



Engineering Encyclopedia

Saudi Aramco DeskTop Standards

MAINTENANCE AND REPAIR OF PRESSURE VESSELS

Note: The source of the technical material in this volume is the Professional Engineering Development Program (PEDP) of Engineering Services.

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<u>Content</u>	<u>Page</u>
INTRODUCTION.....	5
DETERMINING APPROPRIATE INSPECTION FREQUENCIES FOR PRESSURE VESSELS	6
Reasons for Periodic Pressure Vessel Inspection	6
Primary Causes of Pressure Vessel Deterioration.....	7
Corrosion	8
Erosion.....	10
Metallurgical and Physical Changes	11
Mechanical Forces	12
Faulty Material	12
Faulty Fabrication	12
General Considerations Regarding Inspection Intervals.....	13
External Inspection Intervals.....	15
Internal Inspection Intervals.....	15
Safety Precautions and Preparatory Work	16
Safety Precautions.....	16
Preparatory Work.....	17
External Inspection Scope	18
Ladders, Stairways, Platforms, and Walkways	18
Foundations	19
Anchor Bolts	19
Supports	20
Nozzles	20
Grounding Connections	20
Auxiliary Equipment	21
Protective Coatings and Insulation	21

External Metal Surfaces	22
Internal Inspection Scope	23
Surface Preparation	24
Preliminary Visual Inspection	24
Detailed Inspection	25
Inspection of Metallic Linings	27
Inspection of Nonmetallic Linings	27
Thickness Measurement	28
Special Methods for the Detection of Mechanical Defects	28
Metallurgical Changes and In-Place Metal Analysis	29
Inspection and History Report	30
DETERMINING THE SUITABILITY OF CORRODED PRESSURE VESSELS FOR CONTINUED OPERATION.....	34
Determining Minimum Actual Thickness.....	34
Types of Corrosion	35
Major Vessel Sections	38
Type of Loading	39
Location of Corrosion Relative to Welds	40
Acceptability of Corroded Area	46
Potential Actions if Corroded Areas Are Not Acceptable	48
DETERMINING THE APPROPRIATE DESIGN AND FABRICATION DETAILS FOR WELDED REPAIRS OR ALTERATIONS.....	49
Classification of Repairs and Alterations	49
Repair	49
Alteration.....	51
Defect Repairs.....	52
Cracks.....	53
Corroded Areas	54

Welding	56
Procedures and Records	56
Alternatives to PWHT.....	57
Local PWHT.....	58
Design.....	60
EVALUATING THE DESIGN OF EXISTING PRESSURE VESSELS FOR RERATING TO REVISED DESIGN CONDITIONS	61
Changes to Original Design Pressure or Temperature.....	61
Reasons for Derating.....	63
Available Options.....	64
Requirements for New Hydrotest.....	65
SUMMARY	66
WORK AID 1: PROCEDURE FOR DETERMINING THE APPROPRIATE INSPECTION FREQUENCY FOR A PRESSURE VESSEL	67
Work Aid 1A: External Inspection Frequency	67
Work Aid 1B: Internal Inspection Frequency	70
WORK AID 2: PROCEDURE FOR DETERMINING THE SUITABILITY OF A CORRODED PRESSURE VESSEL FOR CONTINUED OPERATION.....	74
Work Aid 2A: Evaluation of Pitting Type Corrosion.....	75
Work Aid 2B: Evaluation of Uniform Type Corrosion	77
WORK AID 3: INFORMATION IN API-510 FOR DETERMINING APPROPRIATE DESIGN AND FABRICATION DETAILS FOR WELDED REPAIRS OR ALTERATIONS ON PRESSURE VESSELS.....	83
WORK AID 4: PROCEDURE FOR EVALUATING AN EXISTING PRESSURE VESSEL FOR RERATING TO REVISED DESIGN CONDITIONS	90
GLOSSARY	92

List of Figures

Figure 1: Blister with Cracks.....	9
Figure 2: Erosion at Metal Surface.....	10
Figure 3: Anchor Bolt Deterioration Below the Surface	19
Figure 4: Corrosion Under Insulation.....	22
Figure 5: Components of Inspection and History Report.....	32
Figure 6: Inspection and History Report Thickness Measurement Data.....	33
Figure 7: Uniform Type Corrosion	36
Figure 8: Pitting Type Corrosion.....	36
Figure 9: Direction of Thickness Measurements	39
Figure 10: Sample Problem 1 Vessel	42
Figure 12: Blend Grinding a Crack	54
Figure 13: Insert Patch Repair	55
Figure 14: Local PWHT Per ASME	59
Figure 15: Pitting Type Corrosion Evaluation	76
Figure 16: Uniform Corrosion Evaluation	78
Figure 17: Temper Bead Welding.....	88

INTRODUCTION

The earlier modules of this course concentrated on Saudi Aramco and industry requirements for the material selection, design, fabrication, inspection, and testing of *new* pressure vessels. After a pressure vessel is placed into service, it will experience various forms of deterioration, the most common form being corrosion.

The following requirements are applicable to an in-service pressure vessel:

- It will need to be inspected to confirm its continued structural integrity.
- It will probably require some degree of maintenance, repair, or alteration.
- It will possibly require a revision to its design conditions. Such revision is known as rerating.

This module discusses the requirements that must be met with respect to these areas of concern regarding pressure vessels that have been placed into service.

DETERMINING APPROPRIATE INSPECTION FREQUENCIES FOR PRESSURE VESSELS

Pressure vessel components will deteriorate to some extent after they have been exposed to the operating conditions. This deterioration must be identified before it affects the structural integrity of the vessel so that appropriate repairs and maintenance are done on a planned basis rather than on an unscheduled basis.

This section discusses the types of deterioration that may occur, considerations and requirements in the determination of appropriate inspection frequencies, and typical scopes of pressure vessel inspections. Additional detail on material deterioration and inspection methods may be found in COE 103 and COE 105.

Reasons for Periodic Pressure Vessel Inspection

Pressure vessels are inspected after they have been placed into operation in order to determine their physical condition and the type, rate, and causes of deterioration that may have occurred. The information that is obtained from each inspection must be recorded to permit both current evaluation and future reference.

Periodic inspection is necessary to determine whether the structural integrity of the vessel is still acceptable and whether the vessel remains safe for continued operation. Trends in vessel condition can be identified, and appropriate corrective action can be taken, before the condition has deteriorated to the point where leakage of hazardous fluid or other failures occur. Such leakage or vessel failure would cause an unplanned shutdown, with consequent disruption in operations plans. Unplanned shutdowns sometimes are more hazardous than planned shutdowns because operations personnel are more likely to make mistakes when they are responding to unplanned situations. These mistakes can lead to other unforeseen consequences. Unplanned shutdowns also cause unexpected losses in production.

Periodic inspection permits the development and execution of a planned maintenance and repair schedule. Corrosion rates and remaining corrosion allowances can be predicted based on the inspection results. This corrosion rate and remaining corrosion allowance information is then used to identify and plan for the necessary materials, labor, time, and costs that are required to keep the vessel in acceptable operating condition.

Periodic inspection may be used to improve overall operating efficiency. External inspections may be made visually, or with other nondestructive techniques, while the vessel is in operation and still closed. These operational inspections may identify problems such as leaks, improper installations, plugged lines, excessive vibration, unusual noise, or other evidence of malfunction. Early identification of these problems and their causes can help in the development of appropriate corrective action, can prevent more extensive damage, and can direct the planning efforts for later inspections and maintenance activities.

Primary Causes of Pressure Vessel Deterioration

The primary causes of pressure vessel deterioration are as follows:

- Corrosion
- Erosion
- Metallurgical and physical changes
- Mechanical forces
- Faulty material
- Faulty fabrication

A periodic inspection program is most effective in the case of vessels for which deterioration is expected and when the program is developed based on the types of deterioration that can be expected in the particular pressure vessel service. The primary causes of pressure vessel deterioration are briefly discussed in the paragraphs that follow.

Corrosion

Corrosion is the primary cause of pressure vessel deterioration and was discussed in COE 103, COE 105, and earlier in this course. As previously discussed, the potential for corrosion is considered in pressure vessel design by the addition of a corrosion allowance to the vessel component thicknesses or by the use of alloy materials or internal linings. The most common corrosive materials that cause internal corrosion in refinery pressure vessel applications are sulfur and chloride compounds. Caustics, inorganic and organic acids, and other chemicals that are used in particular processes may cause internal corrosion problems as well. The degree of external corrosion will vary based on atmospheric conditions and on the presence of airborne contaminants such as corrosive chemicals in industrial locations and salt in the vicinity of salt water.

Corrosion by sulfur compounds may occur at temperatures that are below the dew point of water or at temperatures that are above 260°C (500°F). High-temperature sulfur corrosion is the most damaging condition for most steels, especially in applications where hydrogen is present in significant concentrations with hydrogen sulfide. Corrosion that is due to sulfur compounds may take the form of general corrosion, scale formation, or blistering, depending on the process environment and temperature.

Corrosion by chloride compounds, mainly by hydrogen chloride, occurs in areas where the temperature is below the dew point of water and is general in nature. This type of corrosion may also cause pitting on the surface of carbon steel or stress corrosion cracking of austenitic stainless steel material. Areas that are adjacent to welds are particularly susceptible to this type of corrosion.

Low-temperature hydrogen attack causes the formation of blisters on the steel surface, as illustrated in Figure 1. In this situation, corrosion by a weak acid forms atomic hydrogen that may diffuse into the steel. When the atomic hydrogen reaches a void or a nonmetallic inclusion that is located in the steel, such as at a lamination, it changes into molecular hydrogen (H_2) and can no longer diffuse. Pressure will build in the void as the atomic hydrogen continues to diffuse and as more molecular hydrogen is formed. This pressure buildup will cause blisters if it continues to rise and can also lead to the formation of cracks.

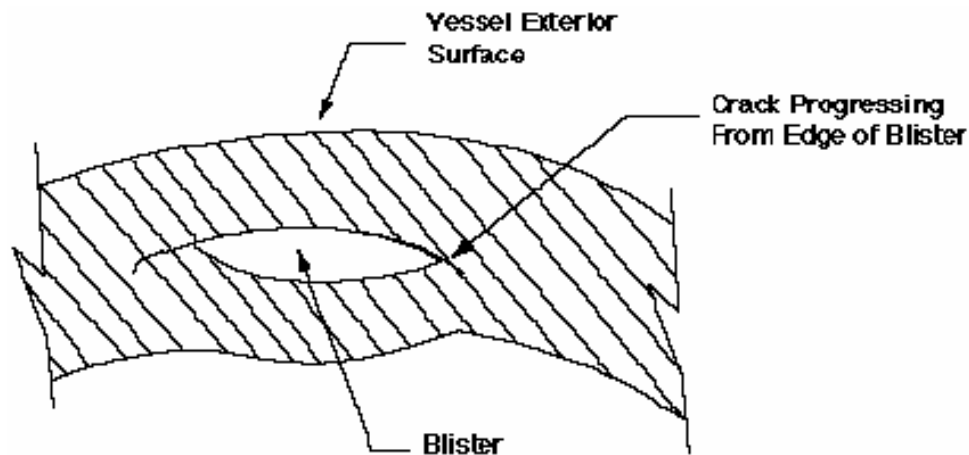


Figure 1: Blister with Cracks

Stress corrosion cracking is a brittle type of failure that can occur in metals that are normally ductile. Such cracking is due to the combined action of corrosion and tensile stress. Common forms of stress corrosion cracking are as follows:

- Caustic embrittlement of carbon steel, which may be caused by sodium hydroxide or other strong alkalis.
- Stress corrosion cracking of copper alloys in aqueous ammonia solutions, particularly brasses with high zinc content.
- Stress corrosion cracking of austenitic stainless steels in the presence of chlorides or polythionic acids.

Erosion

Erosion, as illustrated in Figure 2, is the wearing away of a surface due to the impingement of solid particles or liquid. Erosion is usually found at flow restrictions, changes in flow direction, or other geometric disturbances that cause locally high flow velocities. Erosion may typically be found at inlet or outlet nozzles, on internal piping, internal grid or tray sections, vessel walls opposite inlet nozzles, internal support beams, and on flow impingement baffles.

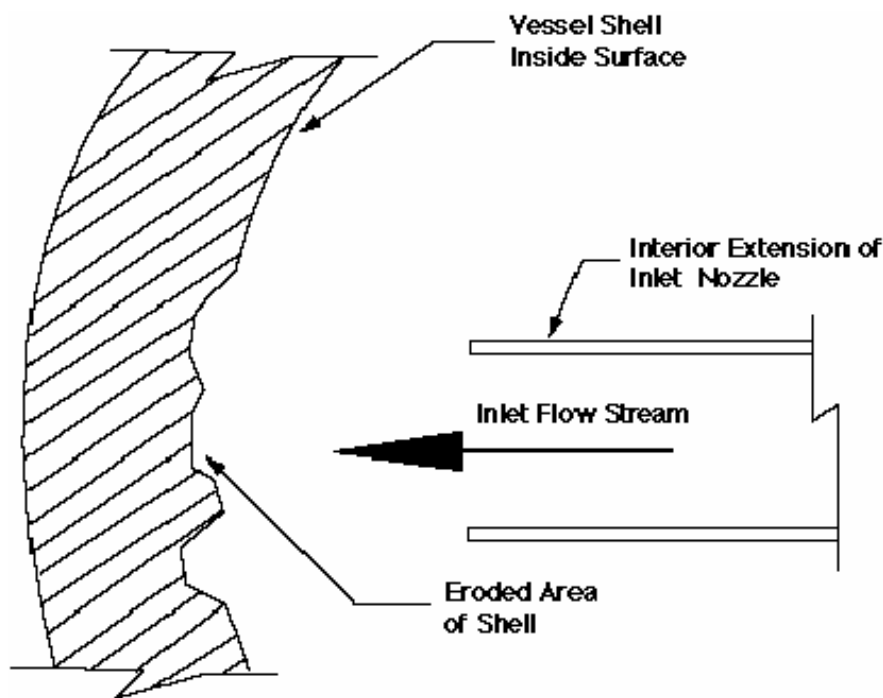


Figure 2: Erosion at Metal Surface

Metallurgical and Physical Changes

The service conditions that are inside pressure vessels may cause microstructural or metallurgical changes in the metal. These changes can affect the mechanical properties of the metal or can make the metal more susceptible to cracking or other forms of deterioration. The primary types of metallurgical and physical changes that are of interest in refinery pressure vessel applications are graphitization, high-temperature hydrogen attack, carbide precipitation and intergranular corrosion, and embrittlement.

Graphitization is a decomposition of the steel metallurgy in which carbon (graphite) is formed and in which the steel is embrittled and more prone to failure. Graphitization may occur in carbon or carbon molybdenum steels when these steels operate for long periods of time at temperatures that are in the range of 440-760°C (825-1440°F).

High temperature hydrogen attack and the Nelson Curves were discussed in MEX 202.02. At temperatures above about 230°C (450°F), steel that is exposed to hydrogen can become embrittled. This hydrogen embrittlement occurs due to the following: the dissociation of molecular hydrogen into atomic hydrogen, the diffusion of the atomic hydrogen into the steel, and the reaction of atomic hydrogen with carbon in the steel to form methane gas. The methane gas is then trapped in internal voids that are located within the steel. Except in cases where blisters are formed, high-temperature hydrogen attack cannot be found by visual inspection. Bend tests and microscopic examination are the normal methods to confirm the occurrence of high-temperature hydrogen attack, although experienced inspectors can detect internal hydrogen damage through the use of ultrasonic inspection instruments.

When unstabilized stainless steels are heated in the temperature range of approximately 510-790°C (950-1450°F) or are slowly cooled through this range, a complex carbide precipitates along the grain boundaries. Steels that are in this condition are more prone to intergranular corrosion that is caused by weak aqueous corrosive materials, particularly near the HAZ of welds. Severe intergranular attack of the carbides that have precipitated may occur due to moisture which may be present after a hydrostatic test, washing operations, or condensation in idle equipment.

