

Factors to Consider When Managing High Temperature Hydrogen Attack on Petroleum and Chemical Facilities

Publication 240

Edition 1

Copyright © 2019 The Engineering Equipment and Materials Users Association
A company limited by guarantee. Registered in England. Company number 477838.

ISBN 978-0-85931-229-5

Imprint reference 01-2019
First published 01-2019

Registered and Trading Address:
EEMUA, Second Floor, 16 Black Friars Lane, London EC4V 6EB
Telephone: +44 (0)20 7488 0801
Email: sales@eemua.org
Website: www.eemua.org



Engineering Equipment and Materials Users Association

About EEMUA

The Engineering Equipment and Materials Users Association is usually known by its initials, EEMUA. EEMUA is governed by a Council of members. This Council is responsible for the policies, financing, membership, and strategy of the Association. Any organisation that is a substantial user or purchaser of engineering products may apply to become a member of EEMUA. Membership is subject to the approval of Council.

EEMUA Aims

EEMUA aims to improve the safety, environmental and operating performance of industrial facilities in the most cost-effective way, pursuing and promoting leadership in industrial asset management by sharing engineering experiences and expertise, and by the active, enlightened promotion of the distinct interests of users of engineering products. These aims are achieved by various means, including:

- Providing the organisation within which networking, information sharing and collaboration among users on non-competitive technical matters can take place.
- Influencing the way written regulations are interpreted and applied in practice.
- Promoting and presenting members' views, and encouraging the application of good sound engineering practices.
- Developing user guides, specifications, training and competency schemes.
- Facilitating members' participation in national and international standards making.
- Influencing relevant national and European legislation and regulation.

The income and resources of EEMUA are applied solely towards the promotion of the aims of the Association. No profit is transferred by way of dividend, bonus or otherwise to members. The work of the Association is mainly carried out by members' representatives on EEMUA Technical Committees, Working Groups, and Forums, supported by EEMUA staff.

Incorporation, Membership and Other Information

For the purposes of conducting its business, EEMUA is incorporated in England and Wales as a company, limited by guarantee, not having share capital. All usual aspects of company management and business administration are dealt with by the EEMUA Executive Director, including policy implementation and leadership of the Executive team (the staff).

A list of EEMUA publications for sale is given at the end of this Publication. The full list is also on the Association's website, including details of on-line shopping facilities.

To enquire about corporate Membership, write to enquiries@eemua.org or call +44 (0)20 7488 0801.

About this Publication

Legal Aspects

All rights, title and interest in this Publication belong to EEMUA. All rights are reserved. No part of this Publication may be reproduced, stored in a retrieval system, or transmitted in any form or by any means: electronic, mechanical, photocopying, recording or other, without the express prior written agreement of the EEMUA Executive Director. Infringement of copyright is illegal and also reduces the Association's income thereby jeopardising its ability to fund the production of future publications.

It has been assumed in the preparation of this Publication that: the user ensures selection of those parts of its contents appropriate to the intended application; and that such selection and application is correctly carried out by appropriately qualified and competent persons for whose guidance this Publication has been prepared. EEMUA and the individual members of the Work Group that prepared this EEMUA publication do not, and indeed cannot, make any representation or give any warranty or guarantee in connection with material contained herein. EEMUA and the individual members of the Work Group that prepared this EEMUA Publication expressly disclaim any liability or responsibility for damage or loss resulting from the use or reliance on this Publication. Any recommendations contained herein are based on the most authoritative information available at the time of writing and on current good engineering practice, but it is essential for the user to take account of pertinent subsequent developments and/or legislation.

Any person who encounters an inaccuracy or ambiguity when making use of this Publication is asked to notify EEMUA without delay so that the matter may be investigated and appropriate action taken.

Consultation and Feedback

EEMUA encourages constructive comments on this Publication from both Members of the Association and others.

Comments should be sent on the standard feedback form, a copy of which is provided towards the end of this Publication. An electronic version of the feedback form is available from EEMUA:

e-mail your request for a copy to:
enquiries@eemua.org

or telephone your request to:
+44 (0)20 7488 0801

or download the form from the EEMUA website at:
www.eemua.org.

Submit comments by e-mail (preferred) or post.

Comments are considered by the relevant EEMUA Technical Committees and may be incorporated in future editions of this Publication. New editions are publicised on the EEMUA website.

Cover photograph reproduced under license with kind permission of noomcpk/Shutterstock.com.

Contents

Preface	VI
Acknowledgements.....	VI
Abbreviations/Acronyms used in this Guide	VII
1 Introduction.....	1
1.1 Purpose	2
1.2 Scope.....	2
1.2.1 Note on Carbon 0.5Mo Steels.....	2
1.3 Joint Industry Projects.....	2
2 General Considerations	3
2.1 Time Dependency.....	3
2.2 Damage Development.....	3
2.3 Management Options.....	4
2.4 Damage Detection	5
3 Specific Considerations.....	7
3.1 Identifying Carbon Steel Equipment and Systems Welded Without PWHT	7
3.1.1 Important Aspects to Consider.....	7
3.2 Accounting for Operating Conditions, Temperature/Pressure Excursions, etc., Including Periods Before Computerised Data Logging	7
3.2.1 Important Aspects to Consider.....	8
3.2.2 Possible Future Outcomes.....	9
3.3 Plant Operating Hours	9
3.3.1 Important Aspects to Consider.....	9
3.4 Issues Associated with Using Reduced Hydrogen Partial Pressure or Reduced Temperature for Assessment of Internally Lined Vessels	10
3.4.1 Linings for Corrosion Protection	10
3.4.2 Linings for Temperature Protection	10
3.4.3 Important Aspects to Consider.....	11
3.5 Plant in Anacortes Arrangement/with Similar Characteristics.....	12
3.5.1 Important Aspects to Consider.....	12
3.6 Dedicated Monitoring and IOWs, Reporting of Exceedances.....	12
3.6.1 Important Aspects to Consider.....	12

3.7 Awareness of Appropriate NDE Techniques and Engagement with Suppliers	13
3.7.1 Traditional Techniques	13
3.7.2 Modern Advanced Techniques.....	13
3.7.3 Important Aspects to Consider.....	14
3.7.4 Possible Future Outcomes.....	14
3.8 What to Inspect and Preparation of Equipment for Inspection.....	15
3.8.1 Preparation for Inspection.....	15
3.8.2 Important Aspects to Consider.....	15
3.9 Application of NDE (Including Validation and Certification).....	16
3.9.1 Important Aspects to Consider.....	16
3.9.2 Possible Future Outcomes:	17
3.10 Inspection Levels – How Much to Inspect (Scale/Extent/Amount)	17
3.10.1 Important Aspects to Consider	18
3.11 Limitations to Weld Inspections Associated With Fittings.....	18
3.11.1 Important Aspects to Consider	19
3.12 Assessment of Hydrogen Partial Pressure in Liquid Packed Lines	19
3.12.1 Important Aspects to Consider	20
References	21

Preface

The accident at Tesoro Anacortes Refinery in 2010 in which seven people lost their lives raised a number of issues about managing the integrity of plant potentially affected by High Temperature Hydrogen Attack. The issues are mainly focussed on carbon steel welds that have not been stress relieved before entering service.

The UK competent authority (Health & Safety Executive) has asked operators to ensure that they are managing HTHA in-line with latest guidance and recommendations and are considering what actions represent good practice in the UK.

This publication provides some background information and related specific elements of managing HTHA and provides a “checklist” of issues that have been identified within an EEMUA Forum on HTHA. It is intended to supplement company policies and procedures and assist facility personnel to manage equipment exposed to HTHA. It is intended to contribute towards good practice guidance.

This Publication focusses primarily on equipment constructed from carbon steel though aspects of the contents are generally relevant to equipment constructed from other materials.

Acknowledgements

This guidance is based on information provided and discussed during a series of meetings of the EEMUA HTHA Forum made up of representatives from operators of major refineries in the UK and Ireland. The guidance reflects the discussions and also reflects general information from published articles and papers on the subject.

