-3 Hydrostatic Test and Service Failure Timeline

The number of test failures increased with increasing test pressure levels from 69% to 80% to 90% SMYS, which was expected. The occurrences of service failures shortly after hydrostatic tests (i.e. within 3 years) in the early years are disconcerting. However, without the results of metallurgical investigations one can only speculate as to the scenario that led to the failure. Possible scenarios include (1) that the test itself caused damage to the subcritical flaw, (2) that the strength and toughness of the pipe was sufficient for the flaw to survive the test, but the flaw was so large that the remaining life was very short, (3) that an upset condition (i.e. overpressure event) occurred. One could also speculate that the service failures that occurred 6 to 13 years after a hydrostatic test could have been prevented by a timely hydrostatic test.

The occurrence of the most recent seam failure, which happened four years after a hydrostatic test, was attributed to a dent that was centered near the ERW seam. The dent was smooth, did not contain mechanical damage, and was located on the bottom of the pipe. A crack initiated at the edge of the dent in the ERW seam and propagated towards the inside surface. The appearance of the fracture surface was not consistent with pressure-cycle-induced fatigue; rather there were multiple, large increments of crack growth. Previous hydrostatic tests were considered to be the cause of the incremental crack growth. The final increments of crack growth prior to the failure were probably due to pressure-cycle fatigue.

Case Study 1 Summary

The early operational history of the pipeline indicated that seam-weld flaws escaped detection at the pipe mill and survived the commissioning hydrostatic test. Furthermore, service failures that occurred after hydrostatic tests implied that fatigue crack growth of seam flaws occurred. The recent test history (i.e. the last four hydrostatic tests conducted at regular intervals) is a demonstration that hydrostatic testing can prevent service failures since three test failures exhibited fatigue crack growth. The only service failure that occurred between these tests (other than two pinhole leaks) involved a dent.

Case Study 1 Conclusions

- Hydrostatic testing of the Case Study 1 Pipeline on a regular basis has eliminated at least three defects that had the potential to become in-service failures because they exhibited fatigue crack growth.
- The occurrence of in-service failures has become less frequent with hydrostatic testing conducted on a regular basis.
- Early in-service seam failures occurred shortly after hydrostatic tests, but it unclear whether these could have been caused by pressure excursions or in-service crack growth.

- During the commissioning hydrostatic test (the first field test before the pipeline was put into operation), failures occurred at pressures less than the required mill hydrostatic test, implying that the mill test was not effective for removing some injurious features.
- Hydrostatic testing did not prevent small in-service leaks caused by pinholes in the seam weld.
- Hydrostatic testing did not prevent a seam failure that occurred between tests involving a dent.

CASE STUDY 2

Case Study 2 involves 12.75-inch diameter, 0.250-inch wall thickness API 5LX Grade X52 pipe installed prior to 1963. The maximum operating pressure corresponded to more than 60% SMYS. The pipe was manufactured by Lone Star Steel using a low-frequency ERW process. The minimum mill hydrostatic test pressure required by API 5LX was 85% of SMYS. Non-destructive examination of the ERW seam was not required by API 5LX at the time this pipe was manufactured. Lone Star performed a full-body normalizing heat treatment (1650 ºF) prior to the hydrostatic test.[3] Table **2** lists the sequence of seam-integrity events that are described in the following paragraphs. Note that the target test pressures are given in terms of % SMYS. The pressure levels at which in-service failures occurred where not always available, but it is reasonable to assume that they could have been in the neighborhood of the maximum operating pressure (about 71% of SMYS).

Table 2. Case Study 2 Seam Integrity Timeline (Year 0 refers to the year the pipelines was commissioned)

Year	Segment	Event
0	1, 2, 3, 4	Pre-service Test (78% SMYS) - 12 failures
22	4	Field Test (84% to 96% SMYS) - 12 failures
23	3	Field Test (86% to 98% SMYS) - 16 failures
40	1	Field Test (92% to 95% SMYS) - 1 failure
41	2	Field Test (90% to 97% SMYS) - 17 failures
43	4	Field Test (83% to 98% SMYS) - 8 failures
45	1	Field Test (89% to 91% SMYS) - 0 failures
46	2	Field Test (89% to 96% SMYS) - 7 failures
46	3	**Service failure, seam split**
47	3	Field Test (91% to 98% SMYS) - 5 failures
48	4	Field Test (89% to 98% SMYS) - 12 failures

[3] Kiefner, J.F., and Clark, E.B., "History of Line Pipe Manufacturing in North America" An ASME Research Report, CRTD-Vol. 43, 1996.

During the commissioning hydrostatic test, 12 seam failures occurred. The maximum test pressure corresponded to about 78% SMYS which was less than the mill test pressure. One failure occurred at a pressure that was significantly less than the mill test (45% SMYS). The implications could be that the mill test was not long enough to cause the defects to fail, or the mill test was not adequately performed on every pipe joint. Whatever the cause may have been, it suffices to say that at least some significant seam-weld manufacturing defects were not detected in the pipe mill.

Pipeline Segment 1 (out of 4 segments discussed) was hydrostatically tested 40 years after the commissioning test. The test pressure was 92-95% SMYS, which was higher than that of the previous tests. Only one seam failure occurred during the test. The segment was re-tested five years later (Year 45) to 88-91% SMYS and no seam failures occurred.

Pipeline Segment 2 was hydrostatically tested 41 years after the commissioning test. The test pressure was 90-97% SMYS, which was higher than that of the previous tests. Seventeen seam failures occurred during the test. The segment was re-tested five years later (Year 46) to 89-93% SMYS and seven seam failures occurred.

