Fatigue Analysis and Life Assessment of Pressurized Structures

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Declaration

I certify that this research work titled *"Fatigue Analysis and Life Assessment of Pressurized Structures"* is my own work. The work has not been presented elsewhere for assessment. The material that has been used from other sources it has been properly acknowledged / referred.

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Language Correctness Certificate

This thesis has been read by an English expert and is free of typing, syntax, semantic, grammatical and spelling mistakes. Thesis is also according to the format given by the university.

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Copyright Statement

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Dedicated to my beloved parents, and adored siblings whose tremendous support and cooperation led me to this wonderful accomplishment

Abstract

One of the common practices used in the industry for safe operation of in-service components is to assess the fitness for service of the components during the service life. A Fitness for service assessment is required to evaluate the structural integrity of the structure under consideration and safely evaluate the remaining life of the equipment. The most popular standard currently being used in the industry is API-579-1/ASME FFS-1, because of its standardized assessment methods and procedures. It is the objective of this thesis to apply the assessment techniques included in the API 579 to a knock out vessel installed at the purge gas service in a petrochemical industry, the vessel under consideration has been exposed to low temperatures, and has recently changed service and location. Some erosion and pitting is also present on the vessel exterior based on preliminary inspection before installation, the study is motivated by the need to conduct a safer operation of pressurized vessels. The API 579 is applied to assess the possibility of brittle fracture in the vessel due to low temperatures and the change of service and location of the vessel, the possibility of general metal loss due to the erosion on the surface in the vessel, and the effects of pitting corrosion on the main vessel exterior is also investigated. The assessment is conducted in a Fitness-for-service software IntegriWISE for the calculation of Fitness-for-service parameters used for determining the safety of operation of the vessel. The results obtained from the assessment are then validated by comparison with the benchmark ASME calculations given in the API 579 Fitness-for-Service Manual (June 2016). The assessment is conducted beginning from Level 1 of Fitness-for-service assessment in the software and then proceeded further if the results of the previous assessment are unacceptable. The results so obtained from the conducted assessment indicate that the vessel was safe for operation, and future operation as per design parameters can be carried out with further inspections to ensure the safe operation of the knock out vessel, A mobile application for the computation of the assessment parameters was also developed.

Key Words: *Pressure vessel, Fitness-for-service, API-579, ASME FFS, Knock out vessel*

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Nomenclature

P = design pressure

R = inside radius of the component

E = weld joint efficiency

S = allowable stress in the component

t^{C}_{min} = Minimum thickness in the circumferential direction

t^{L}_{min} = Minimum thickness in the longitudinal direction

t_{min} = Minimum thickness of the structure

$t_{nominal}$ = Nominal thickness

t_{wall} = Wall thickness

t_{lim}=Limiting thickness

t_{am}=Averaged measured thickness

R_t = Remaining thickness ratio

Q = Parameter Q for thickness averaging

FCA = Future Corrosion Allowance

RSF = Remaining Strength Factor

RSFa = Allowable Remaining Strength Factor

MAWP = Maximum Allowable Working Pressure

MAWPr = Reduced Maximum Allowable Working Pressure

MAT = Minimum Allowable Temperature

CET = Critical Exposure Temperature

R_{ts}=Stress Ratio

P_a = applied pressure for the condition under consideration

P_{rating} = rated pressure value of the shell section of the vessel

COV = Coefficient of Variation

T_R = Temperature Reduction

LTA = Local Thin Area

t_{rd}=uniform thickness away from the damage area established by thickness measurements at the time of the inspection

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CHAPTER 1:
INTRODUCTION

1.1 Overview

Pressure vessels have widespread applications in the industry, ranging from vessels used for storage of fuels, chemicals and petroleum byproducts in refineries and petrochemical industries, to storage of gases for usage in various manufacturing facilities. As for all usage of pressurized equipment in an industrial setup the primary concern in using pressure vessels is the safe operation of the vessel involved during the operation. Currently, many standards are being practiced in the industry to safeguard the equipment against potential failure [1]. A primary method practiced a lot is the assessment of fitness-for-service of a pressure vessel. Fitness-for-service assessment developed in the recent years covers broadly the following aspects of the structure;

(i) evaluation of the present condition of the (damaged) assembly,
(ii) extrapolation from the present condition to approximate the safe and the residual service life [2], and
(iii) provision of procedures to enunciate the run, rerate, repair or replace choices about old pressure components and assemblies with flaws.

API-579-1/ASME FFS-1 [3] defines FFS as "quantitative engineering evaluations that are performed to demonstrate the structural integrity of an in-service component that may contain flaw or damage."

Component design according to code generally has a high specific damage tolerance, if these tolerances are used for the assessment of the component during the service life, the resulting assessments produced are likely to be improperly conservative. The design codes therefore are unlikely to provide guidelines for equipment evaluation while taking into account the degradation during the service life of the equipment and the deficits due to dilapidation or new construction that highlighted by newer reviews [4]. A figure depicting a typical pressure vessel is presented below:

Figure 1.1: A typical pressure vessel

1.2 Fundamentals of the Fitness for Service Assessment

There are many different reasons that may lead to failure in pressurized vessels. Some of the most common reasons that may cause failure include Fracture, corrosion, creep, fatigue loading, plastic collapse, and their interaction are likely to generate a probability of failure in the vessel. This may lead to first the component degradation and ultimately the failure of the critical support components of the pressure vessel.

Many years of investigation and experience based on industrial knowledge with widespread reviews has led to the growth and composing of consistent routes for appraisal of mechanical integrity of structures. These standards are designed so as to categorize a reasonable flaw size in the structures before it causes catastrophic failure. Various techniques grounded upon the code of fitness-for-service have been produced by International Organizations. The most popular of which are;

1. The API 579-1/ASME FFS
2. BS 7910

The API 579-1/ASME FFS is developed by the American Petroleum Institute (API), while the BS 7910 is a general UK assessment procedure for the flaw assessment in metallic structures developed under British Standard Institution (BSI) codes. These procedures usually evaluate fitness-for-service of the structures containing crack like flaws by means of Engineering Critical Assessments (ECA). The basis of these assessments is on fracture mechanics, the results indicate whether the equipment with flaws is safe or not, i.e. preventing fracture due to elastic plastic behavior, and also the failure due to plasticity under specific loadings and conditions based on operation is negligible.

Graphically, to represent the limiting value for the normalized crack driving force (K_r) as a function of the normalized applied load (L_r), a failure assessment diagram (FAD) can be used. The shape of the curve in the FAD depends on the material properties and the geometry of the component under analysis. To provide a more conservative view, a simplified FAD can be developed by applying conservative assessments independent of the geometry and material data. Cases requiring exacting specifications may include material specific data. A combination of these assessments can provide a varying level of complexity depending upon specific requirements for the analysis.

The goal of the current research is to highlight the effectiveness of fitness-for-service assessment techniques based on ASME 579-1 standard for pressure vessels. A case of a knock out vessel in a petrochemical industry is investigated and the assessment techniques based on ASME 579-1 are applied on the knock out vessel to assess the operational parameters of the vessel along with the useful service life of the vessel and the remaining service life is then evaluated using the expressions for the RSF (Remaining Strength Factor) in case of any unsatisfactory fitness assessment.

1.3 Applications

Fitness for service Assessment is a multi-disciplinary engineering methodology used for the determination of the equipment suitability for continued operation for some desired future period based on the initial design parameters. The assessment is flexible and is based on the service life of the equipment and can be varied depending on the following criterions;

i. Equipment containing flaws can be appropriately analyzed based on the particular defect present by referring appropriately to the specific defect assessment methodologies ASME 579-1 standard.

ii. Aging in the equipment causing degradation in the equipment, can be accurately taken into account during the assessment so that appropriate modifications to the original construction code can be applied before the assessment, and assessed according to the ASME 579-1 standard.

The flaws in the equipment can further be categorized into damage mechanisms which may include the effects of brittle fracture, metal loss, pitting corrosion, hydrogen blisters, stress induced cracking, weld misalignments and shell distortions, fire damage, assessment of dents, gouges, laminations and fatigue damage. Depending upon the type of flaw present in the body under consideration, the fitness for service assessment can then be carried out to compute various safety parameters for the body including the Remaining Strength Factor (RSF) and the Maximum Allowable Working Pressure (MAWP) or Maximum Fill Height (MFH), the former being used to calculate the deviation of the pressure from the design conditions while the latter being the limit to the height of the fluid used in storage tanks.

1.4 Motivation

There are significant implications in carrying out the assessment activities for pressure vessels, the fundamentals of which are presented below:

i. A fitness for service assessment of a pressurized vessel implicates a safer operation for a pressurized vessel, since the vessel is pressurized thus operation in unsafe conditions has the possibility of a catastrophic failure.

ii. Service load coupled with the flaws on the surface of the pressurized equipment can limit the useful service life of the vessel, hence the prediction of the remaining service life of the vessel becomes of a significant importance, the API-579-1/ASME FFS-1 procedure is useful in assessing the safe operating conditions of the vessel and helps in the prediction of the service life which can be further reduced if the condition of the vessel starts to deteriorate.

iii. Performing a fitness for service assessment on a pressurized vessel is helpful in reducing the cost of the maintenance due to the fact that equipment out of service is expensive but leaving damaged equipment in service can be risky.

iv. Depending on the inspection schedule for a particular equipment, the information required for running the assessment can be quite brief (if the evaluation being used is Level 1 type) and the necessary information can be collected by a qualified FFS inspector.

1.5 Contribution

Pressurized vessels are used in almost all of the process industry, the vessels used are typically segregated according to the sizes, process applications, pressure and temperature considerations. This thesis investigates the application of the Fitness for service techniques on a knock out pressurized vessel subjected to corrosion, metal loss, and assesses the susceptibility of the vessel to brittle fracture. The results so obtained present a complete picture of the remaining service life of the vessel given the design parameters and loadings. For the purpose of a holistic analysis, the ASME 579 assessment techniques are applied on the vessel data and assessment scenarios are computed for the damage mechanisms present on the vessel, the assessments are run on a FFS software which is then rigorously validated using benchmark ASME techniques to accurately determine the assessment criterions.

The conditions for safe operation of the vessel are then discussed based on the results obtained from the FFS assessment, and a regular inspection schedule is recommended for further continued operation of the vessel. A mobile application for the computation of the assessment parameters has also been developed. Furthermore, the applicability of ASME 579 to a knock out vessel has not yet been found in literature, thus emphasizing the novelty of the work presented in this thesis.

API 579-1/ASME FFS is recommended for Fitness for service assessment of pressurized equipment because of the standardization in the analysis methods used for industrial problems. As the fitness for service techniques commonly used in the industry accommodate multiple different methods making communication and assessment results difficult to compare with each other, the methods for analysis have roots in various industries, codes, and standards, which cannot be consolidated easily into a compendium of standardized assessment. API 579-1/ASME FFS mitigates this issue by providing a complete and comprehensive picture of the life of the equipment under consideration by taking into detail the damage mechanism and the length of the assessment needed to assess the life of the structure.

1.6 Thesis Outline

This thesis is comprised of six chapters, whose description is presented below:
Chapter 1 presents an overview of the fitness for service assessment with the particular emphasis on pressure vessels, along with the applications, contributions and the motivations for the research. In Chapter 2, a detailed literature review of fitness for assessment techniques has been carried out in conjunction with the introduction to the API-579-1/ASME FFS-1 standard, Problem statement and Assessment procedures are also discussed. Chapter 3 discusses the adopted methodology for the fitness for service assessment in detail, while Chapter 4 presents the assessment validation and verification. Chapter 5 discusses the results obtained from the assessment while Chapter 6 concludes the research work, and presents the suggestions and recommendation in conducting future assessments using API-579-1/ASME FFS-1.

The objective of this thesis is to present a simplified methodology for the conduction of the fitness for service assessments for pressure vessels with the emphasis on the knock out vessel.

CHAPTER 2:

LITERATURE REVIEW

Remaining life assessment of structures is a major task in the field of safety using structures. Unforeseen situations may arise if necessary standards are not followed and / or implemented. For pressurized structures, API-579-1/ASME FFS-1, developed by the American Petroleum Institute (API) is vital in assessing the service life of the structures.

2.1 The API 579-1/ASME FFS

ASME and API codes and standards for pressurized vessels deliver directions for design, fabrication, inspection and operational test of new pressure vessels, tanks for storage and systems used for piping. While useful, they typically do not help out in determining the equipment life after degradation from normal service routine, or deficiencies caused by normal operation times. To address these issues, API 510, 570, 653 and NB 23 may be utilized as these standards take into account the degradation of the equipment due to service routine, and normal operation times.

2.1.1 Fitness for Service Definition

Fitness for Service (FFS) are quantifiable engineering calculations which are executed to establish the mechanical reliability of components in-service which might include a defect or impairment, or the operation under a specific condition which can cause catastrophe. The API 579-1 standard delivers guidelines for conduction of FFS assessment by means of practices precisely arranged for pressurized structures. These methodologies can be followed to create run-replace-repair decisions which can help in determining if the mechanisms in the pressurized structures comprising of defects, have been recognized by scrutiny perform continued operation for a specific time. The FFS assessments which are presently acknowledged and referred to by the API codes and standards (510, 570, and 653) and by NB 23 as appropriate way for assessing the structural integrity of new pressure vessels, tanks for storage and systems used for piping where examination has discovered degradation and defects in the structure [5].

2.1.2 Fitness for Service Engineering Assessment Procedure

Fitness for Service (FFS) processes for continued operation are used to assess pressurized vessels covering defects or damage. The consequences of the FFS Assessment indicate whether the apparatus is fitting for operations given the present circumstances or if further conditioning is required provided that the equipment is in unsafe operation condition. If assessment results designate that the equipment is not in the safe margins, then the equipment has to be rerated according to the methods defined in the standard. These analytical methods include the calculation of the Reduced Maximum Allowable Working Pressure ($MAWP_r$) and the calculation of equivalent temperature for pressurized apparatuses including pressure vessels drums, headers, tubings and pipings. The FFS assessment procedures stated in the API standard are ordered by the type of defect and mechanism of propagation. A basic overview of how the flaw is identified and appropriate measures taken for its evaluation can be enumerated below;

a) STEP 1 – Defect and Damage Sizing Documentation

The first step in a FFS assessment entails the identification of the flaw type and the cause of damage to the structure, these steps include the original design, fabrication practices, the material of construction, service history and the environmental conditions. Once the flaw type is ascertained the next step for the evaluation can then be proceeded upon.

b) STEP 2 – Application and the Bounds of the Assessment

The application and the bounds of the assessment procedures are individually explained in the respective part of the standard and cover widely the material and fault assessment criteria, upon further inspection, the selection of the part which is to be evaluated can then be carried out for evaluation.

c) STEP 3 – Information Requirement

The information used for the assessment depends on the defect type or the mechanism defining the defect being evaluated. These necessities may include design data of new machine, maintenance and operational history, service in the long term, and data specifics for the assessment which include defect scope, stress magnitude in the part at the site of the defect, and mechanical properties. The particular requirements which deal with a flaw type depend upon the nature of the fault and then further information can then be used from the particular part of the standard.

d) STEP 4 – Assessment Methods and Approval Principles

Assessment methods and approval principles are elucidated in individual part of the standard. If numerous flaw contrivances are existent, multiple data streams from subsequent parts can be used.

e) STEP 5 – Evaluation for Residual Lifespan

Residual lifespan evaluation basically deals with the determination of the limiting flaw size and remaining life of the structure. This is basically recognized by means of the Assessment methodologies with an approximated imminent loss. This can then be used in combination with code of inspection to institute an interval for review.

f) STEP 6 – Remedial measures

The procedures required for remediation are further explained in a particular part of the standard, these can be further elaborated which are established on flaw mechanism or the damage type. These practices can also be used to regulate forthcoming impairment connected with defect growth or material weakening.

g) STEP 7 – Monitoring during operation

Procedures for monitoring during operation are explained further in the specified parts which are established on flaw mechanism or the damage type. These cases can then be used where residual lifespan and scrutiny check interlude cannot be sufficiently recognized for the reason of operation in complex work environment.

h) STEP 8 – Data consolidation

Data consolidation must include information and decisions that affect in the each of the preceding stages the part for sustained functioning. Consolidation necessities specific to a flaw contrivance or damage type are covered in subject damage mechanism.

2.1.3 Applicability and Limitations of the FFS Assessment Procedures

FFS assessment techniques were established to assess pressure limitations of high pressure vessels, boiler parts, systems of pipings and shell pathways of fuel storage tanks with a damage caused from solitary or numerous defect propagators. The models offered might be used for the evaluation of boundary parts with no pressure areas which include supports. FFS techniques for roof structures with static or fluctuating configurations, and sub surface plates of reservoirs are enunciated in API 653, Part 4.

