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Risk Based Inspection of Gas-Cooling Heat Exchanger

Dwi Priyanta[1], Nurhadi Siswantoro[2], Alfa Muhammad Megawan[3]

***Abstract*— PHE – ONWJ platform personnel found 93 leaking tubes locations in the fin fan coolers/ gas-cooling heat exchanger. After analysis had been performed, the crack in the tube strongly indicate that stress corrosion cracking was occurred by chloride. Chloride stress corrosion cracking (CLSCC) is the cracking occurred by the combined influence of tensile stress and a corrosive environment. CLSCC is the one of the most common reasons why austenitic stainless steel pipework or tube and vessels deteriorate in the chemical processing, petrochemical and maritime industries. In this research purpose to determine the appropriate inspection planning for two main items (tubes and header box) in the gas-cooling heat exchanger using risk based inspection (RBI) method. The result, inspection of the tubes must be performed on July 6, 2024 and for the header box inspection must be performed on July 6, 2025. In the end, RBI method can be applicated to gas-cooling heat exchanger. Because, risk on the tubes can be reduced from 4.537 m^2/year to 0.453 m^2/year. And inspection planning for header box can be reduced from 4.528 m^2/year to 0.563 m^2/year.**

Keywords— chloride stress corrosion cracking, inspection plan, RBI.

I. Introduction[1]

On October, 2013, Pertamina Hulu Energi Offshore North West Java (PHE – ONWJ) platform personnel found 93 leaking tubes reported in gas cooling heat exchanger on the one of Pertamina platform (Figure 1). This situation made the gas cooling heat exchanger not in a good performance. Furthermore PHE-ONWJ need effective maintenance strategy for oil and gas platform equipment especially for gas cooling heat exchanger.

According to the function of heat exchangers, there are view types of heat exchangers used in oil and gas facility, they are; shell and tube, double pipe, plate and frame, aerial cooler, bath type, forced air, and direct fired [1].

Based on the explanation above, Pertamina PHE-ONWJ gas cooling heat exchanger classified as areal cooler heat exchanger because its function is cooling the gas with a fan in to near ambient temperature.

Heat exchanger is the one of crucial equipment in the processing facility especially in the oil and gas industry sector. Heat exchanger is used to transfer heat between one and more fluids. Ones of heat exchanger application is for cooling the gas before injected to the oil reservoir. Gas injection is the method to increase oil production by boosting depleted pressure in the reservoir (figure 2). Another function of gas cooling heat exchanger is for cooling the gas before supply the gas turbine to generated electric power on the platform

American Petroleum Institute (API) is the one of the most widely used standard guideline in oil and gas company around the world besides DNV-GL.

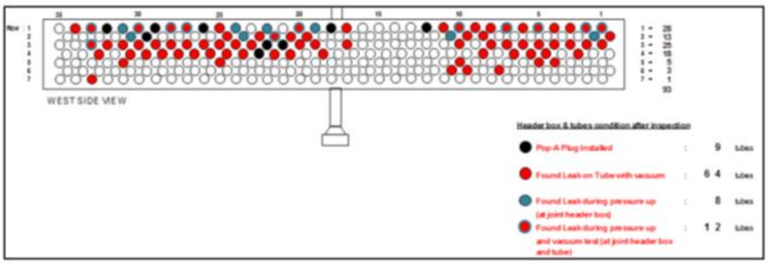

Figure. 1. Gas-cooling heat exchanger leakage report (Company report, 2013)
Source: Pertamina PHE-ONWJ inspection report, 2013

PHE ONWJ platform adopt guidelines from API 660 and API 661 for gas cooling heat exchanger fabrication and installation. One of maintenance strategies for gas cooling heat exchanger can be developed by using Risk Based Inspection (RBI). by using RBI company will get information using risk analysis to develop an effective inspection plan.

[1]Dwi Priyanta, Department of Marine Engineering, Institut Teknologi Sepuluh Nopember, Surabaya, 60111, Indonesia.
Email: priyanta@its.ac.id
[2]Nurhadi Siswantoro, Department of Marine Engineering, Institut Teknologi Sepuluh Nopember, Surabaya, 60111, Indonesia.
Email: nurhadisukses@gmail.com
[3]Alfa Muhammad Megawan of Marine Engineering, Institut Teknologi Sepuluh Nopember, Surabaya, 60111, Indonesia
Email: alfamuhammad@gmail.com.

Identification of company equipment is the beginning of the systematic process in the inspection planning. Probability of failure and consequence of failure are the basic formula to calculate the RBI and must be evaluated by considering all damage mechanism directly effect to the equipment or the system. However, failure scenarios according to the actual damage mechanism should be develop and considered.

RBI methodology produces optimal inspection planning for the asset and make the priority from the lower risk to the higher risk. In other word inspection planning in RBI focused to identification what to inspect, how to inspect, where to inspect and how often to inspect. Inspection planning used to control degradation of the asset and the company will get considerable impact in the system operation and the appropriate economic consequences [2-18].