Pipeline Segment 3 was hydrostatically tested 23 years after the commissioning test. The test pressure was 86-98% SMYS, which was higher than that of the previous tests. Sixteen seam failures occurred during the test. Twenty-three years after the test (Year 46), an in-service seam failure occurred. The segment was re-tested the year after the service failure (Year 47) to 91-98% SMYS, resulting in five seam failures.

Pipeline Segment 4 was hydrostatically tested 22 years after the commissioning test. The test pressure was 84-96% SMYS, which was higher than that of the previous tests. Twelve seam failures occurred during the test. The segment was re-tested 21 years later (Year 43) to 83-98% SMYS and eight seam failures occurred. The segment was tested again five years later (Year 48) to 89-98% SMYS and twelve seam failures occurred.

Case Study 2 Discussion

The Case Study 2 seam integrity timeline contains only one in-service seam failure that occurred 23 years after a hydrostatic test to 86-98% SMYS. The timeline for the four segments is shown in Figure 5 through Figure 8. It was assumed that the 12 pre-service test failures were evenly distributed among the four segments.

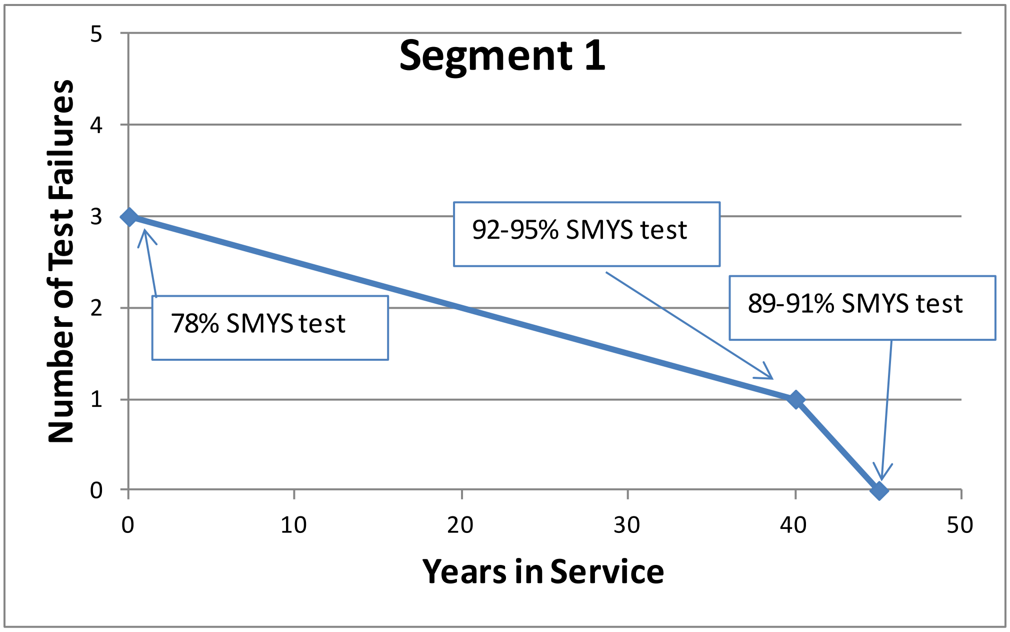

Figure 5. Case Study 2, Segment 1 Hydrostatic Test and Service Failure Timeline

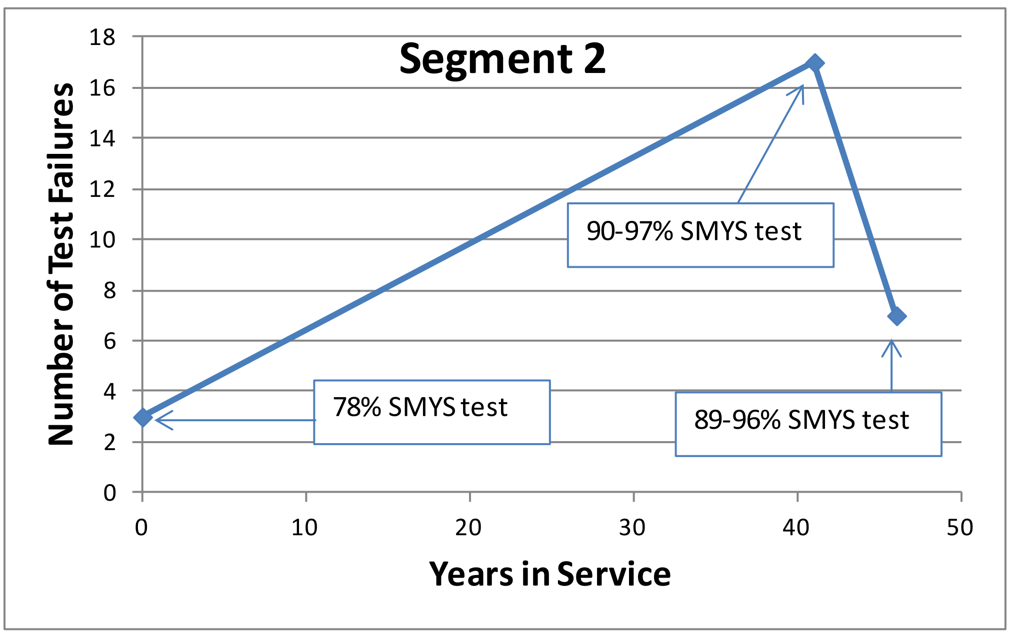