High chromium ferritic steels, such as Types 405, 410, and 410S, are prone to embrittlement after long exposure to temperatures in the range 370-510°C (800-950°F). This embrittlement is caused by precipitation of a microscopic chromium-rich phase of the steel. Low chrome steels, such as 2-1/4 Cr-1 Mo and 1-1/4 Cr-1/2 Mo, are also prone to this embrittlement. This embrittlement, although making the steel more prone to crack formation, is reversible if a heat treatment is applied to the affected steel.

Mechanical Forces

Mechanical forces can result in vessel failure if they have not been properly considered in the design. The primary mechanical forces that are of concern are thermal shock, cyclic temperature changes, vibration, pressure surges, and high external loads. Excessive mechanical forces can cause upset of internal components, cracks, bulges, and permanent distortion. Such mechanical forces will typically have a localized effect on the pressure vessel or its internals. However, a localized failure can progress into a more general failure if sufficient load-carrying capacity is lost and if the local failure is not identified in time to take suitable corrective action.

Faulty Material

The use of faulty or incorrect material may cause problems with pressure vessels after they have been placed into service. Problems that are due to faulty material may be broad in scope and may, if they are severe, result in very rapid vessel deterioration. However, the likelihood that problems will occur due to faulty material is minimal as long as SAESs and SAMSSs are used for material inspection and as long as past experience and testing is used for material selection.

Faulty Fabrication

Faulty fabrication can include poor welding, improper heat treatment, dimensions that are outside acceptable tolerances, improper installation of vessel internals, and improper assembly of flanged or threaded joints. Problems that are due to faulty fabrication will typically be localized, such as weld cracks or flange leakage. As with faulty materials, the likelihood that problems will occur due to faulty fabrication is minimal as long as Saudi Aramco fabrication requirements are followed.

General Considerations Regarding Inspection Intervals

All new pressure vessels are inspected at the time of fabrication, as discussed in MEX 202.04. Internal field inspections of new vessels are normally not required as long as the ASME Code Manufacturer's Data Report (which confirms that the vessel meets the required technical specification) has been provided.

The type, extent, and frequency of pressure vessel inspection are based on the condition of the vessel, the environment in which the vessel operates (internal and external), and past experience with this and other vessels in similar applications. These inspections may be external, internal, or a combination of both. Various nondestructive techniques may be used for this inspection, and these techniques will be highlighted in a later section of this module. Some inspections may be done with the vessel in operation, while others can only be done with the vessel out of service, cleaned, and prepared for safe entry. In all cases, the inspection intervals and methods that are used are intended to ensure that the pressure vessel remains safe for continued operation, without any unplanned shutdowns, until it is inspected again.

The primary Saudi Aramco engineering document that is used to determine the required pressure vessel inspection intervals is SAEP-20, *Equipment Inspection Schedule*. SAEP-20 supplements requirements that are contained in API-510, *Pressure Vessel Inspection Code*. The *National Board Inspection Code* (NBIC) contains requirements that are similar to API-510 and provides additional detail and clarity in several areas. SAEP-20 does not refer to the NBIC, but it is still a good source of pertinent guidelines.

The NBIC does not have "National" application to the Kingdom of Saudi Arabia. Rather, the term "National" in the document title applies to its applicability in the United States (although not all states require its use). Within Saudi Aramco, the NBIC is used as a reference when repairs, modifications, or rerating is required.

SAEP-20 requires that an Equipment Inspection Schedule (EIS) be prepared as part of all new projects for pressure vessels that are in the following services:

- Utilities, production, processing, storage, and transportation of oil, gas, and by-products.
- Critical community facilities where failure could be hazardous or could cause serious inconvenience to the community.
- Critical equipment, defined as equipment that cannot be inspected by any means except during a Test and Inspection (T&I).

The EIS must be included in the Inspection Record Book as part of the Project Record Book. The EIS must be submitted for approval 30 days prior to facility completion. The EIS approval process must involve Saudi Aramco Project Management, as well as the facility's Operations Engineering and Inspection Unit. This approach to the development of vessel inspection requirements forces these inspection requirements to be considered early, results in permanent records, and involves all the appropriate technical areas.

The anticipated or measured rate of corrosion is the primary factor that determines the maximum permitted external and internal inspection intervals. Other special factors that could cause vessel deterioration in particular services are also considered in the development of the maximum permitted inspection intervals. Work Aid 1 may be used to determine the appropriate pressure vessel inspection intervals based on given corrosion rate information, in accordance with SAEP-20 requirements.

SAEP-20 also provides the flexibility to revise the external and internal inspection intervals that were originally developed for the pressure vessel based on actual experience and operational needs. Specific procedures and approval requirements for inspection interval revision are specified in SAEP-20 and must be followed in order to permit these inspection interval revisions. Participants are referred to SAEP-20 for additional information.

External Inspection Intervals

Informal pressure vessel inspections should be performed periodically by operations, maintenance, and inspection personnel during their normal course of doing other work in the area. These informal inspections merely involve being observant and aware of indications that appear to be abnormal. For example, visible signs of leakage, extreme vibration, or other obvious abnormalities should be brought to the attention of appropriate personnel for evaluation to determine an appropriate course of action. It is always preferable to identify potential problems as early as possible so that corrective action can be taken before these problems become more significant.

Formal external inspections, and Onstream Inspection (OSI) Performance, must be done at intervals that are determined in accordance with SAEP-20. SAEP-20 specifies when the initial OSI must be done after the vessel has first been placed in service, and SAEP-20 also specifies subsequent OSI intervals. The initial and subsequent OSI intervals are based on corrosion rate. Sufficient vessel component thickness measurements are made during the OSIs in order to determine the actual corrosion rates being experienced and to estimate the remaining vessel life. Information that is obtained during the OSIs may be used to help determine whether the specified internal T&I intervals should be lengthened or shortened.

Work Aid 1 summarizes the procedure for determining the required external inspection intervals.

Internal Inspection Intervals

Formal internal Test and Inspections (T&I) must be done at intervals that are determined in accordance with SAEP-20. SAEP-20 specifies when the initial T&I must be done after the vessel has first been placed in service, and SAEP-20 also specifies subsequent T&I intervals. The initial and subsequent T&I intervals are based primarily on corrosion rate but are also influenced by the vessel service, whether an internal coating is used, and inspection results. Sufficient vessel component thickness measurements are made during the T&Is in order to determine the actual corrosion rates being experienced and to estimate the remaining vessel life.

Work Aid 1 summarizes the procedure for determining the required internal inspection intervals.

Safety Precautions and Preparatory Work

Pressure vessel inspection must be done in a timely and thorough manner. However, nothing is more important than personnel safety. Therefore, the appropriate safety precautions must be followed both before and during the inspection. Appropriate preparatory work must also be done in order for the inspection to be undertaken in a thorough and efficient manner. The paragraphs that follow highlight these two areas.

Safety Precautions

Safety precautions are extremely important because of the limited access and confined spaces that are involved in pressure vessel inspection. Therefore, appropriate safety precautions must be taken both before the vessel is entered and during the inspection itself. The paragraphs that follow note several areas that must be considered. All locally established safety precautions and procedures, including all local work and entry permit procedures, must be followed before a vessel is entered.

The vessel that is to be inspected must be isolated from all sources of liquids, gases, or vapors. This isolation should be done through the use of blinds or blind flanges that have the appropriate ANSI/ASME B16.5 pressure Class for the design conditions. A closed block valve should not be relied upon as the only source of isolation.

The vessel should be drained, purged, cleaned, and gas-tested before it is entered. This preparation will minimize the danger due to toxic gases, oxygen deficiency, explosive mixtures, and irritating chemicals. Suitable protective clothing should be worn by all personnel who enter the vessel.

The use of nondestructive examination devices is required as part of the vessel inspection. These devices must meet the safety requirements that are appropriate in gaseous hydrocarbon atmospheres. These requirements would most likely necessitate the issuance of a hot work permit in accordance with established Saudi Aramco procedures. Details of precautions that should be followed when a vessel is entered are contained in API Publication 2217A, *Guidelines for Work in Inert Confined Spaces in the Petroleum Industry*.

Before the inspection actually begins, operations personnel and all persons who are working around the vessel should be advised that people will be inside the vessel. As a safety precaution, a worker should be posted outside the manway that is used for vessel entry, to stay in touch with the people who are inside the vessel and to get help should assistance be required. In the case of tall towers, it is advisable to post warning tags at all other manways as well. Workers who are inside a vessel should also be informed when any work will be done on the exterior of the vessel, so that they do not become alarmed should there be unexpected or unusual noises.

Preparatory Work

Existing vessel inspection records and past experience must be reviewed in order to anticipate what forms of deterioration may be present in the vessel and to plan the specific external and internal inspections that will be done. Once this inspection planning has been done, it is possible to determine what specific inspection tools are required. All the tools that are needed to conduct the vessel inspection should be checked for availability and proper working condition prior to beginning the inspection. This equipment check includes anything that is needed for personnel safety. Any necessary safety signs should be installed prior to entering the vessel. All necessary scaffolding, with appropriate safety rails, toeboards, and ladders, should be installed prior to beginning the inspection.

Typical inspection tools include items such as a thin-bladed knife, chisel or scraper, steel tape or rule, inspector's hammer, pit depth gauge, wire brush, magnet, crayons, notebook and pencil, and plastic bags for corrosion product samples. More specialized equipment which may be required for specific tasks may include ultrasonic and magnetic particle test equipment, a portable hardness tester, and a material testing machine. A more complete list of inspection equipment that may be needed is contained in API RP 572, *Inspection of Pressure Vessels*.

External Inspection Scope

Much of the external inspection of a pressure vessel can be done while the vessel is still in operation. In-service inspection will reduce the amount of time that the vessel must be out of service in order for the entire inspection to be completed. The paragraphs that follow highlight the primary areas that are inspected, along with typical deterioration that may be found. More detailed information can be found in API RP 572, *Inspection of Pressure Vessels*.

Ladders, Stairways, Platforms, and Walkways

External inspection should start with any ladders, stairways, platforms, and walkways that are connected to or bearing on the pressure vessel. The inspection should start with these items since they are needed to provide personnel access to other parts of the vessel for other inspections. Therefore, the structural integrity should be confirmed so that they are safe for inspection personnel to use later.

A visual inspection should be made for corroded or broken parts, cracks, bolt tightness, the condition of paint or galvanized material, wear of ladder rungs and stair treads, the security of handrails and ladder cages, and the condition of flooring on platforms and walkways. The visual inspection should be supplemented by hammering and scraping to remove corrosion products and permit more complete examination and assessment. Where corrosion appears to be severe, thickness measurements should be made to permit more detailed evaluation.

Foundations

Pressure vessel foundations are almost always constructed of steel-reinforced concrete, or structural steel that has been fireproofed. These foundations should be inspected for spalling, cracking, and settlement.

Anchor Bolts

The condition of anchor bolts cannot always be completely determined by visual inspection alone. The contact area between the bolt and any concrete or steel should be scraped and examined for corrosion. A sideways blow with a hammer is often used as a means to detect anchor bolt deterioration which may have occurred below the top surface of the foundation base. The anchor bolts should also be checked for visible distortion, which may indicate a foundation settlement problem. See Figure 3.

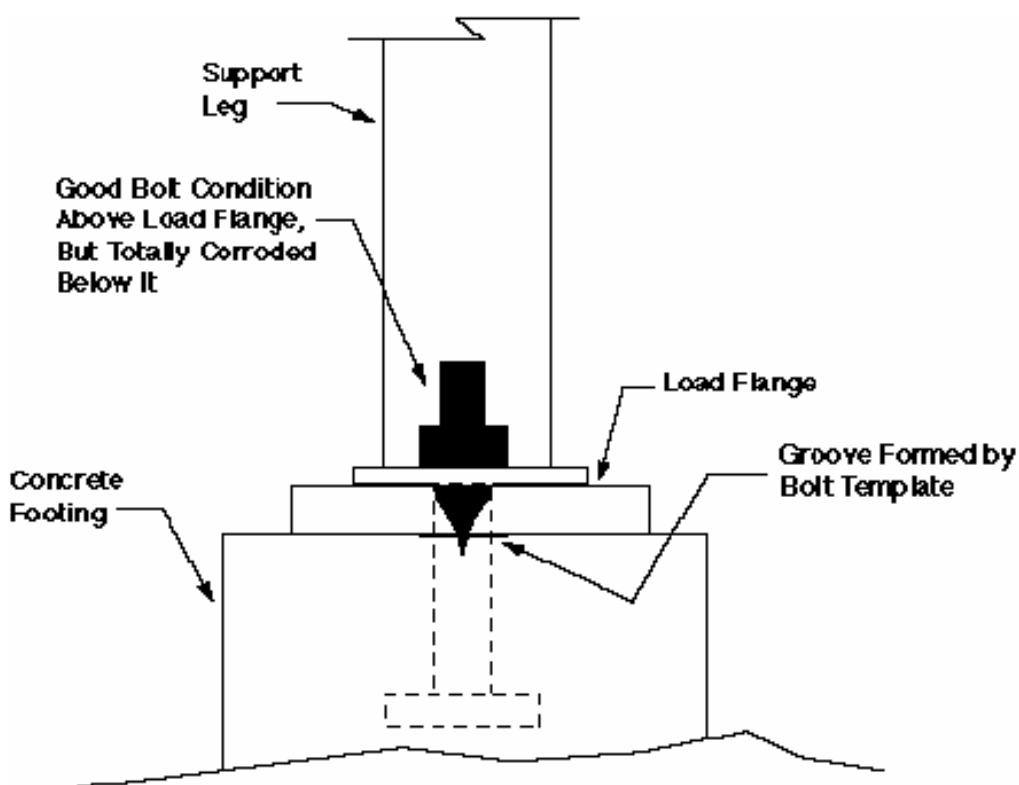


Figure 3: Anchor Bolt Deterioration Below the Surface

Supports

Any opening that is located between a concrete support and the vessel shell or head should be inspected to ensure that it is sealed to prevent the accumulation of water between the support and the vessel shell. A visual inspection, in conjunction with some picking and scraping, should reveal the condition of the seal. A concentration cell can form in this region if it is not sealed, and rapid corrosion can occur. The concrete support itself should be inspected for any cracking.

Steel supports should be inspected for corrosion, distortion, and cracking. The thickness of any areas of significant corrosion should be measured and evaluated for acceptability. Columns, load-carrying members, or skirt supports which have visibly distorted should be evaluated for adequate structural integrity.

Nozzles

The nozzles and adjacent areas of the vessel should be inspected for distortion, weld cracking, and damage or distortion to the flange faces. Nozzle distortion or cracks could be caused by excessive loads that are imposed on the nozzle by connected pipe or equipment. Flange face damage could be caused by improper handling practices during maintenance. If any distortion or damage is noted in the immediate area around the nozzle, the inspection should be extended to include all vessel seams in the area to ensure that there are no weld cracks.

Nozzles should be internally inspected, when possible, for corrosion, cracking, and distortion. Nozzle internal inspection is especially important in situations where erosion or high thermal gradients are expected. Nozzle wall thickness measurements should also be made.

Grounding Connections

Electrical grounding connections should be visually inspected to ensure that good electrical contact is maintained. Grounding connections provide a path for the harmless discharge of lightning or static electricity into the ground.

Auxiliary Equipment

Auxiliary equipment, such as gauge connections, sight glasses, and safety valves, should be visually inspected while the vessel is in operation. Leakage at flanged or threaded connections, or excessive vibration, should be noted for possible corrective action.

Protective Coatings and Insulation

External protective coatings, such as paint systems, are used to protect the vessel from external corrosion. Any coating deterioration should be noted by visual inspection. The usual indications of paint system failure are rust spots, blisters, and lifting of the paint film. The metal that is under areas of paint system failure should be inspected for corrosion thinning and pitting.

