Risk analysis of scrubber vessel using risk-based inspection method in geothermal power plant

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Abstract. The corrosive geothermal fluids combined with high temperature and high-pressure work systems cause intensive corrosion. Corrosion that exceeds the safe limits can cause gas leaks which are hazardous to the environment and personnel. It is important to inspect the location of corrosion in the equipment. The existing methodology for inspection is carried out regardless of the risk level of the equipment. Therefore, it is necessary to apply the appropriate method to conduct inspections based on risk level. This research proposed a Risk-Based Inspection method to determine the scheduling and methods for inspecting scrubber vessel in the gas removal system of the geothermal power plant. Based on the analysis, it is recommended to carry out direct inspection for the shell part of the steam scrubber (VS-81-009) using radiography or ultrasonic scanning.

1. Introduction

Geothermal power plants use dry steam to drive turbines that are coupled with generators to produce electrical energy. The hot steam is produced from geothermal fluids extracted from the ground. Geothermal power plants function by using hot steam inside the earth to produce electrical energy. Heat energy is extracted from the earth in the form of geothermal liquid. Several production wells from the liquids are combined and sent through two-phase lines to cyclonic separators where steam and brine are separated [1].

Geothermal fluids composition also varies between reservoir sites or places, but mostly they are corrosive [2]. Geothermal fluids at the facility have a composition of hydrogen ions (pH), carbon dioxide (CO₂), hydrogen sulfide (H₂S), ammonia (NH₃). With this composition, combined with high temperatures and pressures, that makes the geothermal fluid corrosive. Several corrosive substances in the reservoir, geothermal fluids that contain H₂S, CO, and gasses such as HCl can cause damage to equipment material [3]. H₂S and CO can cause corrosion on steel equipment when steel is exposed to H₂S and CO, it will release hydrogen during the process, this, in turn, leads to delayed fracture under tension or known as hydrogen-induced cracking [4].

Corrosion beyond the safe limit can cause gas leakage which is harmful to the environment and personnel. For this reason, locations where corrosion commonly occur such as scrubber vessels are important to be inspected [5]. To avoid corrosion failure, usually inspections once in every 4 years are conducted [6]. Although there are no government regulations that regulate periodic inspections of
geothermal power plant, the time intervals are determined from the recommendations of the component manufacturers. However, the inspection program is less effective because the inspection of critical and less critical equipment have the same method and interval [7,8].

To improve the inspection plan, the new methods are proposed to inspect static pressurized equipment. Risk-Based Inspection (RBI) is an inspection method that focuses on the risk of tool or component failure. This method is comprehensive because inspection planning and mitigation actions consider the risk of failure of each component. The risk of failure is obtained from the Probability of Failure (PoF) and Consequence of Failure (CoF) [9,10,11,12]. Besides, inspections are designed based on the risk level of equipment according to the risk analysis. Equipment with a higher level of risk will be prioritized for inspection. Inspections are carried out when the risk or condition of the equipment has exceeded the risk target [12,13]. The inspection is carried out to reduce the risk of the equipment and derive the latest information about the condition of the equipment (the implementation of the inspection will only reduce the probability of failure). The accuracy of the inspection method is called inspection effectiveness [6,11,12,13]. This is the reason RBI method is widely used in the world.

The RBI method has been applied to several static types of equipment. The RBI method is used to determine the method and scheduling of inspections in the pipeline carried out by several researchers such as Perumal and Seo et.al [14,15]. On equipment such as heat exchangers, RBI has been proven to be used to determine the damage mechanism caused by fluid, pressure, temperature and environment [10,11]. Besides, the application of RBI has also been used for scheduling program analysis of pressure relief devices (PRD) on production gas separator systems with H2S fluid content [6,16].

Furthermore, this research proposed a Risk-Based Inspection method to determine the recommendation of the inspection date and the specific action of inspection of scrubber vessels on the geothermal power plant.

2. Methodology
Risk, according to API RP 581 can be calculated from the result of the Probability of Failure (PoF) and Consequence of Failure (CoF) of equipment. Probability can be estimated as [12,13]:

\[ P_f (t) = gff. D_f (t). F_{MS} \]  

Where \( P_f (t) \) is the probability of failure determined by \( gff \) (generic failure frequency), \( D_f (t) \) as a damage factor, and system management factor \( F_{MS} \). \( gff \) is representative values of data refining and failure of different types of component types. \( F_{MS} \) is the factor of management system that affects mechanical integrity of components. Damage factor is construction metal deterioration factor, the value of which indicates the metal susceptibility to such damages.

