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Maintenance Strategy for Pressure Vessel at Offshore Platform Using RBI Method

Muhammad Ali Reza[1], Muhammad Badrus Zaman[2], Nurhadi Siswantoro[3]
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***Abstract*—The increasing complexity of installations and operations of oil and gas facility, the growing public awareness need to ensure higher levels of safety have give a high pressure to designers and operators to find innovative solution to ensure a safe and economically viable operation. RBI is one of the solution can be used. RBI is a popular method and trusted for measure and develop inspection plan also provide many advantage such as plant availability, decrease failure happen, decrease risk level based on its failure and decrease inspection cost caused for production facility. The use of RBI can help in determining the inspection schedule of pressure vessel V-001 at offshore platform. RBI method determine the risk level of the object by calculate the probability of failure and consequence of failure of the object based on API 581. The result obtained for probability of failure V-001 is 0.000127099 (left head), 0.000123717 (shell) and 0.000131098 (right head) and the consequence of failure is 438.934 m^2. The risk analysis of V-001 is categorized as medium level with recommendation inspection is 5 years for external inspection and 10 years for internal inspection with recommendation inspection use ultrasonic test, visual test, edy current and radiographic test.**

Keywords—consequence of failure, probability of failure, RBI.

I. INTRODUCTION

Equipment and infrastructure used in industry for lifting, storaging, producting, packing, moving and distributing for customer are valuable and quite expensive [1]. Risk and loss that will caused if failure happen on every plant existing should be guarantee with reliability so that doesn't cause any harm to employee or environment [2].

The increasing complexity of installations and operations of oil and gas facility, the growing public awareness need to ensure higher levels of safety have give a high pressure to designers and operators to find innovative solution to ensure a safe and economically viable operation [3]. RBI method is one of the solution can be used. RBI method has been used on many plant and cases, RBI is a popular method and trusted for measure and develop inspection plan [1], [4]. RBI provide many advantage such as plant availability, decrease failure happen, decrease risk level based on its failure and decrease inspection cost caused for production facility [5]. Risk based inspection is a method used for risk anticipation with inspection and maintenance plan schedule, because the objective of risk based inspection is to optimize time and type of inspection. Identification of company equipment is the beginning of the systematic process in the inspection planning [6].

In carrying out the procress, it can't eliminate the safety during production process. RBI method is used to reduce existing risk, because seeing from several accident that occured on some of countries caused by pressure vessel :

1) on April 3, 2017 at St. Louis, Missouri there was an accident occured that killed 4 people - 1 factory worker and 3 local residents. The accident was caused by a leak that has been indicated during a break but there is No. further action was taken by the management. On Monday local time, the growing leal result is the release of pressurized water and steam fluids that made the pressure vessel float. This happened because the pressure vessel had never been inspected and maintained for 20 years since it was operated [7].
2) The boiler explosion in Algeria on January 20, 2004 result was 27 workers dead and 72 others injured. This happened because the management was negligent about inspection and maintenance.
3) In December 2004, a pressure vessel with weigh 50,000 pounds exploded at oil facility, Houston, Texas. The effect of this accident was 3 dead and damage to most of the plant which is affect the lost of half of the countries electricity access and a fire that lasted for 7 hours. The indications of this accident are due to pressure vessel modification and weld defect.
4) On July 23, 1984 Union Oil Co. refinery Illinois, U.S.A. Experienced considerable damage caused by explosions and fires that occured from pressure vessel amine absorber that rupture. Total 17 people died and the losses reached 100 millions dollar. This was caused by the spark of the mixing gas between propane and butane [8].

Several related studies RBI. Risk analysis using RBI on ethylene compression unit in 2014 consist of gas compression, toxic gas remover, filling gas and condensate dryer. Damage mechanism potential and damage mechanism already occured such as thinning, external corrosion and stress corrosion cracking (SCC). Total of 303 components consist of pressure vessel and pipeline were calculated and analyzed, from analysis obtained 12 high risk, 136 medium high risk, 127 medium risk and 28 low risk component [9]. A