Figure 6. Case Study 2, Segment 2 Hydrostatic Test and Service Failure Timeline

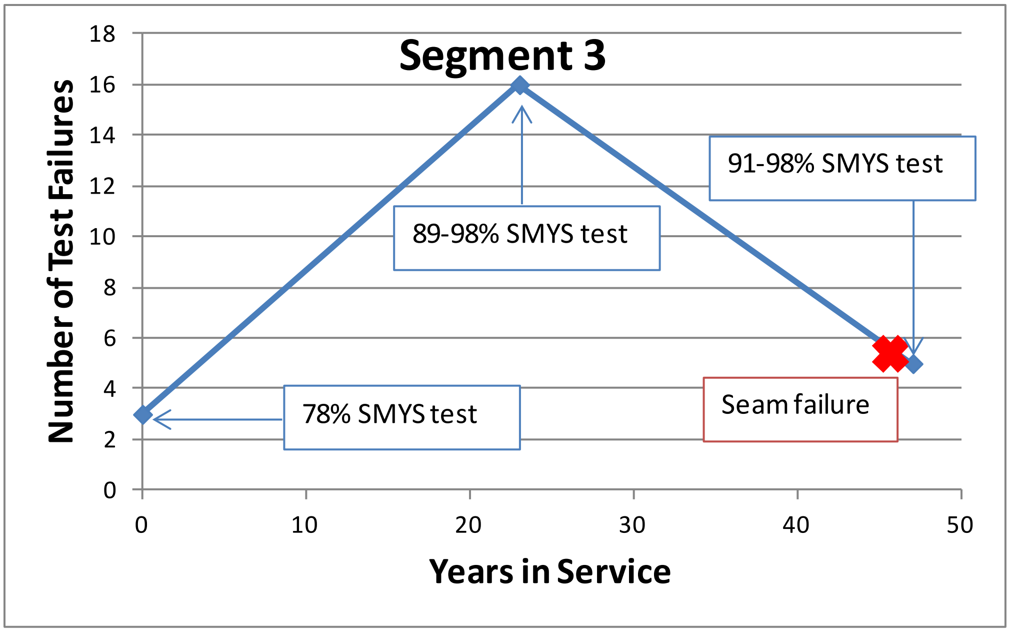

Figure 7. Case Study 2, Segment 3 Hydrostatic Test and Service Failure Timeline

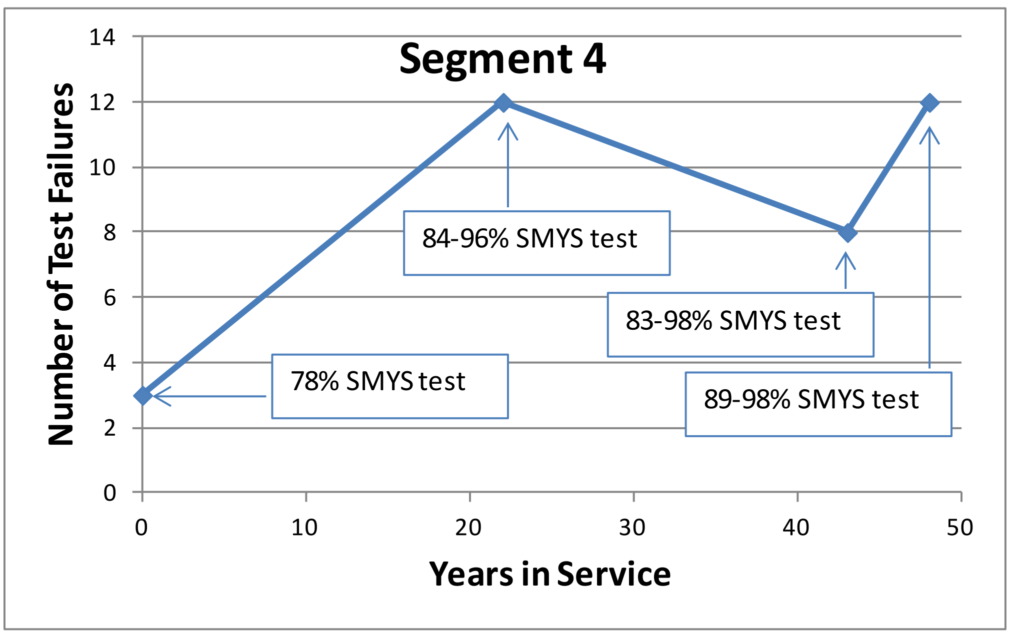

Figure 8. Case Study 2, Segment 4 Hydrostatic Test and Service Failure Timeline

The number of test failures for Segments 2 and 3 has declined and the test pressure in the last two tests of those segments was similar. Segment 1 has only experienced 1 test failure since the pre-service test while in contrast Segment 4 has experienced 32 over the last three tests.

The failure pressures at the site of each test failure are known for this pipeline. Figure 9 shows the average, minimum, and maximum failure stress level as a percentage of SMYS for each test.

The average is denoted by the symbol, and the extremes are indicated by the error bars. Except for Segment 1 which had only one test failure, the first hydrostatic test to pressures higher than commissioning test or mill test produced a wider range of failure stress levels than subsequent tests, and the first test also resulted in a test failure slightly below the mill test pressure level (85% SMYS). The average failure stress level increased with each test and the range of failure pressures generally decreased.