Consequences are calculated using the consequence analysis method which does not concern damage factor. Consequence analysis is divided into two levels items, namely Level 1 and Level 2 consequence of failure. In this analysis, the consequence calculation used is Level 1 which steps are [12]:

- **Step 1.** Determine the released fluid and its properties, including the release phase.
- **Step 2.** Select a set of release hole sizes to determine the possible range of consequence in the risk calculation.
- **Step 3.** Calculate the theoretical release rate.
- **Step 4.** Estimate the total amount of fluid available for release.
- **Step 5.** Determine the type of release, continuous or instantaneous, to determine the method used for modelling the dispersion and consequence.
- **Step 6.** Estimate the impact of detection and isolation systems on release magnitude.
- **Step 7.** Determine the release rate and mass for the consequence analysis.
- **Step 8.** Calculate flammable/explosive consequence.
- **Step 9.** Calculate toxic consequences.
- **Step 10.** Calculate non-flammable, non-toxic consequence.
- **Step 11.** Determine the final probability weighted component damage and personnel injury consequence areas to estimate total consequences.
In this analysis, the financial consequence or economic analysis and such financial analysis is not conducted. The limitation of this analysis is based on the consequence of area (CA). Risk is calculated as a function of time. This equation combines the probability of failure and the consequences of failure.

\[ \text{Risk} = P_f(t) \cdot C_f \] (2)

Risk matrix is a method for determining the level of risk. The probability and consequence of failure criteria in the risk matrix are given by API RBI 581 [12]. Table 1 shows the criteria for the range of values for the risk matrix. Whereas the risk matrix used to determine the level of risk can be seen in Figure 1.

| Category | Probability range | Damage factor range | Consequence Category | Range (m²) |
|----------|-------------------|---------------------|---------------------|------------|
| 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        | \( 3.06E-03 < P_f(t, I_E) \leq 3.06E-02 \) | \( 100 < D_{f-total} \leq 1,000 \) | D             | 929<CA≤9,290 |
| 5        | \( P_f(t, I_E) > 3.06E-02 \) | \( D_{f-total} > 1,000 \) | E             | CA>9,290    |

![Figure 1. Risk matrix of API 581 [12]](image)

In addition, to determine an inspection date a risk target parameter is necessary. This target is a benchmark to trigger inspection planning. In this case, the risk target based on damage factor about 100.

3. Results and Discussions

3.1 Process Description and Steam Scrubber Data

Scrubber vessel serves to reduce the moisture from the steam that flow through it, so it can produce dry hot steam. However, for geothermal power plants, scrubbers also function to remove minerals dissolved in the steam. The scrubber vessel receives steam from a separator containing small amounts of minerals and liquids. The dry hot steam from the scrubber is used to drive the turbine to produce electricity.

To conduct a Risk-Based Inspection analysis, there are some data and the sources of data that can be referred to API RP 581 and API RP 580. The data that is used in this analysis is previous inspection reports, chemical analysis, PFD and P&ID of scrubber vessel. Table 2 and Table 3 show the scrubber vessel data on the geothermal power plant and chemical composition of fluids.
Table 2. Specification of scrubber vessel

| GENERAL SPECIFICATION |
|------------------------|
| Tag Number             | VS-81-009            |
| Quantity               | 1                    |
| Service                | Steam Scrubber       |
| Serial No.             | PV-GSB-099           |
| Type of Pressure Vessel| Drum                 |
| Geometry Data          | 2:1 Ellipsoidal       |
| Code                   | ASME Section VIII Division 1 2015 Edition |
| Design Pressure        | 13.88 bar            |
| Design Temperature     | 198°C                |
| Operating Pressure     | 9.9 bar              |
| Operating Temperature  | 185.4°C              |
| Operating Steam Flow rate | 115.96 Kg/s         |
| Dimension              | 1930 ID x 9070 T-T   |
| Empty Weight           | 18247 kg             |
| Operating Weight       | 21290 kg             |
| Full of Water          | 47754 kg             |
| Vessel Volume          | 28160 liter          |
| Support                | Skirt                |
| Joint Efficiency (Head/Shell) | 1                    |
| Insulation (Hot/Cold)  | 50 mm                |
| Corrosion Allowance    | 3.00 mm              |
|                        | 0.1181 inch          |
| Year built             | 2000                 |
| Material               | SA 516 Gr. 70        |
| Last inspection        | 3 July 2014          |

Table 3. Chemical composition of fluids

| mmole/100 mole H$_2$O |
|------------------------|
| CO$_2$ | H$_2$S | NH$_3$ | N$_2$ | CH$_4$ | He | H$_2$ | Ar |
|--------|-------|-------|------|-------|----|------|----|
| 239.871| 7.3822| 0.2297| 24.557| 0.4563| 0.087| 1.2557| 0.029|

Note: those values are average of the values sample taken on different date in September 2018.

