FRACTURE TOUGHNESS AND BRITTLE FAILURE: A PRESSURE VESSEL CASE STUDY

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Fracture Toughness and Brittle Failure: A Pressure Vessel Case Study

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That the manufacturing and fabrication process can introduce low fracture toughness and cause brittle failure in steel has been documented in well-known studies. These include failure of Liberty ships during World War II and, more recently, weld failures in steel moment frames during the 1994 Northridge earthquake. In both of these cases, the manufacturing and fabrication process introduced stress states that reduced fracture toughness and caused brittle failures.

Control of the manufacturing and fabrication process to maintain sufficient fracture toughness remains a challenge for the Oil and Gas Industry. In this article, we will review an incident of a brittle failure of a pressure vessel. The head of the pressure vessel, which was operating as a low-pressure separator, detached about its circumference at a pressure much less than the vessel's maximum operating pressure. A root cause analysis of the incident identified the performance gaps and root causes from the vessel's service conditions, manufacture, and fabrication that combined to cause the brittle failure.

This article examines the performance gaps that lead to the failure and their root causes. The effect of the root causes on the vessel's mechanical properties is discussed. Further, the performance gaps are related to material and fabrication guidelines in the ASME Boiler & Pressure Vessel Code. Finally, recommendations for correcting the performance gaps are offered. © 2017 American Institute of Chemical Engineers Process Saf Prog 000: 000–000, 2017

Keywords: mechanical integrity; case studies; accident investigations

INTRODUCTION

That the manufacturing and fabrication process can introduce low fracture toughness and cause brittle failure in steel has been documented in well-known studies. One example is failure of the Liberty ships during World War II. The hulls of several early ships broke apart in high seas. Subsequent investigation found one factor to be the weld process introducing residual stresses that reduced hull weld's fracture toughness. When this factor was combined with others, such as low temperatures in the North Atlantic, the consequence was brittle, catastrophic failure [1].

A second example is damage to buildings during the 1994 Northridge earthquakes in California. Post-event investigation found instances of fractured connecting welds in steel moment frames. These fractures were unexpected because structural analysis suggested steel moment frames would perform well in a seismic event, compared to other structural systems. As was observed in fabrication of the Liberty ships, the welding process used to connect moment frames in Northridge introduced residual stresses that reduced the fracture toughness and caused brittle failure [2]. This result led to revision of seismic design guidelines as discussed in *FEMA 356 Prestandard and Commentary for the Seismic Rehabilitation of Buildings* [3].

In a more related example, an investigation lead by Harry McHenry was performed to determine the cause of a pressure vessel burst which resulted in 17 deaths at the Union Oil Plant in 1984 [4]. A catastrophic failure occurred after the vessel had undergone repair. The repair welding process introduced high residual stress and material embrittlement, but a post-weld heat treatment was not performed. Metallography revealed preexisting cracks which initiated adjacent to the weld repair. The presence of hydrogen from a sour environment and a susceptibility of the material near the welds to hydrogen cracking resulted in the formation of a crack in weak material which ultimately led to the final fracture of the vessel under normal operating conditions.

From these examples, it is clear that controlling the manufacturing and fabrication processes to maintain sufficient fracture toughness has been a challenge historically. It remains a challenge to this day, particularly in the Oil and Gas Industry, given its global scope and correspondingly long supply chains. This article presents a case study of a pressure vessel failure to illustrate how manufacturing and fabrication processes affect fracture toughness and can introduce brittle failure.

It is particularly important that fracture toughness be controlled during manufacture and fabrication because, after the unit is installed, operators commonly do not have the means to specifically verify fracture toughness through nondestructive means during routine inspections. Operators that lack third-party verification are particularly vulnerable to inadvertently putting equipment with insufficient fracture toughness into service.