The Forum established contact with the UK's competent authority (HSE), members of the API 941 committee and a number of the Joint Industry Programmes and contributors during its deliberations and the preparation of this guidance. Their opinions and advice were gratefully received. It should however be made clear that this guidance does not claim to represent the positions of these bodies on managing HTHA.

Abbreviations/Acronyms used in this Guide

ABSA	Angle Beam Spectral Analysis
API	American Petroleum Institute
AUBT	Advanced Ultrasonic Backscatter Technique
BINDT	British Institute of Non-Destructive Testing
C&I	Control and Instrumentation
CSB	U.S. Chemical Safety and Hazard Investigation Board
D/FPI	Dye/Fluorescent Penetrant Inspection
E2G	The Equity Engineering Group Inc.
FMC	Full Matrix Capture
HSE	UK Health and Safety Executive
HTHA	High Temperature Hydrogen Attack
IOW	Integrity Operating Window
IR	InfraRed
JIP	Joint Industry Project
MPI	Magnetic Particle Inspection
MTI	Materials Technology Institute
NACE	National Association of Corrosion Engineers
NDE	Non-Destructive Examination
NDT	Non-Destructive Testing
PAUT	Phased Array Ultrasonic Testing
ppH ₂	Partial Pressure of Hydrogen
P _v	A damage parameter for High Temperature Hydrogen Attack
PWHT	Post Weld Heat Treatment
QA	Quality Assurance

RP	Recommended Practice
SES	Stress Engineering Services Inc.
TFM	Total Focussing Method
TOFD	Time Of Flight Diffraction
TWI	The Welding Institute
UT	Ultrasonic Testing

1 Introduction

High Temperature Hydrogen Attack (HTHA) is a well-known time dependant degradation mechanism that can affect the integrity of steels used for pressure containment in petrochemical facilities operating above about 400°F (204°C). The likelihood of damage occurring is mainly influenced by operating time, temperature, hydrogen partial pressure (ppH₂), steel composition and applied and residual stresses – particularly where these have not been relieved after section forming or after welding.

API RP 941¹ currently provides guidance for steel selection (and so susceptibility to attack) in relation to temperature and ppH₂ via Nelson curves. Following the inquiry² (and see footnote*) into the Anacortes accident by the US Chemical Safety Board (CSB) the most recent Edition (8th) contains a new curve for “Carbon steel (welded with no PWHT)”. This sits approximately 50 psi to the left and 50-100°F (28-56°C) below the previous carbon steel curve so reducing the design allowable temperatures and pressures. It also represents a new susceptibility assessment line for existing plant that encompasses a larger number of plant items that now require to be managed for HTHA. The previous carbon steel curve is now retitled “Carbon steel (non-welded or welded with PWHT)”. Annex F of the RP states that owners/operators may choose to replace equipment or prioritise such equipment operating above the new curve for inspection. This latter option however presupposes that effective inspection regimes are available and can be safely applied within the damage development rates. Management can involve replacing susceptible items, inspecting for signs of HTHA and reducing operating parameters.

The new curve in the 8th Edition does not however match the recommendations made by the CSB who later reiterated their proposal in a Safety Bulletin³ for a much lower line and recommended replacement of carbon steel process equipment operating above 400°F (204°C) and greater than 50psia ppH₂. Following this, the competent authority in the UK, the Health & Safety Executive (HSE) visited refinery facilities to assess their current HTHA actions. The HSE also engaged The Welding Institute to review HTHA and provide advice that would inform the HSE’s expectations of good practice in managing the issue.

A Safety Alert⁶ issued recently by the HSE states that: *For existing plant, API RP 941 8th Edition can be regarded as ‘relevant good practice’, and the Nelson curves can be used to help define a safe operating envelope for steels on hydrogen service. However the curves should be used with some caution, and their use is dependent on a number of factors which should be taken in to consideration when assessing risk and developing a management strategy:...* The Alert lists factors to be considered and action required.

This EEMUA publication addresses the areas referred to in the Alert and provides general guidance in those areas, however, users of this publication should satisfy themselves that they are meeting the specific requirements of the Alert in all cases.

*At various stages this document draws on the Investigation Report into the Anacortes accident issued by U.S. Chemical Safety and Hazard Investigation Board to which the reader is referred to for more detailed information.

1.1 Purpose

In response, EEMUA refinery members formed an HTHA Forum to work together on the issue and provide a platform for:

- Establishing current practices in the UK
- Identifying where these may differ between member companies
- Liaison between HSE and the members
- Contact with API 941 Committee and various Joint Industry Projects in the US and Europe that are driving HTHA research and guidance
- Facilitating contact between HSE's contractor (The Welding Institute) who are advising HSE on material and NDE aspects, and the API and members who have up to date information and experience on HTHA
- Providing a collective "voice" to represent the members with the HSE
- Describing elements of good practice

1.2 Scope

The Forum has met on a number of occasions and through sharing information and experience has identified a number of factors that deserve particular attention when managing the problem.

This Publication provides a description of these factors as they currently stand – future updates may be published. It was not the role of the Forum to provide technical solutions to issues (which are being dealt with by refinery companies in conjunction with API Committees and the various Joint Industry Projects, JIPs) but to highlight areas to members where knowledge of different approaches and increased awareness in managing the problem at facility level are beneficial to delivering good practice.

1.2.1 Note on Carbon 0.5Mo Steels

The Nelson curves for Carbon 0.5Mo steels were deleted from API RP 941 in the fourth edition (1990). This was due to cases of HTHA damage in 0.5Mo steel equipment occurring as much as 200°F (111°C) below the curve. The advice, which hasn't changed in the current edition, is that existing C-0.5Mo steel equipment that is operated above the PWHT'd carbon steel curve (i.e. that previously labelled carbon steel) should be inspected to detect HTHA. Future editions are expected to include age based curves for C-0.5Mo steels in the non-PWHT'd and PWHT'd conditions. It is quite possible that these will show a lowering of the current position for the non-PWHT'd condition, requiring additional actions to be taken by operators of such equipment.

1.3 Joint Industry Projects

A number of industry sponsored projects are running on HTHA and these are variously referred to throughout this guidance. Known projects are listed below and readers are advised to contact the associated organisations for further information of the full content of the projects which may not be fully reflected or described in this guidance. API is also funding research work.

Equity Engineering (including Lavender International)
Stress Engineering Services
Materials Technology Institute
The Welding Institute (proposal)

2 General Considerations

2.1 Time Dependency

The Nelson curves are based on reported HTHA failures, damage or freedom of damage from inspections collated over many years by operators. Reporting may not however be comprehensive and the curves do not specifically account for operating time. Whilst they provide a reasonable approach at the design/material selection stage they are less helpful for assessing in-service equipment as the damage is time dependant with a period of incubation when incipient damage is developing. There is some evidence that high residual stress from section forming or welding without stress relief or PWHT reduces the incubation period. Future Editions of API RP 941 may address this with more information on incubation models. Other variables that are not addressed by the curves that could affect the susceptibility to HTHA, include for example, carbide stability, grain size, material compositions, thickness, heat treatment states, type of weld.

An HTHA damage parameter, P_v , is described in literature⁴ for C-0.5Mo steel that relates operating time, ppH₂ and temperature and provides a possible means of ranking the susceptibility of equipment in service to HTHA damage. However, in its original form the parameter is not thought to adequately account for applied stress and particularly residual welding stresses which can be at or near yield stress level and are implicated in driving the more rapid development of fissures and cracking. The parameter was described in the previous editions of API RP 581⁵ guidance but is not present in the current editions. A few Forum members have retained and further developed the damage parameter approach to assist with particular assessment cases of C-0.5Mo steel in specific heat treatment states.