Muhammad Ali Reza is with Department of Marine Engineering, Institut Teknologi Sepuluh Nopember, Surabaya, 60111, Indonesia. E-mail: mareza1198@gmail.com
Muhammad Badrus Zaman is with Department of Marine Engineering, Institut Teknologi Sepuluh Nopember, Surabaya, 60111, Indonesia. E-mail: druz_zaman@ne.its.ac.id
Nurhadi Siswantoro is with Department of Marine Engineering, Institut Teknologi Sepuluh Nopember, Surabaya, 60111, Indonesia. E-mail: nurhadi@ne.its.ac.id

horizontal pressure vessel with capacity of 50 ton that function as LPG storage tank is analyzed using RBI 581 method and ASME sec. VIII as reference standard. This vessel which located at LPG bulk filling station (SPBE) installation has a medium-high risk level with area of consequence 15430431.8 ft^2. If a failure occurred this equipment will have an impact both on the plant and the surrounding environment [10]. The HRSG (Heat Recovery Steam Generator) in Muara Karang evaluated based on API 581 RBI method with inspected equipment including pressure vessel, heat exchangers, pipes and tubes. Several damage factors that occurred in the inspected equipment such as thinning, SCC amine cracking, HTHA, CUI and FAC. The result obtained is 16 low risk and 10 medium risk equipment. The type of inspection for each damage factors such as the use of UT and radiography on thinning. Wet fluorescent magnetic pasrticle on SCC Amine Cracking, AUBT or extensive in-situ metallography on HTHA, UT on CUI and FAC [11]. In 2021 a study case on separator condensate 10V2102 and storage vessel 10V2103 based on API RP 581, obtained that two vessel have low risk category and based on API 510 for determine the inspection schedule, where is the maximum interval inspection is 5 years and for internal inspection is 10 years [12].

Interval inspection can affect the cost that company has provide, it depends on the equipment type that analyzed and help to reduce the available risk. However, this will affect the cost where the closer the interval, the greater the cost will be. The use of RBI can help in determining the inspection schedule. This research proposed to determine the inspection plan on pressure vessel.

II. Method

A. Risk Based Inspection

Risk Based Inspection (RBI) is risk analysis and process management that focused on loss of containment of pressurized equipment at facility process caused of damage on material. RBI is methodological approach focused on measuring, monitoring and mitigating risk caused of the complexity from chemical or physically aspect. To carry out the RBI analysis for each of the equipment, the probability of failure (PoF) and consequence of failure (CoF) are assessed separately [13].

According to API 581, risk is the combination of Probability of Failure (PoF) and Consequence of Failure (CoF) in the mean time. Risk can be calculated with the result of Probability of Failure and Consequence of Failure [14]. Probability of Failure formula based on API 581 can be calculated :

$$P_f(t) = gff.D_f\,(t).F_{MS} \quad (1)$$

On the equation above P_f (t) is Probability of Failure, gff is generic failure frequency, D_f (t) is damage factor and FMS is system management factor.

Consequences of failure is carried out to determine and estimate the impact of consequence that may occur. The CoF is also used to determine the priority of the inspection program of equipment. Consequence of failure analysis divided into two levels, there is Level 1 and Level 2. This analysis use Level 1 to calculate and determine each of value below:

1) The representative fluid, fluid properties and release.
2) Release hole selection.
3) Release rate.
4) The amount of fluid inventory available
5) The release type of each hole size
6) The impact of detection and isolation system
7) The release rate and mass for consequence of failure
8) Consequence of flammable and explosive
9) Consequence of toxic
10) Consequence of non-flammable non-toxic
11) The final consequence area

In this analysis financial consequence is not retrieved and the limitation of this analysis for consequence of failure based on consequence area. Risk is the combination of Probability of Failure (PoF) and Consequence of Failure (CoF), can be calculated using:

$$Risk = P_f\,(t) \times C_f \quad (2)$$

B. Inspection Plan

The result of Risk Based Inspection calculation is risk level that can be continued with risk matrix that were given by API 581, The criteria and the range of value for risk PoF and CoF can be seen in Table 1 and the risk matrix can be seen in Figure 1.

III. Results and Discussion

To analyse risk using Risk Based Inspection method, there are some data that would be needed and some data

TABLE 1.
RISK CATEGORY

Cat.	Probability Category		Consequence Category	
	Probability Range	Damage Factor Range	Cat.	Range (m^2)
1	$P_f(t,I_E) \leq 3.06E-05$	$D_{f-total} \leq 1$	A	CA ≤9.29
2	$3.06E-05 < P_f(t,I_E) \leq 3.06E-04$	$1 < D_{f-total} \leq 10$	B	9.29 < CA ≤ 92.9
3	$3.06E-04 < P_f(t,I_E) \leq 3.06E-03$	$10 < D_{f-total} \leq 100$	C	92.9 < CA ≤ 929
4	$3.06E-03 < P_f(t,I_E) \leq 3.06E-02$	$100 < D_{f-total} \leq 1000$	D	929 < CA ≤ 9,290
5	$P_f(t,I_E) > 3.06E-02$	$D_{f-total} > 1000$	E	CA > 9,290

that referred to API 581. Several data used for this analysis is last inspection data such as thickness, chemical data contain and Process Flow Diagram of vessel V-001. Table 2 shows the vessel V-001 data.

