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Impact of the Latest ASME B31.3 Revisions on PWHT of CS Piping in Oil and Gas Production and Refining Facilities

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ABSTRACT

For oil and gas production and refinery services, carbon steel (CS) piping welds designed to the ASME B31.3 Code have traditionally had two possible reasons for postweld heat treatment (PWHT). One was if the weld exceeded the thickness limits given in B31.3, and the other was if the service resulted in a susceptibility to an environmental cracking mechanism. PWHT reduces both the residual welding stresses and any high hardnesses in the weld and/or heat affected zones, and hence lowers the risk of environmental cracking. In the 2014 Edition of B31.3, there were major changes made to the PWHT requirements that essentially resulted in no thickness requiring PWHT on CS. This paper will describe the impacts of this change in ASME B31.3 on new construction projects, with discussions of the advantages and precautions, including a list of the common environmental cracking services.

BACKGROUND

Carbon Steel (CS) is one of the most favorable materials of construction in various chemical, petrochemical, nuclear and petroleum industries. In applications where it provides acceptable corrosion resistance and meets the required mechanical properties, it also has the benefit of being easily joined together numerous possible welding processes. Its cost effectiveness has resulted in it being the most commonly used material for piping, vessels, tanks, pumps and other equipment. For many industrial plants, the piping is designed to the ASME B31.3 Code, "Process Piping", which will be referred to as "the Code" through the remainder of this paper. This Code provides the design, fabrication, testing and other details for the construction of new facilities.

In the editions of the ASME B31.3 Code issued prior to 2014, postweld heat treatment (PWHT) was required on CS welds when the weld thickness exceeded 18 mm (3/4 inch). It was changed in 2014, as Table 331.1.3, Exemptions to Mandatory Postweld Heat Treatment, now has exemptions for all thicknesses and all types of welds on CS. In other words, there is no longer any thickness limit at which PWHT becomes mandatory per Code. To apply the exemptions, the Code requires that a preheat of 95°C (200°F) must be applied for any CS at thickness >25 mm (1 inch) and multiple layer welds must be used for thicknesses >5 mm (3/16 inch). However, these practices are easy-to-meet and were similar to practices prior to the 2014 Code.

The ASME B31.1 Code, "Power Piping" is a sister code to ASME B31.3, and it is used for designing and fabricating piping in power plants, which primarily handle steam, boiler feed water, condensate and similar services. The B31.1 Code made identical changes in CS PWHT requirements in 2014, so these two Codes (B31.3 and B31.1) are consistent. The commonly-used Code for vessels, ASME Section VIII, Div. 1 currently requires PWHT for CS at thicknesses >37 mm (1.5 inches) and has done so for many years.

In addition to the previous practice of requiring PWHT to meet ASME B31.3, a second reason that CS welds in piping and equipment have been specified to reason PWHT (regardless of thickness) is when the welds are in services where there is a risk of environmental cracking. There are two families of environmental cracking mechanisms which welds with no PWHT can be susceptible to, namely the stress corrosion cracking (SCC) mechanisms where the residual stresses from welding greatly heighten the susceptibility, and cracking mechanisms which occur in zones of higher hardnesses which can also be present in as-welded weldments.

In welding, residual stresses arise primarily due to the expansion and contraction of the weld metal (WM) during its solidification, and of the adjacent base metal. The zone of adjacent base metal (which is non-melted) is referred to as the heat affected zone or HAZ (Figure 1), and it also experiences some expansion and contraction during local heating and subsequent cooling. A more complete list of reasons for welding residual stresses are that they are caused by inhomogeneous cooling, constrained shrinking and solid state phase transformations. Misalignment of the pipes being welded can also add a notch effect. Many variables determine the distribution, patterns and magnitude of residual stresses, but the simplified formula to estimate the maximum level of residual stress from welding is given later in the paper. A sketch showing one pattern for transverse residual stresses is included in Figure 2.

The services and conditions which can cause environmental cracking on CS are given later in this paper, and PWHT should still be required for these services.

BASIS FOR THE CODE CHANGES

The primary test data that was the basis for the Code change was detailed in a published report.[1] This report stated that the justification for the work was: "Setup and performance of PWHT can add significant time and cost to fabrication, modification, and repair of carbon steel components. Elimination of the current mandatory PWHT on thick carbon steel materials can provide significant savings for large construction or modification projects or critical repair activity."