A JIP run by Stress Engineering Services has an element aimed at providing a time dependant through life HTHA damage model which will be available to sponsors. Equity Engineering are running a different JIP which includes delivering a life assessment model with the potential use in fitness for service appraisals. These models are currently under development and experience in their use will be needed to demonstrate their effectiveness.

2.2 Damage Development

At high temperature, molecular hydrogen can dissociate into atomic hydrogen at the metal surface and diffuse into the microstructure of steel where it may react with carbides at grain boundaries to form methane which has a larger molecule size and cannot readily diffuse out of the steel. Methane pressure builds up creating high stresses along grain boundaries which can exceed material strength and cause intergranular fissuring. Given time, atomic hydrogen can penetrate deep into the steel which can result in fissures developing to appreciable through wall extents. As the concentration of fissures builds up at any point they may eventually amalgamate to create micro-cracks which in turn may link and potentially lead to failure. The extent of fissuring damage ahead of established cracking could clearly influence the rate of crack propagation. Fissuring, amalgamation and the development and propagation of cracks may be accelerated by stresses present in the materials (including residual forming and welding stresses).

The stages of damage development are time dependent – diffusion, carbide attack, fissuring and crack development and propagation. The safe operating time between detecting damage and potential failure is currently not well described by available damage models and subject to a number of factors other than temperature and pressure. Some literature reports of C-0.5Mo steel experience suggest that significant fissuring (and hence detection) may only occur late in life and so replacing equipment before damage is detected would not be unusual in managing the issue. The JIPs are attempting to fill the gap in knowledge and provide useful predictive models of damage development. The next edition of API RP 941 is expected to include more information on damage development timescales.

Experience has shown that damage may not develop uniformly in base metals nor uniformly in the vicinity of welds, i.e. whilst exposure to operating time, temperature and ppH_2 is uniform at any position in the equipment the resulting damage is not always consistent, nor uniformly distributed. Where one shell section is free of damage, the adjacent shell section may be affected. This may be a function of compositional variations, carbide stability, differences in supplied heat treatment and local stress variations. As many of these factors and their distributions are difficult to predict, inspection for damage in shells and particularly around welds, needs to be broadly applied rather than just spot checks. A similar precaution should be applied in pipework systems and components.

API is funding research work on HTHA with laboratory samples exposed to elevated temperature hydrogen to improve the understanding of damage progression and crack growth rates to improve fitness for service rules that are being developed for API 579/ASME FFS-16.

2.3 Management Options

Managing the likelihood of failure that HTHA presents can be achieved by avoiding the use materials that are susceptible to HTHA damage at their operating conditions or by replacing existing equipment before HTHA develops to a critical stage. The latter approach relies on inspection with replacement at or before the first sign of damage. This requires a reliable inspection process (a) successfully applied and managed in the field (b) capable of identifying early stage damage and (c) repeated frequently enough, to catch damage before it develops to threaten integrity.

Assessing the likelihood of HTHA in a piece of equipment or system is normally based on the Nelson curves in API RP 941, the majority of companies in the Forum determine that equipment operating above their curve should be replaced (which, from discussions, aligns with expectations of the UK competent authority). Replacement timescales are generally short-term, within an operating cycle for equipment with appreciable operating hours, backed by an assurance of fitness-for-service. Replacement in a less susceptible material recognises the hierarchical and continuous approach to risk reduction.

Before replacement, or where replacement may on balance be deemed undesirable and a safety case can be made, other interventions may be invoked depending on how far above the curve the equipment is operating, for example, very comprehensive inspections, interim inspections, reduction of operating parameters, imposition of strict IOWs and reporting of exceedances. However the challenge of making safety cases should not be underestimated due to the lack of knowledge, for example, in damage development rates and behavioural properties of affected materials.

Some companies aim to replace equipment operating within a margin below their Nelson curve to safeguard against future adverse developments, improve operational flexibility and reduce inspection workloads (and the threat to turn-around programmes from knock-on investigative work). Pipework is a typical candidate for such treatment due to the large number of fittings and welds which can be difficult to access and where the geometry of fittings frequently restricts inspection of welds – but which can be positions where, in one company's experience, cracking can often develop.

The majority of (though not all) companies in the Forum have also determined not to replace but to inspect equipment operating within a defined margin or banding below their Nelson curve.

There is a degree of variation across companies that apply an inspection margin – typically it is in the range of 25-50psi to the left of and 20-50°F (11-28°C) below the curve. It is also noted that a few companies have currently adopted the CSB line as defining the margin below the Nelson curve for inspection.

For equipment operating below the banding, no specific HTHA inspection is carried out. (This aligns to a degree with the susceptibility to damage rankings and damage factor approach in API RP 581.)

If HTHA damage is detected then replacement is normally carried out as soon as possible. If a safety case cannot be made to return the equipment to service it may require a lengthy shut-down of plant whilst repairs are made (e.g. localised damage) or new equipment is procured and installed.

2.4 Damage Detection

Detecting the early stages of damage development is recognised throughout industry as challenging. Internal surface damage may occur early, generally taking the form of a decarburised layer (not related to component manufacture or heat treatments). As described above, damage develops from the hydrogen exposed surface into the steel containment, therefore inspection methods must look volumetrically for the extent of damage and, generally, ultrasonic inspection is applied. MPI and D/FPI techniques are used to detect surface cracking.

Fissuring is at steel grain size (say 50µm), which is well below normal ultrasonic sizing capability (500 – 1000µm), so detection relies on a concentration of fissures building up and/or micro-cracking developing. Even then, a number of different specialised detection techniques in combination are required to build a picture of the likelihood of defect presence and its extent. At this level of damage some material features (e.g. segregations, clouds of inclusions) may also present ultrasonic signatures similar to HTHA damage and differentiating between them can be difficult raising the probability of false calls and the need for invasive investigations. Poor surface preparation for inspection which can reduce ultrasound transmission and increase signal noise ratios could also adversely affect detectability. Effort is therefore needed to ensure surface preparation is properly carried out.

Metallographic inspection of material samples removed from equipment will reliably identify HTHA and characterise damage from other material effects. Similarly, laboratory examination of replicas can be used to identify HTHA. These techniques are generally used to confirm or otherwise whether HTHA is present following indications from ultrasonic inspection. When macro-cracking establishes standard ultrasonic techniques become more capable of detection. However, it is

possible that at this stage there could also be widespread material damage ahead of crack tips. This makes it more difficult to assess margins against failure and brings with it a possibility of rapid crack growth and the potential for material failure in the short term. For this reason, and until reliable damage growth models and fitness for service assessments become available, it is not the accepted practice to wait for macro-cracking to be detected before removing equipment from service.

An element of the current JIP work by E2G is therefore focussed on identifying/developing inspection techniques that are more reliable (i.e. less false calls) and sensitive at detecting damage at the fissuring stage than historically applied techniques.

3 Specific Considerations

The following check list has been developed following review of experience and technical references within the Forum. It is in no special order.

3.1 Identifying Carbon Steel Equipment and Systems Welded Without PWHT

The 8th edition of API RP 941 introduced the new curve for carbon steel and requires the reassessment of carbon steel equipment and systems to identify which were welded without PWHT (or furnace stress relief, etc.). This requires original design, manufacture and construction information. It may be difficult to locate this information particularly for plant built many years ago. (It would be rare for original heat treatment charts to be available, though original QA documentation may be.) In some cases the use or otherwise of PWHT may have to be inferred from the original design standards in which the requirements for PWHT were given. This and the absence of quality assurance data could introduce uncertainty which should be accounted for in the assessment process.

Field hardness testing of welds may provide some indication of whether PWHT was applied but is unlikely to be conclusive. For instance, welding parameters could have been chosen that controlled weld hardness leading to a false decision on PWHT.

3.1.1 Important Aspects to Consider

Facilities should have an auditable and consistent approach to addressing the above and reflecting them in the assessment process.

Maintaining accurate plant records, keeping information and drawings up to date, recording checks and results of inspections are essential for reliable assessments of HTHA.