In the motivating incident for this study, the head of the pressure vessel, which was operating as a separator, detached about its circumference at a pressure that was much less than the vessel's maximum operating pressure. A root cause analysis of the failure determined that factors from the vessel's service conditions, manufacture, and fabrication had combined

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to cause the brittle failure. Performance gaps in prevention and detection were identified, and root causes of these gaps were determined.

After summarizing the failure incident, this article examines the effects of the vessel's manufacture and fabrication on its mechanical properties. The vessel's manufacturing process is further related to the guidelines in the *ASME Boiler & Pressure Vessel Code (BPVC)*. The performance gaps that led to the failure and their root causes are then discussed. Finally, recommendations for correcting the performance gaps are offered.

PRESSURE VESSEL FAILURE

Incident Summary

A full circumferential failure occurred in one head of a low-pressure condensate separator resulting in the total release of gas and condensate. The separator had operated offshore in sour service for over 30 years.

Ten months before the failure, the separator was taken out of service. Industry standard internal and external inspections were performed on it. No relevant findings were identified indicating a problem that would have prevented the start of operation. In fact, it was determined that the remaining operating life was at least 10 years. Operations were accordingly restarted, and the separator was put back into service 2 months before the failure.

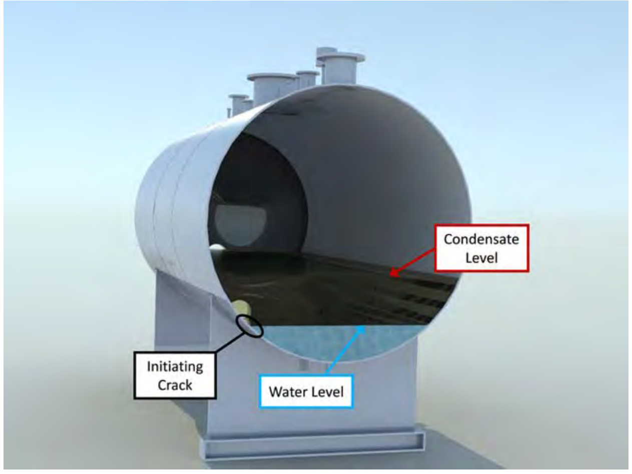

Figure 1. Location of crack initiation. [Color figure can be viewed at **wileyonlinelibrary.com**]

Failure Sequence

A discontinuity in the interior surface of the head, near the weld at about the 7 o'clock position (Figure 1), either existed when the separator was delivered or occurred during operation of the separator. Laboratory findings support the theory that sulfide stress corrosion cracking began at the discontinuity and progressed slowly over years. This corrosion mechanism is consistent with the sour service conditions and age of the separator.

The initial discontinuity and the small, tightly closed cracks were not detected by standard inspection methods before, or after, the accident. Only subsequent laboratory examination was able to identify the cracks. Standard inspection methods before and after the accident did identify thinning from general corrosion; nevertheless, the thickness of the head was above the retirement thickness. The cracking progressed through the thickness and caused a small release that was detected by gas detectors. Within minutes, the crack grew to the critical length that caused the complete circumferential failure of the head. The progress of the crack is illustrated in Figure 2.

The integrity performance of the separator—catastrophic failure following development of a through crack—was inadequate in terms of ASME BPVC Section VIII design philosophy. A vessel designed to the BPVC Section VIII is intended to exhibit leak-before-failure performance. Specifically, the vessel's material must be adequate to develop a through crack and leak product in a controlled manner without catastrophic failure. The integrity performance of the separator did not satisfy this requirement.

The failure sequence described above was developed and verified using onsite personnel interviews, line operation data, postincident evidence gathering, gas detector data, analytical calculations, numerical analysis, and laboratory examination and analysis. Output from a simulation of the failure sequence is shown in Figure 3. That simulation was performed using the Arbitrary-Lagrangian Eulerian method in LS-DYNA, a multi-physics solver developed by Livermore Software Technology Corporation.