TABLE 2.
PRESSURE VESSEL DATA

General data	
Design code :	ASME Sec. VIII
Equipment nama :	V-001
Vessel type :	Drum
Volume total :	5.919 m^2
Year built :	2001
Fluid category :	C1-C2
Design pressure :	102 bar 1480 psig
Design temperature :	60 °C 140 °F
Operating pressure :	99.825 bar 1440 psig 9928.8 kPa
Operating temperature :	37.778 °C 100 °C 310.928 °K

A. Probability of Failure (PoF)

Probability of Failure retrieved from the value of 3 component contains of generic failure frequency (gff), damage factor possible and FMS. According to the data of the environment and operational data, the possibility of damage mechanism occurs in vessel V-001 are thinning, sulfide stress cracking, HIC/ SOHIC-H_2S and external corrosion.

1) Gff for V-001 which is categorized as a vessel is 3.06 x 10^{-5}.
2) Management system factor (F_{MS}) for this pressure vessel V-001 according to the company is 1.
3) Damage factors that occure on pressure vessel V-001 are thinning, sulfide stress cracking, HIC/ SOHIC-H_2S and external corrosion .

- Thinning
  Thinning is a degradation of a metal due to its environment where the thickness of the metal will decrease. Eventually thinning can cause leaks and ruptures in pressure boundary also cause fatal failure in some plants [15]. Calculate the corrosion rate of the material is necessary due to obtain the thinning damage factor. The corrosion rate obtained from the last inspection data. The result of thinning calculation is 0,1.
- Sulfide stress cracking
  The definition of Sulfide stress craking (SCC) is cracking caused by a combination of tensile strength and an environment containing water and H_2S. Sulfide stress cracking also occurs when atomic hydrogen diffuses into the metal but remains in solid solution in the crystal lattice [16]. SCC can occur even there is little H_2S content in water. PWHT (post weld heat treatment) can reduce the susceptibility of the material because of sulfide stress cracking. There is a historical of V-001 regarding PWHT. The result of sulfide stress cracking is 0.
- HIC/ SOHIC-H_2S
  HIC/ SOHIC-H_2S is the abbreviation of hydrogen induced cracking and stress oriented hydrogen induced cracking duet o the influence of H_2S. Some of the low-strength carbon steel can be susceptible to HIC in wet services contain H_2S [17]. Blistering es an example of the the type of this cracking. SOHIC is a specialized type of HIC and insome cases the result is crack through-wall cracks in pressure vessel using carbon steel. SOHIC is another type of sour corrosion with cracking mechanism caused by wet H_2S and it can lead to material failure [18]. There is a record of PWHT treatment on V-001. The result of HIC/ SOHIC-H_2S is 2.2974 SSC and HIC/ SOHIC-H_2S is the type of stress corrosion cracking (SCC). According to RBI method API 581 stress corrosion cracking damage factor is the maximum value of those type damage factor. Then the result of SCC damage factor is 2.2974.

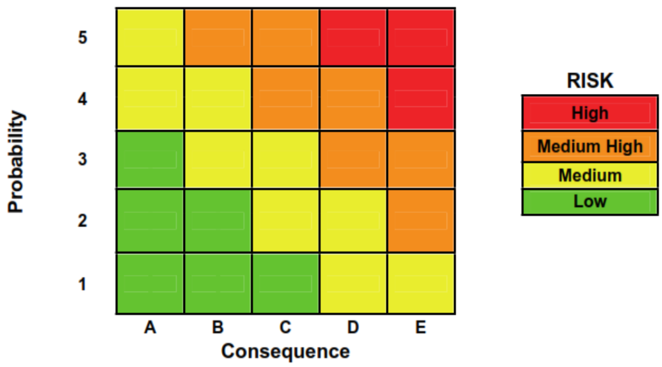

Figure. 1. Risk matrix

- External corrosion
  External corrosion largely dictated by the environment in which the asset is installed [19]. Area with humid environmental conditions are susceptible to external corrosion. In addition to the influence of the surrounding environment, it can also affected by the distance between the unit and cooling tower, steam vent and unit with operating temperature cycle that passes the dew point regularly. The result of external corrosion is 4.15356, 4.0431 and 4.28425.