3.2 Accounting For Operating Conditions, Temperature/Pressure Excursions, etc., Including Periods Before Computerised Data Logging

As already outlined, when assessing the susceptibility to HTHA damage occurring in a piece of equipment, operators generally use the Nelson chart in API RP 941 and plot a temperature and a hydrogen partial pressure for a piece of equipment against the appropriate curve. In the first instance the equipment design data may be used. However the actual operating values need to be checked – either to demonstrate that the design assumptions were valid (and suitably conservative) or to use the actual operating values for the assessment.

A number of issues arise when using operating data.

- How far back in the operational life of the equipment are data records available?
- How can operating conditions be reliably assessed for periods before data logging?
- What operating practices were previously employed that may have subjected equipment to enhanced pressures or temperatures (e.g. hot hydrogen stripping of catalysts, rapid start-up and shut-down)?
- Are there reliable and accurate temperature and pressure data measuring points at critical positions on the equipment under question? (An apparent failing at Tesoro Anacortes.) Has their accuracy been validated?
- How should variations in data values over time be accounted for? Temperature and partial pressure are rarely simple constant values, often changing significantly between on-line and off-line with spikes, exceedances and reductions from normal, and also varying when on-line as the operating process fluctuates. (There may also be a general drift of values up or down over time (typically between turn-arounds) or step changes as process conditions or control calibrations alter, raw feeds change in composition, additional feeds come on-stream, fouling develops in heat exchangers, operators adapt to changing throughputs, etc.)
- Partial pressures are not measured and have to be derived by calculation of gaseous mole fractions or other means for liquids
- Should maximum values be used or can a data averaging statistical approach be used?

Annex F of API RP 941 states that owners/operators should add a safety factor even to the new Figure F.1 curve [an extract of Figure 1] because operations just below the curve may still be at risk due to issues such as discrepancies in temperature measurement, fouling of heat exchanger surfaces, and temperature excursions. This emphasises that a conservative approach should be taken to the above points.

3.2.1 Important Aspects to Consider

Facilities should have an auditable, consistent and conservative approach to addressing the above.

Assumptions made for periods before data logging should be clearly recorded and an assessment included of historical operating practices that could cause excursions above normal operating values and their impact.

It is important to know the actual operating conditions that equipment is subjected to, to make a meaningful assessment of the likelihood of HTHA. This is particularly so when the operating parameters may approach or exceed the Nelson curve when reliable, dedicated instrumentation should be utilised. A review of available monitoring points should identify where accurate measurements are required but not available and a means of measurement installed (e.g. thermowells in-between stacked heat exchangers).

Accuracy of measurements should be validated or an appropriate error band included. Modelling of operating conditions may be required if maximum values are not assumed.

Where significant periods of operation were at higher conditions than the norm then unless the higher values are taken for the assessment, any method for “normalising” the overall effect of the higher conditions (e.g. a time based equivalence, adapting the P_v approach) should be recorded. Damage incubation curves are given in API RP 941 and these could also be used to assist evaluating the impact of exceedances and upsets.

For periods when conditions are reasonably constant, maximum boundary values could be used or a statistical approach could be employed, such as the mean + standard deviation(s). Scatter plots and bar charts may also be useful in determining the envelope of conditions equipment has been exposed to.

3.2.2 Possible Future Outcomes

Documented example(s) of assessing variations in conditions showing good practice approach.

3.3 Plant Operating Hours

HTHA is a time dependent mechanism and the Nelson curves do not directly take account of time in their construction. At present there is no “standard” guidance on whether aged equipment presents a higher likelihood of developing HTHA damage – examples of factors that may be relevant:

- For older plant there is likely to be appreciable time in service before modern data logging and C&I systems were installed and as a result there is possibly less confidence in actual operating controls and knowledge of conditions (see previous Section)
- with longer time for hydrogen to diffuse into materials it may be possible for fissures to develop to a greater through thickness extent. With a high enough density of fissures, the bulk material strength could be significantly reduced. Should cracking develop, growth may be more rapid than expected

Within the Forum there was no common approach to including operating age when assessing likelihood of HTHA damage, with the majority of members’ companies not directly including it. Where it was recognised the action varied between increasing the likelihood ranking one step and increasing the assessment temperature by 15-20°F (8-11°C). In the majority of companies operating age was however considered on a case by case basis when equipment was assessed and when close to a ranking threshold. Additional guidance is expected to be included in future editions of API RP 941 (with age based curves) and the JIP models will also inform this aspect.

3.3.1 Important Aspects to consider

Review age of equipment and consider appropriate changes to likelihood ranking, inspection frequency and extent, or to replacement plans. The operating times (where available) and other information for the points used to derive the Nelson curves may be of assistance with this.

Maintain awareness of the JIP work and the time based models becoming available.

Maintain awareness of changes to API guidance that address equipment (operational) age.

3.4 Issues Associated with Using Reduced Hydrogen Partial Pressure or Reduced Temperature for Assessment of Internally Lined Vessels

Vessels may be lined by a variety of methods to give protection to the pressure containment steel from corrosion and/or high temperature. In Damage Mechanism Hazard Reviews carried out at the Anacortes refinery, corrosion protection cladding was assumed to be present in the full length of the heat exchanger shell that failed whereas in fact it only covered a short length. Rupture occurred just outside the clad zone.

3.4.1 Linings for Corrosion Protection

Corrosion protection is achieved by lining the vessel in a higher alloy or stainless steel protective layer – generally by welding an overlay material to the steel substrate (or cladding by incorporating an inner sleeve within the vessel). Materials used for the lining may inhibit hydrogen diffusion rate and so have the effect of reducing the hydrogen partial pressure at the interface. (Stainless steels are quoted to have coefficients of diffusion two orders of magnitude lower than carbon steels.) API RP 941 provides guidance for calculating the reduction in partial pressure (the next edition is expected to provide better clarity on diffusion coefficients and therefore improve the accuracy of the calculations). Where applicable a lower ppH_2 could then be used in assessment against the Nelson curve. Should the lining corrode its effectiveness will be reduced, as will be the case where the base material is thickened, for example at heavy section branches and nozzles, etc.

The internal lining has to remain intact with no direct leakage path, otherwise the full ppH_2 would be present at the interface and the likelihood of HTHA increased. Freedom from defects such as cracks and bulges may not be easy to prove as, often, large areas are involved as well as complex geometries. Cracks in internal linings may also be sites for crack initiation in the substrate steel. It is therefore general practice not to include any reduction in partial pressure when making an initial HTHA likelihood assessment and take the corresponding replacement and inspection actions for HTHA as if the lining were not present.

However there may be cases where demonstrating the continued effectiveness of linings is preferable to replacement. Careful consideration of how this is done would be needed and appropriate inspection extent and frequency determined. There doesn't appear to be a simple means of identifying from the outside of a vessel where internal lining defects could exist, so extensive internal and external inspection with appropriate techniques would likely be required to ensure integrity.

3.4.2 Linings for Temperature Protection

When linings are fitted for temperature protection, e.g. internal refractories, again if the integrity of the lining is lost then the steel containment may be subject to the full internal temperature and the likelihood of HTHA damage increased. Refractory can degrade over time and be prone to cracking when it is frequently cycled particularly if the supporting arrangements are not well designed to limit flexing.

Assessment for HTHA should therefore initially exclude the benefit of refractories. If the integrity of liner is required to underwrite the continued use of the equipment then it should be possible to demonstrate refractory integrity by examining the equipment from the outside for hot spots even though some limitations due to external insulations may be present. IR cameras are normally used and a clear view of external surfaces is needed. Inspection can however be undertaken frequently. Should hot spots be identified then temperatures can be estimated and inspection pinpointed or other actions taken. Multiple breakdown of refractory may become difficult to manage though in some cases external stream cooling jackets have been engineered though with varying degrees of success.