2.1.4 FFS Assessment Levels

There are actually three levels of assessment which are used to cover all the FFS assessment procedures for a component. Overall, respective assessment level delivers a balance amid conserves' approach, information density for assessment, the proficiency of the staff accomplishing the assessment and the intricacy of the assessment required. Level 1 assessment is the most traditional assessment and is informal to use. Normal practice of the applicability of the assessment for a component sequentially proceeds from Level 1 upto Level 3 unless otherwise required, the assessment can be limited for a particular point of application. Further levels of assessment are only required if the present criteria of assessment do not deliver satisfactory results or a running decision regarding equipment operation cannot be concluded. A basic impression of the assessment levels and the limitations of each assessment level is discussed in section 2.4. In general, during the assessment of the knock out vessel, multiple level analysis is carried out on the vessel which is based on the type of the assessment carried out on the vessel, the details about the individual type of assessments applied are further explained in chapter 3 of this document.

2.2 Fitness for service Assessments in Literature

FFS assessments have been performed previously which included the assessment of industrial equipment under different environmental conditions. Elahe Shekari et. al [6] presented a new Fitness-for-service assessment methodology aimed at apparatus usage in process industry by tracking and predicting the pitting corrosion in the equipment, and modeling the pit density in conjunction to the poisson process and initiation time for pit induction was used to create a non-homogenous Markov model which was used to approximate thorough pit depth. The authors used a pit growth model based on a Markov chain and a pit initiation model as previously suggested in the literature to track and predict maximum pit depth, a non-uniform poisson's dispersal was acquired to regulate pit concentration and likely values of newly formed pits were joined with the total pit depth approximations to regulate the probabilistic dispersal of the most deep pit.

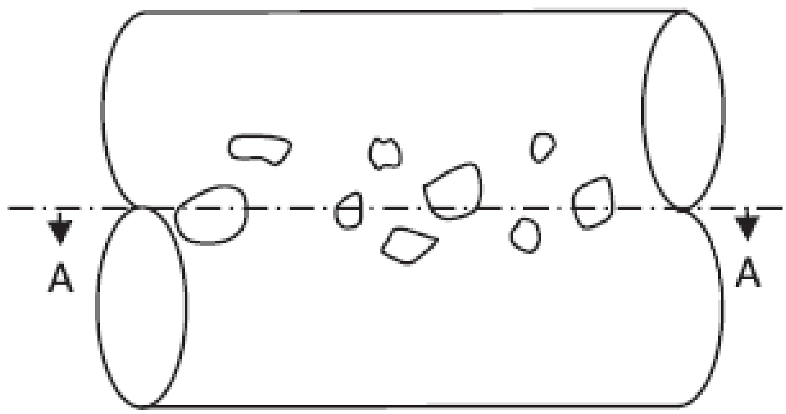

Figure 2.1: A cylindrical component containing pitting defects [6]

R. Bakhtiari et al. [7] used the Fitness-for-service assessment techniques to assess a pressure vessel encountering burning because of fire, according to API 579-1/ASME FFS-1, detailed microscopic as well as visual inspection was employed to assess the weakening of the shielding layer outside of the vessel and the grain structure of the material was assessed based on the usage of vessel according to the design conditions, a reduced Maximum Allowable Working Pressure was also worked out in case of unacceptable assessment results. The design conditions of the vessel were 450 psi(g) at 413°C, the vessel material was SA-204 Grade 70 with A-240 corrosion resistant cladding. The weld joint efficiency was 1.0 with a future corrosion allowance of 1/16 in or 1.59 mm. Detailed microscopic examination was carried out at various magnifications to evaluate the extent of fire damage in the reactor vessel. Optical micrograph was employed in the damage zones to photograph the damage areas, while the damaged area was divided into zones according to the damage intensity. A material hardness study and the FFS assessment was then carried out to ascertain the possibility of future usage of the reactor vessel with the minimum amount of repair.

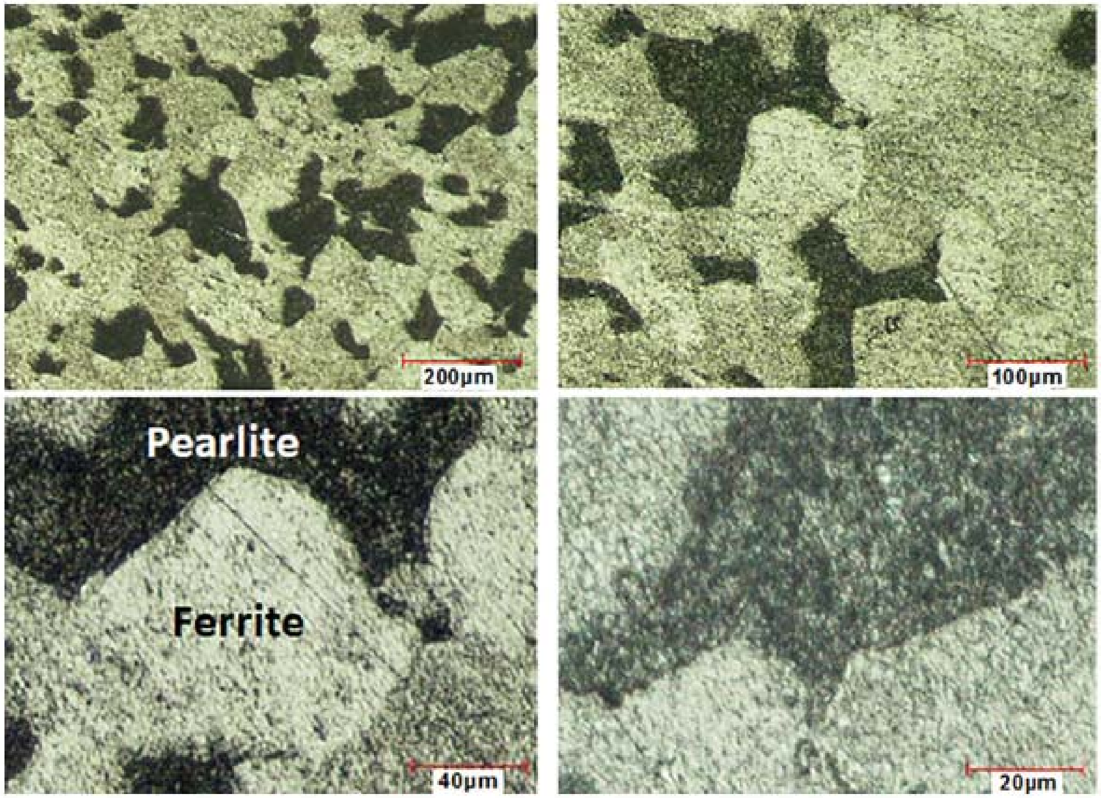

Figure 2.2: Optical micrograph of zone of damage in the vessel [7]

P. Tantichattanont et al. [8] implemented the fitness-for-service assessment on spherical heads of pressure vessels and vessels with high pressure with the primary focus being the development of an alternative method for Level 2 Assessment approximation of sphere-shaped vessel which was subjected to native formation of hotspots which were exposed to temperatures that was higher due to native flaw presence. The authors used a variational formulation for the evaluation of the hotspots on the shell sections and afterwards computed the Remaining Strength Factor of the sections under consideration. Decay length of the spherical shell section was computed by first computing the stress function for spherical shell sections, the spherical shell stress function was then modified by the application of the concentrated load, and edge effect bending moments. Variational formulation was then employed to evaluate the effect of hot spots in the shell. Finally reference volume of the discontinuities was calculated along with the computation of the RSF. The RSF was verified by performing a finite element analysis in ANSYS using a SHELL93 element which verified the adopted methodology for the FFS assessment of the discontinuities present in the vessel subjected to local hot spots.

X.J. Zhou et al. [9] studied the remaining assessment of material strength of crack defects in pressurized structures. In addition, a number of domestic and foreign FFS assessments were studied and then implemented in the form of a software tool based on BS structure coded on SQL server, Visual Studio with a C# database. The software tool so developed was then validated with an already conducted FFS assessment to verify the accuracy of computation of the software developed. For the FFS Assessments, the authors measured the residual strength and the remaining life of the pressure vessel, the readings used primarily indicated that the former is essential in solving the issue of flaw or damage characterization. The software tool then compared the above mentioned parameters by first computing the necessary stress intensity factor and yield stress and then evaluating the assessment criterion as specified in the ASME-FFS standard.

Uwe Zerbst et. al [10] used the Fitness-for-service assessments to analyze crack like flaws in structures using a SINTEP / FITNET procedure, SINTEP was a European developed multidisciplinary collaborative project with the goal of developing a technique to unify the evaluation procedure for fracture behavior, while FITNET was a EU based system which was used for 4 years to further extend the FFS techniques for metals with welds and no welds. The authors used the principles of steady state creep fracture mechanics, J-integral, and Stress Intensity Factor (K) for flaw characterization and deformation characteristics of the material and developed and extended the already present Fitness-for-service procedures (FFS) for structures. The authors gathered data first to model the Stress Intensity Factor (SIF) and yielding in the measured specimens, after which a structural assessment was run which was founded on the Failure Assessment Diagram (FAD) philosophy, the validation was then performed before measuring the reliability of the assessment technique.

John C. Jin et. al [11] ran the Fitness-for-Service assessment of the feeder piping of Canadian reactor in accordance to the Canadian Regulatory expectations, the degradation in the piping structure was studied and the mechanism for the degradation was identified to be Flow Accelerated Corrosion, Low Temperature Creep and Stress Corrosion Cracking, the authors presented a regulator's view in accordance to the degradations of reactor piping and its consequences for safety of nuclear material and the governing outlook on the production's administration of the deep aging in reactors. The flow accelerated corrosion present in the feeder piping resulted in the local wall thinning in the piping which further exacerbated the structural integrity of the piping. Furthermore, the low temperature creep cracking (LTCC) also aggravated the integrity of the pipeline due to hydrogen embrittlement. General regulator expectations along with the assessment and study of the service induced cracks yielded the probable causes of failure in the pipeline, the causes were narrowed down by performing the fitness-for-service assessment of the line, these causes include the presence of the blunt flaws in the pipeline, these flaws are difficult to detect by the means of NDE tools, the presence of wall thinning in the pipeline due to corrosion and degradation in the pipeline material. The effect of wall thinning can further be made more accurate by modeling the extent of the affected flaw type, the evaluation of load calculation and combination, evaluation of the residual stress, the material degradation properties and the stress classification in the pipeline. Regulator expectations in the assessment include the conservative assessments of the fitness for service parameters evaluation, considering the different levels of uncertainties present in the procedure to present a more holistic and accurate evaluation of the service life of the pipeline.

Bilal Dogan [12] applied the fitness for service assessment techniques on fused constituents under loading caused by creep and fatigue, the welds in the material were particularly damaging in the zones in high heat, in the basal metal, the welded parts were assessed to have complex structure in the basal metal, heat-affected zone and the metal used for weld, API-579 along with FITNET were used to evaluate the assessments including the crack commencement and the crack development and a code was developed for the high temperature testing of the weldments to be presented to the International Institute of Welding for presentation to ISO for standardization. For the first part of the assessment, physical computations are obligatory to evaluate in case a specified flaw will develop to an undesirable extent in lifespan under a prescribed loading condition. Basic materials data was gathered after this step and a preliminary creep-fatigue computation was carried out. Assessment calculations along with component rupture life was then computed to assess crack size growth along with size incubation and the cyclic plastic zone size, experimentally creep tests were performed to evaluate the effect of cracks on the creep. In addition, Failure Assessment

Diagrams (FAD) were developed to evaluate the relationship between Stress Intensity Factor (SIF) derived from the J-Integral and the load ratio. Fracture ratio is defined as the effect of the applied stress intensity factor over the material toughness which indicates the stability of the flaw. Finally updated codes and standards based on the tests carried out previously were presented and assessment of crack initiation and crack growth was presented. The presentation was important from an industrial point of view, Furthermore the TADFAD data obtained from the assessment can be applied to specimens of varying geometries and sizes, the residual stresses in the plastic crack initiation region were left as future work for the assessment.

Pingsha Dong et. al [13] studied the effects of stress for fitness-for-service assessment of welds in the pipe diameter, the assessment techniques for existing residual stress profiles were studied and finite element based stress residuals examination process was developed which was then validated for pipe girth welds using BS 7910 standard and API 579 Annex E, and an enhanced approximation method of the residuals examination process was established in the highlights of some shortages present in BS 7910 and API-579. The authors first developed a longitudinal remaining stress outline (equivalent to the weld area) in a rectilinear form of location from the pipe partition by computing the residual stress values from the inner and outer surfaces of the pipe respectively. An oblique remaining stress outline (upright to the weld area) was also developed for Ferritic vs Austenitic material by taking into account the welding heat input levels, a linear heat input function was developed for the oblique remaining stress outline, and the difference of the pressure in the axial direction was computed to compare the results with the theorized stress profile distributions, the results obtained from the study were then compared to a case study with an axisymmetric finite element model. A parametric analysis of the model was also carried out to study the effect of various material properties on the stress outlines for the pipe diametrical welds. Usage of material for the parametric examination was 2 ¼ CrMo-V Steel. The initiation temperature for annealing was set to 1200 degrees Celsius in the integrated model defining weld. The range for the parametric examination was set from ¼ inches to 4 inches (measurement of the wall thickness), the radius oblique thickness ratio used ranged from 2 to 100. The parametric analysis for only a single-v joint type was performed, and the cumulative effects of little, average and high thermal involvement along with small, medium and large wall thicknesses were considered, the effects of axial location dependence, and comparison with FE results were also computed. The final results presented from the study included the linear heat input functions, the effect of thicknesses as well as r/t ratio on the given stress distribution. Furthermore, a constant and mechanically complete pressure approximation system was concluded to be established, this was included to incorporate the equilibrium correspondent of material coating skin taken from a remaining stress outline, and can also easily be connected to the geometry limitations.

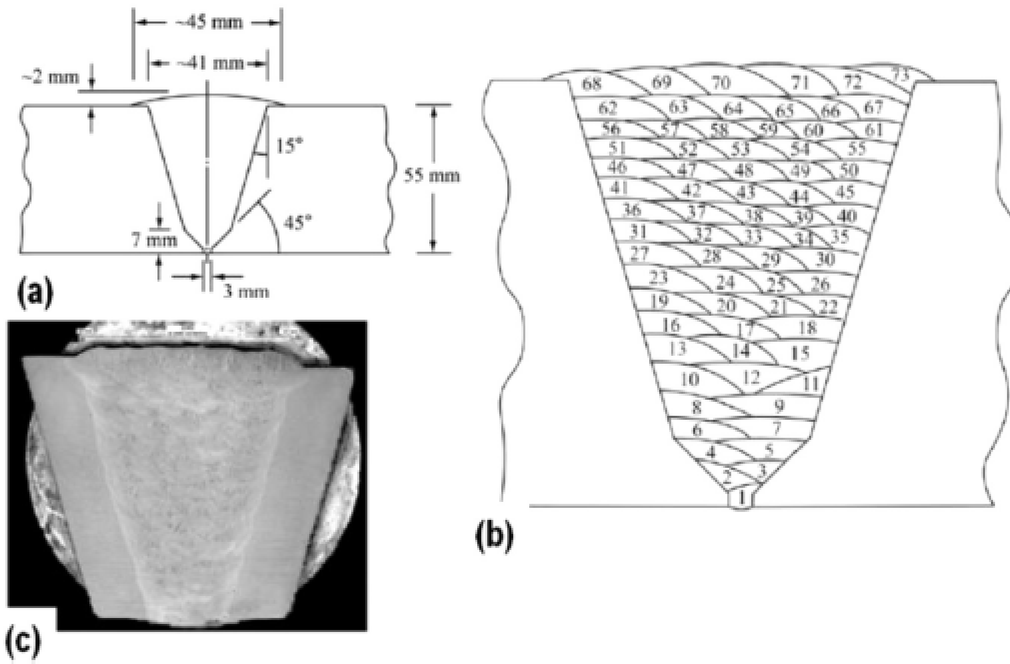

Figure 2.3: Diametrical weld model a) geometry of weld, b) pass arrangement, c) weld micrograph [14]

Feng Yaorong et. al [5] presented a study of the failure assessment for a pipeline, the failure was analyzed during hydro tests for a new pipeline for transporting crude representing the chief reason of failures to be absence of meld in metals due to insufficient energy input in Electrical RW welds of pipes. FFS assessment on the pipeline was run by focusing on fracture mechanics aspect for calculation of remaining life of the pipeline before leakage or breakage under design pressure conditions, Additionally, the effect of meld defects in the welds under fluctuating pressure was also studied and compared to the FFS assessment. The samples used for the assessment included damaged sections of piping and were investigated using a specific analyzer, and were confirmed to conform with the API SPEC 5L and related construction specifications. Before the assessment the pipe samples were tested for hardness by performing Charpy-V notch and tension tests, Furthermore, a metallographic analysis of the specimens was also carried out to verify the microstructures of the pipe body, the microstructure can be either ferrite or pearlite and upper bainite, hence normalizing was not carried out for the specimens under consideration after welding, failure cause analysis and FFS analysis of the pipeline was also carried out, Dugdale approach was used in the FFS assessment with modification applied to consider the bulging effect of the defect and strain toughening of the material, furthermore, an computational approximation for the CTOD of the pipe was also developed, along with the calculation of the opening and residual stresses in the pipeline. A macro analysis on the large sized pipe sections was carried out with the aim to elucidate the lack of the fusion defects on the pipeline, detailed analysis revealed the insufficient energy input on the conduit section which was the chief reason of the formation of huge meld flaws on the pipeline structure, The resulting assessment run on the pipeline indicated that the leakage in the pipe or breakage under the circumstances of the crack length of 2.3 mm and the max stress of 7 MPa while the durability of the material was computed to be around 0.016 mm, For future safety of the pipeline, which includes the protection, consistency and provision life aspects, the pressure fluctuations in the pipeline operational range need to be limited so as to expose the pipeline to reduced effects of variable pulsations of the fluid.

