

Review

# Evaluation and prevention of hydrogen embrittlement by NDT methods: a review

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**Abstract:** This paper comprises of hydrogen embrittlement phenomena in material, factors responsible for the hydrogen embrittlement and Non destructive methods to evaluate the internal defect in machine or component when working in hydrogen atmosphere. Hydrogen embrittlement is responsible for Sub-critical crack growth in materials, fracture and mechanical properties such as ductility, toughness and consequently loss of strength. This hydrogen is induced into the material during electrochemical reactions and in a high pressure hydrogen gas environment. The paper covers the review on the capabilities of non-destructive testing methods with aspects its advantages and disadvantages of it. Sometimes one non-destructive technique is not providing sufficient information about physical integrity and therefore a different combination of methods is required. Ultrasonic testing is very useful to detect internal defects.

**Keywords:** Hydrogen embrittlement; NDT; HEDE; HELP

## 1. Introduction

some of the typical damage that hydrogen induces to metals and alloys is the formation of hydrogen bubbles, HE, breakup due to hydride forming, hydrogen attack, or breakup of inner hydrogen distribution are all forms of hydrogen embrittlement. Hydrogen embrittlement has been the most common effect of hydrogen on high-strength materials. It is defined as a process in which the introduction of hydrogen atoms while working in a hydrogen environment can significantly reduce the strength of a material, Because of their low sensitivity to hydrogen embrittlement, austenitic stainless steels have become commonly accepted for the manufacture of hydrogen - based equipment. [16][22][23].

NDT is a method for evaluating the integrity of a material against surface or internal defects or metal conditions without interfering with the conformity destruction of the material or service in any way. There are various methods for evaluating materials and components according to the conditions of their application. In other words, NDT refers to the process of evaluating or inspecting materials or components for characterization or defects and defects against certain standards without changing the original characteristics or testing the object. This may require a combination of methods and can also lead to exploratory and invasive exposure. A better understanding of the context, advantages and limitations of each NDT methodology is needed to ensure a successful assessment. Composite NDT applications can include many locations such as factories, pipe and tube plants, storage tanks, aerospace, military and defense, nuclear industry, and general defect characterization [15].

## 2. Hydrogen embrittlement

It is loss of ductility of materials or making it brittle. If embrittlement occurs due to effects of hydrogen absorption then it know as hydrogen embrittlement. High-strength steels, high-Mn steels, aluminums alloys, titanium, magnesium and magnesium alloys, and other materials are susceptible to Hydrogen embrittlement. This high-strength steel has been used in a variety of applications, like aerospace, nuclear, high-pressure hydrogen storage facilities, automotive, and transportation. This high Mn grade steel has a number of benefits, including high flexibility and strength. High Mn steels, from the other hand, have a chemical properties that causes HE emission and sensitivity problems [16][22][23][28].

### 2.1. Factors Responsible For The Sensitivity of The Material to HE-

- Material strength and residual stress in the material.
- Pressure, temperature and time of exposure.
- The degree of strain applied and the surface conditions of the material.
- Amount of hydrogen or number of hydrogen traps.
- Certain metal layers and deposits.
- The microstructure of a material.
- Solutions that react with metals (acid solutions).
- Heat treatment of a material.

### 2.2. Mechanism

#### 2.2.1. Hydrogen enhanced decohesion mechanism (HEDE)

Troiano actually proposed this structure in 1959, and it is the simplest.. It depends on lessening the strength of the material in the crack tip locale by the acceptance of hydrogen particles. The strength of the differential connection between molecules diminishes as the 1 s electron from the hydrogen enters the 3D cell from the iron particle. Decohesion happens when the tip of the break arrives at tip removal (CTOP) [16][23].

#### 2.2.2. Hydrogen enhanced local plasticity model (HELP)

This system was first introduced in 1972 and is a generally acknowledged component. In this model, the gathering of hydrogen close to the break tip diminishes the protection from separation movement so the versatility of the disengagement increments and the separation carries on as a transporter for plastic disfigurement in the metal cross section. In any case, it was likewise discovered that there was no immediate connection between the arranged or proposed HELP model. Distinctive break modes can be noticed, for example, intergranular, transgranular and semi gap, contingent upon the hydrogen focus, microstructure and stress power at the break end [16][22][23].

