How to prevent failure accidents!

Failure accidents occur frequently worldwide to the extent that it can be said that there is not a day that goes by without them being seen in the daily news.

Many of these accidents result from natural disasters such as earthquakes, floods, and typhoons, or from human errors. However, all structures, machinery, and facilities are susceptible to **degradation damage** over prolonged periods of use, even under normal conditions.

By understanding **degradation damage**, it becomes possible to contribute to global safety and security as well as the extension of the lifespan of structures, aligning with the Sustainable Development Goals (SDGs).

Let's learn about the failure predictive science and work towards eliminating failure accidents.

Comparison between Age-Related Deterioration and Human Mortality

- Damage in Structures, Facilities, and Equipment
  Failure in structures, facilities, and equipment can be likened to human mortality.
  Degradation damage are analogous to illnesses in humans.
- Structures, facilities, and equipment ultimately reach a state of damage (failure) (death) due to the progression of material deterioration and damage (illness).
- There are 163 mechanisms of material (mainly metals) degradation (refer to Table 1), which can be classified into nine categories of mechanisms (equivalent to types of illnesses):
  fatigue, natural corrosion, dry corrosion, wet corrosion, stress corrosion cracking, creep, wear, erosion, and property deteriolation.

Table 1 Deterioration and damage mechanisms (1)

Middle category	Fatigue		Creep		Natural corrosion	Dry corrosion		
Small category	Mechanical fatigue (high cycle fatigue)	Thermal fatigue	Creep deformation	Dissimilar metal weld cracking (DMW)	Atmospheric (External) corrosion	High temperature oxidation	Sulfidation	Coal ash corrosion
	Low cycle fatigue	Thermal attack (fire cracking)	Creep rupture	Relaxation	External stress corrosion cracking	Steam oxidation	High temperature sulfidation	Black liquor smelt corrosion
	Contact fatigue	Rolling contact fatigue	Long-term creep rupture	Type IV cracking	Corrosion under insulation	Carburization oxidation	High temperature sulfide/hydrogen sufide corrosion	High temperature chloride salt corrosion
	Vibration fatigue	Ratcheting	Short time Creep rupture		Stress corrosion cracking under insulation	Metal dusting	Molten salt corrosion	High temperature carbonate corrosion
	Fretting fatigue		Creep embrittlement			Halogenated corrosion	Vanadium attack	Hydrogen attack
	corrosion fatigue		Creep-fatigue rupture			High temperature Halogen corrosion	Fuel ash corrosion	

Table 1 Deterioration and damage mechanisms (2)

Middle category	Wet corrosion						
Small category	Freshwater corrosion	Inorganic acid corrosion	Phosphate corrosion	Stray current (concentration cell) corrosion	Ammonium hydrosulfide corrosion	Graphitization corrosion	Boric acid corrosion
	Seawater corrosion	Organic acid corrosion	Liquid metal corrosion	Groove corrosion	Ammonia attack	Chemical cleaning corrosion	Acid sour water corrosion
	Contaminated seawater corrosion	Hydrochloric acid corrosion	Pitting corrosion	Intergranular corrosion	$HCl-H_2S-H_2O$ corrosion	Atmospheric tank bottom plate corrosion	Sour water corrosion
	Flow accelerated corrosion	Wet chlorine and hypochlorite corrosion	Crevice corrosion	Filiform corrosion	CO2 corrosion	Intergranular corrosion	Caustic corrosion, Caustic gouging
	Dissolved oxygen corrosion, oxygen concentration cell corrosion	Sulfuric acid corrosion	Galvanic corrosion	Formicary (ants' nest) corrosion	Condensation corrosion	Naphthenic acid corrosion	Chelate corrosion
	Acid dew point corrosion (sulfuric and hydrochloric acid dew point corrosion)	Phosphoric acid corrosion	Corrosion under deposit	Wet sulfide corrosion, wet hydrogen sulfide corrosion	Down-Time Corrosion	Hydrofluoric acid corrosion	Layered (exfoliation) corrosion
	Microbial corrosion	Nitric acid corrosion	Water line attack	Wet chloride corrosion, wet HCl-H2S corrosion	Cooling water corrosion	Amine corrosion	Selective corrosion (dealloying) de-component corrosion
	Soil corrosion	Phenolic corrosion	Knife line attack	Ammonium chloride corrosion	Boiler water condensation corrosion	Carbonic acid corrosion,	Stress corrosion