In general, in all of the previous studies, FFS assessments validate if the equipment can be used for sustained safe process at the proposed pressure and temperature by evaluation of the vessel safety parameters. If the results of the assessments indicate that the vessel cannot safely operate at the design pressure and temperature, then the equipment is rerated according to the calculations given in the specified section of the API 579-1/ASME FFS-1. It is common to find a reduced Maximum Allowable Working Pressure (MAWP) which the vessel can then be operated on to have the same safe operation as was based on the original design pressure.

2.3 Problem Statement and Objectives

A knock out vessel is installed at the purge gas service in a petrochemical industry, the vessel is seperating water content (suspended as moisture droplets) from the natural gas for the petrochemical industry, the primary composition of the natural gas is methane with minute amounts of ethane, hydrogen sulphide and trace amounts of water. The natural gas is used upstream of the knock out vessel. The moisture contained in the gas can cause problems in the metal piping transporting the gas, this can result in either corrosion in the pipeline or formation of hydrates or light emulsions within the pipeline, the formation of hydrates can deteriorate the piping upstream of the gas and can cause problems in gas compressors and other machines utilizing the gas [15]. The knock out vessel is exposed to the atmosphere and the lowest temperature in the zone of installation of the vessel is 10 °C which is based on the seasonal variations of temperature in the zone of operation of the vessel. The vessel recently also has changed service and was reinstalled at a new location from its previous zone of installation. This necessitated the need for Brittle fracture assessment according to the API-579 standard. Upon further visual inspection of the vessel, metal loss was also detected on the shell surface in the circumferential direction along one longitudinal plane of the vessel, which necessitated the inspection for metal loss according to the API-579 standard. Pitting was also present on the vessel exterior which required a pitting corrosion assessment for the vessel to ensure a safe operation of the vessel.

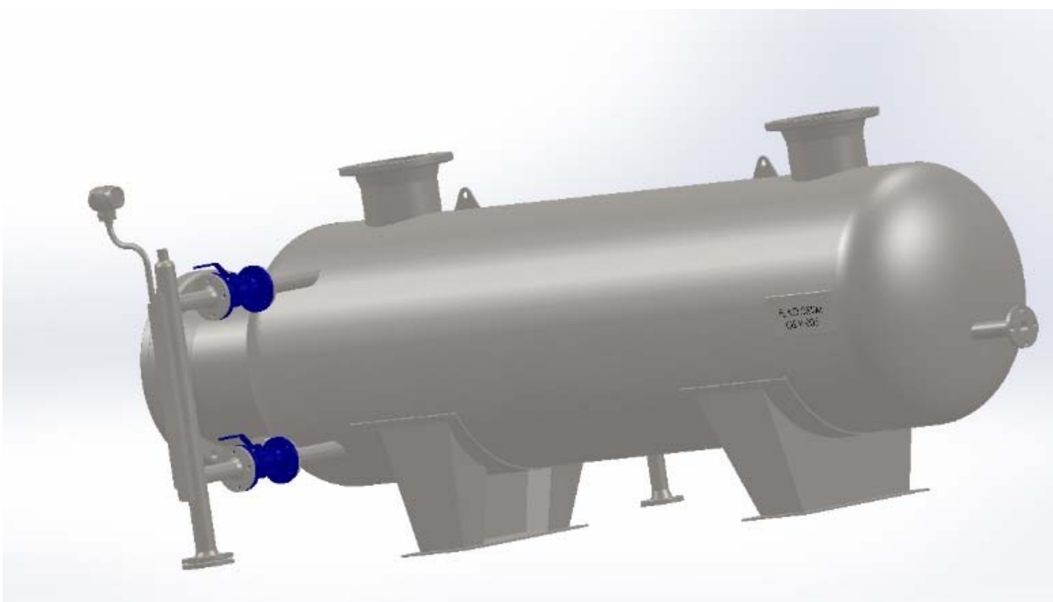

Figure 2.4: A three dimensional Computer Aided Drawing of the Knock out vessel under consideration

Figure 2.4 shows the side view of the knock out vessel, the length is 2300 mm when measured between the tangents to the end flanges. The design of the vessel consists of supply and discharge pipings attached to the shell surface which feed and take away the natural gas from the vessel, and separate the moisture from the natural gas. In addition, a demister is also attached internally to the vessel for removal of the resident moisture in the natural gas.

The specific objectives outlined for this thesis are recommended to be followed for the complete fitness for service assessment of the knock out vessel

2.4 Fitness for Service Assessment Procedure

The fitness-for-service assessment of the knock out vessel, given the operating conditions and the vessel design necessitated the brittle fracture assessment, and the general metal loss assessment. Brittle fracture assessment is carried out for evaluation of the resistance to brittle fracture and is commonly performed for current mild and low carbon based steel pressurized structures, systems of piping and tanks for storage [16]. General Metal Loss assessment is applicable for pressurized components that are focused on general metal loss due to corrosion, erosion, or a combination of both of these flaws. The assessment is carried out to determine either the component operation based on the designed operating conditions or to rerate the components for reduced operating conditions if the assessment comes out to be unacceptable. The assessment for general metal loss and local metal loss is differentiated based on point thickness readings or thickness profile method being used for the assessment. Furthermore, if a difference in the characteristics of the metal loss profile indicate a contained effect on the vessel exterior, a local metal loss assessment is then preferred instead of the general metal loss. The general metal loss assessment is limited to a relatively low coefficient of variation (COV) in the thickness readings. Coefficient of Variation (COV) is defined as the standard deviation of the thickness readings divided by the average of all the thickness readings. A high coefficient of variation, greater than 10% dictates that the method of thickness profile be used for the general metal loss assessment, which includes the inspection and thickness values specified along the circumferential and longitudinal directions of the shell surface [17]. A figure is presented for the differentiation in the longitudinal and circumferential directions for the shell surface of the vessel.

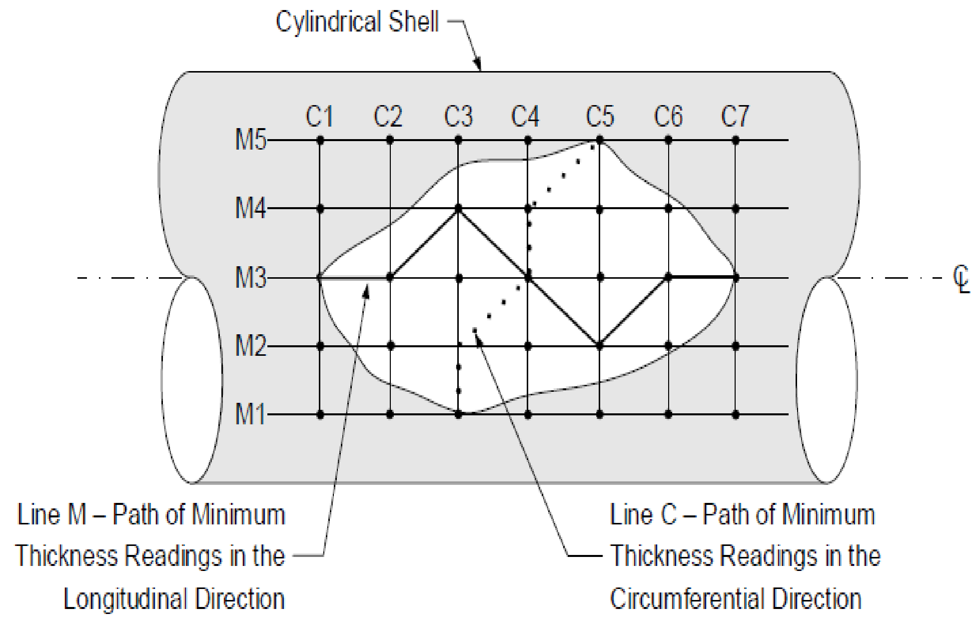

Figure 2.5: Metal Loss directions in the shell along the longitudinal and circumferential directions

Before running the assessment for the metal loss, the grid spacing is adjusted and then the thickness values are then noted to obtain the thickness readings which are then used for the evaluation of the general metal loss. Pitting corrosion assessment is used to evaluate the effect of pitting widely scattered on the shell surface which can affect the vessel integrity by reducing the Maximum Allowable Working Pressure (MAWP) and the Maximum Fill Height (MFH) for storage tanks. Pitting assessment is generally limited to the effects of the pitting on the vessel and other types of flaws on the vessel such as cracks, lamination flaws, hydrogen induced blistering, weld misalignments and shell distortions, creep and fatigue are covered in the respective parts of the API-579-1/ASME FFS-1 Assessment [18].

The assessment for each of the respective parts is divided into levels with each level catering to a less conservative assessment when compared to the previous level. The levels generally covered for the assessment include: *Level 1* – Assessment procedures based on Level 1 are typically the most conservative, the methodology is generally used to screen an equipment with the least extent of scrutiny and constituent information. The Level 1 inspection can be performed by the inspection personnel for plant area. *Level 2* – Assessment procedures are projected to deliver an additional evaluation of the component, the results so obtained are more precise when compared to Level 1 Assessment. In a Level 2 Assessment, similar component information as of Level 1 is required for performing the assessment, however the calculations performed are much detailed to evaluate the component. Level 2 inspection is typically carried out by engineering experts' knowledgeable and conversant with FFS evaluations. *Level 3* – Assessment procedures are intended to provide the most precise results when compared to Level 2 and Level 1 Assessments. The inspection and component information required for this assessment is the most detailed among all of the Levels for Assessment. Furthermore, the equipment may be analyzed based on numerical techniques such as finite element method, experimental techniques may also be used where applicable for the assessment. Level 3 assessment is primarily intended to be used by engineering specialists who are knowledgeable in conducting FFS assessments.

The general FFS assessment procedure that is followed for any flaw characterization as specified in the API 579 is based on the steps specified previously. The steps necessary for the evaluation of the equipment are dependent on the Level of the Assessment which is to be carried out on the equipment and the type of the assessment being performed on the equipment [19].

Once the assessment has been completed for a component, the next step is then to evaluate the residual lifespan of the component, the remaining life determination of each part is further elaborated in each individual part for a damage mechanism. After the assessment, if the results come out to be unacceptable a further step is taken, which is to calculate the Maximum Allowable Working Pressure (MAWP) and reductions founded on flaw type and conditions is applied to the MAWP to yield a reduced MAWP, this is usually done to reduce the working pressure and temperature conditions for the component, because of the reduced fitness present for the service life of the component. This is changed to Maximum Fill Height (MFH) and reduced MFH for storage tanks.

CHAPTER 3:

METHODOLOGY ADOPTED FOR FITNESS-FOR-SERVICE ASSESSMENT

3.1 Fitness-for-service Assessment Model Details in IntegriWISE

Before the process of beginning the Assessment of the knock out vessel, the knock out vessel input design parameters needed first to be defined in the FFS Assessment Tool TWI IntegriWISE. The UI of the tool is structured in a sequential fashion, with the definition of the site if the equipment to be established first, followed by the definition of the facility in which the equipment is installed. Next, the equipment model details need to be populated in the tool database, and lastly, the individual component details need to be defined within the main equipment model.

The benefit of adding the component definition within the main equipment model is having the choice of performing multiple fitness for service assessments on each individual component installed within the main equipment. A figure is presented below which shows the User interface (UI) of the tool.

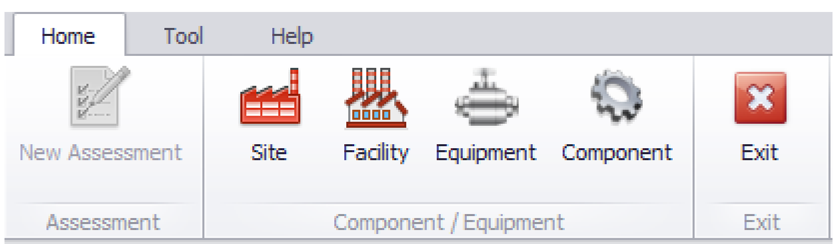

Figure 3.1: User Interface of TWI IntegriWISE

After the definition of the component is complete, the assessment can then be carried out on the individual component as per flaw present on the component. The main assessments which can be run on the assessment tool are presented in the figure below;

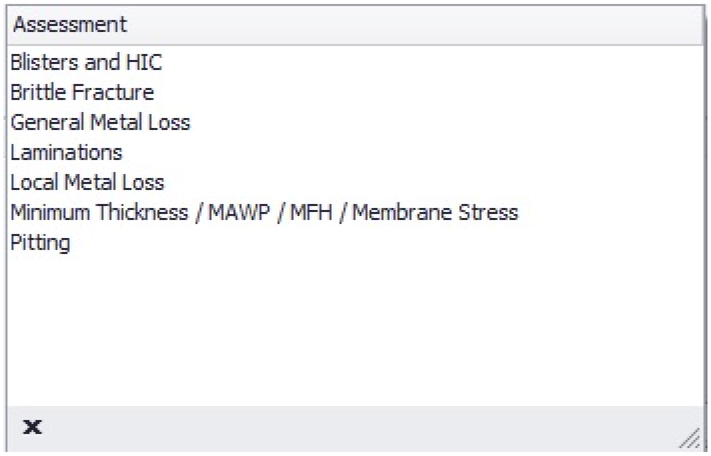

Figure 3.2: Assessment capabilities of TWI IntegriWISE

The assessment type selection is dependent on the flaw present in the component under consideration, furthermore, for each assessment definition, information specific to the assessment level, design and operational parameters, and flaw characterization need to be defined prior to performing the assessment. The process of definition of the material constitutes of first defining the site of installation of the equipment. The site defined in the software for running the assessment is presented as under;

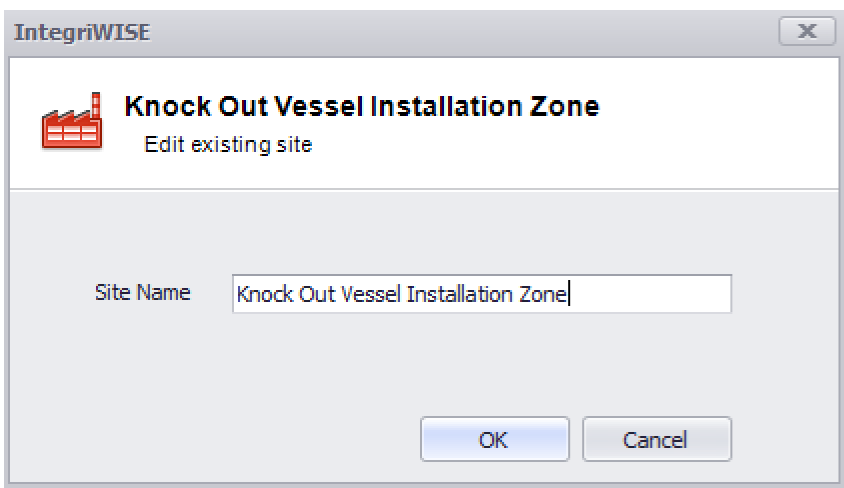

Figure 3.3: Site Definition for running an FFS Assessment

After the definition of the site, the facility was defined forthwith which is presented in the figure below;

Figure 3.4: Facility Definition for running an FFS Assessment

The facility definition is followed by the definition of the equipment details in the assessment database, these include the details relevant to the design pressure, temperature, minimum temperature and the hydrotest pressure (if applicable).

