

Inspection for High Temperature Hydrogen Attack (Draft4 for comment ballot, March 2021)

API RECOMMENDED PRACTICE 586, Section 2

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5 Inspection of High Temperature Hydrogen Attack

Introduction

The form of hydrogen damage called high temperature hydrogen attack (HTHA) is discussed in API RP 571, API RP 941 and API 941 TR-A.

The purpose of this recommended practice (RP) is to describe the wide variety of inspection methods and techniques applicable for reliable detection and assessment of service-induced HTHA damage in the refinery equipment.

This document includes information assembled from the refining industry experience and is anticipated to be balanced with applicable API and other related industry standards and practices.

This RP is intended to provide guidance for the use of optimized inspection techniques but should not be considered the final technical basis for HTHA detection and analysis. The inspection techniques descriptions in this RP are not intended to present an absolute guideline for every possible situation that may be confronted. The reader may need to consult with an inspection engineer or NDE SEM for specific circumstances.

1 Scope

This recommended practice (RP) applies to inspection of equipment in refineries, petrochemical facilities, and chemical facilities in which hydrogen or hydrogen-containing fluids are processed at elevated temperature and pressure. The guidelines in this RP can also be applied to hydrogenation plants such as those that manufacture ammonia, methanol, edible oils, and higher alcohols.

This RP summarizes inspection methods and techniques applicable for reliable detection and assessment of service-induced HTHA damage. This RP is reference document for the historic and new inspection approaches. The techniques discussed and recommended in this RP are optimized for inspection of HTHA.

NDE characterization and categorization related HTHA manifestation is intended to be used for reporting and conducting Fitness-For-Service (FFS) assessments.

Presented in this document considerations when planning an HTHA inspection should be utilized as a reference to other integrity related documents.

Presented in the annex (s) optimized setups, results of experimental tests and actual data acquired from operating plants are foreseen to improve HTHA inspection.

2 Normative References

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For undated references, the latest edition of the referenced document (including any addenda) applies.

API Recommended Practice 571, Damage Mechanisms Affecting Fixed Equipment in the Refining Industry.

API Recommended Practice 941, Steels for Hydrogen Service at Elevated Temperatures and Pressures in Petroleum Refineries and Petrochemical Plants”, Eighth Edition, Addendum 1.

API 941 TR-A, The Technical Basis Document for API RP 941.

API, Recommended Practice 579-1 / ASME FFS-1, Fitness-For-Service, TBD Edition, Part 16, (Draft).

ASME *Boiler and Pressure Vessel Code (BPVC)*¹, Section V: Pressure Vessels; Division 1.

¹ ASME International, 2 Park Avenue, New York, New York 10016-5990, www.asme.org.

3 Summary of Inspection Methods

3.1 General

3.1.1 The selection of optimum inspection methods and intervals for HTHA in specific equipment or applications is the responsibility of the owner/user.

3.1.2 HTHA damage may occur in welds, weld HAZs, or in the base metal. Even within these specific areas, the degree of damage may vary widely. Consequently, if damage is suspected, then a thorough inspection of representative samples of these areas should be conducted. The inspection scope should be determined by owner's subject matter experts (SMEs).

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- 3.1.3 HTHA inspection relies on specialized techniques. These techniques, procedures, and operator proficiency should be demonstrated on a broad spectrum of HTHA-damaged samples (including both damage degree and damage areas, i.e., welds and base metal).
- 3.1.4 Tables 1a-2 provide a summary of available methods of inspection for HTHA damage and include a discussion of the advantages and limitations of each. Encoded ultrasonic testing (UT) techniques as described in Table 1a are effective for detecting HTHA damage, and two or more recommended UT techniques are often used in combination to overcome the limitations of any single technique. High sensitivity (HS) wet fluorescent magnetic testing (WFMT) can detect early stages of HTHA damage. See 3.4 for further description of HSWFMT. HTHA damage detection using HSWFMT is limited to the depth of removed material and highly dependent surface preparation. Metal sample removal and metallurgical analysis is the most effective method for characterization and improving NDE interpretation.
- 3.1.5 Of all the inspection methods for base metal examination, UT techniques and HSWFMT are the most sensitive techniques and have the best chance of detecting HTHA damage while still in the fissuring stage, prior to the onset of significant cracking. The most recent approach is a combination of time of flight diffraction (TOFD), phased array UT (PAUT), and/or full matrix capture/total focusing method (FMC/TFM). The new combined approach is considered to be more effective than the previous approach (i.e. advanced ultrasonic backscatter technique [AUBT] contained in the prior edition of API RP 941). AUBT has limited data recording capability and is highly dependent upon technician training and usage of the proper procedure. Manual scanning techniques (without data recording) should only be considered as a supplement for HTHA detection when encoded data recording is not possible.
- 3.1.6 When the internal surface is accessible, HSWFMT can be used to detect surface-breaking fissures while WFMT is limited to the detection of surface-breaking cracks. HSWFMT has significant surface preparation requirements that are reviewed in the “new approaches” section of this RP. Close visual inspection can detect small, coin-sized surface blisters, which can be an indication of the presence of internal HTHA. Visual inspection for HTHA damage requires a very close examination using light sources capable of being directed at oblique angles on to the surface being examined, permitting observation of shadows created by blistering. The absence of surface blisters does not provide assurance that internal HTHA is not occurring, since HTHA frequently occurs without the formation of surface blisters.
- 3.1.7 Field metallography and replication (FMR), also called in-situ metallography, can be effective in detecting the early stages of HTHA (decarburization and fissuring) at the surface of the steel as well as differentiating between HTHA and other forms of cracking and naturally occurring inclusions in the steel. Skill and experience are required for the surface polishing, etching, replication, and microstructural interpretation. A triple etch/polish procedure is recommended (similar to creep evaluations) to reveal the fine details of HTHA damage so that accurate identification of HTHA can be made. After the final polish step, the surface should be lightly etched so that individual fissures and voids are not obscured by the grain boundaries. Because in situ metallography only examines one surface at a time, in order to evaluate a cross section of damage, either multiple replicas need to be taken at different depths of grinding or the depth can be varied by tapering the grinding so that the replica can extend from shallow to deeper locations of the prepared location. Metallurgical sampling (e.g., “scoop” or “boat” sampling) has the advantage of capturing a cross section and some length of material that can be examined in a metallurgical lab. Metallographic examination should be used to better interpret NDE results and damage classification. One note of caution is that HTHA may be subsurface, so using a surface inspection technique, such as replication or WFMT, may not detect damage. Since HTHA fissuring begins subsurface, it is recommended to remove 0.020 in. to 0.120 in. (0.5 mm to 3 mm) of material during the preparation for FMR examination. If desired, more material can be removed to reveal damage further subsurface or to confirm the depth of damage that was indicated by NDE techniques.