The insulation system should be visually inspected to ensure that its jacketing is intact and that the overall installation is sound. Failure of the external jacketing could permit water or other corrosive material that is in the atmosphere to get under the insulation and externally corrode the vessel shell, as illustrated in Figure 4. It is prudent to remove several samples of insulation to determine the condition of the insulation, metal shell, and insulation support clips that are located beneath it. If local areas of insulation system failure are noted, a more thorough external inspection of the vessel shell should be made to determine if any corrosion has occurred. Areas that are typically of most concern are near geometric changes in the vessel, such as at nozzles and support points. Proper jacket installation is more difficult at vessel geometric changes, and water can accumulate more easily at these sites.

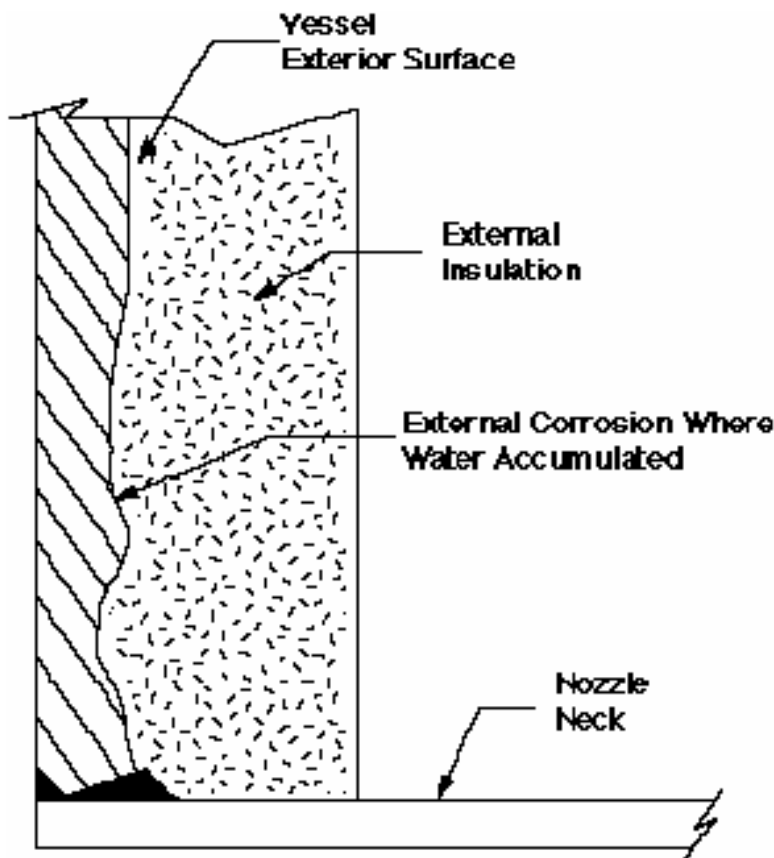


Figure 4: Corrosion Under Insulation

External Metal Surfaces

External vessel surfaces should be inspected for corrosion, leaks, cracks, buckles, bulges, material defects, and deformation and corrosion of external stiffeners. For externally insulated vessels, it is normal practice to remove small sections of insulation, to take thickness measurements, and to replace the insulation with more easily removable insulation plugs. Subsequent thickness measurements are then made at the same locations, so that corrosion rate trends can be monitored more easily. Special attention should be paid to locations where moisture or other corrosive material could accumulate under the insulation, as illustrated in Figure 4.

External metal surfaces are inspected for corrosion by first picking and scraping to locate corroded areas. Follow-up ultrasonic thickness measurements should be made in any corroded areas that have been identified. Thickness measurements of the vessel shell, heads, and nozzles are normally made at each complete vessel inspection. Thickness measurements may be made from outside or inside the vessel, based on the particular location and whether specific corrosion problems are anticipated.

Under normal circumstances, at least one thickness measurement is made in each shell ring and head of the vessel. However, if extensive corrosion is evident or expected, more extensive thickness measurements are required to completely define the situation. More extensive thickness measurements are also required in situations where there is limited corrosion history with a particular vessel or service.

External metal surfaces should also be inspected for cracks and distortions. Cracks are most often found at nozzle connections, welded seams, and attachment welds (such as at brackets or supports). A close visual inspection, with some picking and scraping, will locate most cracks. More extensive inspection is then required if cracks are found. Distortions of the metal surface are normally evident by visual inspection. When cracks or distortions are found, their extent should be measured, and an evaluation should be made to determine their root cause and acceptability.

Internal Inspection Scope

Periodic vessel external inspections, in conjunction with prior experience with the particular vessel and service conditions, help direct the extent of periodic internal inspections that will be required. The paragraphs that follow highlight the primary considerations for periodic vessel internal inspections. More detailed information can be found in API RP 572, *Inspection of Pressure Vessels*.

Surface Preparation

The amount of surface preparation that is required for an internal vessel inspection depends on the type and the location of deterioration that is expected. Normal cleaning methods such as hot water washing, steam or solvent cleaning, and ordinary scraping, are usually sufficient to permit adequate inspection. Where better cleaning is needed, the inspector's common hand tools will normally be sufficient.

More extensive cleaning methods, such as power brushing, abrasive-grit blasting, or power chipping, are sometimes required based on the circumstances. The more extensive cleaning methods are typically required when stress corrosion cracking, wet sulfide cracking, hydrogen attack, or other forms of metallic degradation are suspected. If extensive cracking, corrosion, or pitting are found, thorough cleaning over wide areas is required in order to permit a thorough inspection.

Preliminary Visual Inspection

The vessel internal inspection should always begin with a general, preliminary, visual inspection. The type of corrosion (uniform or pitting), the location and extent of corrosion, and any other obvious data (such as failed internal components) should be noted. The visual inspection should then concentrate on areas where problems could be anticipated based on the vessel service and past experience. The need for additional inspection, as required, should be noted. The paragraphs that follow highlight typical occurrences that should be considered.

- Pressure vessels that are in certain refinery services are subject to corrosion or other forms of attack that tend to concentrate in particular areas. Past experience should highlight the services and areas that are of particular concern. For example:
 - The bottom head and shell of fractionator towers that process high sulfur crude oil are prone to sulfur corrosion that tends to be most severe around the inlet lines.
 - The upper shells and top heads of fractionation and distillation towers are sometimes subject to chloride attack.

- Vessels that are exposed to wet hydrogen sulfide or cyanides are prone to cracks in the welds and HAZ.
- Concentration cell corrosion can occur in vessels where sludge can settle.
- Corrosion is often accelerated in weld and HAZ areas due to metallurgical changes which take place due to the heat of welding.
- In any vessel, galvanic corrosion may occur in locations where dissimilar metals are in close contact or are welded to each other.
- Cracks will most likely occur where there are abrupt geometric changes, such as at nozzles or in weld seams, if high local stresses are applied.
- Vessel shell sections that are adjacent to inlet flow streams or a flow impingement plate are prone to thinning that is caused by erosion. Special attention should be paid to the possibility of erosion in situations with relatively high velocity liquid flows, and to the presence of entrained solids in the flow stream.

The preliminary visual inspection will note areas that require additional cleaning and more detailed follow-up inspection in order to completely define the situation and permit suitable evaluation.

Detailed Inspection

The detailed internal inspection should be done using a systematic procedure that begins at one end of the vessel and works toward the other end. Special attention should be paid to suspect areas that were identified during the preliminary visual inspection. All parts of the vessel should be inspected for corrosion, erosion, hydrogen blisters, deformation, cracks, and laminations. Records should be made of the types and locations of any deterioration that is found. The paragraphs that follow highlight particular items that must be included in this detailed inspection.

- Thickness and size measurements should be made at areas that exhibit general corrosion or pitting. The number and location of the thickness and pit depth measurements that are made will depend on the extent of the deterioration that is found.
- Welded seams are more prone to the formation of cracks when the vessel is in particular services, or if the vessel is fabricated from particular materials. Therefore, the welds should be carefully checked for cracks in these cases.
 - Services that require special attention are amine, wet hydrogen sulfide, caustic, ammonia, cyclic/high temperature applications, or deaerator services.
 - Materials that require special attention are high-strength steels (above 10 152 kPa [70 000 psi] tensile strength), and low chrome steels that are in high temperature services.
- The depth and extent of any cracks that are found must be defined. This crack definition is typically done by the use of liquid penetrant, magnetic particle, and/or ultrasonic shear wave inspection techniques.
- Nozzles should be visually examined for internal corrosion or erosion, and thickness measurements should be made as required.
- Internal components, such as trays, catalyst support grids, and associated structural members should be visually examined for corrosion, erosion, and overall condition. Follow-up thickness and dimensional measurements should be made as required.
- Areas that are directly above or below the liquid level in vessels that contain acidic corrosive materials are subject to hydrogen blisters. The blister size and whether any cracks are associated with the blister should be determined.

Inspection of Metallic Linings

Internal metallic linings (cladding or weld overlay) are often installed to provide corrosion protection for the vessel base metal. Any failures of the metallic lining will subject the base metal to severe and rapid corrosion. Lining inspection is required to ensure that there is no corrosion, that the lining is still intact and properly attached, and that there are no cracks or holes in it.

A thorough visual inspection is normally all that is required to detect lining corrosion. Lining corrosion should not be a factor if the proper lining material was selected for the service conditions.

Cracked lining areas can normally be found by visual inspection and light hammering. Suspect areas of the lining should be inspected by the liquid penetrant method in order to define their extent.

Bulges that are found in a lining normally indicate that the lining has holes or cracks somewhere in the bulged section. The bulges are caused either by the buildup of material that has seeped behind the lining during operation or by differential thermal expansion. In any event, the base metal that is located behind the lining must be inspected for corrosion, and the lining damage must be found and repaired.

Inspection of Nonmetallic Linings

Glass, plastic, rubber, ceramic, concrete, refractory, and carbon block or brick internal linings may be used in pressure vessels. Refractory is the most common type of nonmetallic lining that is used in refinery applications and is the only type that will be discussed here.

Refractory is used primarily as an insulating material to reduce shell metal temperatures in very high temperature applications, such as in the reactor and regenerator vessels of Fluid Catalytic Cracking Units (FCCUs). Refractory may also be used to provide protection for the metal in erosive services. The use of refractory as erosion protection also applies in FCCUs. Failure of a refractory lining could expose the vessel metal to excessive temperature and/or excessive erosion.

Visual inspection, supplemented by light scraping or hammer testing, are the primary means that are used to evaluate the condition of refractory linings. The most likely forms of lining damage that may be found are excessive cracks, spalling, loose sections of lining, and bulges. The extent of this damage must be recorded, and a determination must be made regarding the need for repairs. If there is extensive lining damage, the metal that is located underneath the lining should also be inspected for possible damage that might be caused by high temperature or erosion.

It should be noted that it is normal for a refractory lining to exhibit a random pattern of relatively narrow cracks. This random crack pattern is caused by shrinkage that occurs during the refractory dryout operation. Cracks are only of concern when they are very wide and in a regular pattern and when they cause sections of the lining to become loose.

Thickness Measurement

The primary method that is currently used to measure component thickness is the ultrasonic technique. Ultrasonic inspection may also be used for flaw detection. Ultrasonic inspection was briefly discussed in MEX 202.04, and more information on ultrasonic inspection is included in COE 103.

Special Methods for the Detection of Mechanical Defects

Visual inspection will detect most mechanical defects. Other inspection methods, such as magnetic particle, liquid penetrant, shear wave ultrasonics, radiography, etching, and sample removal, may be used when the situation warrants more detailed examination.

- Radiography and shear wave ultrasonics are used to evaluate defects that are not visible on the surface.
- Etching of small areas of the metal surface is sometimes used to find small surface cracks.

- Small samples of suspect areas are sometimes removed to spot-check welds or to further investigate cracks, laminations, and other flaws. The hole that is left in the vessel wall from removal of the sample must be repaired and carefully inspected; therefore, this inspection approach is only taken under special circumstances.

The use of any of these inspection methods requires more extensive cleaning of the local areas of the vessel.

Metallurgical Changes and In-Place Metal Analysis

The methods that are used to detect mechanical changes can also be used to detect metallurgical changes that may have occurred. In-place metallography can be used to detect metallurgical changes through the use of portable polishing equipment and replica transfer techniques. Hardness measurements, chemical spot tests, and magnetic tests are three other methods that may be used to detect metallurgical changes.

Portable hardness testers may be used to detect locally hard areas that may be more prone to cracking. Faulty heat treatment, carburization, nitriding, decarburization, and other factors may result in local changes in hardness that could have wider implications with respect to vessel reliability.

Local chemical tests are typically used to detect the installation of incorrect materials. Chemicals such as nitric acid in various concentrations are typically used for these chemical tests.

Steels that are normally nonmagnetic usually become magnetic when they are carburized. Therefore, carburization of austenitic stainless steel can sometimes be detected through the use of a magnet.

Inspection and History Report

An Inspection and History Report documents the results of a pressure vessel inspection that is done during a T&I. A typical pressure vessel Inspection and History Report will include at least the following sections:

- Identification and Documentation Information. This section includes items such as the vessel identification number and name, vessel location, vessel service, date of inspection, and inspector's name.
- Scope and History. This section specifies the scope of the current inspection as well as the inspection methods that were used (such as visual observations and ultrasonic measurements). The use of any special inspection techniques should be documented.

This section also summarizes the pressure vessel's history, such as when it was placed into service, when the last T&I was done, and any significant inspection findings or repairs that were made during the last T&I. The Equipment Inspection Schedule (EIS) with the associated Onstream Inspection (OSI) and Test & Inspection (T&I) intervals are not a part of the Inspection and History Report, but they may be referred to if required as part of the evaluation.

The inspector should have reviewed the operating history of the pressure vessel and should have identified any process difficulties that occurred during the last period of operation prior to the T&I. Anything unusual in the operating history should be documented in the report since it might have contributed to problems that are noted during the inspection. This pressure vessel history review should also include whether any problems were found on similar equipment during their T&Is that affected how the current inspection was conducted.

- **Observations and Recommendations.** This section provides the results of the inspection and is divided into subsections based on the main pressure vessel components (such as shell sections, heads, nozzles, and support). The visual observations of the inspector are recorded for each component, as well as the results of any measurements (such as thickness readings) that are made. One or more sketches of the pressure vessel will normally be included in order to identify the locations of the thickness measurements or other observations that are made. Locating the observations and measurements in this manner helps to identify the potential causes of problems and permits inspection at the same locations during subsequent T&Is. Inspection of the same locations during T&Is helps to establish trends in pressure vessel deterioration, especially corrosion.

The complete information file for the pressure vessel will include the Pressure Vessel Data Sheet (Form 2682 or Form 2683 as appropriate), the pressure vessel Safety Instruction Sheet (Form 2694), and the vessel fabrication drawings. It may be necessary to refer to this additional information in order to evaluate the current inspection data. However, this additional information is not part of the Inspection and History Report.

Figures 5 and 6 provide overall formats that summarize the primary sections and information that are combined in an Inspection and History Report.

Identification and Documentation Information	
Scope and History	
Observations and Recommendations	
Item	Observations/Recommendations
Shell	
Conical Section	
External Heads	
Internal Heads	
Nozzles	
Flanges	
Vessel Support	
Support Foundation	
Internal Lining	
Internal Cladding or Overlay	
Trays and Downcomers	
Internal Distribution Piping	
Catalyst Support System	
Paint System	
Insulation System	
Ladders, Stairways, Platforms	
Auxiliary Equipment (Gage connections, sight glasses, etc.)	
Grounding Connections	

Figure 5: Components of Inspection and History Report

**Vessel Sketch With
Thickness Measurement Points
Prepared By Inspector**

Wall Thickness Measurements							
Point Number	Original Nominal Thickness	Minimum Required Thickness	Inspection Date				

Figure 6: Inspection and History Report
Thickness Measurement Data

DETERMINING THE SUITABILITY OF CORRODED PRESSURE VESSELS FOR CONTINUED OPERATION

Since pressure vessel components will corrode during operation, their suitability for continued operation must be determined. The paragraphs that follow discuss the approach that is used for this evaluation. This approach includes the following essential considerations:

- Determining minimum actual thickness.
- Assessing the acceptability of the corroded areas.
- Determining actions that can be taken if corroded areas are not acceptable.

