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RESEARCH ARTICLE

RISK BASED INSPECTION (RBI) OF HYDROGEN EMBRITTLMENT

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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, includin g 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 respectiong 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.

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

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

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

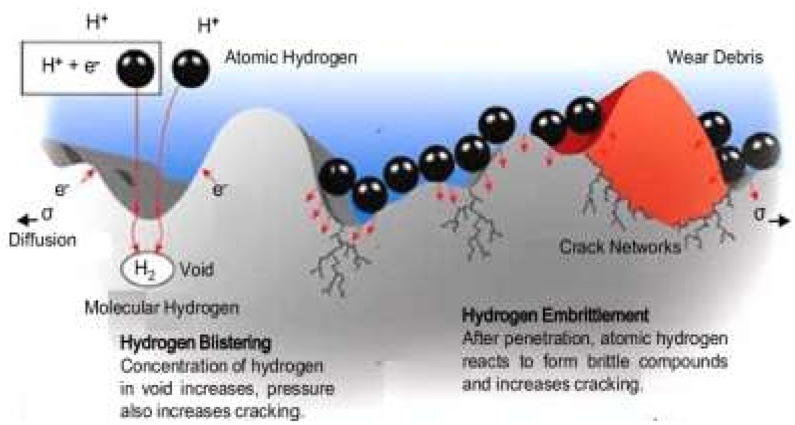


Fig.1 Hydrogen Embrittlement Mechanism.

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

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

Control and Inspection strategies have evolved significantly over time, from reactive and preventive approaches to predictive and prescriptive methods, while reactive Inspection addresses issues after they occur, preventive inspection schedules routine tasks to prevent failures. Predictive Inspection utilizes data analytics to forecast failures, while prescriptive inspection recommends precise actions to prevent them. This evolution reflects a shift towards proactive inspection, optimizing asset performance and reducing downtime. One of the appropriate methods, the risk-based approach which is considered the most beneficial strategy for preventive inspection planning using previous data analytics to expect and forecast possible failures or damages. This approach has been largely adopted in the hydrocarbon, chemical and petrochemical process industries [13].

Risk Based Inspection (Rbi):-

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

A properly-implemented RBI program categorizes individual pieces of equipment by their risks, prioritizes inspection efforts, and provides guidance for risk mitigation efforts, such as changes in materials of construction, the addition of linings, changes in operating conditions, etc. The calculation of risk outlined in API 581 involves the determination of a probability of failure (POF) combined with the consequence of failure (COF). Failure is defined as a loss of containment from the pressure boundary resulting in leakage to the atmosphere or rupture of a pressurized component. Risk increases as damage accumulates during in-service operation as the risk tolerance or risk target is approached and an inspection is recommended of sufficient effectiveness to better quantify the damage state of the component. The inspection action itself does not reduce the risk; however, it does reduce uncertainty and therefore allows more accurate quantification of the damage present in the component [13]. The overall risk of a hydrocarbon plant may be managed by focusing inspection efforts on the process equipment with higher risk. Risk-Based Inspection (RBI) provides a basis for managing risk by making an informed decision on inspection frequency, level of detail, and types of nondestructive examination (NDE). It is a consensus containing methodology that users may apply to their RBI programs.

Rbi Methodology:-

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

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

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

$R_f(t, I_E) = P_f(t, I_E).\ C_f$ Eq (1)

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

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

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

The generic failure frequency is defined as the number of failures per year of a certain type of equipment and relies on statistical analyses of historical data. The damage factor adjusts the gff and considers the level of susceptibility of the component to a defined damage mechanism, depending on the service time, the material, the operating conditions, and the number and effectiveness of previous inspections. The management system factor accounts for the probability that accumulating damage will be detected before the failure occurrence.

The consequence of failure is determined through well-established consequence analysis techniques based on empirical equations and predefined hole sizes. It can be expressed in financial terms or as an impact area in case of flammable or toxic releases [13] as is rewritten in terms of area- and financial-based risk, as shown respectively, in Equation (3) and (4).