3.2 Probability of Failure Analysis

Probability of failure is obtained from the value of damage factor, generic failure frequency, and factor management system of the company. According to operational data, fluids, and environment, the possibility of damage mechanism that occurs in scrubber vessel (VS-81-009) is thinning, sulfide stress cracking, and HIC / SOHIC - H$_2$S.

a. Generic failure frequency ($g_{ff}$) for steam scrubber which categorized as a vessel is 3.06x10^{-5}[12].

b. Factor management system ($F_{MS}$), can be acquired through management system screening which contained in API 581. $F_{MS}$ can be calculated using the formula:

$$F_{MS} = 10^{(-0.02 \times \text{score} + 1)}$$ (3)
Where $pscore$ is a percentage of the management system score. To find the percentage, this formula can be used:

$$pscore = \frac{Score}{1000} \times 100 \text{ [unit is 100%]}$$  \hspace{1cm} (4)

From the screening on the geothermal power plant, the company obtained management system score of 869.5, thus the $F_{MS}$ is 0.18239.

c. Damage factors that correspond to the condition of VS-81-009 are thinning, sulfide stress cracking, and HIC / SOHIC - $H_2S$.

- **Thinning**
  Thinning - is a degradation of the metal due to its environment which results in thinning of the metal thickness. To find out the value of thinning damage factor, it requires data on the material corrosion rate. The data is obtained from the last inspection or calculation of corrosion rate based on the thinning mechanism in Annex 2.B API RP 581. Thinning can occur due to several mechanisms. In this case, the thinning mechanism that matches the API RP 581 corrosion rate screening criteria is sour water corrosion, acid sour water corrosion, and $CO_2$ corrosion. Sour water and acid sour water corrosion occur because of the presence of $H_2S$ in solutions whose pH is below 7.0. While $CO_2$ corrosion occurs because of the presence of water and $CO_2$ and Cr level of construction material (carbon steel) is below <13%. The result of the thinning calculation is $D_{f thin} = 0.241$.

- **Sulfide stress cracking**
  Sulfide stress cracking (SSC) is defined as a crack due to a combination of tensile stress and aqueous environment with presence of $H_2S$. Sulfide stress cracking is a type of hydrogen stress cracking that results from the absorption of hydrogen atoms produced by the process of sulfide corrosion on metal surfaces [17]. Material susceptibility to sulfide stress cracking can be reduced by PWHT (post weld heat treatment) treatment on components. For the shell section of the steam scrubber, there is no historical record regarding of PWHT. The damage factor for sulfide stress cracking is $D_{f SCC} = 5.8651$.

- **HIC / SOHIC – $H_2S$**
  Material vulnerability to HIC/SOHIC will decrease along with lower sulfur concentrations in steel, as well as PWHT treatment on components. The construction material used is SA 516 Gr. 70 with 0.03% sulfur content. There is no history of PWHT treatment on the shell section, resulting in a damage factor of, $D_{f HIC SOHIC-H2S} = 293.26$. Both SSC and HIC/SOHIC are categorized as stress corrosion cracking (SCC). For multiple types of SCC, API 581 stated that the SCC damage factor is the maximum value of those types. Then, the SCC damage factor, $D_{f SCC}^{gov} = 293.26$.

d. Result of probability of failure. Based on the $g_{ff}$, $F_{MS}$ and damage factor, the score of the Probability of Failure (PoF) can be determined. The $g_{ff}$ is 3.06E-05 and the $F_{MS}$ is 0.182. While the damage factor is 293.5 obtained from the sum of thinning damage (0.241) and stress corrosion cracking damage (293.26), which is 293.5. Therefore, the resulting PoF on RBI date is 1.64E-03.

### 3.3 Consequence of Failure Analysis

The consequences that could be analyzed which are flammable/explosive consequences, toxic consequences, and non-flammable non-toxic consequences. These calculations do not estimate the financial consequences.

**Step 1. Determine the released fluid and its properties, including the release phase.**

The representative fluid is the dominant fluid in the system that is used as a reference calculation if there is a leak in the vessel. Generally, representative fluids are compounds with the most moles in the
fluid. However, if there is an inert compound such as CO$_2$ and water, the representative fluid is determined by prioritizing compounds with flammable/toxic effects, in addition to the two compounds [12]. The chemical compositions are shown in Table 3.

The representative fluid is H$_2$S. Where the H$_2$S phase when the vessel operates and exits the vessel is in the gas phase. H$_2$S has the properties of molecular weight (MW) 34 kg/kg-mol, auto-ignition temperature (AIT) at 500°C and ideal gas specific heat ratio (k) of 1.342. It should be noted that H$_2$S is hazardous because it is toxic and flammable.