#### 2.2.3. Adsorption-induced dislocation emission (AIDE)

This part is essentially a hybrid of HEDE and HELP. In this component, the hydrogen particles of the solute adsorbed on a superficial level in the territory of stress fixation for the break end. The adsorbent of hydrogen only at the break tip debilitates the durable power of the holding or interatomic material by the HEDE. Staining and separation at the tip of the break happens because of outflow. Because of the synchronous development of breaks and breaks decohesion and separation outflow at the tip of the break. The enormous measure of hydrogen adsorbed on a superficial level was recognized in Ti, Fe and Ni as proof to help the AIDE system [16][22].

#### 2.2.4. Hydrogen Enhanced Macroscopic Ductility (HEMP)

The hydrogen-enhanced macroscopic plasticity model is another name for it. Hydrogen also affected the mechanical properties of steel when it is accessible in huge amounts and because of dissemination of hydrogen and mellowing of strong arrangements by hydrogen particles, enormous sums (focus) because of the mass of the material and the whole example volume. It is additionally certain that, because of yield, there was a stamped increment in pliancy because of plasticization over the whole length (volume) of the whole example. This yield is decreased by the impact of hydrogen, known as Hydrogen Enhanced Macroscopic Ductility (HEMP) [23][16].

#### 2.2.5. Hydrogen changed micro-fracture mode (HAM)

Hydrogen changes its miniature break method of the material, so the crack formed is changed from malleable to fragile. Hydrogen charge decreases the flexibility of the material and the crack mode at the last rigidity changes from cup and cone to fragile shear break mode. This change in miniature break mode because of the impact of hydrogen is called hydrogen helped micro fracture. (HAM) [16][22].

#### 2.2.6. Decohesive hydrogen fracture (DHF)

Basically it is a brittle fracture initiated by the hydrogen effect and decohesion from the hydrogen and causes the material or sample to fracture [16].

#### 2.2.7. Hydrogen assisted micro void coalescence (HDMC)

Micro-void coalescence (MVC) is essentially a flexible break system. MVC break spread happens in different stages, for example, zero nucleation, zero development, zero covalence and extension of the break and burst of the current tendon by methods for shearing. Because of the hydrogen impact, nearby disengagement and plastic disfigurement developments happen in the material [22][16].

### 2.3. Hydrogen charging characteristic

The charge of hydrogen assumes a significant part during test investigations of the hydrogen accessible in materials. By and large, the hydrogen charge of an example (material) is conveyed by an electrochemical charge (cathodic charge) or a high weight hydrogen charge. This filling procedure makes hydrogen diffuse in the material to debase the properties of the material and makes hydrogen embrittlement of the material. Now and then this hydrogen charge causes or results in a hydrogen trap in the material and the trap accumulates hydrogen molecules [16][23].

### 2.4. Techniques And Tools To Measure HE

#### 2.4.1. Linearly increasing stress test (LIST)

This is a mechanical test technique for determine the HE in a material. In that, two methods that are generally used to decide the impact of HE on materials are the consistent burden test and the second is the persistent extension test. Another strategy called CERT (Constant Expansion Rate Test) has been presented. This test is additionally called a moderate strain rate (SSRT) test. This is an unrealistic procedure [16][22].

#### 2.4.2. TDS

The most well-known technique in the investigation of HE and hydrogen induced dissatisfaction is temperature desorption spectroscopy (TDS), also known as temperature customized desorption (TCD). Diffusible hydrogen can be eligible and characterized using TDS. Traps are present in steel and are responsible for collecting hydrogen. Hydrogen consumes the thermal energy that is delivered when a significant volume of assimilated energy is delivered when steel is heated. The temperature at which hydrogen atoms are distributed in this manner is known as desorption temperature [16].

### 2.4.3. Hydrogen Permeation Test

This transit test is likewise used to quantify diffusive hydrogen in steel and is the most straightforward estimation procedure. For the right execution of this transit test on steel, it is utilized related to other testing methods. This transit test consists of two cells, one from an input space (also referred to as a charge cell) and another with an oxidation space (also referred to as an oxidation cell) (output cell) [16][22].