It is also probable that refractory linings would not usually be removed at turn-arounds to undertake internal surface inspections. This places greater emphasis on the effectiveness of external inspections.

3.4.3 Important Aspects to Consider

The presence of internal corrosion lining is generally ignored when initially assessing HTHA likelihood.

It should be clearly known when HTHA management of particular equipment relies on the presence and integrity of an internal lining to reduce the effective hydrogen partial pressure or exposure temperature so that appropriate operational, inspection and maintenance precautions are taken.

Where claddings and refractories are factored into the assessment parameters, steps should be taken to confirm their presence (overlooked at Anacortes) and effectiveness (i.e. their integrity).

It may be particularly difficult to underwrite the effectiveness of refractories for historical periods of time unless comprehensive temperature data is available.

For refractory linings, comprehensive monitoring (e.g. frequent IR for temperatures) and inspection should be in place to demonstrate their continuing integrity.

Linings may be less effective in reducing ppH_2 at heavy section branches and nozzles, etc.

Maintaining accurate plant records, keeping information and drawings up to date, recording checks and results of inspections of the extent and condition of lining are essential for reliable assessments of HTHA.

3.5 Plant in Anacortes Arrangement/with Similar Characteristics

The equipment that failed catastrophically at Anacortes due to HTHA was the non-PWHT'd shell of a heat exchanger that endured temperature excursions above its normal operating condition over significant periods due to the build-up of internal tube side deposits (mainly in a next in series exchanger). Fouling of heat exchangers can be a common occurrence. (Note: CSB modelling predicted excursion temperatures at the hottest rupture location were however below the C-Steel Nelson curve applicable in API RP 941 prior to the latest edition.) What factors made the Anacortes' heat exchanger so susceptible to temperature excursions?

- Exchangers were arranged in series
- Raw feed changed state from liquid to gas as it was heated through the exchangers and deposition occurred at the "flash point" which was in the hottest exchanger
- Deposition reduced the effectiveness and caused the flash point to transfer back into the next in series exchanger (which eventually failed) with accompanying increase in temperature
- There was no temperature monitoring on the individual exchangers so operatives were not aware of the level of temperatures
- The exchanger that failed was assumed to be fully clad internally so reducing its susceptibility to HTHA (by reducing the effective hydrogen partial pressure). The shell section that failed was not however clad and it would appear that inspections, if carried out, had not registered this in Damage Mechanism Hazard Reviews

3.5.1 Important Aspects to Consider

Facilities should carefully examine their equipment arrangements and processes and where any of the above factors are present should highlight the equipment for special study, report the conclusions and if necessary revise the HTHA likelihood ranking and necessary actions.

3.6 Dedicated Monitoring and IOWs, Reporting of Exceedances

Safe operation and management of equipment requires control of operating conditions within safe operating limits. These are typically the original design conditions and defined envelopes of exceedances. Tighter limits may apply following assessment for HTHA or as plant ages.

3.6.1 Important Aspects to Consider

Where the margins between normal operating conditions and the safe operating limits of equipment in terms of HTHA susceptibility are within possible operating excursions, it would be prudent to define IOWs and ensure actual conditions are continuously or routinely monitored and alarmed, such that significant incursions are brought to the attention of staff and actions taken in terms of operational controls and follow on HTHA assessment. Where repeated alarming occurs, reporting higher up the management chain should be considered so that broader actions can be implemented.

3.7 Awareness of Appropriate NDE Techniques and Engagement with Suppliers

To safely manage HTHA, detection of HTHA damage is required at an early stage – fissuring. However this is challenging due to the small size of fissures.

3.7.1 Traditional Techniques

The detection techniques advised in API RP 941 (current 8th edition) appear to be generally based on development work carried out by Shell Oil Company in the 1990's:

- For plain shell, base metal, sections the use of a frequency dependant backscatter method in combination with the velocity ratio and spectral analysis techniques. The combination of these methods which include pattern recognition stages by the operator, is known as AUBT – Advanced Ultrasonic Backscatter Technique
- Other standard methods are capable of detecting HTHA only after discrete cracks have formed by which time there could be significant degradation of mechanical properties
- For weldment examination (without removal of weld caps) where attack can be localised only two UT methods are considered effective. High frequency (typically 10MHz) shear wave and angle-beam spectrum analysis which are designed to detect damage in the fissuring stage. These are known as ABSA – Angle Beam Spectral Analysis

Training is available in the techniques and individuals are tested for certification and registered to apply the techniques using specific set ups and equipment. Recognition and interpretation of signal patterns in these techniques introduces a degree of subjectivity into the process.

Individual companies such as NDE suppliers or facility operators with NDE capabilities may have also developed similar techniques.

The E2G JIP is examining the ability and reliability of individual techniques to detect damage using a series of test samples taken from affected equipment (Anacortes and other sources) in a blind trial of NDE operatives. To date the published results suggest relatively limited effectiveness of many of the individual techniques. Results from the AUBT and ABSA have yet not been published – it is important to recognise that conventional AUBT and ABSA use a series of individual ultrasonic tests and signal processing *in combination* to determine the likelihood of damage being present.

3.7.2 Modern Advanced Techniques

More advanced ultrasonic techniques are also being developed and tested in the E2G JIP which has access to HTHA damaged samples from Anacortes. Lavender International is appointed within the JIP for NDT testing and development. Individual operating companies may also have developed more advanced techniques.

The advanced volumetric techniques that are currently believed to offer more reliable and sensitive detection of early stage HTHA damage are TOFD (Time Of Flight Diffraction) and PAUT (Phased Array Ultrasonic Testing) with advanced signal processing and analysis, and presentation methods such as FMC (Full Matrix Capture) and TFM (Total Focussing Method). Further development and testing of such advanced techniques is on-going in the JIP but with successful early results, training of NDE operatives is already being given with a certification scheme in place.

Both the TOFD and PAUT techniques can be used as primary methods for detecting and measuring the extent of HTHA damage. Indications are that TOFD provides a sensitive and more rapid screening technique and PAUT a sensitive characterising and sizing technique.

It is expected that the next issue of API RP 941 will provide up-to-date advice on the relative ranking of techniques and their limitations.

3.7.3 Important Aspects to Consider

The value of undertaking internal inspection should be noted.

Testing of inspection techniques and recommendation of optimum techniques are a topic of current project works.

Maintain awareness of the latest techniques and testing results from the current JIPs.

Maintain awareness and where possible advance notice of techniques that are to be recommended in the next issue of API 941.

The following paragraphs are considered to be applicable at the time of issuing this guidance. However, developments in NDT techniques are on-going and therefore the reader is advised to check with API/industry experts to confirm their currency.

Facilities should consider applying a combination of two primary advanced techniques which are now available such as TOFD and PAUT. These are claimed to be more reliable in detecting HTHA damage than traditional techniques and advanced signal analysis, processing and presentation (e.g. FMC and TFM) assists with the interpretation of results, removing some subjectivity. Inspections by AUBT and ABSA are still regarded as applicable and should be utilised as secondary techniques alongside the newer techniques whilst experience is gained.

Whilst each company specifies its required inspection techniques, the latest developments suggest optimum inspections for base material are combinations of TOFD and PAUT (and AUBT); for plain welds a combination of TOFD and PAUT (and ABSA); for nozzle nozzle/branch welds, PAUT. A combination of techniques and signal processing analyses should be applied.

As techniques are sensitive to various material effects as well as HTHA, positive confirmation of HTHA damage and the depth of material affected is provided by metallographic examination of core or scoop samples. Replicas may be taken for laboratory examination provided sufficient of the decarburised layer can be removed. However replication provides a spot check only at the surface and is generally only used to initially investigate positive indications from NDE.

Further development of and experience with the modern advanced techniques may reduce the need for metallographic sampling; currently though, sampling may be frequently required.

3.7.4 Possible Future Outcomes

Discussion and standardisation of reliable HTHA detection techniques.