Table 1 Deterioration and damage mechanisms (3)

Middle category	**Stress corrosion cracking (SCC)**				***Wear***	
Small category	Sulfide stress corrosion cracking	Amine cracking	Hydrogen induced cracking in hydrofluoric acid	Irradiation assisted stress corrosion cracking (IASCC)	Adhesive wear	Fatigue wear
	Hydrogen induced cracking in hydrogen sulfide	Carbonate cracking	Nitrate stress corrosion cracking	Intergranular corrosion cracking	Sliding wear	Abrasive wear
	Hydrogen induced (assisted)cracking (HIC)	Carbonate SCC	Sensitized cracking	Tarnish Rupture	Corrosion wear	
	Stress oriented hydrogen induced cracking (SOHIC)	CO-CO_2-H_2O SCC	High temperature water cracking	Cyanide SCC	Intergranular stress corrosion cracking	
	Caustic cracking	Polythionic acid SCC	Intergranular stress corrosion cracking	Ammonia SCC	Fretting corrosion	
	Caustic soda cracking	Chloride SCC	Intragranular stress corrosion cracking (TGSCC)		Irradiation assisted stress corrosion cracking (IASCC)	

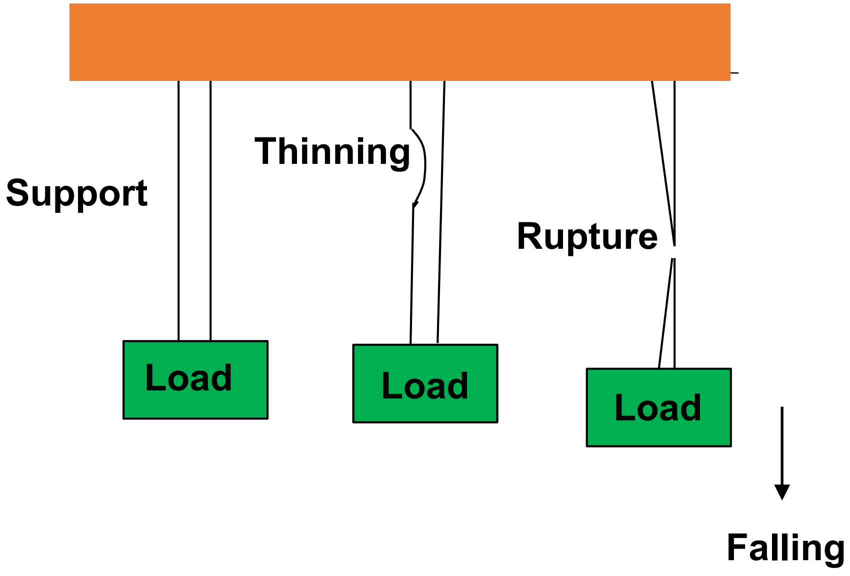
Table 1 Deterioration and damage mechanisms (4)

Middle category	**Erosion**		**Property deterioration**			
Small category	Erosion /Corrosion	Drop Slag erosion	Hydrogen embrittlement	liquid metal embrittlement	Gamma prime (gamma' phase) embrittlement	Volume expansion (swelling)
	Cavitation erosion	Coal particle erosion	Hydrogen embrittlement (Titanium)	Graphitization	Strain aging	Reheat(SR) cracking
	Solid particle impingement erosion		Hydride embrittlement	Isothermal aging embrittlement	Tempering embrittlement	Cladding delamination
	Liquid drop impimgement erosion		Decarburization	Sulfide embrittlemen	Sigma phase and chi phase embrittlement	Under-cladding cracking
	Fly ash erosion		Carburization	Sensitization	Carbide spheroidization	475° C embrittlement
	soot blower erosion		Nitriding	Sigma phase embrittlement	Irradiation embrittlement	Softening (over aging)

The concept of deterioration/damage and failure accidents

Structures support loads through the thickness of their constituent materials, but due to deterioration/damage, the thickness decreases, and cracks develop, causing the structure to no longer support the loads (as shown in the example below). This can lead to major accidents such as collapse, rupture, scattering of components, leakage of hazardous substances, resulting in personal injuries, fires, explosions, and more.

