CHAPTER 1

INTRODUCTION

1.1 Background

Goal setting safety legislation for pressure systems was first introduced in 1989 and retained in the Pressure Systems Safety Regulations (PSSR) 2000. This has enabled a move towards inspection strategies based on the risk of failure or specifically Risk-Based Inspection. This trend towards Risk-Based Inspection (RBI) approach is being supported by extensive plant operating experience, improved understanding of material degradation mechanisms, and the availability of fitness-for-service assessment procedures.

Risk-Based Inspection (RBI) is a method that defines the risk of operating equipment as the combination of two separate terms; the consequences of failure and the likelihood of failure. In addition, Risk-Based Inspection (RBI) provides a systematic approach in reviewing the integrity of the in-service equipment. Through Risk-Based Inspection (RBI), the integrity of the in-service equipment could be improved and maintained by performing the quantitative engineering evaluation. Such assessment would help in way to prioritize the concerned area of equipment.

In today’s highly competitive Power Generation industry, key factors for success are consistently high levels of availability and reliability. It is perhaps no surprise that considerable interest within industry is currently being centered on Risk-Based Inspection (RBI) approaches to managing and maintaining plant. The aim of such approaches is to cost effectively focus maintenance and inspection resources to the critical areas of the plant. Application of RBI approaches to power plant is however still largely in its infancy.

1.2 Problem Statement

Current API 581 Risk-Based Inspection (RBI) Base Resource Document does not cover specified guideline to evaluate on erosion consequence with steam as representative fluid. Usually, incident such as boiler tripping will cost a huge consumption/loss of money to the power plant. One of the major factors to such incident is the presence of in-service defect tubes due to flyash erosion which lead to tube thinning. Conducting an inspection program could help to identify the concerned defect tubes by shutting down the equipment. However, frequent inspections or shutdown would involve a huge consumption of money and could affect the production of the plant. Using solely API 581 RBI approach on the consequence analysis will not reflect the plant loss as steam is classified as nonflammable and nontoxic.

1.2 Objective and Scope of Study

The objective of this study is to propose Flyash Erosion Module and Criticality Assessment based on Risk-Based Inspection (RBI) at Coal-Fired Power Plant Boiler using Semi-Quantitative Analysis.

The study covers flyash erosion effect to the tubes of High Temperature Superheater (HTS) High Temperature Reheater (HTR) and Economizer in the boiler of coal power plant.

CHAPTER 2

LITERATURE REVIEW AND THEORY

2.1 Coal-Fired Thermal Power Plant

Figure 1 shows a typical diagram of coal-fired thermal power plant that consists of a few basic units.

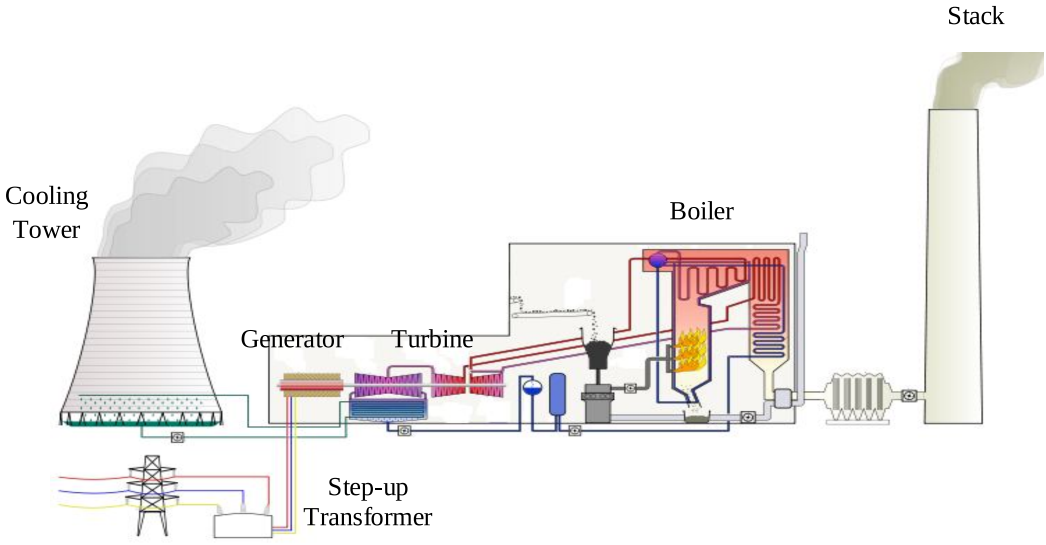


Figure 1: Typical Diagram of a Coal-Fired Thermal Power Plant

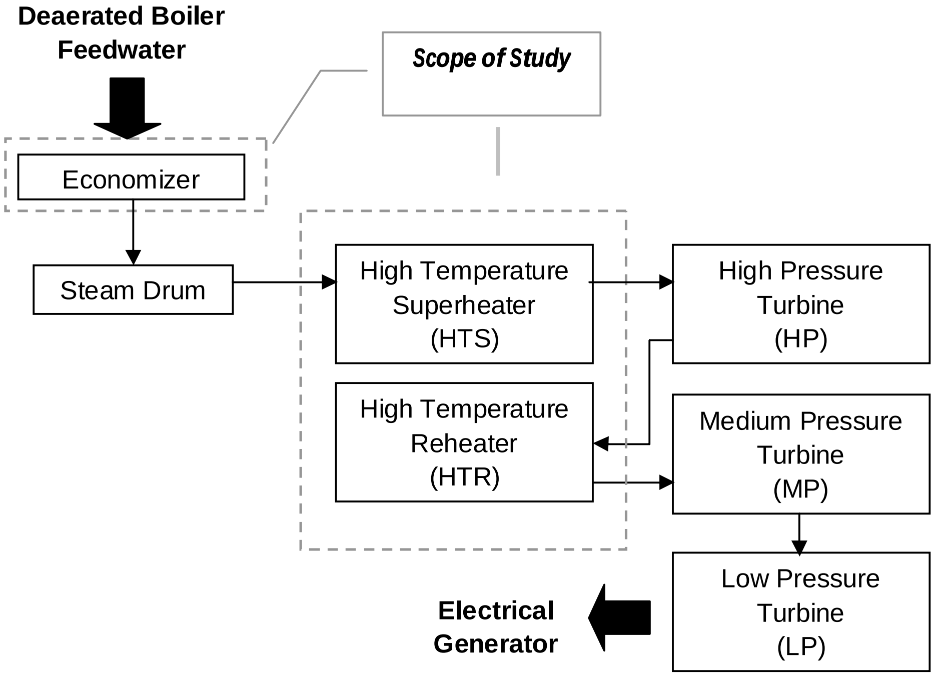


Figure 2: Simplified Steam Generator Schematic

Figure 2 is the common parts of a boiler. The feedwater enters the boiler through a section in the convection pass called the economizer. The process of adding the latent heat of vaporization or enthalpy is done through a few stages in the boiler. The produced steam is then being used to run the turbines.

Brief descriptions of the boiler’s parts are as the following:

- **Economizer** – heat exchange device that uses exhaust gases from the boiler to preheat water up to but not normally beyond the boiling point.
- **Steam Drum** – stores the steam generated in the water tubes and acts as a phase-separator for the steam.
- **High Temperature Superheater (HTS)** – heating steam by increasing its thermal energy and decreasing the likelihood of it to condense. The steam is used to run high pressure (HP) turbine.
- **High Temperature Reheater (HTR)** – exhaust steam from high pressure (HP) turbine is rerouted into reheater, picking up more energy to drive medium (MP) and low pressure (LP) turbine.
- **High (HP), Medium (MP) and Low Pressure (LP) Turbine** – drive electrical generator to generate an intermediate level of voltage.

2.2 Brief Analysis on Erosion Rate

In coal-fired power stations, about 20% of the ash produced in the boilers is deposited on the boiler walls, economizers, air-heaters and super-heater tubes. [1] High local velocity and extent of ash loading are the two principal and most controllable factors influence the fly-ash erosion as show in Figure 3 below. It has been observed that local velocities in excess of 100 ft/sec are required to cause fly-ash erosion failures in 10,000 to 50,000 hours. [2]

A general equation for erosion can be stated as:

$E = k\,M\,V^n$

where: E = erosion rate (mils/hr)

K = proportionality constant

M = fly ash mass flux (lb/hr-sq. ft)

V = particle velocity (ft/sec)

N = velocity exponent ranges from 2-4

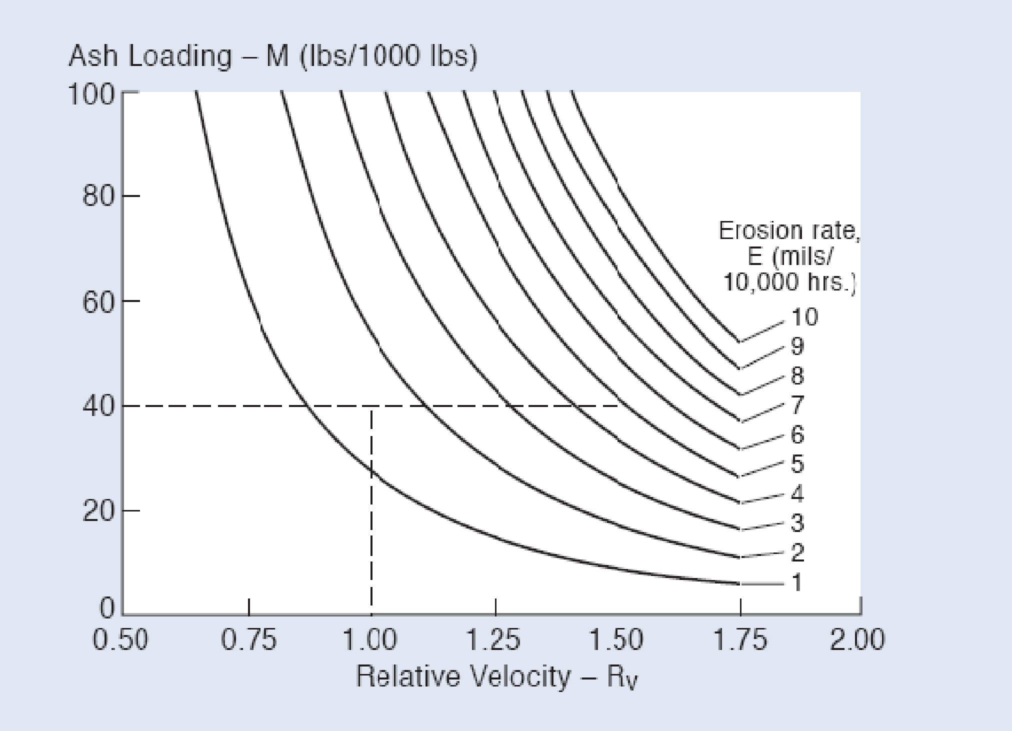


Figure 3: Dependence of Erosion on Particle and Velocity and Flyash Loading

Erosion rate is also a function of the angle of incidence. The most damaging angle is at approximately 35-45°. [4] The composition of the ash impacting a tube can also have a significant effect on the rate at which erosion occurs. Raask has developed an abrasion index and a measure of wear propensity based on coal characteristics. [3] An abrasion index (AI) was derived from the analysis of abrasion wear experiments and the chemical analysis for SiO_2 (silica) and Al_2O_3 (alumina) in coal ash. The abrasiveness of coals can be classified into four general levels as result of their abrasion index and is summarized in Table 1 below:

Table 1: Classification of Coals by Abrasion Propensity

Type of Coal	**Abrasion Index (AI)**	**Wear Propensity (W_p)**	**Category**
Low in ash and quartz	<4	<3	Slightly abrasive
Medium in ash and quartz; high in ash but low in quartz	4-8	3-6	Moderately abrasive
High in ash and quartz	8-12	8-15	Highly abrasive
Exceptionally high in ash and quartz	>12	>15	Exceptionally abrasive

Although a fully predictive model for erosion effects is not in hand, the trends are well known; an increase in erosion rates occurs with higher velocities, high ash loads or other abrasive particles such as quartz, and low angles of incident attack. [1]

2.3 Flyash Erosion

Identifying the type of degradation caused by fly-ash erosion is important to understand how the plant equipment will fail. Fly-ash erosion is one of the five erosion mechanisms that affected the boiler integrity. The others are sootblower erosion, falling slag erosion, coal particle erosion and the erosion of in-bed tubes of bubbling fluidized bed units. Fly-ash erosion accelerates tube wastage by direct removal, and removal of fireside oxide increases the fireside oxidation rate. The latter mechanism becomes dominant at temperature above 425°C.

2.3.1 Features of Failure

Fly-ash erosion damage is usually very localized. Moderate fly-ash erosion is characterized by burnishing or polishing of affected tube surfaces facing the gas flow. The tube surface is very smooth and differs from unaffected tubes by colouring; heavy, black polishing is the first sign of impingement erosion. There is a qualitative difference between a heavy polishing caused by erosion and slight erosive action that removes just paint or scale. [1]

A distinguishing feature is the formation of fresh rust on tubes only a few hours after boiler washing, indicating and advanced erosion problem where the protective scale has been removed. Flat spots, ovality and formation of edges on straight tube sections indicate a condition requiring immediate action

As erosion becomes more severe, tubes begin to thin, flattened areas develop, and eventually internal pressure leads to tube rupture. If the erosion rate was rapid, the failure may be thin edged, a pin-hole shape or a long, “thin” blowout. If the failure was gradual, creep effects may result in a thick-edged failure.

2.3.2 Locations of Failure

The amount of ash loading and its velocity are the key determinants of fly-ash erosion; of the two, velocity is dominant. Therefore, fly-ash erosion will be a concern where nonuniform, high gas flow develops anywhere in the boiler, particularly in the economizer, primary superheater, and inlet sections of reheater tubes as shown in the Figure 4.