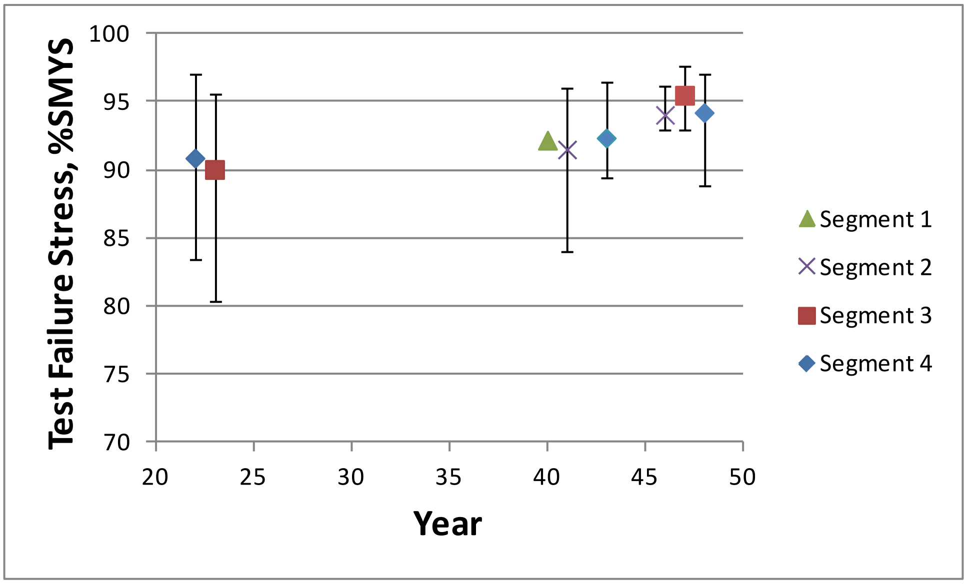

Figure 9. Case Study 2 Hydrostatic Test Failure Stress Levels

The cause of the service failure appears to have been a hook crack that showed some evidence of ductile crack extension. However, the fracture jumped into the bondline, and the bondline portion of the fracture appeared to be a brittle fracture.

None of the 32 recent test failures that were subjected to metallurgical examination showed evidence of in-service growth of the origin flaw. In eight test failures, no distinct origin was found and the failure was attributed to low toughness of the bondline. Some of these fractures exhibited a stitched appearance which is commonly associated with low bondline toughness in low-frequency ERW seams. These failures occurred at stress levels corresponding to 90-96% SMYS.

Four test failures were attributed to cold welds (2 leaks and 2 ruptures). The failure stress levels corresponded to 89-98% SMYS. Some of the failures exhibited a repetitive cold weld pattern, similar to the stitching observed on other test failures.

Fifteen test failures were caused by hook cracks, none of which exhibited growth by fatigue. The failure stress levels corresponded to 91-96% SMYS.

Other test failures were caused by weakly-bonded layers in the seam adjacent to the bondline and a pinhole leak. Weakly-bonded layers resemble hook cracks when viewed in cross section, since the fracture follows the upset material flow lines; however the lack of an adherent oxide on the fracture surface means that the adjacent layers may have been bonded to some degree.

Over the course of the hydrostatic testing, 24 pressure reversals have occurred. A pressure reversal occurs when there is more than one test failure on a given segment, and a test failure occurs at a lower pressure than the pipe experienced on a previous attempt at the target test pressure. Pressure reversal size is defined as the difference between the pressure at failure and the highest test pressure attained on any previous attempt divided by the highest test pressure attained (expressed as a percent).

Most of the pressure reversals were small; 15 were between 1 and 10 psig. Seven pressure reversals were between 10 and 40 psig, and two were relatively large, 84 and 142 psig. As a percentage of the previous highest test pressure, the two largest reversals were 4.2% and 7.7%. The size of the pressure reversal is important because the phenomenon could imply that the integrity of pipe is less than what was demonstrated by a successful pressure test. However, based on pressure reversals that have occurred on this and other pipelines, the likelihood that one could be large enough to cause a service failure following a hydrostatic test has been shown to be negligible.[4]

Case Study 2 Summary

The seam defects exposed by hydrostatic testing would not lead one to believe that the seam integrity was in jeopardy of failure by fatigue or other time-dependent mechanisms, since none of the defects revealed by tests appeared to have enlarged in-service. Pressure reversals occurred during the hydrostatic tests, but a pressure reversal large enough to affect the seam integrity is unlikely. The average failure stress level has increased with each test, and the range of failure stress levels has generally decreased. The service failure occurred 23 years after a hydrostatic test, but the investigators were able neither to confirm nor refute that fatigue or another time-dependent mechanism had played a role in the failure.

[4] Kiefner, J.F., Kolovich, K.M., and Kariyawasam, S., "A Study of Cases of Hydrostatic Tests Where Multiple Test Failures Have Occurred", IPC2010-31157, Proceedings of the 8th International Pipeline Conference, IPC 2010, September 27 – October 1, 2010, Calgary, Alberta, Canada

Case Study 2 Conclusions

- Hydrostatic testing of the Case Study 2 pipeline has eliminated many seam defects, none of which showed evidence of having enlarged in-service.
- Test failures continue to occur when testing to pressures similar to those of previous tests, an indication that testing has not yet eliminated all seam flaws that have relatively similar failure pressures. However, the average test failure stress level has increased with each test and the range of failure stress levels has generally decreased. This could be an indication that the population of remaining seam flaws is on the decline.

