

RISK BASED INSPECTION (RBI) OF HYDROGEN EMBRITTLMENT

ABSTRACT

Hydrogen is considered a promising energy carrier to achieve the ambitious targets by promoting the renewable energy sources and effective technologies in order to address non-renewable energy supply and environmental issues. However, its unique Characteristics, including its environmentally caring nature, high mass energy density, and known as a clean energy carrier, make hydrogen energy an interesting substitute for hydrocarbons in both mobile and fixed applications. Despite its advantages, the Hydrogen-induced material damages are harmful and represent a serious concern, particularly in Hydrocarbon and Petrochemical Industries process. Thus, to guarantee and preserve the complete equipments integrity of this industry kind, Control and Inspections must be carried out in accordance with Inspection Plan founded on the Risk Based Inspection (RBI) approach, by respecting planning, frequencies and Inspection's deadlines. The risk-based inspection (RBI) is the most beneficial approach for inspection plan planning according to API 580 but has never been adopted for components operating in hydrogen environments. This theoretical oncoming aims to implement and applicate an elaborated Inspection plan with (RBI) on only one Pressure vessel integrated into one " Oil & Gas industries Units " of Algerian industry Hydrocarbures.

Keywords:Hydrogen Embrittlement, Risk based inspection (RBI), API 581

INTRODUCTION

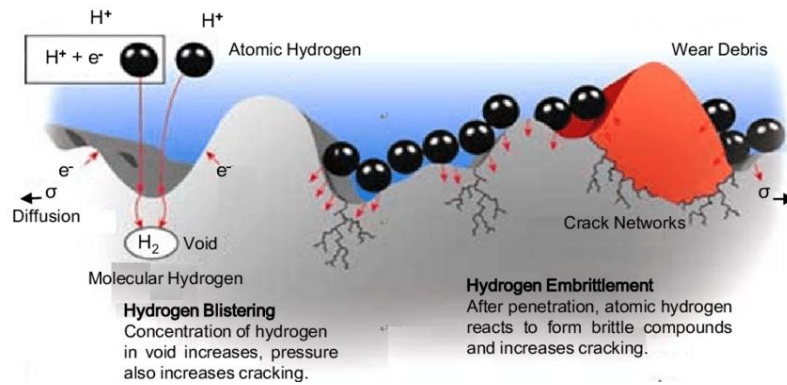
While the world's supply of hydrocarbons carries on to decrease, many governments and corporations have turned their attention to searching for replacement for oil and gas, as the renewable energy source. Although, those corporations and governments have long been familiar with renewable, green energy sources like solar, wind or hydroelectric power. However, looming silently in the background of all these energies is hydrogen gas as a

27 potential solution [1]. Thus, it was indicated that hydrogen is a promising solution to reduce
28 greenhouse gas emissions in power production, transportation and several industrial sectors
29 [2-3]. Among these industrial sectors: liquified natural gas, oil refineries and petrochemical
30 industries.

31 Notwithstanding, despite the advantage of being clean and renewable energy source,
32 hydrogen is a serious safety concern and risk of hydrocarbons facilities and equipments
33 integrity [4]. It can be absorbed by most metals and alloys by accumulating in the proximity
34 of internal defects (e.g., vacancies, grain boundaries, dislocations, precipitates, and
35 inclusions) represents a serious concern for iron, steels, nickel and titanium-based alloys, and
36 many other materials normally employed for industrial applications [4-5], causing
37 degradation of mechanical properties of metallic materials. This phenomenon was first time
38 observe and revealed in 18th century and validated one years after [6-7], Thereafter, the
39 phenomenon responsible for hydrogen-related to mechanisms and damages have been
40 widely investigated in particularly Hydrogen Embrittlement (HE), which has an impact on
41 the mechanical properties of materials and additively manufactured metals is of extreme
42 importance for industries utilizing these materials, including critical hydrogen transportation
43 and storage applications [8].

44 Hydrogen Embrittlement (HE) is the main active degrading mechanism in equipment
45 exposed to hydrogenated environments, if not appropriately accounted for, it can cause
46 failures at unexpectedly low stress levels [9-10]. It is the loss in strenght, ductility, and/or
47 fracture toughness of susceptible materials due the penetration and diffusion of atomic
48 hydrogen, it can lead to brittle cracking [11]. Thus, all equipments exposed tu hydrogenated
49 environment, hydrogen is dissociated and absorbed into materials. The absorbed atoms
50 diffuse into the metal mass towards regions of high triaxial stress and locally affect the
51 material's resistance to internal stresses or external loads [12], as shown by Figure1[10].