Equipment definition is populated in the software database by inputting the material properties as available in the material datasheet for the knock out vessel. The input parameters for the knock out vessel are presented in the figure below;

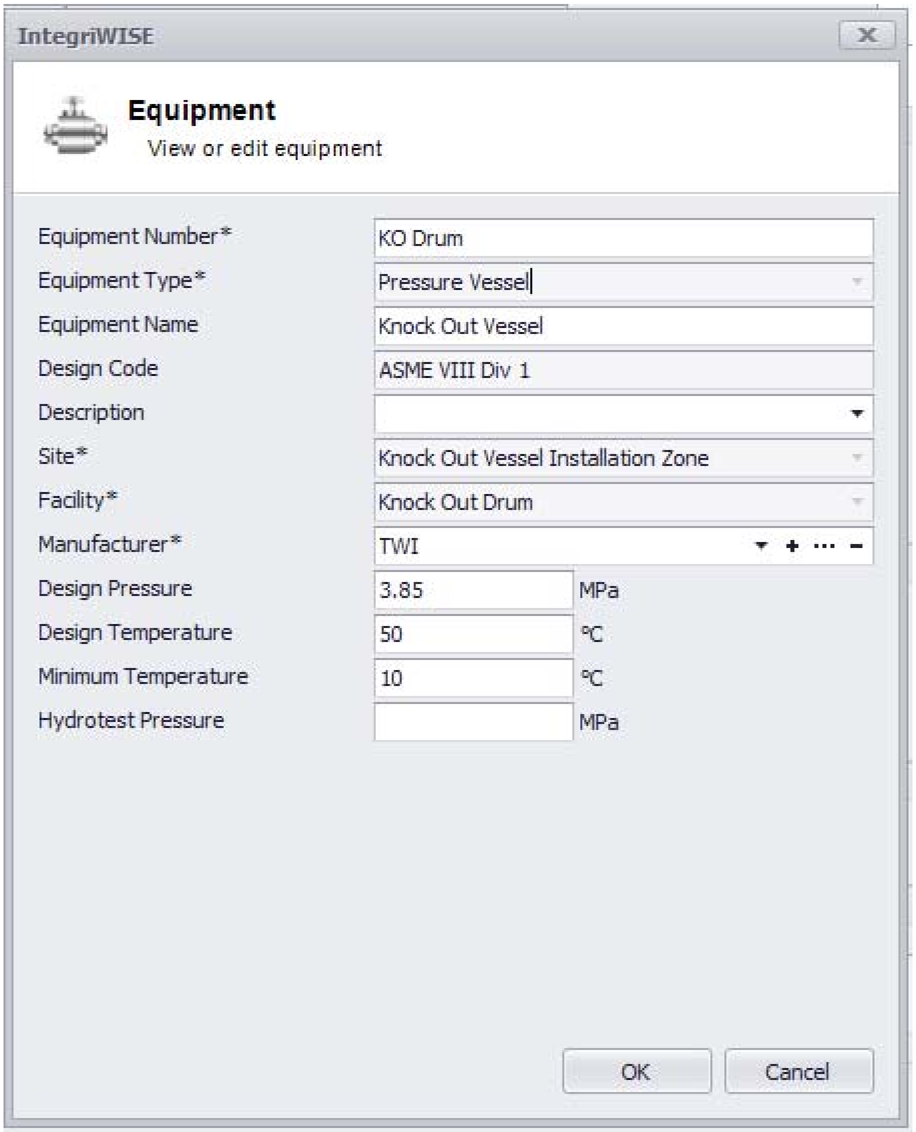

Figure 3.5: Equipment Definition for running an FFS Assessment

Since the knock out vessel being used was in a petrochemical industry, the hydrotest of the vessel was not applicable based on the current conditions for the operation of the vessel. For this reason, the hydrotest pressure of the knock out vessel was omitted in the equipment definition of the vessel. After the definition of the equipment, component details are then added which included the main body assessment for the knock out vessel. The component details include defining the material specification number for the vessel body followed by the grade used in construction of the vessel, the operational conditions then need to be defined which include the temperature of operation of the vessel and the operating pressure used for the normal working operation of the vessel. These details are supplemented by the geometry definition of the vessel body including the nominal inside diameter, the nominal thickness and the weld joint efficiency of the plates used in welding the main vessel body. These details are necessary for the complete component definition which is then used for running the Fitness for service assessment on the knock out vessel. A figure is presented below which shows the details being input in the software database for the FFS assessment.

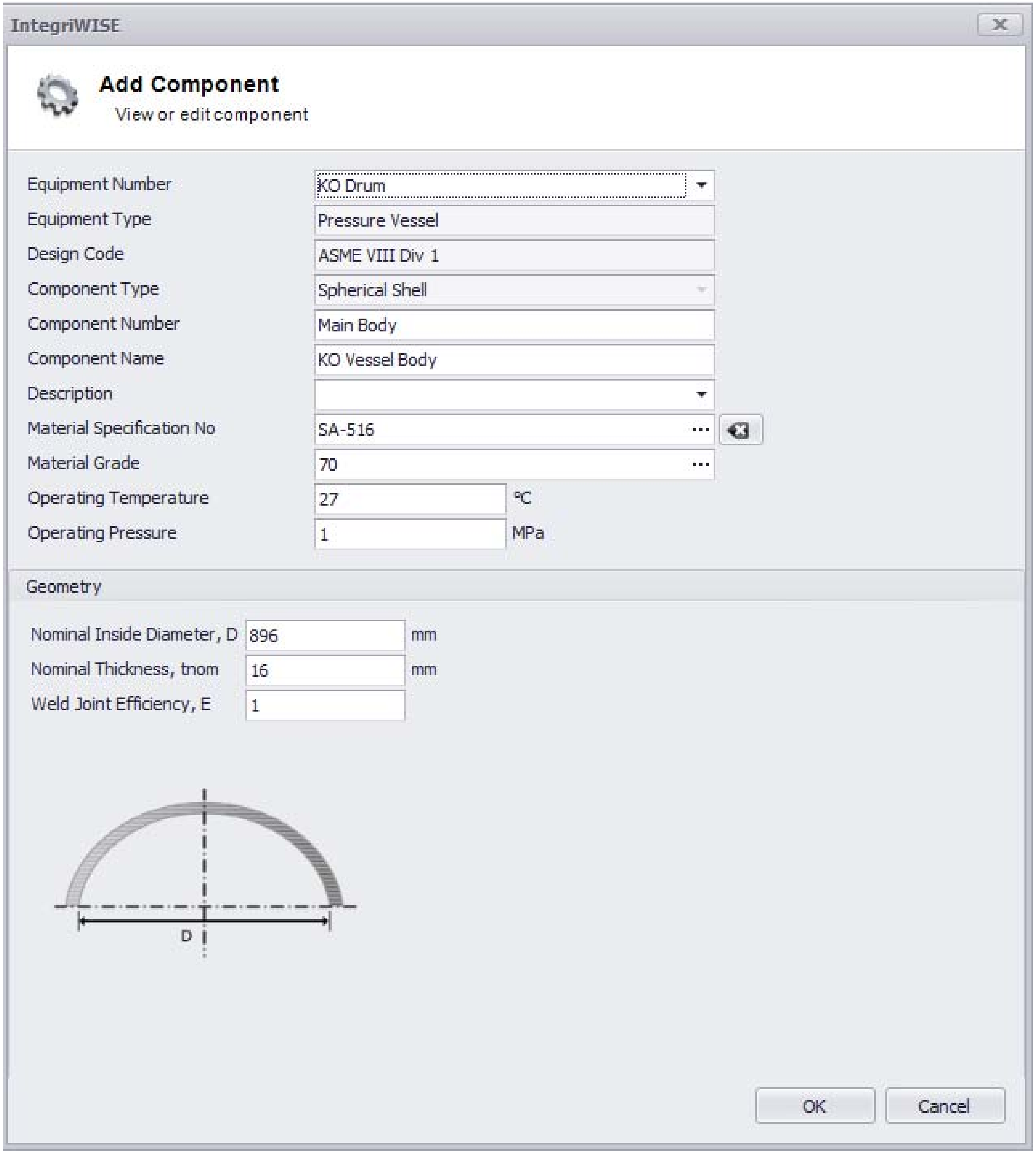

Figure 3.6: Component Definition for running an FFS Assessment of the Knock out Vessel

Complete definition of the component along with the equipment, facility and site details are necessary before running a FFS assessment for the vessel body. In this case, the assessment run was limited to the following based on the flaws present on the vessel, these flaws included;

i. Brittle Fracture Assessment
ii. General Metal Loss Assessment
iii. Pitting Corrosion Assessment
iv. Minimum Thickness / MAWP Assessment

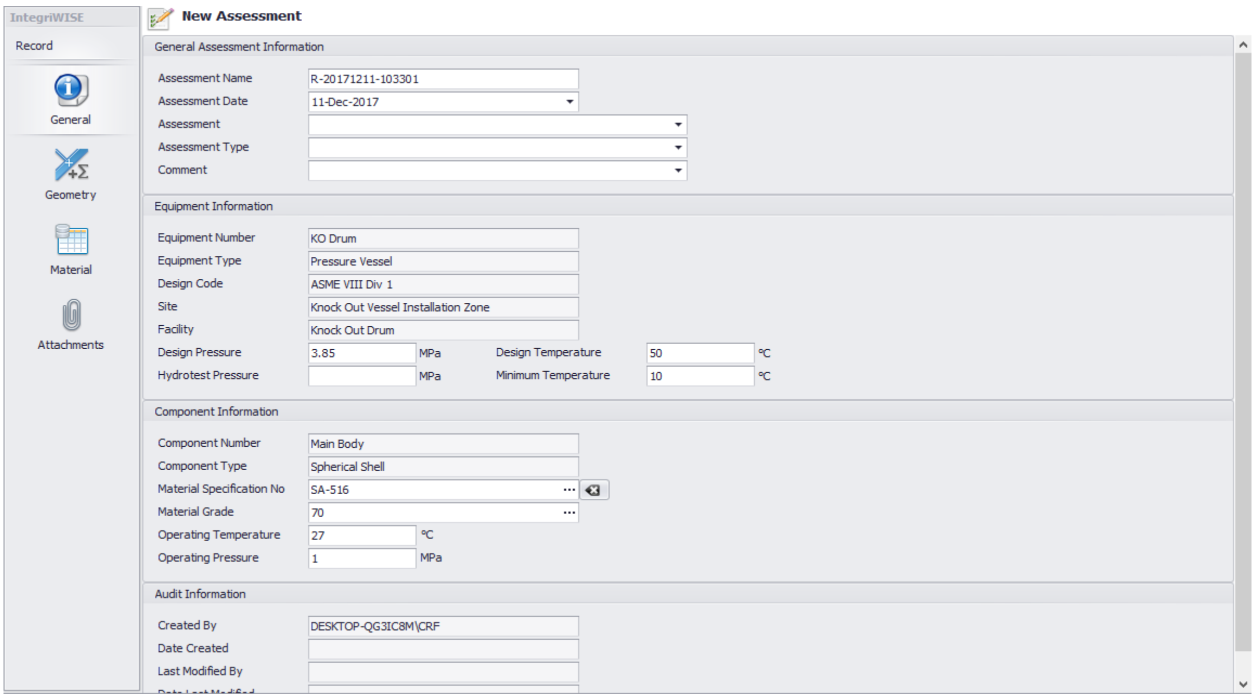

Figure 3.7: New FFS Assessment to be used for the Knock out Vessel

Details of each assessment mentioned above are further elaborated in the respective sections of this chapter.

3.2 Brittle Fracture Assessment

As the knock out vessel was exposed to a minimum temperature of 10 °C in the zone of installation, the first evaluation conducted for the vessel was the Level 1 Assessment for the assessment of brittle fracture. The design data for the vessel is presented in the table below;

Code	ASME SEC. VIII (DIV. 1)	
Design Pressure	(MPa)	3.85
Operating Pressure	(MPa)	1.0
Design Temperature	(°C)	50
Operating Temperature	(°C)	27
Minimum Temperature	(°C)	10
Length between Tangents	(mm)	2300
Shell Material	SA-516	
X-Ray 100%	E = 1.0	

Table 3.1: Material Properties of the vessel under consideration

Level 1 assessment procedure is based on the toughness rules in the ASME Code, Section VIII, Division 1. For the assessment, "Pressure vessels that have a Critical Exposure Temperature (CET) equal to or greater than the Minimum Allowable Temperature (MAT) as determined by the assessment procedure for Level 1 Assessment are safe for operation given the designed operation and maintenance parameters". Minimum Allowable Temperature (MAT) for a pressure vessel is the warmest temperature for any of its components. The MAT can be determined by the exemption curves relating the MAT by the Governing Plate Thickness of the shell section. The curves relating the MAT with the governing plate thickness are divided into four different curve types, with each curve specified for separate material composition. A flow chart is presented below which was followed for the Level 1 Assessment of the knock out vessel. The sequence followed in this flow chart is necessary for assessing the vessel according to the Levels specified by the ASME FFS procedure. The assessment for the brittle fracture of the vessel was limited to Level 1 Assessment only since that assessment was found out to be acceptable and further assessment levels are unnecessary if Level 1 assessment is found to be of acceptable nature. However, to find out the relationship of stress ratio with applied pressure for the condition under consideration, some aspects of Level 2 assessment were used to compute and verify the relationship between the above mentioned parameters, this analysis also gives a resulting parameter of temperature reduction which can be carried out to reduce the MAT for the vessel. The reduced MAT can be computed by subtracting the computed temperature reduction from the max. MAT value obtained from the exemption curves.

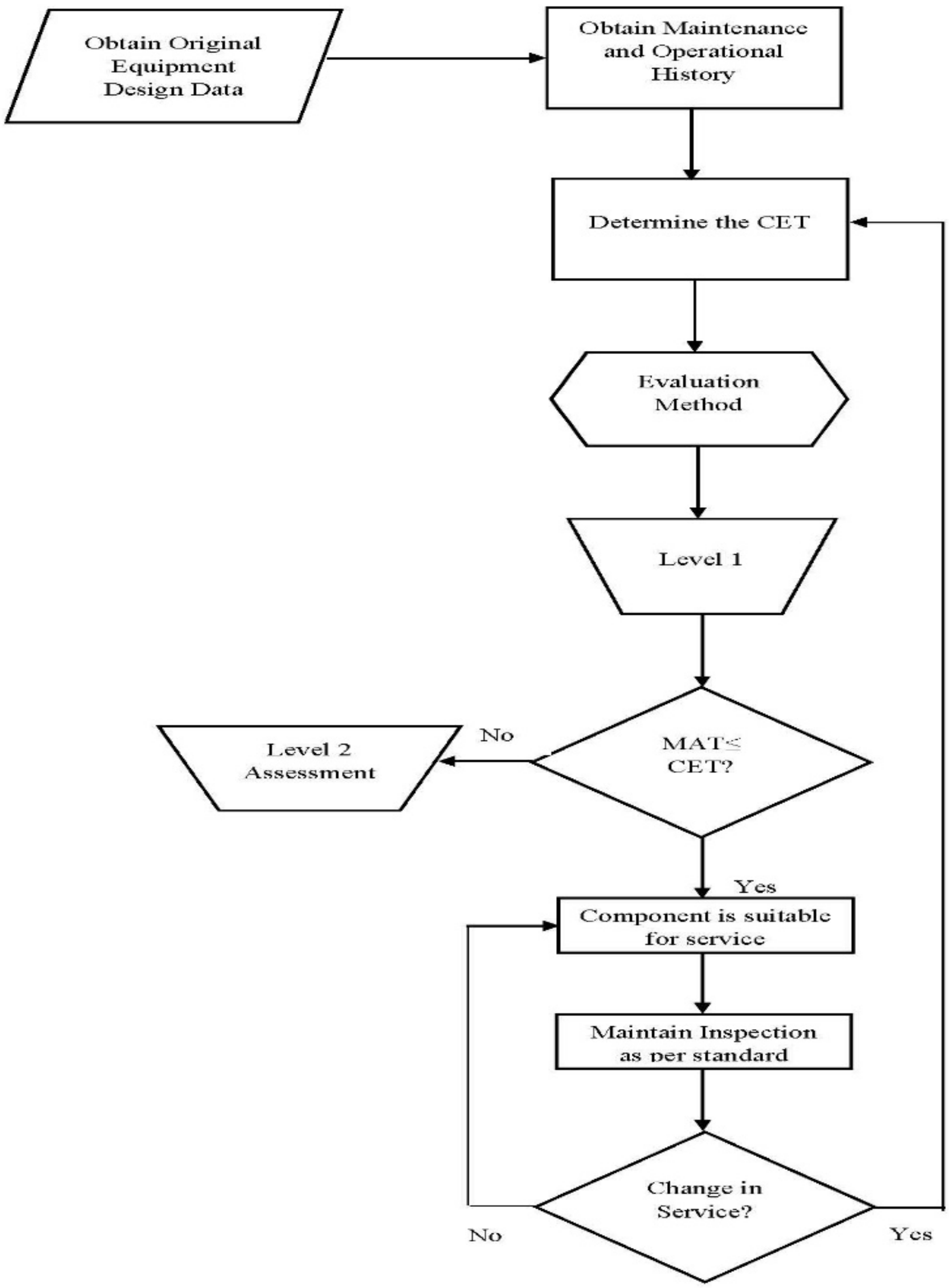

Figure 3.8: Flowchart for Brittle Fracture Assessment

3.3 General Metal Loss Assessment

General Metal Loss Assessment usually dictates that the material be first inspected for total metal loss along the specified directions, i.e. circumferential and longitudinal directions. The general metal loss assessment procedure generally covers metal loss due to corrosion, erosion or a combination of both. After the outcome of the evaluation, the equipment can either be operated as per the design conditions or rerated to a lower Maximum Allowable Working Pressure (MAWP) if the assessment is unacceptable. With regards to this assessment, "point thickness readings" or a thickness profiles can be used for assessing the equipment. "Point thickness readings" can be used in the assessment if there is no significant difference in the thickness readings values along the specified inspection points, whereas thickness profiles are used where there is a major disparity in the values of thickness parameter of the component, and for significant thickness variations, further assessment can then be used based on thickness profiles, thickness averaging approach, stress analysis approach or localized metal loss approach.