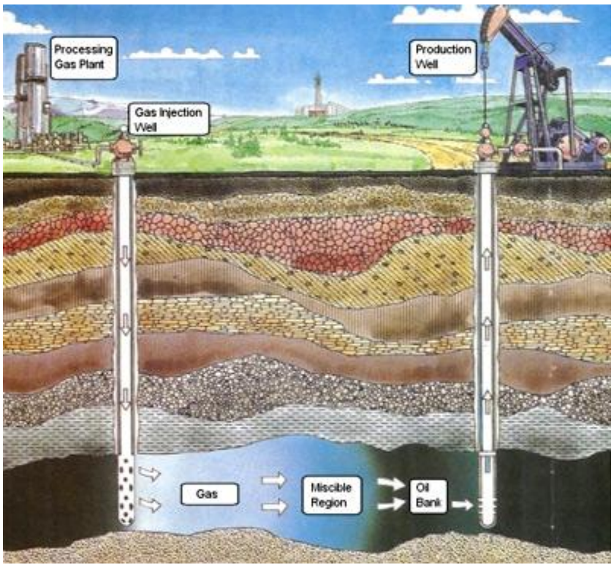

Figure. 2. optimization oil production by gas injection method

II. Method

The information of inspection planning in risk based inspection based on the risk analysis of the equipment. The purpose of the risk analysis is to identify the potential degradation mechanisms and threats to the integrity of the equipment and to assess the consequences and risk of failure [3].

A. Risk

Risk is defined as the combination probability of asset failure and consequence if the failure happened. Risk can be expressed numerically with formula (1) as shown below.

$$Risk = Probability \times Consequence \quad (1)$$

Probability of Failure

The probability of failure may be determined based on one, or a combination of the following methods:

- *Structural reliability models*

In this method, a limit state is defined based on a structural model that includes all relevant damage mechanisms, and uncertainties in the independent variables of this models are defined in terms of statistical distributions. The resulting model is solved directly for the probability of failure.

- *Statistical models based on generic data*

In this method, generic data is obtained for the component and damage mechanism under evaluation and a statistical model is used to evaluate the probability of failure.

- *Expert judgment*

In this method, expert solicitation is used to evaluate the component and damage mechanism, a probability of failure can typically only be assigned on a relative basis using this method.

In API RBI, a combination of the above is used to evaluate the probability of failure in terms of a generic failure frequency and damage factor. The probability of failure calculation is obtained from the equation (2).

$$Pof(t) = gff \times Df(t) \times FMS \quad (2)$$

Where:
gff = generic failure frequency
Df (t) = damage factor
FMS = management system factor

B. Generic Failure Frequency (gff)

The generic failure frequency can be determined by asset failure of common industries. The generic failure frequency is expected to the previous failure frequency to any specific damage happening from exposure to the operating environment. There are four different damage hole sizes model the release scenarios covering a full range of events they are small, medium, large, and rupture.

If the data of the asset is complete, actual probabilities of the failure could be calculated with actual observed failures. Even if a failure has not occurred in a component, the true probability of failure is likely to be greater than zero because the component may not have operated long enough to experience a failure. As a first step in estimating this non-zero probability, it is necessary to examine a larger set of data of similar components to find enough failures such that a reasonable estimate of a true probability of failure can be made.

This generic component set of data is used to produce a generic failure frequency for the component. The generic failure frequency of a component type is estimated using records from all plants within a company or from various plants within an industry, from literature sources, and commercial reliability data bases. Therefore, these generic values typically represent an industry in general and do not reflect the true failure frequencies for a specific component subject to a specific damage mechanism.

The generic failure frequency is intended to be the failure frequency representative of failures due to degradation from relatively benign service prior to accounting for any specific operating environment, and are provided for several discrete hole sizes for various types of processing equipment (i.e. process vessels, drums, towers, piping systems, tankage, etc.).

A recommended list of generic failure frequencies is provided in Table 1. The generic failure frequencies are assumed to follow a log-normal distribution, with error rates ranging from 3% to 10%. Median values are given in Table 1. The data presented in the Table 1 is based on the best available sources and the experience of the API RBI Sponsor Group.

The overall generic failure frequency for each component type was divided across the relevant hole sizes, i.e. the sum of the generic failure frequency for each hole size is equal to the total generic failure frequency for the component.

TABLE 1
SUGGESTED COMPONENT GENERIC FAILURE FREQUENCIES (GFF)

Equipment type	**Component type**	***gff* as a Function of Hole Size (failures/yr)**				***gff(total)***
		Small	**Medium**	**Large**	**Rupture**	**(failures/yr)**
Pipe	PIPE-1	2.80E-05	0	0	2.60E-06	3.06E-05
Vessel/ FinFan	FINFAN	8.00E-06	2.00E-05	2.00E-06	6.00E-07	3.06E-05

C. *Management System Factor*

Management system factor used to measure how good the facility management system that may arise due to an accident and labor force of the plant is trained to handle the asset. This evaluation consists of a series of interviews with plant management, operations, inspection, maintenance, engineering, training, and safety personnel.

