Executive Summary

The SOHIC Study Team was formed by the Vice President of Engineering Services following the incident in the Plant on October 4, 1998. After more than five months of study, the Team is now presenting its findings and recommendations in this report.

Within a week after the incident our metallurgical staff identified the failure to be a rare case of stress-oriented hydrogen induced cracking (SOHIC). SOHIC is one of several cracking mechanisms that are possible in wet sour service. This type of failure has never happened before on plant piping within our company. It has been reported a few times on cross-country pipelines throughout the oil and gas industry.

The consequences of the Plant incident could have been disastrous, if personnel had been exposed to the released gas or it had caught fire. Engineering Services Management not only recognized the seriousness of the incident, but was also concerned about the possibility of similar problems in other operating facilities. First of all, there are numerous sour gas facilities within the company. Secondly, the cracking happened so rapidly, after only seven months' service. Accordingly, a team consisting of members from all concerned engineering disciplines was assembled to investigate the broader issues of SOHIC.

The Team's objectives were:

1. investigate the root causes of the failure
2. recommend required actions for the prevention of the reoccurrence of the incident throughout the Company.

The Team developed an action plan as follows:

a) Short-term actions
   - investigate the Plant failure.
   - conduct a Company-wide SOHIC survey.
   - assist in bringing the Plant back to service safely and expeditiously.

b) Intermediate-terms activities
   - review Company standards and material specifications related to wet, sour service and propose changes.
   - identify areas for improvement in material identification and traceability.

c) Long-term activities involved lab testing (in-house and research contractors) for better understanding of the fundamentals of SOHIC.

After the investigation of the Plant incident, the Team is convinced that the failed pipe has been exposed to a very severe wet sour environment. The pipe surface was in contact with very low pH water containing high concentrations of H_2S and CO_2. This severe environment was the principal reason for the failure. However, the Team and the operating organization could not determine the actual process conditions resulting in a water-wet environment. The failed joint was a spiral-welded pipe. The residual stresses associated with the spiral-welded joint contributed to the cracking.

The Plant was successfully placed back in service again in February 1999. The Plant implemented a series of corrosion control and monitoring measures suggested by the Team. As long as these measures are enforced, the Team is confident that the Plant will have a safe and continuous operation.

The Company-wide SOHIC survey has not detected any other apparent SOHIC damage. This finding and the industry's lack of incidents with SOHIC lead the Team to believe that SOHIC should not be a common concern for the Company.

For the current Engineering Standards and Material Specifications related to wet, sour services, the Team concludes that no sweeping revisions are required. However, the Team believes that extra precautionary measures are required for systems handling single-phase, wet, sour gas. As a result, the Team recommends some Standard revisions to meet this requirement.

A separate Subcommittee on Material Handling was created in response to the discovery of the installation of non-sour service pipe into sour gas lines in the Plant. The Subcommittee studied ways to improve pipe traceability and to reduce the chances of misapplications of pipe on Company jobs. Among various marking systems considered for pipe joints, paint-striping and adhesive-label methods can be implemented soon; the magnetic chip technology needs further investigation.

Lab testing has confirmed that even if pipe steels are resistant to hydrogen-induced cracking (HIC), they could still experience SOHIC damage if service environments are severe enough. Under such severe environments, the threshold stress levels for SOHIC failure could be so low that all carbon steels would be unsuitable.

The SOHIC Study Team will disband after the Team Report is issued. However, each department will continue to work on the various tasks identified by the Team. Specifically, Engineering will initiate Standard revisions, monitor Plant operations, and complete the contracted studies. The Laboratory will continue with its studies on SOHIC. Inspection Department will be involved in activities concerning SOHIC detection and material handling.

1. Conclusions & Recommendations

1.1 Conclusions

1.1.1 The Plant failure in a 24-inch x 0.500” w.t., spiral-welded pipe was due to stress-oriented hydrogen induced cracking, commonly known as SOHIC.

1.1.2 The P-511 line was exposed to a severe wet sour environment prior to its failure. The Team and the Plant could not determine the actual process conditions resulting in a water-wet environment.

1.1.3 High residual stresses in a spiral-welded pipe contributed to the failure in this severe wet, sour gas environment.

1.1.4 Enforcement of the additional corrosion protection measures taken is essential to the safe operations of the rebuilt Plant.

1.1.5 SOHIC damage should not be a common concern within the Company. The Plant incident in 1998 is a rare case.

1.1.6 There are only limited cases of SOHIC failures in the oil industry. The Team is not aware of any SOHIC failure on plant piping except in this Plant.

1.1.7 A long-term concerted effort is needed to resolve a number of unknown fundamental issues on SOHIC.

1.2 Recommendations

1.2.1 Implement proposed standard changes described in Chapter 7.

1.2.2 Implement procedures for the improvement of materials identification and traceability as proposed in the Appendix.

1.2.3 After the Team is disbanded, continue the lab testing programs on SOHIC fundamentals and conditions leading to a water-wet environment in the Plant.