Each of these considerations is discussed below.

Determining Minimum Actual Thickness

A complete evaluation of an existing pressure vessel for continued operation must consider the entire vessel, all the loads that are imposed on it, and all the potential forms of vessel deterioration. This module only discusses corrosion evaluation since corrosion is the most common form of deterioration that limits vessel integrity. This module will primarily discuss internal pressure loads since they are the most common factor that limits vessel suitability for operation. Participants are referred to the Consulting Services Department for assistance in the evaluation of other forms of pressure vessel deterioration.

The minimum actual thickness of pressure vessel components must be determined before the condition of an existing pressure vessel can be evaluated. Thickness data are obtained from the periodic vessel inspections that are made. In determining thicknesses that are measured, and how these thicknesses are treated, the factors listed below must be considered:

- Type of corrosion
- Major vessel sections
- Type of loading
- Location of corrosion relative to welds

The required procedures for determination of the minimum actual thicknesses to use in the evaluation of corroded regions of a pressure vessel are contained in Work Aid 2.

Types of Corrosion

Corrosion may take the form of a uniform metal loss, or may occur by leaving a pitted appearance. Uniform corrosion is a general, even wastage over a surface area. Pitting corrosion has an obvious, irregular surface appearance. Uniform corrosion may be difficult to detect visually, and thickness measurements are required to determine its extent. Pitted surfaces may be thinner than they appear visually, and thickness measurements are typically required for pitted areas as well. Uniform and pitting types of corrosion are illustrated in Figures 7 and 8. These types of corrosion must be evaluated differently.

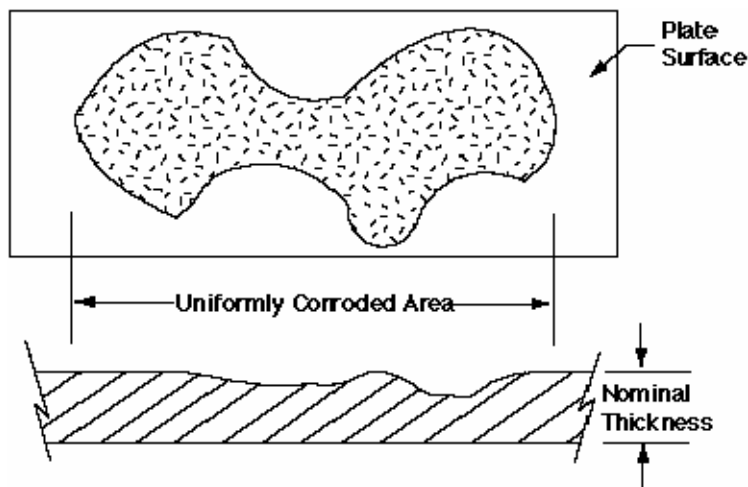


Figure 7: Uniform Type Corrosion

Recall that MEX 202.03 discussed procedures for calculation of the wall thickness of various pressure vessel components. For example, a uniform minimum required wall thickness was calculated for an applied internal pressure. Uniform corrosion results in a thinner vessel component over a relatively large area. This relatively uniform thinning will make the component suitable for less severe conditions than it was originally designed for.

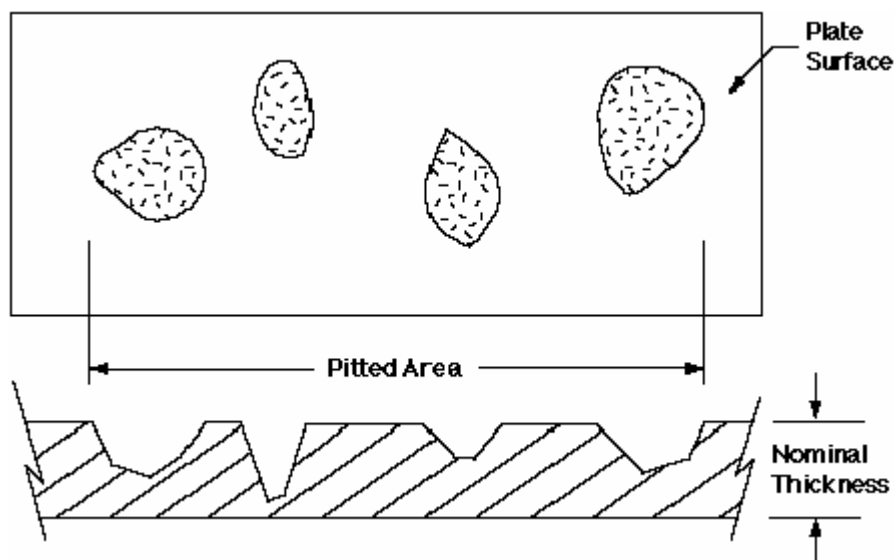


Figure 8: Pitting Type Corrosion

From a practical standpoint, even nominally uniform corrosion will not result in exactly the same thickness throughout a vessel component, even in relatively local regions of the component. It is permissible, but conservative, to use the minimum thickness that is measured anywhere in the uniformly corroded region for evaluation purposes. However, areas of the component that are thicker will tend to reinforce adjacent areas that are thinner. This reinforcement concept is similar to the nozzle reinforcement calculation requirements that were discussed in MEX 202.03. Therefore, it is permissible to "average" the measured thicknesses over a larger area in order to arrive at a constant thickness that will be used in the evaluation of a uniformly corroded region. API-510, *Pressure Vessel Inspection Code*, provides a procedure to determine the minimum actual thickness to be used in the evaluation of a uniformly corroded region. The API-510 procedure is contained in Work Aid 2.

Pitted regions on the surface of a pressure vessel are plainly visible and have the appearance of craters or locally thinned regions that are surrounded by thicker areas. These thicker areas act as local reinforcement. Because of this local reinforcement, the pitting must be fairly extensive and deep before it will have a practical impact on vessel integrity. The pitting can actually be ignored if it can be classified as "widely scattered." If pitting cannot be classified as widely scattered, pitting corrosion is evaluated with the same approach as for uniform corrosion. Pit depth, size, and area measurements must be made in order to determine if the pits can be considered widely scattered and if they may be safely ignored. API-510 provides a procedure to determine whether pitting can be considered as widely scattered. The API-510 procedure is contained in Work Aid 2.

Major Vessel Sections

The pressure vessel must be divided into major sections, and the minimum actual thicknesses to use in the integrity evaluation must be determined for each major section. It may also be necessary to subdivide these major sections further and to evaluate the smaller regions separately, based on the type and extent of corrosion that is found and on the size and geometry of the section. Each section of the vessel is evaluated separately, and the section that limits the overall operation of the vessel is then determined based on the weakest section. This concept of identifying the weakest section of a pressure vessel is the same as the approach to MAWP calculation that was discussed in MEX 202.03.

Division of the vessel into major sections may be based on the following factors:

- Geometry. For example, cylindrical or conical shells, heads, and nozzles can each be considered as a separate section of a vessel.
- Thickness. There may be a thickness transition between two adjacent cylindrical shell sections, and each shell section should be evaluated separately.
- Material. Different materials may be used in different vessel sections due to different design conditions and/or corrosion rates.
- Corrosion rates and types. Experience may indicate that corrosion rate or type may vary in different parts of the vessel, and different sections of the vessel may therefore require separate evaluation.
- Changes in Design Conditions. Design conditions may vary in different sections of the vessel, such as temperature variations in a tall tower. Therefore, the different sections of the vessel should be evaluated separately.

Type of Loading

The type of loading that governs the design of a vessel section determines how the minimum actual thickness is determined. For the primary shell and head sections of a pressure vessel, it should be determined whether the governing stress is in the circumferential or meridional (axial) direction, since the direction of the governing stress will govern the direction of the thickness measurements. Thickness measurements should be made along lines in the meridional (axial) direction in vessel sections where the required thickness is governed by circumferential stress. Thickness measurements should be made along lines in the circumferential direction in vessel sections where the required thickness is governed by longitudinal stress. The concept of shell thickness measurement direction is illustrated in Figure 9, and additional details are provided in Work Aid 2.

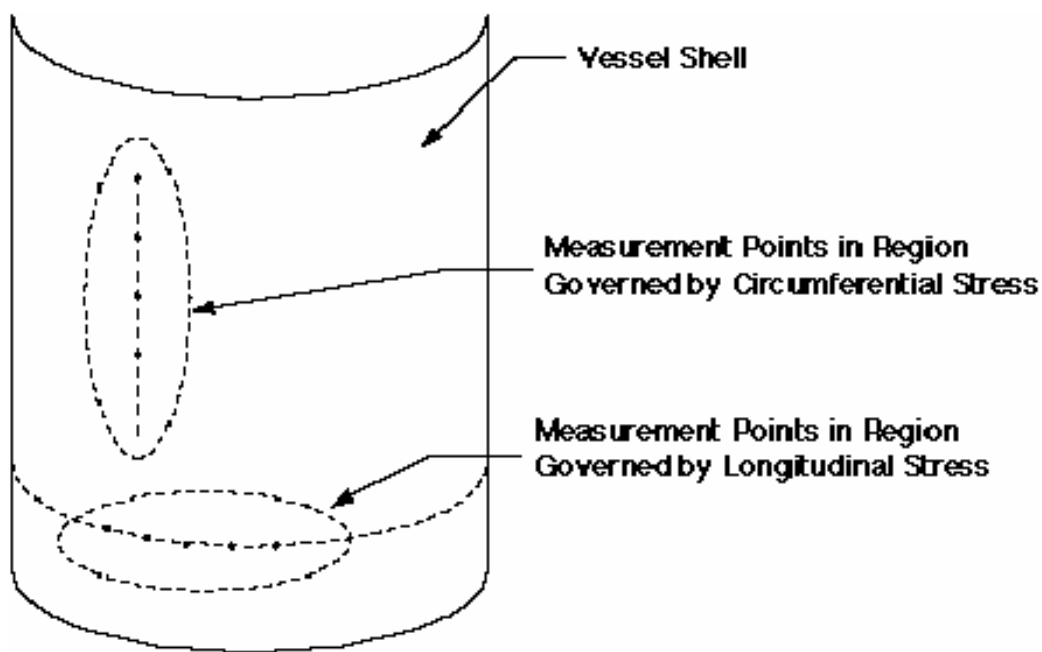


Figure 9: Direction of Thickness Measurements

If the design of a particular vessel section is governed by local load conditions, and if there is significant corrosion in that section, sufficient thickness measurements should be made to permit a local stress calculation. For example, if the reinforcement design of a nozzle is governed by the loads that are imposed by the connected pipe, enough thickness measurements should be made to permit calculation and evaluation of the local nozzle and shell stresses. MEX 202.03 discussed the evaluation of loads that are applied at a vessel nozzle.

Other special cases where localized loads and corrosion must be considered are at cone-to-cylinder junctions, stiffener ring locations, and vessel support attachment locations. In all these cases, sufficient thickness measurements should be made to permit adequate evaluation of the local area for the applied loads.

Location of Corrosion Relative to Welds

Recall from MEX 202.03 that a weld joint efficiency is used to determine the required wall thickness for vessel components such as shells and heads. For existing pressure vessels, the weld joint efficiency must be considered only for the weld itself and areas of the component that are adjacent to the weld. The weld joint efficiency does not need to be considered in regions away from the weld because the weld strength and quality do not affect regions of the base metal that are away from the weld. Therefore, regions that are away from the weld do not have to be penalized by the weld joint efficiency. Accordingly, the thickness measurements that are made should indicate their location relative to any nearby shell or head welds. In this manner, the weld joint efficiency is not used in the vessel evaluation if it is not necessary to do so.

API-510 defines the distance from a weld where the joint efficiency still applies, as contained in Work Aid 2.

**Sample Problem 1 -
Determining Minimum
Actual Thickness of
a Corroded Region**

Thickness measurements have been made on the cylindrical shell of a pressure vessel during a T&I. Figure 10 and the thickness measurements in Figure 11 have been taken from the Inspection and History Report that was prepared. For this vessel, determine the following:

- The maximum distance, $L_{\max}$, over which thickness measurements can be averaged.
- The minimum number of thickness readings that can be averaged.
- The average wall thickness for the vessel shell that should be used in subsequent evaluations.

Work Aid 2 may be used to solve this problem.

For this vessel, assume that internal pressure, rather than weight and wind loads, governs the design.

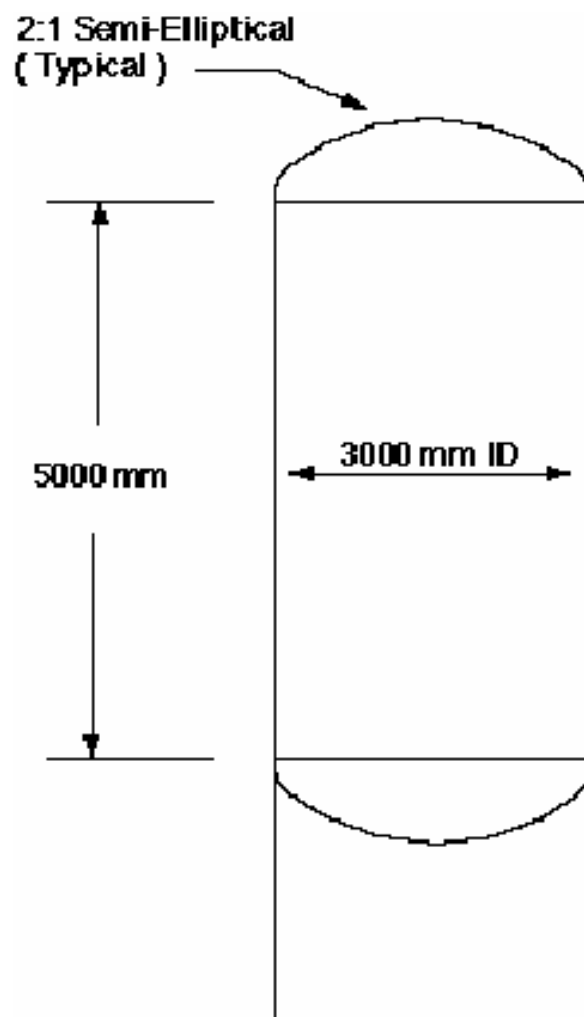


Figure 10: Sample Problem 1 Vessel

Point	Distance From TTL,	Thickness Measurements Along Four Longitudinal Lines Along Shell, mm			
		N	E	S	W
1	0	12.3	12.4	12.2	12.2
2	250	12.4	12.3	12.1	12.1
3	500	12.5	12.4	12.2	12.2
4	750	12.4	12.3	12.2	12.2
5	1 000	12.3	12.2	12.2	12.2
6	1 250	12.1	12.0	12.2	12.1
7	1 500	12.1	12.0	12.1	12.1
8	1 750	12.6	12.3	12.2	12.0
9	2 000	12.7	12.7	12.2	12.0
10	2 250	12.3	12.2	12.0	12.0
11	2 500	12.5	12.4	11.8	12.0
12	2 750	12.6	12.5	12.1	12.0
13	3 000	12.7	12.6	12.2	12.0
14	3 250	12.3	12.2	12.3	12.0
15	3 500	12.6	12.5	12.3	12.0
16	3 750	12.7	12.7	12.3	12.0
17	4 000	12.3	12.1	12.3	12.2
18	4 250	12.3	12.2	12.4	12.2
19	4 500	12.5	12.4	12.4	12.3
20	4 750	12.2	12.1	12.5	12.4
21	5 000	12.1	12.2	12.5	12.5

Figure 11: Sample Problem 1 Thickness Data

Solution:

- (a) Since $D_o = 3\,048\text{ mm} > 1\,500\text{ mm}$, $L_{\max} = 1\,000\text{ mm}$
- (b) API-510 does not give guidance on the number of readings in $L_{\max}$ that should be used to get a good average, but typically a minimum of 5 data points should be used. If local thinning is a concern, a maximum distance of 50 mm between measurement points is typically used.