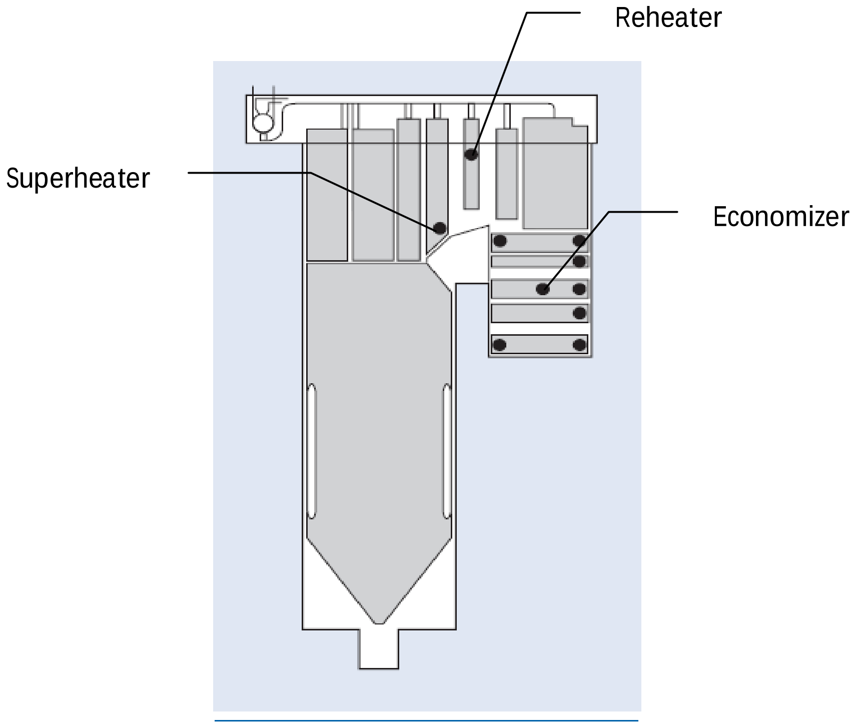


Figure 4: Typical Boiler Locations Where Flyash Erosion Can Occur

The economizer is particularly susceptible because of the tight spacing of tubes, often on 3 to 4 inch centers, and because the cooler temperatures lead to harder, more abrasive ash particles.

In the superheater and reheater, fly-ash erosion in generally more prevalent in the cooler regions either toward the top of the furnace or in the back pass, although an occasional failure has been found in austenitic material nearer to the furnace exit.

2.4 Boiler Tube Material

The material for the boiler tube is identified to be A-213, grade T22 and T91; austenitic alloy (2¼Cr–1Mo and 9Cr–1Mo–½V–X) steel of seamless tube. Chromium (Cr) content yields improved properties, particularly higher strength, creep properties, improves corrosion resistance as well as resistant to graphitization. Verifying on the specification would be helpful in verifying on the suitability of the material and cost per item that will be used in the Semi-Quantitative Analysis later.

2.5 Risk-Based Inspection (RBI)

The Risk-Based Inspection (RBI) method defines the risk of operating equipment as the combination of two separate terms; the consequences of failure and the likelihood of failure. Risk-Based Inspection (RBI) programs consist of qualitative, semi-quantitative, and quantitative approach of risk evaluation as shown in Figure.

2.5.1 Qualitative Analysis

The qualitative approach is similar to that of the quantitative analysis, except that the qualitative approach requires less detailed and is far less time consuming. Qualitative approach applies when the required data for both probability of failure (PoF) and consequence of failure (CoF) is limited for the analysis. While the results it yields as five-by-five matrix are not as precise as those of the quantitative analysis, it provides a basis for prioritizing a risk based inspection program.

2.5.2 Semi-Quantitative Analysis

Semi-Quantitative approach is the combination of both qualitative and quantitative approach. Semi-quantitative applies when either one of the data for probability of failure (PoF) or consequence of failure (CoF) is found to be limited. The result will yield in five-by-five matrix as well.

2.5.3 Quantitative Analysis

In quantitative approach, various scenarios are developed to show how leaks may occur and how they can progress into undesirable events. In the quantitative Risk-Based Inspection (RBI) calculation, one-to-one correspondence between hole size and scenarios, these terms are often used interchangeably. A risk calculation is performed for each scenario, for all risk categories if desired. The risk for each equipment item is then found by summing the individual risk components from each scenario calculation.

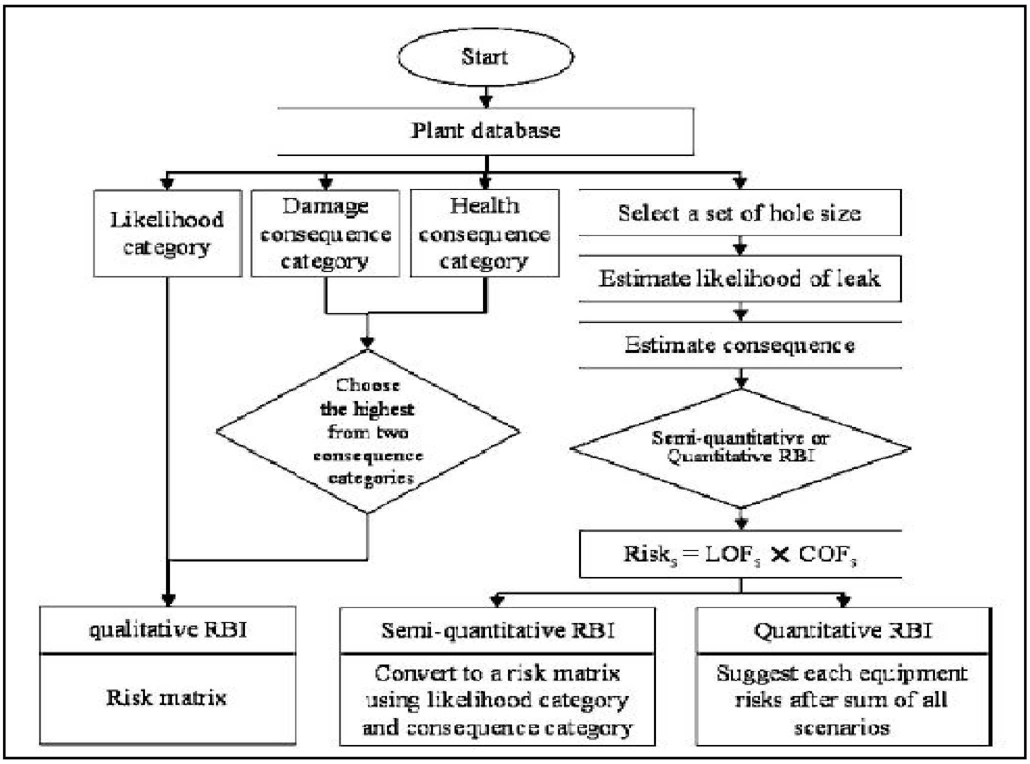


Figure 5: Risk Evaluation Process of the Qualitative, Semi-quantitative, and Quantitative RBI Approaches based on API Code

(Adopted from API 580, Risk-Based Inspection)

2.6 Consequence Analysis for Steam

Risk-Based Inspection (RBI) consequence of failure (CoF) is established based on one of the following four consequences:

- Flammable Effect
- Toxic Effect
- Environmental Impact
- Business Interruption Cost

The representative fluid in the boiler tube of economizer, superheater as well as reheater is steam; classified as a nonflammable and nontoxic. Thus, both flammable and toxic effects are not applicable. The specific concern is mostly on the cost that will involve if the equipment is down, business interruption cost specifically. However, API 581 Risk-Based Inspection (RBI) Based Resource Document stated that a flammable consequence need to be undergone first in order to proceed with the business interruption cost consequence.

Loganathan Krishnasamy, Faisal Khan and Mahmoud Haddara suggested in their paper that the business interruption cost is established through the estimation of maintenance and the production loss costs. [5]

2.6.1 Estimation of Maintenance Cost

Maintenance cost typically includes the cost of labour, and the down time associated with the repair. The maintenance cost is calculated using the following equation:

$$MC = C_f + DT \cdot C_v$$

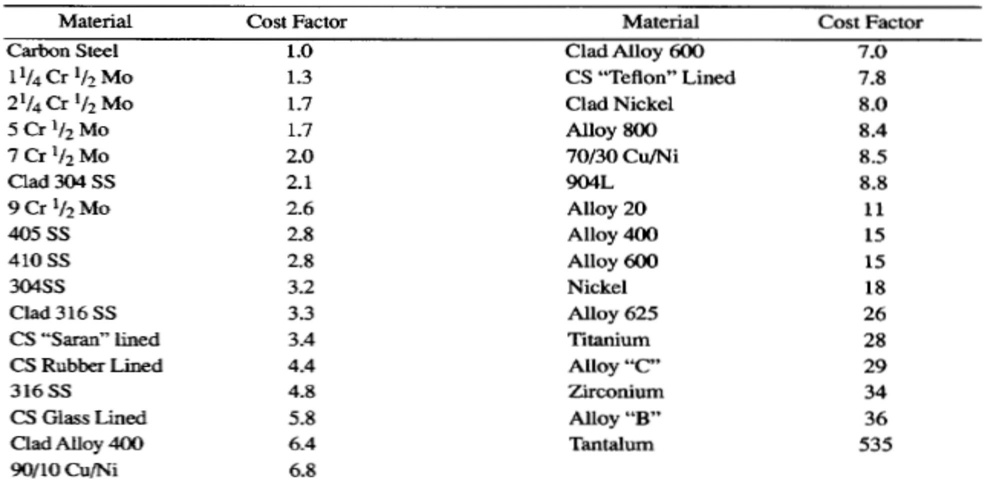
Where C_f is the fixed cost of failure (cost of spare parts), DT is the down time, and C_v is the variable cost per hour of down time, it includes labour rate and crew size. Brief descriptions of these costs are given in the following tables.

Table 2: Labour Rates

Trade	**Description**	**Hourly Rate**
Boiler maker	General foreman	$46.21
	Foreman	$44.90
	Fitter/welder	$41.26
	Apprentice 3	$38.04
	Apprentice 2	$32.81
	Apprentice 1	$27.64
	Helper	$38.04
Pipe fitter	Foreman	$45.49
	Welder/journeyman	$42.64
Millwright	Foreman	$41.47
	Welder/journeyman	$40.22
	Apprentice	$38.60
	Journey	$34.64
	Electrician	$25.00

Table 3: Equipment Damage Cost for Carbon Steel

(Adopted from API 581, Risk-Based Inspection)



Material	Cost Factor	Material	Cost Factor
Carbon Steel	1.0	Clad Alloy 600	7.0
$1\frac{1}{4}$ Cr $\frac{1}{2}$ Mo	1.3	CS "Teflon" Lined	7.8
$2\frac{1}{4}$ Cr $\frac{1}{2}$ Mo	1.7	Clad Nickel	8.0
5 Cr $\frac{1}{2}$ Mo	1.7	Alloy 800	8.4
7 Cr $\frac{1}{2}$ Mo	2.0	70/30 Cu/Ni	8.5
Clad 304 SS	2.1	904L	8.8
9 Cr $\frac{1}{2}$ Mo	2.6	Alloy 20	11
405 SS	2.8	Alloy 400	15
410 SS	2.8	Alloy 600	15
304SS	3.2	Nickel	18
Clad 316 SS	3.3	Alloy 625	26
CS "Saran" lined	3.4	Titanium	28
CS Rubber Lined	4.4	Alloy "C"	29
316 SS	4.8	Zirconium	34
CS Glass Lined	5.8	Alloy "B"	36
Clad Alloy 400	6.4	Tantalum	535
90/10 Cu/Ni	6.8		

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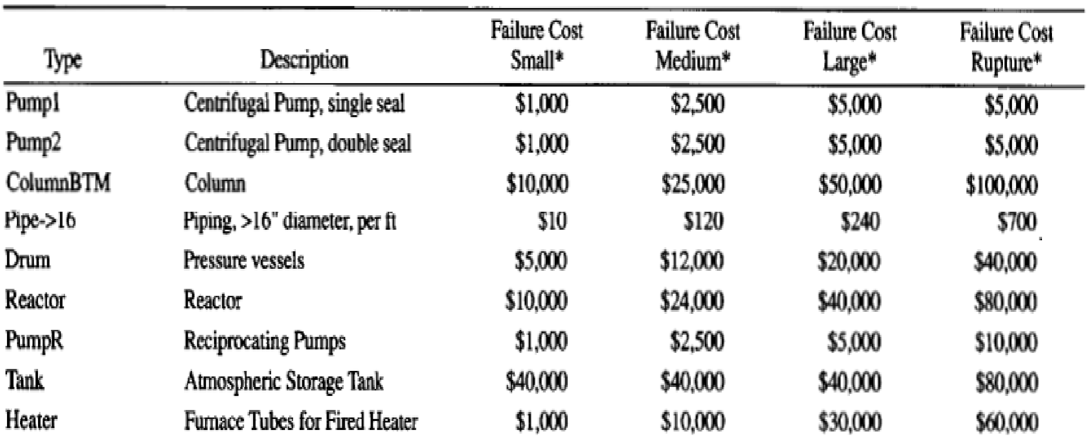
Table 4: Material Cost Factor

(Adopted from API 581, Risk-Based Inspection)



Type	Description	Failure Cost Small*	Failure Cost Medium*	Failure Cost Large*	Failure Cost Rupture*
Pump1	Centrifugal Pump, single seal	$1,000	$2,500	$5,000	$5,000
Pump2	Centrifugal Pump, double seal	$1,000	$2,500	$5,000	$5,000
ColumnBTM	Column	$10,000	$25,000	$50,000	$100,000
Pipe->16	Piping, >16" diameter, per ft	$10	$120	$240	$700
Drum	Pressure vessels	$5,000	$12,000	$20,000	$40,000
Reactor	Reactor	$10,000	$24,000	$40,000	$80,000
PumpR	Reciprocating Pumps	$1,000	$2,500	$5,000	$10,000
Tank	Atmospheric Storage Tank	$40,000	$40,000	$40,000	$80,000
Heater	Furnace Tubes for Fired Heater	$1,000	$10,000	$30,000	$60,000

2.6.2 Estimation of Production Loss Cost

The production loss cost is estimated using the following formula:

$PLC = DT \, . \, PL \, . \, SP$

Where DT denotes down time, PL denotes production loss in Megawatt, and SP is the selling price for the unit product of electricity. The combination of production loss cost and the maintenance cost gives the consequence of failure in dollars.