The concept of failure accident by thinning



Reduced thickness causes the stress (load per unit area) on the component to exceed its strength, leading to failure.

To prevent failure accidents due to degradation damage

As shown in Table 2, degradation damage can manifest in forms such as thinning and crack formation, even though some of it may be invisible, similar to symptoms of an illness for human.

Table 2 Mechanisms and visible appearance of degradation damage

Degradation damage mechanisms		Mode of degradation damage（visible appearance）
Fatigue		**Crack**（Initiation→propagation→rupture）
Creep		Deformation, **Crack**（Initiation of voids →propagation of crack → rupture）
Corrosion	Natural	**Thinning**（General）
	Dry	**Thinning**（General and local）, Attack（Swelling, Deformation, Cracking, thinning
	Wet	**Thinning**（General, local and pitting）
	Stress Corrosion Cracking（SCC）	**Crack**（Initiation→propagation→rupture）
Erosion		**Thinning**（General）
Wear		**Thinning**（General）
Property deterioration		Property deterioration (Embrittlement, deterioration of corrosion resistance) invisible, Brittle fracture (Crack) , *Corrosion (thinning and crack)*

Failure predictive science

To prevent failure accidents caused by degradation and damage

- It is necessary to focus on mechanism of degradation damage and implement inspections and measures (prediction and prevention), similar to regular health check-ups for humans.
- While humans will inevitably die from natural causes, structures, facilities, and equipment can avoid failure (death) by undergoing repairs and updates before failure occurs.
- Predicting which degradation mechanisms may occur and implementing appropriate maintenance (inspections, repairs, updates) can prevent failure.
- As the foundation of failure predictive science, I will provide an overview of nine degradation damage mechanisms on the following pages.

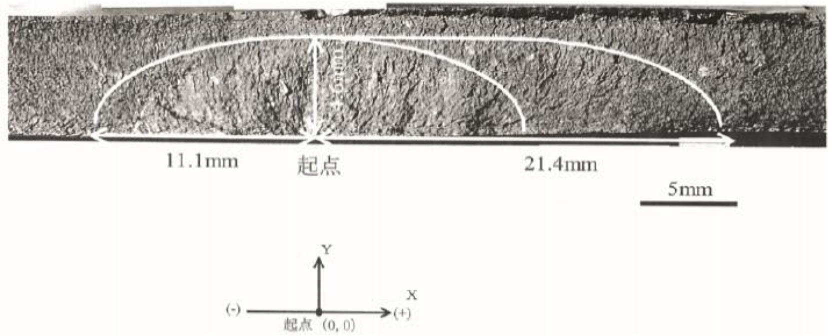
Fatigue

All materials will fracture under cyclic stress, even at levels below the point of failure under static stress. This phenomenon is known as fatigue.

Failure case by fatigue

Failure of inducer blade by fatigue

In the case of the H-II rocket's first-stage engine L-7, the fatigue failure of the titanium alloy inducer blade led to the rocket's crash.



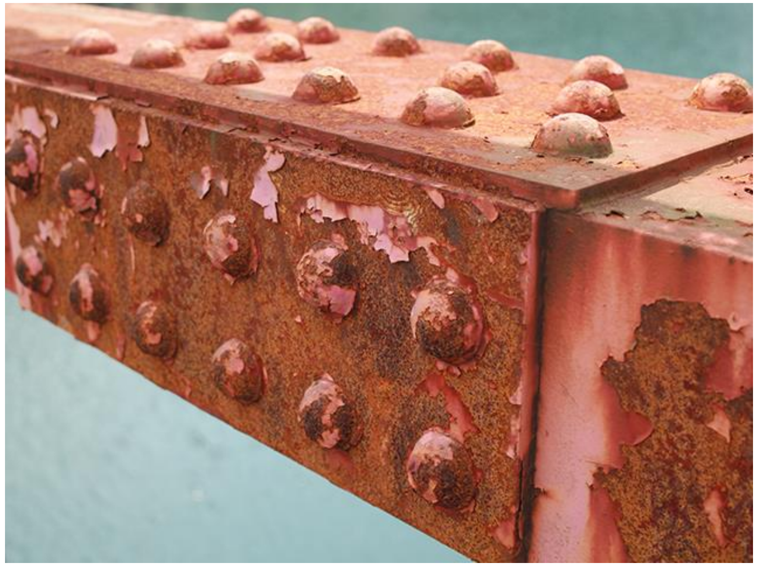
Observation of fracture surface (crack initiation and propagation)

Afterwards, the H-IIA rocket with its improved engine, achieved a success rate of 55 out of 56 launches over a span of 20 years.