$R_f(t, I_E)= P_f(t, I_E). C_f^{(flam)}$ Eq (3)
$R_f(t, I_E)= P_f(t, I_E). C_f^{(fin)}$ Eq (4)
Where: Eq (3): for area-based risk &Eq (4): for financial-based risk
Any error in estimating both the (P_f) and the (C_f) can be propagated to the resulting determination of risk and subsequently affect the inspection planning decisions. The logical progression of the RBI methodology, as presented in API RP 581, is depicted in Figure 2 below [13].

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

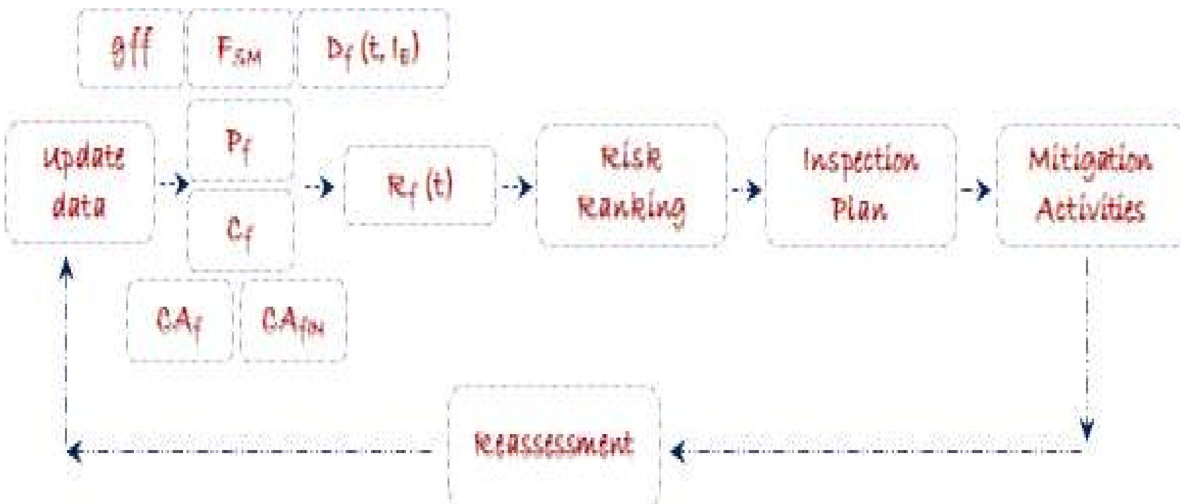


Fig.2 Risk-Based Inspection Analysis Process.

- The RBI Process starts with collecting and validating technical data and historical information on the facility;
- All the damage mechanisms likely to occur must be identified, determining the damage susceptibility of each component, and calculating the (P_f);
- All the credible failure modes and the related consequence scenarios should be considered;
- The analysts must calculate the risk associated with each piece of equipment and rank them;
- The inspection plan should be developed, prioritizing the high-risk components;
- Finally, the entire process is reassessed accordingly to the results of previous inspections.

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

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

Reforming Process & Hydrogen Embrittlement Damages:-
The refinery reforming process, specifically Catalytic reforming is a chemical process used in petroleum refineries to convert naphthas from crude oil into liquid products called reformates, which are premium "blending stocks" for high-octane gasoline.