Step 2. Select a set of release hole sizes to determine the possible range of consequence in the risk calculation.

There are 4 categories of holes size, namely, small, medium, large and rupture. API 581 provides a range of diameter for the size of each hole. Each hole is calculated as a level of the resulting consequences. This is related to how much the rate of representative fluid leaks. The diameters chosen are:

Small = 0.25 inch  Large = 4 inch
Medium = 1 inch      Rupture = 16 inch

Step 3. Calculate the theoretical release rate.

Theoretical release rate ($W_n$) is calculated for each output hole size to get the mass rate value of H$_2$S in each output hole size. $W_n$ calculated using formula of:

$$W_n = \frac{C_d}{C_2} \times A_n \times P_s \left( \frac{k \times MW \times gc}{R \times Ts} \right)^{\frac{k+1}{k-1}}$$  (5)

where;
- $A_n$ = release hole size area (m$^2$)
- $P_s$ = storage operating pressure (kPa)
- $P_{atm}$ = atmospheric pressure (kPa)
- $k$ = ideal gas specific
- $MW$ = molecular weight (kg/kg-mol)
- $gc$ = gravitational constant (m/s$^2$)
- $R$ = universal gas constant
- $Ts$ = operating temperature (K).

The obtained results are,

- $W_{small}$ = 0.001927330 kg/s
- $W_{medium}$ = 0.090034545 kg/s
- $W_{large}$ = 0.460167685 kg/s
- $W_{rupture}$ = 23.04312731 kg/s.

Step 4. Estimate the total amount of fluid available for release.

Total fluid mass is estimated from the mass inventory equipment. Mass inventory is the total mass that can be released. This means the amount of fluid which is held within pressure containing equipment between isolation valves that can be quickly closed. The estimated mass value is based on the assumed volume portion of liquid and gas for the type of equipment scrubber (knock-out drum) in Annex 3.A API RP 581, which is 90% gas and 10% liquid. Here is the result of the calculation, $\text{Mass}_{\text{inventory}} = 2489.9$ kg.

Next step is the estimated total mass of the inventory added to by the mass of additional components that can provide additional mass. For the additional mass itself, API 581 estimates that there is a mass limit because within 3 minutes there will be an intervention from the operator on leakage. The total fluid that can be removed in each output hole ($\text{Mass}_{\text{avail}, n}$):

- $\text{Mass}_{\text{avail}, small}$ = 182.838 kg/s
- $\text{Mass}_{\text{avail}, medium}$ = 198.697 kg/s
- $\text{Mass}_{\text{avail}, large}$ = 265.321 kg/s.
Mass_{avail, rupture} = 1,220,670 kg/s.

**Step 5. Determine the release type, continuous or instantaneous, to determine the method used for modeling the dispersion and consequence.**

An instantaneous release is one that occurs so rapidly that the fluid disperses as a single large cloud or pool. A continuous or plume release is one that occurs over a longer period, allowing the fluid to disperse in the shape of an elongated ellipse (depending on the weather conditions). The output is declared instantaneous if it releases a mass of 4,536 kg in less than 180 seconds. Calculations are carried out to see the duration of releasing 4,536 kg of fluid in each hole size. This formula is used to calculate the durations:

\[ t_n = \frac{C_3}{W_n} \]  

where,

- \( t_n \) = release duration of 4,536 kgs (10000 lbs) of fluid.
- \( C_3 \) = 4,536 kgs
- \( W_n \) = theoretical release rate associated with hole sizes.

Results of the calculations are:

\[ t_{small} = 2,353,511.3 \text{ s} \]
\[ t_{medium} = 50,380.662 \text{ s} \]
\[ t_{large} = 9,857.2763 \text{ s} \]
\[ t_{rupture} = 196.84828 \text{ s} \]

The calculation results show that each hole size releases a mass of 4,536 kg with a time of more than 180 seconds. So, this is categorized as a continuous release type.

**Step 6. Estimate the impact of detection and isolation systems on release magnitude.**

Classifying detection and isolation systems are required to determine maximum leak time and reduction factor \((fact_{di})\), which values have been determined in API 581. The company facilities have a detection system in the form of visual detection, cameras or detectors with marginal coverage, according to API 581, this is classified as class C. For the isolation system, isolation is dependent on manually operated valves, this also classified as class C. If both are classified as class C, then the maximum leakage time for each hole is:

\[ Id_{max,small} = \text{1 hour} \]
\[ Id_{max,medium} = \text{40 minutes} \]
\[ Id_{max,large} = \text{20 minutes} \]
\[ Id_{max,rupture} = \text{20 minutes} \]

The maximum leak time here includes the time to detect leakage, the time to analyze the incident and determine the corrective action, and the time to carry out the corrective action. For the reduction factor, if both systems are classified as C then there is no any release magnitude adjustment, or \(fact_{di} = 0\).