The Probability of Failure value obtained 0.000127099, 0.000123717 and 0.000131098. The probability of V-001 is categorized as category 2.

B. Consequence of Failure (CoF)

The are some type of CoF can be analyze such as flammable/ explosive consequence, consequence of toxic, consequence of non-flammable and non-toxi..

1) Determine the representative fluid, fluid properties and release
   Representative liquid is the dominant liquid on the pressure vessel and a reference if there is a leak on the vessel. The representative fluid in API 581 categorized as C_1-C_2. With the following data : if the fluid exit the pressure vessel while operating is in the gas phase. C_1-C_2 has molecular weight (MW) 23 kg/kg-mol, auto ignition temperature (AIT) 558K, ideal gas spesific ratio 1,19349.
2) Select release hole selection
   There are 4 categories of hole size provided by API 581 : small, medium, large and rupture. With the size as follow :
   Small = 6.4 mm   medium = 25 mm
   large =102mm   rupture = 406 mm
3) Determine the release rate
   The release rate of each hole size is calculated to get the mass rate of C_1-C_2 using the equation below and the result can be seen on Table 3.

$$W_n = \frac{C_d}{C_2}\, x\, A_n\, x\, P_s \sqrt{\frac{k\, x\, MW\, x\, g_c}{R\, x\, T_s}\left(\frac{2}{k+1}\right)^{\frac{k+1}{k-1}}} \quad (3)$$

Where :
A_n = area of release hole size (m^2)
P_s = storage operating pressure (kPa)
k = amospheric pressure (kPa)
MW = molecular weight (kg/kg-mol)
g_c = gravitanional constant
R = universal gas constant
T_s = operating temperature

TABLE 3.
RELEASE RATE EACH HOLE SIZE

Hole size	Small	Medium	Large	Rupture
W_n (kg/s)	0.01602	0.24446	4.0693	64.4732

4) Estimate the amount of fluid inventory available
   To determine the total fluid mass is determine mass inventory equipment and the total mass can be released is mass inventory. The total of mass inventory, $Mass_{inv}$ = 2712.390 kg.

TABLE 4.
MASS AVAIL EACH HOLE SIZE

Hole size	Small	Medium	Large	Rupture
Mass avail (kgs)	744.27	785.393	1473.88	2712.35

5) Determine the release type of each hole size
   There is 2 type of release according to API 581 there is continous release and instantaneous release. Continous release is occur over a longer period of time. Instantaneoud release is occurs so rapidly that the fluid disperse as a single large cloud or pool. Instantaneous type if the release mass 4.536 kg and happen in less than 180 seconds. Calculate the duration can used the formula :

$$t_n = \frac{C_3}{W_n} \quad (4)$$

Where :
t_n = release duration
C_3 = 4,536 kgs
W_n = theoritical release rate hole size
The result obtained :
t_{small} = 283129.9948 s
t_{medium} = 18555.20734 s
t_{large} = 1114.6678 s
$t_{rupture}$ = 70.355 s
The result shows the 3 hole size : small, medium, large categorized as continous release type and rupture categorized as instantaneous with release mass 4,536 kg within less than 180 seconds.

6) Estimate the impact of detection and isolation system
   Based on API 581 classify the detection and isolation system required to determine the leak time reduction factor ($fact_{di}$). The detection system the company has is visual detection, cameras or detector with marginal coverage which is categorized as C and the isolation system is isolation or shutdown systems activated directly from process instrumentation or detector, with No. operator intervention which is categorized as than the $fact_{di}$ is 0.1. The total leak duration for each hole is :
   $Id_{max.small}$ = 40 minutes
   $Id_{max.medium}$ = 30 minutes
   $Id_{max.large}$ = 20 minutes
   $Id_{max.rupture}$ = 20 minutes

7) Determine the release rate and mass for consequence of failure
Each of hole size release rate that is used in the analysis is the theoritical released as in step 3 before. The release rate equatias as in below :

$$rate_n = W_n\left(1 - fact_{dl}\right) \quad (5)$$

Where :
$rate_n$ = release rate for associated hole size
W_n = theoritical release rate
$fact_{di}$ = reduction factor
The result of release rate is :