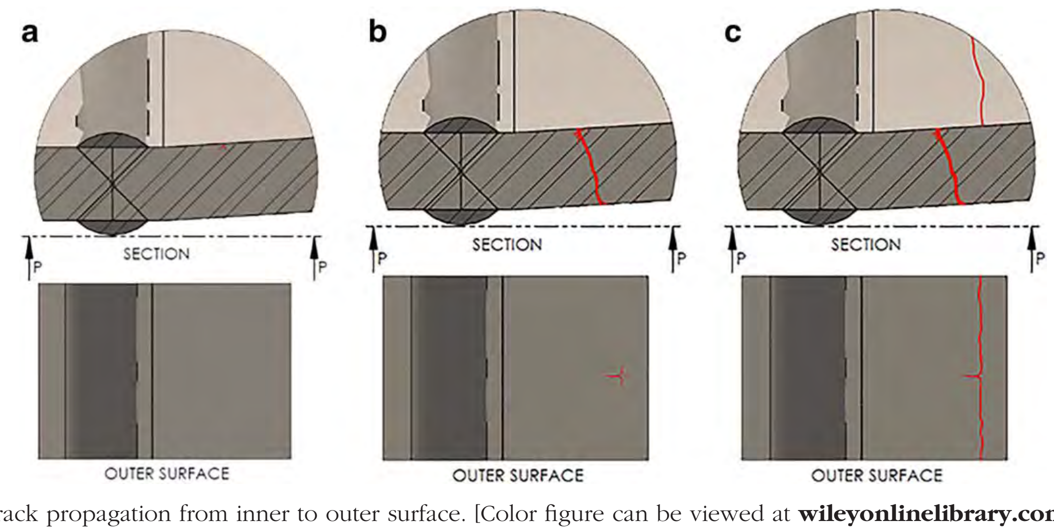

Figure 2. Crack propagation from inner to outer surface. [Color figure can be viewed at **wileyonlinelibrary.com**]