Minimum number of readings per $L_{\max} = 5$

Maximum distance between readings = $L_{\max}/4 = 250\text{ mm}$

- (c) For the thickness measurements given, the minimum thickness can be found by inspection of the data. The average thickness, " t_{avg} ", can be found for a section of the shell that is $L_{\max}$ long and that passes through this minimum thickness point.

$t_{\min, \min} = 11.8\text{ mm}$ Occurs at point 11 on the S plane.

$t_{\text{avg}, \min} = 12.06\text{ mm}$ Based on averaging 5 readings about the above point.

However, note that there is a row of 12 mm thickness readings in the "W" plane. Averaging these thickness readings results in a minimum average thickness in the shell of 12 mm.

Alternative Procedure:

Alternatively, the shell can be divided up into sections that are $L_{\max}$ long starting at Point 1. A value for " $t_{\min}$ " can then be found for each section of the shell.

		N	E	S	W
Section 1	$t_{\text{avg}} =$	12.38	12.32	12.18	12.18
	$t_{\min} =$	12.3	12.2	12.1	12.1
	$t_{\text{avg, min}} =$	12.18 mm			
	$t_{\min, \min} =$	12.1 mm			
Section 2	$t_{\text{avg}} =$	12.36	12.24	12.18	12.08
	$t_{\min} =$	12.1	12.0	12.1	12.0
	$t_{\text{avg, min}} =$	12.08 mm			
	$t_{\min, \min} =$	12.0 mm			
Section 3	$t_{\text{avg}} =$	12.56	12.48	12.06	12.00
	$t_{\min} =$	12.3	12.2	11.8	12.0
	$t_{\text{avg, min}} =$	12.00 mm			
	$t_{\min, \min} =$	11.8 mm			
Section 4	$t_{\text{avg}} =$	12.52	12.42	12.28	12.04
	$t_{\min} =$	12.3	12.1	11.8	12.0
	$t_{\text{avg, min}} =$	12.04 mm			
	$t_{\min, \min} =$	12.0 mm			
Section 5	$t_{\text{avg}} =$	12.28	12.20	12.42	12.32
	$t_{\min} =$	12.1	12.1	12.3	12.2
	$t_{\text{avg, min}} =$	12.20 mm			
	$t_{\min, \min} =$	12.1 mm			
Minimum $t_{\text{avg}} =$		12.00 mm			

The minimum average thickness for the shell is termed " t_{actual} " and is used for subsequent calculations. This sample problem demonstrates that the minimum average thickness of the vessel will not necessarily be around the point of the minimum actual thickness. It should also be noted that subsequent evaluations may account for the actual pressure at a given elevation along with the minimum average thickness at that elevation.

Acceptability of Corroded Area

After the minimum actual thicknesses for the different sections of the pressure vessel have been determined, the vessel is then evaluated for acceptability. Each corroded area is evaluated separately, and a decision is made with regard to the vessel's suitability for continued operation at the specified design conditions.

In very broad terms, the goal is to confirm that the MAWP of the vessel in the corroded condition is still acceptable for the required design conditions. This determination must consider both the current thicknesses of the vessel components and the expected future corrosion that will take place before the next vessel inspection. This evaluation can be done through use of the following methods:

- Determine the remaining life of the vessel and maximum permitted subsequent T&I interval, based on the minimum actual thicknesses (less future corrosion) and the required thicknesses of the primary vessel sections. The vessel is acceptable as long as the remaining life is acceptable and as long as the permitted T&I interval is at least as long as that required by SAEP-20.
- Determine a revised MAWP of the vessel based on the minimum actual thicknesses of each corroded section (less future corrosion). The vessel is acceptable as long as the revised MAWP exceeds the required design pressure. Calculation of the MAWP was discussed in MEX 202.03.

- Calculate the stresses in the vessel components for the actual thicknesses (less future corrosion), and compare these stresses to their allowable values to determine acceptability.

The first approach is the most direct and the quickest; also, the first approach minimizes the number of calculations that are required. All the information that is needed is available from the inspection results in the Inspection and History Report and the vessel Safety Instruction Sheet, Form 2694. Form 2694 was discussed in MEX 202.03. The second approach is only necessary if it is found that either the remaining life of the vessel or T&I interval is not acceptable, and a decision must be made whether to repair the vessel or rerate the vessel to less severe design conditions. The third approach is normally only required when it is necessary to evaluate local load conditions or if a detailed Division 2 stress analysis is required to determine the acceptability of locally corroded regions.

The vessel evaluation is normally based on the requirements of the Code to which the vessel was built. This method is consistent with the minimum thickness requirements that are on Form 2694 for the vessel. However, a later edition of the Code may be used if desired, as long as the vessel meets all the requirements of the later Code edition.

It is also permissible to perform a Division 2 detailed stress analysis of corroded regions of a vessel if it is felt that this analysis would be advantageous. If the Division 2 analysis approach is used, the following procedures are employed:

- The allowable stress that was used in the original design must be used in place of the Division 2 design stress intensity, as long as this allowable stress is less than or equal to $2/3$ of the Specified Minimum Yield Strength (SMYS) of the material at the design temperature.
- If the original allowable stress exceeds $2/3$ of the SMYS of the material at the design temperature, then $2/3$ of the SMYS is to be used for the Division 2 design stress intensity.

Work Aid 2 summarizes the procedure to use for the evaluation of a corroded area for acceptability based on the remaining life and subsequent T&I interval requirements.

Potential Actions if Corroded Areas Are Not Acceptable

If a corroded area of a pressure vessel is found to be unacceptable for continued operation, only two options are available:

- Repair the corroded area as needed to make it acceptable for the required design conditions.
- Rerate the vessel to less severe design conditions.

Repair of the corroded area restores the vessel to the strength that is required to withstand the specified design conditions. Restoration of the vessel integrity in this manner will thus not have any effect on future process operations. Several repair options are available. The choice of which repair option to use depends on the nature and extent of the corrosion and the vessel material of construction. Several of these options will be discussed in a later section of this module.

In some cases, it may not be practical to repair the vessel due to either the extent and cost of the required repairs or to the time it would take to make the repairs. If the vessel is not repaired, it can only be returned to service at less severe design conditions. This reduction in vessel capability can affect process operations because the mechanical strength of the vessel is now a restriction on how the vessel may be operated. Rerating a pressure vessel to less severe conditions will be discussed in a later section of this module.

DETERMINING THE APPROPRIATE DESIGN AND FABRICATION DETAILS FOR WELDED REPAIRS OR ALTERATIONS

Pressure vessel repairs and alterations must be done in a manner such that the resulting vessel integrity is comparable to that of new construction. The paragraphs that follow discuss appropriate design and fabrication details that may be used to ensure that welded repairs or alterations are effective.

Classification of Repairs and Alterations

There is a distinction between a repair and an alteration on an existing pressure vessel. This distinction must be understood in order to determine appropriate design and fabrication details and whether a subsequent hydrostatic pressure test is required. A hydrostatic pressure test is normally required after alterations but may not be required after repairs. Repairs and alterations are defined in API-510, as described in the paragraphs that follow.

Repair

A repair is the work that is necessary to restore a pressure vessel to a condition that is suitable for safe operation at the design conditions. If any restorative changes result in the need to change the design pressure or design temperature, the requirements for rerating the vessel must also be satisfied. Rerating is discussed in a later section of this module. Several examples of repairs are as follows:

- Weld repair or replacement of pressure parts or attachments that have failed in a weld or in the base material.
- The addition of welded attachments to pressure parts, such as studs for insulation or refractory lining, ladder clips, brackets, tray support rings, strip lining, corrosion resistant weld overlay, and weld buildup of corroded areas.

- Replacement of pressure-containing parts that are identical to those that exist in the pressure vessel and that are described on the original ASME Code Manufacturers' Data Report. The following are examples:
 - Shell or head replacement in accordance with the original design.
 - Rewelding a circumferential or longitudinal seam in a head or shell.
 - Replacement of nozzles that are of a size where reinforcement is not a consideration.
- Installation of new nozzles or openings of such a size that reinforcement is not a consideration. For example, a 76 mm (3 in.) or smaller pipe size nozzle in a shell or head that is 10 mm (3/8 in.) or less thickness, or a 50 mm (2 in.) pipe size nozzle into a shell or head of any thickness.
- The addition of a new nozzle where reinforcement is a consideration, provided that the nozzle is identical to one in the original design, that the nozzle is located in a similar part of the vessel, and that the nozzle is not closer than three times its diameter from another nozzle.
- Installation of a flush patch or replacement of shell courses.
- Replacement of slip-on flanges with weld neck flanges, or vice versa.

Alteration

An alteration is a physical change in any component that has design implications which affect the pressure-containing capability of a pressure vessel beyond the scope of the items that are described on the original ASME Code Manufacturers' Data Report. Several examples of alterations are as follows:

- An increase in the MAWP or design temperature, regardless of whether or not a physical change was made to the vessel.
- A decrease in the minimum design temperature such that additional mechanical tests are required (such as impact tests).
- The addition of new nozzles or openings, except for those that may be classified as repairs.
- The addition of a pressurized jacket to a pressure vessel.
- Replacement of a pressure-containing part with a material that has a different allowable stress or nominal chemical composition from that used in the original design. (However, such a replacement may be considered a repair if the material satisfies the material and design requirements of the original construction Code that was used for the vessel.)

Defect Repairs

Unacceptable defects that are found during a T&I, such as cracks or excessively corroded areas, must be repaired before the pressure vessel can be returned to service at the specified design conditions. The particular method that is used for the repair depends primarily on the type and extent of the defect.

In all cases, the repaired area must be inspected for acceptability. The inspection method that is used and the extent of inspection depends on the type and extent of repairs that are made. The basic intent of inspection after repair is for the repair welds to receive the same level of quality control that the original construction welds received. This will typically involve PT or MT inspection of weld overlay type repairs and RT and/or UT examination of full penetration type weld repairs. The required procedures and acceptance criteria for the actual inspection method that is used is the same as for new construction, as was discussed in MEX 202.04. The inspection requirements are developed at the same time as the repair procedures are developed. The Consulting Services Department should be consulted as required.

The paragraphs that follow discuss several different weld repair options that may be considered, based on API-510 and Saudi Aramco and industry practice. Work Aid 3 summarizes an overall procedure which may be used to determine appropriate repair and alteration procedures.

Cracks

Whenever cracks are found, an evaluation should always be made to identify their root cause and to eliminate it, rather than to just repair the cracks. For example, cracks may be due to the following:

- Original construction defects that were not found.
- High local stresses that are caused by applied loads or thermal gradients.
- More general material degradation, as might be caused by hydrogen attack, caustic cracking, or stress corrosion cracking.

The Consulting Services Department should be consulted as required for the determination of the root cause of cracks.

Crack repair cannot be made until the crack has first been completely removed. Crack removal before repair is necessary in order not to leave a geometric discontinuity at the repair location. Such a geometric discontinuity could act as a stress concentration point and could be a location for new crack initiation after the vessel is returned to service. Crack removal is typically done by grinding the crack to sound metal and by performing a PT or MT inspection to confirm that the crack has been completely removed. It is common to find that cracks which are thought to be fairly small may actually be much longer and deeper than originally expected. The grinding and subsequent inspection of cracks will define their complete extent.

After the crack has been completely removed, the area must be prepared for welding. This weld preparation will typically be in the form of a U- or V-shaped groove that extends the full length and depth of the crack. If the crack extends through the full thickness of the material, the preparation should be for a full penetration double-butt weld or for a single-butt weld with or without a backing strip. The area that is to be welded is then filled with weld metal through the use of a qualified weld procedure.

It should be noted that it might not always be necessary to do a weld repair after grinding out a crack. If the crack is shallow enough such that the remaining vessel thickness after grinding is still acceptable for continued operation, subsequent weld repair is not required. If weld repair is not necessary, the area of the ground out crack should be blended into the adjacent material so that there are no sharp corners that could act as stress concentration points. Blend grinding a crack is illustrated in Figure 12.

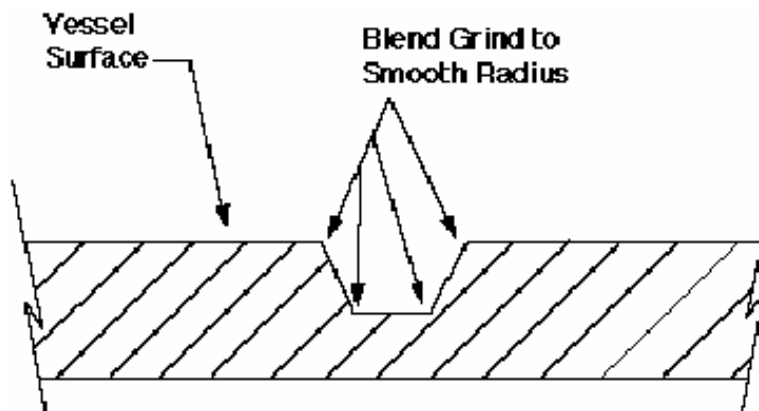


Figure 12: Blend Grinding a Crack

Corroded Areas

Several repair options are available for areas that have experienced excessive corrosion. The approach that is taken depends primarily on the extent of the corrosion and or the cost and time that are required to make the repair. These options are highlighted below.

- Relatively small corroded areas may be repaired by weld overlay, provided that it is determined that this approach will not reduce the overall strength of the vessel. Strength should not be an issue as long as appropriate weld procedures and qualifications have been developed and as long as the repaired area has been inspected. Use of weld overlay does not require any weld preparation other than cleaning the surfaces to be welded.

- Nozzles may be installed to encompass relatively small corroded areas. The nozzles are made large enough to extend beyond the corroded area.
- A larger corroded area of a shell or head may be repaired by removing it and replacing it with an insert patch that is welded into the vessel with full-penetration welds, as illustrated in Figure 13. The insert patch is fabricated with rounded corners in order to minimize local stress concentrations. Extensive corrosion may require replacement of major shell or head sections or other vessel components such as nozzles.

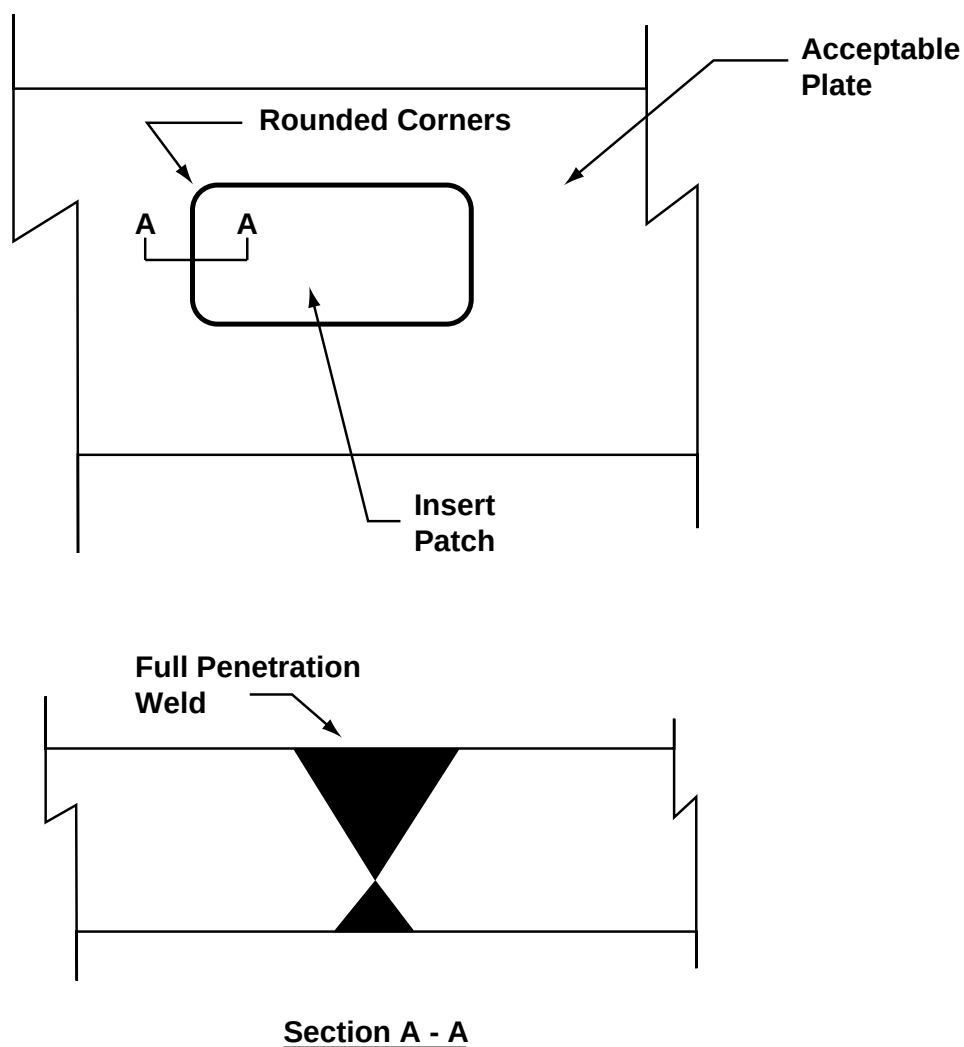


Figure 13: Insert Patch Repair

- Corroded areas of flange faces may be thoroughly cleaned and built up with weld metal. The flange faces then must be remachined to provide the required contact surface to seal against the gasket. The weld buildup and subsequent machining must be done such that the flange thickness is not less than the thickness required by the original design. Use of less than the original flange design thickness must be verified as acceptable based on calculations that are done in accordance with ASME Code criteria.