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

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

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

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

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

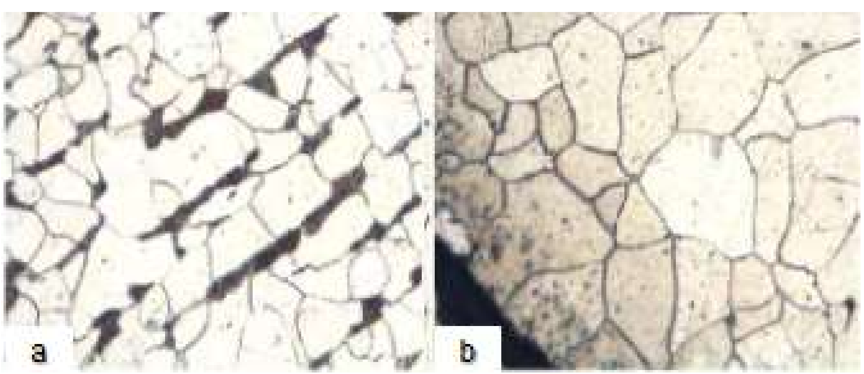


Fig. 2 (a) Typical low-carbon-steel microstructure showing ferrite phase (light grains) and pearlite (dark layered constituent) & (b) Microstructure illustrating a decarburized low carbon steel where the strength providing pearlite constituent has been decomposed as the result of the removal of carbon 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 procees (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, Hydorgen embrittlement and High temperature Hydrogen attack issues in process industries, particulary 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.

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

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

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

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

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

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

Damage Factor (Df^{Htha}):-

Standards codes API RP 581 is the most recommended reference for putting in action a estimated Quantitative approache Risk-based Inspections (RBI). Hence, the methodology proposed in this study to calculate the High Tempertare Hydrogen Attack (HTHA) damage factor is based on this recommended practice.

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

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

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.

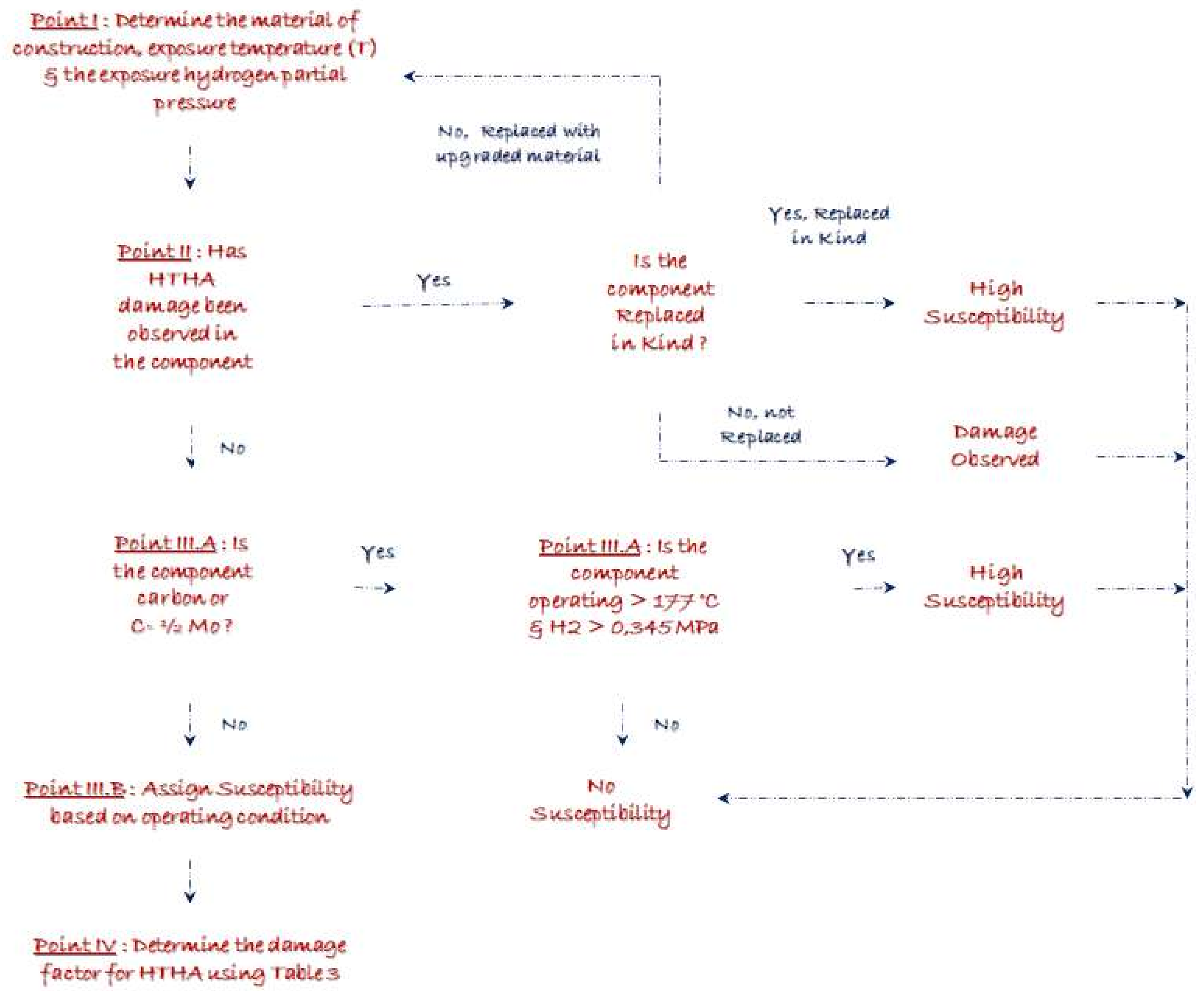
The determination of the steps flowchart required for the **(DF^{HTHA})** is shown in Table 3