Natural corrosion

Metals exist on Earth as compounds (oxides, sulfides, etc.) and are extracted through reduction processes for industrial use. Therefore, in the presence of oxygen in the natural environment, metals tend to oxidize as they attempt to revert to their oxide forms. This phenomenon is called natural corrosion.

Case of natural corrosion



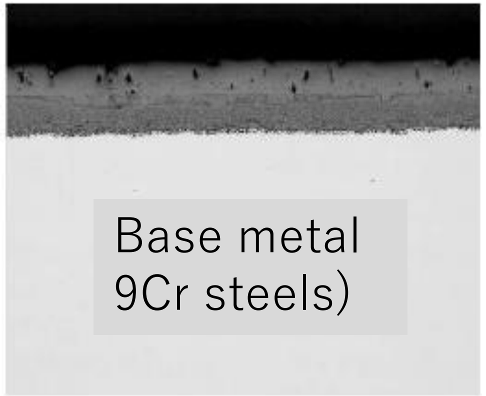
Formation of rust (Iron oxide)

Dry corrosion

The phenomenon in which a metal directly reacts with reactive gases such as oxygen, water vapor (in gaseous state), carbon dioxide, or molten salts upon contact, resulting in the formation of solid reaction products (primarily oxides) on the metal surface while the metal itself is consumed.

Case of dry corrosion

Corrosion of boiler tube in combustion atmosphere



Fe_2O_3(outer scale)

(Fe,Cr)O(Inner scale)

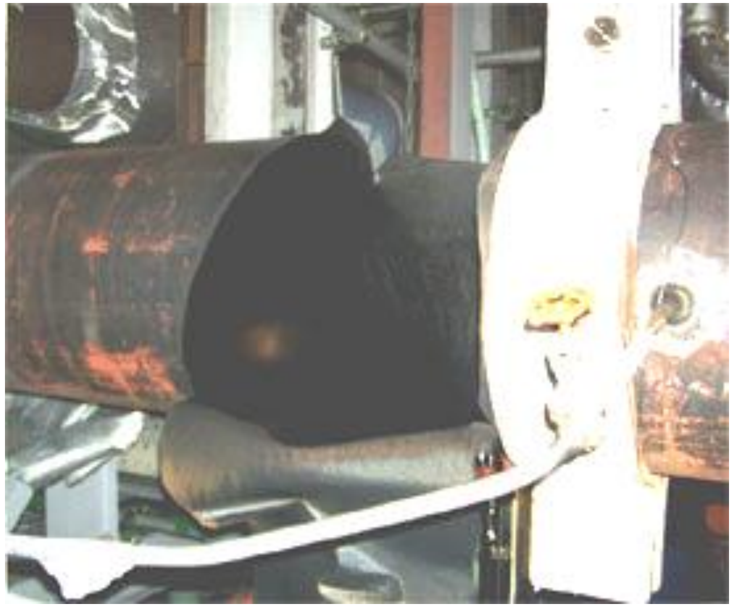
Microscopic observation of oxides formed on boiler tube surface