The management systems evaluation procedure developed for API RBI covers all areas of a plant's PSM system that impact directly or indirectly on the mechanical integrity of process equipment. The management systems evaluation is based in large part on the requirements contained in API Recommended Practices and Inspection Codes. It also includes other proven techniques in effective safety management. A listing of the subjects covered in the management systems evaluation and the weight given to each subject is presented in Table 2.

The management systems evaluation covers a wide range of topics and, as a result, requires input from several different disciplines within the facility to answer all questions. Ideally, representatives from the following plant functions should be interviewed:

a) Plant Management
b) Operations
c) Maintenance
d) Safety
e) Inspection
f) Training
g) Engineering

The scale recommended for converting a management systems evaluation score to a management systems factor is based on the assumption that the "average" plant would score 50% (500 out of a possible score of 1000) on the management systems evaluation, and that a 100% score would equate to a one order-of magnitude reduction in total unit risk. Based on this ranking, equation (3) and equation (4) may be used to compute a management systems factor, F_{MS}, for any management systems evaluation score.

TABLE 2
MANAGEMENT SYSTEMS EVALUATION

Table	Title	Questions	Points
2.A.1	Leadership and Administration	6	70
2.A.2	Process Safety Information	10	80
2.A.3	Process Hazard Analysis	9	100
2.A.4	Management of Change	6	80
2.A.5	Operating Procedures	7	80
2.A.6	Safe Work Practices	7	85
2.A.7	Training	8	100
2.A.8	Mechanical Integrity	20	120
2.A.9	Pre-Startup Safety Review	5	60
2.A.10	Emergency Response	6	65
2.A.11	Incident Investigation	9	75
2.A.12	Contractors	5	45
2.A.13	Audits	4	40
Total		**102**	**1000**

*Note that the management score must first be converted to a percentage (between 0 and 100) as follows:

$$pscore = \frac{Score}{1000}\ x\ 100\ [unit\ is\ \%] \quad (3)$$

$$F_{MS} = 10^{(-0.01 pscore+1)} \quad (4)$$

D. Thinning Damage Factor

The calculation procedures of thinning damage factor are:

a) Determine the number of inspections, and the corresponding inspection effectiveness category for all past inspections. Combine the inspections to the highest effectiveness performed.
b) Determine the time in-service (*age)* since the last inspection thickness reading (t_{rd}).
c) Determine the corrosion rate for the base metal ($C_{r,bm}$) based on the material of construction and process environment, where the component has cladding, a corrosion rate ($C_{r,cm}$) must also be obtained for the cladding.
d) Determine the minimum required wall thickness (t_{min}) per the original construction code or using API 579. If the component is a tank bottom, then in accordance with API 653 (t_{min} = 0.1 in) if the tank does not have a release prevention barrier and (t_{min} = 0.05 in) if the tank has a release prevention barrier.
e) For clad components, calculate the time or age from the last inspection required to corrode away the clad material, age_{rc} , using equation (5).

$$age_{rc} = \max\left[\left(\frac{t_{rd}-t}{C_{r,cm}}\right), 0.0\right] = N/A \quad (5)$$

f) Determine the A_{rt} parameter using Equation below, based on the age and from step b, from step c, from step d and the age required to corrode away the cladding, age_{rc}, if applicable from step e. For components without cladding, and for components where the cladding is corroded away at the time of the last inspection (i.e. age_{rc} = 0.0), use Equation (6).

$$A_{rt} = \max\left[1 - \frac{t_{rd} - C_{r,cm} \cdot age}{t_{min} + CA}, 0.0\right] \quad (6)$$

g) Determine the damage factor for thinning, D_f^{thin}, using Equation (2.13).

$$D_f^{thin} = \frac{D_{fB}^{thin} \cdot F_{IP} \cdot F_{DL} \cdot F_{WD} \cdot F_{AM} \cdot F_{SM}}{F_{OM}} \quad (7)$$

E. Stress Corrosion Cracking Damage Factor

The calculation procedures of chloride stress corrosion cracking (CL-SCC) damage factor are:

a) Determine the number of inspections, and the corresponding inspection effectiveness category for all past inspections. Combine the inspections to the highest effectiveness performed.
b) Determine the time in-service (*age)* since the last *Level A*, *B*, *C* or *D* inspection was performed.
c) Determine the susceptibility for cracking using Table 3 based on the operating temperature and concentration of the chloride ions. Note that a HIGH susceptibility should be used if cracking is known to be present.