1.2.4 Address the avoidance of SOHIC and high rate of metal-loss corrosion in the early stages of any new gas projects. Exert diligent efforts to study and review process designs, material selection and corrosion control procedures.

1.2.5 Make MagnaScan ultrasonic inspection available to operating organizations on an as-needed basis for critical inspection requirements.

SOHIC FAILURE ANALYSIS

3.1 Summary

Following a pipe failure that resulted in a major release of sour gas, a metallurgical failure analysis was performed. The joint of pipe that failed plus another 39 joints were examined. It was concluded that the gas leak was caused by stress-oriented hydrogen-induced cracking (SOHIC), a rare failure mechanism, and that the P-511 Line contained a very severe wet, sour environment. HIC-resistant spiral-weld pipe in the P-511 Line was more susceptible to SOHIC than HIC-resistant straight-seam pipe. Correlation of environments for three of the four known SOHIC pipe failures, including this Plant, enables proposal of a hypothesis that high pressure wet, sour gas service may be conducive to SOHIC if 1) there is no significant liquid hydrocarbon phase, and 2) H_2S partial pressure ≥ 1.0 bar (14.5 psia), and 3) H_2S + CO_2 partial pressure ≥3.0 bar (43.5 psia), and 4) calculated pH ≤ 3.6. Materials selection precautions for SOHIC environments are discussed. The SOHIC mechanism and need for additional work by the industry are discussed.

3.1 Background

3.1.1 Plant background

Work under a recent construction project was commissioned in January 1998. The primary purpose of the project was to increase gas capacity and reduce flaring by replacing the Plant molecular sieve gas dehydration system with a new ethylene glycol (EG) system that requires no regeneration gas. See Chapter 4 for Plant process details. A simplified process flow diagram for the Plant overhead gas is shown in Section 3.9. The operating conditions in the P-511 Line, where the failure occurred, involved a pressure of 390 psig and temperature in the insulated line of 52° F. The H_2S content was approximately 10% or higher, with an equal amount of CO_2. Therefore, the partial pressures of H_2S and CO_2 were both approximately 2.7 bar (39 psia) for a combined partial pressure of 5.4 bar (78 psia).

The project is reported to have installed 2,080 ft. of 24" O.D. x 0.500" wall thickness (w.t.) SAW-spiral pipe. Some 1,475 ft. of 24" O.D. x 0.562" w.t. SAW-straight (HIC-resistant) pipe was installed. However, by mistake, 1,700 ft. of 24" O.D. x 0.625" w.t. SAW-straight (non-HIC-resistant) pipe from DC Surplus was also installed in wet, sour service.

The Plant was shut down for the six-month post-commissioning T&I on August 17, 1998 and restart began at 0900 on October 3, 1998. On October 4th at 1855 the plant operator noted a loud noise and major gas leak. The line was isolated and depressurized with no injuries or damage to other plant equipment. Visual inspection of the leak location in the 24-inch line revealed a crack approximately 20 inches long parallel to the spiral weld seam and about one-quarter inch from the toe of the weld. A five foot long section of pipe containing the crack was shipped to the Materials Engineering Unit for metallurgical failure analysis. Many additional background details may be found in the Plant Operations Department's Failure Report.

3.2.2 History of SOHIC

Our company's current belief is that the first pipeline failure confirmed to have involved stress-oriented hydrogen-induced cracking (SOHIC) was the Saudi Aramco GART Line in 1974[1, 2]. This failure was also listed by Ikeda[3] as the fourth known occurrence of HIC and the second case involving stepwise cracking. The GART Line failure, following the HIC failure of a sour crude subsea line two years earlier, helped to focus efforts toward understanding the HIC mechanism and developing the HIC-resistant steels that are so useful today. Nevertheless, although massive HIC was found, the mechanism that initiated the GART ruptures was not conventional HIC, but what was called at the time "SCC type cracking along the spiral weld" and later was called by Ikeda and others "sulfide stress corrosion cracking in low strength steel" and "Type I SSCC." The 1975 GART Line report by Sumitomo[1] identified the effects of residual stress and stress concentration to explain cracking along the spiral weld. However, the cracking along the weld was believed to be closely related to the HIC and subsequent action by Aramco and the industry focused on developing HIC-resistant steel.

A decade later, Bruckhoff[4] proposed the term "stress oriented hydrogen-induced cracking (SOHIC)", which has subsequently been widely adopted, to describe the failure of a German 8-5/8" O.D. ERW sour gas line. This mechanism is, in fact, the same as the one cited in the paragraph above. The partial pressure of the 23% H_2S in the line was over 20 bar (290 psia) and the CO_2 partial pressure exceeded 7.5 bar (109 psia).