3.2 Historic Inspection Approach

“Conventional” backscattered UT has been a primary technique in the past [1]. Backscattered UT includes several “sub-techniques” and are listed in this section, and these techniques for detection and characterization of HTHA are considered less effective than the new techniques listed in section 3.3.

3.2.1 Amplitude-based

- High-frequency ultrasonic waves backscattered from within the metal are measured. HTHA can increase backscatter signal amplitude.
- Has been shown to detect HTHA fissures in base metal, away from weldments.
- Original manufacturing flaws/material inclusions can cause falsepositives.

3.2.2 Pattern Recognition

- High-frequency ultrasonic waves backscattered from within the metal are analyzed. HTHA causes a rise and fall in backscatter pattern.
- Has been shown to detect HTHA fissures in base metal, away from weldments.

3.2.3 Spatial Averaging

- Backscatter data are collected over an area scanned. The signal is averaged to negate grain noise.
- Has been shown to detect HTHA fissures in base metal, away from weldments.

3.2.4 Directional Dependence

- Compares backscatter signal as taken from inside diameter (ID) and outside diameter (OD) directions. HTHA- damaged materials will show a shift in indicated damage towards the exposed surface (ID).
- Has been shown to detect HTHA fissures in base metal, away from weldments.
- Orientation of damage affected by stress planes and grain structure.
- Evidence of more than one directional plane has been observed opposing this principle.

3.2.5 Frequency Dependence

- Compares backscatter of two different frequency transducers. HTHA-damaged material will show a shift and spread of backscatter in time.
- Has been shown to detect HTHA fissures in base metal, away from weldments.

3.2.6 Velocity Ratio

- Velocity ratio is a technique for indication characterization by measuring the ratio of shear wave velocity versus longitudinal wave velocity of straight beam on base metal. Based on empirical data, velocity ratio increases when there is HTHA damage in the base metal. The threshold value commonly used in the past is 0.555.

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- Velocity ratio is more effective when the depth percentage of damage is relatively large, usually when it is more than 20 %. The measurement locations of shear wave and L-wave need to match very well to reduce measurement error. There are also some recent cases demonstrated that the characterization result did not match metallurgical analysis.

3.3 New Inspection Approach

While backscattered UT approach may be appropriate for complementary HTHA inspection, TOFD, PAUT (beam forming) and FMC/TFM (i.e., non-beam forming synthetic aperture PAUT techniques) are now the recommended techniques for HTHA inspection—see Table 1a, Ultrasonic Techniques. More details about these techniques and essential variables can be found in 2019 Edition of ASME BPV Code Section V, Articles 1 and 4 and related Appendixes and other publications focused on in-service inspections [2–11]. The use of the highest practical frequency (e.g., 7.5 MHz to 10.0 MHz) is recommended to achieve maximum detection sensitivity for the detection of microdamage. Selection of frequency of equivalent wavelength for the purpose of discriminating HTHA from metallurgical imperfections is recommended. For example, use of 10 MHz 0-degree longitudinal wave to be compared with 5 MHz transverse wave angle beam in order to determine orientation of imperfection. The use of “typical” shear wave frequency in the 3.5 MHz to 5.0 MHz range may also be included to enhance characterization of coalesced or macrocracking associated with adjacent microdamage.

3.3.1 Time of Flight Diffraction (TOFD)

- TOFD involves a pair of angled longitudinal wave probes with discrete transmitter and receiver facing towards each other on the same surface of the material being inspected.
- The transmitter emits a broad beam of energy that insonifies the area of interest. Responses from the direct path between the probes (lateral wave), reflected and diffracted energy from features within the material, and reflected energy from the far surface are detected by the receiver.
- The probe pair is scanned with a fixed separation while ultrasonic waveforms are digitized at predetermined intervals. These are used to create real-time B or D-scans typically with grayscale imaging.