2.6.3 Down Time

The equipment down time period is determined by considering the worst event scenario.

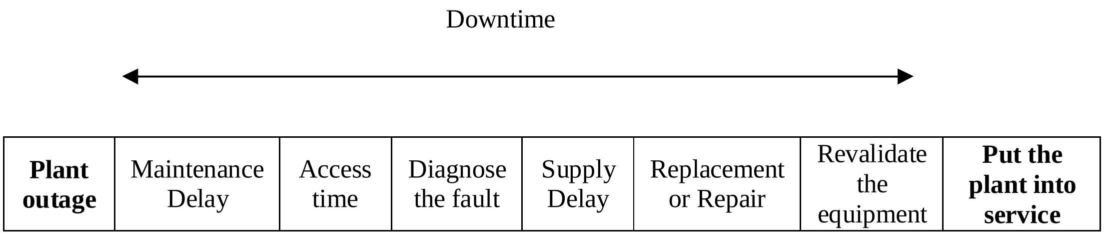


Figure 6: Analysis of Downtime

CHAPTER 3

METHODOLOGY/PROJECT WORK

3.1 Project Implementation Approach

The project implementation includes few stages as presented in Figure 7 below. The project will be more or less implemented using the adaptation of API 581 Risk-Based Inspection (RBI), Semi-Quantitative Analysis.

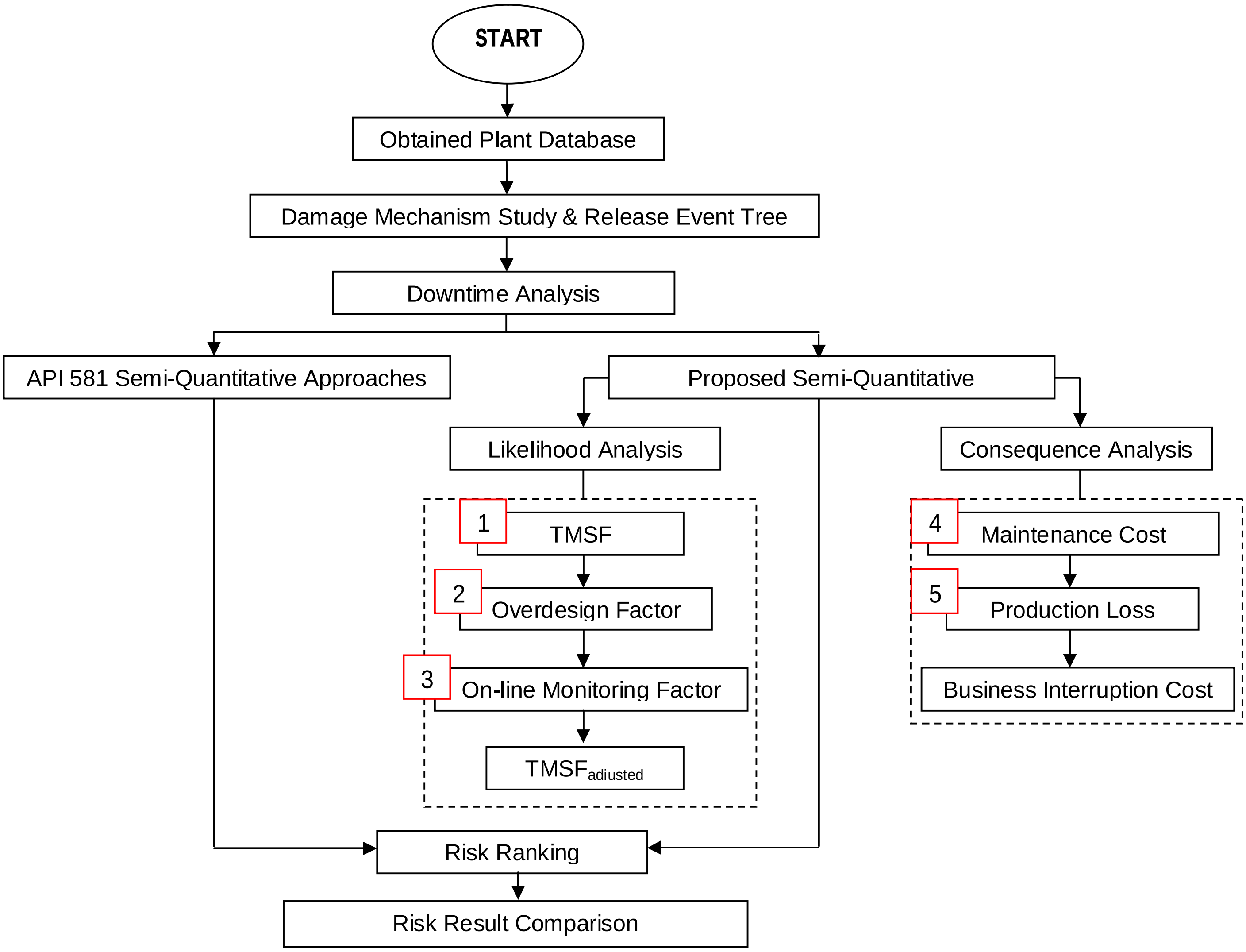


Figure 7: Project Implementation Stages

3.1.1 Obtaining Boiler Database

Understanding the requirement and priority of each data are useful for Risk-Based Inspection (RBI) Assessment. Table 5 shows the list of the required data which will be used in Semi-Qualitative Analysis.

Table 5: Classification of Boiler Tube Data

Item	Data Requirement
1	Operating period (years)
	Current thickness (mm)
	Corrosion rate (mm/yr)
2	Maximum Allowable Working Pressure, MAWP
	Operating pressure
	Corrosion allowance (mm)
	Tube Metal Temperature, TMT
3	Type of on-line monitoring being employed (probes, coupons, etc)
	Inspection Effectiveness Category (Highly, Usually, Fairly, Poorly)
	No of Inspection being conducted
4	Equipment damage cost
	Cost per hour for downtime (repairing work cost, manpower cost)
	Shutdown time (hrs)
5	Production Loss (Megawatt)
	Electricity selling price ($/Megawatt.hr)

3.1.2 Damage Mechanism Study & Release Event Tree

A comprehensive analysis is conducted on the damage mechanism and release outcomes which includes a literature study on materials and erosion to identify susceptibility to potential damage mechanism and to address the possible effect as well as affected plant equipment.

3.1.3 Semi-Quantitative Analysis

Semi-quantitative analysis is an approach utilizing all of the possible methods of the Risk-Based Inspection (RBI) Base Resource Document. As the study is being conducted on a new Coal-Fired Thermal Power Plant, thus the range of data on the inspection history to determine the erosion rate is very limited. Therefore, Semi-quantitative approach is employed for the analysis

- Likelihood Analysis

The likelihood of failure category is established through the calculation of Technical Module Sub-factor (TMSF). Thus API 581 RBI Based Resource Document Appendix G is used to establish the Technical Module Sub-factor (TMSF) for process equipment subject to damage by mechanisms that result in thinning

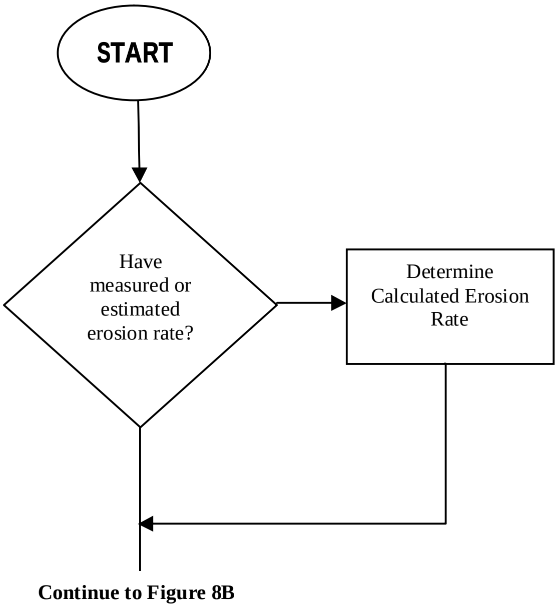


Figure 8A: Determination of Technical Module Subfactors for Thinning (Adopted from API 581 Risk-Based Inspection)

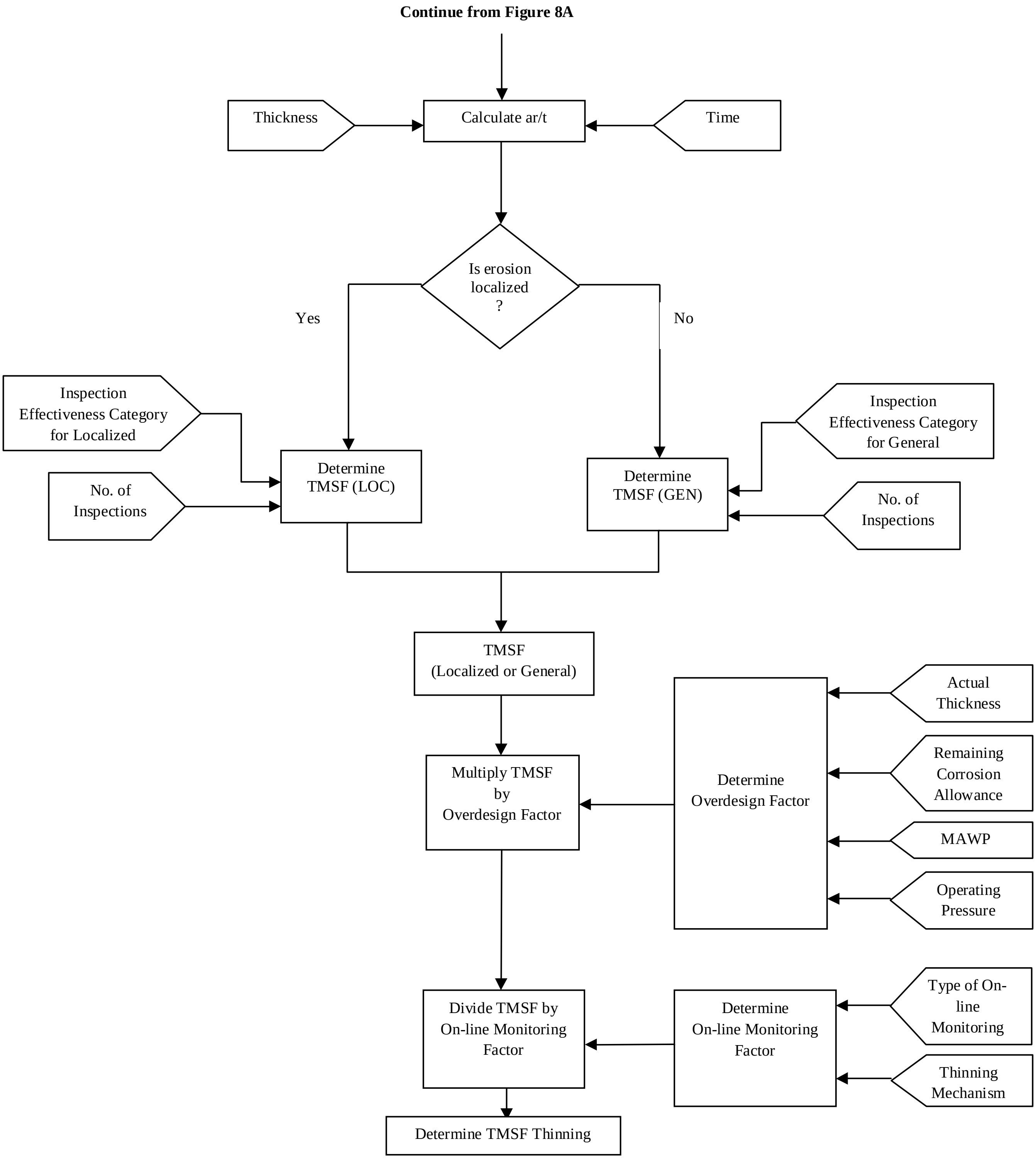


Figure 8B: Determination of Technical Module Subfactors for Thinning

(Adopted from API 581 Risk-Based Inspection)

Technical Module Subfactor (TMSF) for thinning is computed through modification of Fraction of Wall Loss by Overdesign Factor and On-line Monitoring Factor as shown below. With obtaining Fraction of Wall Loss, TMSF value is attained from API 581 Risk-Based Inspection (RBI) Base Resource Document Appendix G, TMSF Table as provided in Appendix A. On-line Monitoring Factor is obtained base on API 581 Risk-Based Inspection (RBI) Base Resource Document Appendix G as well, On-line Monitoring Factor Table and will be discussed later in the result. The value for TMSF is classified within the five “Likelihood Category” as shown in Table 6.

$$Fraction\ of\ Wall\ Loss\ = \frac{ar}{t_{act}}$$

a = *operating time (year)*

r = *erosion rate (mm/yr)*

t_{act} = *actual thickness*

$$TMSF_{adj} = \frac{(TMSF\ X\ OF)}{OMF}$$

$TMSF_{adj}$ = *adjusted TMSF*

OF = *overdesign factor*

OMF = *on-line monitoring factor*

Table 6: TMSF Conversion

Likelihood Category	**TMSF$_{adjusted}$**
1	<1
2	1-10
3	10-100
4	100-1000
5	>1000

- API 581 Risk-Based Inspection (RBI) Consequences Analysis

API 581 suggested the Business Interruption Cost is ascertained from release rate calculation and flammable consequence calculation. In release rate calculation, a few parameters need to be established foremost which are determination of Inventory Category and Transition Pressure. The obtaining results are then used to calculate the flammable event consequence. Inventory Category is chose base on the result in deinventory of item being evaluated as shown in Appendix B.

