Impact of Hydrogen Embrittlement on Minimum Pressurization Temperature for Thick-wall Cr-Mo Steel Reactors in High-pressure H_2 Service—Initial Technical Basis for RP 934-F

API TECHNICAL REPORT 934-F, PART 1
FIRST EDITION, SEPTEMBER 2017

energy API
AMERICAN PETROLEUM INSTITUTE

Impact of Hydrogen Embrittlement on Minimum Pressurization Temperature for Thick-wall Cr-Mo Steel Reactors in High-pressure H_2 Service—Initial Technical Basis for RP 934-F

API TECHNICAL REPORT 934-F, PART 1
FIRST EDITION, OCTOBER 2017

Prepared under contract for API by:

Dr. Richard P. Gangloff
Emeritus Ferman W. Perry Professor of Materials Science and Engineering
Department of Materials Science and Engineering
School of Engineering and Applied Science
University of Virginia, Charlottesville, Virginia

energy API
AMERICAN PETROLEUM INSTITUTE

Special Notes

API publications necessarily address problems of a general nature. With respect to particular circumstances, local, state, and federal laws and regulations should be reviewed.

Neither API nor any of API's employees, subcontractors, consultants, committees, or other assignees make any warranty or representation, either express or implied, with respect to the accuracy, completeness, or usefulness of the information contained herein, or assume any liability or responsibility for any use, or the results of such use, of any information or process disclosed in this publication. Neither API nor any of API's employees, subcontractors, consultants, or other assignees represent that use of this publication would not infringe upon privately owned rights.

API publications may be used by anyone desiring to do so. Every effort has been made by the Institute to assure the accuracy and reliability of the data contained in them; however, the Institute makes no representation, warranty, or guarantee in connection with this publication and hereby expressly disclaims any liability or responsibility for loss or damage resulting from its use or for the violation of any authorities having jurisdiction with which this publication may conflict.

API publications are published to facilitate the broad availability of proven, sound engineering and operating practices. These publications are not intended to obviate the need for applying sound engineering judgment regarding when and where these publications should be utilized. The formulation and publication of API publications is not intended in any way to inhibit anyone from using any other practices.

Any manufacturer marking equipment or materials in conformance with the marking requirements of an API standard is solely responsible for complying with all the applicable requirements of that standard. API does not represent, warrant, or guarantee that such products do in fact conform to the applicable API standard.

Users of this technical report should not rely exclusively on the information contained in this document. Sound business, scientific, engineering, and safety judgment should be used in employing the information contained herein.

Foreword

Nothing contained in any API publication is to be construed as granting any right, by implication or otherwise, for the manufacture, sale, or use of any method, apparatus, or product covered by letters patent. Neither should anything contained in the publication be construed as insuring anyone against liability for infringement of letters patent.

Questions concerning the interpretation of the content of this publication should be directed in writing to the Director of Standards, American Petroleum Institute, 1220 L Street, NW, Washington, DC 20005. Requests for permission to reproduce or translate all or any part of the material published herein should also be addressed to the director.

Generally, API standards are reviewed and revised, reaffirmed, or withdrawn at least every five years. A one-time extension of up to two years may be added to this review cycle. Status of the publication can be ascertained from the API Standards Department, telephone (202) 682-8000. A catalog of API publications and materials is published annually by API, 1220 L Street, NW, Washington, DC 20005.

Suggested revisions are invited and should be submitted to the Standards Department, API, 1220 L Street, NW, Washington, DC 20005, standards@api.org.

Contents

Contents

Contents

Contents

Contents

Contents

Tables

EXECUTIVE SUMMARY

The objective of this study, in support of API Recommended Practice 934-F [*Guidance for Establishing a Minimum Pressurization Temperature (MPT) for Heavy Wall Reactors in High Temperature Hydrogen Service During Startups and Shutdowns*], is to establish the technical basis for determining a minimum pressurization temperature (MPT) necessary to avoid internal hydrogen-assisted cracking (IHAC) of weld metal and base plate of temper embrittled 2¼Cr-1Mo steel in high-pressure H_2 service. The threshold condition for the onset of subcritical crack propagation—and its dependencies on dissolved hydrogen concentration, temperature, and steel purity/temper embrittlement—are targeted as particularly important to pressure vessel safe operations. A second objective is to improve the underlying data base for fracture mechanics fitness-for-service (FFS) modeling of IHAC. Both analyses are built on the conservative rising displacement threshold stress intensity factor for IHAC (K_{IH}).

This investigation has accomplished five tasks, leading to the following conclusions and key figures taken from the body of this report. These conclusions are sufficient to establish the API 934-F section on MPT to conservatively avoid IHAC in 2¼Cr-1Mo steel.