3.3.2 Phased Array Ultrasonic Testing (PAUT)

- In the 2019 Edition of ASME *BPVC* Section V, *Nonmandatory Appendix E*, E-474, “the UT-phased array technique is a process wherein UT data are generated by controlled incremental variation of the ultrasonic beam angle in the azimuthal or lateral direction while scanning the object under examination.”
- This process offers an advantage over processes using conventional search units with fixed beam angles, as it acquires considerably more information by covering a large range of angles (sweep).

3.3.3 Full Matrix Capture/Total Focusing Method (FMC/TFM)

- In the 2019 Edition of ASME *BPVC* Section V: Article 1, *Mandatory Appendix I, Glossary of Terms for Nondestructive Examination*, FMC/TFM is an industry term for an examination technique involving the combination of classic FMC data acquisition and TFM data reconstruction.
- Classic FMC: A subset of elementary FMC where the set of transmitting elements is identical to the set of receiving elements.
- Total focusing method (TFM): A method of image reconstruction where the value of each constituent datum of the image results from focused ultrasound. TFM may also be understood as a broad term encompassing a family of processing techniques for image reconstruction from FMC. It is possible that equipment of different manufacture may legitimately generate very different TFM images using the same collected data.

3.3.4 High Sensitivity Wet Fluorescent Magnetic Testing (HSWFMT)

The following is a description of the work process associated with HSWFMT. The following steps are recommended to provide and enhance the inspection sensitivity, which have been developed and optimized for HTHA damage detection, especially of non-PWHT carbon steels where cracking is most likely related to welds. Additional discussion regarding HSWFMT is provided in Table 2.

- Surface Preparation:
 - Abrasive blasting (gar net is the preferred media) followed by smooth blending of weld cap, heat affected zone, and base material.
 - Metal removal performed using fiber discs with a final grind of 80 to 100 grit. Surface roughness should not impair particle mobility.
 - Remove 0.030 in to 0.090 in. of the wall thickness within the area to be inspected. Be mindful of the corrosion allowance.
 - Macro-etch the ground surface to be inspected. Success has been reported using three rounds of 5 % Nital in 3 minute intervals. The advantage of etching is to remove smeared metal from grinding that bridges grain boundaries. Care should be taken to avoid overetching as this may result in false positive indications.
- Application
 - Use multiple directions for both magnetic flux lines and HSWFMT solution flow. Primary direction is with the yoke positioned across the weld with the arms spaced close to concentrate magnetic flux to only 4 to 6 in. of weld length.
 - Apply magnetic fluxes using an AC yoke and HSWFMT solution for extended durations (at least 15 seconds per orientation and location) in areas to be inspected.
 - Use nonaerosol-based deployments of HSWFMT solution to allow for better particle flow control. Aerosol deployments can have similar performance, but experience has shown that indications take longer to appear.
 - Follow ASTM guidelines for fluorescent particle-to-carrier solution ratio.
 - Assure ultraviolet (UV) light source intensity and wavelength is correct.
 - Check AC yoke magnetic field strength frequently. Long durations of use can cause overheating and lack of magnetic flux line strength. Having two yokes will allow one to cool down while the other is in use and will ensure magnetic field strength.
 - Background light limits should be checked and managed in area of inspection.
 - Acute vision is essential for this inspection.

4 HTHA Manifestation, NDE Characterization/Categorization and Reporting

In API 579-1, draft section on assessment of HTHA damage, HTHA damage is categorized as (1) volumetric, (2) blister, (3) crack-like flaw, and (4) combination of volumetric, blister, and crack-like flaw damage. An example for damage reporting is shown in Table 3.

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- a) HTHA Volumetric Damage—Typically occurs in base metal and is widespread on the component. An exception is for local hot spots on high temperature components where accelerated HTHA damage may occur locally because of the high temperature. This damage is characterized by submicron intergranular voids and fissuring (see Figure 1). Proposed NDE characterization/categorization/reporting acronym—(V).

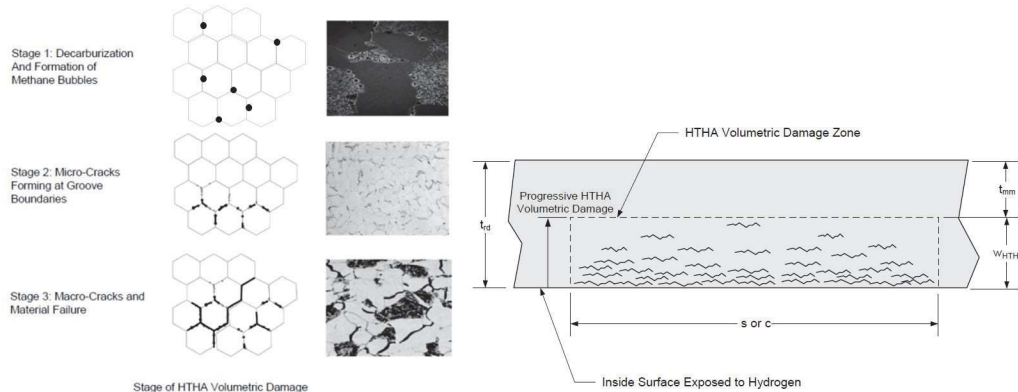


Figure 1—HTHA Volumetric Damage Manifestation

- b) HTHA Blisters—An advanced form of volumetric damage, where the methane pressure results in macro-scale fissuring in the form of blisters on the inside surface of a component (see Figure 2). Proposed NDE characterization/categorization/reporting acronym—(B).