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Fig.1 Hydrogen Embrittlement Mechanism.

55 Metal or equipments, can be exposed to hydrogen from two types of sources : Gaseous
 56 hydrogen : which is pure hydrogen gas as a direct Source for absorption of atomic Hydrogen,
 57 others Hydrogen gas species (Hydrogen Sulfid H_2S - Hydrogen Chlorid HCl - Hydrogen
 58 Bromid HBr) [10], Or Hydrogen chemically generated at the metal surface, coming from the
 59 following : Welding process, Corrosion reactions, Service in high-temperature ($> 205\text{ }^\circ C$),
 60 Manufacturing process and Melting practices, Cleaning and Pickling in acid solutions and
 61 Cathodic Protection [10 - 11].

62 The industrial equipments exposed to hydrogen is subjected to damaging effects of which
 63 hydrogen embrittlement (HE) is still responsible for many failures, affecting their
 64 mechanical and metallurgical integrity. Thus, the occurrence of hydrogen-induced
 65 equipments (e.g., in pipeline systems, cylinders, fitting, and tanks) deterioration and failures
 66 requires rigorous controls and inspections in order to preserve the mechanical integrity and
 67 fitness for service of equipments exposed to hydrogen environment.

68 Control and Inspection strategies have evolved significantly over time, from reactive and
 69 preventive approaches to predictive and prescriptive methods, while reactive Inspection
 70 addresses issues after they occur, preventive inspection schedules routine tasks to prevent
 71 failures. Predictive Inspection utilizes data analytics to forecast failures, while prescriptive
 72 inspection recommends precise actions to prevent them. This evolution reflects a shift
 73 towards proactive inspection, optimizing asset performance and reducing downtime. One of

74 the appropriate methods, the risk-based approach which is considered the most beneficial
75 strategy for preventive inspection planning using previous data analytics to expect and
76 forecast possible failures or damages. This approach has been largely adopted in the
77 hydrocarbon, chemical and petrochemical process industries [13].

78 **RISK BASED INSPECTION (RBI)**

79 Risk-Based Inspection (RBI) is an analysis methodology used to identify and understand
80 risk, risk drivers, and where equipment is in its lifecycle in order to focus inspection efforts
81 and resources on higher-risk assets. According to API RP 580, Risk-Based Inspection (RBI)
82 is primarily focused on maintaining the mechanical integrity of pressure equipment, piping,
83 tankage, pressure-relief devices (PRDs), and heat exchanger tube bundles items and
84 minimizing the risks associated with of loss of containment due to deterioration [14].

85 A properly-implemented RBI program categorizes individual pieces of equipment by their
86 risks, prioritizes inspection efforts, and provides guidance for risk mitigation efforts, such as
87 changes in materials of construction, the addition of linings, changes in operating conditions,
88 etc. The calculation of risk outlined in API 581 involves the determination of a probability
89 of failure (POF) combined with the consequence of failure (COF). Failure is defined as a
90 loss of containment from the pressure boundary resulting in leakage to the atmosphere or
91 rupture of a pressurized component. Risk increases as damage accumulates during in-service
92 operation as the risk tolerance or risk target is approached and an inspection is recommended
93 of sufficient effectiveness to better quantify the damage state of the component. The
94 inspection action itself does not reduce the risk; however, it does reduce uncertainty and
95 therefore allows more accurate quantification of the damage present in the component [13].

96 The overall risk of a hydrocarbon plant may be managed by focusing inspection efforts on
97 the process equipment with higher risk. Risk-Based Inspection (RBI) provides a basis for
98 managing risk by making an informed decision on inspection frequency, level of detail, and

99 types of nondestructive examination (NDE). It is a consensus containing methodology that
100 users may apply to their RBI programs.

101 **RBI METHODOLOGY**

102 Once the risk is known and the magnitude of the risk is established, risk evaluation allows
103 for the determination of whether or not risk reduction is needed or desired, and risk
104 management provides methodologies to maintain risks at or below an acceptable level. The
105 inspection activities are a fundamental part of predictive inspection.

106 Thus, risk reduction is typically accomplished using mitigation, the results of inspection
107 activities and/or process control. The inspection does not reduce the risk of failure by itself
108 but allows the monitoring of the equipment degradation level and indicates when it will
109 reach a critical point, making possible intervention before the predicted failure date [9].