The testing was done on:

- Materials: ASME SA-516 and SA-515, CS plate material
- Thicknesses: ½", ¾", 1.5" and 2" (9 welds total)
- Material Carbon Equivalents (CE)*: 0.417, 0.385, 0.418 and 0.389
- Welding Processes: SMAW, FCAW and SAW
- Heat Input ranges: 20 – 159 KJ/in (intentional wide variation)
- Weld Technique: Multi-pass Stringer beads
- Joint details: Butt joints with single bevel or single vee

* These CE values were calculated using a different formula than shown in the referenced report. These values are based on:

$$CE = C + Mn/6 + (Cr + Mo + V)/5 + (Ni + Cu)/15$$

The primary testing that was done on the welds included: Hardness, Tensile, Charpy Impact at room temperature, and Side Bend tests. For the hardness and impact tests, no absolute criteria was given and instead the conclusions were primarily based on comparing the thicker welds to the thinner welds which were "already exempted from PWHT" in the pre-2014 Code.

The 1½ and 2 inch test welds were quoted as "expected to be an adequate thickness to show that the properties would still be adequate in even greater thicknesses." Part of the basis for this statement was that the "welding procedure qualification requirements of ASME Section IX would allow a qualification test on 1½ inch thick material without PWHT to qualify for an as-welded material thickness of 8 inches." It was also emphasized that for all welding on ASME piping and equipment, only weld procedures which are qualified per ASME Section IX can be used, regardless of whether or not PWHT is specified.

The Code committee quoted a few additional reports on testing of non-PWHT welds with only giving summaries of the hardness and toughness results. All proposed changes in the ASME Code are reviewed and balloted by the Code committee which is comprised of industry experts on the given topic. Also, another key point is that the Code is intended to provide the minimum requirements to provide an acceptable mechanical design. It intentionally does not cover the added design or fabrication steps that may be beneficial for unique services. It is the Owner, Designer and/or Licensor's responsibility to specify these added steps (such as PWHT) when appropriate for the service.

The purpose of the paper is to highlight the special refinery and oil and gas services where PWHT should still be required, and to discuss the impact of this change in PWHT practices on other industry trends/issues.

BENEFITS OF CODE CHANGE ON CS PIPING

There are obvious benefits in avoiding PWHT, including:

1. Cost and schedule savings for new construction projects or major repairs/replacements – This change reduces the number of welds and spools requiring PWHT. There are savings in both piping shop fabrication where PWHT is typically done by placing entire spools in a furnace and in field fabrication where in most cases, local PWHT is done using electric

resistance coils. A recent trend has been to require the larger band widths for local PWHT as specified in AWS D10.10[2] in order to improve the PWHT effectiveness, and this trend would result in the costs and complexity for a given local PWHT being somewhat higher than in the past.

2. Avoiding some “difficult” PWHTs – one example is welds to valves, where heat treatment has a risk of distorting or oxidizing the seating surfaces or other valve internals. For these cases, valves with special extensions, or special PWHT procedures are required,
3. Avoiding possible low toughness issues for very thick-walled CS piping - long duration PWHT can lower HAZ and base metal toughness in some cases[3] (however for thinner wall piping with their typical PWHT durations, PWHT improves toughness compared to non-PWHT welds).

Note that on most projects, some piping will still require PWHT (i.e., the lines in environmental cracking services), so arranging for PWHT equipment, and including it in scheduling and costs will rarely be completed avoided on projects.

IMPLICATIONS TO CONSIDER

For numerous CS welds, when considering the specific CS pipe material grade, weld joint details, welding procedure, service, etc., the change in the 2014 B31.3 Code to no longer require PWHT at >18 mm (>3/4 inch) can be shown to be acceptable. However, some scenarios which now require more careful review are:

- Environmental Cracking Services susceptible due to high residual stresses,
- Environmental Cracking Services susceptible to possible high hardnesses,
- Cyclic Loading Services which may have increased susceptibility to fatigue, and
- Fitness-For-Service analyses which may be done on indications found during future inspections.

For the services which cause environmental cracking, it was important to require PWHT before the 2014 Code change, and the Code change does not change this practice. However, for one service, high temperature hydrogen, the benefits of PWHT have only recently been published, as shown by the new curve for CS without PWHT added to API RP 941, “Steels for Hydrogen Service at Elevated Temperatures in Petroleum Refineries and Petrochemical Plants” in the 2016 Eighth Edition. [4] With the new 2014 B31.3 Code change, it becomes especially critical that Owners and materials selection/specification experts, are aware of the conditions that require PWHT of CS in hydrogen service. This is discussed further later in the paper, as additional details on both environmental cracking and fitness-for-service are given below.