General Metal loss assessment in the standard is independent from the effects of flaw type and is limited by the operating temperature for the assessment, since a higher temperature will likely result in the creep flaw starting to present itself in the component. The assessment parameters are used to calculate reduced Maximum Allowable Working Pressure ($MAWP_r$) for pressure vessels or a "reduced Maximum Fill Height" (MFH_r) for storage tanks. Based on the assessment methods for general metal loss, some limitations need to be addressed for this assessment.

i. The new proposed standards are in agreement to the documented codes.

ii. The zone of the loss has significantly even outlines minus indentations, i.e. no stress concentrations.

iii. The part under consideration should not be affected by fatigue loading. If the part is subjected loading frequency of less than 150, i.e. stress and / or temperature disparities comprising operating variations, system on and off conditions through its earlier operating history and upcoming scheduled operations, or fulfills the fatigue screening process in the fatigue part of the API-579-1/ASME FFS-1 standard, then the component is not in cyclic service.

Subject to these limitations the assessment can then be run for the general metal loss according to the level of detail required for the component, less detailed assessments point to the Level 1 while more detailed assessments point to the Level 2 section of the standard. A Level 3 assessment may be performed if neither Level 1 nor Level 2 assessments give suitable results. An important parameter in running the assessments for general metal loss is the measurement of the thickness of the component which is then used to run the assessment according to the thickness readings or the thickness profiles based on the wear conditions of the vessel.

A flow chart is presented below for the general metal loss assessment carried out on the knock out vessel. The sequence followed in the flowchart is necessary for the assessment of the vessel according to the ASME FFS procedure. The assessment for the general metal loss of the vessel was limited to Level 1 Assessment only since that assessment was found out to be acceptable and further assessment levels are unnecessary if Level 1 assessment is found to be of acceptable nature.

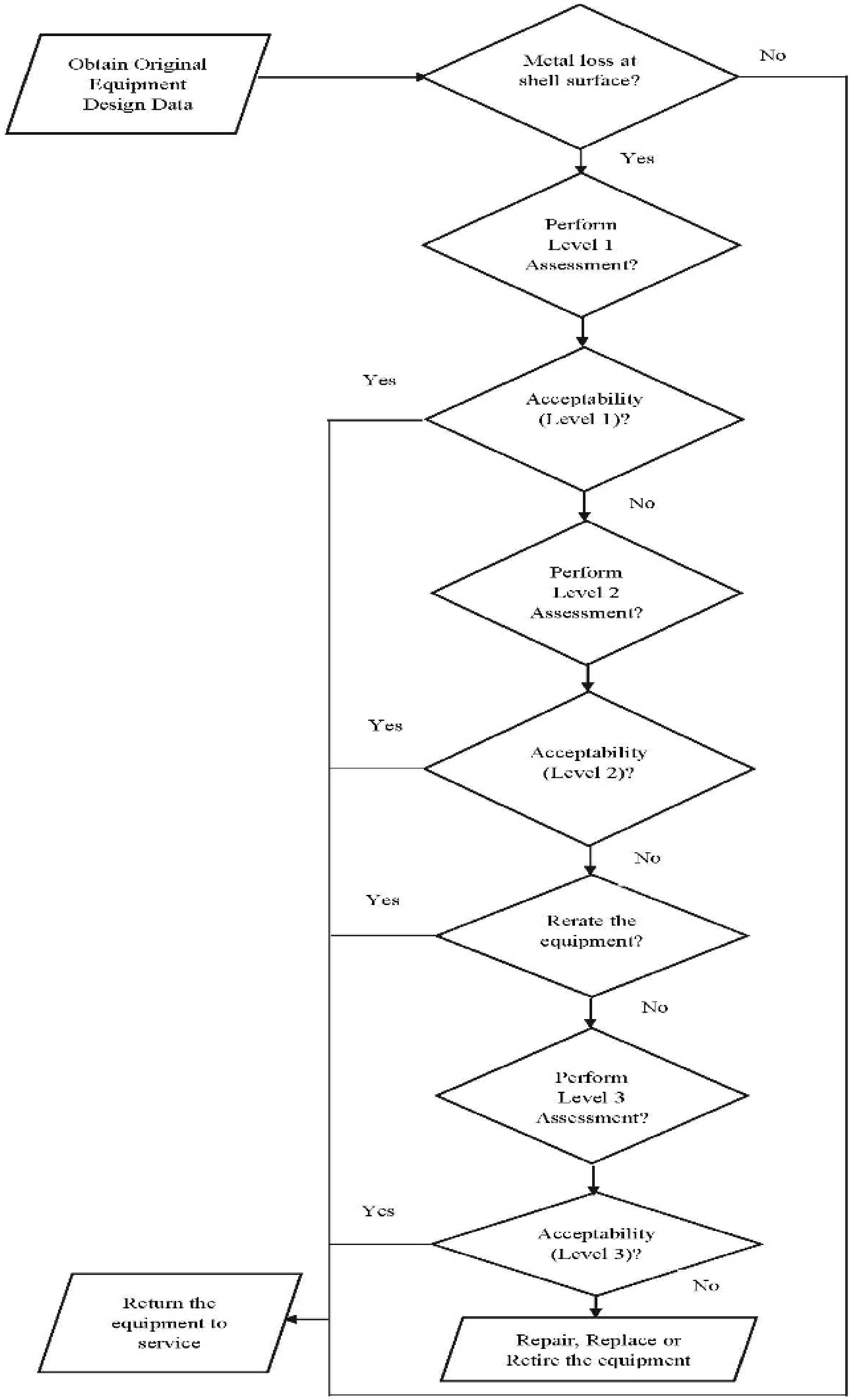

Figure 3.9: Flowchart for General Metal Loss Assessment

3.4 Pitting Corrosion Assessment

Pitting Corrosion Assessment is mostly used to assess the metal loss because of corrosion in a pressurized structure. The loss is usually categorized by the diametrical dimension according to the plate width or less, and the flaw depth that is less than the width. Pitting corrosion assessment is evaluated based on the four types of pitting in the vessel under consideration, these include: extensively dispersed pitting which is visible on a substantial area of the part, a local thin area (LTA) situated in an area of extensively dispersed pitting area, contained areas of pitting and pitting confined within a region of the LTA. Depending on the type of the pitting corrosion present in the structure, the pitting corrosion assessment can then be run either based on the complete pitting analysis or a combination of the local or general metal loss in conjunction with the pitting assessment in the structure. In performing the pitting assessment in the vessel, care has to be taken so that limitations based on the flaw type and temperature are taken care of accordingly, as the effects of both of these parameters is not covered in the pitting corrosion assessment.

Pitting corrosion methods being used in the API-579-1/ASME FFS-1 are independent from the effect of defect type and temperature effects on the assessment and are used to calculate reduced Maximum Allowable Working Pressure ($MAWP_r$) for pressure vessels or a reduced Maximum Fill Height (MFH_r) for storage tanks. Based on the assessment methods for pitting corrosion, some limitations need to be addressed for this assessment;

i. The original design criteria of the vessel must be used in accordance to the recognized code and standards.

ii. The material under consideration is considered as to have adequate physical durability. If there is an ambiguity present regarding the physical durability, an assessment for the brittle fracture must first be performed. Moreover, the presence of inundation during operation due to temperature and / or operational characteristics also dictates the application of the brittle fracture assessment before the pitting corrosion assessment.

iii. The component under consideration should not be affected by fatigue service. If the part is subjected to a frequency of less than 150, i.e. stress and / or temperature differences including operating variations, system on and off through its preceding operational history and forthcoming operations, or fulfills the fatigue screening process in the fatigue part of the API-579-1/ASME FFS-1 standard, then the component is not in cyclic service.

Subject to these limitations the assessment can then be run for the pitting corrosion according to the level of detail required for the component, less detailed assessments point to the Level 1 while more detailed assessments point to the Level 2 section of the standard. A Level 3 assessment may be performed if neither Level 1 nor Level 2 assessments give suitable results. An important parameter in running the assessments for pitting corrosion is the future corrosion allowance (FCA) which is founded on the anticipated impending metal loss in the defect areas. The measurement of the FCA is used to calculated the critical thickness of the component which can sustain the pitting corrosion. The pitting corrosion assessment is again run for subsequent levels until a level yields the assessment of the acceptable nature. During the analysis, Level 1 yields an acceptable assessment, hence the analysis for the pitting corrosion stops at this step.

A flow chart is presented below which is followed for the pitting corrosion assessment.

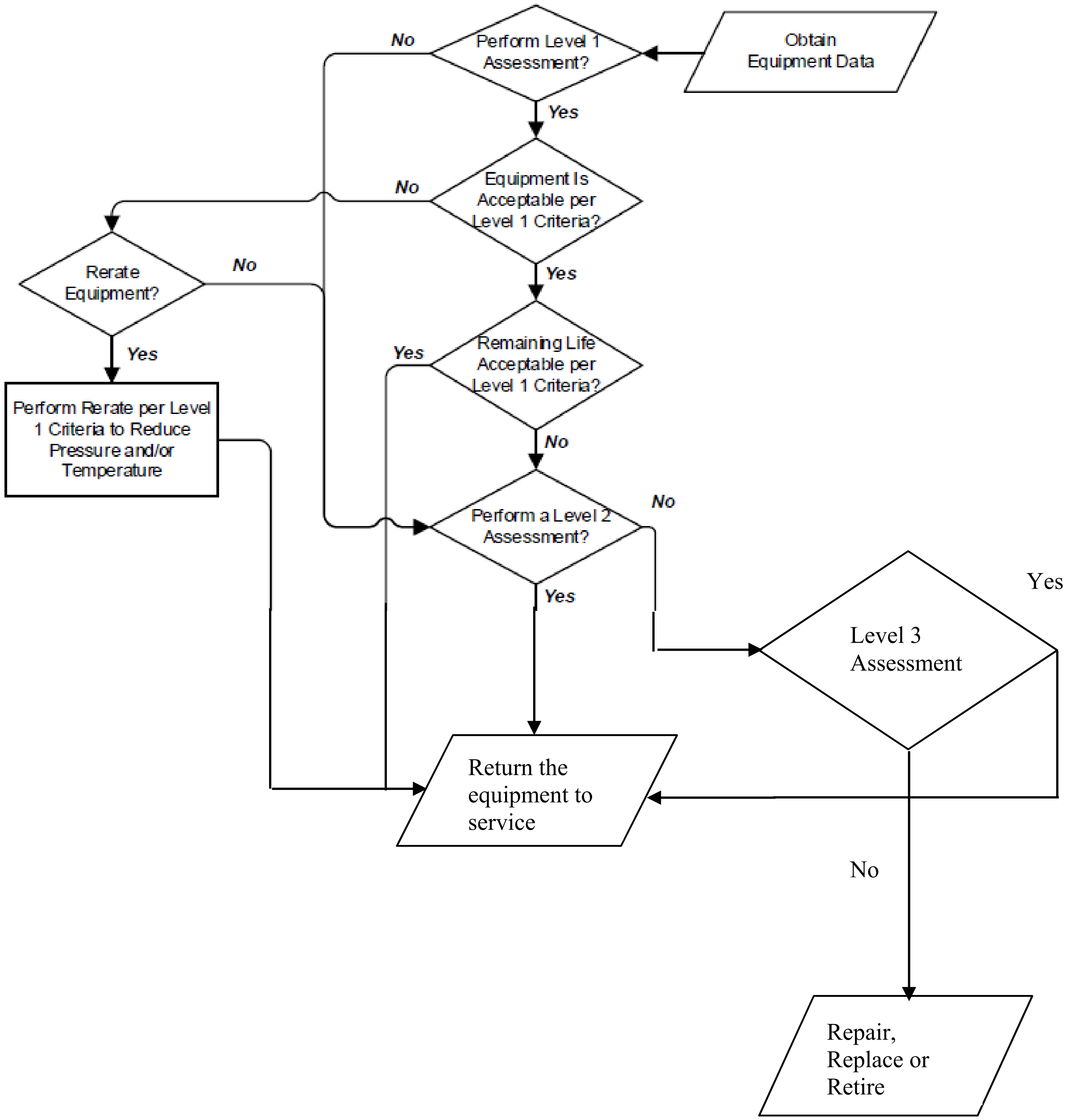

Figure 3.10: Flowchart for Pitting Corrosion Assessment

3.5 Min Thickness / MAWP Assessment

The lowest essential wall width, MAWP and stress in the skin for shared pressure parts are required for many of the Level 1 and Level 2 Fitness-for-service assessment in the API-579-1/ASME FFS-1 standard. These parameters can be computed from the constituent equations and code specified in this standard. In calculating the above mentioned parameters, the choice of the equations must be carefully done by the intended user for the specified assessment, the safe operating pressure capability of a pressure vessel is usually described by computing the MAWP for the vessel. In order to ensure accurate assessment of the maximum allowable stress, the following parameters need to be determined before running the assessment.

i. Physical Qualifications
ii. Temperature restrictions for the specified materials
iii. Design details
iv. Distinct proposal requirements for fatigue and high temperature circumstances
v. Construction details and the value of the workmanship
vi. Assessment requirements
vii. Weld joint efficiency
viii. Physical robustness (Charpy Impact Energy) requirements

The allowable stress to be used in the determination of the minimum required wall thickness and MAWP or MFH can be determined based on the following terms:

i. The stress for all constituents should be based on the design building code.

ii. If the description of building material cannot be identified, an acceptable stress can be assessed depending on the chemical nature determined by the analysis, procedures used for affirmative resources documentation (API RP 578), e.g. properties of the magntic nature, corrosion based results, and other physical properties. The chemical nature can then be related to the physical description and position in the design code. The permissible stress must be equivalent to the original material which will result in the lowermost value of the stresses in the code at the proposed temperature.

iii. If the building was based on rigorous requirements than requisite by the code, the permissible stress may be computed by making an allowance for the advanced facets of the part while considering the foundation for creating the material permissible stress in the code.

iv. For damaged regions (e.g. corrosion, erosion, pitting etc.) outside of the weld or riveted joint band in components without closely spaced openings, a joint efficiency of 1.0 can be utilized in the minimum thickness and MAWP or MFH calculations. For components with multiple closely spaced openings, the ligament efficiency with the hole pattern should be utilized in the calculations.

3.6 API-579 Android App Development

Taking into consideration the complexities of performing the assessments according to the API-579 standard, a mobile app was developed which helped to facilitate in running the assessments on the fly in the field without the need for detailed information and data input which is required for performing the assessment in a software. The app was developed in a modular fashion comprising the major damage assessment modes while taking into account the level which was required for the computation of the assessment. The application was validated using the methodologies mentioned in the standard to verify that the results obtained from the application were indeed consistent according to the results obtained from the governing equations.