TABLE 5.
RELEASE RATE EACH HOLE SIZE

Hole size	Small	Medium	Large	Rupture
Mass (kg/s)	0.014418	0.22	3.66243	58.02588

There is leak duration than can be calculated with equation :

$$ld_n = min\left[\left\{\frac{mass_{avail,n}}{rate_n}\right\}\{60.ld_{max,n}\}\right] \quad (6)$$

Where :
ld_n = leak duration each hole size
$mass_{avail.n}$ = mass available for release each hole size
$rate_n$ = release rate each hole size
$ld_{max.n}$ = maximum leak duration
Obtained value is :

TABLE 6.
LEAK DURATION EACH HOLE SIZE

Hole size	Small	Medium	Large	Rupture
Leak duration (s)	2400	1800	402.431	46.754

For the release mass equation:

$$mass_n = min\left[\{rate_n \, x \, ld_n\}, \, mass_{avail,n}\right] \quad (7)$$

The release mass result :

TABLE 7.
RELEASE MASS EACH HOLE SIZE

Hole size	Small	Medium	Large	Rupture
mass (kg)	36.6052	396.025	1473.878	2712.915

8) Calculate flammable and explosive consequence
The final output of flammable and explosive consequence is to obtain flammable consequence area of component ($CA^{flam}_{cmd,n}$) and area of personnel injury ($CA^{flam}_{inj,n}$).
There are some value such as consequence area of component damage and personnel injury in auto-ignition likely and auto-ignition not likely to get CA^{flam}_{cmd} and CA^{flam}_{inj} . Blending factor also needed for flammbale consequence calculation with value 0. The formula of those are :

$$CA^{flam}_{cmd,n} = CA^{AIL}_{cmd,n} \cdot fact^{AIT} + CA^{AINL}_{cmd,n} \cdot (1 - fact^{AIT}) \quad (8)$$

$$CA^{flam}_{inj,n} = CA^{AIL}_{inj,n} \cdot fact^{AIT} + CA^{AINL}_{inj,n} \cdot (1 - fact^{AIT}) \quad (9)$$

And the equation for flammable consequence damage and flammable personnel injury fomulated :

$$CA^{flam}_{cmd} = \left(\frac{\sum_{n=1}^{4} gff_n \, . CA^{flam}_{cmd,n}}{gff_{total}}\right) \quad (10)$$

$$CA^{flam}_{inj} = \left(\frac{\sum_{n=1}^{4} gff_n \, . CA^{flam}_{inj,n}}{gff_{total}}\right) \quad (11)$$

Where :
CA^{flam}_{cmd} = flammable consequence of component damage each hole size
CA^{flam}_{inj} = flammable consequence of personnel injury each hole size
gff_n = generic failure frequency each hole size
gff_{total} = generic failure frequency total

The result of component damage is 265.393 m^2 and personnel injury is 438.934 m^2.

9) Calculate toxic consequence
The category of H_2S is toxic and flammable consequence. There are some step to calculate the toxic consequence as follow :
The first tep is to calculate the efective duration of toxic release using formual as follow :

$$Id^{tox}_n = min\left(3600, \left\{\frac{mass_n}{W_n}\right\}, \{60. Id_{max,n}\}\right) \quad (12)$$

Where :
Id^{tox}_n = toxic release duration each hole size
$mass_n$ = mass rate each hole size
W_n = theoretical release each hole size
$ld_{max.n}$ = maximum leak duration for associated hole size

Calculate release rate of toxic and mass rate of toxic:

$$rate^{tox}_n = mfrac^{tox} . W_n \quad (13)$$

Where :
$rate^{tox}_n$ = toxic release rate of each hole size
$mfrac^{tox}$ = toxic substance percentage of release fluid

Toxic release rate and mass rate are used for calculate the toxic consequence area using formula as follow :

$$CA_{inj,n}^{tox-CONT} = C_8 . 10^{\left(c.\log_{10}\left[C_{4B}.rate_n^{tox}\right]+d\right)} \quad (14)$$

$$CA_{inj,n}^{tox-INST} = C_8 . 10^{\left(c.\log_{10}\left[C_{4B}.mass_n^{tox}\right]+d\right)} \quad (15)$$

Where :

$CA_{inj,n}^{tox-CONT}$ = consequence area of toxic for continuous release of associated hole size

$CA_{inj,n}^{tox-INST}$ = consequence area of toxic for instantaneous release of associated hole size

C_8 = 0.0929 (m^2)

C_{4B} = 2.205

c and d = constant associated with each hole size

Calculate the total consequence area of toxic using equation as follow is the final step :

$$CA_{inj}^{tox} = \left(\frac{\sum gff_n . \ CA_{inj,n}^{tox}}{gff_{total}}\right) \quad (16)$$

The result is 0.702 m^2.