Welding

All pressure vessel repairs and alterations must be done in accordance with the principles that are contained in the ASME Code, as modified by the applicable SAESs and SAMSSs that were discussed in MEX 202.04. However, it is recognized that specific ASME Code and Saudi Aramco welding requirements may be difficult to apply in all cases. This difficulty arises because the ASME and Saudi Aramco requirements are for new construction that is done in a fabrication shop, whereas repairs and alterations to existing pressure vessels are done under field conditions.

It is always preferable to make vessel repairs and alterations based on the same welding requirements that are used for new construction. However in situations where this approach may not be practical, alternative approaches may be considered as long as they are technically acceptable for the intended purpose. The Consulting Services Department should be contacted for assistance as required, especially if it is necessary to deviate from ASME Code and Saudi Aramco original construction requirements. The paragraphs that follow highlight several specific topics.

Procedures and Records

Before any welding is done, welding procedures must be prepared and qualified, and the welders who will perform the work must be qualified to the procedures. The same welding procedure and welder qualification review and approval process that is used for new vessel construction must also be used for the welding that is done for repairs and alterations. These qualification requirements were discussed in MEX 202.04. The intent here is that there should be no distinction between original construction welds and repair or alteration welds with respect to welding procedure and welder qualification requirements.

Repair and alteration welding will typically be done manually rather than through the use of automatic or semi-automatic equipment. Such welding will also be done under field conditions rather than shop fabrication conditions. Therefore, it is extremely important that the welding procedure and welder qualifications be performed in the positions and with any restrictions that will be encountered in the actual vessel. For example, if repair welding will be done in a very restricted space and overhead, these conditions should be duplicated to the extent possible in the procedure and welder qualification tests. A procedure or welder may be able to pass the qualification test under ideal conditions, but either the procedure or the welder may be unacceptable under the actual field conditions that must be dealt with.

Welding procedure and welder qualification records must meet the same requirements that are used for new vessel construction. Here again, the intent is to have no difference between original construction and repair or maintenance welding with respect to record keeping and accountability. These records will have added importance in situations where a subsequent failure occurs at a location that has been repaired or altered, since the records might help in the development of an alternative repair approach.

Alternatives to PWHT

A pressure vessel may have been given a PWHT as part of its original fabrication. This PWHT may have been based on either stress relief considerations in accordance with ASME Code requirements or on Saudi Aramco requirements based on either the vessel service or to achieve acceptable weld hardness. PWHT was discussed in MEX 202.02 and MEX 202.04.

Performance of a PWHT in the field after repair or alteration welding is commonly done. However, based on the amount of welding that is done and the materials that are involved, field PWHT can become difficult and time consuming. Therefore, it is sometimes advantageous not to PWHT after repairs or alterations, even if the vessel had originally received PWHT.

There are two possible alternatives to PWHT that may be considered in the case of repairs or alterations: the use of a higher than normal preheat temperature or the use of a temper bead welding technique. These alternatives may only be considered for the specific cases that are summarized in Work Aid 3. Use of either higher preheat temperature or temper bead welding as a means to avoid PWHT should only be considered after consultation with the Consulting Services Department.

Higher Preheat Temperature - Use of a higher than normal preheat temperature reduces the differential temperatures in the weld joint area and thus reduces the residual stresses that are induced due to weld shrinkage.

If higher preheat temperature is used for cases where impact testing was done as part of the original fabrication requirements, the welding procedure that is used for the repairs should be requalified at the higher preheat temperature. This requalification is necessary to confirm that the toughness is still acceptable in the as-welded condition.

The details and additional restrictions on the use of higher preheat temperature are contained in Work Aid 3.

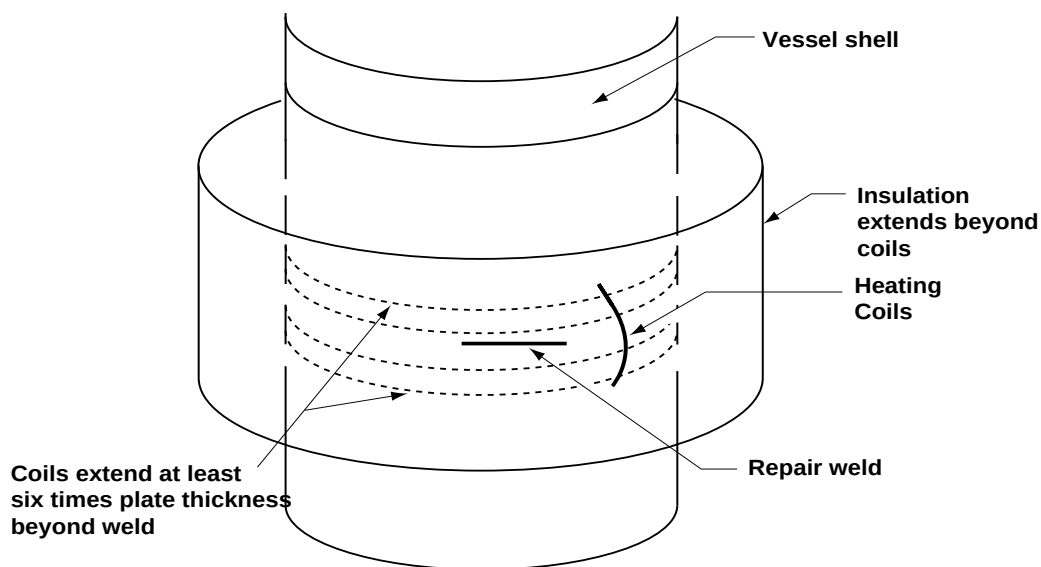
Temper Bead Welding - The temper bead welding technique is also known as the half-bead welding technique. The basic concept of temper bead welding is to use the heat from subsequent layers of weld metal to provide a heat treatment of the weld metal and HAZ of weld layers that are underneath. Weld metal that has not been tempered in this manner is removed by grinding.

Details and restrictions on the use of temper bead welding are contained in Work Aid 3.

Local PWHT

PWHT of a new pressure vessel is typically done by placing the entire vessel into a heat treating furnace. However, the ASME Code also permits use of a local PWHT for new construction under certain circumstances, such as if a new nozzle or attachment must be added to a vessel after it has already received a PWHT.

In the ASME approach to local PWHT, as illustrated in Figure 14, an entire 360° circumferential band around the vessel must be uniformly brought up to the required temperature and held at this temperature for the specified time. Heating is typically done through the use of electric resistance heating coils. This circumferential band contains the weld that requires the PWHT and is to extend at least six times the plate thickness beyond each side of the weld. The circumferential band and adjacent area of the vessel are externally insulated to the extent necessary to ensure that the thermal gradients that result from the high PWHT temperature do not cause excessive thermal stresses in the vessel shell.



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Figure 14: Local PWHT Per ASME

API-510 states that local PWHT of vessel repairs or alterations does not have to encompass a 360° circumferential band around the vessel if the requirements and precautions that are summarized in Work Aid 3 are applied.

Design

The design details for all repairs and alterations (such as the addition of new connections) should generally meet the principles that are established in the ASME Code, as supplemented by Saudi Aramco requirements. Vessel components should be replaced rather than repaired when the integrity of the repair might be questionable. Vessel design and fabrication requirements were discussed in MEX 202.03 and MEX 202.04.

Buttwelded joints that are used for repairs or alterations must have complete penetration and fusion in all cases, consistent with new construction requirements. Fillet-welded patches should not be used, except for exceptional cases (such as in very low pressure applications that involve nonhazardous services). The use of fillet-welded lap patches requires special design considerations, and the Consulting Services Department should be consulted before the use of fillet-welded lap patches is considered.

EVALUATING THE DESIGN OF EXISTING PRESSURE VESSELS FOR RERATING TO REVISED DESIGN CONDITIONS

Rerating a pressure vessel involves a change in either or both the design temperature or the maximum allowable working pressure of the vessel. It is sometimes necessary to rerate an existing pressure vessel due to either of the following:

- Changes in original design pressure or temperature.
- Vessel deterioration that was found during a T&I.

Rerating calculations will typically be done in accordance with the Code that was used in the original vessel design. All the necessary design information to permit rerating in accordance with the original construction Code is contained on the Pressure Vessel Design Sheet, the Safety Instruction Sheet, and the original vessel fabrication drawings. Rerating calculations may also be done based on a later edition of the original construction Code. However, to use a later Code edition, it must be confirmed that all essential vessel details comply with the requirements that are contained in this later edition of the Code.

The sections that follow discuss the reasons for pressure vessel rerating. Work Aid 4 provides a procedure for the evaluation of a pressure vessel for rerated design conditions.

Changes to Original Design Pressure or Temperature

It is sometimes desirable to change the original design conditions of an existing pressure vessel for process operations reasons. For example:

- There may be an increase in unit throughput that will result in a higher operating pressure. MEX 202.03 pointed out that the operating pressure is used to set the design pressure of a pressure vessel. The design pressure is found on both the Pressure Vessel Design Sheet (Form 2682 or Form 2683) and the Safety Instruction Sheet (Form 2694).

- Changes in flow arrangements or heat transfer scheme may result in a higher vessel operating temperature, which will increase the design temperature that is required for the vessel. The design temperature is also found on the Pressure Vessel Design Sheet and Safety Instruction Sheet.

The pressure vessel must then be evaluated for the desired design conditions in order to determine if the vessel is acceptable. With the following exceptions, this evaluation is done in the same manner as for a new vessel (as was discussed in MEX 202.03):

- The current vessel component thickness data must be used.
- An allowance for future corrosion that is based on actual corrosion rate data must be included.

Either the design pressure, design temperature, or both might be revised. As MEX 202.03 explained, the design pressure and design temperature must be considered together when a pressure vessel design is developed. This combination of design pressure and design temperature must also be considered when a vessel is rerated. Items that must be considered when rerating a pressure vessel are as follows:

- The effect of a design temperature increase on material allowable stress, flange Class, and vessel MAWP.
- Whether the new design pressure is below the vessel MAWP.
- The remaining corrosion allowance in the vessel, considering current component thicknesses and measured corrosion rates.
- The need to reset the safety valve set pressure, based on a new design pressure.

In some situations, it may be necessary to provide process operations personnel with acceptable design condition alternatives when their ideal case is too severe. For example, the vessel might not be adequate for the desired combination of *both* design pressure and temperature. However, the vessel might be adequate for the following applications:

- Some lower pressure at the desired design temperature.
- Some lower temperature at the desired design pressure.
- A shorter future inspection interval, which will permit use of a smaller future corrosion allowance.
- Multiple combinations of the above applications.

This information defines an acceptable design envelope for the vessel. This acceptable design envelope, if it is not adequate for a long duration of service, might be satisfactory for at least shorter term operational needs.

Reasons for Derating

Less demanding operational requirements that need less severe design conditions than those that were originally required is one reason for derating (or downrating) a pressure vessel. However, a formal derating evaluation is not done if a pressure vessel is being used for less severe conditions than were specified for the original design. The reason for derating that is of more interest is when derating is required due to a deteriorated vessel condition.

An earlier section of this module discussed the evaluation of corroded pressure vessels to determine their suitability for continued operation. If a corroded pressure vessel is not suitable for continued operation, one option which may be considered is to derate the vessel to less severe design conditions. Derating a vessel involves determining the design conditions that the vessel is suitable for, reducing the operating conditions such that these design conditions are valid, and resetting the safety valve to correspond to the new design pressure.

Derating a pressure vessel can have process operations implications, such as reduced throughput or lower product yields. However, these process implications might have to be accepted in certain situations, such as if they are preferable to taking the time that is necessary to make any needed repairs or modifications to the vessel.

Available Options

If an existing pressure vessel is not suitable for operation at revised operating conditions, three options are available:

- Repair or modify the vessel such that it will be acceptable.
- Modify the process requirements such that the vessel will be acceptable without repair or modification.
- Use a new pressure vessel.

The choice of which option to take depends on cost, schedule, and available operating flexibility.

The repairs or modifications that are required to make an existing pressure vessel suitable for revised operating conditions must be defined in order to determine the feasibility, cost, and time to implement the repairs or modifications. For example, relatively simple repairs such as localized weld overlay, the use of insert patches, or the replacement of corroded components such as nozzles or flanges might be all that is required and might be relatively simple to accomplish. However, the replacement of major sections of the shell or of entire heads will be more expensive and time consuming.

It will sometimes be possible to modify the originally desired process requirements sufficiently to permit continued use of the pressure vessel. Other operational alternatives might be available that will place less severe demands on the vessel and that will be less costly and time consuming to implement than vessel repair, modification, or replacement. It might also be possible to use process operations alternatives on a temporary basis until there is sufficient time to make the needed vessel repairs or modifications.

Use of a new pressure vessel to meet revised operating conditions or to replace a deteriorated pressure vessel is always an alternative. This approach is the most expensive and time consuming, but it will sometimes be necessary.

Requirements for New Hydrotest

A new hydrotest is normally not conducted as part of a routine T&I. However a hydrotest will typically be done in certain situations as follows:

- After pressure vessel alterations.
- After rerating to new design conditions that result in a higher than original MAWP.
- After certain repairs.
- To provide an extra measure of safety when there is doubt as to the extent of a defect or detrimental condition that exists in a vessel.

A new hydrotest is performed in the first two situations for the same reason that it is done for a new vessel. The hydrotest is done to confirm that the mechanical integrity of the vessel is still acceptable after alterations are done. A hydrotest is also done to determine when the vessel has been rerated to a higher MAWP. If the vessel MAWP has not been changed from the original value, the hydrotest pressure will typically be equal to that shown on the Pressure Vessel Design

Sheet (Service Test Pressure) and the Safety Instruction Sheet. If the vessel MAWP is changed, the hydrotest pressure is adjusted accordingly. Procedures to use in the calculation of the hydrotest pressure were discussed in MEX 202.04.

Doing a hydrotest for the last two situations will depend on the particular details that are involved. The Consulting Services Department should be consulted as required.

SUMMARY

This module discussed the maintenance and repair of existing pressure vessels after they have been placed into service. Participants can now determine appropriate external and internal inspection frequencies, evaluate corroded pressure vessels for their suitability for continued operation, determine appropriate vessel repair requirements, and evaluate vessels for desired rerate design conditions.