The 1992 failure of a Shell Canada line in seamless pipe was attributed to HIC and SOHIC[5, 6]. A large hydrogen blister occurred at an area of anomalous iron oxide and slag inclusions. Stepwise cracking connected one end of the blister to the O.D. surface. SOHIC initiated at the I.D. surface and cracked through to the blister at roughly the center of the blister. The 10-inch line was operating at only 8.0 bar (116 psig) at the time of the failure, but the maximum allowable operating pressure was 72.1 bar (1045 psig) and the line had been in service since 1951. The line contained 3.2% H_2S, 6.5% CO_2, and Shell calculated the pH to be 3.8. The line had been exposed to moist air during a hydrotest a year before the failure and Shell thought this may have converted a normally protective scale to a non-protective form.

3.3 Investigation

3.3.1 Failed pipe

A five-foot long section of failed spiral-weld pipe (identified as "Pipe 1") was received at the Metallurgy Lab. The sample was examined visually and photographs were taken. Figure 3.8.1 shows the sample as received. (Figures are in Section 3.8.) The pipe failure was a leak through a 20-inch long crack running parallel to the spiral weld seam (See Figure 3.8.2). Visual examination and magnetic particle inspection confirmed that cracks were present on the I.D. surface parallel to the spiral weld for the entire length of the pipe sample. In some places the crack was on one side of the weld, in other locations it was on the other side, and in some places cracking occurred on both sides of the weld. Although the project design called for 0.562” wall thickness, all of the 24-inch spiral-weld pipe was found to have an original nominal wall thickness of 0.500”, which was adequate for the design pressure but did not contain as much corrosion allowance.

Figure 3.8.3 shows a cross-section specimen that was cut and polished for metallographic examination. As can be seen, the cracks occurred approximately 0.2” to 0.5” from the toe of the internal seam weld. A Vickers hardness traverse was made across the base metal, heat-affected zone (HAZ), and weld. The base metal hardness averaged 167 HV (equivalent to 84 HRB). Hardnesses in the HAZ ranged from 145 to 176 HV with a distinct soft zone of approximately 150 HV (eq. 79 HRB) located at the outer edge of the HAZ. Weld metal hardnesses were only slightly higher, averaging 175 HV (eq. 86 HRB).

A ring was cut from one end of the section of failed pipe shown in Figure 3.8.1 in order to measure the residual stress as specified in 01-SAMSS-035. As shown in Figure 3.8.4, when the ring was split axially, the circumferential “gap” was negative – the pipe ring closed, overlapping over an inch, which means the net residual stress measured by this method was compressive. There was also an axial displacement of the pipe ends of a little less than an inch.

Pipe 1 was found to have a spiral weld pitch of 1300 mm and was manufactured from 1080-mm wide skelp (coiled plate). Further, it was concluded that the skelp had been procured from “Coilmaker B”. Pipe mill records indicated that this pipe complied with purchase specifications. A number of metallographic specimens were removed from the failed pipe and prepared for examination. Figure 3.8.5 is a composite of three low magnification photomicrographs. This shows a crack system similar to the two cracks seen on the left in Figure 3.8.3, except that in Figure 3.8.5 the two cracks are joined. The crack in Figure 3.8.5 extends over 75% of the wall thickness. Figure 3.8.6 shows part of another crack at a slightly higher magnification extending in the through thickness direction from the I.D. (above the photo) toward the O.D. (below the bottom of the photo). Note that the crack consists of short horizontal segments, corresponding to the pipe rolling direction, that are joined by cracks perpendicular to the rolled surface. Figure 3.8.7 is a close-up of a crack tip area that clearly shows the two components.

Figure 3.8.8 shows another crack, again with the I.D. toward the top and the crack tip at the bottom of the photo. In this crack, it can be seen that hydrogen pressure has created voids significantly enlarging the original crack. Figure 3.8.9 is a close-up of the area marked by the arrow in Figure 3.8.8. Note that hydrogen pressure has exerted a great deal of force, actually yielding the steel and producing the deformation shown.

Figures 3.8.10 and 3.8.11 are photomicrographs of a roughly longitudinal section through an area containing cracks near the failure location. Figure 3.8.10 (as polished) shows typical Pipe 1 base metal containing a number of inclusions. Many of the inclusions have irregular shapes, but there is no pattern of elongation in the rolling direction (horizontal in the photograph). Figure 3.8.11 shows the same area after nital etching. The microstructure can be characterized as fine grain (ASTM 10) pearlite and ferrite with some elongation in the rolling direction and just a hint of banding.

Metallographic examinations of conventional transverse sections and longitudinal sections did not disclose any effect that inclusions may have had and did not reveal any pattern of inclusion elongation in the rolling direction. Generally, all of the inclusions were discrete particles, either globular or irregular in shape.