110 Risk-Based Inspection is an inspection planning methodology developed by the American
111 Petroleum Institute (API) which assumes that most of the total risk in a plant is associated
112 with a small number of components [13]. Therefore, risk management focuses on these high-
113 risk elements, prioritizing their inspection to ensure key benefits and reduce overall risk. The
114 risk associates and combines the probability of failure (P_f) with its consequences (C_f):

$$115 R_f(t, I_E) = P_f(t, I_E) \cdot C_f \text{Eq (1)}$$

116 The probability of failure is calculated as the product of a generic failure frequency (gff), a
117 damage factor (D_f), and a management system factor (F_{MS}):

$$118 P_f(t, I_E) = \text{gff} \cdot D_f(t, I_E) \cdot F_{MS} \cdot C_f \text{Eq (2)}$$

119 Where: $P_f(t)$: Consequences of failures & (C_f): Consequences of failures

120 The generic failure frequency is defined as the number of failures per year of a certain type
121 of equipment and relies on statistical analyses of historical data. The damage factor adjusts
122 the gff and considers the level of susceptibility of the component to a defined damage
123 mechanism, depending on the service time, the material, the operating conditions, and the

124 number and effectiveness of previous inspections. The management system factor accounts
125 for the probability that accumulating damage will be detected before the failure occurrence.
126 The consequence of failure is determined through well-established consequence analysis
127 techniques based on empirical equations and predefined hole sizes. It can be expressed in
128 financial terms or as an impact area in case of flammable or toxic releases [13] as is
129 rewritten in terms of area- and financial-based risk, as shown respectively, in Equation (3)
130 and (4).

131 $R_f(t, I_E) = P_f(t, I_E) \cdot C_f^{(flam)}$ Eq (3)

132 $R_f(t, I_E) = P_f(t, I_E) \cdot C_f^{(fin)}$ Eq (4)

133 Where: Eq (3): for area-based risk & Eq (4): for financial-based risk

134 Any error in estimating both the (P_f) and the (C_f) can be propagated to the resulting
135 determination of risk and subsequently affect the inspection planning decisions. The logical
136 progression of the RBI methodology, as presented in API RP 581, is depicted in Figure 2
137 below [13].

138 The Risk-Based Inspection Analysis Process is a methodology Flow diagram, iterating as
139 follows:

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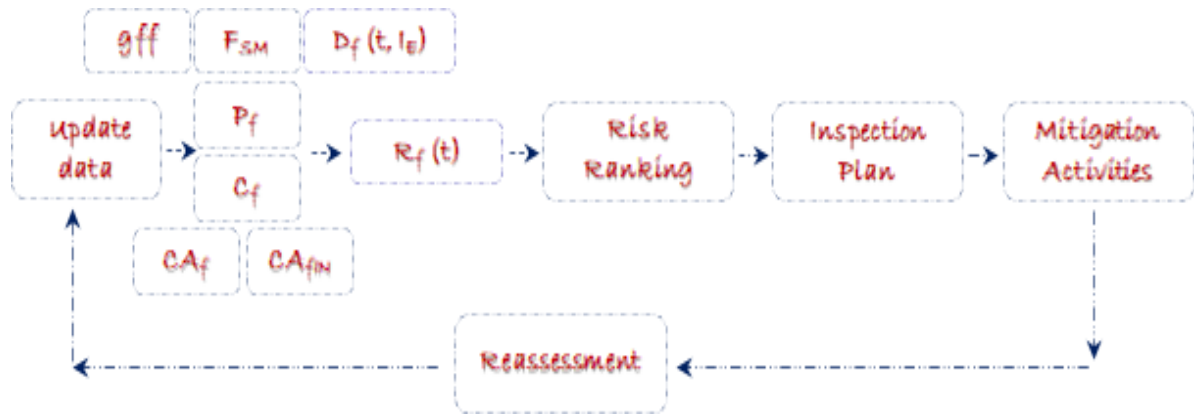


Fig.2 Risk-Based Inspection Analysis Process.

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145 - The RBI Process starts with collecting and validating technical data and historical
 146 information on the facility;

147 - All the damage mechanisms likely to occur must be identified, determining the damage
 148 susceptibility of each component, and calculating the (P_f);

149 - All the credible failure modes and the related consequence scenarios should be considered;

150 - The analysts must calculate the risk associated with each piece of equipment and rank
 151 them;

152 - The inspection plan should be developed, prioritizing the high-risk components;

153 - Finally, the entire process is reassessed accordingly to the results of previous inspections.