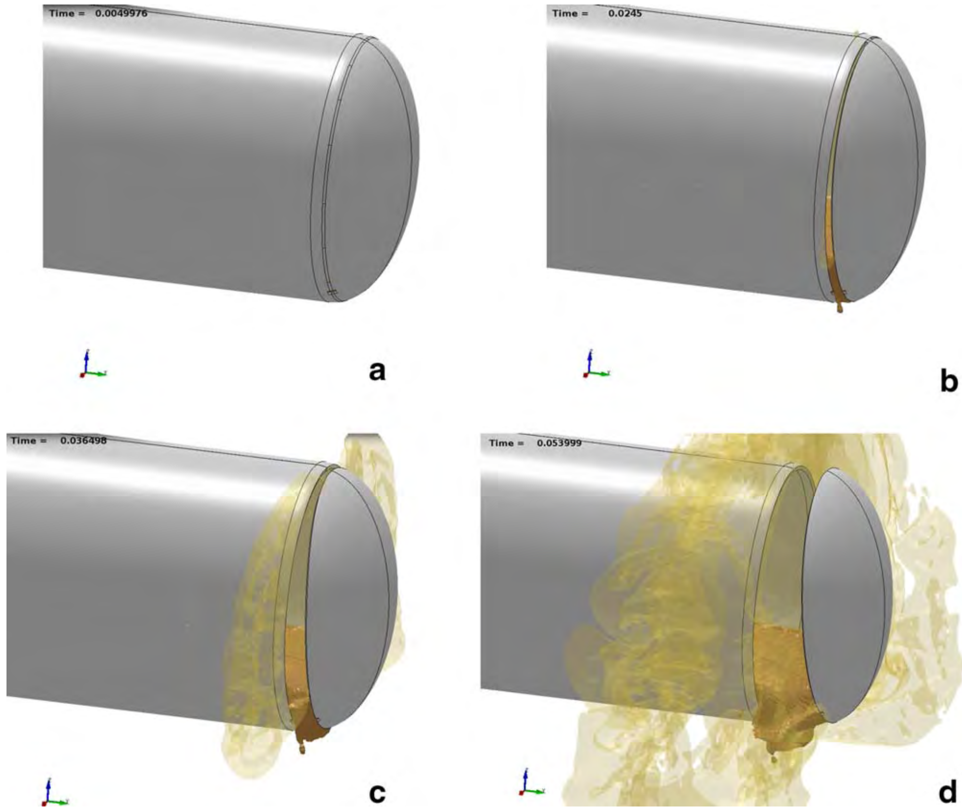

Figure 3. Separator failure sequence. [Color figure can be viewed at **wileyonlinelibrary.com**]

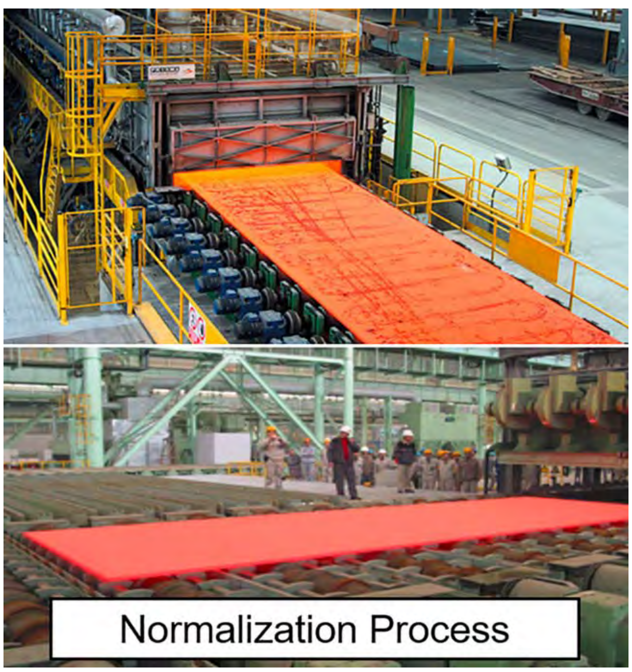

Figure 4. Normalization process (image courtesy of Prisma Impianti, **www.prismagroup.it** and Wesman Group, **www.wesman.com**). [Color figure can be viewed at **wileyonlinelibrary.com**]

MANUFACTURING PROCESS

Mechanical Properties

Laboratory analyses performed following the incident revealed the effects of the manufacturing process on the separator's mechanical properties with the results showing that the head metal was not normalized steel. Normalization is a heat treatment that produces a more uniform microstructure in the steel; the process is illustrated in Figure 4. In terms of mechanical properties, the mill plate used to manufacture the heads had relatively low fracture toughness and was thus vulnerable to brittle failure. In practical terms, lack of normalization meant that the heads did not have the heat treatment that would reduce the potential for crack growth and propagation.

The head manufacturing process further increased this vulnerability to brittle failure. The cold working during dishing and flanging (Figure 5) introduced high residual stresses, increased the ultimate strength of the steel, decreased its ductility, and reduced its fracture toughness. These observations came from laboratory tests comparing mechanical properties at the apex of the head to properties at the knuckle.

The residual stresses introduced during manufacture remained because of a lack of heat treatment and/or insufficient post-weld heat treatment. These processes are shown in Figures 6 and 7. Residual stresses in the vicinity of the failure were further increased by welding the head to the vessel shell. The reduction in residual stress concentrations due to stress relief and post-weld heat treatment is illustrated in Figure 8. In the figure, "T" refers to tensile stress and "C" refers to compressive stress.

