

The Effects of Hydrogen for Establishing a Minimum Pressurization Temperature (MPT) for Heavy Wall Steel Reactor Vessels

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The Effects of Hydrogen for Establishing a Minimum Pressurization Temperature (MPT) for Heavy Wall Steel Reactor Vessels

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The Effects of Hydrogen for Establishing a Minimum Pressurization Temperature (MPT) for Heavy Wall Steel Reactor Vessels

1 Executive Summary

Hydrogen, dissolved in the thick wall of a steel pressure vessel during steady-state operation in elevated temperature high-pressure H_2 , can cause both slow-subcritical crack advance, as well as unstable catastrophic fracture during shutdown and startup. This behavior is defined in Section 2. It follows that modern fracture mechanics assessments of the minimum pressurization temperature (MPT) and fitness for service (FFS) must include the deleterious effect of H on both subcritical and unstable internal hydrogen-assisted cracking (IHAC). Two approaches are in draft stage to develop standard procedures that address this need: an API 934-F recommended practice and a WRC Bulletin 562 basis for ASME/API 579.

The objective of this technical report is to establish the technical basis necessary to enable and validate these best practices for quantifying the effects of hydrogen on (a) the MPT, and (b) FFS of a thick wall hydroprocessing reactor. The approach entails two parts. Part 1 emphasizes critical assessment and collection of two primary H-cracking properties: the threshold stress intensity for the onset of subcritical H cracking under slow-rising stress intensity (K_{IH}), and the critical stress intensity for the onset of unstable catastrophic cleavage-like crack growth promoted by H (K_{IC-H}). Part 2 focuses on the methods to use these data to quantitatively to predict an MPT that precludes H cracking during shutdown and startup. The sum of these two parts—validated-extensive IHAC data and science-based engineering analysis—establishes a single technical basis that can be consistently incorporated in API 934-F and API/ASME 579 recommended practices to control H cracking.

Section 3 documents extensive K_{IH} and K_{IC-H} data that conservatively characterize IHAC in 2¼Cr-1Mo weld metal and base plate. The effects of critical variables are documented; including the degree of temper embrittlement in terms of the FATT and thermal exposure ($FATT_{Thermal}$), total H concentration, and stressing temperature. K_{IH} data are aggregated for three classes of steel purity: Database A (low purity/high FATT) with $FATT_{Thermal} > 50^\circ C$; Database B (intermediate purity/intermediate FATT) with $-30^\circ C < FATT_{Thermal} < 50^\circ C$; and Database C (high purity/low FATT) with $FATT_{Thermal} < -30^\circ C$. These three steel composition categories were defined to both recognize the critical interaction of temper embrittlement with hydrogen cracking, and to optimize the combination of existing multiple IHAC data sets from different laboratories. [Alternately, the user can combine databases B and C to quantify IHAC in 2¼Cr-1Mo steels fabricated before and after (Database A) impurity-chemistry control.]

Subcritical H cracking (Section 3.2) is eliminated below a critical-dissolved H concentration and above a critical temperature, which are related through H-trapping theory to a single-critical parameter. The beneficial effect of increasing temperature is affirmed by fracture mechanics experiments with several specimen geometries, and provides the basis for MPT definition to eliminate subcritical H cracking. Fracture mechanics experiments (Section 3.3) clearly establish that dissolved H can reduce the unstable-fracture toughness of 2¼Cr-1Mo weld metal and base plate, from K_{IC} to K_{IC-H} , consistent with the deleterious effect of H on Charpy impact energy and Charpy FATT. However, previous studies have not correctly eliminated those data that were improperly interpreted to yield a false K_{IC-H} (e.g. due to the occurrence of innocuous pop-in events).

Validated K_{IC-H} experiments covering a range of H-free FATT values establish that the occurrence of true-unstable crack growth correlates with $(T-FATT_{Thermal})$, essentially independent of dissolved H concentration and showing a distribution of behavior for a given temperature. H-promoted unstable cracking is eliminated; that is, K_{IC-H} approaches the H-free K_{IC} above a critical temperature equal to (Charpy $FATT_{Thermal} + 66^\circ C$) for base plate and above the Charpy impact $FATT_{Thermal}$ for weld metal. (H-promoted unstable cracking was never observed at absolute temperatures above $86^\circ C$ for base plate and