154 There are two main approaches to Risk-based Inspections (RBI), Qualitative and
 155 Quantitative approaches.

156 The Qualitative method is based on expert judgment and historical data, the Use of risk
 157 matrices to categorize equipment into low, medium, or high risk, this method is suitable for
 158 assets with limited operational data. However, the Quantitative method is based on the use of
 159 statistical models and engineering calculations to determine risk, Involves Probability of
 160 Failure (P_F) and Consequence of Failure (C_F) metrics and provides a more precise and data-
 161 driven risk assessment.

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165 **REFORMING PROCESS & HYDROGEN EMBRITTLEMENT DAMAGES**

166 The refinery reforming process, specifically Catalytic reforming is a chemical process used
167 in petroleum refineries to convert naphthas from crude oil into liquid products called
168 reformates, which are premium "blending stocks" for high-octane gasoline.

169 The process converts low-octane linear hydrocarbons (paraffins) into branched alkanes
170 (Isoparaffins) and cyclic naphthenes, which are then partially dehydrogenated to produce
171 high-octane aromatic hydrocarbons. During the process, the dehydrogenation also produces
172 significant amounts of byproduct hydrogen gas, which is fed into other refinery processes
173 such as hydrocracking.

174 Thus, the costs generated hydrogen gas are relatively low by process reforming, however,
175 the costs related to its impact on the environment are very high, making in particular an
176 enormous harmful impact on the equipments of process reforming installation himself. This
177 Industrial equipment exposed to hydrogen gas are subject to phenomenon responsible for
178 hydrogen-related to mechanisms and damages in particularly Hydrogen Embrittlement (HE)
179 [13] and High Temperature Hydrogen Attack. Hydrogen embrittlement is a degradation
180 mechanism that may result in the material loss of ductility, strength, and resistance to crack
181 both under static and cyclic loading and it is connected to the interaction of metallic
182 components when exposed to hydrogenated environments [13 - 14].

183 Hydrogen Embrittlement effect on mechanical properties can be roughly divided into two
184 categorie distinct: Quasi-static and Dynamic [15]. The former indicates a constant or slowly
185 varying load, which allows for a general hydrogen distribution equilibrium; it is often
186 relevant for components exposed to high gas pressure. On the other hand, the latter is
187 associated with dynamic components (e.g., compressors), vibrations in static equipment, or
188 fluctuations in gas pressure [15].

189

190 Hydrogen Embrittlement is responsible for the brittle cracking of otherwise ductile materials
191 and may affect a variety of hydrogen technologies, such as cylinders, pipes, fuel cells,
192 transport pipelines and particularly Hydrogen storage tank. In this case, hydrogen
193 embrittlement refers to quasi-static loading conditions resulting from the gas pressure within
194 the containment system or from internal stresses, especially in weldments and
195 dehydrogenation phase.

196 High Temperature Hydrogen Attack (HTHA) also called hot Hydrogen Attack or Methane
197 Reaction, is a problem which concerns steels operating at elevated temperatures (typically
198 above 400 °C) in hydrogen-rich atmospheres, such as refineries, petrochemical and other
199 chemical facilities and, possibly, high pressure steam boilers. It is one such form of
200 degradation which is due to the formation of Methane (CH₄) by reaction with carbides in
201 steel, the hydrogen / carbon reaction can cause surface decarburization of the steel. Surface
202 decarburization alone is normally not detrimental to the point of limiting the life of
203 equipment but may be indicative of internal HTHA. Extensive decarburization will reduce
204 component strength (See Figure 2.a & Fig.2.b). Thus, If diffusion of carbon to the surface is
205 limited, CH₄ is formed internally from internal decarburization. Internal CH₄ cannot diffuse
206 through the steel. As a result, internal CH₄ pressure builds up, initially forming bubbles or
207 cavities, then microfissures, and finally fissures that may combine to form cracks. Internal
208 damage leading to cracking is the more serious effect of HTHA, and it can lead to equipment
209 failure. Failure can occur when the cracks reduce the load (Pressure) carrying ability of the
210 pressure-containing part. Blistering may also occur due to either molecular hydrogen (from
211 re-combined hydrogen atoms) or CH₄ accumulating in laminations or other conducive sites
212 in the steel as previously, shown in Figure 1 steel as, previously, shown in Figure 1 [11].