Transition Pressure will be used in determining the type of released steam, either sonic or subsonic. If operating pressure is less than transition pressure, subsonic equation will be used. If not, vise versa. The used equations for release rate calculation are shown below.

$$P_{trans} = P_a(\frac{k+1}{2})^{\frac{k}{k-1}}$$

P_{trans} = *transition pressure*

P_a = *atmospheric pressure*

k = C_p/C_v *of steam (1.28)*

Having identified the released steam either sonic or subsonic; the following equation is used to calculate the release rate.

$$W_g(sonic) = C_d A P \sqrt{\left(\frac{KM}{RT}\right)\frac{g_c}{144}\left(\frac{2}{K+1}\right)^{\frac{k+1}{k-1}}}$$

W_g *(sonic) = gas discharged rate (lb/sec)*
C_d *= discharged coefficient (for gas* $C_d = 0.85$ *to 1)*
A *= leak cross-section area* (in^2)
P *= upstream pressure (psia)*
M *= molecular weight (lb/lb-mol)*
R *= gas constant (10.73* ft^3*-psia/lb-mol°R)*
T *= upstream temperature*

Then, the Business Interruption Cost is calculated through the following equation.

$$Loss\ per\ Day\ If\ Unit\ is\ Shutdown = PL\ X\ SP\ X\ 24\ hrs$$

PL *= production loss (700,000 kW)*
SP *= selling price of electricity ($0.08/kWh)*

$$Businnes\ Interruption\ Cost = LPD\ X\ FEOD$$

LPD *= loss per day if unit is shutdown*
$FEOD$ *= flammable event outage days*

- Proposed Consequences Analysis

Just like API 581 RBI, consequence of failure category is established by calculating the cost of business interruption. However, the cost estimation is a basis of maintenance cost and production loss cost as provided in Figure 9.

$$MC = C_f + DT \, . C_v$$

MC = *maintenance cost*

C_f = *equipment damage cost (fixed cost)*

DT = *downtime*

C_v = *cost per hour for downtime (variable cost)*

$$C_f = EDC_{cs} \, X \, MF$$

EDC_{cs} = *equipment damage cost for carbon steel*

MF = *material cost factor (A-213 T-22 and T-91*

$$PLC = PL \, X \, SP \, X \, DT$$

PLC = *production loss cost*

PL = *production loss (kW)*

SP = *selling price of electricity (0.08/kWh)*

DT = *downtime*

$$Business \ Interruption \ Cost = MC + PLC$$

MC = *maintenance cost*

PLC = *production loss cost*

Both result for Business Interruption Cost from API 581 and proposed consequence approach is categorized within the five "Consequence Category" as shown in Table 7.

Table 7: Consequence Category

Consequence Category	**Business Interruption Cost (USD)**
A	<10K USD
B	10K-100K USD
C	100K – 1M USD
D	1M-10M USD
E	10M USD

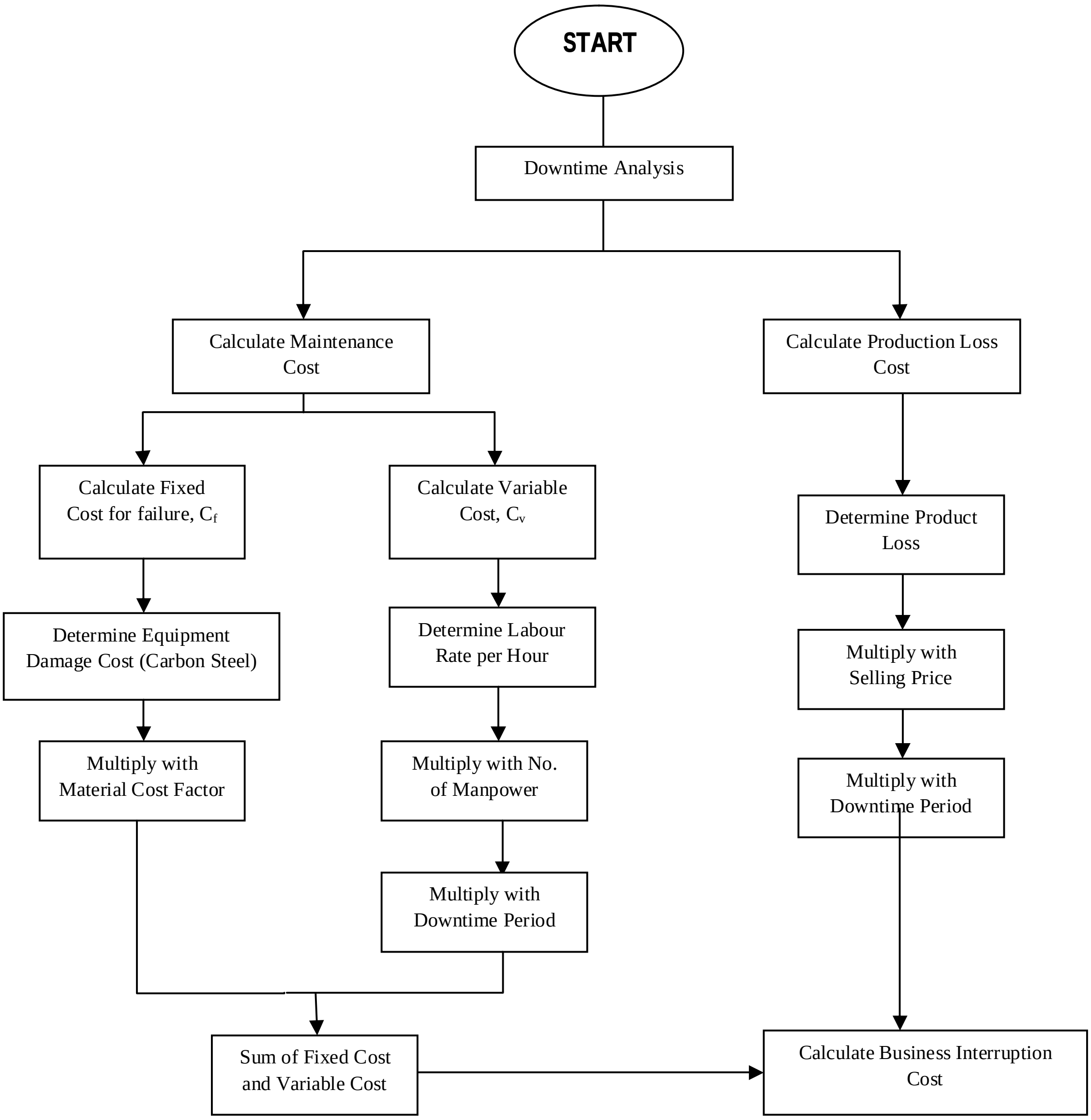


Figure 9: Determination of Business of Interruption Cost (Proposed Approach)

3.1.4 Risk Ranking

The obtaining results from Semi-Quantitative analysis for both approaches are plotted on a five-by-five Risk-Matrix

3.1.5 Risk Result Comparison

Final risk results of both approaches are then being compared.

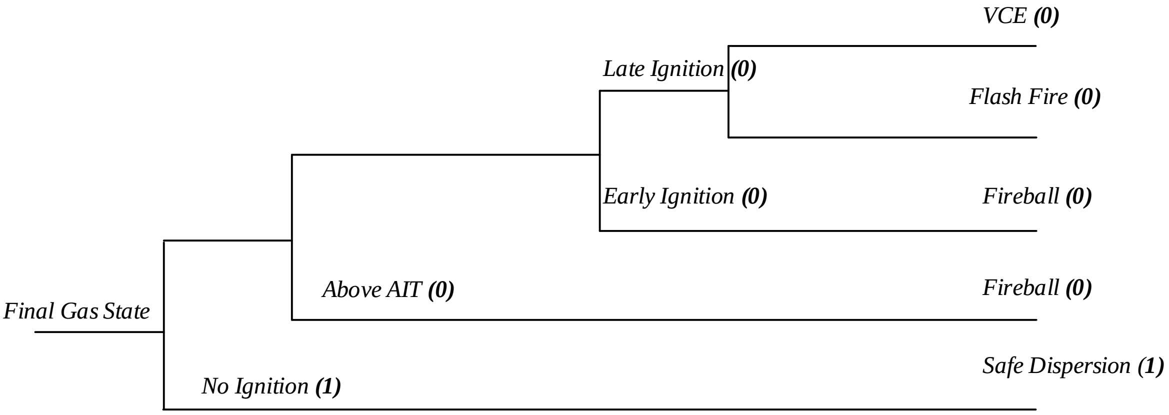
CHAPTER 4

RESULT AND DISCUSSION

The Probability of Failure analysis here is done using the organized methodology developed by API as outlined in the API 581 RBI Base Resource Document Appendix G; governs process equipment subject to damage by mechanism that result in general or localized thinning. As for Consequence of Failure analysis, both API 581 and proposed approaches are performed. The obtaining results on the two approaches are compared.

4.1 Release Event Tree

API 581 Risk-Based Inspection (RBI) measures flammable consequences in terms of the area affected by the ignition of release. Thus, for any release involving a flammable material, there should be several potential outcomes. For this particular part, steam is evaluated to be inflammable and is shown in Figure 10 below. Throughout the release rate calculation, any failure will cause a continuous-type release as shown in Appendix D.

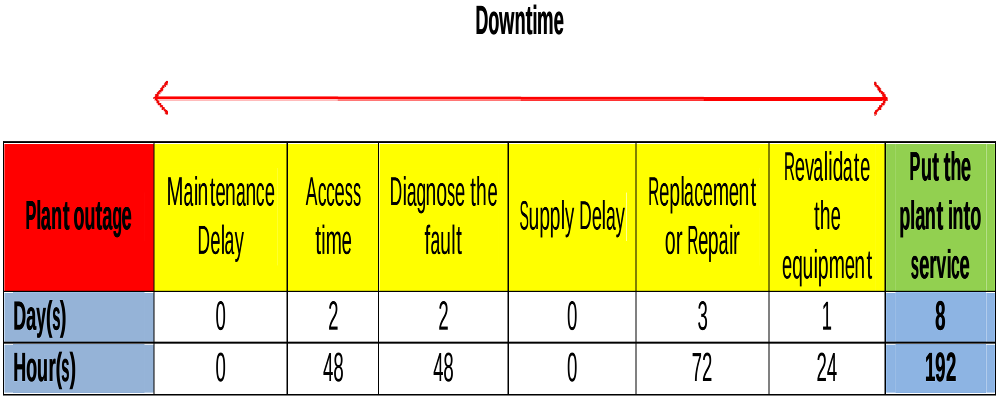


Instantaneous-Type Release

Figure 10: RBI Release Event Tree

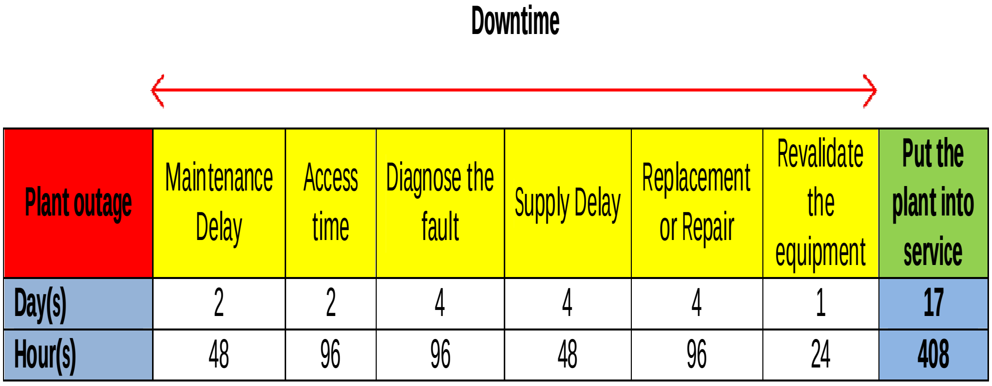
4.2 Downtime Analysis

Base on the discussion with one of the power plant engineer, the shortest downtime is approximately 1 week (192 hours) and the longest is approximately 3 weeks (408 hours). The analysis is shown in Figure 11 and Figure 12 below:



Plant outage	Maintenance Delay	Access time	Diagnose the fault	Supply Delay	Replacement or Repair	Revalidate the equipment	**Put the plant into service**
Day(s)	0	2	2	0	3	1	**8**
Hour(s)	0	48	48	0	72	24	**192**

Figure 11: Shortest Downtime Period



Plant outage	Maintenance Delay	Access time	Diagnose the fault	Supply Delay	Replacement or Repair	Revalidate the equipment	**Put the plant into service**
Day(s)	2	2	4	4	4	1	**17**
Hour(s)	48	96	96	48	96	24	**408**

Figure 12: Longest Downtime Period

4.3 API 581 Probability of Failure Analysis

Probability of failure is the result of a number of factors. In semi-quantitative RBI, the technical module subfactor (TMSF) is used to determine the probability of failure. TMSF determination required the alteration on overdesign and on-line monitoring factor. Through overdesign factor, higher corrosion allowance could significantly decrease the likelihood of failure. In addition, efficient on-line monitoring would allow an earlier detection which usually permits more timely action to be taken that should decrease the likelihood of failure as well. Base on discussion with the power plant engineer, the inspection effectiveness category and number of conducted inspection are 5 times usually effective inspections.