### 2.4.4. Microstructural Analysis

Microstructure examination assumes a significant job in evaluating the affectability of materials and alloys. Scan Analytical methods are broadly used to contemplate electron microscopy (SEM) and transmission electron microscopy (TEM). SEM is the least difficult to utilize, adaptable and most loved Technique for this. TEM is the most remarkable and favored strategy. TEM works At higher amplifications and goals to defeat SEM challenges. TEM is fit for working large number of times Nanometric amplification and goal. Crystallographic data is additionally gotten from this magnifying lens. The example should be under 100 nm [23][16].

### 2.4.5. Hydrogen Microprint Technique (HMT)

This method is utilized to discover the way of diffusible Hydrogen in metals. In the event that this way is known, it is explicit the microstructure of these pathways can be recognized and impacted hydrogen should be distinguished. This HMT procedure is basic and it is accessible with interesting and prevalent exactness and high goal. HMT strategies can be applied various materials, for example, low carbon, high strength steel Austenitic prepares and hardened steels [16].

## 3. Nondestructive Testing (NDT):

NDT is most widely used method for internal defect identification and Nondestructive inspection is a technique for evaluating structural stability for surface or internal defects, as well as metallurgical condition, without destroying the material or endangering its suitability for use. In many other terms, NDT refers to a method of measuring, testing, and examining products or parts in order to characterize or locate faults and flaws in contrast to other criteria while maintaining the original qualities and causing no damage to the product being examined. NDT procedures make a cost-effective way of testing a specimen for specific investigation and analysis possible, or they may be used to verify the whole sample in a manufacturing quality management system. In certain cases, detecting a defect generally requires to use of more than one NDT test method. It may be appropriate to use a variety of strategies as well as experimental, destructive openings [15].

### 3.1. Non-Destructive Testing Methods

There are several NDT methods are available. These techniques may be used to detect holes, inner defects, surface cavities, hydrogen embrittlement, imperfect faulty welds, and whatever other fault that may lead to premature breakdown of plastics, metals, ceramic materials, composite materials, porous materials, and coatings [15].

#### 3.1.1. Visual inspection

The demonstration of collecting visual information about the state of a substance is known as visual inspection. Visual inspection is the best tool for investigating objects or articles without making any modifications. Visual inspection may be performed with the use of a magnifying glass, with overseers examining any object or property from the outside. A Remote Visual Inspection (RVI) tool, such as a camera, may also be used to perform visual examination [15][19].

### 3.1.2. Ultrasonic testing.

The method of transmitting high-frequency sound waves through a material to detect changes in its properties is known as ultrasound testing. The principle of operation of an ultrasound test is similar to echo sound in some cases. In general, ultrasound tests utilize sound waves to identify deformities or flaws in the outside of the subsequent material. Perhaps the most widely recognized ultrasonic test techniques are beat reverberation. With this strategy, the administrator embeds sound into the material and measures the echoes (or sound reflections) created by defects on the outside of the material as they re-visitation of the collector [15][19].

### 3.1.3. Radiography

Radiography is the demonstration of utilizing X radiation or gamma on a material to recognize abandons in non-damaging testing. The radiographic test coordinates radiation from a radioactive isotope or X-beam generator through the test material and onto a film or other kind of indicator. The identifier readings structure a picture chart, which uncovers the basic parts of the investigation material [15][19].

### 3.1.4. Eddy Current testing

Eddy current test is a type of electromagnetic test that measures the strength of an electric current (also called eddy current) in a magnetic field around a substance to determine the extent to which the material is damaged. The supervisor tests the movement of eddy currents in the magnetic field around the conductive material to detect blockages caused by defects or imperfections in the material during the eddy current test. [15][19].

### 3.1.5. Magnetic Particle inspection.

Magnetic particle testing is the process of detecting defects in a material by looking for disruptions in the movement of magnetic fields within it. This method uses a magnetic field and small magnetic particles, such as iron dust. To detect damage to components. The only requirement from the point of view of inspection capability is the components checks should be made on ferromagnetic materials such as iron, nickel, cobalt or some of their alloys, because of this materials that can be magnetized to a level that allows inspection [15][19].

### 3.1.6. Acoustic Emission testing.

Acoustic emissions Non-destructive testing is the act of using acoustic emissions to detect possible flaws and shortcomings in a substance is known as non-destructive testing. Investigators looking at acoustic emission samples look for blasts of acoustic radiation, also known as acoustic emissions, which are induced by material failures. [15][19].