Wet corrosion

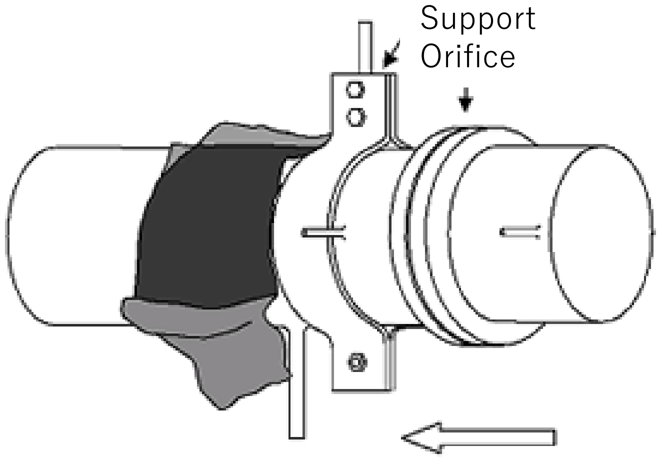
In the context where a material dissolves in a gas, it is referred to as "dry corrosion," whereas when a material dissolves in a liquid, including considerations for liquid components and materials (including corrosion prevention measures such as coatings), it is called "wet corrosion." The degree of corrosion varies depending on the combination of liquid components and materials.

Case of wet corrosion

Flow Accelerated Corrosion(FAC)



Steam discharge from downstream of the orifice in the recirculation pipe of Unit 3 at the Kansai Electric Power Company's Mihama Power Plant in 2004.

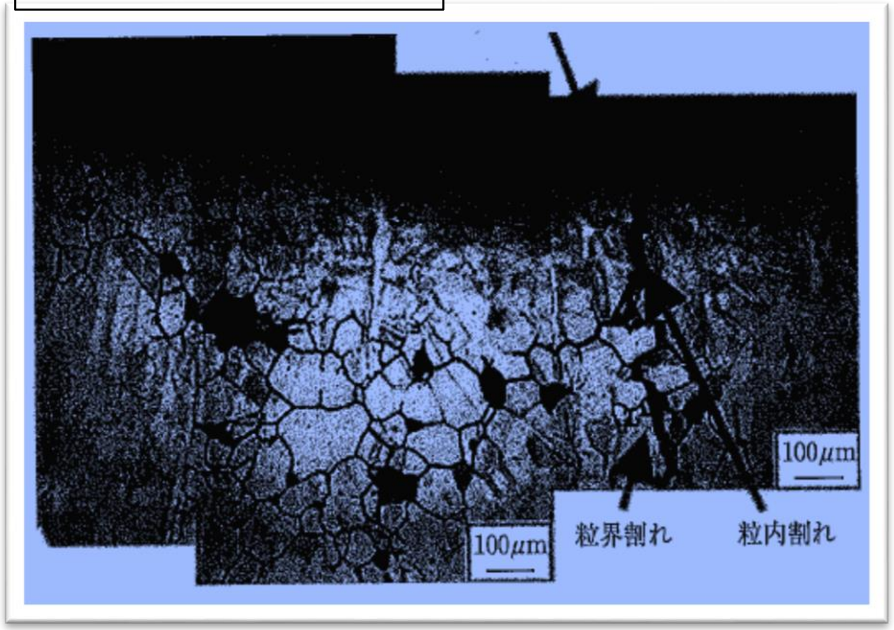


It occurs only in turbulent regions such as elbows, orifices, and downstream of reducers, so preventing it can be achieved by thorough thickness measurement at these locations.

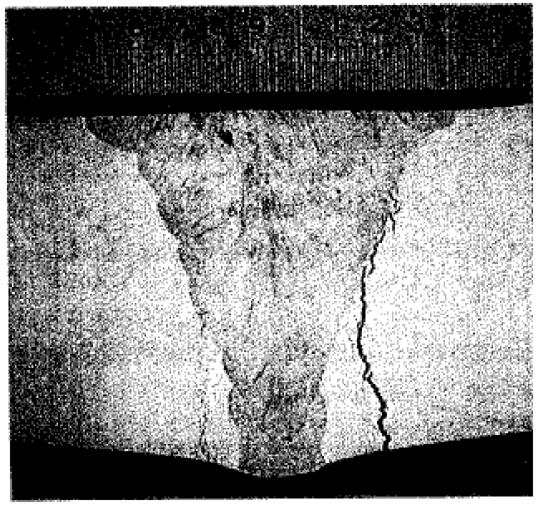
Stress Corrosion Cracking (SCC)

Corrosion is a phenomenon in which materials dissolve in the surrounding environment. In typical corrosion, materials dissolve either uniformly or locally, leading to a reduction in thickness. However, under certain stress conditions, in very confined areas, corrosion progresses in a crack-like manner, and this phenomenon is referred to as stress corrosion cracking(SCC). It occurs when three conditions are met: the environment, the material, and the stress.