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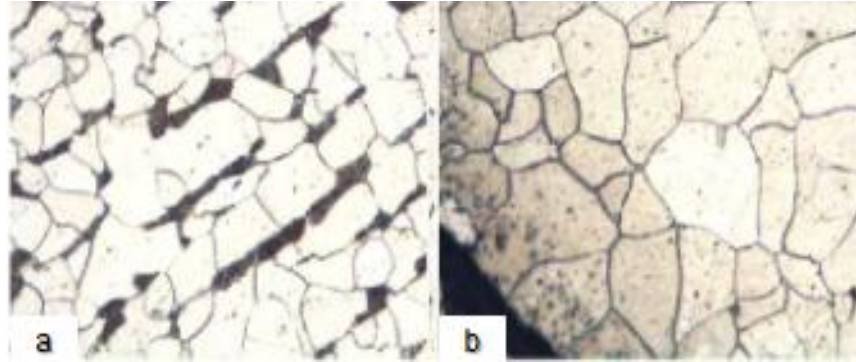


Fig. 2 (a) Typical low-carbon-steel microstructure showing ferrite phase (light grains) and pearlite (dark layered constituent) & (b) Microstructure illustrating a decarburized low carbon steel where the strength providing pearlite constituent has been decomposed as the result of the removal of carbon atoms by diffusion to the surface [11].

Hydrogen Embrittlement happens as a result of the synergistic interplay of several factors [11] :

- Environment : (hydrogen partial pressure, temperature, form atomic or molecular and source of Hydrogen either cathodic protection or manufacturing process (e.g. Reforming process) ;
- Material : chemical composition, grain size, grain boundaries, phase stability, strength, surface conditions, presence of welds and heat-affected zones (HAZ) ;
- Loading Condition : level of applied and residual stresses, type of loading (monotonic or cyclic).

INSPECTION PLANNING PLAN BASED RBI

If disregarded, Hydrogen embrittlement and High temperature Hydrogen attack issues in process industries, particularly in reforming process, can lead to heavy consequences in terms of safety and business interruption. On the other hand, performing highly frequent and extensive inspections and/or monitoring activities implies unaffordable costs and may even be ineffective. Thus, Risk-based Inspections (RBI) and Integrity Operating Windows (IOW) are two powerful tools to effectively manage asset integrity.

241 Risk-based Inspections analysis is used to identify and understand risk, risk drivers, and
242 where equipment is in its lifecycle. RBI can indicate whether or not inspection is needed and
243 can predict its mitigation effect on future risk. In this way, inspection-related activities are
244 prioritized and inspection techniques specifically prescribed, based on the active damage
245 mechanisms and historical data. Along with Risk-based Inspections, the establishment of
246 Integrity Operating Windows (IOWs) can support a rigorous mechanical integrity program
247 by managing possible changes/deviations in the process.

248 Integrity Operating Windows (IOWs) establish limits for process variables that can affect the
249 integrity of the equipment if the process operation deviates from them. Once integrity limits
250 are defined, a convenient monitoring and control activity can be put in place to prevent
251 integrity issues related to limits' exceedance.

252 Inspection planning based on risk assumes that at some point in time, the risk as defined by
253 Equation (Eq 3) & (Eq 4) will reach or exceed a user-defined area or financial risk target.so,
254 when or before the user defined risk target is reached, an inspection of the equipment is
255 recommended based on the component damage mechanisms with the highest($D_f(t, I_E)$).

256 The Operator - owner may set additional targets to initiate an inspection, such as (P_F), (D_F),
257 (C_F), or thickness. In addition, inspection may be conducted solely to gather information to
258 reduce uncertainty in the component condition or based on an engineering evaluation of the
259 fitness for continued service rather than the RBI results. Although inspection of a component
260 does not reduce the inherent risk, inspection provides improved knowledge of the current
261 state of the component and therefore reduces uncertainty. The probability that loss of
262 containment will occur is directly related to the known condition of the component based on
263 information from inspection and the ability to accurately quantify damage.

264 Reduction in uncertainty in the damage state of a component is a function of the
265 effectiveness of the inspection to identify the type and quantify the extent of damage.