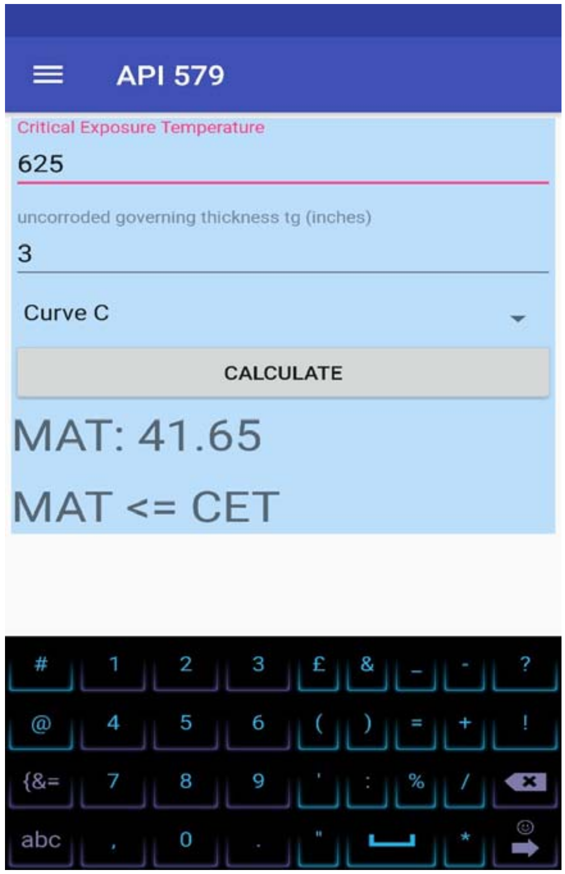

Figure 3.11: Snapshot of the API-579 App in Brittle Fracture Assessment Mode

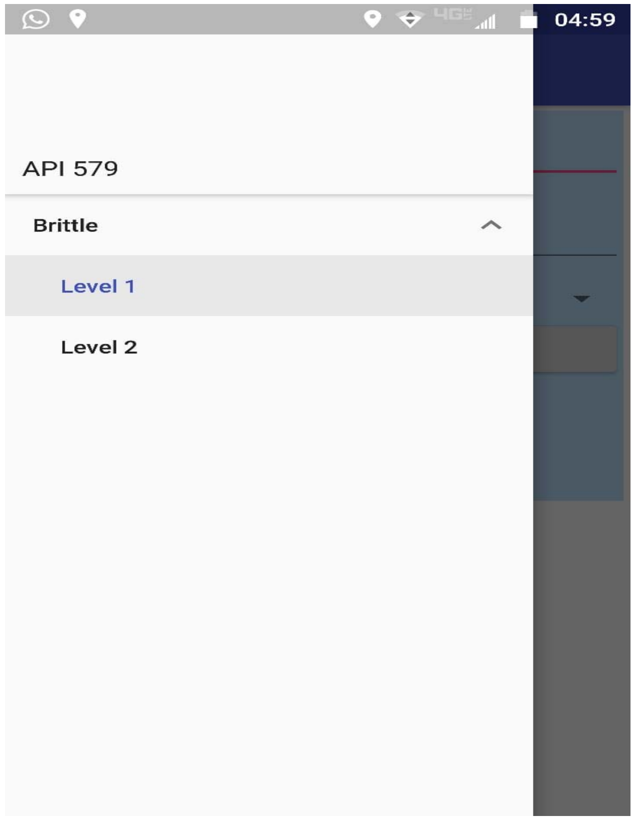

Figure 3.12: Snapshot of the API-579 App in Brittle Fracture Assessment Selection Mode

The results and discussions of the conducted assessments are presented in the Chapter 5 of this document.

CHAPTER 4:

FITNESS-FOR-SERVICE ASSESSMENT TECHNIQUE VALIDATION AND VERIFICATION

4.1 Tools used for Fitness for Service Assessment

To analyze the knock out vessel for fitness-for-service, a broad assessment comprising of critical lifecycle parameters needs to be established before running the assessment. Nowadays, numerous tools are available to facilitate in conducting assessments for fitness-for-service. The FFS assessment tools considered for selection are mentioned below:

1. TWI IntegriWISE [20]

2. Codeware INSPECT [21]

3. Quest Integrity SIGNAL [22]

Each of the above mentioned tools offer a wide range of FFS computations that can be performed for analyzing a particular assessment based on the ASME FFS. In general, these tools are API 579/ASME FFS-1 compliant FFS assessment software, commonly used for assessing the reliability of piping systems, lines, tanks, boilers and vessels [20]. Some common features of the ASME complaint software are described in detail below:

4.1.1 Assessment Tool compliance requirements

In general, before running a FFS Assessment, some capabilities are dictated by the API 579/ASME FFS-1 which must be present in a software to complete a successful assessment run. These capabilities include;

i. Calculation of critical operational conditions
ii. Assessment of different damage mechanisms
iii. Assessment of equipment with varying geometry and component geometry assessment.

iv. “What-if” scenario assessments based on the design conditions of a particular equipment.

v. Material database for material selection before running the assessment.

4.2 Assessment Tool Selection

Among the tools discussed above, the decision has to be made to select a FFS tool which was then to be used for the FFS assessment. Firstly, efforts were made to acquire the license for the Code ware INSPECT through their licensing channel, unfortunately, due to financial and industrial usage constraints, INSPECT could not be acquired, similar was the case for Quest Integrity SIGNAL, Only the license for TWI IntegriWISE could be reasonably acquired hence it was the tool which was then used for running the FFS assessments for the knock out vessel. In selecting the tools used for FFS assessments, care was taken so as to make sure that the tools comply with the Assessment tool compliance requirements for the ASME FFS which are discussed in the previous section, furthermore tool validation was also carried out with the benchmark ASME calculations so that the assessments run on the tool for various scenarios give a complete and an accurate picture of the operational conditions obtained during the computation of the fitness-for-service assessment. The validation of the assessment tool TWI IntegriWISE before proceeding on for the assessment is presented in the next section before this tool can be used for further assessment criterions.

4.3 Validation of the Assessment Tool with benchmark ASME Calculations

To validate the results obtained from the tool for further assessment, a known problem [23] is first solved on the IntegriWISE tool and the results are then compared with the benchmark equations from the API-579-1/ASME FFS-1 standard. As an example for this assessment, a problem involving the corrosion aspect on a longitudinal weld seam is solved both analytically and numerically on the software IntegriWISE, before the solution of the problem the vessel data needs to be identified and presented, the material used for the vessel is SA-516 Grade 70, Year 1999, with the design pressure of 300 psi (gauge) at 350 degrees Fahrenheit. The inside diameter of the vessel is 48 inches while the uniform metal loss and the future corrosion allowance of the vessel are 0 inch and 0.1 inch respectively. The weld joint efficiency of the vessel is 0.85. The inspection data obtained from the vessel used the thickness readings approach, grid spacing set by the inspector was both in longitudinal and circumferential directions respectively with 1.5 in increments based on the corrosion profile of the vessel under consideration. The inspection data required the Level 1 Assessment of the local metal loss to be considered. Before proceeding, the data of the vessel was populated in IntegriWISE and numerically solved to validate the results of the assessment conducted on the software and numerically. The results from the assessment are presented below;

Assessment for validation of the software generated results with the benchmark ASME calculations as presented in the API-579-1/ASME FFS-1 standard		
Parameter	**TWI IntegriWISE Results**	**Numerical Solution (API-579-1/ASME FFS-1 standard)**
Minimum Required Thickness (Longitudinal)	0.429 inches	0.430 inches
Minimum Required Thickness (Circumferential)	0.211 inches	0.212 inches
Minimum Measured Thickness	0.360 inches	0.360 inches
Uniform thickness away from the total metal loss location	0.75 inches	0.75 inches
Remaining Thickness Ratio	0.400	0.400

Parameter Q	0.458	0.4581
Length for the thickness averaging	2.564 inches	2.564 inches

Table 4.1: Assessment Validation for TWI IntegriWISE with the Numerical Solution (API-579-1/ASME FFS-1 standard)

Upon running the assessment of the above mentioned problem, it was immediately clear that the vessel under analysis was not acceptable for further continued operation based on the metal loss on the surface of the vessel and the numerical and software analysis proved to verify this observation. Both the numerically performed and the software verified results generated proved that both Level 1 and Level 2 Assessments for this vessel were unacceptable. The MAWP computed for the vessel yielded the values of 254.072 psi in the circumferential direction and a value of 515.848 psi in the longitudinal direction, both the MAWP values are above the design conditions of the vessel and hence the thickness losses have posed a dangerous problem on the maximum allowable working pressure of the vessel under consideration. This issue has the potential of causing a catastrophic failure within the vessel structure if it is continued to be operated with the same metal loss under the design conditions, hence it is recommended that the vessel be retired and replaced with a new vessel compliant to the service requirements. For reference, the benchmark ASME computations are presented below which were used numerically to validate the solution obtained from the software;

$$t_{min}^{C} = \frac{P * R}{S * E - 0.6P}$$

$$t_{min}^{L} = \frac{P * R}{2S * E + 0.4P}$$

$$t_{min} = \max\left[t_{min}^{C}, t_{min}^{L}\right]$$

where P is the design pressure, R is the inside radius of the component, E is the weld joint efficiency and S is the allowable stress in the component.

$$t_{wall} = t_{nominal} - Future\ Corrosion\ Allowance$$

$$R_t = \frac{t_{mm} - Future\ Corrosion\ Allowance}{t_{wall}}$$

$$Q = 1.123\left[\left(\frac{1-R_t}{1-R_t/RSF_a}\right)^2 - 1\right]^{0.5} \qquad (for\ R_t < RSF_a)$$

$$Q = 50.0 \qquad (for\ R_t \geq RSF_a)$$

Where Q is the factor used to determine the length of thickness averaging based on the allowable Remaining Strength Factor and the Remaining Thickness Ratio.

In general, the numerical solution of the above mentioned problem and its comparison with the software generated results have validated the approach for continuing the Fitness for service Assessment of the knock out vessel, the results of the assessment performed are presented in the next chapter.

4.4 Validation of the FFS Assessment with an FEA Model

In order to validate the results obtained from the API-579 Assessment, the CAD model of the knock out vessel was analyzed in ANSYS Workbench, Simulation results verified the FFS assessment calculations, i.e. the vessel was within the safe operational conditions as already demonstrated by the API-579 Assessment.

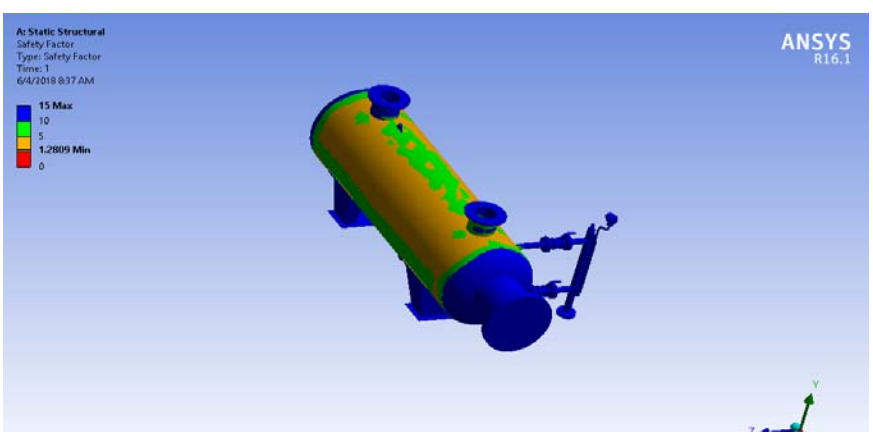

Figure 4.1: Safety Factor Analysis of the computational model on ANSYS Workbench

CHAPTER 5:

RESULTS AND DISCUSSIONS

5.1 Brittle Fracture Assessment Results

Level 1 Assessment for Brittle fracture of the knock out vessel was carried out in the Fitness-for-service software TWI IntegriWISE.

Figure 5.1: Fitness-for-service Assessment Tool

The results from the assessment are presented below.

Code	ASME SEC. VIII (DIV. 1)	
Design Pressure	(MPa)	3.85
Operating Temperature	(°C)	27
Material Specification Number	SA-516	
Minimum Yield Strength	(MPa)	260
Minimum Tensile Strength	(MPa)	485
Nominal Inside Diameter	(mm)	896
Uncorroded Governing Thickness	(mm)	16
Critical Exposure Temperature, (CET)	(°C)	10

Table 5.1: Equipment Information and Intermediate Assessment Results for Brittle Fracture

For Level 1 Assessment, Critical Exposure Temperature (CET) must be greater or equal to the Minimum Allowable Temperature (MAT) for the material.

Level 1 Assessment (Brittle Fracture)

$CET \geq MAT$

The results obtained from IntegriWISE confirm that the MAT is indeed less than CET. MAT is generally determined from the exemption curves given in Part 3 of the API 579 Standard. The results from the Assessment yielded the MAT to be 6.9092 °C which is less than 10 °C which was the CET of the vessel.

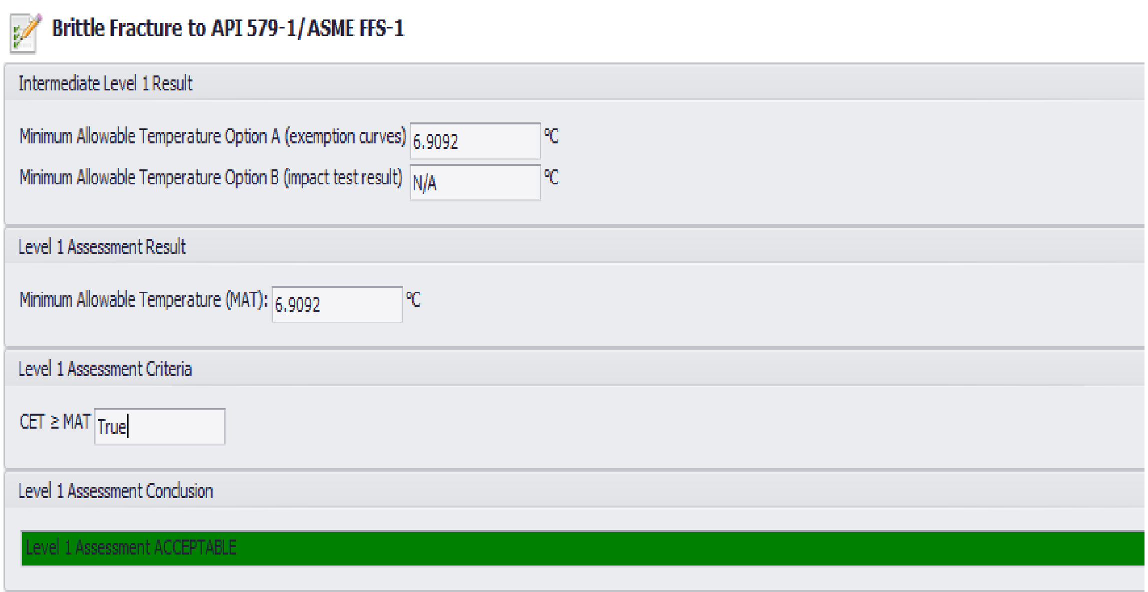

Figure 5.2: Level 1 Brittle Fracture Assessment results from IntegriWISE

The exemption curves from the Part 3 of the API 579 are presented below:

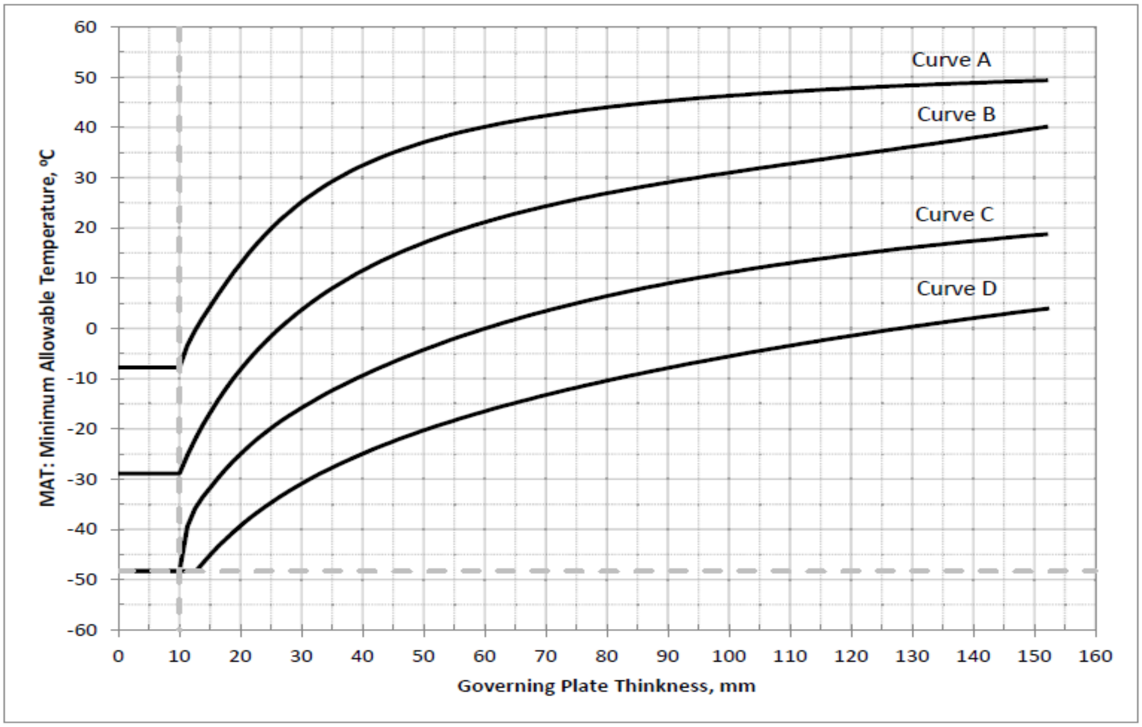

Figure 5.3: Minimum Allowable Temperature (MAT) Exemption Curve [16]

The exemption curves presented in Figure 7 are valid for material specification classes as defined in the Table 3.2, Part 3 of the API 579 standard, which is presented below.