10) Calculate non-flammable non-toxic consequence

Steam and acid/caustic is a substance that not flammable nor toxic but have their own consequences. V-001 doesn't contain acid/caustic substance category in the fluids, but there is steam. Steam is at 100°C (212°F) immediately after exitting a hole in a equipment item. Within a few feet, depending upon its pressure, steam will began to mix with air, cool and condense. At a concentration about 20%, the steam/ air mixture cools to about 60°C (140°F). This vessel V-001 operating temperature is 100°C. The steam leaks will cause impact to surrounding area. The calculation for consequence of non-flammable non-toxic of steam as follow :

$$CA_{inj,n}^{CONT} = C_9 . rate_n \quad (17)$$

$$CA_{inj,n}^{INST} = C_{10} . (mass_n)^{0.6384} \quad (18)$$

Where :

$CA_{inj,n}^{CONT}$ = consequence area of non-flammable non-toxic associated with hole size for continuous release

$CA_{inj,n}^{INST}$ = consequence area of non-flammable non-toxic associated with hole size for instantaneous release

C_9 = 0.123 (m^2.sec/kg)

C_{10} = 9.744 (m^2/kg)

$$CA_{lak,n}^{leak} = CA_{inj,n}^{INST} . fact_n^{IC} + CA_{inj,n}^{CONT} . (1 - fact_n^{IC}) \quad (19)$$

Where :

$CA_{inj,n}^{leak}$ = personnel injury consequence of steam leak

$$CA_{inj}^{nfnt} = \left(\frac{\sum gff_n . \ CA_{inj,n}^{leak}}{gff_{total}}\right) \quad (20)$$

Where :

CA_{inj}^{nfnt} = consequence area of non-flammable non-toxic

The result of consequence calculation is 42.464 m^2.

11) Determine the final consequence area

For consequence component damage the consequence of component is the same as flammable consequence of component.

$$CA_{cmd} = CA_{cmd}^{flam} \quad (21)$$

Where :

CA_{cmd} = consequence area of component damage (m^2)

CA_{cmd}^{flam} = flammable consequence of component damage (m^2)

$$CA_{inj} = \max\left[CA_{inj}^{flam}, CA_{inj}^{tox}, CA_{inj}^{nfnt}\right] \quad (22)$$

The result is CA_{cmd} = 265.393 and CA_{inj} = 438.934 m^2

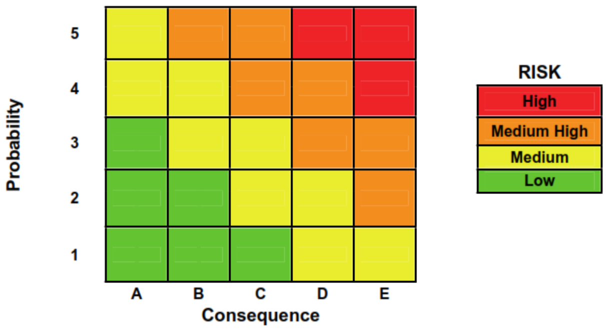

Figure. 2. Risk level of V-001.

$$CA = \max\left[CA_{cmd}, CA_{inj}\right] \quad (23)$$

The final consequence of areas (CA) is 438.934 m^2 and categorized as category C.

The parts of vessel that has been analyzed is categorized as medium risk. Based on API 510 the recommendation of interval inspection of internal inspection in 10 years and for external inspection is 5 years, interval for inspection planning of external shall not exceed 10 years. The recommendation inspection are ultrasonic test, visual test, radiography tes and edy current test.

IV. Conclusion

The results show that the probability of failure V-001 is 0.000127099 (left head), 0.000123717 (shell) and 0.000131098 (right head), also all the component have been analyzed is category 2 .The consequence of failure is 438.934 m^2 and categorized as category C. The V-001 risk analysis is the risk level of pressure vessel categorized as the medium level with recommendation for inspection : internal inspection in 10 years and for external inspection is 5 years, interval for inspection planning of external shall not exceed 10 years.

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