### 3.1.7. Liquid Penetrate testing.

This technique is based on the ability to draw liquid to a "clean" surface. Solve defects with capillary action. Usually materials that use DPT or LPI include metal. (Aluminum, steel, titanium, copper, etc.), glass, many materials ceramics, rubber, plastics [15][19].

## 4. literature Survey

**Bae et al. (2014)** Using acoustic emission (AE) a non-destructive methods, investigate the results of different hydrogen charging concentrations in austenitic stainless steel for designed to allow improvements in periods of 2, 4, 10, and 24 hours. The effect of hydrogen charging concentrations was investigated using 18cr-8ni stainless steel (AISI 304) in this analysis. The discovery exposes a dimple type ductile fracture mode with a large number of quasi-cleavage type brittle fracture mode,

as well as several micro and macro fractures. This research discovered a number of AE occurrences in the elastic zone, such as hydrogen free specimens, but not so many in the plastic zone [1].

**Capriotti et al. (2000)** XRD residual stress identification procedure, mechanical experiments, and microscopy were used to validate the hydrogen embrittlement detection capability. In this research, AISI 4130 steel was used, and hydrogen embrittlement of high strength was observed after the electroplating and pickling processes. The discoveries shows that XRD strategy can successfully utilized as fundamental NDT test to check pressure varieties of airplane high strength steel segments which are associated with hydrogen embrittlement [2].

**Yashar javadi et al.(2020)** The effect of welding residual stress (WRS) on the shape and size of hydrogen-induced cracks (HIC) in S275 structural steel plates was investigated using a water quenching method used for hydrogen crack manufacturing in a predetermined location, phased array ultrasonic testing (PAUT) used during the welding process, and a high temperature in-process method used to detect hydrogen induced cracks (HIC) in real time (WRS). This research examines the impact of residual stress on hydrogen cracking in multi pass-robotic welding using four samples with thicknesses of 15mm and lengths of 300mm. The finding shows the no. of large cracks deposition of filling process from (PAUT, inspection and welding camera) process. Residual stress measurement using the hole drilling methods gives difference of 78MPa was measured in transverse direction [3].

**Motomichi koyama et al. (2011)** is observed hydrogen embrittlement in Fe-18Mn-1.2C (wt. %) austenitic steel then tensile drastically reduced by hydrogen charged using tensile testing method. In this rigidity and malleability were both diminished by hydrogen charging (about 20% decreased strength and about 40% diminished pliability). In discovering two kinds of breaks are noticed in particular intergranular crack and transgranular crack along twin limits. Present outcomes propose significant elements in hydrogen embrittlement of Fe-Mn-C austenitic steel are decrease of union energy grain limits and twin limits and the pressure fixation brought about by disfigurement twins and the breaks were started from twin limits in light of the fact that twining is basically needed to accomplish the prevalent mechanical properties of TWIP steel [4].

**Haiting Zhou et al. (2020)** a non destructive testing (NDT) has been studied to evaluate mechanical performance based on eddy current signals analysis. The low alloy (S500MC) steel was tested under tensile condition with aim to qualifying hydrogen embrittlement (HE). A electrochemical hydrogen charging experiment and tensile tests were conducted to study the hydrogen embrittlement assessment. The finding are that hydrogen content low alloy steel increase with increasing hydrogen charging time and then reaches the saturation level after 40h. This suggested that increasing the hydrogen charging time will reduce the tensile elongation of sample [5].

**Dmitry. L. Merson et al. (2008)** is practices and experiences obvious difficulties of hydrogen embrittlement in that steel that are used in gas and oil producing industry. Using a NDT method name acoustic emission spectral analysis method. In this corrosion resistant pipe steel (13HFA) has been chosen. AE appears to sensitive hydrogen damage during first 10 hour of immersion in H<sub>2</sub>S solution . Which are commonly obtained during standard testing, after noticeably only after about 300 hour holding the same solution [6].

**D. X. Yang et al. (2001)** in this, study of magnetic based nondestructive evaluation (NDE) and used the ultra low carbon (ULC) steel to correlate the magnetic and mechanical properties and to examine the development of barkhausen effect and measurement of hysteresis loop in the sample. The NDE test equipment can detect minor variations in the stress strain curve that appear below the 0.2 offset strain. Jumpsum and jumpsum rate, as well as deferential absorption, are carefully variable with minor defects well below the 0.2 offset strain in extremely low carbon steel, according to the results of this report [7].