Table 3 - (DF^{HTHA}).

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

Currently there is no level of Inspection effectiveness for High Tempertaure Hydrogen Attack damage.

The following steps may be used to determine the (DF^{HTHA}) :
I - Determine the material of construction, exposure temperature (T°), and the exposure hydrogen partial pressure, $P(H_2)$;
II - Has High Tempertaure Hydrogen Attack damage historically been observed in the component ?
II.A - If yes and component has not been replaced, assign susceptibility to Damage Observed and skipto (Point VI);
II.B - If yes and the component has been replaced in kind, assign susceptibility to High and skip to (Point VI) ;
II.C - If a component has been replaced with an upgrade in the materials of construction, the component shall be re-evaluated in Point I for the susceptibility based on the new material of construction ;
III – Assign component susceptibility to High Tempertaure Hydrogen Attack as outlined below ;
III.A – For Carbon and C-½ Mo Alloy Steels :
III.A.1 – If the exposure temperature is >177 °C and the exposure hydrogen partial pressure is > 0.345 MPa, assign a high susceptibility to HTHA;
III.A.2 – If exposure temperature is ≤ 177 °C and the exposure hydrogen partial pressure is ≤ 0.345 MPa, assign HTHA susceptibility to None;
III.B – For All Other Cr-Mo Low Alloy Steels:
III.B.1 – If the exposure temperature is > 177 °C and exposure hydrogen partial pressure is > 0.345 MPa, calculate (ΔT)proximity to the API 941 curve using (T°),and $P(H_2)$ from Point A. Assign HTHA susceptibility using Table 2;
VI – Determine the DF for HTHA, (DF^{HTHA}), using Table 3 based on the susceptibility fromPoint II or Point III.



Determination of, (DF ^{HTHA}).

Conclusion:-

Risk-Based Inspection (RBI) is revolutionizing asset management in the oil and gas industry by enabling operators to focus on high-risk equipment, thus improving safety, reducing costs, and ensuring regulatory compliance. By adopting RBI principles, companies can adopt a more proactive approach to maintenance, enhance operational efficiency, and better manage their assets.As the industry continues to evolve, RBI will remain an essential component of best practices in asset integrity management.

This study proposes a qualitative methodology for calculating the High Tempertaure Hydrogen Attack damage factor, based on environmental severity and material susceptibility. An example of inspection technique for High Tempertaure Hydrogen Attack detection is also provided. This methodology is compliant with the existing API RBI and thus can be used for planning inspection activities of hydrogen technologies. Nevertheless, this method could only qualitatively indicate the severity of the H_2-induced material damage, without providing numerical values for a quantitative or semi-quantitative RBI.

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