This module has now completed the life cycle of a pressure vessel. MEX 202.06 will apply the information that was discussed throughout the course to work that the Participants have brought to class.

WORK AID 1: PROCEDURE FOR DETERMINING THE APPROPRIATE INSPECTION FREQUENCY FOR A PRESSURE VESSEL

This Work Aid may be used in conjunction with the copy of SAEP-20, *Equipment Inspection Schedule*, in order to determine the appropriate external and internal inspection frequencies for a pressure vessel.

Work Aid 1A: External Inspection Frequency

The procedure that follows is to be used to determine the maximum permitted initial and subsequent Onstream Inspection (OSI) Performance intervals for pressure vessels.

1. Determine the Corrosion Service Class for the pressure vessel in accordance with the criteria that follows:

Corrosion Service Class	Criteria
0 - Performance Alert	380 $\mu\text{m/a}$ (15 mpy) and up corrosion rate, or Special Problems. This Class refers to special material or process conditions to address problems such as dearator cracking, weld repairs done without PWHT, molecular sieve plugging, etc. It also refers to problems that require special monitoring such as for cracking, blistering, oxidation, creep, fatigue, fouling, and localized corrosion/erosion attack sites.
1 - Corrosive Service	150 to 380 $\mu\text{m/a}$ (6 to 15 mpy) corrosion rate.
2 - Mild Corrosive Service	75 to 150 $\mu\text{m/a}$ (3 to 6 mpy) corrosion rate.
3 - Low Corrosive Service	Less than 75 $\mu\text{m/a}$ (3 mpy) corrosion rate.

2. The initial maximum OSI interval must be one year for Corrosion Classes 1 and 2, and two years for Corrosion Class 3.

The initial maximum OSI interval must be one year for Corrosion Class 0, unless a shorter interval has been specified based on specific Performance Alerts.

3. Subsequent OSI intervals must be scheduled either annually, or calculated based on the remaining vessel life using data that is developed by the OSI program. See Step 4 for the procedure that is used to calculate the required subsequent OSI interval.
4. Subsequent OSI Intervals Based on Remaining Vessel Life.

Subsequent OSI intervals may be calculated based on the remaining vessel life as follows.

- a. Determine the supplied nominal thickness, t_{nom} , and minimum required thickness, t_m , for each major vessel section (such as shell sections or heads). These should be available on the Safety Instruction Sheet for the vessel, Form 2694.
- b. Determine the actual measured thicknesses for the same major vessel sections, t_{actual} , as determined from the previous OSI.
- c. Determine the maximum corrosion rate for the vessel, CR, based on the larger of the following:
 - Historical information based on experience with other vessels in the same service, or
 - The actual maximum CR for the vessel, based on the OSI data for each major vessel section, as determined based on the equation that follows.

$$CR = \frac{t_{nom} - t_{actual}}{\text{Initial OSI Interval}}$$

The CR for the vessel is taken as the maximum value that is calculated for the major vessel sections.

- d. Determine the remaining life, RL, for the vessel. This is the minimum RL that is calculated considering all the major vessel sections, based on the equation that follows:

$$RL = \frac{t_{\text{actual}} - t_m}{CR}$$

- e. Determine the maximum subsequent OSI interval from the table that follows.

Corrosion Service Class	Vessel RL, Years	Maximum Subsequent OSI Inspection Interval
0	Less than or equal to 4	RL/4
1	4 - 10	12 months
2	10 - 20	30 months
3	Greater than or Equal to 20	60 months

5. Any revisions to the specified inspection intervals can only be made based on the procedures and approval requirements that are stated in SAEP-20.

Work Aid 1B: Internal Inspection Frequency

The procedure that follows is to be used to determine the maximum permitted initial and subsequent Test and Inspection (T&I) intervals for pressure vessels.

1. Determine the Corrosion Service Class for the pressure vessel in accordance with Step 1 of Work Aid 1A.
2. Is the technology, process, or vessel new to Saudi Aramco?

Yes ____ No ____

3. Determine the maximum interval before the Initial T&I based on the information in Steps 1 and 2 as follows:
 - If Step 2 is "No", the Initial T&I interval is 24 months for all Corrosion Service Classes.
 - If Step 2 is "Yes", the Initial T&I interval is 12 months for Corrosion Service Classes 0 and 1, and 12 - 24 months for Corrosion Service Classes 2 and 3.

Assignment of a time interval for Corrosion Service Classes 2 and 3 is flexible within the stated range, and must be determined by Area Operations Inspection. However, the actual time interval that is used must not be influenced by material selection and/or design considerations.

4. The maximum interval for subsequent T&Is must be the smallest of the values that are determined based on the three separate determination criteria that are summarized in Steps 5 through 7: the vessel remaining life, Corrosion Service Class, or equipment items as specified in SAEP-20.

5. Subsequent T&I Interval Based on Vessel Remaining Life.

The maximum subsequent T&I interval must not be longer than that determined based on the procedure below.

- a. Determine the vessel remaining life, RL, using the procedure in Work Aid 1A, Step 4.
- b. The maximum subsequent T&I interval must be the lower of $RL/2$ or 10 years.

6. Subsequent T&I Interval Based on Corrosion Service Class.

The maximum subsequent T&I interval must not be longer than that specified below for the specified Corrosion Service Class.

Corrosion Service Class	Subsequent T&I Interval, Months
0 - Performance Alert	30 (1)
1 - Corrosive Service	60 (1)
2 - Mild Corrosive Service	120 (1 & 2)
3 - Low Corrosive Service	120 (1 & 2)

Notes

- (1) When equipment life depends on the integrity of an internal coating or is in Corrosion Service Class 1, as determined by Area Operations Inspection, the maximum T&I interval must be 60 months.
- (2) Equipment with internal critical coatings that are in Corrosion Service Classes 2 or 3, as determined by Area Operations Inspection, should have their T&I intervals based on anticipated coating life.

7. Subsequent T&I Interval Based on Specific Equipment Items.

The maximum subsequent T&I interval must not be longer than that specified below for the equipment items specified. The actual subsequent T&I interval may be shorter than these times.

Equipment Item	T&I Interval, Months
Air Receivers, Portable	36/72 (1)
Air Receivers, Stationary	60/120 (1)
Air Surge Drums, Small (2)	120
Deaerators	24/48 (3)
GOSP Desalters	60
GOSP Traps, Dry Crude	120
GOSP Traps, Wet Crude	60
Process Vessels in Corrosive Service	60 (4)
Process Vessels in Mild Corrosive Service	60

NOTES

- (1) The longer interval is acceptable if a UT OSI survey (for pitting) is passed 6 to 12 months before the start of the scheduled interval.
- (2) Small air surge drums have a capacity of 4 cubic feet (30 gallons or 114 liters) or less. Larger air surge drums fall under the regular "air receiver" category for T&I intervals.

- (3) All internal welds of the Deaerator must be 100% Wet Fluorescent Magnetic Particle Tested (WFMPT). The T&I intervals that follow must apply based on the results of those tests:
 - a. If deep cracks (approaching or exceeding t_m) are found, then the T&I interval must be 12 months.
 - b. If shallow surface cracks are found, then the T&I interval must be 24 months.
 - c. If no cracks are found after two successive T&Is, then an EIS Revision, along with support documentation, should be submitted for the maximum 48 months T&I interval.
 - (4) Corrosive Service - Vessels that are in Corrosion Class 0 or 1, or that have corrosion rates in excess of $150 \mu\text{m/a}$ (6 mpy), or that are in wet (free water) sour (over 70 ppm H_2S in the water phase) service.
8. Any revisions to the specified inspection intervals can only be made based on the procedures and approval requirements that are stated in SAEP-20.

WORK AID 2: PROCEDURE FOR DETERMINING THE SUITABILITY OF A CORRODED PRESSURE VESSEL FOR CONTINUED OPERATION

The procedures that are contained in this Work Aid are based on API-510, *Pressure Vessel Inspection Code*, and may be used to determine the suitability of a corroded pressure vessel for continued service, based on information that is provided in an Inspection and History Report and elsewhere. Use of this procedure requires the following information:

- Vessel component current wall thickness data. The wall thickness data would have been obtained during a T&I and should be summarized in an Inspection and History Report that is prepared during the T&I.
- Minimum required component wall thicknesses. The minimum required thickness data are available from the Pressure Vessel Design Data Sheet or Safety Instruction Sheet.
- Vessel geometric details and design conditions. Again, these are available from the Pressure Vessel Design Data Sheet or Safety Instruction Sheet.
- The number of years the vessel has been in service, the desired remaining life, and the desired minimum inspection interval. This information should be part of the Inspection and History Report.

Data Collection

Use the procedure that follows to collect the data that is needed for the vessel evaluation.

1. From the inspection data, original component thickness information, and the number of years the vessel has been in service, determine the maximum corrosion rate for the vessel.
2. From the maximum corrosion rate, desired remaining vessel life, and desired minimum inspection interval, determine the required remaining corrosion allowance to achieve the minimum inspection interval and remaining vessel life.

3. From the inspection data, determine whether the corrosion is pitting type or general type.

Work Aid 2A: Evaluation of Pitting Type Corrosion

The procedure that follows is used to evaluate pitting type corrosion. Refer to Figure 15 in the application of this procedure.

1. Locate the worst area of pitting within the corroded area, and inscribe a 200 mm (8 in.) diameter circle around it.
2. Measure the total pit area within the 200 mm (8 in.) circle.
3. Inscribe a straight line or lines within the circle such that they cross the pits. The objective is to locate the straight line that results in the largest total length of pits that are within the circle whose boundaries cross the straight line (see Figure 15).
4. Determine the maximum pit depth that is located within the circle.
5. The pitting may be considered as widely scattered and ignored if all the following conditions are satisfied:
 - The pit depth is no more than half the required wall thickness minus the required allowance for future corrosion.
 - The total area of the pits in any 200 mm (8 in.) diameter circle does not exceed 45 cm^2 (7 in.²).
 - The sum of the pit dimensions along any straight line within the circle does not exceed 50 mm (2 in.).
6. It may be necessary to repeat this process to confirm that the entire pitted area satisfies the criteria.
7. Pitted areas that cannot be considered widely scattered must be repaired or treated as general corrosion.

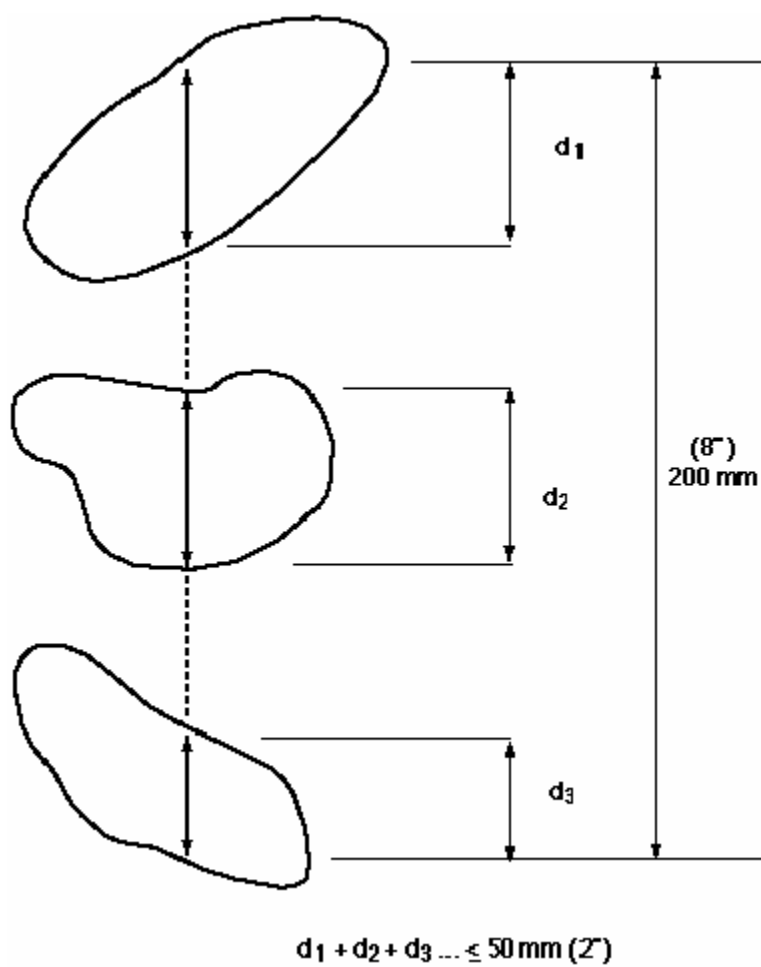
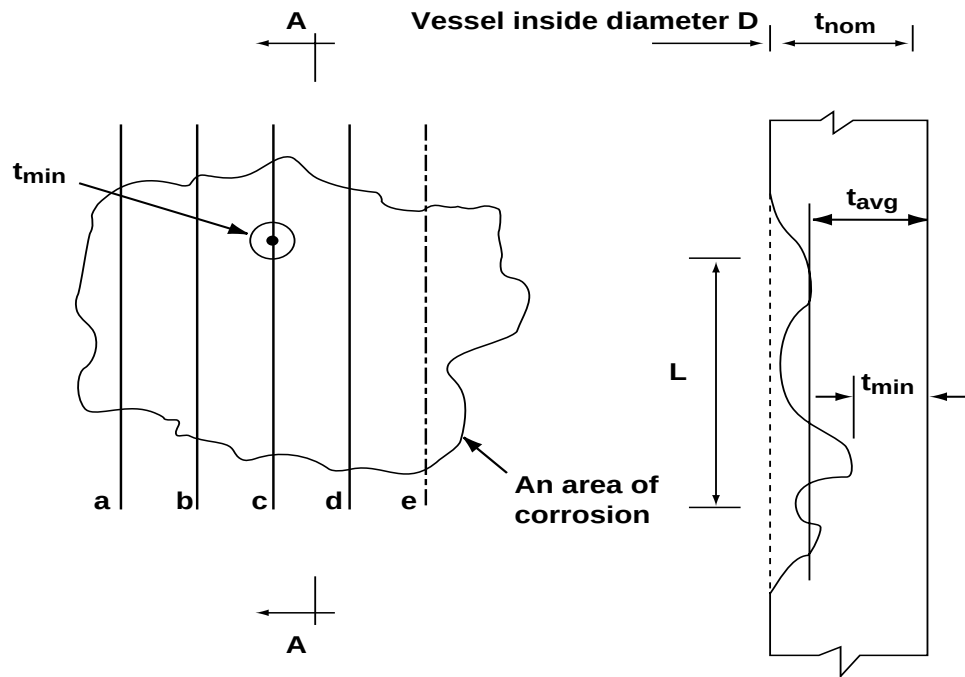


Figure 15: Pitting Type Corrosion Evaluation

Work Aid 2B: Evaluation of Uniform Type Corrosion

The procedure that follows is used to evaluate uniform type corrosion. Refer to Figure 16 in the application of this procedure.

1. The minimum thickness that is measured anywhere within the generally corroded area may be used for the subsequent evaluation. However, use of the minimum thickness may be too conservative. Therefore, the thickness within the corroded area may be averaged over a maximum length, L , based on the procedure that follows.
 - a. For vessels with an inside diameter of 1 500 mm (60 in.) or less, L is the smaller of one half the vessel diameter or 500 mm (20 in.).
 - b. For vessels with an inside diameter over 1 500 mm (60 in.), L is the smaller of one third the vessel diameter or 1 000 mm (40 in.).
 - c. L is as follows for the stated cases:
 - When the corroded area contains an opening, L must not extend beyond the limits of reinforcement as defined by the ASME Code (discussed in MEX 202.03).
 - When the corroded area is in the vicinity of a cone-to-shell junction, $L = \sqrt{Rt}$. " R " and " t " are the mean radius and wall thickness respectively at the junction.
 - When the corroded area is in the knuckle area of an ellipsoidal or torispherical head, L is equal to the arc length of the knuckle region.