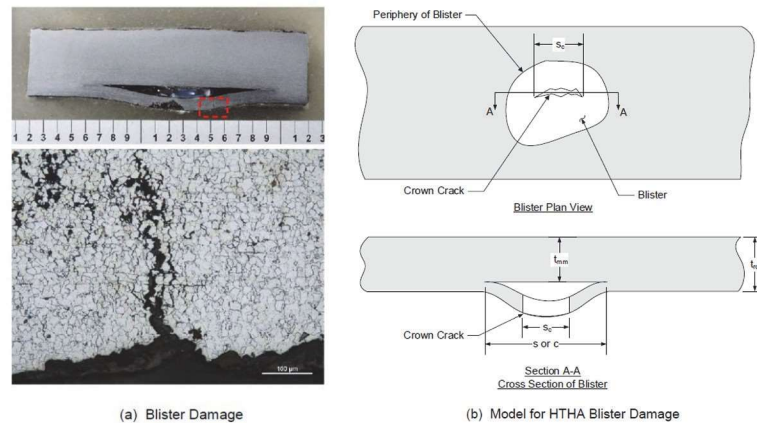


Figure 2—HTHA Blister Damage Manifestation

- c) HTHA Crack-like Flaw Damage—Typically associated with the HAZ of welds. This crack-like flaw is planar for this damage mechanism. It is characterized by cracking in the heat affected zones or fusion boundary of welds (see Figure 3). Proposed UT characterization/categorization/reporting acronym—(C). Although this macro image highlights the crack-like flaw, less advanced HTHA damage (Stage 1 or Stage 2 damage) may be present elsewhere in the sample, as it is likely that HTHA damage extends beyond crack-like flaws.

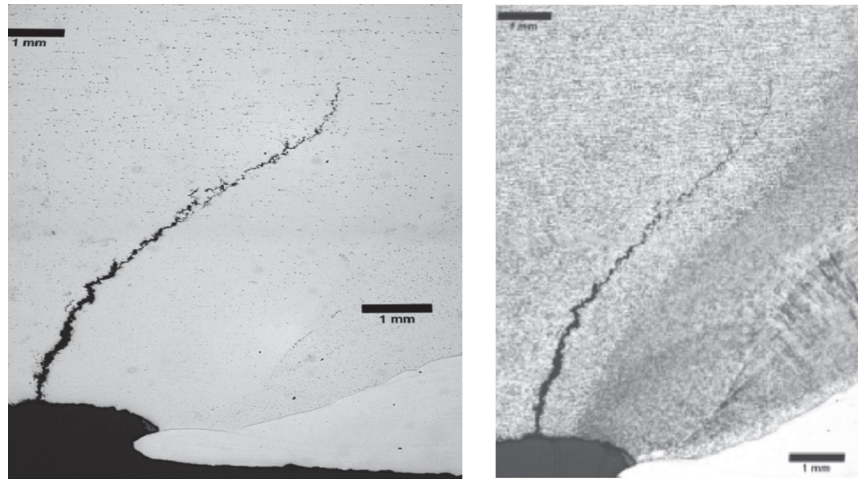


Figure 3—HTHA Crack-like Flaw Damage Manifestation

- d) HTHA Combination of Volumetric, Blister, and Crack-like Flaw Damage—Volumetric damage can occur to the base metal while crack-like flaws are occurring within the HAZ of welds (See Figure 4). Volumetric damage that occurs ahead of the crack tip can weaken the nearby material, leading to even faster crack growth rates. Proposed UT characterization/categorization/reporting acronym—(CVBC). Note that it is also possible to have volumetric and crack-like flaws without necessarily having blisters. In advance of the cracking, it is possible to have Stage 2 damage, which is usually detectable by NDE, and Stage 1 damage, which is usually not detectable by NDE.

NOTE Metallurgical imperfections such as inclusions (I) and laminations (L) will probably be detected and may act as HTHA damage nucleation points. Welding imperfections such as lack of fusion (LOF) and lack of penetration (LOP) will probably be detected also. Additional NDE characterization is required to avoid miscategorization and false positive indications.



Figure 4—HTHA Combination of Volumetric, Blister, and Crack-like Flaw Damage Manifestation.

Table 1a – Ultrasonic Techniques (Recommended)