266 Inspection plans are designed to detect and quantify the specific types of damage expected
 267 such as local or general thinning, cracking, and other types of damage. An inspection
 268 technique that is appropriate for general thinning will not be effective in detecting and
 269 quantifying damage due to local thinning or cracking. Therefore, the inspection effectiveness
 270 is a function of the inspection method and extent of coverage used for detecting the type of
 271 damage expected [13].

272 **DAMAGE FACTOR (DF^{HTHA})**

273 Standards codes API RP 581 is the most recommended reference for putting in action a es-
 274 timated Quantitative approach Risk-based Inspections (RBI). Hence, the methodology pro-
 275 posed in this study to calculate the High Tempertare Hydrogen Attack (HTHA) damage fac-
 276 tor is based on this recommended practice.

277 The following Data required for the determination of the damage factor for High Tempera-
 278 ture Hydrogen Attack (DF^{HTHA}) where only the calculation for carbon steel, (C-½ Mo), and
 279 (Cr-Mo) low alloy steel components subject to High Temperature Hydrogen Attack are co-
 280 vered in this section. The basic data required for analysis are provided in Table 4.1 (Conform
 281 to API 581), and the specific data required for determination of the (D_F), for HTHA are pro-
 282 vided in Table 2.

Required Data	Comments
Material Construction	The component generic construction material (e.g., carbon steel, C-½ Mo, 2 ¼ Cr-1 Mo).
Hydrogen partial pressure (MPa)	Determine the hydrogen partial pressure, which is equal to the product of the mole fraction of hydrogen and the total pressure (absolute).
Temperature, (°C)	The temperature of exposure.

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Table 2 - Data Required for Determination of Susceptibility to HTH.

285 The determination of the steps flowchart required for the (DF^{HTHA}) is shown in Table 3

Susceptibility	(DF)
Damage Observed	5000
High Susceptibility	5000
Medium Susceptibility	2000
Low Susceptibility	100
No Susceptibility	0

286 Table 3 - (DF^{HTHA}).

287

288 Currently there is no level of Inspection effectiveness for High Temperature Hydrogen At-
289 tack damage.

290 The following steps may be used to determine the (DF^{HTHA}) :

291 I - Determine the material of construction, exposure temperature (T°), and the exposure hy-
292 drogen partial pressure, P(H₂) ;

293 II - Has High Temperature Hydrogen Attack damage historically been observed in the com-
294 ponent ?

295 II.A - If yes and component has not been replaced, assign susceptibility to Damage Observed
296 and skip to (Point VI);

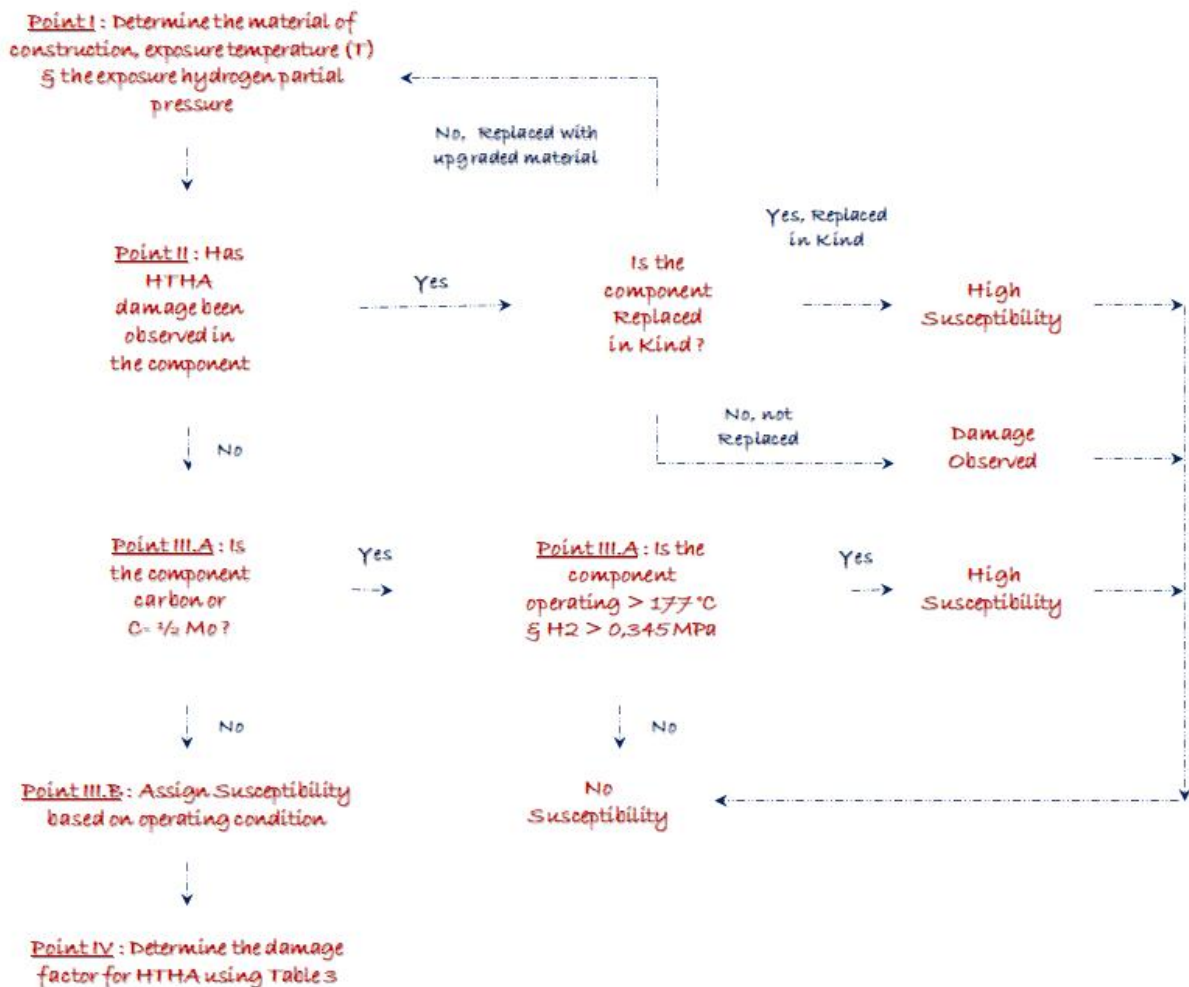
297 II.B - If yes and the component has been replaced in kind, assign susceptibility to High and
298 skip to (Point VI) ;