TABLE 3
SUSCEPTIBILITY TO CRACKING – CLSCC

pH ≤ 10				
Temperature (°C)	**Susceptibility to Cracking as a Function of Chloride ion (ppm)**			
	1-10	**11-100**	**101-1000**	**>1000**
38 – 66	Low	Medium	Medium	High
>66 – 93	Medium	Medium	High	High
>93 – 149	Medium	High	High	High
pH > 10				
Temperature (°C)	**Susceptibility to Cracking as a Function of Chloride ion (ppm)**			
	1-10	**11-100**	**101-1000**	**>1000**
< 93	Low	Low	Low	Low
93 -149	Low	Low	Low	Medium

TABLE 4
DETERMINATION OF SEVERITY INDEX – CLSCC

Susceptibility	**Severity Index – S_{VI}**
High	5000
Medium	500
Low	50
None	1

d) Based on the susceptibility in step c, and determine the severity index, S_{VI} from table (4).

e) Determine the base damage factor for CLSCC, D_{fb}^{CLSCC} using table (5) based on the number of, and the highest inspection effectiveness determined in step a, and the severity index, S_{VI}, from step d.

f) Calculate the escalation in the damage factor based on the time in-service since the last inspection using the *age* from step b and equation below. In this equation, it is assumed that the probability for cracking will increase with time since the last inspection as a result of increased exposure to upset conditions and other non-normal conditions.

$$D_f^{CLSCC} = D_{fB}^{CLSCC} (\text{age})^{1.1} \quad (8)$$

TABLE 5
SCC DAMAGE FACTORS – ALL SCC MECHANISMS

S_{VI}	E	Inspection Effectiveness											
		1 Inspection				**2 Inspections**				**3 Inspections**			
		D	**C**	**B**	**A**	**D**	**C**	**B**	**A**	**D**	**C**	**B**	**A**
1	1	1	1	1	1	1	1	1	1	1	1	1	1
10	10	8	3	1	1	6	2	1	1	4	1	1	1
50	50	40	17	5	3	30	10	2	1	20	5	1	1
100	100	80	33	10	5	60	20	4	1	40	10	2	1
500	500	400	170	50	25	300	100	20	5	200	50	8	1
1000	1000	800	330	100	50	600	200	40	10	400	100	16	2
5000	5000	4000	1670	500	250	3000	1000	250	50	2000	500	80	10

F. Consequence Analysis

The calculations of consequence procedures are:

a) Select a representative fluid group from Table 6.

b) Determine the stored fluid properties using equation (9) and Table 7 (MW: Molecular weight; k: ideal gas specific ratio, AIT: Auto Ignition Temperature).

$$k = \frac{C_p}{C_p - R} \quad (9)$$

c) Determine the steady state phase of the fluid after release to the atmosphere, using Table 8 and the phase of the fluid stored in the equipment as determined in step b.

d) Based on the component type and Table 9, determine the release hole size diameters (d_n).

e) Determine the generic failure frequency (gff_n), and the total generic failure frequency from this table or from equation (10).

$$gff_{total} = \sum_{n-1}^{4} gff_n \quad \textbf{(10)}$$

TABLE 6
LIST OF REPRESENTATIVE FLUIDS AVAILABLE FOR LEVEL 1 ANALYSIS

Representative Fluid	Fluid TYPE	Examples of Applicable Materials
C_1 -C_2	TYPE 0	methane, ethane, ethylene, LNG, fuel gas
C_3 -C_4	TYPE 0	propane, butane, isobutane, LPG
C_5	TYPE 0	Pentane
C_6 -C_8	TYPE 0	gasoline, naptha, light stright run, heptane
C_9 -C_{12}	TYPE 0	diesel, kerosene
C_{13} -C_{16}	TYPE 0	jet fuel, kerosene, atmospheric gas oil
C_{17} -C_{25}	TYPE 0	gas oil, typical crude

TABLE 7
PROPERTIES OF THE REPRESENTATIVE FLUIDS USED IN LEVEL 1 ANALYSIS

Fluid	MW	Liquid Density (kg/m³)	NBP (°C)	Ambient State	Ideal Gas Specific Heat Eq.	Cp: Ideal Gas Constant *A*	Cp: Ideal Gas Constant *B*	Cp: Ideal Gas Constant *C*	Cp: Ideal Gas Constant *D*	Cp: Ideal Gas Constant *E*	Auto-Ignition Temp. (°C)
C_1 -C_2	23	250.512	-125	Gas	Note 1	12.3	1.15E-01	-2.87E-05	-1.30E-09	N/A	558
C_3 -C_4	51	538.379	-21	Gas	Note 1	2.632	0.3188	-1.35E+04	1.47E-08	N/A	369
C_5	72	625.199	36	Liquid	Note 1	-3.626	0.4873	-2.60E-04	5.30E-08	N/A	284
C_6 -C_8	100	684.018	99	Liquid	Note 1	-5.146	6.76E-01	-3.65E-04	7.66E-08	N/A	223
C_9 -C_{12}	149	734.012	184	Liquid	Note 1	-8.5	1.01E+00	-5.56E-04	1.18E-07	N/A	208
C_{13} -C_{16}	205	764.527	261	Liquid	Note 1	-11.7	1.39E+00	-7.72E-04	1.67E-07	N/A	202
C_{17} -C_{25}	280	775.019	344	Liquid	Note 1	-22.4	1.94E+00	-1.12E-03	-2.53E-07	N/A	202
C_{25+}	422	900.026	527	Liquid	Note 1	-22.4	1.94E+00	-1.12E-03	-2.53E-07	N/A	202