**Step 7. Determine the release rate and mass for the consequence analysis.**

All release for each hole sizes categorized as continuous type. This means that the release rate has drawn out stable at a certain rate. The release rate that is used in the analysis is the theoretical release (step 3) adjusted for the presence of unit detection and isolations as formulated in the equation below:

\[ Rate_n = W_n \left(1 - fact_{di}\right) \]

Where:

- \( Rate_n \) = release rate associated with hole sizes
- \( W_n \) = theoretical release associated with hole sizes
- \( fact_{di} \) = reduction factor.

Here is the results for each release hole sizes.

\[ Rate_{small} = 0.001927333 \text{ kg/s} \]
Rate_{medium} = 0.090034545 \text{ kg/s} \\
Rate_{large} = 0.460167685 \text{ kg/s} \\
Rate_{rupture} = 23.04312731 \text{ kg/s}

In addition to release rate, the transient mass rate must also be calculated as consideration for spontaneous output that is temporary. Mass rate estimation could be formulated in the equation:

\[
Mass_n = \min\{rate_n, Id_n\} \cdot Mass_{avail,n}
\]

(8)

Where,

\( Mass_n \) = mass rate associated with hole sizes

\( rate_n \) = release rate associated with hole sizes

\( Id_n \) = leak duration associated with hole sizes

\( Mass_{avail,n} \) = mass available for release for each size.

Before going further, the leak duration has to be estimated. To estimate the leak duration, using formula as follows:

\[
Id_n = \min \left\{ \frac{Mass_{avail,n}}{rate_n} \right\} \cdot 60 \cdot Id_{max,n}
\]

(9)

where,

\( Id_{max,n} \) = maximum leak duration for each hole size.

Here is the results of mass rate calculations:

\( Mass_{small} = 6.93839882 \text{ kgs} \)
\( Mass_{medium} = 198.697418 \text{ kgs} \)
\( Mass_{large} = 265.321383 \text{ kgs} \)
\( Mass_{rupture} = 1,220.67031 \text{ kgs} \).

**Step 8. Calculate flammable/explosive consequence.**

Calculations of flammable/explosive consequence are performed to obtain the flammable consequence area of component damage \((CA_{cmd, n}^{lam})\) and consequence area of personnel injury \((CA_{inj, n}^{lam})\). Both areas are required to determine the total consequence area. But before able to calculate both areas, energy efficiency and area mitigation reduction factor \((\text{fact}_{mit})\) have to be determined at first. \(\text{Fact}_{mit}\) is determined by referring to the classification of a mitigation system in API 581. For mitigation system, the company currently only has fire water monitor which leads to a consequence area reduction of 5%, so \(\text{Fact}_{mit} = 0.05\). For energy efficiency, using the equation (10) to calculate.

\[
eneff = 4 \cdot \log_{10} \left[ C_{AA} \cdot mass_n \right] - 15
\]

(10)

where,

\( eneff \) = energy efficiency associated with hole sizes
\( C_{AA} = 2205 \text{ l/kg} \)
\( mass_n \) = mass rate associated with release hole sizes

To obtain the flammable consequence of component damage and personnel injury, there are several values that need to be calculated first. Those are flammable consequence area of component damage in auto-ignition likely condition \((CA_{cmd, n}^{lam})\) and in auto-ignition non-likely condition \((CA_{cmd, n}^{A\text{IT}})\), flammable consequence area of personnel injury in auto-ignition likely condition \((CA_{inj, n}^{lam})\) and auto-ignition non-likely condition \((CA_{inj, n}^{A\text{IT}})\). Despite that, the operating temperature is around 185.4°C and \(\text{H}_2\text{S}\) auto-ignition temperature is 500°C, calculation of auto-ignition likely condition also needs to be conducted. The result then will be in corrective measure by adding a blending factor \((f^{A\text{IT}})\). The mathematical forms of those definitions are:

\[
CA_{cmd, n}^{lam} = CA_{cmd, n}^{A\text{IT}} \cdot f^{A\text{IT}} + CA_{cmd, n}^{A\text{IT}} \cdot (1 - f^{A\text{IT}})
\]

(11)
\[
CA_{\text{ff}} = CA_{\text{ff,n}} \cdot f_{\text{AIT}} + CA_{\text{ff,n}}^{\text{INL}} \cdot (1 - f_{\text{AIT}})
\]

where,

- \(CA_{\text{cmd,n}}^{\text{ff}}\) = flammable consequence area of component damage associated with each hole size
- \(CA_{\text{inj,n}}^{\text{ff}}\) = flammable consequence area of personnel injury associated with each hole size.