Upon the recommendation of a Japanese steelmaker, it was decided to section a sample parallel to the rolled surface. This will be referred to as a Z-section. It was accomplished by machining a flat area on the I.D. surface of the same sample used for Figure 3.8.10 and 3.8.11 and then grinding and polishing that surface for metallographic examination. This technique revealed clusters of inclusions oriented in the rolling direction, but the clusters were widely separated. Figure 3.8.12 shows a Z-section (as polished) that reveals a cluster and line of inclusions in the rolling direction. The arrow indicates the rolling direction. To see this feature in a longitudinal specimen, one would have to section right through it and the spacing of the clusters is so wide that one would probably not be lucky enough to do this. Figure 3.8.13 shows this same area at 500X.

The Z-section specimen described above also contains a SOHIC crack in one corner. This crack is in the pipe base metal. Examination of the zone close to the crack revealed some cluster inclusions, strings of inclusions, and features that appeared to have been clusters of inclusions that were affected by hydrogen. Figure 3.8.14 shows a small portion of the SOHIC mentioned above. Several clusters of inclusions can be seen and the arrow marks a thin line of very small inclusions. Figure 3.8.15 shows the area at higher magnification.

The laboratory in Japan measured the “cleanliness” of pipe steel samples using the ASTM E-45 Method A[7]. They found no Type A (sulfide stringer) inclusions, a number of Type B (discontinuous oxide stringer) thin series inclusions with a severity level of 2.0, only a few isolated Type C (oxide and silicate solid stringers), and quite a few Type D (globular oxide non-stringer) inclusions with a severity level of 1.5. The Type B inclusions were found by EPMA analysis to be composed of calcium, aluminum, and oxides, as well as other elements. Our own metallographic observations were generally consistent with the above measurements, although the Type B discontinuous stringers were only seen in the Z-section specimen.

3.3.2 Other spiral-weld pipe

In addition to the failed pipe joint, 39 other joints of pipe from the Plant were delivered to the MEU lay down area for non-destructive testing (NDT) and metallurgical examination. The pipes were numbered sequentially as they were received, beginning with Pipe 1, the sample containing the failure. Visual examinations and NDT screening were conducted, including manual UT, automated P-Scan, and automated Magna-Scan. Eight of the 39 joints were spiral-weld. There were two 20-inch spiral-weld joints that had been removed from “Section 4” the C-203 Overhead to E-223/224. (See 3.9) One ultrasonic indication was found in each of these two pipes. Metallurgical examination found these indications to be minor lack of fusion at the toe of the seam weld. No HIC or SOHIC were found in these two joints.

In addition to Pipe 1 (the failed joint), SOHIC was found in Pipe 14 and Pipe 45. All of these were in "Section 2," the P-511 Line downstream of the D-262 Reflux Drum. (See 3.9) Pipe 45 was the joint immediately upstream of the failure location. Figure 3.8.16 shows minor HIC in the base metal and moderate SOHIC in the weld heat-affected zone (HAZ) of Pipe 14. The maximum penetration is about 22% of wall thickness, although in this plane the crack has not reached the I.D. surface. A Vickers hardness traverse was made across the base metal, HAZ, and weld. The base metal hardness averaged 165 HV (eq. 83 HRB). Hardness in the HAZ soft zone ranged from 142 to 153 HV. Weld metal hardnesses were only slightly higher, averaging 181 HV (eq. 87 HRB).

Figure 3.8.17 shows SOHIC in the HAZ of Pipe 45. It is similar to that shown in Pipe 14 above. Pipe 45 also evidenced SOHIC in the base metal – see Figure 3.8.18. Figure 3.8.19 is a close-up clearly showing the horizontal (rolling plane) and vertical (through-thickness) components of the cracking.

Figures 3.8.20 and 3.8.21 are photomicrographs of a Pipe 14 longitudinal section. Figure 3.8.20 (as polished) shows typical Pipe 14 base metal containing a number of inclusions. Many of the inclusions have irregular shapes, but there is no pattern of elongation in the rolling direction (horizontal in the photograph). Figure 3.8.21 shows the same area after nital etching. The microstructure can be characterized as fine grain (ASTM 10) pearlite and ferrite with some elongation in the rolling direction, but no significant banding.

3.3.3 Straight-seam HIC-resistant pipe

Out of 22 joints of HIC-resistant straight-seam pipe from throughout Plant , HIC/SOHIC was only found on one piece – Pipe 24, which was from P-511 Section 2. (See 3.9) Figure 3.8.22 shows a crack system with multiple mechanisms. The cracks are entirely in the base metal; however, the seam weld is just to the left. At the left, the through-thickness crack is very characteristic of SOHIC. The long horizontal series of cracks appears similar to conventional HIC; however, no elongated inclusions were observed to be serving as crack initiation sites. Small patches of this "HIC" each approximately an inch in diameter were found scattered throughout the body of the pipe by ultrasonic inspection. At the right in Figure 3.8.22, the crack curves toward the I.D. surface. This morphology seems to have some relation to the SOHIC mechanism in that no elongated inclusions are present. The curve is more or less continuous, not stepwise, and the curved crack cuts across rolling planes.