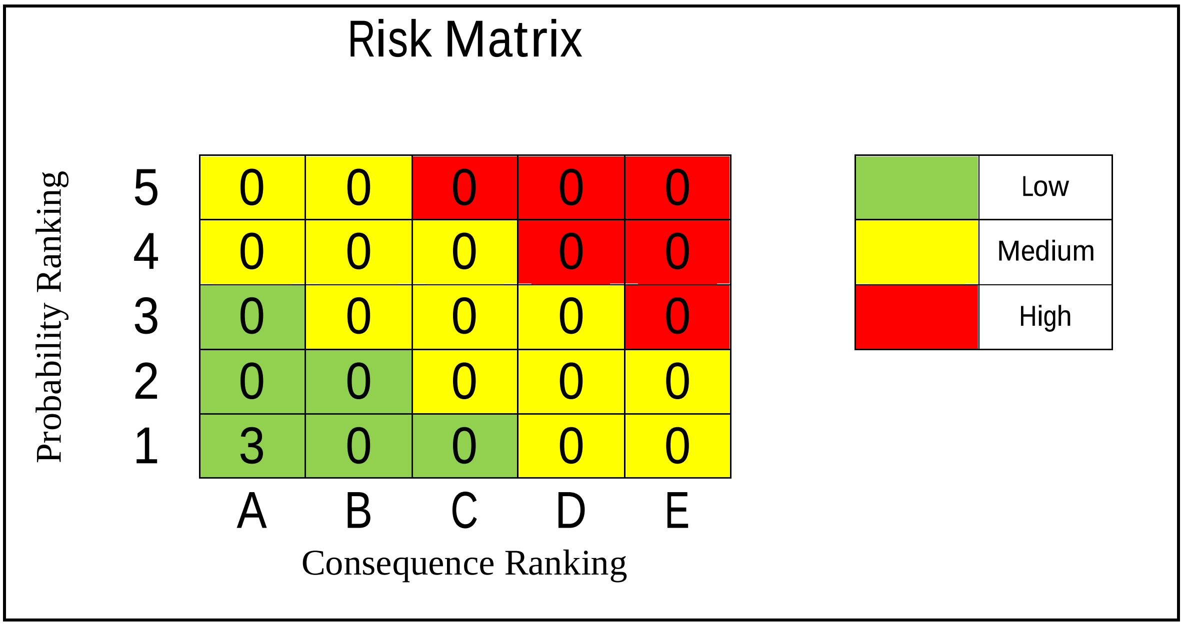
Thinning mechanism data provided in API 581 RBI Appendix G are Hydrochloric Acid (HCl) Corrosion, High Temperature Sulfidic/Naphthenic Acid Corrosion, High Temperature H_2S/H_2 Corrosion, Sulfuric Acid (H2SO4) Corrosion, Hydrofluoric Acid (HF) Corrosion, Sour Water Corrosion, Amine Corrosion as well as High Temperature Oxidation. In API RBI Appendix G, flyash erosion is not listed in the thinning mechanism data. From the earlier literature study, flyash erosion has been identified as a function of velocity and extent of ash loading. There are 3 types of thinning mechanisms that associated with velocity; sulfuric acid corrosion, sour water corrosion and amine corrosion. However, none of these led to similar appearance damage as erosion. Taking velocity as the similar trait, in this case study, the unavailable data for flyash erosion for on-line monitoring will be substituted with amine corrosion. Amine corrosion is localized for high velocities associated with turbulence. Key process variable such as velocity, temperature and pressure is use as the on-line monitoring on this particular power plant. Thus the On-Line Monitoring Factor will give a value of 10. The related calculation for PoF is shown in Appendix A. The sample calculation is provided in Appendix A. Summarization for Likelihood Analysis are included in Appendix E.

4.4 API 581 Consequence of Failure Analysis

The consequence if analysis is performed by estimating of what might be expected to happen if a loss of containment were to occur in the equipment being modeled. API 581 RBI Based Resource Document stated that a flammable consequence needs to be undergone first in order to proceed with the business interruption cost consequence. The analysis on both material, A-213 grade T-22 and T-91 are done using API 581 Semi-Quantitative Workbook and is simplified through Microsoft Excel Spreadsheet. Throughout the analysis, a few difficulties are found which lead to irrelevant result as highlighted below:

- 4 predefined set of hole sizes only valid for pipe and not applicable for boiler tube analysis; 1/4”, 1”, 4” and rupture. Thus, only rupture case will be consider in the consequence analysis.
- No leak durations based on detection and isolation system included in API 581 RBI Appendix G table for rupture case scenario.
- In order to calculate equipment damage area, Continuous Release Consequence Equations will be employed. However, steam is not listed in the table. Thus, the result will yield with a result value of 0 and there are no consequences due to flammable event.
- The resulting flammable consequence will give a value of $0.00 for equipment damage loss, 0 days for time of shutdown and no potential damage as well as consequence on neighbouring critical equipment.
- The end result of Business Interruption Loss for all evaluated items evaluated lie in category A, indicating low impact on business loss which is not reasonable.

The results for both PoF and CoF using the API 581 Semi-Quantitative Workbook are presented in five-by-five risk matrix, Figure 13 and Figure 14:

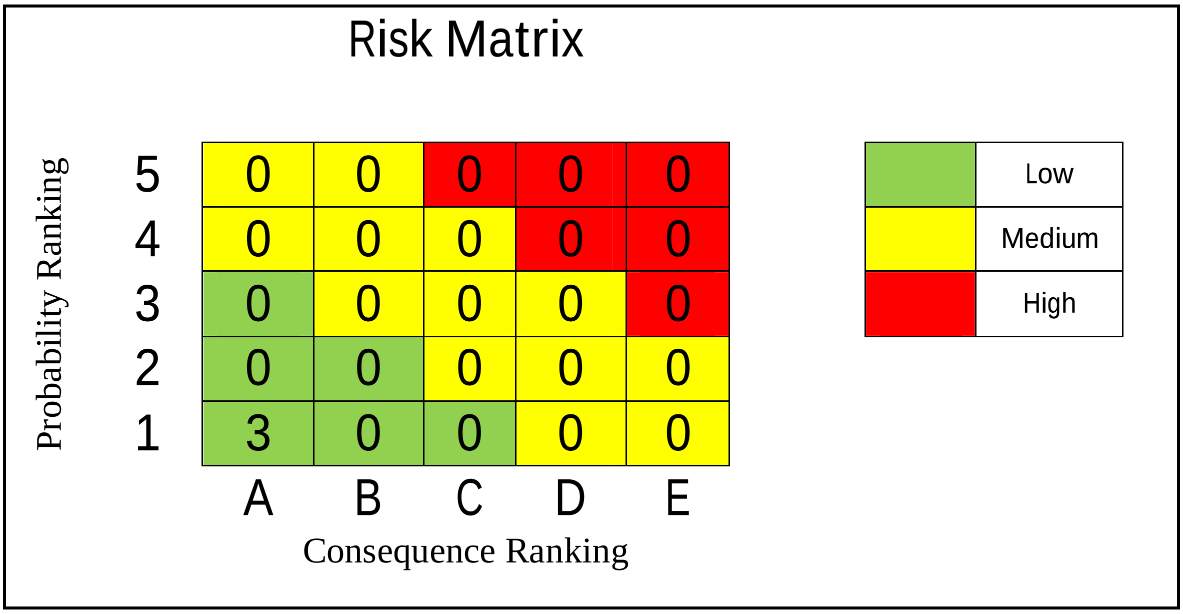


Risk Matrix

Probability Ranking					
5	0	0	0	0	0
4	0	0	0	0	0
3	0	0	0	0	0
2	0	0	0	0	0
1	3	0	0	0	0
	A	B	C	D	E
	Consequence Ranking				

🟩	Low
🟨	Medium
🟥	High

Figure 13: API 581 Semi-Quantitative Approach Risk Matrix for A-213 T22



Risk Matrix

Probability Ranking					
5	0	0	0	0	0
4	0	0	0	0	0
3	0	0	0	0	0
2	0	0	0	0	0
1	3	0	0	0	0
	A	B	C	D	E
	Consequence Ranking				

🟩	Low
🟨	Medium
🟥	High

Figure 14: API 581 Semi-Quantitative Approach Risk Matrix for A-213 T91

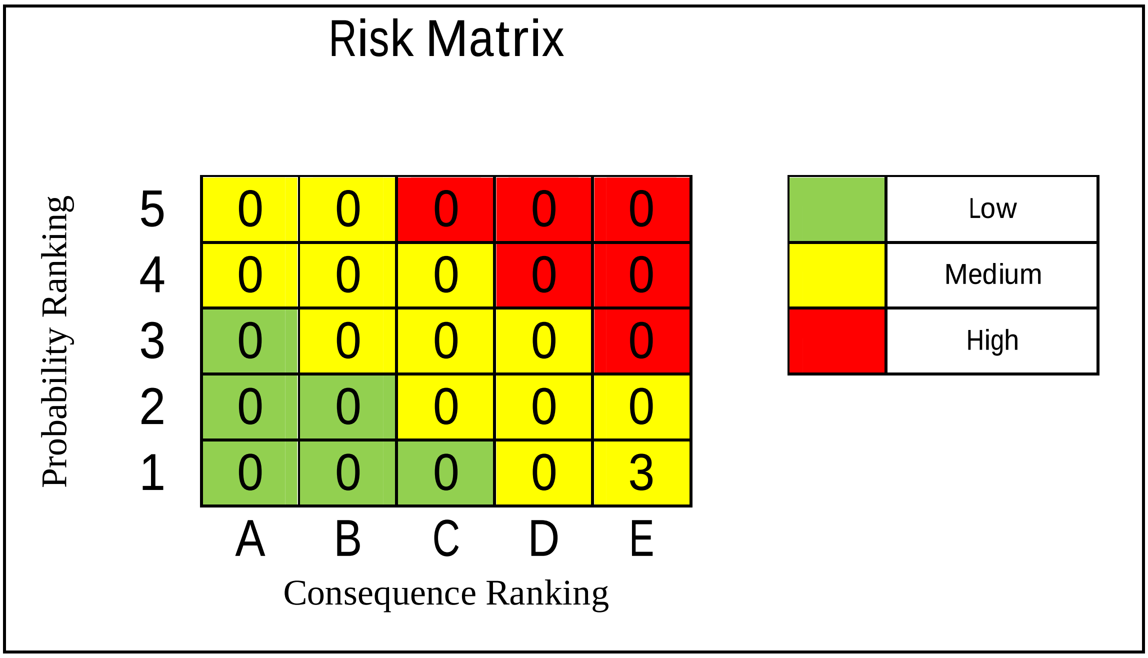
4.6 Proposed Consequence of Failure Analysis

Having considered steam as a nonflammable and nontoxic substance, the consequence of failure analysis on both material, A-213 grade T-22 and T-91 are established on the basis of maintenance and production loss costs. Due to plant confidential issue, the obtaining results might be flawed as most of the conservative data for costs are obtained from the relevant literature reviews and based on plant experiences to generate the necessary assumptions for the approach. Thus, taking account on the worst case scenario, the assumptions include:

- The produced electricity is 700MW for each unit
- The average price of electricity is \$0.08 USD (RM 00.26) per kWh
- Shortest downtime = 192 hours
- Longest downtime = 408 hours
- Maximum expenditure allocated for manpower is \$757.49 USD
- The damage cost is based on total rupture
- Carbon steel is taken as the reference damage cost, \$60,000 USD

For this particular power plant, the licensed capacity for 3 units is 2,100MW. Thus for a single unit, it can produced a total of 700MW. The average price of electricity is taken from the 2006 Performance and Statistical Information. [6] The expenditure allocated for manpower and downtime period are based on the plant experiences.

Using API 581 probability of failure analysis and proposed consequence of failure analysis, the results for are presented in five-by-five risk matrix; the following four figures.



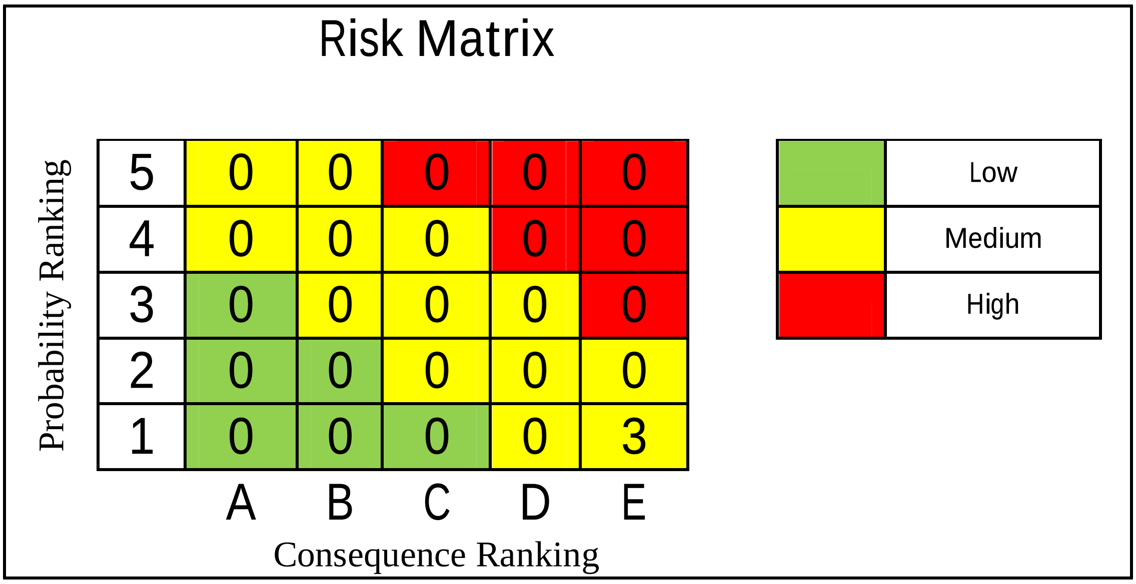
Risk Matrix

Probability Ranking					
5	🟨 0	🟨 0	🟥 0	🟥 0	🟥 0
4	🟨 0	🟨 0	🟨 0	🟥 0	🟥 0
3	🟩 0	🟨 0	🟨 0	🟨 0	🟥 0
2	🟩 0	🟩 0	🟨 0	🟨 0	🟨 0
1	🟩 0	🟩 0	🟩 0	🟨 0	🟨 3
	A	B	C	D	E

Consequence Ranking

🟩	Low
🟨	Medium
🟥	High

Figure 15: Proposed Semi-Quantitative Approach Risk Matrix for A-213 T22 (Shortest Downtime)