TABLE 8
CONSEQUENCE ANALYSIS GUIDELINES FOR DETERMINING THE PHASE OF A FLUID

Phase of Fluid at Normal Operating (Storage) Conditions	Phase of Fluid at Ambient (after release) Conditions	API RBI Determination of Final Phase for Consequence Calculation
Gas	Gas	model as gas
Gas	Liquid	model as gas
Liquid	Gas	model as gas *unless* the fluid boiling point at ambient conditions is greater than 80°F, then model as a liquid
Liquid	Liquid	model as liquid

TABLE 9
RELEASE HOLE SIZES AND AREA USED

Release Hole Number	Release Hole Size	Range of Hole Diameters (mm)	Release Hole Diameter, d_n (mm)
1	Small	0 – 6.4	D_1 = 6.4
2	Medium	>6.4 – 51	D_2 = 25
3	Large	>51 – 152	D_3 = 102
4	Rupture	>152	D_4 = min[D, 406]

f) Select the appropriate release rate equation as described above using the stored fluid phase
g) For each release hole size, compute the release hole size area (A_n) using equation (11).

$$A_n = \frac{\pi d_n^2}{4} \quad (11)$$

h) For each release hole size, calculate the release rate (W_n) with equation (12) for each release area (A_n)

$$W_n = \frac{C_d}{C_2} \times A_n \times P_s \times \sqrt{\left(\frac{k \times MW \times g_c}{R \times T_s}\right) x \left(\frac{2}{k+1}\right)^{\frac{k}{k-1}}} \quad (12)$$

i) Group components and equipment items into inventory groups using Table 10.
j) Calculate the fluid mass ($mass_{comp}$) in the component being evaluated.
k) Calculate the fluid mass in each of the other components that are included in the inventory group ($mass_{comp,i}$).
l) Calculate the fluid mass in the inventory group ($mass_{inv}$) using Equation (13).

$$mass_{inv} = \sum_{i=1}^{N} mass_{comp,i} \quad (13)$$

TABLE 10
ASSUMPTION WHEN CALCULATING LIQUID INVENTORIES WITHIN EQUIPMENT

Equipment Description	Component Type	Examples	Default Liquid Volume Percent
Knock-out Pots and Dryers	KODRUM	Compressor Knock-outs, Fuel Gas KO Drums, Flare Drums, Air Dryers.	10% liquid Much less liquid inventory expected in knock-out drums
Compressors	COMPC COMPR COMPR	Centrifugal and Reciprocating Compressors	Negligible, 0%
Heat Exchangers	HEXSS HEXTS	Shell and Tube Heat Exchangers	50% shell-side, 25% tube-side
Fin Fan Air Coolers	FINFAN	Total Condensers, Partial Condensers, Vapor Coolers and Liquid Coolers	25% liquid
Filters	FILTER		100% full
Piping	PIPE-xx		100% full, calculated for Level 2 Analysis

m) Calculate the flow rate from a 203 mm [8 in] diameter hole (W_{max8}) using equations above, as applicable, with $A_n = A_8 = 32{,}450$ mm^2 [50.3 in^2]. This is the maximum flow rate that can be added to the equipment fluid mass from the surrounding equipment in the inventory group.

n) For each release hole size, calculate the added fluid mass ($mass_{add,n}$) with equation (14) resulting from three minutes of flow from the inventory group using equation below where W_n is the leakage rate for the release hole size being evaluated and W_{max8} is from last step.

$$mass_{add,n} = 180 \cdot \min\left[W_n , W_{max8}\right] \quad (14)$$

o) For each release hole size, calculate the available mass for release using equation (15).

$$Mass_{avail,n} = \min[\{mass_{comp} + mass_{add,n}\}, mass_{inv}] \quad (15)$$

p) For each release hole size, calculate the time required to release 4,536 kgs [10,000 lbs] of fluid.

$$t_n = \frac{C_3}{W_n} \quad (16)$$

q) For each release hole size, determine if the release type is instantaneous or continuous using the following criteria.
- If the release hole size is 6.35 mm [0.25 inches] or less, then the release type is continuous.
- If 180 $t_n \leq sec$ or the release mass is greater than 4,536 kgs [10,000 lbs], then the release is instantaneous; otherwise, the release is continuous

r) Determine the detection and isolation systems present in the unit.

s) Using Table 11 select the appropriate classification (A, B, C) for the detection system.