Manufacturing Standards

A normalized steel provides better material ductility to reduce the possibility of a complete circumferential failure

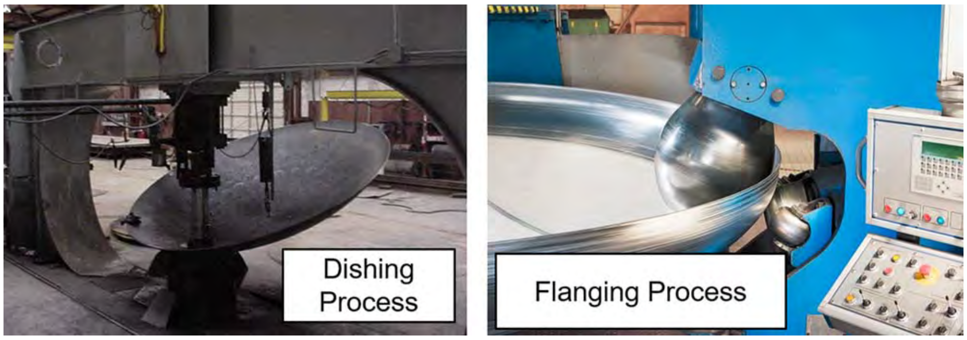

Figure 5. Head dishing and flanging process (image courtesy of Slawinski, **www.slawinski.de**). [Color figure can be viewed at **wileyonlinelibrary.com**]

Figure 6. Stress relief process (image courtesy of Myungjjn Heat-Treatment, Inc., **www.mhti.co.kr**). [Color figure can be viewed at **wileyonlinelibrary.com**]

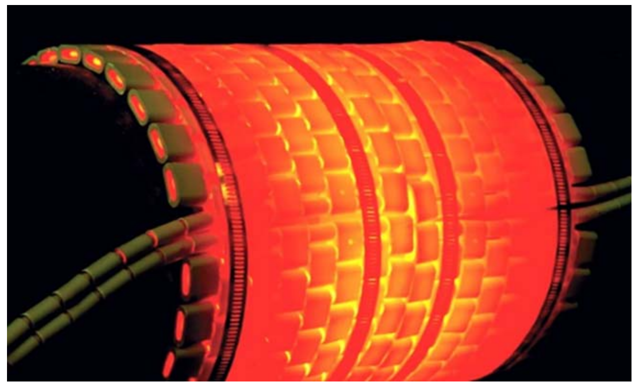

Figure 7. Post-weld heat treatment process (image courtesy of Indiamart, **http://dir.indiamart.com/**). [Color figure can be viewed at **wileyonlinelibrary.com**]

when a through-thickness crack is produced. Stress relieving allows a significant reduction in residual stresses that occur from the cold-forming processes. However, the BPVC accepted at the time of the separator's manufacture did not require that the metal used in forming the sour service separator heads be a normalized steel or that stress-relief after cold forming be applied to the head.

The post-weld heat treatment allows a significant reduction in residual stresses that occur from the welding process. The BPVC at the time of the separator's manufacture did require post-weld heat treatment, but the operator accepted the separator, presumably because the manufacturer had indicated that all requirements had been met. Pressure vessels for sour service do not require verification of sufficient heat treatment. Therefore, the inspections performed during maintenance of the pressure vessels were not focused to identify insufficient heat treatments in the separator's manufacture or the small, tightly closed cracks that might form under these conditions.

PERFORMANCE GAPS AND FAILURE ROOT CAUSES

The root cause analysis process involved first focusing on the identification of equipment failures or front-line personnel performance gaps that are the causal factors contributing to the incident. A single equipment-related causal factor for the failure was identified: the separator lost mechanical integrity.

Once the causal factor was identified, the root cause analysis focused on the identification of performance gaps that contributed to the occurrence of the causal factor and the full development of the relevant root cause paths. The investigation team used a root cause map to help direct the asking of why-why-why until the management system weaknesses representing the root causes contributing to the incident were identified. Specifically, associated with the causal factor were two performance gap categories:

- Prevention gaps—the separator was initially put into service with the heads having insufficient heat treatment during fabrication and assembly.
- Detection gaps—insufficient or nonexistent heat treatment of the separator heads was not detected after the separator's installation.