	TOFD	PAUT	FMC/TFM
Description	Diffraction and time-based. Longitudinal-longitudinal diffraction mode setup of pair transducers. B- and D-grayscale 2D image of the digitized A-scan. Higher frequencies increase capability for detection of HTHA at weldments.	Reflective and diffraction-based. Longitudinal and shear waves. Linear, 2-D matrix and annular arrays. A-, B-, C-, D-, S- scan 2D imaging. Pulse-echo scheme (using higher frequency sound) increases capability for detection of HTHA in base material and weldments/HAZ.	Reflective, diffraction and scatter-based. Longitudinal and waves. Linear and 2-D matrix arrays. A-, B-, C-, D- scan 2/3D imaging. FMC data acquisition scheme that involves the collection of all possible combinations of sources and receivers in an array, and TFM imaging scheme that involves computation of a focused image on every point of an imaged region (using high-frequency sound) to increase the capability for better detection and sizing of HTHA in base material and weldments/HAZ.
Detection Capability Effectiveness ^a	Usually Effective: Can detect HTHA in base metal, weld HAZ, and at weldments.	Usually Effective: Can detect HTHA in base metal, weld HAZ, and at weldments.	Usually effective: Can detect HTHA: in base metal, weld HAZ, and at weldments.
Sizing Effectiveness	Usually effective for length and depth (location) and height sizing. Not effective for precise location and sizing (width) perpendicular to the scanning direction.	Usually effective for length and depth (location), height and width sizing when appropriate inspection setup is used.	Usually effective for length and depth (location), height and width sizing. When appropriate inspection setup is used, better effectiveness can be achieved than PAUT.
Characterization Capability	<ul style="list-style-type: none"> With a combination of these techniques, proper characterization between HTHA damage and large fabrication flaws (e.g. lamination in base metal, LOP, LOF, slag, isolated porosity, and inclusion) can be effective through indication location and pattern recognition Difficult to distinguish early-stage HTHA from inclusions/impurities. Difficult to distinguish HTHA-induced cracking versus cracks induced with potentially other damage mechanisms from one inspection data set. Encoded data storage makes it possible to perform more reliable monitoring of indication from multiple inspections than conventional methods. The fundamental principles of historical characterization techniques (backscatter signal pattern recognition, frequency spectrum analysis, and velocity ratio) are still applicable to further assist in indication characterization. These techniques can be applied on data collected from new techniques (TOFD, PAUT, and TFM) to improve capability and confidence for characterization between HTHA and other damage mechanisms. 		
Comments	<ul style="list-style-type: none"> Higher inspection speed for a parallel scan and lower inspection speed for combined parallel and nonparallel scans. Consideration is to be given to the blind zone created by the leading edge of the ID response masking low amplitude responses from adjacent flaws and/or flaws located in the shadow zone caused by the ID geometry. Similarly, inspections from the ID will create a near-surface blind zone due to the lateral wave. Supplemental techniques such as PAUT or FMC/TFM should be considered where damage within the blind zones is a concern. 	<p>Greatest effectiveness achieved in near field of the transducer used.</p> <p>(Typ. minimum of 32 elements for thickness ≤ 1 in. and 64 for > 1 in.).</p> <p>Lower inspection speed.</p>	<p>Greatest effectiveness achieved in near field of the transducer used and using high-density reconstruction grid. (typ. minimum of 64 elements for a typical 10 MHz transducer).</p> <p>Lower inspection speed.</p>
NOTE 1 Techniques must be developed/assessed/applied according to case-specific applications (e.g. thickness, geometry, material of construction, access, etc.)			
NOTE 2 Optimized and validated procedures to include well-tuned application specific setups for TOFD, PAUT, and FMC/TFM.			
NOTE 3 Operators should have HTHA-specific training and qualifications.			
NOTE 4 Validation or progressive qualification may be conducted using scoop or boat sampling or destructive testing.			
NOTE 5 Readers should reference API RP586 (once available) for additional detailed guidance.			
NOTE 6 Early-stage HTHA damage may not be ID surface connected.			
^a Full inspection effectiveness (versus detection capability) will be covered in future effort (e.g. 586) to address 581 inspection effectiveness guidance.			

Table 1b—Historic Ultrasonic Techniques for Detection and Sizing

	Single Element A Scan Straight Beam Manual Scanning	Single Element A Scan Angle Beam Manual Scanning
Description	Use single element straight beam probe in initial scanning targeted to detect indications equivalent to the size of HTHA fissures.	Use high-frequency single element angle beam probe (flat or contour focused) in initial scanning targeted to detect indications equivalent to the size of HTHA fissures and microcracking in the heat affected zone.
Effectiveness	<ul style="list-style-type: none"> — Performance of manual scanning without data recording is very dependent on technician capability and condition during inspection. Therefore, the effectiveness of manual scan for detection is considered less effective than new techniques with data recording capability. — These techniques can be used as supplemental techniques in situations where initial scanning techniques with encoded data recording is not practical. 	

Table 1c—Historic Ultrasonic Techniques for Characterization

	Velocity Ratio	Attenuation	Longitudinal Spectral Analysis	Angle-beam Spectrum Analysis	Conventional Single Element A-scan Backscatter Pattern Recognition
Description	Ratio of shear and longitudinal wave velocity is measured. HTHA changes the ratio.	Dispersion of ultrasonic longitudinal wave is measured by recording drop in amplitude of multiple echoes. HTHA increases attenuation.	The first backwall signal is analyzed in terms of amplitude versus frequency. HTHA will attenuate high-frequency response more than low frequencies.	<p>The spectrum of any suspect signal from pulse-echo inspection of weld/HAZ is compared with a reference spectrum taken in the pitch-catch mode from the base metal.</p> <p>HTHA causes the pulse-echo spectrum to increase amplitude with increase of frequency.</p>	<ul style="list-style-type: none"> — Amplitude-based — Pattern Recognition — Spatial Averaging — Directional Dependence — Frequency Dependence
Capability	<ul style="list-style-type: none"> — A combination of these techniques is historically used to assist in characterizing an indication of HTHA from other flaws. — Reliability and repeatability of angle beam spectrum analysis are very dependent on subjective judgement of personnel during inspection. — Very limited data is collected for monitoring purposes, and the data collection process is time consuming. 				