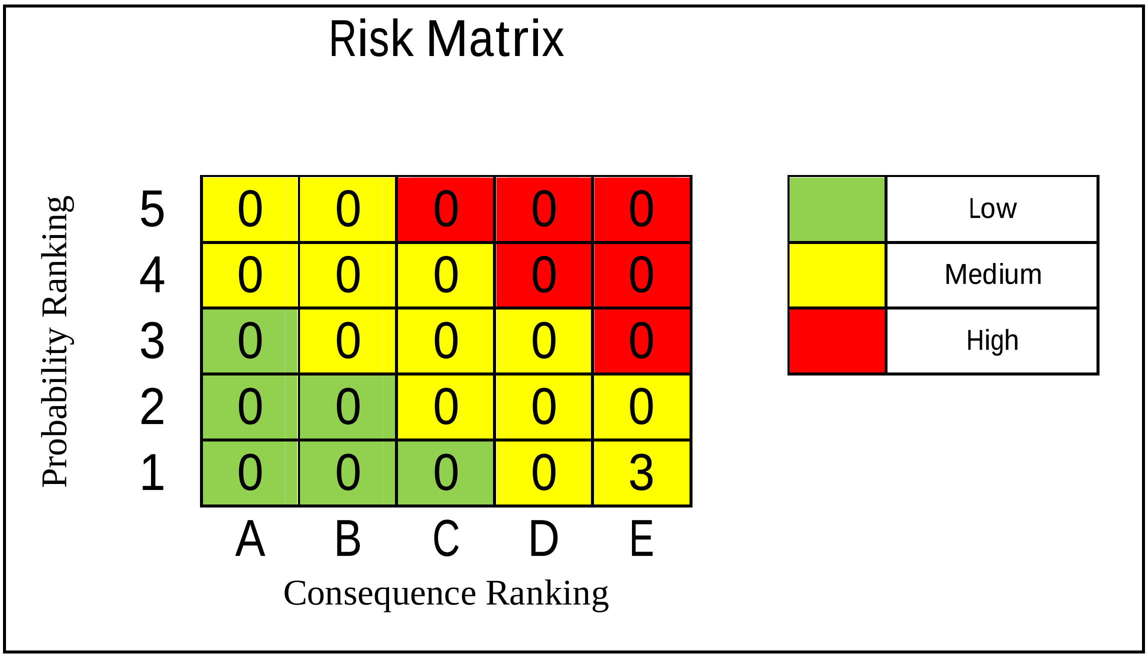
Risk Matrix

Probability Ranking					
5	🟨 0	🟨 0	🟥 0	🟥 0	🟥 0
4	🟨 0	🟨 0	🟨 0	🟥 0	🟥 0
3	🟩 0	🟨 0	🟨 0	🟨 0	🟥 0
2	🟩 0	🟩 0	🟨 0	🟨 0	🟨 0
1	🟩 0	🟩 0	🟩 0	🟨 0	🟨 3
	A	B	C	D	E

Consequence Ranking

🟩	Low
🟨	Medium
🟥	High

Figure 16: Proposed Semi-Quantitative Approach Risk Matrix for A-213 T91 (Shortest Downtime)



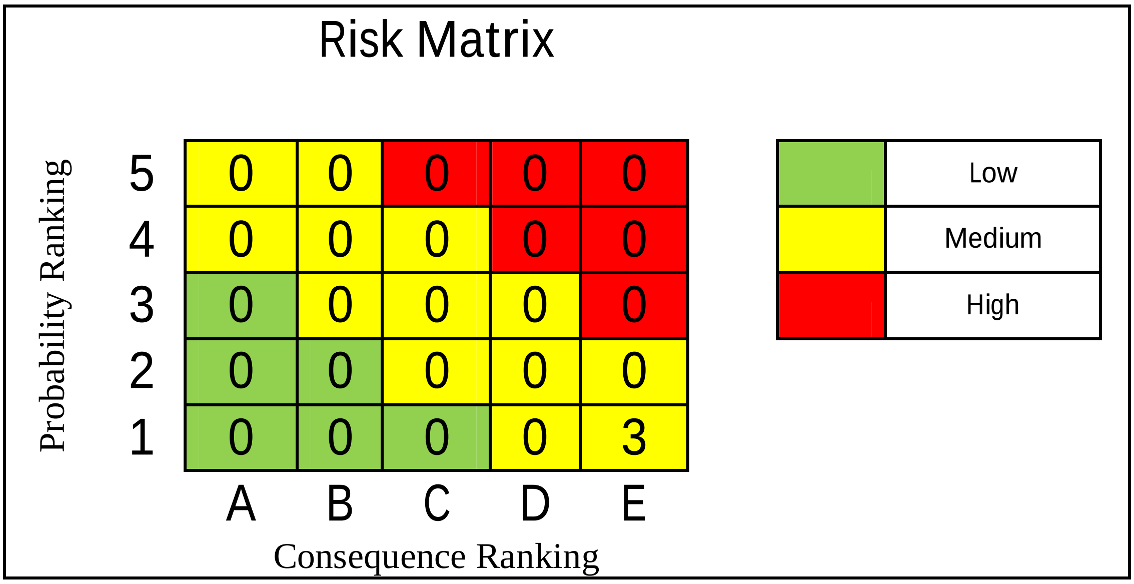
Risk Matrix

Probability Ranking	A	B	C	D	E
5	0	0	0	0	0
4	0	0	0	0	0
3	0	0	0	0	0
2	0	0	0	0	0
1	0	0	0	0	3

Consequence Ranking

🟩	Low
🟨	Medium
🟥	High

Figure 17: Proposed Semi-Quantitative Approach Risk Matrix for A-213 T22 (Longest Downtime)



Risk Matrix

Probability Ranking	A	B	C	D	E
5	0	0	0	0	0
4	0	0	0	0	0
3	0	0	0	0	0
2	0	0	0	0	0
1	0	0	0	0	3

Consequence Ranking

🟩	Low
🟨	Medium
🟥	High

Figure 18: Proposed Semi-Quantitative Approach Risk Matrix for A-213 T91 (Longest Downtime)

4.6 Result Comparison

Comparing on the risk result, if the analysis is based on the affected area, business interruption cost will be \$0.00, therefore the risk is zero. Using only the consequence area as the basis of risk, the three boiler items are plotted in a low risk item. The problem with this approach is that the cost of the equipment and shutdown loss are cancelled out by the affected area due to flammable event which is 0 ft^2. Thus, any failure with zero affected area led to zero risk. This is not realistic, since a failure of a boiler steam tube definitely has a cost impact, even though if it does not result in a large area of damage as compared to a flammable fluid such as hydrocarbon.

Through the proposed consequence approach, the risk levels for all the equipment components move from low to medium risk level which is more reasonable due to high consumption of maintenance and production loss cost. Although the cost for both materials and downtime varied, the business interruption cost of the equipment still remains above \$10,000,000 USD for all equipments. Sample calculation for Consequences Analysis is provided in Appendix B and Appendix C. Summarization for Consequence Analysis is included in Appendix F until Appendix K.

CHAPTER 5

CONCLUSION & RECOMMENDATION

5.1 Conclusion

- Through the developed module; determination of adjusted Technical Module Subfactor for Probability of Failure (PoF) and proposed Consequence Analysis for Consequence of Failure (CoF), risk level for High Temperature Superheater (HTS), High Temperature Reheater (HTR) and economizer using Semi-Quantitative Analysis could be evaluated practically and systematically.

- API 581 RBI Consequence Approach could not be applied if the concerned representative fluid is inflammable-type and will only reflect a fallacious Business Interruption Cost.

- Proposed Consequence Approach which is established base on maintenance and production loss cost is more applicable as compared to API 581 RBI Consequence Approach as it will result with a more realistic Business Interruption Cost.

- The result for Proposed Consequence Approach could not be assumed 100% accurate as some of the figures were obtained from the relevance literature review. Such data gathering is time consuming. However the values are still reliable.

- The accuracy of RBI study solely depends on the availability of reliable and dependable data. The more data available, the more accurate result will be.

5.2 Recommendation

The following are recommendations for further work that can be carried out to improve the accuracy of the result and to ensure the project objective is met:

5.2.1 Enhancement of Probability of Failure Analysis

- To perform a detail measurement for On-line Monitoring Factor concerning on steam erosion so that an accurate value could be used to calculate $TMSF_{adj}$

5.2.2 Enhancement of Consequence of Failure Analysis

- Predefined 4 sets of hole size could be refined to suit with the tube size. Diameter of the tube is normally smaller as compared to pipe. Thus the set of hole size for tube leaking should be varied as compare to pipe.

- To include rupture case scenario in the leak duration API 581 RBI Appendix G table base on detection and isolation systems by conducting proper experiment and thorough monitoring.

- High pressure steam could cause damage to the equipment. Instead of accounted flammable event that would affect on the damage equipment, equipment damage area should be calculated from the erosion effect of the steam.

- Obtaining exact figure for costing from the power plant to give a more accurate Business Interruption Cost result.

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APPENDICES

APPENDIX A

Likelihood of Failure

1. Calculating Adjusted Technical Module Subfactor (TMSF$_{adj}$)

The adjusted TMSF$_{adj}$ is an alteration from Overdesign Factor and On-line Monitoring Factor.

1.1. Determination of TMSF

TMSF is obtained from the TMSF table after Fraction of Wall Loss is calculated.

Fraction of Wall Loss

$$\frac{ar}{t_{act}} = \frac{8\ X\ 0.2}{6.5}$$

$$= 0.25$$

Overdesign Factor

$$\frac{t_{act}}{t_{act} - CA} = \frac{6.5}{6.5 - 0.5}$$

$$= 1.08$$

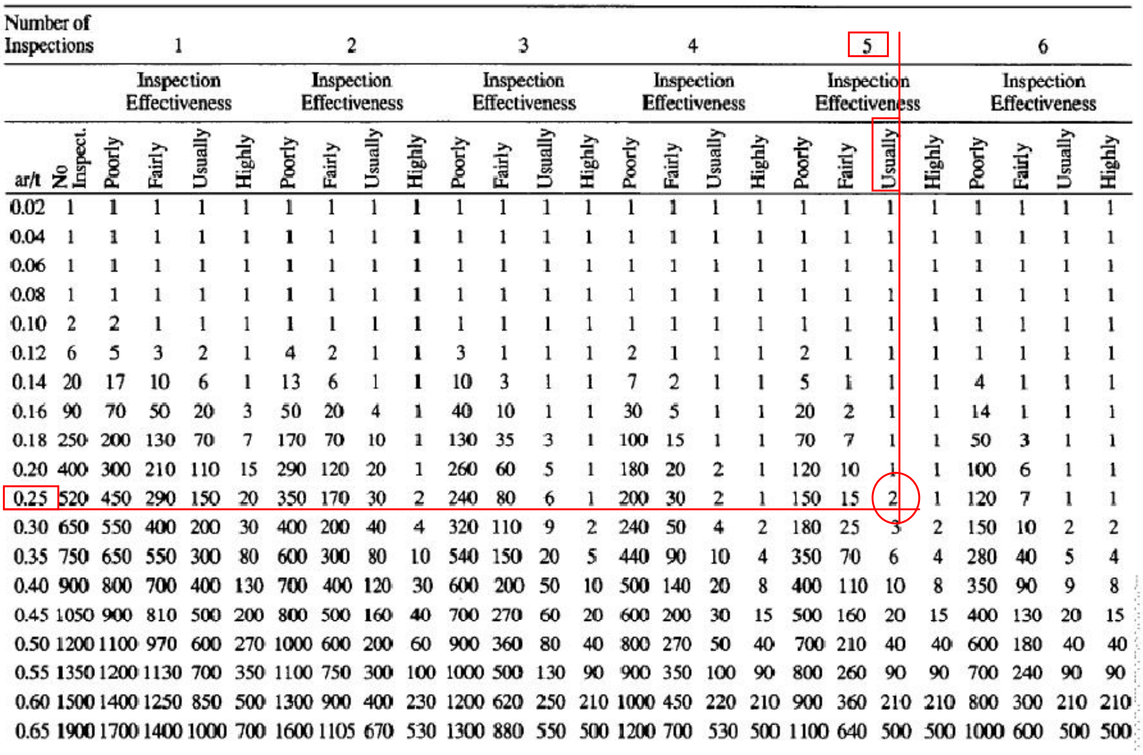
- Overdesign Factor = 1 if calculated value range from 1 to 1.5
- Overdesign Factor = 0.5 if calculated value >1.5

$TMSF_{adj}$

$$\frac{(TMSF\ X\ OF)}{OMF} = \frac{2\ X\ 1}{10}$$

$$= 0.2$$

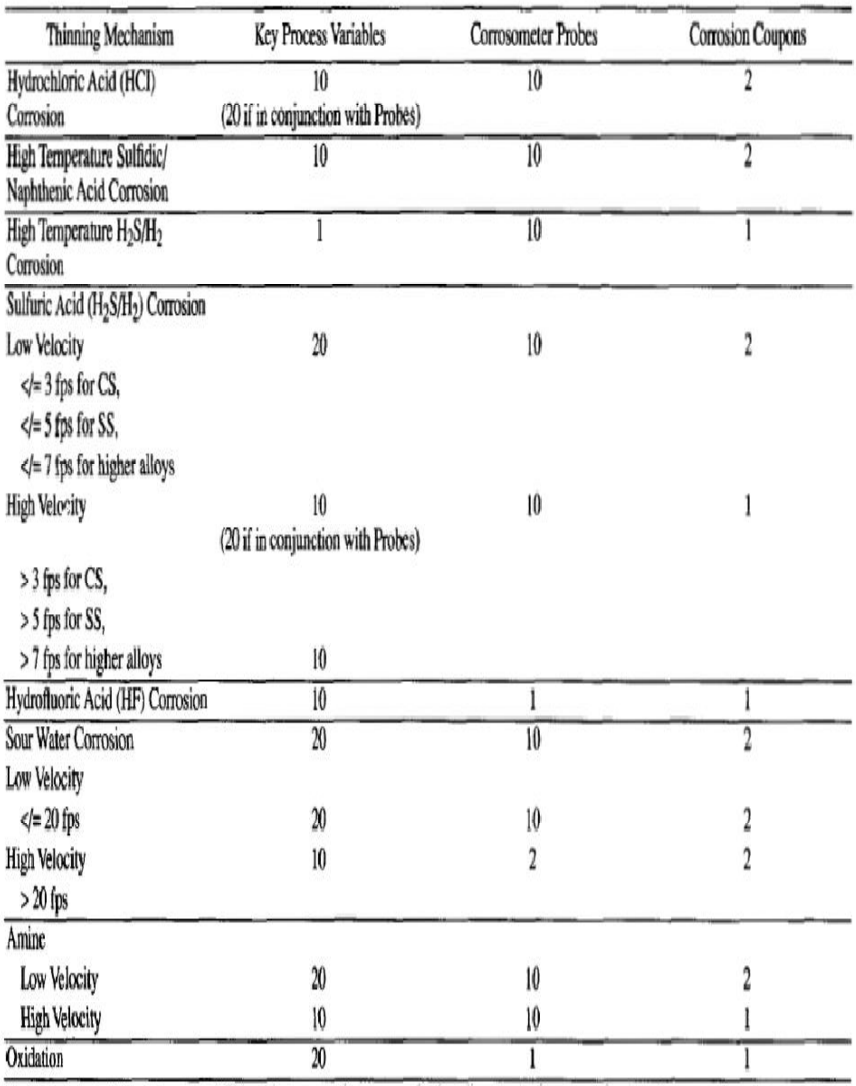
Table A1: Thinning Technical Module Subfactor