The root causes of these performance gaps are discussed in the following subsections.

Prevention Gaps

Five root cause paths related to preventing resulted in the separator being put into service with the heads having insufficient heat treatment.

Two of the root cause paths were related to design. First, the mill plates used in the fabrication of the heads were not made of normalized steel. The use of normalized steel is recommended in the technical literature for construction of vessels operating in corrosive environments [5,6]. Evidence suggests that there was no requirement for steel normalization of sour service pressure vessel heads less than 1.5 inch thick in internal design standards, nor was there such a requirement in international design standards (e.g., BPVC) at the time of design. Second, the separator heads did not receive effective stress relief after cold forming. Evidence suggests that there was no requirement for stress relief of pressure vessel heads with less than 5% fiber elongation during forming in internal design standards, nor was there such a requirement in international design standards (e.g., BPVC) at the time of design.

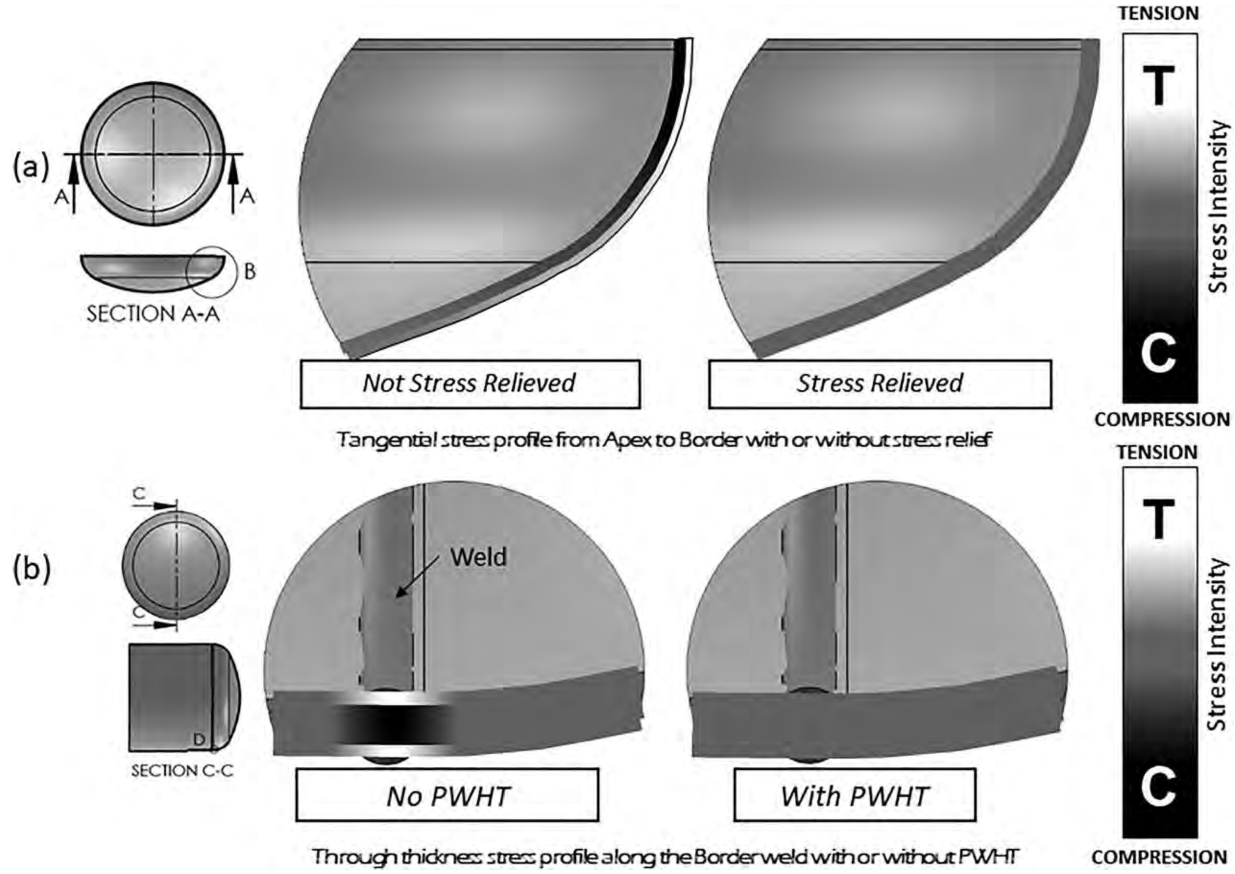

Figure 8. Reduction in residual stress concentration due to (a) stress relief and (b) post-weld heat treatment.

Post-weld heat treatment after fabrication was, however, required by the BPVC at the time of design.

Three additional causes were related to the user's procurement process for the separator. It was inferred that purchasing documentation for the separator (which were not available for review) did not include requirements for normalization or stress relief because the design standards did not have such a requirement. In addition, the separator was designed to the ASME BPVC, but the operator had no requirement that an ASME stamp be on the separator. Finally, it was deduced that the separator was accepted from the manufacturer (receipt documents were not available for review) either without, or with insufficient, post-weld heat treatment. Accordingly, a measure to verify that the heat treatment had occurred was either not in place or not exercised.

Detection Gaps

Three root cause paths related to detection that allowed the separator, vulnerable to brittle failure, to remain in service over 30 years. The root cause paths were limitations in hazard/defect identification and analysis through inspection. First, the pre-startup review, which was performed prior to initial start-up of the separator, did not identify the insufficient heat treatment. Verification of heat treatment documentation was not required as a part of the pre-startup review. Second, the inspections performed throughout the life of the separator did not identify the non-normalized steel. Pressure vessel inspection plans did not include a requirement to verify steel normalization.