Table 2—Non-ultrasonic NDT Methods for HTHA ^a

	Wet Fluorescent Magnetic Particle Testing (WFMT)	High Sensitivity Wet Fluorescent Magnetic Particle Testing (HSWFMT)	Radiographic Testing (RT)	Visual Testing (VT)	Acoustic Emission Testing (AET)
Description	Ferrous particles with fluorescent coatings suspended in liquid gather at interruptions in magnetic flux lines at the surface creating an indication. Magnetic flux should be generated by alternating current (ac). Surfaces are prepared via wire wheel or sand blasting.	See description of WFMT. Additionally, detailed surface preparations (grinding, material removal, and macro-etching) are used along with detailed application work processes. Specific work processes are discussed in more detail above.	Radiation energy is used to create an image on film or an electronic detector. Radiography is commonly used for weld quality evaluation and wall thickness measurement.	Internal VT of pressure vessels for surface blistering. White light applied parallel to the internal surface can aid in revealing blisters protruding beyond the surface plane.	Low-frequency sound waves are generated either when crack-like flaws propagate (microscopically), or during crack-tip blunting. AET for HTHA is usually executed during monitoring of thermal gradients associated with temperatures of interest so actual process-induced stresses are used. Detects and locates sound wave origins.
Detection Capability	Can detect HTHA only after cracks have formed. Cannot detect fissures or voids.	Capable of detecting randomly oriented incipient, early-stage, and late-stage HTHA damage at the inspection surface.	Can detect late-stage HTHA damage in the form of cracks. Cannot detect early-stage HTHA damage.	Surface blisters are readily apparent. HTHA damage has been detected below blistered or damaged cladding.	Capable of detecting discontinuities with high-stress concentration factors and has a higher probability of detection for late-stage HTHA damage.
Damage Sizing	Provides high confidence in indication length dimensions along with location and orientation. Cannot nondestructively determine depth.	Provides high confidence in indication width and length dimensions along with location and orientation. Cannot nondestructively determine depth.	Provides indication width and length dimensions along with location and orientation. Cannot size depth.	Can only size the perimeter of the deformed blister immediately adjacent to the surface.	AET cannot size the detected indications.
Advantages	Crack indications can be seen visually, and little interpretation is required. Large surface areas and complex geometries (including nozzles) can be inspected.	Can detect HTHA early-stage at the prepared surface. Large surface areas and complex geometries (including nozzles) can be inspected.	RT provides a visual image and can be used as a permanent record.	No special inspection tools are needed. Blister interpretation is clear.	AET is capable of inspecting several vessels and piping sections simultaneously. No practical limitation on material temperature. Often used prior to T/A to guide shutdown inspection efforts.
Limitations	Cannot detect HTHA fissures or voids. Detects only the advanced stages after surface cracks have formed. Cannot determine the depth of HTHA damage.	Only detects surface-breaking HTHA damage. Requires highly skilled technician and significant interpretation. Cannot determine the depth of HTHA damage. Only effective on the prepared surfaces.	May miss cracks, depending upon the orientation of the crack plane. RT of equipment with external coverings will reduce inspection detection sensitivity.	HTHA frequently occurs without the formation of surface blisters. Blisters, when present, are likely to be an indication of advanced HTHA. Cracking is not always visible.	Needs adequate applied stresses to create release of sound waves from the stress risers, e.g., HTHA cracks, being sought. Consequently, it is imperative that all stresses are well understood, especially during the monitoring of thermal changes, such as a planned cooldown, in order to generate a valid AET inspection.
Recommendations	Recommended for internal inspection of pressure vessels to detect surface-breaking cracks.	Recommended for internal inspection of pressure vessels to detect surface-breaking cracks and HTHA damage.	Not recommended as a primary HTHA inspection method.	Not recommended for general HTHA detection but may detect base metal or cladding blisters.	Recommended as a layer of protection for high risk equipment or as a global screening method. In both cases, additional more focused follow-up inspections using alternative methods are recommended.

^a The effectiveness of all these inspection methods are dependent on highly skilled and trained NDT personnel.

Table 3—Example for FMC/PAUT/TOFD Reporting Table

[illegible]

5 General Inspection Plan

The following are considerations when planning an HTHA inspection:

- Operational-based screening of equipment to estimate damage state, extent, and location with owner's mechanical integrity and operation personnel.
- PMI: Consider PMI (and alloy composition analysis) of weld filler metal on all welds and base metal to confirm uniform HTHA susceptibility.
- UT techniques should be applied from outside to the maximum extent possible. If performed from internal surface, NDE sensitivity will be reduced for near ID surface damage.
- Surface preparation is a critical parameter influencing effectiveness of all ultrasonic techniques, especially for frequencies above 5 MHz.
 - In some situations, there is incentive for the removal of weld reinforcement (cap) to enable specialized UT techniques across the weld cap.
- Inspection screening based on TOFD (to extent possible due to productivity and tolerance of flaw tilt) and complimentary FMC or PAUT techniques to confirm.
- If the inspection is based on FMC or PAUT techniques, consider complementary TOFD (to extent possible) to confirm and assist with interpretation of indications.
- Limitations: The use of highly sensitive UT techniques (e.g., high-frequency TOFD, PAUT, and FMC) are susceptible to false positive calls and challenging signal interpretation depending on circumstances. Some factors that led to these challenges include:
 - dirty steels with significant inclusions;
 - poor surface condition (scanning or non-scanning sides);
 - welds with significant fabrication flaws;
 - single-sided weld access (e.g., nozzles); and
 - NDE analysis by examiners with limited HTHA experience.
- Due to limitations of individual inspection technique, higher effectiveness is achieved using combinations of nonintrusive and intrusive technologies. Nonintrusive examples are TOFD, PAUT, and FMC. Intrusive technology examples are internal visual, HSWFMT, and metal extraction using scoop or boat sampling. The aforementioned NDT techniques are used to identify location(s) for metal extraction. Metal samples are then analyzed using metallurgical techniques for final verification.
- Effectiveness is based upon Stage 2 volumetric damage (see section on HTHA characterization within this NDE Annex) and higher for ultrasonic techniques.
- Data encoding is recommended to the extent possible since it assures full coverage, enables secondary data review and correlation among multiple techniques).
- Single element UT transducer may be useful for limited access locations when current techniques (e.g., TOFD/ PAUT/FMC are not possible).
- Recommend consulting NDE subject matter expert (SME) for review and approval for all proposed HTHA inspection techniques procedures and