ENVIRONMENTAL CRACKING OF CS

Stress corrosion cracking (SCC) has been one of the most serious potential damage mechanisms during operation of petroleum and refineries facilities. SCC is a risk when three conditions are simultaneously present:

- A susceptible material, typically in a special condition,
- A cracking service (a certain chemical, contaminant, temperature, etc.), and
- A significant tensile stress.

One of the primary sources of high localized tensile stresses are weld residual stresses, which are significantly “relieved” by PWHT. An alternate term often used for PWHT is “stress relieving”. Welding residual stresses are highest in the HAZ and extend out to a farther distance than the HAZ. This distance of the stress field is illustrated by the fact that numerous cases of amine

SCC have initiated on the inner diameter (ID) surface of piping across from external attachment welds with pipe wall thicknesses.[5] Also, carbonate SCC has been reported in the HAZ and up to 50 mm (two inches) away from welds, but always in the zones that still had residual stresses.[6]

A photo showing carbonate SCC emanating from the residual stresses of a fillet weld is included as Figure 3.

API 579-1/ASME FFS-1, "Fitness-For-Service",[7] section 9D.3.3 states that the welding residual stresses on an as-welded weld will approach the material's actual yield strength. Often only the grade of steel and its specified minimum yield stress (σ_{ys}) are known, but the actual yield strength will vary for each heat of steel. If the actual yield strength is not known, API 579-1/ASME FFS-1 recommends using the following formula to estimate the maximum residual stress near welds:

$$\sigma^{r} = \sigma_{ys} + 69 \text{ Mpa } (10 \text{ ksi})$$

PWHT is very helpful in reducing these residual stresses and this will be addressed in more detail later in the paper in the section discussing Fitness-for-Service analyses.

Besides SCC, a second family of CS environmental cracking mechanisms occur at areas of high hardnesses (which typically equates to high strength). The areas can be narrow zones such as one section of a weld HAZ or the entire component such as a valve stem. Another benefit of PWHT is that it typically reduces high hardnesses which form in CS weld deposits or HAZs.[8] A common limit for HAZ hardness for wet sour services is 248 Hv, and the hardnesses in the test data obtained by the ASME committee as the basis for the Code change in 2014, had some readings which exceeded this.

Hence, PWHT is often a key preventative measure for avoiding environmental cracking which is a risk due to either high stresses or high hardnesses.

Services which Can Cause Environmental Cracking on CS

To describe each environmental cracking mechanism in depth would make this paper much too long. Luckily, there are industry standards giving good descriptions of the mechanisms, including the conditions, cracking locations, cracking morphologies, preventative measures and more. Tables 1A, 1B and 1C list:

- each mechanism,
- the applicable industry standard covering the details listed above,
- the key variables affecting the risk of the cracking, and
- the typical industry practices with regards to PWHT.

Additional summary information on each mechanism can also be found in API RP 517, "Damage Mechanisms Affecting Fixed Equipment in the Refining Industry."

These tables are one of the most important "messages" from this paper – it is now more critical that PWHT be specified for the specific services and conditions that may cause environmental cracking on CS. A list of the mechanism covered in each table is:

Table 1A – Stress Corrosion Cracking Mechanisms:

- Amine SCC
- Caustic SCC
- Carbonate SCC
- Anhydrous Ammonia SCC

- Ethanol SCC

Table 1B – Hydrogen Charging Due to Corrosion / High Hardness Mechanisms:
- Sulfide Stress Cracking (SSC)
- Stress Oriented Hydrogen Induced Cracking (SOHIC)
- Hydrofluoric Acid Cracking

Table 1C – Hydrogen-Containing Services with Cracking Mechanism Exacerbated by High Stress
- High Temperature Hydrogen Attack (HTHA)

One subtle example of where PWHT must be specified is in FCC Units, in the Fractionator Tower Overhead system, whenever there is a risk of carbonate SCC. Even though this SCC mechanism requires an aqueous phase to occur, in susceptible systems, rapid cracking has occurred in all the streams coming from the Fract. Overhead drum – the water stream, the liquid hydrocarbon and the gas stream (Figure 4). The latter two are susceptible due to water carryover, and even relatively minutes amount of carryover have led to SCC. This cracking is prevented by specifying PWHT. The industry experience and susceptible areas are described in NACE Publication 34108.

Materials selection for services with the possible conditions of HTHA are based on of API RP 941, "Steels for Hydrogen Service at Elevated Temperatures and Pressures in Petroleum Refineries and Petrochemical Plants." In the latest edition (2016), a new design curve was added for "CS Welded with No PWHT". The previous CS curve was retained, but it is now designated as "CS Non-welded or Welded with PWHT" as shown in Figure 5 of this paper. This was due to a number of recent reports of cracking due to hydrogen attack, some of which led to leaks and fires, which were below the previous CS curve. The common factor for these cases was that the piping wall thicknesses were below 18 mm (3/4 inch) and hence the piping welds had not received PWHT. This is one of the most important cases where PWHT should be specified and could be missed. Most Owners also use of safety margin when selecting materials to meet the API 941 curves.