Third, the inspections performed throughout the life of the separator did not detect the cracks that had formed and grown. There was no requirement for the determination of manufacture adequacy of operating sour service pressure vessels which would have identified this vessel as inadequate (due to lack of post-weld heat treatment) and prompted mitigation or removal from service. The root causes for these three root cause paths all involved the lack of requirements to support detection.

It is noted that the material condition created a situation where, quite likely, inspections may not have been able to detect the initial damage, and even if the inspections did detect the initial damage, the inspections would be under the thresholds of criticality. In this way, inspections serve as a limited second line of defense against manufacture and fabrication process control.

CONCLUSIONS AND RECOMMENDATIONS

Loss of mechanical integrity of a separator operating at low pressure (the head fractured about its circumference in the flange region) had eight root causes. These causes resulted in prevention gaps in design and procurement and detection gaps in inspections. These performance gaps combined to result in the loss of mechanical integrity.

Several recommendations were proposed to address the performance gaps. First, with regard to the prevention gaps, it was recommended that the operator design standard add a requirement that all carbon steel plate and low-alloy steel plate, used in the manufacturing of the shell and heads of pressure vessels in sour service, be normalized. A second recommendation was to add a requirement that any cold-formed shell and head should be heat-treated for stress relieving.

It remains the operator's responsibility to verify that the stress relief is performed. To that end, it was recommended that the heat-treatment requirements (normalization, stress relief, and post-weld heat treatment) for pressure vessels in sour service in offshore installations be included in the contracts for purchasing, design, or construction. In addition, establishing a requirement that all new pressure vessels in sour service in offshore installations have an ASME stamp was recommended; such a requirement had not existed previously for this international operator.

With regards to the detection gaps, it was recommended that the pre-startup safety review verify the evidences that the required heat treatment has been adequately performed, and, if applicable, that the ASME stamp for new pressure vessels in sour service in offshore installations is the correct. A final recommendation was that the operator verify the required heat treatment was performed on other vessels that are currently in service.

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