CASE STUDY 3

Case Study 3 involves a 34-inch diameter hazardous liquid pipeline comprised of 0.281-inch wall thickness, API 5LX Grade X52 pipe manufactured by A.O. Smith using the flash-weld process. The pipeline was constructed in stages beginning before the first API 5LX pipe specification to require non-destructive testing of the pipe seams (March 1963 edition). A.O. Smith reportedly began continuous ultrasonic inspection of the flash-weld seams in 1957, and began seam normalizing the welds in 1966.[5] So all of the pipe seams should have been inspected and some of them would be expected to have been seam normalized. The minimum mill hydrostatic test pressure required by API 5LX was 90% of SMYS.

This pipeline experienced fourteen in-service seam-weld leaks within the first 30 years of operation. Two in-service seam-weld ruptures occurred as a result of overpressure events. Three seam-weld leaks occurred as a result of hydrostatic re-tests. All 19 of these seam-weld failures were attributed to fatigue, although it is noted that not all were subject to metallurgical examination. The trend of service leaks over time (Figure 10) showed fewer and fewer failures with increasing time intervals between them, suggesting that the population of fatigue-sensitive seam defects is on the decline.

[5] Kiefner, J.F., and Clark, E.B., "History of Line Pipe Manufacturing in North America" An ASME Research Report, CRTD-Vol. 43, 1996.

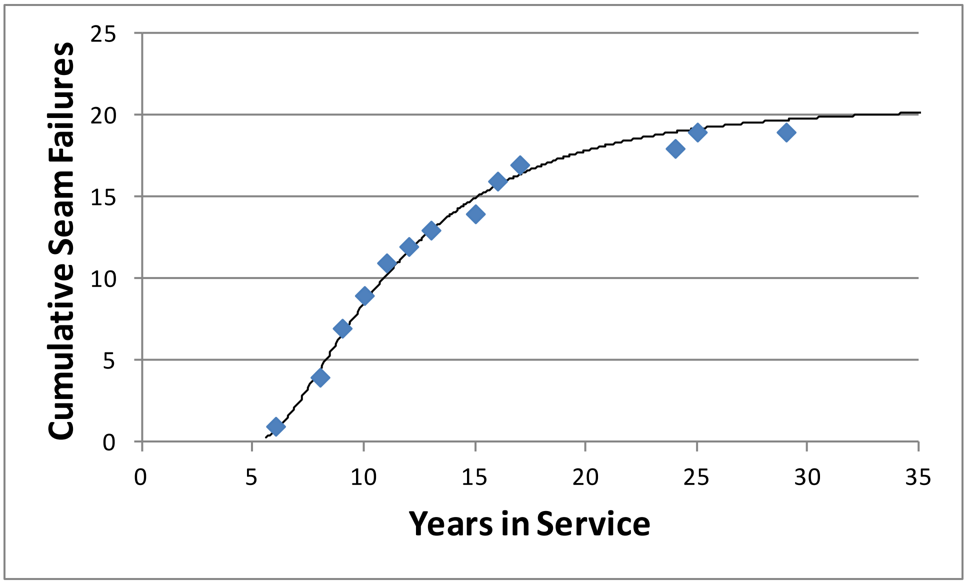

Figure 10. Case Study 3 Cumulative In-Service and Test Seam Failures Involving Flash-Weld Defects

The pipeline was hydrostatically tested as it was constructed to pressure levels corresponding to 85-95% SMYS. Seam leaks began to occur 6 to 11 years after the pre-service tests. The entire pipeline was then retested to about 85% SMYS, producing three seam leaks which were attributed to fatigue. A year after this test a seam leak occurred, followed by another in the following year.

Segments of the line were re-tested 18-20 years after construction (the third test of these segments) to 85-95% SMYS. Presumably no fatigue-related seam failures occurred since none were reported. In segments not tested for the third time, two seam leaks occurred 8 and 9 years after the previous test. In those segments that were tested for a third time, five seam leaks occurred 8 and 9 years after the test. The entire line was retested 28-29 years after construction to 85-105% SMYS and no fatigue-related seam failures occurred.

Case Study 3 Discussion and Summary

The in-service leak history of the Case Study 3 pipeline suggested that seam-weld defects were not detected by the mill NDE inspection, the minimum required mill hydrostatic test to 90% SMYS, or the pre-service hydrostatic test to 85-95% SMYS. The types of defects that began to fail after 6 to 11 years of being in service were hook cracks thought to have enlarged by fatigue.

A re-test of the pipeline to about 85% SMYS resulted in three seam leaks, but the test did not prevent leaks which happened 1 and 2 years after the test. Several leaks then occurred 8 and 9 years after the test which prompted a retest in which no failures occurred. Based on the trend of seam failures over time (Figure 10), the presumption was that after 30 years of service in which numerous leaks, two ruptures, and three test leaks occurred, the seam-weld integrity was improving as a result of the elimination of seam-weld defects capable of enlarging by fatigue.

Case Study 3 Conclusions

- The mill NDE which was required by API 5LX, a form of which had been in use by A.O. Smith six years before the requirement first appeared in 1963, did not eliminate some seam-weld defects which were capable of enlarging in-service.
- The mill hydrostatic test and pre-service hydrostatic test did not eliminate some seam-weld defects, and leaks began to occur after 6 to 11 years of service. The leaks were attributed to fatigue.
- Hydrostatic testing eliminated three defects which could have become in-service failures, but the tests were not successful in preventing two leaks which happened 1 to 2 years after the tests.
- The trend of cumulative seam failures over time suggests that the seam integrity is improving over time, but the evidence does not suggest that there is no risk of experiencing another seam failure. However, timely seam integrity inspections likely would go a long way toward preventing any future seam failures. It is believed that the pipeline's operator is continuing to perform periodic seam integrity inspections.