Case of SCC



Microscopic observation of SCC on shroud of reactor in nuclear power plant



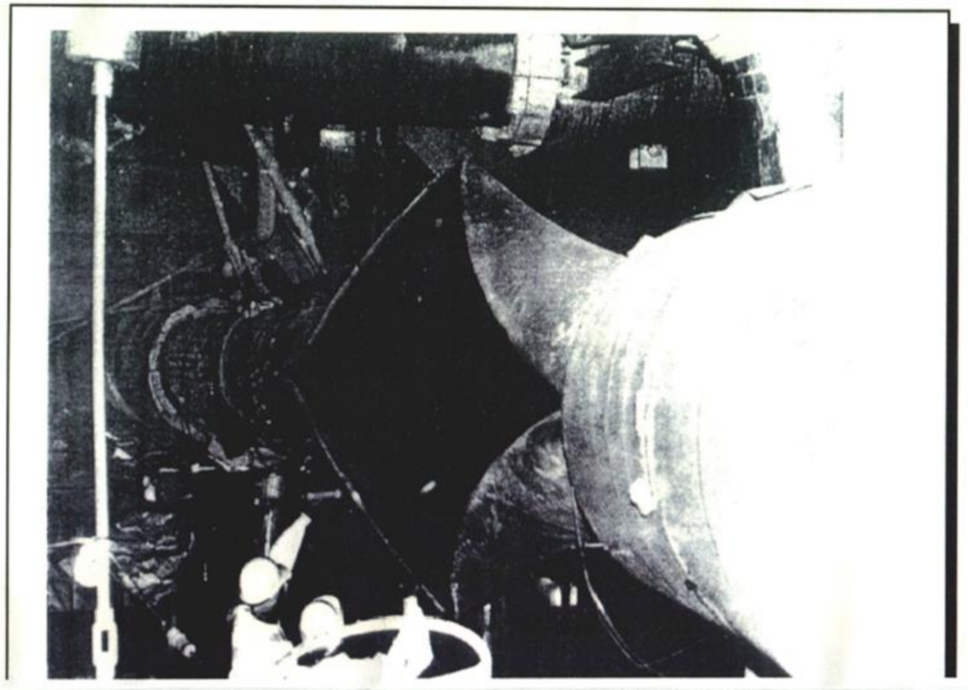
Microscopic observation of SCC on weld joint of pipe of nuclear power plant

Material: Stainless steel
Environment : High temperature pure water

Creep

Material exhibits permanently non deformation nor fracture under stress at room temperature or below a certain constant temperature (which varies depending on the material), but gradually undergoes deformation at elevated temperatures and eventually fractures after a certain period. This phenomenon is called "creep."

Case of creep failure



米国発電所の再熱蒸気管（低合金鋼）溶接継手部のクリープ破壊

Failure accident in thermal power plant in USA.

Creep failure occurred in the weld joint of the reheat pipe seam welded after 20 years operation.

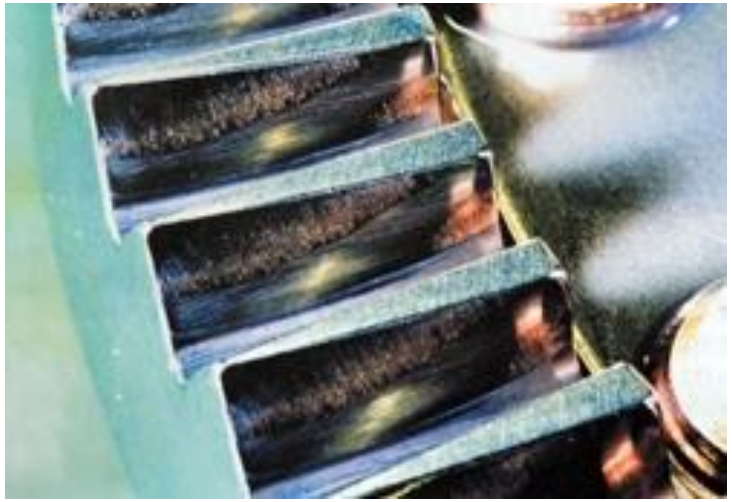
8 persons died by the blast of hot steam and water

Wear

The phenomenon where solid materials, when used in a state of friction or rubbing against each other, experience wear and a reduction in thickness in either one or both of them is referred to as "wear."