**Legend:**

$a-e$ are inspection planes selected by inspector.

t_{min} = least minimum thickness in entire area, exclusive of pits.

SECTION A-A

Profile along plane "c," the plane having the lowest average thickness, t_{avg} .

$$T_{actual} = \min(t_{avg})$$

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Figure 16: Uniform Corrosion Evaluation

- d. Note the following with respect to the thickness measurements and averaging.
- API-510 does not indicate how many thickness measurements should be taken in the corroded area for averaging purposes. Typically, at least 5 readings should be used.
 - If localized thinning is a concern, a maximum distance of 50 mm (2 in.) should be used between measurement points.
 - The smallest value of average thickness must be found within the corroded area, and this is used in the subsequent evaluation. In order to determine this smallest value, it will typically be necessary to use multiple locations for thickness averaging (see Figure 16), and the least average thickness is the critical value for the area.

One location for "L" must pass through the minimum measured thickness in the corroded area. However, the "L-location" that contains the minimum measured thickness will not necessarily be the one that yields the critical average thickness. For example, the minimum measured thickness might be relatively isolated within a generally thicker region. Other areas may be thicker, but might yield a lower average value within a distance, L.

2. For vessel sections where the minimum required thickness is governed by internal or external pressure, the governing stress is circumferential and the distance, L, that was determined in Step 1 should be located along meridional lines on the vessel section (axial lines on a cylindrical shell). Circumferential stress will govern the design of most vessel shell and head sections.

If the combination of pressure, weight, and wind or earthquake loads governs the design of a vessel section (such as the lower part of a tall tower), the governing stress is longitudinal and the distance, L, that was determined in Step 1 should be located along circumferential lines on the section.

If it is unknown what type of stress governs the design of the section, the "L-distances" should be located along both meridional and circumferential lines.

3. For corroded areas that are at or near welds that have a joint efficiency other than 1.0, the weld joint efficiency must be considered.

Corroded areas that are within the greater of 25 mm (1 in.) or twice the minimum thickness on either side of the weld must be evaluated based on the weld joint efficiency. Corroded areas that are located further from the weld may be evaluated based on a joint efficiency of 1.0. If the inspection data does not specify the distance between the corroded area and the welds, the actual weld joint efficiency must be used in the evaluation.

4. When the corroded thicknesses of ellipsoidal or torispherical heads are evaluated, thickness measurements may be made in both the knuckle and central regions of the head, and the two regions of the head may be evaluated separately. Note that if the inspection data does not indicate where the thicknesses were measured in the head, they must be assumed to be in the knuckle region.
 - a. Thicknesses that are measured in the knuckle region are evaluated by the appropriate ASME Code head formula.
 - b. Thicknesses that are measured in the dished region may be evaluated considering this to be a spherical segment. The MAWP for the dished region is then calculated by the formula for spherical shells.

The spherical segment of both ellipsoidal and torispherical heads is the area that is located entirely within a circle whose diameter is equal to 80% of the shell diameter.

- The dish radius of a torispherical head is to be used as the radius of the segment, and this normally equals the shell diameter of standard heads.

- The dish radius of ellipsoidal heads is equal to an equivalent spherical radius, K_1D , where K_1 is given in the table that follows:

D/2h	3.0	2.8	2.6	2.4	2.2	2.0	1.8	1.6	1.4	1.2	1.0
K_1	1.36	1.27	1.18	1.08	0.99	0.90	0.81	0.73	0.65	0.57	0.50

Where:

D = Shell inside diameter, mm (in.).

h = One-half the length of the minor axis, equal to the inside depth of the head, measured from the tangent line, mm (in.).

5. Use the procedure that follows to determine if the generally corroded area, or pitted area if not "widely scattered," is acceptable.
 - a. Calculate the available remaining corrosion allowance, CA_{avail} , in the corroded area.

$$CA_{avail} = t_{avg} - t_m$$

Where:

t_{avg} = Critical value of average thickness within the corroded area, mm (in.).

t_m = Minimum required thickness within the corroded area, mm (in.).

- b. Determine the remaining life of the vessel, RL , based on the corroded area.

$$RL = \frac{CA_{avail}}{\text{Corrosion Rate}}$$

- c. Compare the calculated RL with the desired RL.
 - If the calculated RL equals or exceeds the desired RL, the corroded area is suitable for continued operation.
 - If the calculated RL is less than the desired RL, either the corrosion must be repaired, the RL shortened, or the vessel downrated.
- d. Determine the maximum permissible T&I interval based on the calculated RL as $RL/2$.
- e. Compare the calculated maximum permissible T&I interval with the desired T&I interval.
 - If the calculated maximum T&I interval equals or exceeds the desired T&I interval, the corroded area is suitable for continued operation.
 - If the calculated T&I interval is less than the desired T&I interval, either the corrosion must be repaired, the T&I interval shortened, or the vessel downrated.
- f. Repeat this procedure for each generally corroded area that is found in the vessel.

WORK AID 3: INFORMATION IN API-510 FOR DETERMINING APPROPRIATE DESIGN AND FABRICATION DETAILS FOR WELDED REPAIRS OR ALTERATIONS ON PRESSURE VESSELS

The following procedure must be used to define acceptable repair details and procedures for a pressure vessel.

1. Unacceptable defects that are found during a T&I must be repaired before the pressure vessel is returned to service.
2. All repaired areas must be inspected for acceptability. This inspection will typically be as follows:
 - a. PT or MT of weld overlay type repairs.
 - b. RT and/or UT of full penetration type weld repairs.
 - c. Inspection procedures and acceptance criteria must be the same as are used for new construction.
 - d. The Consulting Services Department must be consulted as required for special cases.
3. Cracks must be repaired as follows:
 - a. Grind crack to sound metal, followed by PT or MT to confirm its complete removal.
 - b. Prepare ground area for welding using a U- or V-shaped groove that extends the full length and depth of the crack area. If the crack extends through the full thickness of the material, the preparation must be for a full-penetration double-butt weld, or a single butt-weld with or without a backing strip.
 - c. Fill the repair area with weld metal.
 - d. If the crack is shallow enough such that the remaining vessel thickness after grinding is acceptable for continued operation, subsequent weld repair is not required.

4. Corroded Areas

The repair option that is used for unacceptable corroded areas is based on the extent of the corrosion, cost, and the time required to make the repair. Note that it is acceptable to repair only portions of a corroded area, as long as the remaining thicknesses in the unrepaired portions are acceptable for the design conditions.

- a. Repair relatively small corroded area by weld overlay, or by installing a new nozzle to encompass it.
 - b. Repair larger corroded area by removing it and replacing it with a buttwelded insert patch. Extensive corrosion may require replacement of major shell or head sections, or other vessel components such as nozzles.
 - c. If corroded area is very localized, consider if design modification is appropriate to reduce the local corrosion rate. For example, localized shell corrosion that is located opposite from inlet nozzles may be reduced by the use of an impingement plate welded to the shell or a flow deflector plate attached to the nozzle.
 - d. For corroded flange faces, clean thoroughly and build up with weld metal. Remachine the flange face to provide required gasket contact surface. Confirm that the final flange thickness is acceptable.
5. Welding procedures, qualifications, and record keeping must meet new construction requirements. Consult the Consulting Service Department for assistance as required and for special situations.

6. Was vessel given PWHT as part of original fabrication?

No _____ Yes _____

If No, PWHT is not required for repair welding.

If Yes, it may be possible to use a higher preheat temperature or temper bead welding as an alternative to PWHT after repair welding if all the conditions that follow are met:

- P-No. 1 or 3 materials (carbon steels and carbon-molybdenum steels).
- Routine type weld repair.
- Non highly-stressed location in the vessel.
- Original PWHT was not required due to process considerations.
- Materials are not subject to hydrogen embrittlement.

Use of either approach should only be considered after consultation with the Consulting Services Department to develop appropriate procedures.

a. Requirements for the Use of Higher Preheat Temperature

- May not be used for Mn-Mo steels in P-No. 3, Groups 1 and 2.
- The weld area must be preheated and maintained at a minimum temperature of 149°C (300°F) during welding.
- The 149°C (300°F) minimum preheat temperature must extend for a distance on each side of the joint that is the greater of 102 mm (4 in.) or four times the material thickness. The temperature in this area must be checked periodically to ensure that this requirement is met.

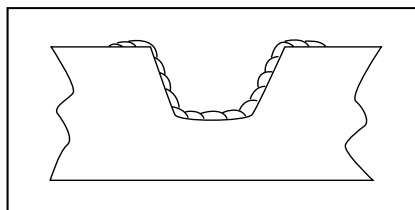
- The maximum weld interpass temperature must not exceed 232°C (450°F).

b. Requirements for the Use of Temper Bead Welding

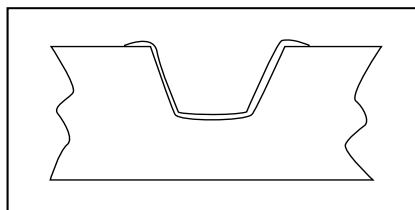
- For P-No. 1 materials, the total depth of repair must not exceed 38 mm (1-1/2 in.). For P-No. 3 materials, the total depth of repair must not exceed 16 mm (5/8 in.).
- After removal of the defect, the weld preparation must be examined by either MT or PT.
- The welding procedure and welders must be qualified based on the same Saudi Aramco requirements that are used for new construction. The welding procedure should include the following (Refer to Figure 17):
 - The weld metal must be deposited by the manual shielded metal arc process using low hydrogen electrodes. The maximum weld bead width must be four times the electrode core diameter.
 - The weld area must be preheated and maintained at a minimum temperature of 177°C (350°F) during welding. The maximum interpass temperature must be 232°C (450°F).
 - The initial layer of weld metal must be deposited over the entire area with a 3 mm (1/8 in.) maximum diameter electrode. Approximately one-half the thickness of this layer must be removed by grinding before depositing subsequent layers.
 - Subsequent weld layers must be deposited with a 4 mm (5/32 in.) maximum diameter electrode in a manner that will ensure tempering of the prior weld beads and their HAZ's. Partial removal of these subsequent layers is not required.

- A final temper bead weld must be applied to a level above the surface that is being repaired, without contacting the base material, but close enough to the edge of the underlying weld bead to assure tempering of the base material HAZ.
- The weld area must be maintained at a temperature of $260^{\circ}\text{C} \pm 28^{\circ}\text{C}$ ($500^{\circ}\text{F} \pm 50^{\circ}\text{F}$) for a minimum of two hours after completion of the weld repair. The final temper bead reinforcement layer must be removed substantially flush with the surface of the base material.
- After the finished weld repair has reached ambient temperature, the weld repair must be inspected using MT or PT. Weld repairs that are over 9.5 mm (3/8 in.) deep must also be given an RT inspection.

Step 1: Initial weld layer deposited using 3 mm (1/8") maximum diameter coated electrode.



Step 2: Remove half of first layer by grinding.



Step 3: Subsequent layers shall be deposited with welding electrodes 4 mm (5/32") maximum diameter. Bead deposition performed in manner shown.

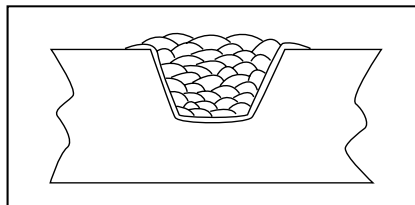


Figure 17: Temper Bead Welding

7. If PWHT is required, it may be done locally and not encompass a 360° circumferential band if the requirements that follow are met:
 - The PWHT procedure to be used must be developed and approved by an engineer who is experienced in pressure vessel design and PWHT requirements. The Consulting Services Department should be consulted if this approach is considered.

- The procedure must consider the items that follow.
 - Base metal thickness
 - Thermal gradients and the stresses that they cause
 - Material properties (such as hardness, chemistry, strength)
 - Metallurgical changes that could occur due to PWHT
 - Subsequent inspection requirements
 - Minimum preheat of 150°C (300°F) must be maintained while welding, and be included in the welding procedure qualification.
 - Required PWHT temperature must be maintained for a minimum distance on each side of the weld of two times the base metal thickness. The temperature must be monitored by at least two thermocouples. More thermocouples may be required based on the size and shape of the area that is being heat treated.
 - Heat must also be applied to any nozzle or other attachment that is located within the PWHT area, even if the nozzle or attachment were not involved in the welding that was done.
8. Butt-type joints that are used for repairs must have complete penetration and fusion. Insert type patches must have rounded corners. Design details for all repairs must meet the same requirements as are used for new construction. The Consulting Services Department should be consulted when alternatives are being considered.

WORK AID 4: PROCEDURE FOR EVALUATING AN EXISTING PRESSURE VESSEL FOR RERATING TO REVISED DESIGN CONDITIONS

The procedure that is contained in this Work Aid may be used to evaluate the suitability of an existing pressure vessel for rerated design conditions. This procedure is based on the assumptions that follow:

- Evaluation of corroded vessel components is not a factor. If corrosion is an issue for a particular case, this Work Aid must be used in conjunction with Work Aid 2 in the evaluation of the rerated design conditions.
 - The originally specified corrosion allowance is acceptable for the rerated design conditions, and evaluations of remaining vessel life and maximum permitted inspection interval are not required.
1. Determine the originally specified design pressure and temperature, material allowable stresses, vessel geometric information, nominal and minimum required component thicknesses, corrosion allowance, and vessel MAWP. This information is available from the Pressure Vessel Design Data Sheet or Safety Instruction Sheet.
 2. Determine the desired rerated design pressure and temperature. This information is provided by process or operations engineers.
 3. Evaluate the suitability of the vessel for the rerated design conditions based on which case is appropriate, as described below.
 - a. Case 1: New design temperature is unchanged (or lowered), and the new design pressure does not exceed the original MAWP of the vessel.

The rerate is acceptable.

b. Case 2: Design temperature is increased.

Determine a new MAWP for the vessel if the new design temperature decreases the material allowable stress, or the Class that was used for the vessel flanges must be increased for the new conditions. The vessel MAWP is unchanged if the material allowable stress and flange Class are unchanged.

- If the new MAWP exceeds the desired design pressure, the vessel is acceptable.
- If the new MAWP is less than the desired design pressure, the vessel is not acceptable for the desired rerated conditions.
- If the vessel is not acceptable for the initially desired rerate conditions, operations personnel may ask that one or more alternative combinations of pressure and temperature be evaluated for suitability. This subsequent evaluation is done based on the same procedure as above.

c. Case 3: Design temperature is lowered.

Determine a new MAWP for the vessel if the new design temperature increases the material allowable stress or maximum allowable flange design pressure. Then proceed as in Case 2. If the temperature decrease does not affect material allowable stress or flange allowable pressure, then the original MAWP is unchanged.

4. In all cases, the safety valve set pressure must be reset to the revised design pressure.

GLOSSARY

alteration	A physical change in any component that has design implications which affect the pressure-containing capability of a pressure vessel beyond the scope of the items that are described in existing data reports.
corrosion allowance	Actual wall thickness minus the retirement or minimum wall thickness (t_m). This measurement may be different than the "specified corrosion allowance" that is found on the Safety Instruction Sheet, Form 2694, or on other vessel drawings that are prepared during the original design.
I-T&I interval	The initial interval between new or rebuilt equipment commissioning and the first T&I overhaul. (See T&I.)
minimum allowable shell thickness	The thickness that is required for each element of a vessel based on calculations that consider temperature, pressure and all other loadings.
Performance Alert, Corrosion Service Class 0	The service class of equipment that requires more attention and more intense monitoring than the next service class, Class 1, which is based on corrosion rate only.
repair	The work that is necessary to restore a vessel to a condition that is suitable for safe operation at the design conditions.
rerating	A change in either or both the temperature rating or the maximum allowable working pressure rating of a vessel.
T&I	Test & Inspection, with the main purpose to guarantee the mechanical integrity, operation and safety of the plant/structure. This is primarily accomplished by thorough inspection and testing by plant inspection personnel.
T&I interval	The time between scheduled T&I equipment downtimes.