Figure 3.8.23 shows one of the isolated "HIC" spots mentioned above. Figure 3.8.24 shows a portion of the crack after nital etching and Figure 3.8.25 is a close-up at 200X. The crack does not appear to be following elongated inclusions, but may have some relation to microstructure. At high magnification the crack is seen to be a network of hydrogen voids and islands of remaining base metal.

Figures 3.8.26 and 3.8.27 show transverse metallographic specimens of this straight-seam HIC-resistant pipe. Note in Figure 3.8.26 that the steel is very clean with no elongated inclusions. Figure 3.8.27 shows a fine grain (ASTM 9) ferrite-pearlite microstructure with no significant banding. There is some deformation of grains from rolling.

3.3.4 Straight-seam non-HIC-resistant pipe

Nine joints of straight-seam non-HIC-resistant pipe were examined (other joints were disposed of by Plants). These were the 24" O.D. x 0.625" w.t. joints that were ordered and installed by mistake. Large hydrogen blisters were visible on many pieces and numerous HIC areas were found along the pipe wall centerline. This generally is the type of damage to be expected in non-HIC-resistant pipe. However, the rapid occurrence of the blisters was surprising and there was one very interesting phenomenon observed – "HIC" that curved from the centerline to the O.D.

At the lay-down area, cracks were found in the O.D. surface of Pipe 12 running parallel to the seam, but several inches away. Upon sectioning, it was found that these cracks consisted of two zones: 1) fairly normal looking HIC at the centerline, and then 2) a portion where the crack curves toward the O.D. The curved portions begin at locations where the intermittent centerline inclusions are no longer present. Figure 3.8.28 shows the curved end of one of the "HIC" cracks. The centerline portion is to the left. Although the curved part is wandering a little, it is not "stepwise." It is a basically continuous curve, snaking up toward the O.D. Figure 3.8.29 shows the end of the crack. Clearly, it is crossing the bands that show the rolling plane and, although it is difficult to see in the photograph, there is a fine SOHIC crack at the very tip that turns up perpendicular to the rolled surface. At first glance under low magnification, the curved portion shown in Figure 3.8.28 looks a lot like conventional HIC. However, there are no elongated inclusions and some parts of the crack, under high magnification, provide insight to the mechanism. In Figures 3.8.30 and 3.8.31, it can be seen that the crack propagates as a network of fine cracks, possibly involving a hydrogen embrittlement mechanism. This is the location shown by arrows in Figures 3.8.28, 3.8.30, and 3.8.31. Figures 3.8.32 and 3.8.33 characterize this steel at locations away from the centerline. Figure 3.8.32 shows a fairly clean steel with globular inclusions. Figure 3.8.33 shows a fine grain (ASTM 12) moderately banded ferrite-pearlite microstructure.

3.3.5 Non-HIC-resistant blistered elbow

A heavily blistered 24-inch 45-degree elbow was found in the P-511 Line (Section 2). This elbow was of welded construction. No blisters were seen in a seamless 90-degree elbow immediately upstream. No SOHIC was found in the blistered elbow.

3.3.6 Miscellaneous tests and analyses

Scale analysis. Three scale analyses were performed using XRD and EDXRF techniques. The scales were found to be sour service corrosion products, including 9% to 10% elemental sulfur.

Tensile tests. A number of tensile tests were conducted during the investigation. The failed pipe (Pipe 1) was found to have a yield strength of 58,400 psi and a ultimate tensile strength of 72,700 psi by testing a full size API 5L transverse strip specimen. Yield strength, ultimate tensile strength, and elongation exceeded the requirements of API 5L Grade B. Several small round tensile bars (0.25" dia. x 1.00" gage length) were pulled to support the TM0177 NACE tensile tests. Transverse to the weld, the measured yield strength of Pipe 1 was 62,560 psi and the ultimate tensile strength was 79,070 psi. Parallel to the weld, Pipe 1 showed an yield strength of 61,480 psi and a ultimate tensile strength of 77, 640 psi.

HIC tests. A number of HIC tests were conducted in accordance with 01-SAMSS-016 and NACE TM0284. A sample of steel from Pipe 1 passed a HIC test in the TM0284 Solution A (same as TM0177 solution). This solution, which has a starting pH of 2.7, is more severe than the standard Company test per 01-SAMSS-016, which uses TM0284 Solution B. Pipe 24, a 24-inch straight-seam joint believed to be HIC-resistant per 01-SAMSS-016, also passed the HIC test in Solution A. See Chapter 8 for additional details.