Case of wear failure

Wear in shaft contacting bearing

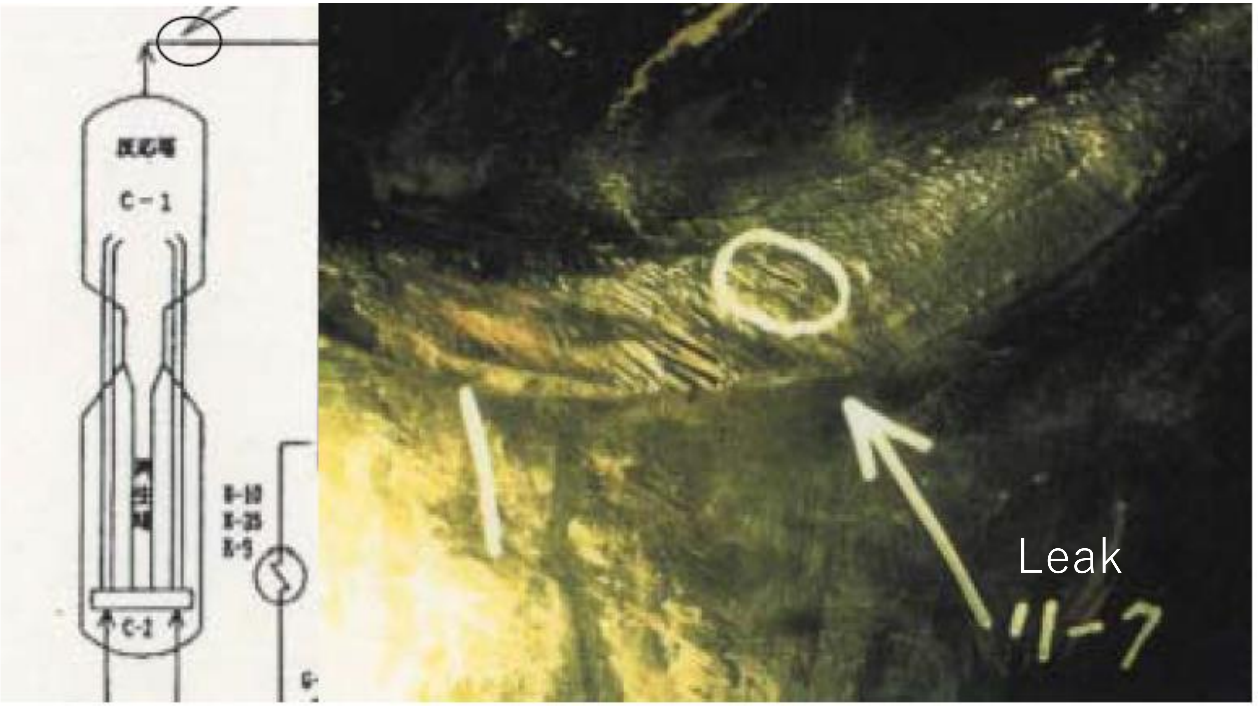


Wear in gear tooth surface

Erosion

The phenomenon in which materials experience mechanical wear and some of their parts detach due to repeated collisions (or impacts) with a fluid is called "erosion."

Case of erosion failure



Erosion-induced thinning, leakage, and minor fires caused by a mixture of fluids such as LPG, gasoline, and decomposition gases at a pressure of 0.113 MPa and a temperature of 474° C.