CASE STUDY 4

Case Study 4 involves a 16-inch-diameter hazardous liquid pipeline comprised of segments of 0.250-inch-wall, API 5LX Grade X52 pipe manufactured by Youngstown Sheet & Tube in the 1950s using the DC-ERW process. Other segments were comprised of seamless pipe. The minimum mill hydrostatic test pressure required by API 5LX was 85% of SMYS. Non-destructive examination of the ERW seam was not required by API 5LX at the time this pipe was manufactured. Table 3 lists the sequence of seam-integrity events that are described in the following paragraphs. Note that the target test pressures are given in terms of % SMYS. The pressure levels at which in-service failures occurred where not always available, but it is reasonable to assume that they could have been in the neighborhood of the maximum operating pressure (about 72% of SMYS).

Table 3. Case Study 4 Seam Integrity Timeline (Year 0 refers to the year the pipeline was commissioned)

Year	Event
0	Pre-service test to 81-86% SMYS (failures unknown)
13	**Service failure (pressure surge)**
23	**Service failure (hook crack)**
25	**Service failure**
25	**Service failure (hook crack)**
26	**Service failure**
26	Portions hydrotested to 91-94% SMYS (failures unknown)
30	**Service failure (fatigue)**
37	Hydrotest (84-94%), 2 failures
40	Portions hydrotested to 91-94% SMYS (failures unknown)
45	Hydrotest (94% SMYS), 3 failures
54	Portions Hydrotested (94% SMYS), 1 failures

The pre-service hydrostatic test was conducted to pressures corresponding to 81-86% SMYS. The number and type of test failures are unknown. An in-service seam failure occurred due to a pressure surge thirteen years after the line was put into service. Another in-service seam failure occurred in Year 23 followed by three additional in-service seam failures that occurred within the next 3 years. Two of these failures were caused by hook cracks, however no evidence of fatigue was found.

In Year 26, following the Year-26 in-service failure, the portions of the pipeline containing ERW pipe were hydrostatically tested to pressures corresponding to 91-94% SMYS. The numbers and type of test failures are unknown. Four years after the test in Year 30, an in-service seam failure occurred due to fatigue at a lamination.[6]

In Year 37, the pipeline was hydrostatically tested to pressures corresponding to 84-94% SMYS. Two seam failures occurred, and one of these exhibited fatigue crack growth. Three years later, portions of the pipe were again tested to 91-94% SMYS. The numbers and types of test failures are unknown.

In Year 45, the pipeline was again hydrostatically tested to pressures corresponding to 94% SMYS. Three seam failures occurred; one caused by an arc burn defect which failed at a historically high pressure, another caused by a hook crack with no evidence of fatigue that failed at a historically high pressure, and the third caused by fatigue of a seam defect.

[6] The lamination extended into the seam-weld area, so it probably had characteristics similar to that of a hook crack.

Following the Year 45 test, portions of the line were retested at intervals based on fatigue-life calculations. One test failure occurred at a hook crack which showed evidence of fatigue crack growth.

Case Study 4 Discussion and Summary

Other than an in-service seam failure caused by a pressure surge, the Case Study 4 pipeline operated without an in-service seam failure for 23 years. Then four in-service failures occurred within three years of each other. Although two of these in-service failures were known to have been caused by hook cracks, none of them were attributed to fatigue. It is not known whether pressure surges had anything to do with these failures, but that could be implied by the absence of evidence of any other degradation mechanism.

Portions of the pipeline were hydrostatically tested, and 4 years later an in-service seam failure was caused by fatigue. The pipeline was subjected to two hydrostatic tests of the entire pipeline, and also several tests of smaller segments that were conducted at intervals based on fatigue calculations. At least three test failures exhibited evidence of fatigue crack growth. No in-service failures occurred between tests.

Case Study 4 Conclusions

- The early service history of the Case Study 4 pipeline indicated that seam defects were not detected by the mill hydrostatic test or the pre-service test, and some defects were capable of enlarging in-service by fatigue.
- During the time the pipeline was hydrostatically tested at regular intervals based on fatigue calculations, no in-service failures occurred between these tests. This suggests that the seam integrity can be effectively managed by periodic hydrostatic testing.
- Three of the test failures from the last four tests exhibited fatigue crack growth and could therefore be considered to be prevented in-service failures.

CASE STUDY 5

Case Study 5 involves 12.75-inch outside diameter, 0.250-inch wall thickness, API 5LX grade pipe manufactured by A.O. Smith in the late 1940’s using the flash-weld process. The specified minimum yield strength was 45 ksi, which was an alternate strength agreed upon between the purchaser and manufacturer as allowed by API 5L. Non-destructive examination of the seam was not required by API 5LX at the time this pipe was manufactured. A.O. Smith began continuous ultrasonic inspection of the flash-welded seams in 1957, after this particular pipe was manufactured.[7] The minimum required mill hydrostatic test would have been to 85% SMYS. The pipeline was placed into hazardous liquid service and had a maximum operating pressure corresponding to approximately 72% SMYS.

A hydrostatic test to 90% SMYS was conducted 34 years after the pipeline was commissioned. The pipeline was tested again to similar pressures 23 years later. Three seam failures occurred at areas of misaligned plate edges during this latter test. Within 3 years of the test, an in-service failure occurred at a misaligned plate edge. Fatigue crack growth was determined to be the cause of the in-service failure.