3.8 What to Inspect and Preparation of Equipment for Inspection

Inspection should be directed at the range of exposed sections of equipment – plain shell/pipe sections and joining welds and other features including: closures and ends, rolled geometries (e.g. certain ends and closures), branches, nozzles, pipework bends/elbows, reducers, including flange connections, etc.; weldments, compensations, weld intersections, internal weld attachments.

It seems less likely that HTHA damage will develop in simple plain shell sections before it develops in the associated joining weldments and shell zones local to welds particularly where welds received no PWHT. Whilst not excluding a representative sample of simple plain shell areas, consideration could be given to directing inspection at weldments and local shell zones in preference to areas of simple plain sections. An exception to this would be where shell sections were exposed to higher operating conditions than associated welds. Hot spots in cold wall vessels caused by damaged internal cladding would be an example of this as well as at heavy wall nozzle forgings where cladding effectiveness may be relatively lower.

Welds themselves vary in design (e.g. partial penetration, full penetration, with/without backing rings, butt, fillet, single/double sided, branch/nozzle, plug, at tapered/abrupt changes of section, angled, transition/dissimilar metal welds) and on a case by case approach may be categorised as potentially more critical or prone to developing damage than others. Welds with significant peaking could experience higher stresses.

As well as welded internal attachments, the areas opposite external attachments such as support skirts, stiffeners, lugs, stays and gussets, etc., could act as local stress raisers at the internal surface. The latter is considered more likely to be significant in thinner wall sections, such as pipework.

3.8.1 Preparation for Inspection

Surface preparation for MPI, FPI and ultrasonic testing is invariably required. The testing procedure should specify the acceptable flatness and surface finish or roughness (which should align with the technique validation) and whether achieved by grinding, polishing, wet/dry blasting, etc. Poor preparation for the advanced ultrasonic inspection techniques needed for detecting HTHA could inhibit coupling and reduce signal amplitude by scattering beams and so the effectiveness and reliability of the test, however, modern couplant methods can avoid the need for very high standards of preparation.

Surface preparation for testing is often carried out by a main contractor under instruction of the facility client/operator which can introduce an interface between the test company and the contractor, or may be part of a turnkey contract which potentially distances the client/facility operator from the testing company. Care is needed to ensure that neither arrangement becomes a barrier to good communication between all parties to ensure that preparation is carried out to the test company requirements. Otherwise the test results may be compromised.

3.8.2 Important Aspects to Consider

HTHA damage is not always consistent in its distribution as there are examples of adjacent shell sections and weldments with and without damage. Inspection should take this into account. Weldment inspections should include a zone of plain shell on either side of the weldment.

When necessary, consider whether the inspection is sufficient to include all relevant base material heats and equipment features. Hot spots identified in plain shells should be inspected in addition to associated weldments.

Surface preparation requirements for testing should be clearly understood by all parties involved and meet the test validation standards. Surface requirements should be readily achievable.

The test company should verify surface preparation is to the required standard.

3.9 Application of NDE (Including Validation and Certification)

Detecting the early stages of HTHA damage using volumetric techniques from the outside surfaces of equipment is recognised as a challenging aspect of HTHA management. It is therefore important to carefully manage the whole inspection process including selecting the inspection agency, applying the best available techniques, reporting and assessing results and identifying where inspection did not meet objectives (e.g. should geometry or space around weldments restrict ultrasonic probe positioning – an issue often associated with bend/reducer/flange fitting welds) so further action can be taken if necessary.

It is important to ensure that NDE suppliers are following validated inspection procedures and have certification that demonstrates their capability and recent experience. Suppliers may have PAUT and TOFD experience but it should be specific to HTHA detection.

3.9.1 Important Aspects to Consider

NDE companies used for HTHA inspection should be able to demonstrate they have TOFD and PAUT expertise specifically for HTHA detection (applies equally to AUBT and ABSA) – this would generally be demonstrated by certification from a recognised training (e.g. Lavender for PAUT and TOFD and back scatter techniques/Shell Global Solutions for AUBT and ABSA) or an equivalent company expert approval.

Techniques employed should have been ‘validated’ as far as possible using samples containing HTHA damage and designed for the specific geometry under test. Records should be available showing the geometry range, sensitivity and limitations of the technique as well surface preparation required.

Equally important is that NDE staff on site applying the ‘validated’ techniques are specially trained and hold appropriate, valid, certification. Records should be checked.

Facilities should ensure that their NDE suppliers can satisfy the above and may require suppliers to undergo site training. Blind testing of samples, some of which contain HTHA damage could be used to demonstrate techniques and operator ability. This requires characterised samples – some may be accessible within companies, but the availability is known to be limited.

Whenever possible facilities should remove suspect samples from their plants for characterisation and retain them for NDE testing. This should apply where equipment is replaced for HTHA.

3.9.2 Possible Future Outcomes:

Wider accessibility to damaged and characterised material samples.

A wider industry training and certification scheme for HTHA NDT, e.g. in the UK through BINDT

3.10 Inspection Levels – How Much to Inspect (Scale/Extent/Amount)

Company policies and procedures determine the scale and extent of inspection and there is some variation within the Forum members.

Regarding scale, it is generally not considered adequate to nominate and only inspect lead vessels or pipework systems – due to the variability of damage found in the field, all equipment and systems judged with likelihood of developing HTHA damage are normally treated as individual cases and inspected in their own right.

The extent of inspection refers to the quantity of each of the features on a vessel or pipe system inspected and the amount or proportion of each feature that is inspected. It covers both base materials – percentage area of individual shell strokes, branch pieces, etc., and welds – percentage length of weldments.

The extent of inspection is generally determined by the assessed likelihood of damage based on the Nelson curves. At its simplest, when the worst combination of operating conditions positioned a piece of equipment below its curve – LOW extent of inspection; when positioned above the curve – HIGH extent of inspection. This would be broken down further for equipment above the curve if different parts of the equipment were exposed to widely different operating conditions – here, those parts and components operating below the curve – LOW extent; only those parts above the curve – HIGH extent.

As discussed earlier, the majority of companies in the Forum amend this approach and include one (sometimes two) additional bands or margins below the Nelson curve which qualify parts and components for INTERMEDIATE or HIGH extent of inspection.

LOW extent is generally no specific inspection for HTHA; INTERMEDIATE extent and HIGH extent typically vary between 25-100%, with the extent generally reflecting proximity to the curve, age of equipment, and other factors and uncertainties present in the assessment.

Base metal inspection would generally be of patches (typically in squares 200-400mm sided) remote from welds including representative vessel construction plates and strokes and attached branches and nozzles. In general it takes into account the range of operating conditions experienced at different positions in the equipment with increased extent at higher exposure positions. Base metal bordering welds (typically 100mm each side) should be included as part of weldment inspections.

Regarding welds within the Forum, the inspected extent ranged between 25% – 100% inspection every turn-around (see above), with the majority of members adopting the higher extent.

Welds categorised as critical are generally subject to 100% extent with other welds at a lower extent. In some cases the most likely areas of damage were focussed on – typically based on a combination of design/construction features, repair history and higher operating conditions (temperatures and partial pressures, areas more affected by exceedances, fatigue, etc.).

Where equipment operated above the curve, inspection extent was generally quoted at 100% with intermediate and opportunity inspection also carried out between turn-arounds driven by the level of margin above the curve.

Facilities are responsible for managing HTHA based on their detail knowledge of equipment construction, repairs and operating conditions and should specify extent of inspection; this should not be left to NDE suppliers who neither have the knowledge nor expertise.

Information on damage incubation time, a limited amount of which is included in API RP 941 may also be incorporated into the assessment. (Limitations to the use of incubation curves are given in API RP 941 and the next edition is expected to include more comprehensive information.) Incubation curves may not be applicable where high residual (secondary) stresses exist or for equipment in liquid service. JIP life models and Pv approaches may also provide useful information for considering in assessments.

3.10.1 Important Aspects to Consider

It is generally not considered adequate to nominate and only inspect lead vessels or pipework systems for HTHA.