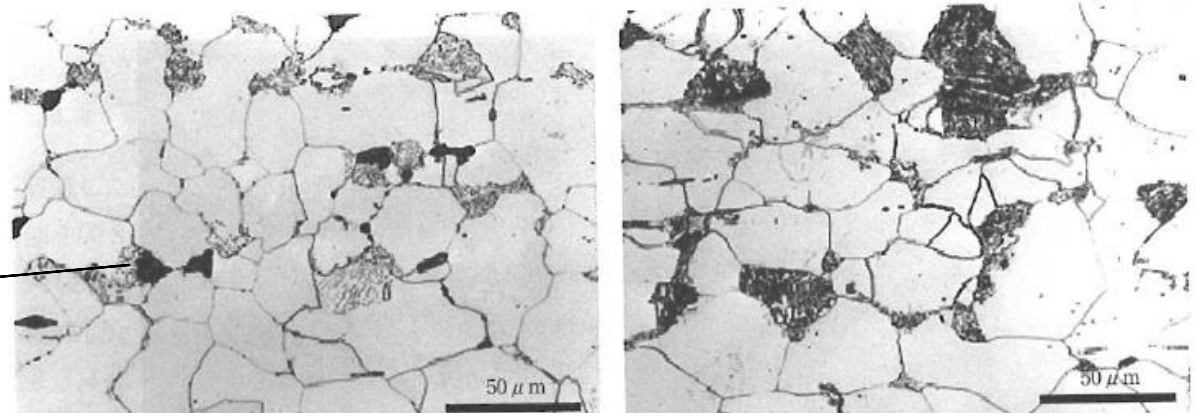
Property deterioration

Metals are adjusted (e.g., through heat treatment) to exhibit optimal properties when used. At room temperature, there is no change in properties since atomic movement does not occur. However, at elevated temperatures, changes in properties occur as atoms transition to energetically stable states. Many of these changes are inconvenient for use, such as a decrease in material strength, ductility, and corrosion resistance, and they can become the causes of accidents after long-term use. This is referred to as “Property deterioration."

Failure case of property deterioration

Graphitization

Graphite



Microstructure before use: Ferrite + Pearlite

After 30 years of using a boiler steel pipe (0.5Mo steel) at 476 C, carbides have turned into graphite, causing the material to become brittle and leading to brittle fracture.

How to confirm the occurrence of potential degradation damage mechanisms

Table 3 outlines the essential conditions required for the occurrence of each degradation damage mechanism. By confirming the presence or absence of these essential conditions in the target equipment, it is possible to determine which degradation damage mechanisms are of concern. In some cases, multiple mechanisms may be concerned. The dependencies for environment and temperature are varies on metarial.

Table 3 Essential conditions required for the occurrence of each degradation mechanism

Degradation damage mechanisms		Essential conditions		
		Stress	Environment	Temperature
Fatigue		Cyclic stress		
Creep		Tensile stress		Over 100 C
Corrosion	Natural corrosion		Atmosphere	
	Dry corrosion		Corrosive gas, Molten salt	
	Wet corrosion		Corrosive liquid	
	Stress Corrosion Cracking（SCC）	Tensile stress	Corrosive liquid	
Erosion			Fluid	
Wear			Contact of solid	
Property deterioration				Over 100 C

Tools confirming the degradation damage mechanism

As mentioned before, the degradation damage mechanisms depend on the stress applied to the structural materials, the temperature in use, and the environmental conditions. Therefore, tools have been developed to assess the occurrence of these mechanisms based on these conditions.

1) With "Failure Prediction AI CLASS 1" (https://en.failure-prediction.info/class1/), you can enter the name of the structure you are concerned about and determine whether any of the nine degradation damage mechanisms are "likely to occur" or "unlikely to occur" for that specific structure. This may provide you with valuable insights, especially when considering potential future employers and their facility assets.

2) If you want to assess whether the nine degradation and damage mechanisms are "likely to occur" or "unlikely to occur" based on usage conditions without specifying a particular structure, you can use “Failure prediction AI CLASS 2” (https://en.failure-prediction.info/class2/)

Further information to study more

FPLPac provides

- Detailed explanations of the 163 degradation mechanisms
- Plant materials degradation case study handbook

In addition,

- In FPAI Classes 3, you can confirm which degradation mechanisms are likely to occur among the 163 subcategories.
- In Class 4, you can determine to what extent concerning degradation damage is progressing.
- In Class 5, advanced AI methods are provided to accurately predict data related to existing degradation damage.

If you are interested in the following maintenance tools, please access the following:

RBM(Risk Based Maintenance)	FFS（Fitness For Service）
https://b-mat.co.jp/ or https://ai-rbm.com/	https://www.jmuc.co.jp/imc/services/itsystem_uni.html