Tensile testing of the pipe body indicated the material was much stronger than the specified minimum yield strength (45 ksi). The pipe body would have met the strength requirements for Grade X60 which were not incorporated into API 5LX until 1967. Tensile testing of the flash-welded seam resulted in even higher strength values. The Charpy V-notch fracture characteristics of the pipe body and seam weld were considered good for the pipe vintage. The full-size equivalent upper-shelf energies were in the 33 to 36-ft-lb range and the transition temperatures were not high relative to the operating temperature.

Case Study 5 Discussion and Summary

The seam defect that caused the in-service failure was a fatigue crack that developed at a mismatched plate edge. The manufacturing defect survived the mill test to 85% SMYS, a field hydrostatic test to 90% SMYS, and then failed less than three years after another field hydrostatic test to 90% SMYS. It is believed that the high strength of the material combined with adequate toughness prevented the manufacturing defect, which likely had already initiated a fatigue crack, from failing during the pressure test. The size of the fatigue crack was large enough that the remaining life was less than 3 years.

Case Study 5 Conclusions

- Hydrostatic testing did not eliminate a manufacturing defect that had enlarged by fatigue, and the defect failed in-service shortly after the test.
- The crack-like defect that survived the hydrostatic test was large (not because the test pressure was low in terms of % SMYS, but because the pipe strength and toughness were better than might be expected) therefore the fatigue life remaining after the test was short.

[7] Kiefner, J.F., and Clark, E.B., "History of Line Pipe Manufacturing in North America" An ASME Research Report, CRTD-Vol. 43, 1996.

CASE STUDY 6

Case Study 6 involves mostly 10.75-inch outside diameter, 0.250-inch wall thickness, API 5LX Grade X46 pipe manufactured by A.O. Smith in the early 1950's using the flash-weld process. The pipeline also contains shorter segments of 0.307-inch wall thickness ERW pipe manufactured by Kaiser Steel and Republic Steel using a low-frequency ERW process. Non-destructive examination of the seam was not required by API 5LX at the time this pipe was manufactured. A.O. Smith began continuous ultrasonic inspection of the flash-welded seams in 1957, after this pipeline was built.[8] The minimum required mill hydrostatic test would have been to 85% SMYS. The pipeline was pressure tested prior to being placed into service, but the details of the commissioning test are unknown. The pipeline transports hazardous liquids with a maximum operating pressure corresponding to approximately 67% SMYS.

Over approximately 39 years of service, the Case Study 6 pipeline experienced seven in-service seam failures. The details involving the nature and causes of the first six seam failures are not well-documented. The last in-service seam failure was a leak in an ERW pipe that was caused by a hook crack enlarged by fatigue.

The pipeline was then hydrostatically tested, which resulted in eight seam failures (see Table 4). Two of the test failures exhibited fatigue crack growth; one occurred at a mismatched plate edge in the A.O. Smith pipe and the other occurred at a hook crack in the Republic pipe.

Six test failures occurred in the Kaiser pipe, none of which exhibited evidence of in-service growth. Four test failures were ruptures caused by stitching, and two test failures were leaks caused by short lack of fusion defects adjacent to the girth welds. One of the stitching defects failed at 79% SMYS, which was less than the mill hydrostatic test pressure (85%). This was possibly due to the short duration of the mill test, or the mill test not being properly performed, since stitching typically does not enlarge in-service.

[8] Kiefner, J.F., and Clark, E.B., "History of Line Pipe Manufacturing in North America" An ASME Research Report, CRTD-Vol. 43, 1996.

Table 4. Case Study 6 Hydrostatic Test Failures

Segment	Failure Pressure (% SMYS)	Manufacturer	Cause
1	80%	A.O. Smith	Mismatched edges + fatigue
	81%	Republic	Hook crack + fatigue
2	no seam failures	n/a	n/a
3	79%	Kaiser	Stitching
	95%	Kaiser	Stitching
	88%	Kaiser	Stitching
	92%	Kaiser	Stitching
	leak	Kaiser	End-weld lack of fusion
	leak	Kaiser	End-weld lack of fusion

Because test failures occurred that exhibited fatigue crack growth, the pipeline was hydrostatically tested again four years later. One test failure occurred in Test Section 1 (see Table 5). The test failure was caused by a hook crack that had enlarged by fatigue.

Table 5. Case Study 6 Hydrostatic Test Failures (reassessment)

Segment	Failure Pressure (% SMYS)	Manufacturer	Cause
1	96%	A.O. Smith	Hook crack + fatigue
2	no seam failures	n/a	n/a
3	no seam failures	n/a	n/a

Case Study 6 Discussion and Summary

After an in-service seam leak caused by a hook crack and fatigue, the pipeline was hydrostatically tested resulting in two fatigue-related test failures. Six other test failures were caused by manufacturing defects that might have been stable since no evidence of growth was observed. One of the test failures occurred at a lower pressure than the minimum mill hydrostatic test pressure. No evidence of growth was observed, implying that the mill hydrostatic test was inadequately performed or perhaps the short duration (typically 5-10 second) test was of insufficient duration to expose the defect.

A hydrostatic test was conducted four years after the first test, and one fatigue-related failure occurred. Evidence of fatigue crack growth suggested that this was a prevented in-service failure.