Curve	Material, (1), (2), (6)
A	All carbon and all low alloy steel plates, structural shapes and bars not listed in Curves B, C, and D below. SA-216 Grades WCB and WCC if normalized and tempered or water-quenched and tempered; SA -217 Grade WC6 if normalized and tempered or water-quenched and tempered. The following specifications for obsolete materials: A7, A10, A30, A70, A113, A149, A150 (3). The following specifications for obsolete materials from the 1934 edition of the ASME Code, Section VIII: S1, S2, S25, S26, and S27 (4). A201 and A212 unless it can be established that the steel was produced by a fine-grain practice (5).

Curve	Material, (1), (2), (6)
B	SA-216 Grades WCA if normalized and tempered or water-quenched and tempered. SA-216 Grades WCB and WCC for thicknesses not exceeding 2 inches if produced to a fine grain practice and water-quenched and tempered. SA -217 Grade WC9 if normalized and tempered. SA-285 Grades A and B SA-414 Grade A SA-442 Grade 55>1 in. if not to fine grain practice and normalized. SA-442 Grade 60 if not to fine grain practice and normalized. SA-515 Grades 60 SA-516 Grades 65 and 70 if not normalized. SA-612 if not normalized. SA-662 Grade B if not normalized. Except for cast steels, all materials of Curve A if produced to fine grain practice and normalized which are not listed for Curve C and D below. All pipe, fittings, forgings, and tubing not listed for Curves C and D below. Parts permitted from paragraph UG-11 of the ASME Code, Section VIII, Division 1, shall be included in Curve B even when fabricated from plate that otherwise would be assigned to a different curve. A201 and A212 if it can be established that the steel was produced by a fine-grain practice.
C	SA-182 Grades 21 and 22 if normalized and tempered. SA-302 Grades C and D. SA-336 Grades F21 and F22 if normalized and tempered. SA-387 Grades 21 and 22 if normalized and tempered. SA-442 Grades 55 < 1 in. if not to fine grain practice and normalized. SA-516 Grades 55 and 60 if not normalized. SA-533 Grades B and C. SA-662 Grade A. All material of Curve B if produced to fine grain practice and normalized and not listed for Curve D below.
D	SA-203. SA-442 if to fine grain practice and normalized. SA-508 Class 1. SA-516 if normalized. SA-524 Classes 1 and 2. SA-537 Classes 1 and 2. SA-612 if normalized. SA-662 if normalized. SA-738 Grade A.

Figure 5.4: Material Specification Classes required for the Exemption Curves [16]

The material specification number for the knock out vessel being assessed falls into the Curve B of the exemption curves. Thus only the Curve B is used for further assessment. Curve B is approximated by the following equation:

$$MAT = \begin{cases} -20 \text{ (for } 0 < \text{t} \leq 0.394) \\ -135.79 + 171.56t^{0.5} + 103.63t \\ - 172.0t^{1.5} + 73.737t^2 - 10.535t^{2.5} \text{(for } 0.394 < \text{t} \leq 6.0) \end{cases} \quad (5.1)$$

In the equation specified above, the governing thickness is expressed by t with the units of inches, while MAT is expressed in Fahrenheit. The exemption curve and the approximating equation both were used to validate the MAT obtained from the software, the MAT generated from the equation came out to be about 6.91 °C, thus validating our software generated results.

The vessel was further analyzed for a relationship between the stress ratio R_{ts} and MAT. To determine the relationship between MAT and stress ratio, the ratio must first be computed for the shell section which is given by Eq. (5.2):

$$R_{ts} = \frac{P_a}{P_{rating}} \quad (5.2)$$

Where P_a is the applied pressure for the condition under consideration and P_{rating} is the rated pressure value of the shell section of the vessel. After the determination of stress ratio, the reduction in MAT can then be processed as a function of stress ratio, For the computation of reduced MAT, Temperature reduction (T_R) must be computed as well which can then be finally subtracted from the MAT to give a reduced MAT corresponding to the specified stress ratio, T_R is given by the Eq. (5.3):

$$T_R = \begin{cases} 100.0\,(1 - R_{ts}), \qquad \text{(for } R_{ts} \geq 0.6) \\ -9979.57 - 14125.0R_{ts}^{1.5} + 9088.11\exp[R_{ts}] \quad - 17.3893 \\ , (0.6 > R_{ts} > 0.3) \end{cases} \quad (5.3)$$

The above equations for T_R are valid for the temperature values in Fahrenheit, and the temperature data for this vessel was converted into Fahrenheit to evaluate the values of T_R, furthermore the applicability is also limited provided that the component has a proposed permissible stress at standard room temperature of less than or equal to 17.5 ksi. Calculated component design allowable stress in this case is 7.6622 ksi. The reduction in MAT can then be calculated from Eq. (5.4):

$$MAT_{reduced} = \max[MAT_{previous\,step} - T_R] \quad (5.4)$$

Pressure	R_{ts}	T_R	$MAT_{(reduced)}$
(MPa)	(P_a / P_{rating})	**(°*F*)**	**(°*F*)**
3.85	1.00	0	44.43656
3.465	0.90	10	34.43656
3.08	0.80	20	14.43656
2.695	0.70	30	-15.5634
2.31	0.60	40	-55.5634

Table 5.2: Reduction in MAT corresponding to the Stress Ratio (R_{ts})

The operational pressure and equivalent values of the vessel shell have a MAT as specified in this table which are equated to the real vessel functioning environment to ratify that the metal temperature (CET) is not below the MAT at the equivalent functioning condition. This procedure is used for further refinement of the assessment as the component allowable stress value is less than 172.5 MPa (25 ksi). The obtained results of the reduction in MAT are further validated from the reduction curves from the FFS standard in Part 3.

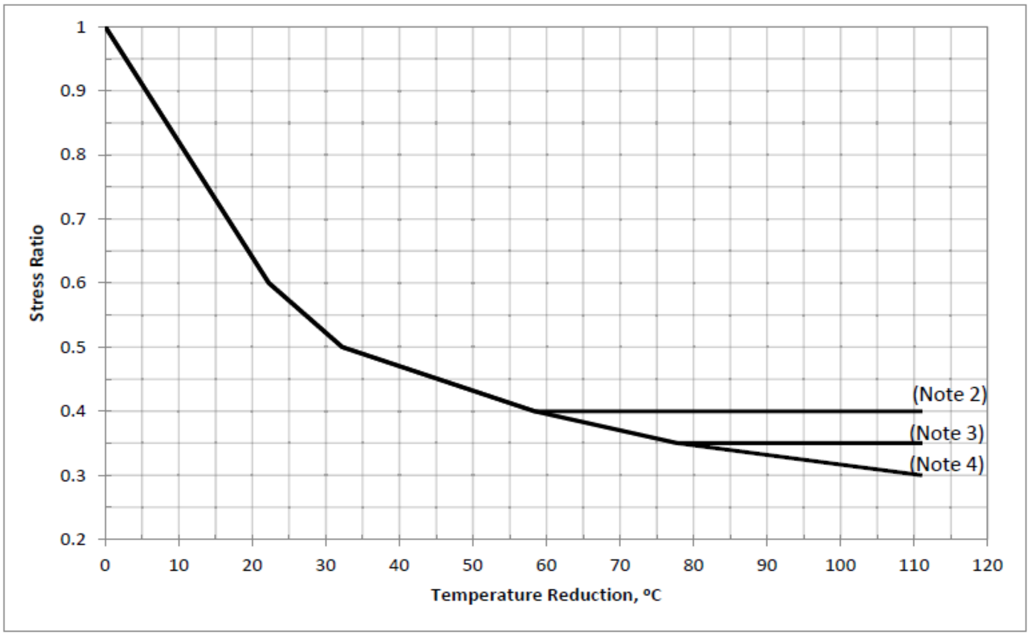

Figure 5.5: Reduction in Minimum Allowable Temperature (MAT) against Stress Ratio Curve [16]

5.2 General Metal Loss Assessment Results

Level 1 Assessment for General Metal Loss of the knock out vessel was carried out in the Fitness-for-service software TWI IntegriWISE. The data used for the assessment is presented in Table 2. Thickness Readings approach was adopted for the assessment based on visual inspection, as the thickness variation was present only along a single longitudinal plane, hence the circumferential readings were taken at 15 different locations on that single longitudinal plane. Thickness Readings approach is valid if the coefficient of variation (COV) in the thickness readings is less than 10%. Coefficient of Variation (COV) is defined as the standard deviation of the thickness readings divided by the average of all the thickness readings. A high coefficient of variation, greater than 10% dictates that the method of thickness profile be used for the general metal loss assessment, which includes the inspection and thickness values specified along the circumferential and longitudinal directions. The intermediate results from IntegriWISE are presented below:

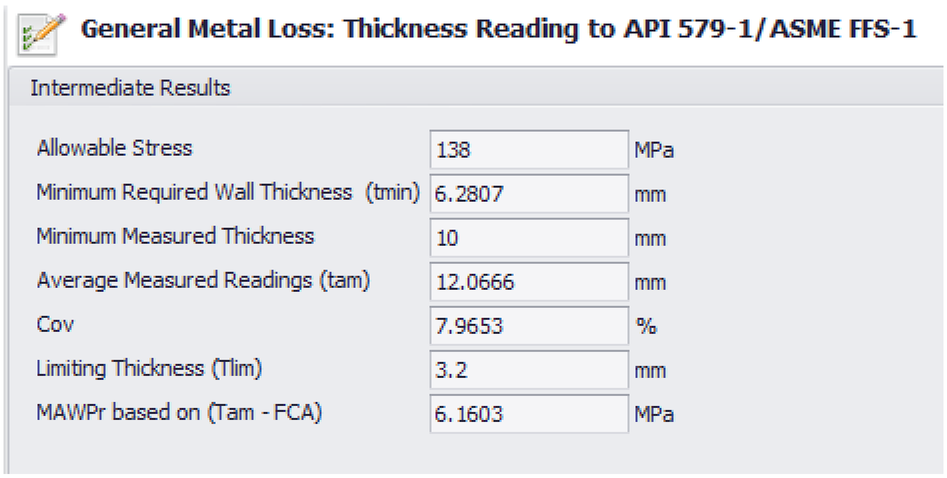

Figure 5.6: Intermediate Results of Level 1 Assessment for General Metal Loss in a Knock out Vessel in IntegriWISE

The thickness readings used for the assessment are presented in Table 5.4.

Location	Thickness Reading *t, mm*
1	13
2	12
3	11
4	13
5	10
6	12
7	11
8	12
9	13
10	13
11	11
12	12
13	12
14	13
15	13

Table 5.3: Thickness Readings used for Level 1 General Metal Loss Assessment of the Knock out Vessel

These thickness readings were taken for 1 Longitudinal Inspection plane with the location readings spanning in the Circumferential Inspection Plane. The coefficient of variation (COV) for the thickness readings comes out to be 7.9653% which as per the Part 4 of API 579 can be assessed based on thickness readings approach. The Level 1 Assessment run on the knock out vessel came out to be acceptable.

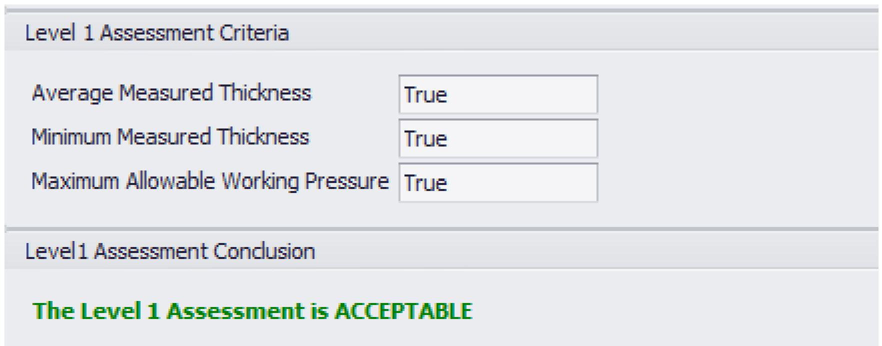

Figure 5.7: Level 1 Assessment Result for General Metal Loss in a Knock out Vessel in IntegriWISE

The minimum measured thickness for the vessel was 10 mm and the averaged measured thickness (from the thickness readings) was 12.0666 mm, against an uncorroded governing thickness of 16 mm. The LOSS can then be calculated as per Eq. (5);

$$LOSS = t_{nom} - t_{avg} \qquad (5)$$

The LOSS comes out to be 3.9334 mm. The minimum required thickness can be evaluated as per Eq. (6);

$$t_{min}^{C} = \frac{P * R}{S * E - 0.6P}$$

$$t_{min}^{L} = \frac{P * R}{2S * E + 0.4P}$$

$$t_{min} = \max\left[t_{min}^{C}, t_{min}^{L}\right] \qquad (6)$$

where P is the design pressure, R is the inside radius of the component, E is the weld joint efficiency and S is the allowable stress in the component, the minimum required thickness for the shell section comes out to be 6.2807 mm. Finally, the acceptability of the vessel for continued operation can then be computed from Eq. (7);

$$(t_{am} - FCA) \geq (t_{min}) \qquad (7)$$

As the Eq. (7) was satisfied, the vessel was deemed safe for the operation under the designed pressure ratings despite the metal loss.

Additionally, the reduced MAWP can also be computed from Eq. (8):

$$MAWP = \frac{S * E * t}{R + FCA + LOSS + 0.6t} \quad (8)$$

Where S is the allowable stress, E is the weld joint efficiency, t is the component thickness and FCA is the future corrosion allowance. The reduced MAWP for the shell section came out to be 6.1603 MPa which is less than MAWP of 8.5525 MPa and is acceptable as per the material specifications.