TABLE 11
DETECTION AND ISOLATION SYSTEM RATING GUIDE

Type of Detection System	Detection Classification
Instrumentation designed specifically to detect material losses by changes in operating conditions (i.e., loss of pressure or flow) in the system	A
Suitably located detectors to determine when the material is present outside the pressure-containing envelope	B
Visual detection, cameras, or detectors with marginal coverage	C
Type of Isolation System	**Isolation Classification**
Isolation or shutdown systems activated directly from process instrumentation or detectors, with no operator intervention	A
Isolation or shutdown systems activated by operators in the control room or other suitable locations remote from the leak	B
Isolation dependent on manually-operated valves	C

TABLE 12
ADJUSTMENTS TO RELEASE BASED ON DETECTION AND ISOLATION SYSTEMS

System Classifications		Release Magnitude Adjustment	Reduction Factor, $fact_{di}$
Detection	**Isolation**		
A	A	Reduce release rate or mass by 25%	0.25
A	B	Reduce release rate or mass by 20%	0.20
A or B	C	Reduce release rate or mass by 10%	0.10
B	B	Reduce release rate or mass by 15%	0.15
C	C	No adjustment to release rate to mass	0.00

TABLE 13
LEAK DURATIONS BASED ON DETECTION AND ISOLATION SYSTEMS

Detecting System Rating	Isolation System Rating	Maximum Leak Duration, ld_{max}
A	A	20 minutes for 6.4 mm leaks
		10 minutes for 25 mm leaks
		5 minutes for 102 mm leaks
A	B	30 minutes for 6.4 mm leaks
		20 minutes for 25 mm leaks
		10 minutes for 102 mm leaks
A	C	40 minutes for 6.4 mm leaks
		30 minutes for 25 mm leaks
		20 minutes for 102 mm leaks
B	A or B	40 minutes for 6.4 mm leaks
		30 minutes for 25 mm leaks
		20 minutes for 102 mm leaks

t) Using Table 11 select the appropriate classification (A, B, C) for the isolation system.

u) Using Table 12 and the classifications determined in step s & t, determine the release reduction factor, $fact_{di}$.

v) Using Table 13 and the classifications determined in step s & t, determine the total leak durations for each of the selected release hole sizes, $ld_{max,n}$.

w) For each release hole size, calculate the adjusted release rate ($rate_n$) using equation (17) where the theoretical release rate (W_n).

$$rate_n = W_n(1-fact_{di}) \quad (17)$$

x) For each release hole size, calculate the leak duration (ld_n) of the release using Equation 4.13, based on the available *mass* ($mass_{avail,n}$), and the adjusted release rate ($rate_n$) from step. Note that the leak duration cannot exceed the maximum duration ($Id_{max,n}$) determined in step w.

$$ld_n = min\left[\left\{\frac{mass_{avail,n}}{rate_n}\right\}, \left\{60 x ld_{max,n}\right\}\right] \quad (18)$$

y) For each release hole size, calculate the release mass ($mass_n$), using equation (19) based on the release rate ($rate_n$), the leak duration (ld_n), and the available mass ($mass_{avail,n}$).

$$mass_n = min\ [\{rate_n\ .\ ld_n\}\ ,\ mass_{avail,n}] \quad (19)$$

z) Select the consequence area mitigation reduction factor ($fact_{mit}$) from Table 14.

aa) b For each release hole size, calculate the energy efficiency correction factor, ($eneff_n$) using equation below.

$$eneff_n = 4\ x\ log_{10}\left[C_4\ x\ mass_n\right] - 15 \quad (20)$$

bb) Determine the fluid type, either TYPE 0 or TYPE 1 from Table 6.

cc) For each release hole size, compute the component damage consequence areas for Autoignition Not Likely, Continuous Release (AINL-CONT) $\left(CA_{cmd,n}^{AINL-CONT}\right)$.

- Determine the appropriate constants *a* ($a_{cmd}^{AIL-CONT}$) and *b* ($b_{cmd}^{AIL-CONT}$) from the Table 15 will be needed to assure selection of the correct constants.
- If the release is a gas or vapor and the fluid type is TYPE 0, then use equation (21) for the consequence area and for the release rate.

$$CA_{cmd,n}^{AINL-CONT} = a(rate_n)^b \ \ x \ \ (1 - fact_{mit}) \quad (21)$$

TABLE 14
ADJUSTMENTS TO FLAMMABLE CONSEQUENCES FOR MITIGATION SYSTEMS

Mitigation System	**Consequence Area Adjustment**	**Consequence Area Reduction Factor (factmit)**
Inventory blowdown, coupled with isolation system classification B or higher	Reduce consequence area by 25%	0.25
Fire water deluge system and monitors	Reduce consequence area by 20%	0.20
Fire water monitors only	Reduce consequence area by 5%	0.05
Foam spray system	Reduce consequence area by 15%	0.15