BENEFIT OF PWHT IN FITNESS-FOR-SERVICE ANALYSES

Many plant Owners are applying API 579/ASME FFS-1 when localized thin areas or other defects are found in piping or equipment during the inspection programs applied periodically over the item's life. Crack-like defects may be present due to:
- Original weld defects that were not detected during original fabrication,
- SCC or other environmental cracking that resulted from a short-term upset or excursion,
- SCC or other environmental cracking from past or current operating conditions,
- A growing crack due to fatigue and/or creep where the cyclic and/or high temperature conditions are known to limit the component life and crack growth rates can be estimated, etc.

The FFS analysis often demonstrates that the localized defect is acceptable for continued service and avoids the cost and delays of an immediate repair. The savings can be significant, especially if the repair or replacement would be the sole reason for a shutdown, or would extend the duration of a turnaround both of which would result in high lost production costs. Also, if access to the repair is limited, costs can be high due to scaffolding, internal cleaning and purging, etc. In many cases, postponing the repairs or replacement to an optimum time period, can provide a significant savings.

For the FFS evaluation of crack-like flaws, the primary goal is typically to show that the defect will not be susceptible to propagating by brittle fracture. In some scenarios, the defect will be determined to be non-growing, and in others, the possible crack growth mechanisms and rates will be estimated, and the predicted crack size at various future time periods will be evaluated. API

579/ASME FFS-1 uses a Failure Assessment Diagram (FAD) to evaluate the defects which is schematically shown in Figure 6. The chart shows the input data that is needed to calculate the values of a “Toughness Ratio” and “Load Ratio”. By plotting these two points, it can be shown whether a defect falls into the Acceptable or Unacceptable regions.

For defects in the vicinity of welds (and this is a significant percentage of the defects), PWHT can play a significant role in Load Ratio calculations. Without PWHT, if the defect’s crack tip is located in a residual stress field from a weld, the residual stresses can approach the material’s actual yield strength as discussed earlier. API 579-1/ASME FFS-1 also gives formulas for the typical stress reductions achieved by PWHT, namely:

- Residual Stress Perpendicular to the Weld Seam for Uniform PWHT:

  $\sigma^r (x) = 0.2\sigma^r_{ys}$

- Residual Stress Parallel to the Weld Seam for Uniform PWHT:

  $\sigma^r (x) = 0.3\sigma^r_{ys}$

  where, $\sigma^r = \sigma_{ys} + 69$ Mpa (10 ksi)

These 70% and 80% reductions in the level of residual stress could easily make the difference in whether a defect is acceptable for service. If the defect is deemed to be not acceptable for the given operating conditions, it would need to be immediately repaired. Since the change in PWHT requirements in the B31.3 Code, applied to the thicker piping and welds, this means that any defects being evaluated by FFS, would involve potential repairs that could take longer (due to more volume of welding) and have longer deliveries for any replacement materials. The authors have not heard of any Owners who required PWHT just to achieve this benefit in any future FFS analysis, but it would be interesting if any Owner with numerous facilities who regularly uses FFS could study the frequency of FFS use on CS piping and review the pipe sizes, thicknesses and other details to determine whether there are conditions where the potential of future FFS analyses justify PWHT.

SUMMARY AND CONCLUSIONS

1. The recent changes to the ASME B31.3 Code result in PWHT no longer being required for CS based on thickness.

2. This will provide a cost savings on many projects, and there are numerous non-corrosive services where these savings are justified.

3. However, in the environmental cracking services affecting CS, it is critical that the services carefully be reviewed to determine if PWHT is required.

4. This is especially important in high temperature hydrogen services, as defined in API RP 941. The latest edition of that standard, issued in 2016, has added a new design curve with limits for CS Welded with No PWHT. There are conditions of certain hydrogen partial pressures and temperatures, where CS should only be used with PWHT.

5. Another effect of “deleting” PWHT, is that in any future FFS analyses of crack-like defects in weld HAZ, the residual stresses from welding will be a significant factor. The FFS analyses will be less likely to find the defect acceptable for further service.

REFERENCES

1. "Welding and Repair Technology Center: 2009-2010 PWHT Exemption Thickness Test Results," Electric Power Research Institute (EPRI), Palo Alto, CA, Report No. 1022883, Aug. 2011.