5.3 Pitting Corrosion Assessment Results

Pitting corrosion assessment was run on the knock out vessel because of the effects of pitting on the vessel surface were evident from visual examination. In general, pitting corrosion can be categorized into four different types, which are;

i. Local Thin Area (LTA) analysis
ii. Scattered pitting
iii. Localized Pitting Areas
iv. Pitting confined within a region of Local Thin Area

Pitting present in the vessel is assessed by means of the Level 1 pitting evaluation, Level 1 pitting assessment uses the standard pit charts presented in the API-579-1/ASME FFS-1 standard, in conjunction with the specification of the largest flaw depth in the area under evaluation to approximate the RSF of the vessel. If Level 1 assessment is not qualified, then the assessment is conducted according to the Level 2 or Level 3 specifications of the FFS standard. The assessment results obtained for Level 1 assessment are presented below;

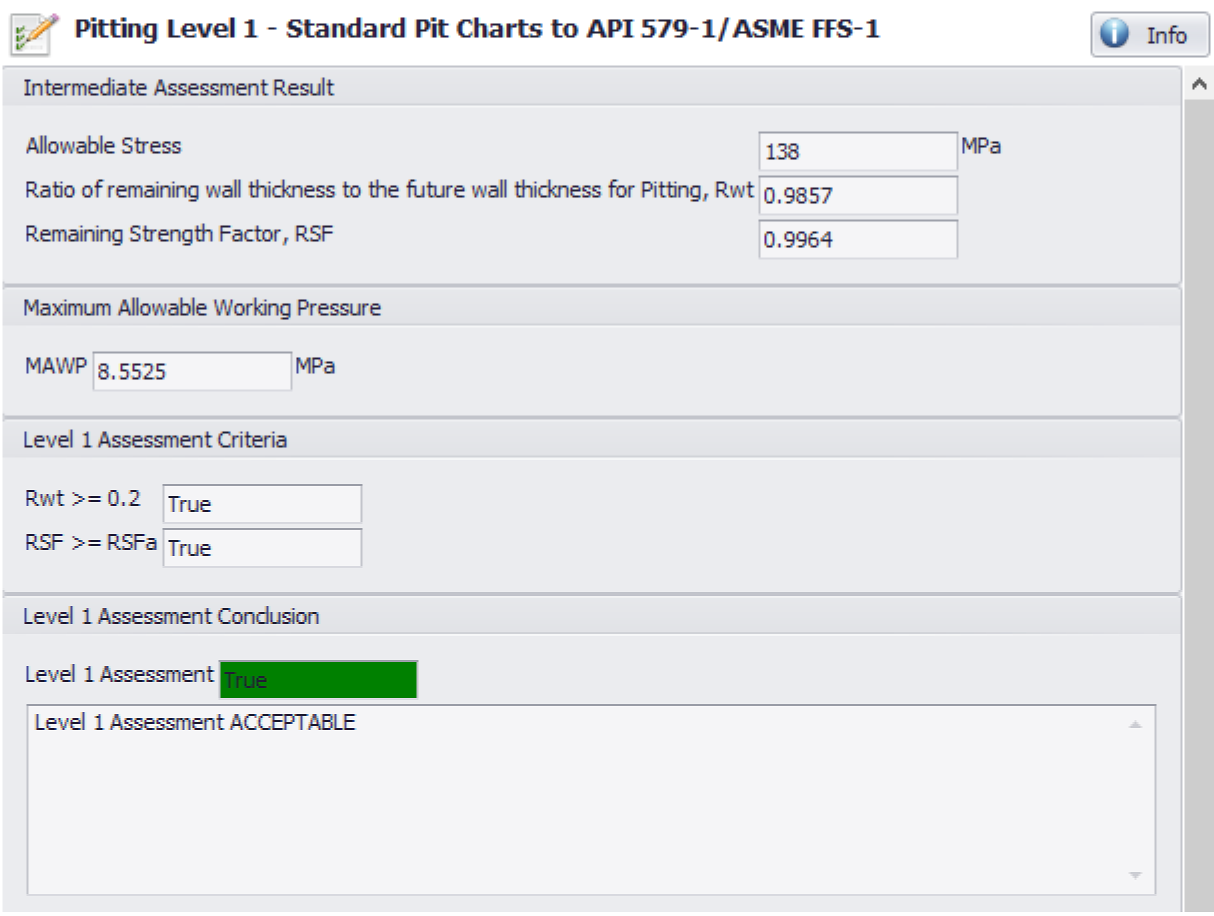

Figure 5.8: Level 1 Assessment Result for Pitting Corrosion on a Knock out Vessel in IntegriWISE

The maximum pit depth present on the vessel was 2.2 mm in depth and the pitting grade evaluated from the details of the vessel available indicated as grade 3 being the most suitable for the pitting present on the vessel. The grade 3 pitting profile used for evaluation of the assessment is presented below;

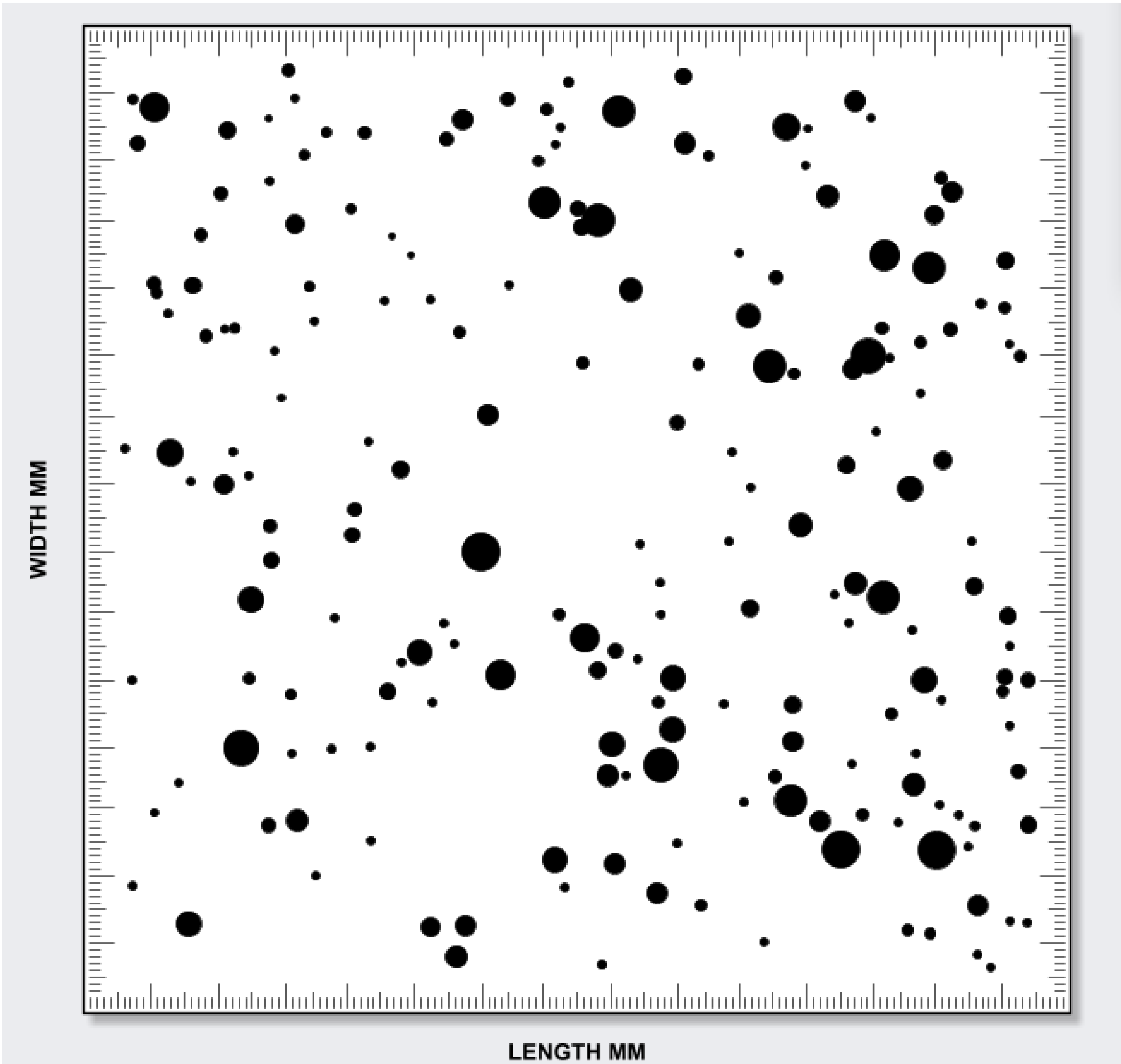

Figure 5.9: Grade 3 Pitting profile used for conducting the Level 1 pitting assessment of the knock out vessel

Pitting corrosion assessment entails the calculation of the wall thickness which is to be used for the assessment, this can be computed from either of the equations specified below;

$$t_c = t_{nom} - LOSS - FCA$$

$$t_c = t_{rd} - FCA$$

The selection for the wall thickness assessment is based on the LOSS if present on the vessel surface, depending on the data appropriate equation selection can be made. Next the area located on the surface with the highest amount of pit density is identified, the max pit depth determined and minimum measured thickness evaluated for the region with the maximum amount of pitting corrosion. Furthermore, the relation of the residual wall width to the imminent wall width in the flawed region is then determined, If the minimum measured thickness for the pit is satisfied and the ratio mentioned above is greater than or equal to 0.2, Level 1 Assessment criteria is satisfied, otherwise Level 2 or 3 Assessment is needed for further evaluation. Finally, MAWP and RSF for the vessel are then computed for acceptability as per the FFS standard. If the RSF ≥ RSFa, the pitting corrosion is adequate for functioning at MAWP. Otherwise, MAWPr needs to be computed and the vessel is then rerated for operation at the reduced working pressure.

5.4 Min Thickness / MAWP Assessment Results

Minimum thickness assessment and MAWP assessment are carried out individually for the vessel to determine both of the above mentioned parameters. The minimum thickness parameter indicates the minimum possible thickness for the shell wall of the vessel which is necessary for sustaining the pressure loadings and the supplemental loadings developed due to the flaws present on the vessel surface, while the Maximum allowable working pressure of the vessel is an indication of the refers to the wall strength of a pressurized vessel and in actual is the amount of pressure that the weakest surface of the vessel can bear based on the design pressure values. Normally, standard wall thickness components are used in the fabrication of the pressurized equipment, and hence some portions of the vessel can withstand a pressure value greater than the MAWP for the vessel. The values of the minimum thickness needed for the design pressure and the safe operation of the vessel has been calculated and presented below. Also, the value of the MAWP computed for the assessment is presented below;

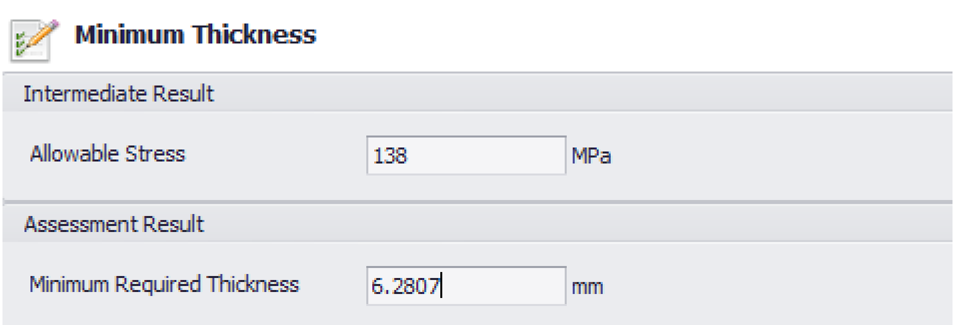

Figure 5.10: Minimum Thickness of the wall of the pressurized vessel in IntegriWISE

In the figure above, allowable stress based on the design conditions of the vessel has also been computed. The results obtained from this evaluation match the results that were obtained from the previous evaluations of the vessel thus verifying the integrity of the vessel.

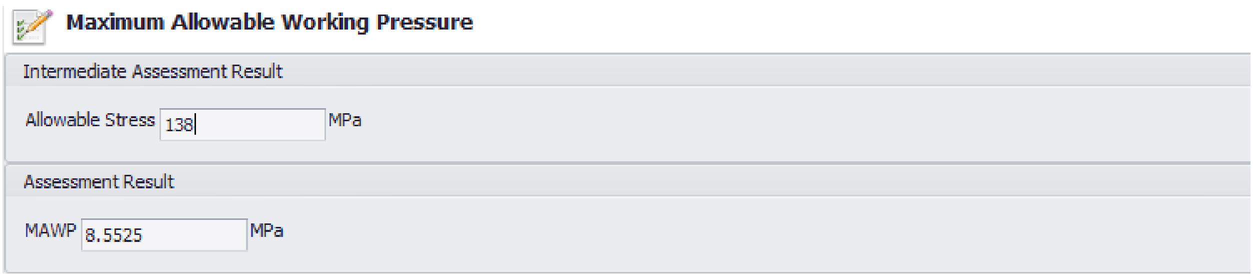

Fig 5.11: Maximum Allowable Working Pressure of the Knock out Vessel in IntegriWISE

In this chapter, the flaws present is the vessel were first characterized and the necessary assessments were performed pertaining to the flaws present on the vessel surface, the low temperature values were an important factor in necessitating a brittle fracture assessment of the main vessel section. As Level 1 Assessment for the brittle fracture was acceptable, the vessel is safe for further operation.

There were signs present of metal loss on the vessel surface, and hence as per observations and criteria of ASME FFS standard, a general metal loss assessment was needed to ensure that the metal loss is not outside the safe design parameters necessary for the vessel operation. This yielded an acceptable Level 1 Assessment result which cleared the metal loss as being in the acceptable range for the continued operation of the vessel. A pitting corrosion assessment was also performed for the vessel because of the localized pitting present on some of the surface of the vessel, the pitting profile was identified and the assessment carried out, fortunately the pitting effects were insignificant and yielded an acceptable Level 1 assessment of the vessel thus the vessel was deemed suitable for further operation based on acceptable fitness for service assessments subject to continued further inspections as documented in the ASME FFS standard.

CHAPTER 6:

CONCLUSIONS

The use of fitness for service techniques for the vessel assessment greatly simplifies the evaluation of the remaining service life of the vessel and safety of the vessel for continued future operation based on the design parameters.

The knock out vessel is placed in the field and exposed to the environmental conditions and low temperatures, also the vessel is also recently moved into a new service area for operation, this factors combined necessitated the need for the brittle fracture assessment on the vessel surface, Because of the erosion on the vessel surface, a general metal loss assessment was also required to confirm that the vessel had no metal loss which could negatively affect the vessel structural strength. The presence of pitting flaws on the vessel required a pitting assessment to be run for the residual lifespan estimation of the vessel. In Chapter 2, Introduction to the API-579-1/ASME FFS-1 is presented with details on the applicability and limitations on implementing the fitness for service assessment techniques, the assessment levels for API-579-1 are then discussed further to clarify for the reader the extent of the assessment which needs to be performed for the evaluation of the vessel parameters. The problem statement and the objectives are presented in the next section highlighting the vessel design and operational conditions required for the assessment, towards the end of the chapter the necessary fitness for service procedure is discussed which needs to be implemented for the detailed analysis of the vessel, this includes brittle fracture, metal loss and the pitting corrosion assessment of the vessel. Chapter 3 starts with the introduction to the software which is to be used along with the problem definition in IntegriWISE. Definition of the problem is followed by the development of the assessment flowcharts which detail the process of assessment for the flaws present in the vessel. This completes the methodology selection for further analysis on IntegriWISE. The software selection done needs to be justified and validated in order for the results to be accurate and meaningful, this is accomplished in Chapter 4 of the document where justification is presented for the software selection along with the ASME compliance requirements needed for a standardized assessment. A test case is run on the software and analyzed numerically and the results are compared for the validation of the test scenario. Chapter 5 presents the results and discusses the outcomes of the assessment conducted. It also includes information on the numerical aspects of the conducted assessment and compares the different scenarios based on design conditions. Lastly, Chapter 6 concludes the study of the vessel assessment by providing conclusions and recommendations for future work. Based on the assessment results, the following recommendations are suggested for the knock out vessel:

1. The vessel was analyzed for brittle fracture assessment because of the change in service and location of the vessel, furthermore the conditions for operation of the vessel both previously and in the current location were hazardous which could result in an unfortunate brittle fracture. In this regard, the vessel was first analyzed using Level 1 Assessment, which for ASME 579 dictates that the vessel MAT and CET be established and compared from the exemption charts for an acceptable result. Furthermore, a relationship between stress ratio and applied pressure for the condition under consideration was also established which could reduce the MAT further based on operating pressure reduction. This would be helpful in mitigating the reduction in service life of the vessel based on reduced pressure applications pertaining to brittle fracture.

2. The current operating conditions of the knock out vessel are sufficient for the safe operation of the knock out vessel provided that inspection parameters remain the same as those considered for the assessment. In this regard, Regular inspection of the vessel be carried out to detect any changes in the vessel structure, with particular emphasis upon the formation microstructure flaws which can be the precursor of brittle fracture. For this particular industry, the inspection is performed after every year of operation based on design parameters and is based on both internal and external inspections starting from Level 1 inspection and proceeding onto Level 2 if the Level 1 inspection comes out to be unacceptable.

3. General Metal Loss assessment was run on the vessel because of the fact that the loss measurement on the vessel surface was present in the circumferential inspection plane in a single longitudinal inspection plane, Thickness readings were taken and the COV was calculated, According to the GML section of the ASME 579, if the COV is under 10%, the

thickness readings method can be utilized for the assessment which was the case with this knock out vessel, hence thickness readings approach was adopted for the assessment of the general metal loss present in the vessel. The assessment results indicated that the Level 1 Assessment of the GML was acceptable, hence further analysis was stopped at this point and the parameters were noted down for future inspections.

4. Minor pitting was also present on the vessel surface which was due to be analyzed according to the Pitting corrosion section of the ASME 579 standard, in start of the pitting assessment, the initial parameters are measured and recorded and the type of pitting selected, the pitting present on the vessel fell into the category of local pitting areas, Level 1 assessment for the pitting came out to be acceptable, hence further analysis was stopped at this point and the parameters were noted down for future inspections.

5. Additionally, Minimum thickness and MAWP were also computed for the vessel, these parameters are necessary for the calculation of the MAWPr and critical thickness calculations.

The measurement of erosion and corrosion present on the vessel surface must also be monitored regularly, furthermore previous assessment results should be logged and the next assessment run should include the start point of the previous assessments so future inspections can accurately yield the extent of flaws present in the vessel which can then be used to make future assessments more precise thus accurately predicting the remaining life of the vessel.

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