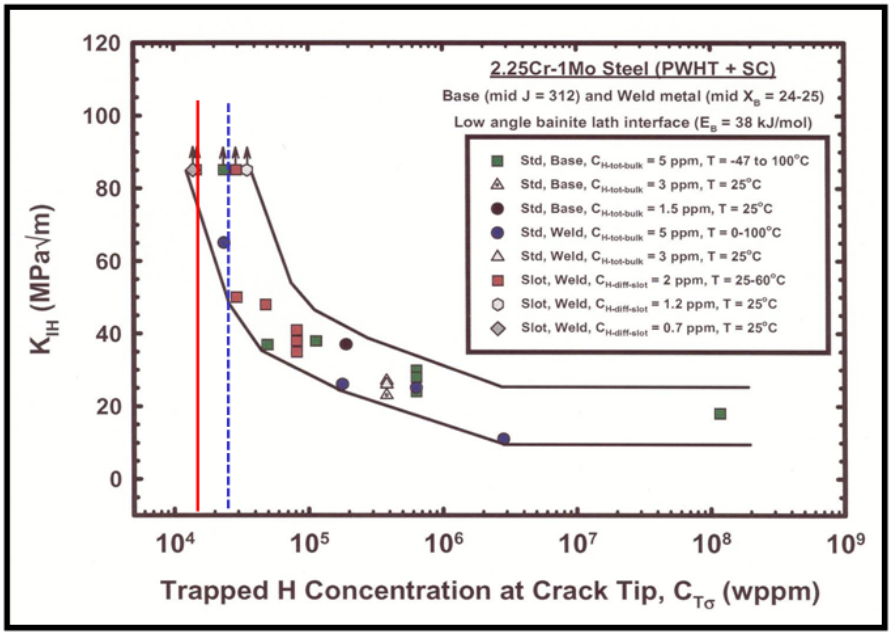
Task 1.0—Summarize and clarify the technical approach, assumptions, data, and modeling results used in Phase II JIP research to quantitatively establish the H concentration and temperature dependencies of the threshold stress intensity, K_{IH}, for IHAC and the concentration dependence of MPT for moderate-impurity 2¼Cr-1Mo steel.

1) Measured threshold stress intensity factor (K_{IH}) for the onset of IHAC increases with decreasing bulk-dissolved H concentration and increasing temperature, as proved by experimental results for multiple specimen geometries of 2¼Cr-1Mo steel.

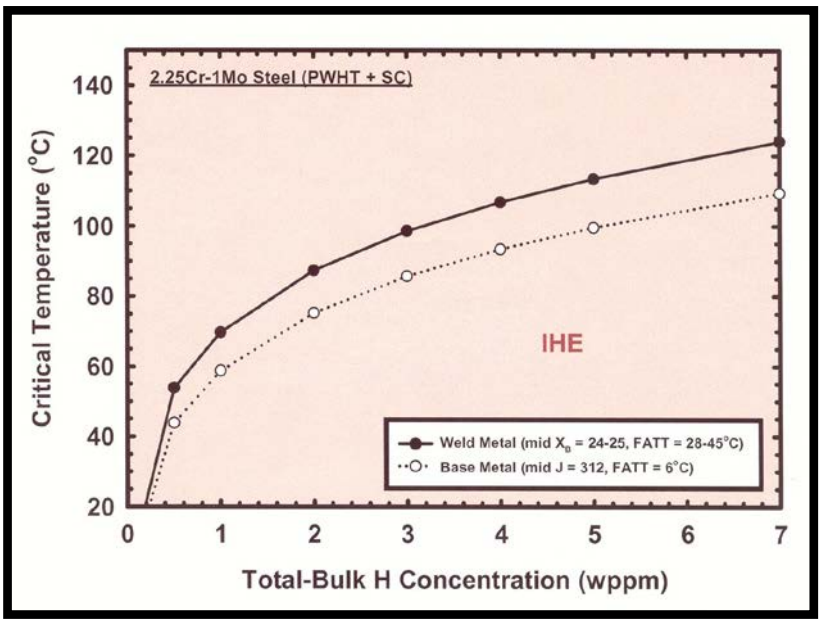
2) The H concentration and temperature dependencies of K_{IH} are explained physically by the interactive effect of each variable on the concentration of H ($C_{T\sigma}$) that is enhanced at a reference location in the crack tip fracture process zone due to localized hydrostatic stress and microstructure sites for H trapping that constitute the crack path.

3) The steps necessary to predict $C_{T\sigma}$ as a function of total dissolved H concentration and temperature, proposed by Al-Rumaih in a joint industry program (JIP) Phase II PhD study at the University of Virginia, are validated as fully correct and are clarified to provide the scientific basis for engineering applications that seek to avoid IHAC. This analysis was guided by mechanistic consideration of H trapping and embrittlement in the crack tip region of a complex steel microstructure.