299 II.C - If a component has been replaced with an upgrade in the materials of construction, the
300 component shall be re-evaluated in Point I for the susceptibility based on the new material of
301 construction ;

302 III – Assign component susceptibility to High Temperature Hydrogen Attack as outlined
303 below ;

304 III.A – For Carbon and C-½ Mo Alloy Steels :

305 III.A.1 – If the exposure temperature is $>177\text{ }^{\circ}\text{C}$ and the exposure hydrogen partial pressure
 306 is $> 0.345\text{ MPa}$, assign a high susceptibility to HTHA;
 307 III.A.2 – If exposure temperature is $\leq 177\text{ }^{\circ}\text{C}$ and the exposure hydrogen partial pressure is \leq
 308 0.345 MPa , assign HTHA susceptibility to None;
 309 III.B – For All Other Cr-Mo Low Alloy Steels:
 310 III.B.1 – If the exposure temperature is $> 177\text{ }^{\circ}\text{C}$ and exposure hydrogen partial pressure is $>$
 311 0.345 MPa , calculate (ΔT) proximity to the API 941 curve using (T°) , and $P(\text{H}_2)$ from Point
 312 A. Assign HTHA susceptibility using Table 2;
 313 VI – Determine the DF for HTHA, $(\text{DF}^{\text{HTHA}})$, using Table 3 based on the susceptibility
 314 from Point II or Point III.



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Determination of, $(\text{DF}^{\text{HTHA}})$.

318 **CONCLUSION**

319 Risk-Based Inspection (RBI) is revolutionizing asset management in the oil and gas industry
320 by enabling operators to focus on high-risk equipment, thus improving safety, reducing
321 costs, and ensuring regulatory compliance. By adopting RBI principles, companies can adopt
322 a more proactive approach to maintenance, enhance operational efficiency, and better ma-
323 nage their assets.

324 As the industry continues to evolve, RBI will remain an essential component of best prac-
325 tices in asset integrity management.

326 This study proposes a qualitative methodology for calculating the High Temperature Hydro-
327 gen Attack damage factor, based on environmental severity and material susceptibility. An
328 example of inspection technique for High Temperature Hydrogen Attack detection is also
329 provided. This methodology is compliant with the existing API RBI and thus can be used for
330 planning inspection activities of hydrogen technologies. Nevertheless, this method could
331 only qualitatively indicate the severity of the H₂-induced material damage, without providing
332 numerical values for a quantitative or semi-quantitative RBI.

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