**Shejun xie et al. (2014)** is observed the type of micro damage in structure develop during manufacturing process in plastic deformation in austenitic stainless steel using the NDT method namely eddy current testing. In this study 9 test piece of AISI304 austenitic stainless steel are used. The thickness adjustment of specimens may not give massive impact on the pulsed ECT signals, and

subsequently, the analysis of the ductile fracture. Furthermore, the influence of electromagnetic physical properties on plastic deformation has been investigated using numerical analysis, with the findings revealing a reduction in electrical conductivity and an improvement in magnetic flux density as the plastic strain increases. [8].

**Jinyi Lee et al. (2008)** An efficient non-destructive testing tool (NDT) for detecting surface cracks in magnetised ferromagnetic materials is using magnetic flux leakage test (MFLT), which tests the spread of a magnetic field over a magnetised specimen using a magnetic sensor such as a Hall sensor. In this article, we have proposed 64 Inba LIHaS with Ni-Zern ferrite wafers with spacers 0.52mm resolution for reduced height differences and protectors of each sensor on the PCB. Cracks were detected by using two processed image, the smallest cracks detected was a hole type with radius 0.25mm and depth 0.4mm [9].

**Takayuki shiraiwa et al. (2020)** is to measure the hydrogen-induced cracking activity of high strength steel using the acoustic emission (AE) technique as well as the finite element process (FEM) in the slow strain rate tensile (SSRT) test as well as the welding test. In this study HT980 high tensile strength steel are used. The onset of crack was detected by the time evaluation of AE signals, and stress concentration and hydrogen diffusion was calculated by FEM. In SSRT test, AE signals were detected due to crack introduced. The initial crack stress estimated from AE signals decreases as the hydrogen content increases from the initial deviation. Hydrogen diffusion coefficient and solubility of hydrogen are determined by Vickers hardness and equivalent plastic distribution of plastic deformation in FEM [10].

**AV Bochkaryova et al. (2015)** is studied the effect of hydrogen embrittlement on mechanical properties of aluminum alloy. In this aluminum alloy duralumin (D1) alloy which are used as sample. It is found that the mechanical properties of aluminum alloy are negatively affected by hydrogen embrittlement. Hydrogenated alloy has lower degree of ductility with respect to the original alloy; however, the behavior of plastic flow in material has practically not changed. Micro hardness test is carried out for treatment of D1 alloy [11].

**Xingle Chen et al. (2015)** is evaluating the electrical conductivity measurement of ferromagnetic metallic materials by using pulsed eddy current testing (PECT) method. In this a ferromagnetic metallic plate are used as sample. It resolved the least squares problems between the estimated and tested induced voltage values. The findings of electrical conductivity tests for three carbon steel plates were compared using the DCPO method and the four-point PECT method for calculating electrical conductivity verification of ferromagnetic metal plates. [12].

**Meisam Sheikh et al. (2009)** In this article it studied the discontinuities of materials. In this a standard carburizing low-carbon low-alloy steel (AISI4118) is used and eddy current technique/method are used to detection of discontinuities, physical and metallurgical properties of steel. In this article, it established the relationship between surface carbon content and various parameter like impedance, phase angle and voltage. In this study the findings are shown any measured or calculated parameter have good relationship with surface content [13].

**K.Beyer et al. (2011)** this study is that it shows the feasibility of measuring hydrogen effusion in austenitic stainless steel (1.4301) using neutron radiography NDT method is used. This method is suitable to measure hydrogen effusion of concentration as small as 20PPM<sub>H</sub>. In this study temperature is between room temperature to 533k. Neutron radiography is suitable method to study the hydrogen effusion behavior in austenitic stainless steel. In finding of this study it can say that increase in temperature increases hydrogen flow [14].