NACE Tensile Tests. A number of TM0177 Method A (NACE Standard Tensile) tests were conducted by LR&DC using the proof ring device. Samples machined from Pipe 1 perpendicular to the weld were exposed in the low pH (initial pH = 2.7) TM0177 solution that is the same as TM0284 Solution A. The specimens were stressed to various percentages of the measured ultimate tensile strength (79 ksi). The 70% coupon failed in 29 hours, the 60% coupon failed in 125 hours, and the 50% coupon at 238 hours. The 40% coupon, although it did not break, showed evidence of SOHIC when examined metallographically. The 20%, 30%, and 40% specimens were subjected to a post-exposure tensile test. The 30% and 40% specimens had reduced properties (yield, ultimate tensile strength, and elongation about half of original), while the 20% specimen was only slightly affected (properties > 83% of original). See Chapter 8 for additional details.

Arc-Met chemical analysis of steels. A number of analyses were performed using the Metorex Arc-Met 900 optical emission analyzer. Table 1 in Para. 3.7 summarizes the results. One item of interest was that the chemical analysis of the straight-seam pipe that suffered HIC/SOHIC damage (Pipe 24 from Section 2) was not significantly different from other straight-seam HIC-resistant pipe that was undamaged (Pipe 41 from Section 3, Pipe 42 from Section 1, and Pipe 43 from Section 3).

3.4 Discussion

3.4.1 Discussion of SOHIC

The cracks that caused the failure were almost immediately recognized as being similar to the failure mechanism for which Bruckhoff [4] introduced the term SOHIC.

Typically, the first stage is formation of a vertically (through thickness) stacked array of short HIC-like cracks. Each short crack is typically parallel to the rolling direction and the array is believed to form perpendicular to the overall resultant stress. Subsequently, the array is joined by cracks between the individual short elements, typically producing a significant through-thickness crack system. Some of the characteristics of SOHIC that appear evident from our Plant investigation and that may be helpful in distinguishing SOHIC vs. HIC vs. SSC include: 1) high strength and hardness are not required for SOHIC, 2) elongated inclusions are not required for SOHIC, 3) SOHIC can occur in HIC-resistant steel, 4) SOHIC is frequently associated with stress concentrators such as welds, but does not always occur in the HAZ, 5) for SOHIC, generally a high nominal stress, high residual stress, and/or stress concentration is present, 6) less severe environments require higher stresses for SOHIC and more severe environments require less stress.

Although there has been a tendency to speak about SOHIC as a single mechanism, the present failure analysis has disclosed three different, but related, morphologies: 1) SOHIC in the base metal as stacked, connected arrays of cracks, 2) soft-zone cracking in the HAZ, which may appear as somewhat distorted stacked/connected arrays, and 3) HIC in nominally HIC-resistant steel – this can look like conventional HIC or the crack path can be curved.

For this case, why is HIC in HIC-resistant steel considered to be related to SOHIC? It is because the cracks may be initiating in the same way for the short HIC-like "starter" cracks in the stacked SOHIC array and the HIC in HIC-resistant material. It should be noted that almost all of the pipe involved in our failure analysis was HIC-resistant – some was spiral-weld and some was straight-seam. Even the non-HIC-resistant steel was only susceptible at the mid-wall centerline. One thing that is puzzling is that the "HIC" appears to be initiating without benefit of elongated inclusions. What seems to be happening, and should be the subject of further work, is that the "HIC" cracks may be self-initiating. Consider a mechanism where first a fine crack, or network of cracks, forms from a hydrogen embrittlement effect. This very fine crack then serves as a hydrogen trap and enlarges itself by hydrogen pressure to form a more conventional looking "HIC" crack. Fine hydrogen embrittlement cracks could be stress-influenced in their orientation and would not require elongated inclusions -- they are not limited to the rolling plane and can cut across rolling planes, producing the curved shapes observed.

3.4.2 Discussion of Plant environment

It was evident from the beginning of the investigation that the Plant in general, and the P-511 Line in particular, had a very severe wet, sour environment. The large hydrogen blisters that formed in seven months of operating time have, in the past, been observed in other sour service pipelines after 15 or 20 years service. As part of a 1995 paper by D. R. McIntyre[8], six sulfide stress cracking (SSC) failures were identified in the company's operating history where the H_2S partial pressure was over 1.0 bar (14.5 psia). Two of these failures were at the subject Plant. In addition, a search of MEU records located a report of HIC and hydrogen blistering in the Plant's non-HIC-resistant pipe in 1992.