reports.

- Operator Qualification and Training: HTHA NDT examiner should have damage mechanism-specific training using a broad spectrum of samples (damage extent and type), and sample geometries (e.g., girth welds and nozzle welds). Recommend that HTHA-specific UT method training should be a minimum of 40 hours for currently qualified and certified UT examiners. HSWFMT examiners should have similar training requirements and a minimum of 24 hours of HTHA specific training.

6 Cladding/WOL

The following are considerations for inspection of clad or weld overlaid equipment subject to HTHA:

- Integrity and inspection of cladding/WOL should be considered to determine HTHA susceptibility due to cladding damage.
- Cracks in cladding/WOL will decrease its effectiveness as a hydrogen barrier. A method to determine the effective hydrogen partial pressure in clad or overlaid steel is discussed in RP 941, Annex D.
- Inspection of cladding/WOL itself should also be considered typically using VT, PT, and UT for cladding/WOL interface integrity.

7 Intrusive Inspection-narrative on When/How to Use Complementary Tools

The following are considerations when planning an intrusive inspection to look for HTHA damage:

- Planning: Review the history of the equipment item to be inspected. Search for history of indications noted, removed, repaired etc. Also, modifications made such as nozzle installation or removal, corrosion repair, crack repairs etc. Include all such items on the list for visual, PMI, and HSWFMT.
- Visual Inspection:
 - It is recommended to abrasive-blast the inside surface of the equipment being inspected.
 - White light positioned oblique to the inside surface is needed to search for blisters.
- HSWFMT may be applied to locations such as:
 - representative sample of circumferential, axial, nozzle, and attachment welds;
 - weld repaired areas;
 - those with complex geometry;
 - in areas of incorrect materials of construction;
 - high-stress areas; and
 - poor workmanship areas that indicate locations of high stress common to weld repairs and modifications.
- Metal Extraction: Prioritization of areas selected for metal extraction should include the following:

- locations where UT examinations revealed indications;
 - where HWFMTs revealed indications;
 - where visual inspection detected blistering; and
 - where PMI detected incorrect materials of construction.
- Metal extraction locations should not be selected at random. Locations should be selected and prioritized based on evidence of anomalies.
- Localized thin area (LTA) calculations should be conducted prior to the start of an internal inspection. Hemispherical scoop-type extractions are most favorable. Hemispherical-shaped material removal does not require weld repair if diameter and depth do not exceed LTA calculations per ASME FFS-1/API 579-1.
- Boat samples are most common for metal extractions. Weld repair is needed in most cases. Weld repair on material with HTHA damage can be difficult. Boat sample extraction configuration can be changed to hemispherical shape by grinding techniques.

8 Use of SEM for Metallurgical Validation of HTHA

In some cases, even when using advanced inspection techniques, it may not be possible to interpret the results without additional metallographic examination. The use of a scanning electron microscope (SEM) at magnifications greater than 1000x is recommended for the metallurgical validation process. HTHA damage (fine methane bubbles or tight cracks) near or below optical light microscopy (OLM) resolution limits has been documented in ex-service components and laboratory generated samples ^[18–20]. The resolution limit of OLM makes distinguishing critical differences between voids versus polishing and etching pits challenging. Both appear as dots at 1000x with OLM or very tight fissures versus heavily etched grain boundaries (both appear as dark grain boundaries at 1000x with OLM). As the NDT technologies continue to advance, it has become apparent that even early-stage HTHA damage may be detected. Use of SEM allows for more clear and definitive analysis that will help prevent false positive and false negative metallurgical validations. Metallurgical validation methods for HTHA are provided in Table 4.

API 941 TR-A provides several examples of non-PWHT'd carbon steel equipment items in which crack-like HTHA damage has been metallurgically validated without observable decarburization ^[11-12]. Additionally, there are calculations to support this finding, which indicate the required amount of decarburization associated with crack-like HTHA formation that may be below the resolution capabilities of OLM. Thus, HTHA cracks viewed by OLM may look similar to cracks resulting from other damage mechanisms: e.g., reheat cracking, weld metal cracking, hydrogen-induced cracking (HIC), stress corrosion cracking, and creep cracking. Guidance on HTHA manifestation and appearance is also provided in Section 4 of this RP as well as the API 941 TR-A. Careful examination of the equipment operating conditions and use of SEM is critical for proper diagnosis.