## 5. Summary of Literature Survey

TABLE NO.1 - SUMMARY OF LITERATURE SURVEY

S.No.	Author name (Year)	Remarks/ Findings
1	Bae et al. (2014)	It depicts the dimple type ductile fracture mode in conjunction with the sum of quasi-cleavage type brittle fracture mode.
2	Capriotti et al. (2000)	It reveals that the XRD technique is being used as a basic NDT test to determine residual stress differences in aircraft high strength steel components.
3	Yashar javadi et al.(2020)	The micrograph and microscopic investigation shows very large no. of cracks has been measured from water quenched process and large number of cracks was subsequently detected.
4	Motomichi koyama et al. (2011)	In finding two types of cracks are observed namely intergranular fracture and transgranular fracture along twin boundaries.
5	Haiting Zhou et al. (2020)	The finding are that hydrogen content low alloy steel increase with increasing hydrogen charging time and then reaches the saturation level after 40h.
6	Dmitry. L. Merson et al. (2008)	AE appears too sensitive in hydrogen damage during first 10 hour of immersion in H <sub>2</sub> S solution. After noticeably only after about 300 hour holding the same solution.



7	D. X. Yang et al. (2001)	The result are extracted three properties from the study are jumpsum and jumpsum rate and deferential permeability are vary sensitively with small deformations well below the 0.2 offset strains in ultra low carbon steel.
8	Shejun xie et al. (2014)	With increasing plastic pressure, the findings indicate a decrease in electrical conductivity and an improvement in magnetic permeability.
9	Takayuki shiraiwa et al. (2020)	Two processed images were used to locate cracks; the smallest crack found was a hole form with a radius of 0.25mm and a depth of 0.4mm..
10	Takayuki shiraiwa et al. (2020)	The initial crack estimated from AE signals decreases as the hydrogen content increases from the initial deviation.
11	AV Bochkaryova et al. (2015)	Hydrogenated alloy has lower degree of ductility with respect to the original alloy; however, the behavior of plastic flow in material has practically not changed.
12	Xingle Chen et al. (2015)	The Pulsed eddy current testing conductivity measuring approach is highly useful for sorting ferromagnetic materials.
13	Meisam Sheikh et al. (2009)	It established the relationship between surface carbon content and impedance, phase angle. The carbon content of surface is increasing with decreased the calculated and measurement parameters.
14	K.Beyer et al. (2011)	Finding of this study is it can say that increase in temperature increases hydrogen flow.

## 6. Evaluation of Hydrogen Embrittlement through NDT

A nondestructive method named ultrasonic testing was used to study and analyze the mechanical properties of hydrogen-charged stainless steel. The velocity and magnitude of ultrasound waves for hydrogen charged specimens is measured. Those measured values were compared with the tensile strength according to hydrogen charging concentrations. To remove the impact of couplant, an ultrasonic test was conducted in water with a 10 MHz sensor. Using an electronic oscilloscope, the velocity was determined by measuring the thickness ( $t$ ) of the sample and the propagating time ( $T$ ) of the ultrasound waves through the sample. It represents the variations in ultrasonic wave velocity as a function of hydrogen charging time. Given material brittleness induced by hydrogen charging, the waves propagating velocities remained stable at around 5800 m/s. The shear wave, which was about 3200 m/s in both specimens, was very similar to the longitudinal wave. It was obvious that the velocity of the ultrasound waves was not a good criterion for determining the degree of embrittlement caused by hydrogen charged in stainless steel. Due to the ultrasonic testing methods it evaluates that, since the attenuation coefficient and tensile strength have a similar relationship, we will be able to measure the difference in tensile strength by calculating the attenuation coefficient of an ultrasound waves. As the attenuation coefficient of hydrogen charge sample was increased as compare to uncharged sample and this was due to brittleness induced by hydrogen charging [1]. The acoustic emission event generated at hydrogen charged samples for 12

and 24 hours was completely different from the acoustic emission event generated at hydrogen free samples. That is, several acoustic emission events occurred in the elastic region, such as in the hydrogen free sample, but few occurred in the plastic zone [1][10].

## 7. Conclusion

Hydrogen embrittlement is a very serious problem in automotive and hydrogen transportation industries as they are using a high strength material. This paper is basically critical review of various NDT methods and HE mechanism, with aiming towards how these NDT methods can be used for defect analysis in hydrogen related research. With the help of NDT, internal defects or irregularities are known and prevention activities are taken care before the final failure of a material. Ultrasonic testing is very useful for determining inter defects in material. Sometime one NDT method is not sufficient to give accurate results then two or more NDT methods are used for accurate defect analysis of a material and then prevention activities will be implemented to increase the availability and reliability of machine or critical components.

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