Plant /Line P-511 processes gas with a high level of H_2S and CO_2 at relatively high pressure. If one assumes the presence of liquid water, the InterCorr International computer program "Strategy-A, ver. 2.1, Smart Software for Evaluation of Steels in Sour Pipeline Service" rates the P-511 environment severity as 8.00 out of 10.00 and predicts a pH of 3.38.

It is true that another plant, which processes smaller volumes of similar gas, has not demonstrated HIC/SOHIC failures. The primary explanation is probably that the other plant consists largely of smaller diameter, seamless piping. It is also possible that the operation of the other plant has allowed the formation of a stable, protective sulfide scale.

In the final analysis, of course, it must be pointed out that SOHIC did occur and SOHIC has been a very rare failure mechanism worldwide, being chiefly associated with severe sour environments, low pH, and high stress.

3.4.3 Discussion of Spiral-Welded Pipe

Although work is still in progress at two research labs in Houston, our current belief is that high residual stress in spiral-welded pipe made it particularly susceptible to SOHIC in this Plant. Using the ASTM E 387 blind hole drilling method, Stress Engineering Services[9] has measured residual stresses on the I.D. of a spiral-weld pipe sample (Pipe 14) that exceeded 130% of the specified minimum yield strength (SMYS). Measurements on the I.D. of a straight-seam sample were generally less than 50% of SMYS. During the course of examining 40 joints of pipe from Plants, nine joints of spiral-weld pipe were examined and three of the seven 24-inch joints were confirmed to have SOHIC. By comparison, out of 22 joints of straight-seam HIC-resistant pipe, only one piece had cracks.

Among the seven joints of 24-inch spiral-weld pipe, the failure joint, Pipe 1, was unique in that it is the only one that was manufactured from 1080-mm wide skelp from Coilmaker B, and contained approximately 0.3% nickel and less than 0.02% copper. The other six joints of 24-inch spiral-weld, including two that had lesser SOHIC damage, were all made from 1300-mm wide skelp from Coilmaker A with a somewhat different chemistry. The work in progress in Houston may help to explain the difference in performance of the two types of spiral-weld pipe. (See Chapter 9) The difference in skelp width means that the failed joint, with Skelp B, had a tighter spiral than the joints with lesser damage. This could have a possible effect on residual stress. Skelp B was higher in carbon, manganese, and nickel than Skelp A, but lower in silicon and copper. Material B seemed to have somewhat more inclusions and the inclusions had more irregular shapes.

3.4.4 Discussion of straight-seam pipe

Pipe supplied to API 5L is designated as either non-expanded or cold expanded. Cold expansion strengthens the pipe and is generally believed to reduce residual stresses. Large diameter double submerged-arc (DSAW) straight seam pipe produced in volume by major manufacturers is produced by the "UOE" process that includes cold expansion (the "E" in UOE). All of the straight-seam pipe installed in Plant is believed to be cold expanded UOE pipe. Non-expanded DSAW straight seam pipe is less common and is made by the pyramid-rolling, three roll bending, or press bending processes. Although the issue is under discussion within the industry, non-expanded DSAW pipe is believed to retain higher residual stresses from welding of the seam.

3.4.5 Discussion of material selection for SOHIC environment

If a tentative SOHIC environment envelope can be proposed, then it will be prudent to take certain precautionary measures for piping systems operating in those environments. Seamless pipe is believed to be much more resistant than welded pipe and seamless is available from multiple manufacturers up to 20-inch, possibly from several manufacturers at 24-inch, and from one manufacturer up to 36-inch. Cold-expanded SAW straight-seam pipe is generally believed to have lower residual stresses than spiral-weld and this seems to be confirmed by initial results from Stress Engineering Services. Some other oil companies require welded pipe to be stress relief heat treated for wet, sour service and this should reduce residual stresses. During this failure investigation, no cracks were found associated with girth welds; however, welding research has shown that very high residual stresses can occur in and near the HAZ of welds.

For extremely severe environments, or if cost-effective for intermediate environments, corrosion-resistant alloys such as stainless steels can be used. For example, a tremendous quantity of Type 304 stainless steel is produced worldwide and it can be cost-effective for some applications. For smaller sizes, solid stainless steel is sometimes affordable. For larger sizes, the preferred approach is usually internal cladding. Internally clad pipe, made from co-rolled or explosion-bonded plate, is available. Individual pieces, such as fittings, can have an internal surface applied by weld overlaying. Internal non-metallic coatings can be used for some applications, but may not be suitable for all applications.

3.4.6 Discussion of future work (see also Chapter 9)

There is a need for additional work on SOHIC by the Company and others in the industry. Current work in progress under contract to Stress Engineering Services will provide information on the significance of residual stress. Work under contract at InterCorr International will provide information about the relative SOHIC susceptibility of several materials. Industry research should attempt to fully determine the initiation mechanism for SOHIC. In the absence of elongated inclusions, how and where do the first HIC-like cracks initiate? What is the possible influence of microstructure or very fine dispersed inclusions? What is the effect of clusters of inclusions? In the absence of obvious elongated inclusions, why is the rolling plane frequently the preferred orientation for the very first cracks, even when it is parallel to the major stress? On the microscopic scale, is anisotropic strength or fracture toughness a factor?