2. AWS D10.10, "Recommended Practices for Local Heating of Welds in Piping and Tubing," American Welding Society (AWS), Miami, FL, 1999 (R2009).

3. C. Chauvy, L. Coudreuse, and PI Toussaint, "Potential Detrimental Consequences of Excessive PWHT on Pressure Vessel Steel Properties," ASME Pressure Vessels & Piping Conference, American Society of Mechanical Engineers, New York City, NY, PVP2010-25274.

4. API RP 941, "Steels for Hydrogen Service at Elevated Temperatures and Pressures in Petroleum Refineries and Petrochemical Plants," American Petroleum Institute, Washington, D.C., Feb. 2016.

5. API RP 945, "Avoiding Environmental Cracking in Amine Units," American Petroleum Institute, Washington, D.C., June 2016.

6. NACE Publication 34108, "Review and Survey of Alkaline Carbonate Stress Corrosion Cracking in Refinery Sour Waters," NACE International, Houston, TX, Jan. 2008.

7. API 579-1/ASME FFS-1, "Fitness-for-Service," American Petroleum Institute, Washington, D.C., April 2008.

8. NACE Standard Practice SP0472, "Methods and Controls to Prevent In-Service Environmental Cracking of Carbon Steel Weldments in Corrosive Petroleum Refining Environments," NACE International, Houston, TX, Mar. 2015.

TABLE 1A – STRESS CORROSION CRACKING MECHANISMS

Mechanism	Industry Standard	Variables Affecting Susceptibility	Typical Refinery or Gas Plant Units	Industry CS PWHT Practices
Amine SCC	API RP 945	Tensile Stress (primarily residual stresses from welding); Amine Concentration (above minimum threshold, no sig. effect); Temperature; Rich vs. Lean Amine	Amine Treating; Any unit with Amine contactors – Hydrotreaters, FCC, Cokers, etc.	Many Owners PWHT all CS welds in amine service. Some Owners have guidelines for PWHT considering amine type, temperature, etc. (see API RP 945)
Caustic SCC	NACE SP0403	Tensile Stress (primarily residual stresses from welding); Caustic Concentration; Temperature	H_2S and Mercaptan Removal Units; Alkylation Units; Crude Units	Many Owners PWHT all CS welds in caustic service. Some Owners have guidelines for PWHT considering caustic concentration, temperature, etc. (see NACE SP0403)
Carbonate SCC	NACE 34108	Tensile Stress (primarily residual stresses from welding); Aqueous phase pH, and CO_3 conc.	FCC Fractionator OH; Wet Gas Compression; Sour Water Stripper	All CS welds in carbonate SCC services (including the water, hydrocarbon liquids and hydrocarbon gas streams from FCC Fract. OH Drums – the latter two due to water carryover); Higher PWHT temperatures than minimum are recommended.
Anhydrous Ammonia SCC	NACE 5A192	Tensile Stress (primarily residual stresses from welding); Water content (>0.2% water reduces risk)	Ammonia Refrigeration systems; Some Lube Oil Refining Processes	Either PWHT and/or control strength and hardness.
Ethanol SCC	API Bull. 939-E	Tensile Stress (primarily residual stresses from welding); Aeration, water content, blending, etc.	Product Blending, terminals	Either PWHT or apply coatings.

TABLE 1B – HYDROGEN CHARGING DUE TO CORROSION / HIGH HARDNESS MECHANISMS

Mechanism	Industry Standard	Variables Affecting Susceptibility	Typical Refinery or Gas Plant Units	Industry CS PWHT Practices
Sulfide Stress Cracking (SSC)	NACE MR0175, NACE MR0103, NACE SP0472	High Hardnesses; Tensile Stress; Corrosion from Water, H_2S and pH	Oil and Gas Separation Units; Hydrotreaters, FCC, Cokers, Amine Treating, Sour Water Strippers, Crude, wherever a wet H_2S environment is present	Either PWHT and/or control strength and hardness.
Stress Oriented Hydrogen Induced Cracking (SOHIC)	NACE 8x194	Tensile Stress; Corrosion from Water, H_2S and pH; Steel Quality	Oil and Gas Separation Units; Hydrotreaters, FCC, Cokers, Amine Treating, Sour Water Strippers, Crude, wherever a wet H_2S environment is present	PWHT of equipment (PWHT practices are mixed on piping).
Hydrofluoric Acid	API RP 751	High Hardnesses or Strengths; Tensile Stress; Corrosion from HF	HF Alkylation	Either PWHT and/or control strength and hardness.