The extent of inspection should be carefully considered and reflect the assessed likelihood of HTHA damage occurring in any part of the equipment or system. Uncertainties in the assessment parameters (e.g. operating conditions, whether welds were PWHT'd) should generally lead to a higher extent of inspections.

Facilities should specify the extent of inspections; it should not be left to NDE suppliers.

Extent should address and reflect a wide range of factors from equipment design and construction features, repair history, operating conditions and operating age. Particular design features of vessels, pipeworks and weldments may require increased extent (refer to Section 3.5).

3.11 Limitations to Weld Inspections Associated With Fittings

With any inspection programme the actual extent of inspection achieved may be less than that specified. Discounting practical matters such as access and surface preparation and time issues that should be manageable, the main causes of reduced extent are likely to be material quality aspects (inclusions, laminations, etc.,) and component geometry aspects that inhibit ultrasonic probe positioning to provide full weldment coverage (tandem setup for TOFD probes, shear wave angles). These aspects should be noted and their impact assessed by a risk assessment process. HTHA inspections on associated plant (with similar operational conditions, materials and fabrication practices) may provide valuable information for the risk assessment though should be used with caution (see Section 2.2).

Experience within the Forum has highlighted weldments on pipe fittings as being critical and often where HTHA damage has occurred and developed into macro-cracking. This may be due to material aspects or increased stresses e.g. due to changes of section thickness across weldments, or the effect of thicker sections within a system (e.g. flanges being stiffer sections or at terminal points). In some cases replacement has been adopted in preference to inspection.

Material quality may be more difficult to work around. Samples could be removed for laboratory inspection or, if practical, internal access could be provided for replication, etc.

Geometry aspects may be partially or wholly overcome by removing weld caps and adjusting inspection techniques. The use of miniature ultrasonic probes may also be a solution.

3.11.1 Important Aspects to Consider

Experience within the Forum of limitations to inspection of fitting welds should be noted and also that welds to fittings have been a position of HTHA damage occurring particularly on pipework, which was overcome by replacement.

Ensure that limitations to inspection are identified and overcome by different inspection techniques where possible or that a risk assessment process is applied.

3.12 Assessment of Hydrogen Partial Pressure in Liquid Packed Lines

HTHA damage has been experienced in equipment containing hydrogen dissolved in liquids. The current issue of API RP 941 contains a new informative Annex, G, dealing with the assessment of liquid packed lines. Hydrogen still acts to cause HTHA when dissolved within a liquid filled line as well as in the liquid and gaseous phases of partially filled lines. There are numerous examples including failures of pipework which were thought to be in compliance.

Assessing the hydrogen partial pressure in liquid services is less straight forward than in gaseous mixtures and Annex G gives descriptions of five methods.

Three are described as other possible calculation methods to Conventional Thermodynamics and the Total Pressure Method. The Conventional Thermodynamics method is quoted as being consistent with previous API RP 941 and applies to liquid steams from vessels to pumps. An example of applying three of the techniques is given.

A presentation at NACE 2012 can be obtained⁷ which further describes the methods.

API RP 941 also reports that recent experience with HTHA in liquid-filled hydrocarbon service showed that damage occurred more rapidly than the incubation curves predicted and that they should not to be used for liquid-filled lines.

The experience of one of the Forum members is that of equipment previously assessed below the curve to now, after reassessment to Annex G, as being above the curve.

Indications are that the next edition of API RP 941 will better define and make clearer the calculation methods.

3.12.1 Important Aspects to Consider

Fully and partially filled lines that convey liquids containing dissolved hydrogen are prone to HTHA damage in the same way that gas/vapour lines are.

Check that fully and partially liquid-filled lines have been assessed for HTHA in-line with Annex G in API RP 941.

Note the experience within the Forum of reassessing liquid-filled lines to Annex G. The assessment is less straight forward than for gas/vapour and an audit of the methods followed and results should be considered.

Incubation curves should not be applied to liquid-filled lines.

References

- 1 Steels for Hydrogen service at Elevated Temperatures and pressures in Refineries and Petrochemical Plants, API Recommended Practice 941, Eighth Edition February 2016, American Petroleum Industry.
- 2 Investigation Report, Catastrophic Rupture of Heat Exchanger (Seven Fatalities) Tesoro Anacortes Refinery, Anacortes Washington, April 2nd 2010, Report 2010-08-I-WA, May 2014, U.S Chemical Safety and Hazard Investigation Board.
- 3 CSB Safety Alert, Preventing High Temperature Hydrogen Attack, CSB Recommendation, 11 August 2016, U.S Chemical Safety and Hazard Investigation Board.
- 4 RR1133 – Maintaining the integrity of process plant susceptible to high temperature hydrogen attack. Part 1: analysis of non-destructive testing techniques, UK HSE website, www.hse.gov.uk.
- 5 RR1134 – Maintaining the integrity of process plant susceptible to high temperature hydrogen attack. Part 2: factors affecting carbon steels, UK HSE website, www.hse.gov.uk.
- 6 High Temperature Hydrogen Attack: Safe use of carbon steel, Health and Safety Executive - Safety alert, CEMHD 2 – 2018, December 2018.
- 7 A Qualitative Risk-Based Assessment Procedure for High Temperature Hydrogen Attack of C-1/2Mo Steel, James E McLaughlin, PVP2007-26129, Proceedings of ASME PVP, July 2007.
- 8 Risk-based Inspection Methodology, API Recommended Practice 581, Third Edition April 2016, American Petroleum Industry.
- 9 Fitness-For-Service, American Petroleum Institute/American Society of Mechanical Engineers, API 579-1/ASME FFS-1, (current edition published in June 2016)
- 10 Methods for Approximating H₂ Partial Pressure in Subcooled Liquids, Shargay, Cuevas, Mathias, Jacobs, NACE CTW, Sept 2012.

EEMUA Publication: feedback form

An electronic version of this form is available at www.eemua.org

Date feedback provided: (dd/mm/yyyy)		EEMUA Publication 240 Edition 1: Factors to Consider when Managing High Temperature Hydrogen Attack on Petroleum and Chemical Facilities				
Feedback provided by: Contact name: Phone: E-mail:		Feedback provided on behalf of which organisation? Organisation name: Location:				

EEMUA ref (EEMUA use only)	Page no.	Paragraph Figure/ Table concerned	Type of comment (General/ Technical/ Editorial)	COMMENTS	Proposed change (Please provide alternative wording, or propose removal of, or addition to, existing wording.)	OBSERVATIONS OF THE EXECUTIVE (EEMUA use only) on each comment submitted
	4	Fig 2	E	This is an example only	No change to wording required	Example only

When you have completed this form with all your comments, please save and e-mail to ask@eemua.org or post a paper copy to: Publications Department, EEMUA, Second Floor, 16 Black Friars Lane, London EC4V 6EB.

EEMUA E-Learning and Publications Catalogue

All EEMUA publications can be purchased online at www.eemua.org

Alternatively, please contact EEMUA by telephone: +44 (0)20 7488 0801 or by email:

sales@eemua.org

EEMUA E-Learning Courses

Storage Tanks

This course provides an introduction to EEMUA Publication 159 and the CompeTank® series of training courses.

The Subsea Materials

This course provides an introduction to EEMUA Publication 194 and the 'Subsea engineering: materials selection and corrosion control' training course.

Opslagtanks

Deze cursus geeft een inleiding tot EEMUA Publication 159 en de CompeTank® reeks trainingen.

Alarm Systems

This course provides an introduction to EEMUA Publication 191 and the associated classroom training course.

Cyber Security

This course provides an introduction to the topic of industrial cyber security and EEMUA's Cyber security assessment process for industrial control systems.

Functional Safety

The e-learning is positioned at the awareness/introductory level and is an optional precursor to working through EEMUA Publication 222 – Guide to the application of IEC 61511 (Edition 1) to safety instrumented systems in the UK process industries.