To calculate the blending factor, there are 3 conditions that should be concerned. First, if \(T_s + C_6 \leq AIT\) then \(f_{\text{AIT}} = 0\). Second, if \(T_s - C_6 \geq AIT\) then \(f_{\text{AIT}} = 1\). Third, if \(T_s + C_6 > AIT > T_s - C_6\) then \(f_{\text{AIT}}\) is calculated using:

\[
f_{\text{AIT}} = \frac{(T_s - AIT + C_6)}{2 \times C_6}
\]

where,

- \(f_{\text{AIT}}\) = blending factor
- \(T_s\) = operating temperature
- \(C_6\) = 55.6 K
- \(AIT\) = auto-ignition temperature (500°C for H₂S).

After obtaining the blending factor, the flammable consequence of component damage and personnel injury can be calculated. Here is the result for the component damage area for each hole size:

\[
\begin{align*}
CA_{\text{cmd,small}}^{\text{ff}} &= 0.019317 \text{ m}^2 \\
CA_{\text{cmd,medium}}^{\text{ff}} &= 1.166541 \text{ m}^2 \\
CA_{\text{cmd,large}}^{\text{ff}} &= 6.288756 \text{ m}^2 \\
CA_{\text{cmd,rupture}}^{\text{ff}} &= 344.6559 \text{ m}^2.
\end{align*}
\]

For personnel injury area, the results of each hole size:

\[
\begin{align*}
CA_{\text{inj,small}}^{\text{ff}} &= 0.025365 \text{ m}^2 \\
CA_{\text{inj,medium}}^{\text{ff}} &= 1.428887 \text{ m}^2 \\
CA_{\text{inj,large}}^{\text{ff}} &= 7.567999 \text{ m}^2 \\
CA_{\text{inj,rupture}}^{\text{ff}} &= 315.4428 \text{ m}^2.
\end{align*}
\]

Then the flammable consequence of component damage and personnel injury calculated using formulas:

\[
\begin{align*}
CA_{\text{cmd}}^{\text{ff}} &= \left( \frac{\sum gff_n \cdot CA_{\text{cmd,n}}^{\text{ff}}}{gff_{\text{total}}} \right) \\
CA_{\text{inj}}^{\text{ff}} &= \left( \frac{\sum gff_n \cdot CA_{\text{inj,n}}^{\text{ff}}}{gff_{\text{total}}} \right)
\end{align*}
\]

where,

- \(CA_{\text{cmd,n}}^{\text{ff}}\) = flammable consequence area of component damage associated with each hole sizes
- \(CA_{\text{inj,n}}^{\text{ff}}\) = flammable consequence area of component damage associated with each hole sizes
- \(gff_n\) = generic failure frequency for each hole sizes based on the equipment type, for small size is 8.0E-06, for medium size is 2.0E-05, for large size is 2.0E-06, for rupture size is 6.0E-07
- \(gff_{\text{total}}\) = generic failure frequency based on the type of equipment, for ko-drum vessel it is 3.06E-05.

Here is the final result of flammable consequence areas,

\[
CA_{\text{cmd}}^{\text{ff}} = 7.94 \text{ m}^2
\]
\[ CA_{\text{inj}}^{\text{lam}} = 7.62 \text{ m}^2. \]

**Step 9. Calculate toxic consequences.**

Toxic fluids are somehow similar to flammables but, not all of toxic fluids releases result in a single type effect. For example, any substance or containment like Hydrogen Fluoride (HF), chlorine (Cl), and ammonia (NH\(_3\)), normally cause only toxic hazard. Meanwhile, some toxic materials such as Hydrogen Sulfide (H\(_2\)S) is categorized as both toxic and flammable consequence. Because both of NH\(_3\) and H\(_2\)S present in the fluids then both calculations should be done. First the effective duration of toxic release must be calculated as:

\[
ld_{n}^{\text{tox}} = \min\left(3000, \left\{ \frac{\text{mass}_n}{W_n} \right\}, \left\{ 60 \cdot ld_{\text{max},n} \right\} \right)
\] (16)

where,
- \( ld_{n}^{\text{tox}} \) = toxic release effective duration for each sizes
- \( Mass_n \) = mass rate associated with hole sizes
- \( Id_{\text{max},n} \) = maximum release duration for each hole sizes.

The next step is to calculate toxic release rate and toxic mass rate for both NH\(_3\) and H\(_2\)S. Using formula as follow:

\[
rate_{n}^{\text{tox}} = \text{mfrac}_{n}^{\text{tox}} \cdot W_n
\] (17)

Where,
- \( rate_{n}^{\text{tox}} \) = toxic release rate associated with hole sizes
- \( mfrac_{n}^{\text{tox}} \) = toxic substance percentage of released fluid
- \( W_n \) = theoretical release for each hole sizes.