Number of Inspections		1				2				3				4				5				6			
		Inspection Effectiveness				Inspection Effectiveness				Inspection Effectiveness				Inspection Effectiveness				Inspection Effectiveness				Inspection Effectiveness			
ar/t	No Inspect.	Poorly	Fairly	Usually	Highly	Poorly	Fairly	Usually	Highly	Poorly	Fairly	Usually	Highly	Poorly	Fairly	Usually	Highly	Poorly	Fairly	Usually	Highly	Poorly	Fairly	Usually	Highly
0.02	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
0.04	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
0.06	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
0.08	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
0.10	2	2	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
0.12	6	5	3	2	1	4	2	1	1	3	1	1	1	2	1	1	1	2	1	1	1	1	1	1	1
0.14	20	17	10	6	1	13	6	1	1	10	3	1	1	7	2	1	1	5	1	1	1	4	1	1	1
0.16	90	70	50	20	3	50	20	4	1	40	10	1	1	30	5	1	1	20	2	1	1	14	1	1	1
0.18	250	200	130	70	7	170	70	10	1	130	35	3	1	100	15	1	1	70	7	1	1	50	3	1	1
0.20	400	300	210	110	15	290	120	20	1	260	60	5	1	180	20	2	1	120	10	1	1	100	6	1	1
0.25	520	450	290	150	20	350	170	30	2	240	80	6	1	200	30	2	1	150	15	2	1	120	7	1	1
0.30	650	550	400	200	30	400	200	40	4	320	110	9	2	240	50	4	2	180	25	3	2	150	10	2	2
0.35	750	650	550	300	80	600	300	80	10	540	150	20	5	440	90	10	4	350	70	6	4	280	40	5	4
0.40	900	800	700	400	130	700	400	120	30	600	200	50	10	500	140	20	8	400	110	10	8	350	90	9	8
0.45	1050	900	810	500	200	800	500	160	40	700	270	60	20	600	200	30	15	500	160	20	15	400	130	20	15
0.50	1200	1100	970	600	270	1000	600	200	60	900	360	80	40	800	270	50	40	700	210	40	40	600	180	40	40
0.55	1350	1200	1130	700	350	1100	750	300	100	1000	500	130	90	900	350	100	90	800	260	90	90	700	240	90	90
0.60	1500	1400	1250	850	500	1300	900	400	230	1200	620	250	210	1000	450	220	210	900	360	210	210	800	300	210	210
0.65	1900	1700	1400	1000	700	1600	1105	670	530	1300	880	550	500	1200	700	530	500	1100	640	500	500	1000	600	500	500

**Source: API 581 Risk-Based Inspection – Base Resource Document*

Table A2: On-line Monitoring Factor Table



Thinning Mechanism	Key Process Variables	Corrosometer Probes	Corrosion Coupons
Hydrochloric Acid (HCl) Corrosion	10 (20 if in conjunction with Probes)	10	2
High Temperature Sulfidic/ Naphthenic Acid Corrosion	10	10	2
High Temperature H_2S/H_2 Corrosion	1	10	1
Sulfuric Acid (H_2S/H_2) Corrosion			
Low Velocity	20	10	2
</= 3 fps for CS,			
</= 5 fps for SS,			
</= 7 fps for higher alloys			
High Velocity	10 (20 if in conjunction with Probes)	10	1
> 3 fps for CS,			
> 5 fps for SS,			
> 7 fps for higher alloys	10		
Hydrofluoric Acid (HF) Corrosion	10	1	1
Sour Water Corrosion	20	10	2
Low Velocity			
</= 20 fps	20	10	2
High Velocity	10	2	2
> 20 fps			
Amine			
Low Velocity	20	10	2
High Velocity	10	10	1
Oxidation	20	1	1

**Source: API 581 Risk-Based Inspection – Base Resource Document*

Table A3: Inspection Effectiveness – Localized Thinning

Inspection Effectiveness Category	Example: Intrusive Inspection	Example: Nonintrusive Inspection
Highly	100% visual examination (with removal of internal packing, trays, etc) and thickness measurements	50-100% coverage using automated ultrasonic scanning, or profile radiography in areas specified by a corrosion engineer or other knowledgeable specialist
Usually	100% visual examination (with partial removal of internals) including manways, nozzles, etc. and thickness measurements	20% coverage using automated ultrasonic scanning, or 50% manual ultrasonic scanning, or 50% profile radiography in areas specified by a corrosion engineer or other knowledgeable specialist
Fairly	Nominally 20% visual examination and spot ultrasonic thickness measurements	Nominally 20% coverage using automated or manual ultrasonic scanning, or profile radiography, and spot thickness measurements at areas specified by a corrosion engineer or other knowledgeable specialist
Poorly	No Inspection	Spot ultrasonic thickness measurements or profile radiography without areas being specified by a corrosion engineer or other knowledgeable specialist

**Source: API 581 Risk-Based Inspection – Base Resource Document*

APPENDIX B

Consequence of Failure (API 581 RBI Approach)

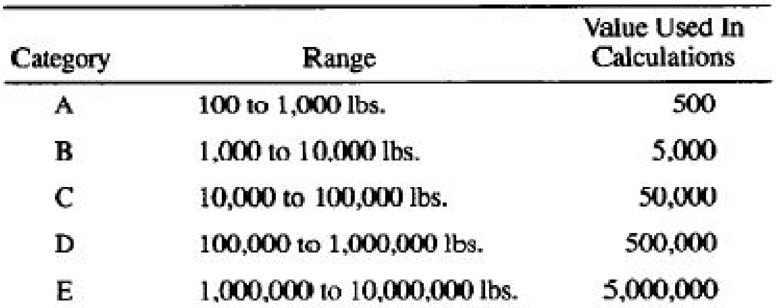
1. Calculating the Release Rate of Steam

In order to calculate release rate, few parameters need to be identified:

1.1. Establishing Default Inventory

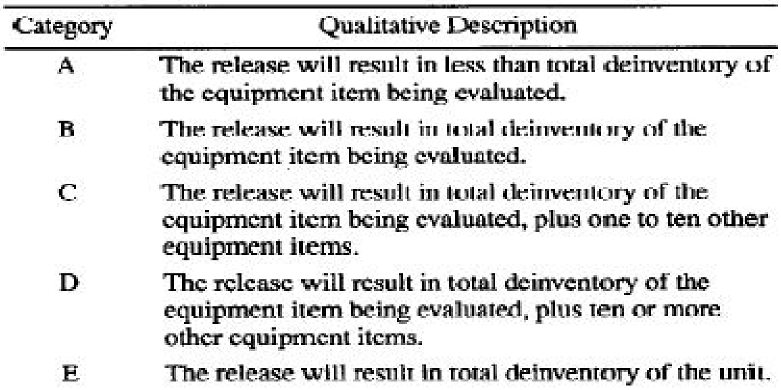
Default gas inventory – 5,000 lbs

Table B1: Inventory Category Ranges



Category	Range	Value Used In Calculations
A	100 to 1,000 lbs.	500
B	1,000 to 10,000 lbs.	5,000
C	10,000 to 100,000 lbs.	50,000
D	100,000 to 1,000,000 lbs.	500,000
E	1,000,000 to 10,000,000 lbs.	5,000,000

Table B2: Description of Inventory Categories



Category	Qualitative Description
A	The release will result in less than total deinventory of the equipment item being evaluated.
B	The release will result in total deinventory of the equipment item being evaluated.
C	The release will result in total deinventory of the equipment item being evaluated, plus one to ten other equipment items.
D	The release will result in total deinventory of the equipment item being evaluated, plus ten or more other equipment items.
E	The release will result in total deinventory of the unit.

**Source: API 581 Risk-Based Inspection – Base Resource Document*

1.2. Estimating Release Rate

The transition pressures were first calculated which defines the pressure at which the flow regimes change from sonic to subsonic. This sample calculation is based on High Temperature Superheater (HTS) data.

Transition Pressure

$$P_{trans} = P_a \left(\frac{k+1}{2}\right)^{\frac{k}{k-1}}$$

$$P_{trans} = 14.7 \left(\frac{1.28+1}{2}\right)^{\frac{1.28}{1.28-1}}$$

$$= 26.73\, psia$$

- If $P_{equipment} > P_{trans}$ – use sonic gas discharge rate equation
- If $P_{equipment} < P_{trans}$ – use sub-sonic gas discharge rate equation

Sonic Gas Discharge Rate Calculation

$$\boldsymbol{C_d A P \sqrt{\left(\frac{KM}{RT}\right)} \frac{g_c}{144} \left(\frac{2k}{k-1}\right)^{\frac{k+1}{k-1}} = 0.87\ X\ 28.27\ X\ 304.8 \sqrt{\left(\frac{1.28\ X\ 18}{10.73\ X\ 1535}\right)} \frac{32.2}{144} \left(\frac{2\ X\ 1.28}{1.28-1}\right)^{\frac{1.28+1}{1.28-1}}}$$

$$= 864.26\ lbs/sec$$

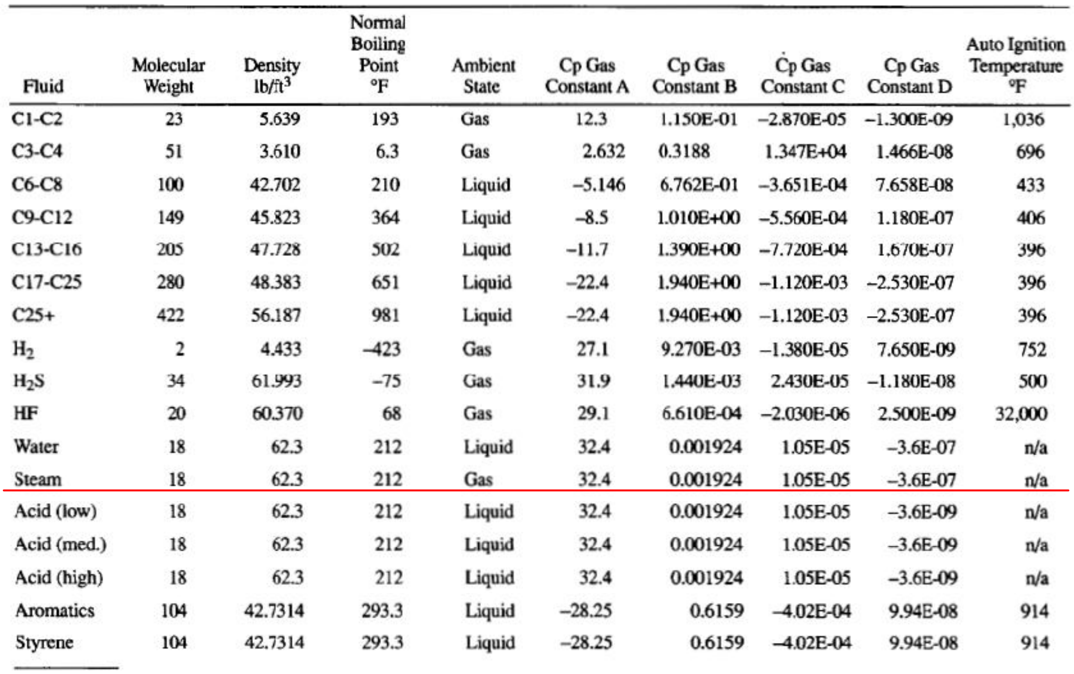
2. Business Interruption Cost

Business Interruption Cost in calculate through the following:

$$Businnes\ Interruption\ Cost = \$1{,}344{,}000\ per\ day\ X\ 0\ day$$

$$= \$0.00$$

Table B3: Physical Properties of BRD Representative Fluid



Fluid	Molecular Weight	Density lb/ft^3	Normal Boiling Point °F	Ambient State	Cp Gas Constant A	Cp Gas Constant B	Cp Gas Constant C	Cp Gas Constant D	Auto Ignition Temperature °F
C1-C2	23	5.639	193	Gas	12.3	1.150E-01	–2.870E-05	–1.300E-09	1,036
C3-C4	51	3.610	6.3	Gas	2.632	0.3188	1.347E+04	1.466E-08	696
C6-C8	100	42.702	210	Liquid	–5.146	6.762E-01	–3.651E-04	7.658E-08	433
C9-C12	149	45.823	364	Liquid	–8.5	1.010E+00	–5.560E-04	1.180E-07	406
C13-C16	205	47.728	502	Liquid	–11.7	1.390E+00	–7.720E-04	1.670E-07	396
C17-C25	280	48.383	651	Liquid	–22.4	1.940E+00	–1.120E-03	–2.530E-07	396
C25+	422	56.187	981	Liquid	–22.4	1.940E+00	–1.120E-03	–2.530E-07	396
H_2	2	4.433	–423	Gas	27.1	9.270E-03	–1.380E-05	7.650E-09	752
H_2S	34	61.993	–75	Gas	31.9	1.440E-03	2.430E-05	–1.180E-08	500
HF	20	60.370	68	Gas	29.1	6.610E-04	–2.030E-06	2.500E-09	32,000
Water	18	62.3	212	Liquid	32.4	0.001924	1.05E-05	–3.6E-07	n/a
Steam	18	62.3	212	Gas	32.4	0.001924	1.05E-05	–3.6E-07	n/a
Acid (low)	18	62.3	212	Liquid	32.4	0.001924	1.05E-05	–3.6E-09	n/a
Acid (med.)	18	62.3	212	Liquid	32.4	0.001924	1.05E-05	–3.6E-09	n/a
Acid (high)	18	62.3	212	Liquid	32.4	0.001924	1.05E-05	–3.6E-09	n/a
Aromatics	104	42.7314	293.3	Liquid	–28.25	0.6159	–4.02E-04	9.94E-08	914
Styrene	104	42.7314	293.3	Liquid	–28.25	0.6159	–4.02E-04	9.94E-08	914

**Source: API 581 Risk-Based Inspection – Base Resource Document*

APPENDIX C

Consequence of Failure (Proposed Module)

The sample calculation is based on material A-213 T22 at shortest downtime for High Temperature Superheater (HTS).