TABLE 1C – HYDROGEN-CONTAINING SERVICES WITH CRACKING MECHANISM EXACERBATED BY HIGH STRESS

Mechanics Exacerbated by High Stress in the presence of hydrogen				
Mechanism	**Industry Standard**	**Variables Affecting Susceptibility**	**Typical Refinery or Gas Plant Units**	**Industry CS PWHT Practices**
High Temperature Hydrogen Attack (HTHA)	API RP 941	Temperature; Hydrogen Partial Pressure; Tensile Stress; Steel Carbide types	Hydrotreaters; Hydrogen Manufacturing Units; Catalytic Reformers.	PWHT (or use higher alloy) per API RP 941 with a safety margin such as 28°C.

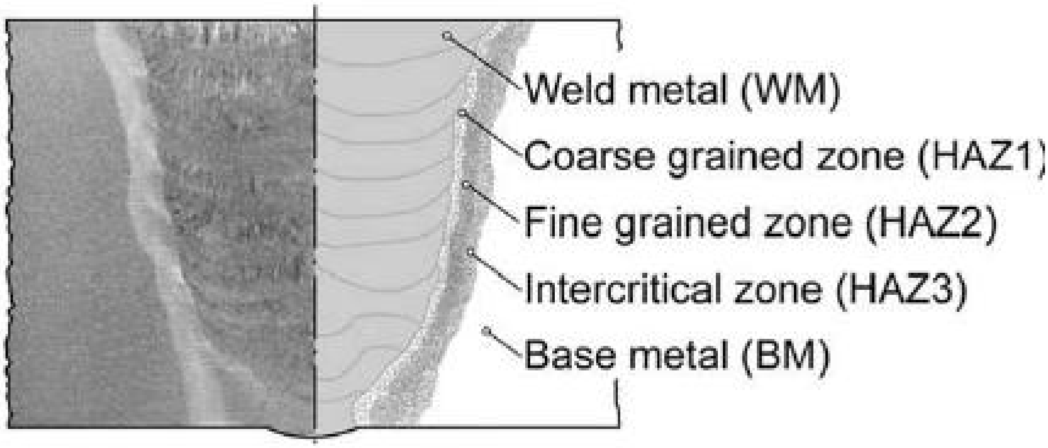

FIGURE 1 – The left half shows an etched cross-section of a typical one-sided butt weld using a vee groove, showing the weld metal, heat affected zone and base metal. The right half further identifies the various zones.

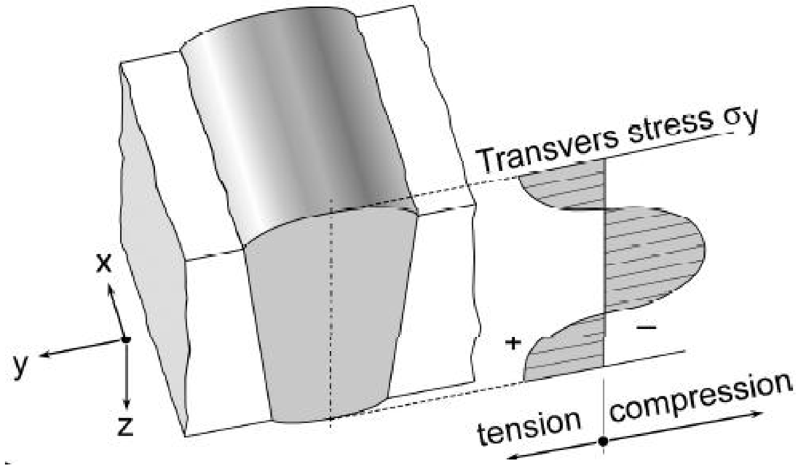

FIGURE 2 – Sketch showing a typical pattern for transverse residual stresses in a butt weld.

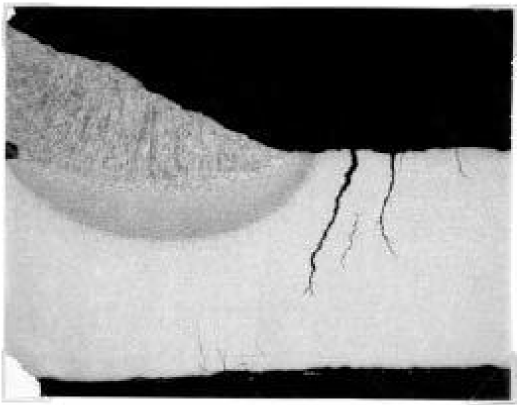

FIGURE 3 – Example of Carbonate SCC in the zone of residual stresses from a fillet weld. In susceptible services, this cracking is avoided by requiring PWHT. (From NACE 34108)