Table 4—Metallurgical Validation Methods for HTHA

	Field Metallography and Replication (FMR)	Scoop Sampling and Metallurgical Examination	Boat Sampling and Metallurgical Examination	Full Thickness Sample Removal and Metallurgical Examination
Description	Field metallography uses a microscope to directly observe the prepared surface's microstructure, and replication produces a negative film of the surface that is examined in a laboratory. In both cases, three rounds of polishing and etching are recommended for detection of HTHA damage.	Removal of metal using a spherical-shaped cutter to produce a lens of metal. Metallurgical specimens are then extracted and examined in a laboratory setting using optical microscopy, scanning electron microscopy (SEM), and limited mechanical testing.	Requires a common angle grinder. Recommend using thin wafer cut off blades to remove samples. Metallurgical specimens are then extracted and examined in a laboratory setting using OLM, SEM, and limited mechanical testing.	Hot or cold cutting of a geometric shape and remove the full wall thickness of material. Metallurgical specimens are then extracted and examined in a laboratory setting using optical microscopy, SEM, and mechanical testing.
Detection Capability	On the prepared surface, it can detect cracks, fissures, changes in microstructure, i.e., decarburization, and possibly voids. FMR is the most limited of the validation methods.	High magnification optical or electron microscopy can be used for confirmation of early-stage damage.	High magnification optical or electron microscopy can be used for confirmation of early-stage damage.	Specimens extracted from the removed material can be evaluated using high magnification optical microscopy or electron microscopy to confirm early-stage HTHA damage.
Damage Sizing	Very accurate width and length. Depth may be determined through controlled grinding and follow-up FMR. The typical area of inspection is small (less than 1 in. ²), so it is commonly used for surface area damage sizing.	Can quantify the depth that a specific HTHA feature is observed, provided the damage is contained in the prepared metallurgical specimen.	Can quantify the depth that a specific HTHA feature is observed, provided the damage is contained in the prepared metallurgical specimen.	Can quantify the depth that a specific HTHA feature is observed, provided the damage is contained in the prepared metallurgical specimen.
Advantages	Can be carried out at weld metal, heat affected zone, and base metal. May confirm damage mechanism and may validate indications detected by inspection methods, e.g., UT or AET. FMR is a nondestructive method and a negative result enables the section tested to remain in service. Its biggest advantage is that results can often be found quickly while on-site.	In addition to the FMR advantages: laboratory examination results in higher sensitivity. Repair may not be necessary per results of API 579-1 FFS (Part 5) assessment.	In addition to the FMR advantages: laboratory examination results in higher sensitivity. If the boat sample divot is blend ground, repair may not be necessary per results of an API 579-1 FFS (Part 5) assessment.	Provides the most material for metallurgical examination and testing.
Limitations	Cladding must be removed. Best if 0.02 in. to 0.125 in. (0.5 mm to 3 mm) of base material is removed to reveal subsurface damage. Only surface-breaking damage on the prepared surface is detectable.	Access space is required for equipment. Specialized equipment and training is required and can be arranged to be on-site proactively or contracted once the need is identified.	Access space is required for equipment but may be less than what is required for scoop cutting equipment. Location may require repair. Welding on HTHA damage material can be challenging. Skilled technicians are required to avoid unnecessary damage to equipment.	Location must be repaired. Welding on HTHA damage material can be challenging. Consider using a nozzle or pipe cap welded so that weld metal contacts the external surface where there is rarely any HTHA damage. Typically takes the most time to analyze the metallurgical samples.
Additional Considerations	Recommended as an informative inspection only and will be supported by the other validation methods listed in this table. May be used to trigger additional inspections.	Recommended as a high confidence follow-up inspection to the limited inspection area.	Recommended as a high confidence follow-up inspection due to limited inspection area.	Recommended as a high confidence follow-up inspection due to limited inspection area.

NOTE 1 Evidence of decarburization at the ID surface may or may not be associated with HTHA damage and should not be used as a primary detection approach for HTHA. Surface decarburization can be associated with the manufacturing process and may be present on both inner and outer surfaces.

NOTE 2 Regardless of metallurgical validation technique, three rounds of light etching followed by polishing are recommended to remove plastic deformation that may obscure voids and fissures.

NOTE 3 If cleaning between polishing steps is needed, cotton balls, or lint free wipes are recommended.

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Annex A

(informative)

Ultrasonics Array Techniques

A.1 General

The purpose of this annex is to provide an additional information and experience regarding the use of Ultrasonic array techniques (PAUT and FMC/TFM) for HTHA inspection.

A.2 Basics

Both PAUT and FMC/TFM use an array transducer with multiple piezo-composite elements in a common housing. The aperture is chosen such that the inspection volume is placed in the near field of the sound beam.

TBD...

A.3 Array Probes Selection

TBD...

A.4 Setups and Calibration

TBD...

A.5 Progressive Validation

TBD...

Annex B

(informative)

TOFD Technique

B.1 General

The purpose of this annex is to provide an additional information and experience regarding the use of TOFD technique for HTHA inspection.

TBD...

Annex C

(informative)

Other Techniques (Historical UT, WFMT, HSWFMT, VT, RT, AE)

C.1 General

The purpose of this annex is to provide an additional information and experience regarding the use of Other techniques for HTHA inspection.

TBD...