4) A master experimental correlation exists between measured K_{IH} and diffusion-model-predicted $C_{T\sigma}$ for moderate-purity temper embrittled [6 °C < fracture appearance transition temperature (FATT) < 43 °C] 2¼Cr-1Mo, including a critical level of locally trapped H below which K_{IH} rises toward K_{IC} ($C_{T\sigma\text{-}CRIT}$). The critical H concentration is marginally lower for weld metal compared to base plate, with each microstructure temper embrittled by laboratory step cooling. Figure 15 follows, specific to $C_{T\sigma}$ predicted at 2CTOD ahead of the crack tip; δ_{FPZ} = 9 μm:

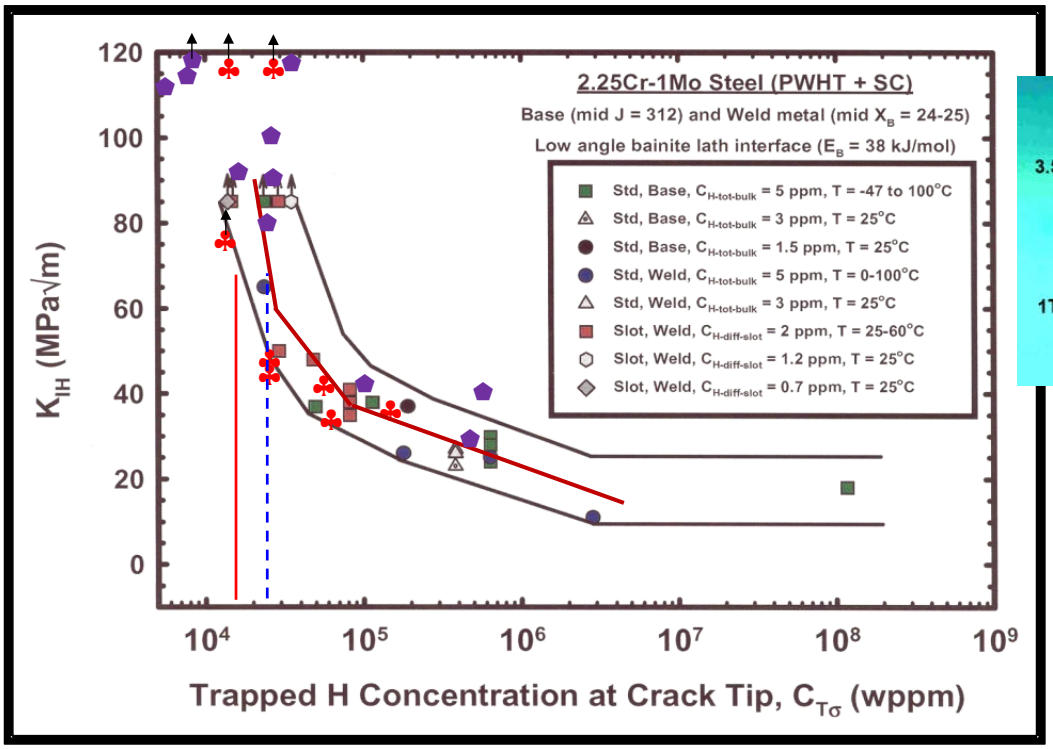


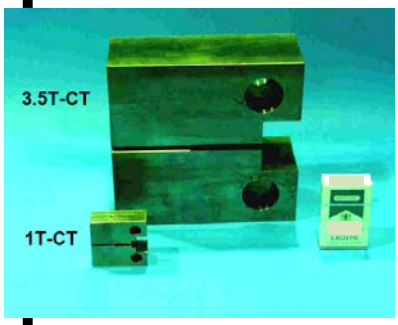
5) The master K_{IH} vs $C_{T\sigma}$ correlation provides the basis for a critical temperature, T_{CRIT}, above which IHAC is not observed and that is the foundation for MPT determination. The T_{CRIT} increases with increasing $C_{H\text{-}Total}$ dissolved in the "structure" at high temperature, with a quantitative dependence reported in Phase II work specific to the compact tension geometry and moderate-FATT 2¼Cr-1Mo weld metal and base plate. Figure 16 follows based on K_{IH} vs $C_{T\sigma}$ in Figure 15. Diffusion analysis (see Task 4.0) is required to apply this specific result to a cracked reactor vessel in H_2 service.



Task 2.0—Validate the Phase II correlation of K_{IH} and critical temperature vs H concentration, based on new analyses of post-Phase-II IHAC data.

1) Japanese experiments with unusually thick and H_2-precharged compact tension specimens of moderate-purity temper embrittled 2¼Cr-1Mo weld metal and base plate (22 °C < FATT < 43 °C) quantitatively validate the master correlation between K_{IH} and $C_{T\sigma}$. Figure 21 follows showing agreement between these thick-specimen results (♣,⬟) and the small-specimen master curve from Figure 15, each related to δ_{FPZ} = 9 μm:





Task 3.0—Enhance the Phase II analysis of K_{IH} vs crack tip H concentration, and thus MPT, by describing the interaction between temper embrittlement and IHAC using JIP Phase I data so as to predict the influence of modern steel purity.

1) Results of extensive JIP Phase I IHAC experiments, conducted with H_2-precharged compact tension specimens of multiple high-purity lots of laboratory step-cooled 2¼Cr-1Mo weld metal and base plate (−90 °C < FATT < −28 °C) are well correlated by a master correlation between K_{IH} and $C_{T\sigma}$, as verified by additional literature K_{IH} data.