1. Calculation of Maintenance Cost

1.1 Determine Fixed Cost

Equipment Damage Cost for Carbon Steel (ED) = \$60,000

Material Cost Factor (MF) = 1.7

Fixed Cost: $C_f = ED.MF$

\$60,000 X 1.7 = \$102,000

1.2 Determine Variable Cost

Table C1: Labour Rates (Variable Cost)

Trade	Description	Hourly Rate	Total of Manpower	Cost	Description
Boiler maker	General Foreman	$46.21	1	$46.21	Worker or tradesman who in charge of the whole crew
	Foreman	$44.90	2	$89.80	Worker or tradesman who in charge of the specific crew
	Fitter/Welder	$41.26	2	$82.52	Tradesman who specialises in welding material together
	Apprentice 3	$38.04	1	$38.04	Craftsman who has a limited or low level of skills
	Aprrentice 2	$32.81	0	$0.00	As described
	Aprrentice 1	$27.64	0	$0.00	As described
	Helper	$38.04	1	$38.04	Helper
Pipe fitter	Foreman	$45.49	2	$90.98	As described
	Welder	$42.64	2	$85.28	As described
Millwright	Foreman	$41.47	2	$82.94	As described
	Welder	$40.22	2	$80.44	As described
	Apprrentice	$38.60	1	$38.60	As described
	Journeyman	$34.64	1	$34.64	Craftsman who has an adequate level of skills
	Electrician	$25.00	2	$50.00	Tradesman specializing in electrical wiring of buildings, stationary machines and related equipemnt
			Total Cost	$757.49	

Variable Cost: $C_v = \$757.49$

$MC = C_f + DT\,.\,C_v$

$102,000 + (192 hrs X $757.49) = $247,438.08

2. Calculation of Production Loss Cost

$PLC = DT \,.\, PL \,.\, SP$

Production Loss = 700 MW

Downtime = 192 hrs

Electricity Selling Price = $0.08 per kWh

700 MW X 192 hrs X $0.08 per kWh = $10,752,000

3. Calculation of Business Interruption Cost

$BIC = MC + PLC$

$247,438,08 + $10,752,000 = 10,999,438.08

APPENDIX D – Summarization of Release Rate Calculation

Release Rate Calculation

	C_d	$A(in^2)$	P (psia)	M	R	T	g_c	P_a	K	W_g (subsonic)	C_d.A.P	k+1/k-1	(KM/RT) X (g_c/144)	2/K+1)	Release Rate (lb/sec)
HTS	0.87	28.27	304.8	18	10.73	1535	32.2	29.39	1.28	864.26	7497.67	0.78125	0.0029	7.14	864.26
HTR	0.87	28.27	58.02	18	10.73	1535	32.2	29.39	1.28	164.52	1427.21	0.78125	0.0029	7.14	164.52
Economizer	0.87	28.27	58.02	18	10.73	1008	32.2	29.39	1.28	203.02	1427.21	0.78125	0.0044	7.14	203.02

Release Type

	deinventory time (min)	release rate in 3 mins (lb)	Type	Instantaneous Release Mass (lbs/min)
HTS	0.096421432	155567.0735	instantaneous	14.40435866
HTR	0.506536582	29612.86615	instantaneous	2.741932051
Economizer	0.41047517	36543.01427	instantaneous	3.383612432

APPENDIX E – Summarization of Likelihood of Failure Analysis

Calculation for Probability of Failure

	High Temperature Superheater	High Temperature Reheater	Economizer
Part A: Technical Module Subfactor			
Operating Time, a (yr)	8	8	8
Thickness actual, t_{act} (mm)	6.5	6.5	6.3
Erosion Rate, r (mm/yr)	0.2	0.2	0.2
Fraction of Wall Loss, ar/t	0.25	0.25	0.25
No of Inspection Conducted	5	5	5
Inspection Effectiveness	Usually	Usually	Usually
TMSF	1	1	1
Part B: Overdesign Factor			
MAWP			
Operating Pressure, OP			
MAWP/OP	N/A	N/A	N/A
Erosion Allowance, CA (mm)	0.5	0.5	0.5
$t_{act}/(t_{act}$-CA)	1.08	1.08	1.09
Overdesign Factor, OF	1	1	1
Part C: On-line Monitoring Factor			
On-line Monitoring Factor	10	10	10
Computed Result			
$TMSF_{adjusted}$	0.1	0.1	0.1
PoF Category	1	1	1

APPENDIX F – API 581 RBI Consequence Analysis for Material A-213 T22

Calculation for Consequence of Failure

Material: A-213 T22	High Temperature Superheater	High Temperature Reheater	Economizer
Flammable Consequence Calculation			
Release Rate (lb/min)	14.40435866	2.741932051	3.383612432
Representative Fluid	Steam	Steam	Steam
Release Type	Instantaneous Gas	Instantaneous Gas	Instantaneous Gas
Detection Rating	A	A	A
Isolation Rating	A	A	A
Adjusted Release Rate (lb/min)	10.80326899	2.05644904	2.53770932
Equipment Damage Area	0	0	0
Flammable Consequence (ft²)	0	0	0
Business Interuption Calculation			
Loss Per Day if Unit is Shutdown ($)	$1,344,000.00	$1,344,000.00	$1,344,000.00
Cost of Equipment per Square Feet ($/ft²)	$12.00	$12.00	$12.00
Equipment Damage Loss due to Flammable Event	$0.00	$0.00	$0.00
Outage Days due to Flammable Event (day)	0	0	0
Probability on Damaging Neighbouring Critical Equipment	0	0	0
Damage of Neighbouring Critical Equipment Downtime (day)	0	0	0
Business Interuption Loss	$0.00	$0.00	$0.00
CoF Category	A	A	A

APPENDIX G – API 581 RBI Consequence Analysis for Material A-213 T91

Calculation for Consequence of Failure

Material: A-213 T22	High Temperature Superheater	High Temperature Reheater	Economizer
Flammable Consequence Calculation			
Release Rate (lbs)	5000	5000	5000
Representative Fluid	Steam	Steam	Steam
Release Type	Instantaneous Gas	Instantaneous Gas	Instantaneous Gas
Detection Rating	A	A	A
Isolation Rating	A	A	A
Adjusted Release Rate (lb/min)	3750	3750	3750
Equipment Damage Area	0	0	0
Flammable Consequence (ft²)	0	0	0
Business Interuption Calculation			
Loss Per Day if Unit is Shutdown ($)	$1,344.00	$1,344.00	$1,344.00
Cost of Equipment per Square Feet ($/ft²)	$12.00	$12.00	$12.00
Equipment Damage Loss due to Flammable Event	$0.00	$0.00	$0.00
Outage Days due to Flammable Event (day)	0	0	0
Probability on Damaging Neighbouring Critical Equipment	0	0	0
Damage of Neighbouring Critical Equipment Downtime (day)	0	0	0
Business Interuption Loss	$0.00	$0.00	$0.00
CoF Category	A	A	A

APPENDIX H – Proposed Consequence Analysis for Material A-213 T22 Shortest Downtime

Calculation for Consequence of Failure

Material: A-213 T22	High Temperature Superheater	High Temperature Reheater	Economizer
Maintenance Cost			
Equipment Damage Cost for Carbon Steel ($)	$60,000	$60,000	$60,000
Material Cost Factor	1.7	1.7	1.7
Equipment Damage Cost, C_f (Fixed Cost)	$102,000.00	$102,000.00	$102,000.00
Cost for Manpower ($ per hour)	$757.49	$757.49	$757.49
Downtime, DT (hr)	192	192	192
Cost per Hour for Downtime, Cv (Variable Cost)	$757.49	$757.49	$757.49
Total	$247,438.08	$247,438.08	$247,438.08
Production Loss Cost			
Production Loss, PL (kW)	700,000	700,000	700,000
Electricity Selling Price, SP ($/kWh)	$0.08	$0.08	$0.08
Total	$10,752,000.00	$10,752,000.00	$10,752,000.00
Computed Result			
Business Interruption Cost	$10,999,438.08	$10,999,438.08	$10,999,438.08
CoF Category	E	E	E

APPENDIX I – Proposed Consequence Analysis for Material A-213 T91 Shortest Downtime

Calculation for Consequence of Failure

Material: A-213 T91	High Temperature Superheater	High Temperature Reheater	Economizer
Maintenance Cost			
Equipment Damage Cost for Carbon Steel ($)	$60,000	$60,000	$60,000
Material Cost Factor	2.6	2.6	2.6
Equipment Damage Cost, C_f (Fixed Cost)	$156,000.00	$156,000.00	$156,000.00
Cost for Manpower ($)	$757.49	$757.49	$757.49
Downtime, DT (hr)	192	192	192
Cost per Hour for Downtime, Cv (Variable Cost)	$757.49	$757.49	$757.49
Total	$301,438.08	$301,438.08	$301,438.08
Production Loss Cost			
Production Loss, PL (kW)	700,000	700,000	700,000
Electricity Selling Price, SP ($/kWh)	$0.08	$0.08	$0.08
Total	$10,752,000.00	$10,752,000.00	$10,752,000.00
Computed Result			
Business Interruption Cost	$11,053,438.08	$11,053,438.08	$11,053,438.08
CoF Category	E	E	E

APPENDIX J – Proposed Consequence Analysis for Material A-213 T22 Longest Downtime

Calculation for Consequence of Failure

Material: A-213 T22	High Temperature Superheater	High Temperature Reheater	Economizer
Maintenance Cost			
Equipment Damage Cost for Carbon Steel ($)	$60,000	$60,000	$60,000
Material Cost Factor	1.7	1.7	1.7
Equipment Damage Cost, C_f (Fixed Cost)	$102,000.00	$102,000.00	$102,000.00
Cost for Manpower ($)	$757.49	$757.49	$757.49
Downtime, DT (hr)	408	408	408
Cost per Hour for Downtime, Cv (Variable Cost)	$757.49	$757.49	$757.49
Total	$411,055.92	$411,055.92	$411,055.92
Production Loss Cost			
Production Loss, PL (kW)	700,000	700,000	700,000
Electricity Selling Price, SP ($/kWh)	$0.08	$0.08	$0.08
Total	$22,848,000.00	$22,848,000.00	$22,848,000.00
Computed Result			
Business Interruption Cost	$23,259,055.92	$23,259,055.92	$23,259,055.92
CoF Category	E	E	E

APPENDIX K – Proposed Consequence Analysis for Material A-213 T91 Longest Downtime

Calculation for Consequence of Failure

Material: A-213 T91	High Temperature Superheater	High Temperature Reheater	Economizer
Maintenance Cost			
Equipment Damage Cost for Carbon Steel ($)	$60,000	$60,000	$60,000
Material Cost Factor	2.6	2.6	2.6
Equipment Damage Cost, C_f (Fixed Cost)	$156,000.00	$156,000.00	$156,000.00
Cost for Manpower ($)	$757.49	$757.49	$757.49
Downtime, DT (hr)	408	408	408
Cost per Hour for Downtime, Cv (Variable Cost)	$757.49	$757.49	$757.49
Total	$465,055.92	$465,055.92	$465,055.92
Production Loss Cost			
Production Loss, PL (kW)	700,000	700,000	700,000
Electricity Selling Price, SP ($/kWh)	$0.08	$0.08	$0.08
Total	$22,848,000.00	$22,848,000.00	$22,848,000.00
Computed Result			
Business Interruption Cost	$23,313,055.92	$23,313,055.92	$23,313,055.92
CoF Category	E	E	E

APPENDIX L– Boiler Tube Data

		Value		
Item	**Data Requirement**	**HTS**	**HTR**	**Economizer**
1	Operating period (years)	8	8	8
	Current thickness (mm)	6.5	6.5	6.5
	Corrosion rate (mm/yr)	0.2	0.2	0.2
2	Maximum Allowable Working Pressure, MAWP	-	-	-
	Operating pressure, P (psia)	304.8	58.02	58.02
	Erosion allowance (mm)	0.5	0.5	0.5
	Tube Metal Temperature, TMT (°C)	579	579	287
3	Type of on-line monitoring being employed (probes, coupons, etc)	Process Variables	Process Variables	Process Variables
	Inspection Effectiveness Category (Highly, Usually, Fairly, Poorly)	Usually	Usually	Usually
	No of Inspection being conducted	5	5	5
4	Equipment damage cost ($)	As shown	As shown	As shown
	Cost per hour for downtime (repairing work cost, manpower cost)	As shown	As shown	As shown
	Shutdown time (hrs)	As shown	As shown	As shown
5	Production Loss (Megawatt)	700	700	700
	Electricity selling price ($/Megawatt.hr)	0.08	0.08	0.08

APPENDIX M – FYP Gantt Chart

Action Plan	**Semester Jan 2010**													
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**
Problem Definition														
Literature Review	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦
Damage Mechanism & Fault Event Tree														
Possible damage and outcomes study	🟦	🟦	🟦	🟦	🟦									
`														
Likelihood of Failure Analysis														
Determination of TMSF	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦			
Consequence of Failure Analysis														
API 581 Consequence Analysis							🟦	🟦	🟦	🟦	🟦	🟦		
Proposed Consequence Analysis							🟦	🟦	🟦	🟦	🟦	🟦		
FYP II														
Submission of Progress Report I				🟥										
Submission of Progress Report II								🟥						
Seminar								🟥						
Poster Exibition										🟥				
Submission of Project Dissertation (soft bound)													🟥	
Oral Presentation														🟥
Submission of Project Dissertation (hard bound)														🟥