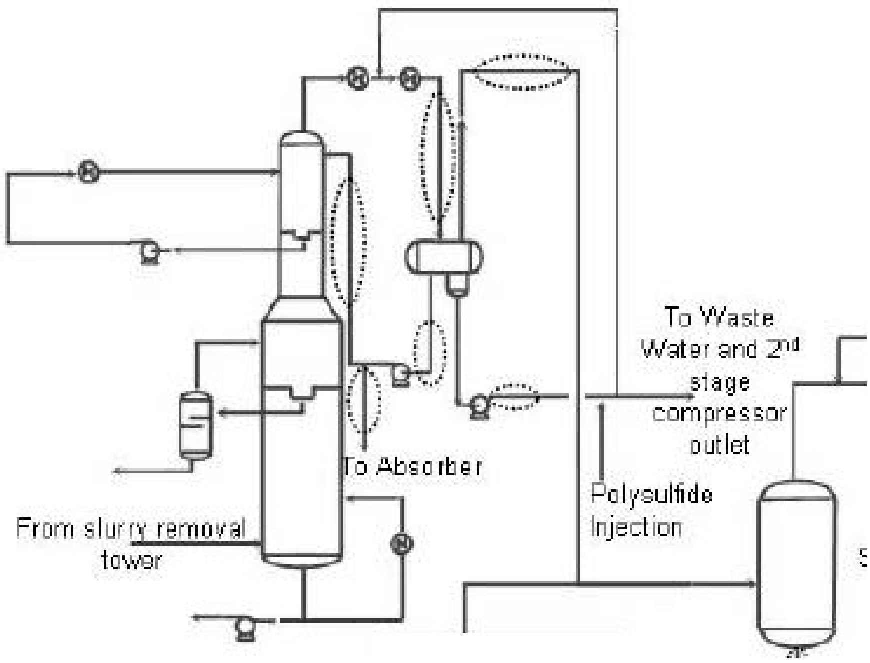

FIGURE 4 – Piping locations where Carbonate SCC has been reported in an FCC Fractionator Tower Overhead system. As shown by the circled locations, SCC has occurred in the Fract Overhead line downstream of water injection, and in the water, hydrocarbon liquid and gas streams leaving the Overhead Separator. The latter two streams experience SCC due to water carryover. (From NACE 34108 which also shows additional locations of potential cracking.