TABLE 15
COMPONENT DAMAGE FLAMMABLE CONSEQUENCE EQUATION CONSTANTS

Fluid	**Continuous Releases Constants**							
	Auto-Ignition Not Likely (CAINL)				**Auto-Ignition Likely (CAIL)**			
	Gas		Liquid		Gas		Liquid	
	a	*b*	*a*	*B*	*A*	*b*	*a*	*B*
C_1 -C_2	8.669	0.98			55.13	0.95		
C_3 -C_4	10.13	1.00			64.23	1.00		
C_5	5.115	0.99	100.6	0.89	62.41	1.00		
C_6 -C_8	5.846	0.98	34.17	0.89	63.98	1.00	103.4	0.95
C_9 -C_{12}	2.419	0.98	24.6	0.90	76.98	0.95	110.3	0.95
C_{13} -C_{16}			12.11	0.90			196.7	0.92
C_{17} -C_{25}			3.785	0.90			165.5	0.92
C_{25+}			2.098	0.91			103.0	0.90
Fluid	**Instantaneous Releases Constants**							
	Auto-Ignition Not Likely (IAINL)				**Auto-Ignition Likely (IAIL)**			
	Gas		Liquid		Gas		Liquid	
	a	*b*	*a*	*B*	*A*	*b*	*a*	*B*
C_1 -C_2	6.469	0.67			163.7	0.62		
C_3 -C_4	4.590	0.72			79.94	0.63		
C_5	2.214	0.72	0.271	0.85	41.38	0.61		
C_6 -C_8	2.188	0.66	0.749	0.78	41.49	0.61	8.180	0.55
C_9 -C_{12}	1.111	0.66	0.559	0.76	42.28	0.61	0.848	0.53
C_{13} -C_{16}			0.086	0.88			1.714	0.88
C_{17} -C_{25}			0.021	0.91			1.068	0.91
C_{25+}			0.006	0.99			0.284	0.99

dd) For each release hole size, compute the component damage consequence areas for Autoignition Likely, Continuous Release (AIL-CONT), ($CA_{cmd,n}^{AIL-CONT}$)

- Determine the appropriate constants, *a* ($a_{cmd}^{AIL-CONT}$) and *b* ($b_{cmd}^{AIL-CONT}$) The release phase will be needed to assure selection of the correct constants.

- If the release type is gas or vapor, Type 0 or Type 1, then use equation (21) to compute the consequence area and compute the effective release rate.

$$CA_{cmd,n}^{AIL-CONT} = a(rate_n)^b \text{ x } (1 - fact_{mit}) \quad (22)$$

ee) For each release hole size, compute the component damage consequence areas for Autoignition Not Likely, Instantaneous Release (AINL-INST)

- Determine the appropriate constants *a* ($a_{cmd}^{AINL-INST}$) and *b* ($b_{cmd}^{AINL-INST}$). The release phase will be needed to assure selection of the correct constants.
- If the release is a gas or vapor and the fluid type is TYPE 0, or the fluid type is TYPE 1, then use equation (23) for the consequence area and the effective release rate.

$$CA_{cmd,n}^{AINL-INST} = a(mass_n)^b \text{ x } \left(\frac{1-fact_{mit}}{eneff_n}\right) \quad (23)$$

ff) For each release hole size, compute the component damage consequence areas for Autoignition Likely, Instantaneous Release (AIL-INST) ($CA_{cmd,n}^{AIL-INST}$)

- Determine the appropriate constants *a* ($a_{cmd}^{AIL-INST}$) and *b* ($b_{cmd}^{AIL-INST}$). The release phase will be needed to assure selection of the correct constants.
- If the release type is gas or vapor, Type 0 or Type 1, then use equation (24) to compute the consequence area and to compute the effective release rate.

$$CA_{cmd,n}^{AIL-INST} = a(mass_n)^b \text{ x } \left(\frac{1-fact_{mit}}{eneff_n}\right) \quad (24)$$

gg) For each release hole size, compute the personnel injury consequence areas for Auto-ignition Not Likely, Continuous Release (AINL-CONT) ($CA_{inj,n}^{AINL-CONT}$)

- Determine the appropriate constants *a* ($a_{inj}^{AINL-CONT}$) and *b* ($b_{inj}^{AINL-CONT}$). The release phase will be needed to assure selection of the correct constants.
- Compute the consequence area using Equation (25) where $effrate_n^{AINL-CONT}$ is from step cc.

$$CA_{inj,n}^{AINL-CONT} = a(effrate_n^{AINL-CONT})^b \text{ x } (1 - fact_{mit}) \quad (25)$$

hh) For each release hole size, compute the personnel injury consequence areas for Auto-ignition Likely, Continuous Release (AIL-CONT) ($CA_{inj,n}^{AIL-CONT}$)

- Determine the appropriate constants *a* ($a_{inj}^{AIL-CONT}$) and *b* ($b_{inj}^{AIL-CONT}$). The release phase will be needed to assure selection of the correct constants.
- Compute the consequence area using equation (26) where $effrate_n^{AIL-CONT}$

$$CA_{inj,n}^{AIL-CONT} = a(effrate_n^{AIL-CONT})^b \text{ x } (1 - fact_{mit}) \quad (26)$$

For each release hole size, compute the personnel injury consequence areas for Auto-ignition Not Likely, Instantaneous Release (AINL-INST) ($CA_{inj,n}^{AINL-INST}$)

- Determine the appropriate constants *a* ($a_{inj}^{AINL-INST}$) and *b* ($b_{inj}^{AINL-INST}$). The release phase will be needed to assure selection of the correct constants.
- Compute the consequence area using equation (27) where $effrate_n^{AINL-INST}$

$$CA_{inj,n}^{AINL-INST} = a(effrate_n^{AINL-CONT})^b \text{ x } \left(\frac{1-fact_{mit}}{eneff_n}\right) \quad (27)$$

ii) For each release hole size, compute the personnel injury consequence areas for Auto-ignition Likely, Instantaneous Release (AIL-INST) ($CA_{inj,n}^{AIL-INST}$)