3.5 Conclusions

- The 24” O.D. x 0.500” w.t. spiral-welded pipe failed due to stress-oriented hydrogen-induced cracking (SOHIC), which extended for the entire 40 foot length of the pipe joint, although the through-thickness crack that produced the leak was only 20 inches long.
- The joint of pipe that failed was found to comply with Company standards, Moreover, the failed joint was found to be HIC-resistant per NACE TM0284, Solution A.
- No conventional HIC was found in the failed pipe joint, only SOHIC, which was confined to a zone outside the weld HAZ but within one inch of the weld.
- Pipe 24, which was confirmed to be HIC-resistant, contained numerous small scattered spots of HIC and also SOHIC in the body of the pipe.
- Because of the rapid onset of SOHIC and hydrogen blistering, which occurred in approximately seven months of operating time, it is believed that the wet, sour corrosiveness of the P-511 Line was extremely severe. The calculated pH was 3.4, the partial pressure of H_2S was 2.7 bar (39 psia), and the partial pressure of CO_2 was 2.7 bar (39 psia). This, along with the damage to Pipe 24 mentioned above, indicates that the P-511 Line environment was more severe than the TM0177 and TM0284-Solution A accelerated test environments
- Within the Plant it appears that the P-511 Line had the most severe environment. Although hydrogen blistering was found in numerous pieces of non-HIC-resistant straight-seam pipe, no SOHIC was found outside of the P-511 Line
- Spiral-welded pipe in the P-511 Line was more susceptible to SOHIC than HIC-resistant straight-seam pipe. Out of 22 joints of HIC-resistant straight-seam pipe, only one (Pipe 24) was found to be damaged.
- Although all of the spiral-weld pipe removed from service has not been received for examination yet, the failure joint, Pipe1, thus far has some unique characteristics. It was made from 1080-mm wide skelp from Coilmaker B and contains approximately 0.3% nickel and less than 0.02% copper.
- Six other joints of 24-inch spiral-weld pipe were examined, all made of 1300-mm wide skelp from Coilmaker A. Two of these joints, including the one immediately upstream of the failure, contain HAZ SOHIC that penetrated less than 25% of the wall thickness.
- High pressure wet, sour gas service may be conducive to SOHIC if: 1) there is no significant liquid hydrocarbon phase, and 2) H_2S partial pressure $\geq$ 1.0 bar (14.5 psia), and 3) $H_2S + CO_2$ partial pressure $\geq$3.0 bar (43.5 psia), and 4) calculated pH $\leq$ 3.6.

3.6 References

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9) Stress Engineering Services, “Residual Stress Measurement Report of Spiral Welded Process Piping,” February 1999.

3.7 Tables

Table 1 – Arc-Met Chemical Analyses

Element	Pipe 1	Pipe 12	Pipe 14	Pipe 17	Pipe 24	Avg. Pipes 41,42,43
	Failed joint, spiral, HIC resistant	Cracked long seam, non-HIC resistant	Cracked, spiral, HIC resistant	Uncracked 20" spiral, HIC resistant	Cracked, long seam, HIC resistant	Uncracked long seam, HIC resistant
Fe	98.41	97.97	98.46	98.61	97.62	97.72
C	0.097	0.12	0.039	0.055	0.062	0.075
Si	0.16	0.20	0.30	0.29	0.34	0.33
Mn	1.00	1.43	0.81	0.73	1.50	1.41
Cr	0.0047	0.0027	0.0065	0.0027	0.007	0.006
Ni	0.23	0.041	0.062	0.057	0.097	0.09
Mo	0.011	0.019	0.0018	0.0018	0.015	0.008
Cu	0.0099	0.0072	0.20	0.20	0.17	0.15
Al	0.034	0.033	0.031	0.049	0.035	0.043
V	0.0018	0.033	0.0018	0.0058	0.049	0.051
W	0.0018	0.030	0.013	0.0018	0.0018	0.01
Ti	0.0072	0.019	0.017	0.022	0.011	0.011
Nb	0.015	0.040	0.029	0.024	0.055	0.049
B	<0.0005	<0.0005	<0.0005	<0.0005	<0.0005	<0.0005
S(1)	0.011	0.0099	0.010	0.010	0.011	0.008
P(1)	0.028	0.042	0.027	0.026	0.027	0.036
Ce	0.28	0.374	0.192	0.192	0.34	0.34

Note (1) – Questionable results, S and P levels measured by other laboratories and other methods are typically less than one-third of these values.