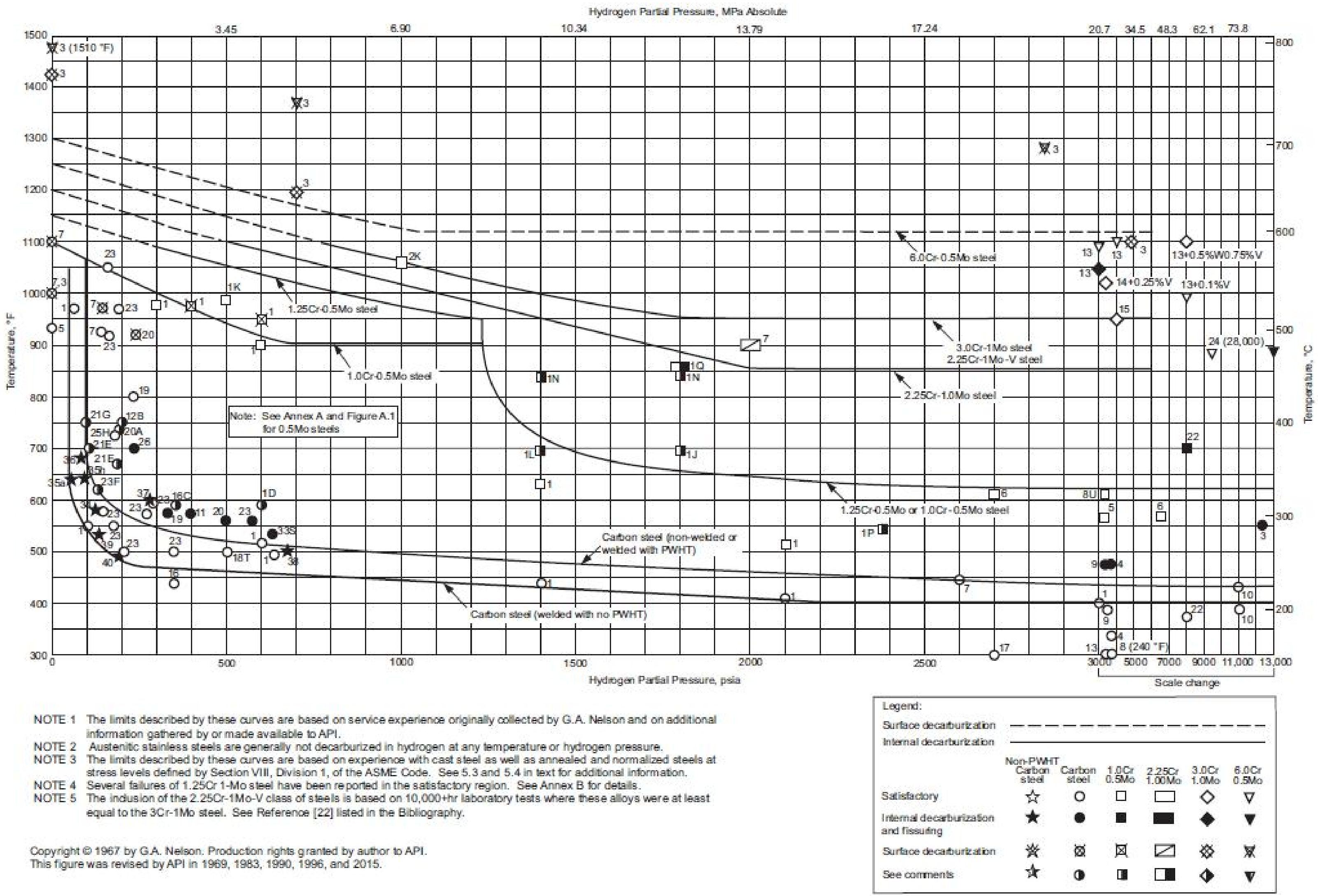

FIGURE 5 – Curves from API RP 941 showing operating limits for steels in hydrogen service to avoid HTHA. Note that there are separate curves for CS with and without PWHT.

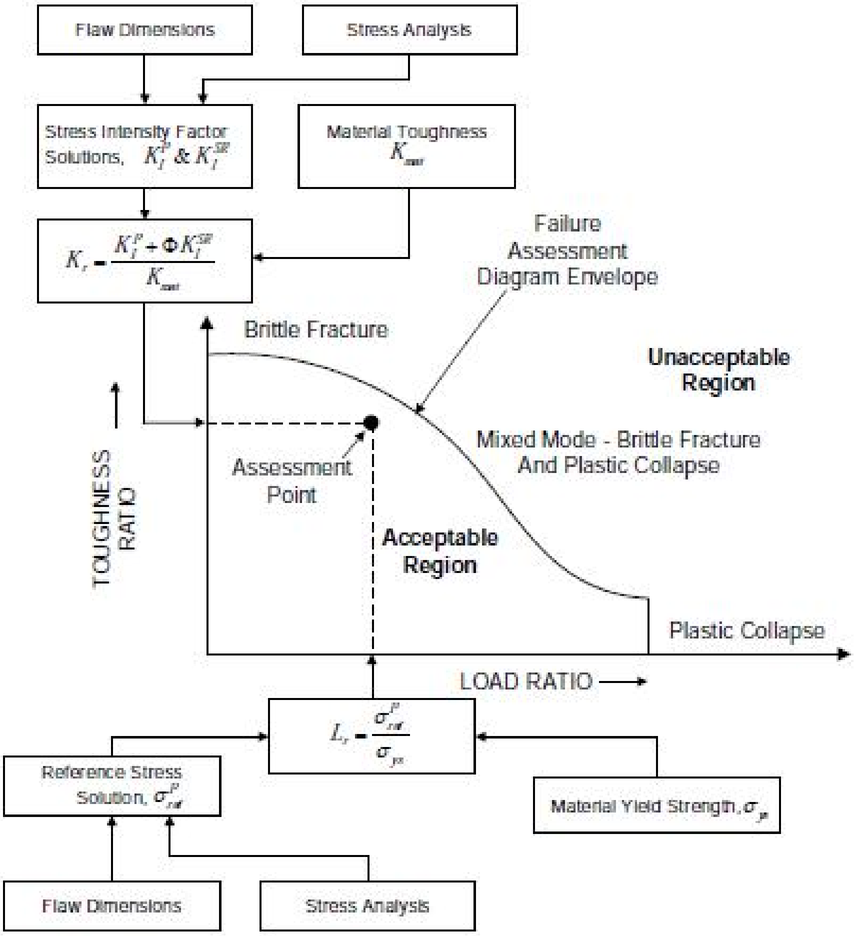

FIGURE 6 – Overview of a Fitness-for-Service analysis for crack-like flaws using the API 579-1/ASME FFS-1 failure assessment diagram.
(From API 579-1/ASME FFS-1)