Toxic release rate and mass rate are utilized to estimate the toxic consequence area for each hole sizes. For continuous release, using the formula 18 for NH\(_3\) and formula 19 for H\(_2\)S:

\[
CA_{\text{inj},n}^{\text{tox\,CONT}} = e^{(Rate_{n}^{\text{tox}})^f} \] (18)

\[
CA_{\text{inj},n}^{\text{tox\,CONT}} = C_8 \cdot 10^{(c \cdot \log_{10}[C_{AB} \cdot rate_{n}^{\text{tox}}] + d)} \] (19)

where,
- \( CA_{\text{inj},n}^{\text{tox\,CONT}} \) = toxic consequence area for continuous release associated with hole sizes
- \( Rate_{n}^{\text{tox}} \) = toxic release rate for each hole sizes
- \( C_8 \) = 0.0929 m\(^2\) sec
- \( C_{AB} \) = 2.25 sec/kg
- \( c, d, e \) and \( f \) = constants associated with release duration. The constants of \( c, d, e \) and \( f \) for H\(_2\)S and NH\(_3\) are shown in Table 4.

**Table 4. Constants for toxic consequence calculations**

| Continuous release duration (minutes) | H\(_2\)S | NH\(_3\) |
|--------------------------------------|---------|---------|
|                                      | \( c \) | \( d \) | \( e \) | \( f \) |
| 20                                   | 1.237   | 4.238   | 1256    | 1.178   |
| 40                                   | 1.2297  | 4.3626  | 2029    | 1.169   |
| 60                                   | 1.2266  | 4.4365  | 2714    | 1.145   |

Continuing to calculate of toxic consequence area for each hole size, the total toxic consequence area is estimated using equation (20):
\[ CA_{\text{inj}}^{\text{tox}} = \left( \frac{\sum gff_n \cdot CA_{\text{inj},n}^{\text{tox}}}{gff_{\text{total}}} \right) \]  

where,
- \( CA_{\text{inj},n}^{\text{tox}} \) = toxic consequence area of personnel injury
- \( CA_{\text{inj},n}^{\text{tox}} \) = toxic consequence area for each hole size
- \( gff_n \) = generic failure frequency for each hole size
- \( gff_{\text{total}} \) = generic failure frequency total

Here is the result of calculation of toxic consequence, \( CA_{\text{inj}}^{\text{tox}} = 10.43 \text{ m}^2 \).

**Step 10. Calculate non-flammable, non-toxic consequence.**

Presence of steam and acid-caustic substances which are not flammable and toxic also has its consequences. For this case, there is no any acid-caustic categorized substance in the fluids, but there is steam. Steam represents a hazard to personnel who are exposed to it at high temperatures. In general, steam is at 100°C (212°F) immediately after exiting a hole in an equipment item. Within a few feet, the steam will begin to mix with cool air and condensed. The approach used here is that injury occurs above 60°C (140°F). The operating temperature of steam scrubber (VS-81-009) is working around 185.4°C. So, if the steam leaks it will impact the surrounding area. To calculate the non-flammable and non-toxic consequence area, the consequence for each hole sizes must be calculated as:

\[ CA_{\text{inj},n}^{\text{CONT}} = (C_9 \cdot Rate_n) \]  

\[ CA_{\text{inj},n}^{\text{INST}} = (C_{10} \cdot Mass_n)^{0.6384} \]  

where,
- \( CA_{\text{inj},n}^{\text{CONT}} \) = non-flammable non-toxic consequence area of each hole sizes for continuous release
- \( CA_{\text{inj},n}^{\text{INST}} \) = non-flammable non-toxic consequence area of hole sizes for transient instantaneous release
- \( C_9 = 0.123 \text{ m}^2 \cdot \text{sec/kg} \)
- \( C_{10} = 9.744 \text{ m}^2/\text{kg}^{0.6384} \)
- \( Mass_n \) = mass rate associated with hole sizes.
- \( Rate_n \) = release rate associated with hole sizes.

Then the consequence of each hole sizes combined with blending factor. Using formulas as follow:

\[ f_{act\text{IC}} = min \left( \left[ \frac{rate_n}{C_5} \right], 1.0 \right) \]  

\[ CA_{\text{inj},n} = CA_{\text{inj},n}^{\text{INST}} \cdot f_{act\text{IC}} + CA_{\text{inj},n}^{\text{CONT}} \cdot (1 - f_{act\text{IC}}) \]  

where,
- \( f_{act\text{IC}} \) = blending factor associated with hole sizes
- \( C_5 = 25.2 \text{ kg/sec} \)
- \( CA_{\text{inj},n}^{\text{leak}} \) = personnel injury consequence of steam leaks.