EEMUA Publications

Most EEMUA publications can be purchased as a print version. We also offer some digital versions. Please see listings below for more details.

Automation, Control, Electrical

- 226** Design and installation of on-line analyser systems: a guide to technical enquiry and bid evaluation
Available as [Print version](#) and [Digital version](#)
- 222** Guide to the application of IEC 61511 to safety instrumented systems in the UK process industries
Available as [Print version](#) and [Digital version](#)
- 214** Toolbox Guide: Electrical installation, inspection and maintenance in potentially explosive atmospheres – Available to purchase from CompEx™ only, by email CompexAdmin@jtltraining.com

- 209** Guide to the development and implementation of on-line analyser applications
Available as [Print version](#) and [Digital version](#)
- 201** Process plant control desks utilising human-computer interfaces: a guide to design, operational and human-computer interface issues
Available as [Print version](#) and [Digital version](#)
- 191** Alarm systems - a guide to design, management and procurement
Available as [Print version](#) and [Digital version](#)
- 187** Analyser systems - a guide to maintenance management
Available as [Print version](#) and [Digital version](#)
- 186** Practitioner's Handbook for potentially explosive atmospheres
Available as [Print version](#)
- 178** A design guide for the electrical safety of instruments, instrument / control panels and control systems
Available as [Print version](#) and [Digital version](#)
- 175** Code of Practice for calibration and validation of process analysers
Available as [Print version](#) and [Digital version](#)
- 138** Design and installation of on-line analyser systems
Available as [Print version](#) and [Digital version](#)

Engineering, Procurement, Construction

- 234** 90/10 Copper nickel alloy piping for offshore applications (Specification)
Available as [Print version](#) and [Digital version](#)
- 233** Line pipe Specification: Clauses in addition to API 5L/ISO 3183
Available as [Print version](#) and [Digital version](#)
- 224** A guide to risk-based procurement
Available as [Print version](#) and [Digital version](#)
- 218** Quality requirements for the manufacture and supply of duplex stainless steels
Available as [Print version](#) and [Digital version](#)
- 215** Industrial cooling tower fans and fin fans - Guide for design, maintenance and operation
Available as [Digital version](#)
- 211** Guidance on the specific of pressure vessels
Available as [Print version](#) and [Digital version](#)
- 207** Double concrete tanks for liquefied gas - guide to design, construction and operation
Available as [Print version](#) and [Digital version](#)

- 197** Specification for the fabrication of non-primary structural steelwork for offshore installations
Available as [Print version](#) and [Digital version](#)
- 194** Guidelines for materials selection and corrosion control for subsea oil and gas production equipment
Available as [Print version](#) and [Digital version](#)
- 192** Guide for the procurement of valves for low temperature (non cryogenic) service
Available as [Print version](#) and [Digital version](#)
- 185** Guide for hot tapping on piping and other equipment
Available as [Print version](#) and [Digital version](#)
- 176** Specification for structural castings for use offshore
Available as [Print version](#) and [Digital version](#)
- 179** A working guide for carbon steel equipment in wet H₂S service
Available as [Print version](#) and [Digital version](#)
- 158** Construction specification for fixed offshore structures
Available as [Print version](#)
- 154** Guidance to owners on demolition of vertical cylindrical steel storage tanks and storage spheres
Available as [Print version](#) and [Digital version](#)
- 149** Code of Practice for the identification and checking of materials of construction in pressure systems in process plants
Available as [Print version](#) and [Digital version](#)
- 143** Recommendations for tube end welding
Available as [Print version](#) and [Digital version](#)
- 141** A Guide to the use of EEMUA 140 Noise procedure Specification
Available as [Print version](#) and [Digital version](#)
- 140** Noise procedure Specification
Available as [Print version](#) and [Digital version](#)
- 133** Specification for underground armoured cable protected against solvent penetration and corrosive attack
Available as [Print version](#) and [Digital version](#)
- 105** Factory stairways, ladders and handrails (including access platforms and ramps)
Available as [Print version](#) and [Digital version](#)
- 104** A guide to information required from equipment vendors
Available as [Print version](#) and [Digital version](#)

- 101** Lifting points - a design guide
Available as [Print version](#) and [Digital version](#)

EEMUA Publications Bundle Control of noise in equipment and plant (**140, 141, 161**)
Available as [Print version](#) and [Digital version](#)

Equipment Operation & Maintenance

- 230** Ageing rotating equipment - a guide to maintenance and operation
Available as [Print version](#) and [Digital version](#)
- 223** Pressure equipment testing after repair, modifications or re-rating: a guide to the Pressure Test Waiver
Available as [Print version](#) and [Digital version](#)
- 208** Guide to life-cycle management of pressure relief systems
Available as [Print version](#) and [Digital version](#)
- 205** A Guide to the production testing of valves for the energy, process and related industries
Available as [Digital version](#)
- 200** Guide to the specification, installation and maintenance of spring supports for piping
Available as [Print version](#) and [Digital version](#)
- 199** On-line leak sealing of piping: Guide to safety considerations
Available as [Print version](#) and [Digital version](#)
- 188** Guide for establishing operating periods of safety valves
Available as [Print version](#) and [Digital version](#)
- 185** Guide for hot tapping on piping and other equipment
Available as [Print version](#) and [Digital version](#)
- 184** Guide to the isolation of pressure relieving devices
Available as [Print version](#) and [Digital version](#)
- 182** Specification for integral block and bleed valve manifolds for direct connection to pipework
Available as [Print version](#) and [Digital version](#)
- 177** Guide to the UK Pressure System Safety Regulations (2000)
Available as [Print version](#) and [Digital version](#)
- 168** A guide to the pressure testing of In-service pressurised equipment
Available as [Print version](#) and [Digital version](#)
- 164** Seal less centrifugal pumps: Class 1
Available as [Digital version](#)
- 151** Liquid ring vacuum pumps and compressors
Available as [Print version](#) and [Digital version](#)

Inspection and Integrity Management

- 232** Specifying, procuring and managing third party inspection services
Available as [Print version](#) and [Digital version](#)
- 231** The mechanical integrity of plant containing hazardous substances - a guide to periodic examination and testing
Available as [Print version](#) and [Digital version](#)
- 206** Risk Based Inspection - a guide to effective use of the RBI process
Available as [Digital version](#)
- 193** Managing competence assurance for personnel undertaking in-service inspection of pressure equipment
Available as [Print version](#) and [Digital version](#)
- 181** A guide to risk based assessments of in-situ large Ex 'e' and Ex 'N' machines
Available as [Print version](#) and [Digital version](#)
- 161** Guide to the selection and assessment of silencers and acoustic enclosures
Available as [Print version](#) and [Digital version](#)
- 159** Above ground flat bottomed storage tanks - a guide to inspection, maintenance and repair
Available as [Print version](#) and [Digital version](#)
- 149** Code of Practice for the identification and checking of materials of construction in pressure systems in process plants
Available as [Print version](#) and [Digital version](#)

Storage and Distribution

- 217** Safe and effective operation of storage tanks
Available as [Print version](#) and [Digital version](#)
- 213** Emission reduction from oil storage tanks and loading operations
Available as [Print version](#) and [Digital version](#)
- 190** Guide for the design, construction and use of mounded horizontal cylindrical steel vessels for pressurised storage of LPG at ambient temperatures
Available as [Print version](#) and [Digital version](#)
- 183** Prevention of tank bottom leakage - a guide for the design and repair of foundations and bottoms of vertical, cylindrical, steel storage tanks
Available as [Digital version](#)
- 180** Frangible roof joints for fixed roof storage tanks: Guide for designers and users
Available as [Digital version](#)
- 159** Above ground flat bottomed storage tanks - a guide to inspection, maintenance and repair
Available as [Print version](#) and [Digital version](#)

- 147** Recommendations for refrigerated liquefied gas storage tanks
Available as [Print version](#) and [Digital version](#)