Case Study 6 Conclusions

- Hydrostatic testing of the Case Study 6 pipeline after an in-service fatigue failure eliminated two seam-weld manufacturing defects that showed evidence of fatigue crack growth.
- Subsequent hydrostatic testing conducted four years later eliminated another seam-weld manufacturing defect that showed evidence of fatigue crack growth, suggesting that hydrostatic testing can effectively manage the seam-weld integrity.

DISCUSSION

The six case studies evaluated herein highlight the effectiveness of hydrostatic testing where test failures occurred at seam-weld defects that showed evidence of having enlarged in-service. In these cases it is easy to draw the conclusion that hydrostatic testing has prevented in-service failures. Furthermore, the fact that repeated hydrostatic test have resulted in decreasing numbers of test and in-service failures and that test breaks that do occur tend to happen at higher pressures, suggest that hydrostatic testing has worked to eliminate the most injurious seam-weld defects.

The limitations of hydrostatic testing are demonstrated by cases where in-service failures occurred shortly after a hydrostatic test (i.e. within 1 to 4 years of the test). Some of these occurrences cannot be easily explained because metallurgical examinations were not conducted. A possible reason for some of them is that they occurred at a time when management of pipeline operations leading to pressure surges was not as well understood as it is today (many of these failures occurred in the 1970s). Where a pressure excursion could be completely ruled out and a metallurgical examination was conducted, as was the case for two in-service failures discussed herein, it was found that a combination of features may have contributed to the overall defect growth rate being faster than anticipated. In one case a shallow dent was located adjacent to the seam, and in another a mismatched seam weld containing a crack was able to survive a previous hydrostatic test due to better-than-average material strength and toughness. These and perhaps other exacerbating features affecting seam welds could possibly be better detected with in-line inspection since the test pressures and test intervals (which were carefully considered in both cases) were apparently not high enough and not short enough, respectively, to prevent the failures.

Another shortcoming of hydrostatic testing for managing seam-weld integrity is shared with in-line inspection. That is the inability to find short (typically less than 1 inch), through-wall lack-of-fusion defects (a.k.a. pinholes or penetrators) that seem to leak at random times in-service.

These are bondline flaws that occur during the welding process and the leak path is typically plugged by an oxide. Hydrostatic testing would not be expected to find these defects unless they happen to leak during a test, which some have.

In cases where in-service failures occurred well after a hydrostatic test (for example, many in-service failures discussed herein happened eight or more years after a hydrostatic test), a general statement can be made that a test was not conducted on a frequent enough basis. This is not a shortcoming of hydrostatic testing itself per-se, rather it suggests that the means to recognize a time-dependent seam-weld threat or to model the defect growth was inadequate. This may have been the case for many of the early in-service failure discussed herein. In recent times, fatigue crack growth modeling has been extensively used to determine retest intervals for some pipelines, including several of the pipelines discussed in this study. The challenge is to be able to predict what size flaws could possibly remain in the pipeline following a hydrostatic test, and to know what the growth rate is. This topic will be discussed more thoroughly in the Subtask 2.5 report on Predicting Times to Failure for ERW Seam Defects that Grow by Pressure-Cycle-Induced Fatigue.

Although none of the case studies discussed herein involved selective seam weld corrosion, this integrity threat can potentially be effectively managed by hydrostatic testing, however it is probably more commonly managed by in-line inspection. This topic will also be discussed in the Subtask 2.5 report.

A pressure reversal is said to occur when a test break occurs at a lower pressure than the test segment experienced on a previous pressurization attempt. As the failure pressure of a particular defect is approached, it will begin to extend by stable ductile tearing. If the test is terminated before the ductile tearing can become unstable, perhaps by the event of a failure of another defect with a similar failure pressure, the depressurization can result in further degradation and a lower failure pressure might be experienced on the next attempt.

One of the case studies (Number 2), experienced 24 pressure reversals over the course of the hydrostatic tests. This and other case studies have been evaluated in a previous study to determine the likelihood that a pressure reversal could affect the integrity of a pipeline.[9] If a pressure reversal could affect the integrity of a pipeline, then the effectiveness of hydrostatic testing would be diminished. The pressure reversal phenomenon could only affect pipeline integrity if a reversal was large enough to completely erode the margin between the test pressure and operating pressure. In the Case 2 pipeline, a relatively large pressure reversal did occur

[9]Kiefner, J.F., Kolovich, K.M., and Kariyawasam, S., "A Study of Cases of Hydrostatic Tests Where Multiple Test Failures Have Occurred", IPC2010-31157, Proceedings of the 8th International Pipeline Conference, IPC 2010, September 27 – October 1, 2010, Calgary, Alberta, Canada

(142-psig) however the margin between the test pressure at a high elevation and the MOP was 402 psig (1.28 x MOP). Examining the distribution of the pressure reversals, most were small (less than 20 psig), and an exponential distribution fit the data reasonably well. Using the distribution to determine the likelihood of a 402-psig reversal, the event was given a probability of 3.5e-19. This clearly demonstrates that a pressure reversal should not be considered an integrity threat for this pipeline. However, it is important in all cases to maintain high test-pressure-to-operating pressure ratios to ensure that a pressure reversal remains a negligible integrity threat. A test pressure of 1.25 or 1.39 times the MOP will likely provide a suitable margin for a low likelihood of a pressure reversal that could affect the integrity of the pipeline, however, it is noted that higher test-pressure-to-operating pressure ratios should be considered for pipelines that operate at lower stress levels since a test to 1.25 or 1.39 times MOP may not eliminate large flaws that could have short times-to-failure.