Despite the continuous type of release, the instant release calculation is still carried out as a consideration of the temporary instant output and for blending. For non-flammable and non-toxic especially steam, the consequence area to damaged component is 0. Continuing to calculate the consequence area for each leak hole sizes, the total non-flammable and non-toxic consequence area is estimated using formula:

\[ CA_{\text{inj}}^{\text{nontnt}} = \left( \frac{\sum gff_n \cdot CA_{\text{inj},n}^{\text{leak}}}{gff_{\text{total}}} \right) \]
where,
\[ CA_{inj}^{nft} = \text{non-flammable and non-toxic consequence area for personnel injury} \]
\[ gff_n = \text{generic failure frequency for each hole sizes} \]
\[ gff_{total} = \text{generic failure frequency total} \]
The result of calculations of consequence, \( CA_{inj}^{nft} = 0.0634 \text{ m}^2 \).

**Step 11. Determine the final probability weighted component damage and personnel injury consequence of areas.**

For consequences on components, because there is the only flammable consequence, the value is the same as the flammable consequences of component damages.

\[ CA_{cmd} = CA_{cmd}^{flam} \]  
(26)

where,
\[ CA_{cmd} = \text{consequence area of component damages} \]
\[ CA_{cmd}^{flam} = \text{flammable consequence of component damages.} \]

As for the personnel impact, several consequences affect the flammable consequences of personnel, toxicity, as well as non-flammable and non-toxic. Three values are chosen with the highest value of:

\[ CA_{inj} = \max \left[ CA_{inj}^{flam}, CA_{inj}^{tox}, CA_{inj}^{nft} \right] \]  
(27)

where,
\[ CA_{inj} = \text{consequence area of personnel injury} \]
\[ CA_{inj}^{flam} = \text{flammable consequence of personnel injury} \]
\[ CA_{inj}^{tox} = \text{toxic consequence of personnel injury} \]
\[ CA_{inj}^{nft} = \text{non-flammable non-toxic consequence of personnel injury.} \]

The results of step 11 calculations are following,
\[ CA_{cmd} = 7.94 \text{ m}^2 \]
\[ CA_{inj} = 10.43 \text{ m}^2 \]

**Step 12. Total consequence of areas.**

Total consequence of areas is the maximum values of both consequence on component damage and personnel injury. The definition then formulated to:

\[ CA = \max \left[ CA_{cmd}, CA_{inj} \right] \]  
(28)

Finally, the total of consequence of areas (CA) is 10.43 m2

### 3.4 Inspection Plan

Inspection planning refers to the target set by the company which is a DF (damage factor) target of 100. Therefore, an inspection plan was carried out to prevent damage factors from component exceeding 100. A summary calculation of the steam scrubber shell is shown in Table 5.

From the data in Table 5, plotting the risk level of the shell of steam scrubber (VS-81-009) on the RBI date is medium risk. The risk matrix at the RBI date of the shell section of VS-81-009 shown in Figure 2. To get the target inspection date, obtained by simulating the age of the scrubber after carrying out the RBI date to exceed the damage factor target. Figure 3 shows the comparison between damage factor and time of VS-81-009.
### Table 5. Calculation results of VS-81-009

| Date                  | Damage factor | Probability of Failure | Consequence of Failure | Risk (m²/year) |
|-----------------------|---------------|------------------------|------------------------|----------------|
| July 3rd, 2014        | Last inspection | 50.241                 | 0.0002804              | 0.002924572    |
| July 1st, 2019        | RBI date      | 293.498                | 0.001638               | 0.01708434     |
| July 1st, 2023        | Plan date     | 492.328                | 0.0027493              | 0.028675199    |

Note: Inspection effectiveness level E

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**Figure 2.** The risk matrix at the RBI date of the shell section of VS-81-009

**Figure 3.** Damage Factor (DF) to time of VS-81-009

The date format for Figure 3 is day/month/year. The blue line in Figure 3 is the damage factor of the steam scrubber shell if no inspection is carried out. The orange line is the target damage factor. While the grey line is the damage factor of the steam scrubber if it is inspected as soon as possible. Immediate inspection is advised because, on the RBI date, the DF component has far exceeded the risk target. If there is immediate inspection, then the component will reach the target on May 16th, 2021.

### 4. Conclusions

Based on the analysis, it is recommended to carry out direct inspection for the shell part of the steam scrubber (VS-81-009). According to RBI date calculations, component conditions have exceeded the
target parameters. Therefore, it needs to be inspected immediately. For further inspection, if the inspection is carried out immediately then the component will reach the risk target again on May 16, 2021. It is recommended to carry out an inspection using radiography or ultrasonic scanning.

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