- Determine the appropriate constants *a* ($a_{inj}^{AIL-INST}$) and *b* ($b_{inj}^{AIL-INST}$). The release phase will be needed to assure selection of the correct constants.
- Compute the consequence area using equation (28) where $effrate_n^{AIL-INST}$.

$$CA_{inj,n}^{AIL-INST} = a(effrate_n^{AIL-CONT})^b \text{ x } \left(\frac{1-fact_{mit}}{eneff_n}\right) \quad (28)$$

jj) For each release hole size, calculate the instantaneous/continuous blending factor ($fact_n^{IC}$).

- For Continuous Releases – To smooth out the results for releases that are near the continuous to instantaneous transition point (4,536 kgs [10,000 lbs] in 3 minutes, or a release rate of 25.2 kg/s [55.6 lb/s]), then the blending factor use equation (29).

$$fact_n^{IC} = \min\left[\left\{\frac{rate_n}{C_5}\right\}, 1.0\right] \quad (29)$$

- For Instantaneous Releases – Blending is not required. Since the definition of an instantaneous release is one with a adjusted release rate ($rate_n$) greater than 25.2 kg/s [55.6 lb/s] (4536 kg [10,000 lbs] in 3 minutes), then the blending factor use equation (30).

$$fact_n^{IC} = 1.0 \quad (30)$$

kk) Calculate the AIT blending factor $(fact^{AIT})$, using some equations, as applicable. Since Ts (450.15 kelvin) + C_6 (56) < AIT (831.150) then the equation (313)

$$fact^{AIT} = 0 \quad (31)$$

ll) Compute the continuous/instantaneous blended consequence areas for the component using equations (32) – (35).

$$CA_{cmd,n}^{AIL} = CA_{cmd,n}^{AIL-CONT} \, x \, fact_n^{IC} + CA_{cmd,n}^{AIL-INST} \, x \left(1 - fact_n^{IC}\right) \quad (32)$$

$$CA_{inj,n}^{AIL} = CA_{inj,n}^{AIL-CONT} \, x \, fact_n^{IC} + CA_{cmd,n}^{AIL-INST} \, x \left(1 - fact_n^{IC}\right) \quad (33)$$

$$CA_{cmd,n}^{AINL} = CA_{cmd,n}^{AINL-CONT} \, x \, fact_n^{IC} + CA_{cmd,n}^{AINL-INST} \, x \left(1 - fact_n^{IC}\right) \quad (34)$$

$$CA_{inj,n}^{AINL} = CA_{inj,n}^{AINL-CONT} \, x \, fact_n^{IC} + CA_{cmd,n}^{AINL-INST} \, x \left(1 - fact_n^{IC}\right) \quad (35)$$

mm) Compute the AIT blended consequence areas for the component using equations (36) and (37). The resulting consequence areas are the component damage and personnel injury flammable consequence areas.

$$CA_{cmd,n}^{flam} = CA_{cmd,n}^{AIL} \, x \, fact^{AIT} + CA_{cmd,n}^{AINL} \, x \left(1 - fact^{AIT}\right) \quad (36)$$

$$CA_{inj,n}^{flam} = CA_{inj,n}^{AIL} \, x \, fact^{AIT} + CA_{inj,n}^{AINL} \, x \left(1 - fact^{AIT}\right) \quad (37)$$

nn) Determine the final consequence areas (probability weighted on release hole size) for component damage and personnel injury using equations below.

$$CA_{cmd}^{flam} = \left(\frac{\sum_{n=1}^{4} gff_n \, x \, CA_{cmd,n}^{flam}}{gff_{total}}\right) \quad (38)$$

$$CA_{inj}^{flam} = \left(\frac{\sum_{n=1}^{4} gff_n \, x \, CA_{inj,n}^{flam}}{gff_{total}}\right) \quad (39)$$

III. Result

The result of calculation shown in the Table 16 and 17.

TABLE 16
CALCULATION RESULTS SUMMARIES FOR TUBE

Damage factor at RBI date	3790.5977
Damage factor at plan date	8716.0138
Total generic failure frequency	0.0000306
Total factor management system	50%
Probability of failure (RBI date)	0.083562
Probability of failure (Plan date)	0.197204
Total consequence area for equipment damage	14.07017389 m^2
Total consequence area for personnel injury	34.02010644 m^2
Risk at RBI date	1.973035017 m^2/year
Risk at Plan Date	4.536751674 m^2/year
Risk target	3.71612 m^2/year
Next inspection date	12/20/2019
Risk Area with Inspection	0.29248 m^2/year

TABLE 17
CALCULATION RESULTS SUMMARIES FOR HEADER BOX

Damage factor at RBI date	7154.9457
Damage factor at plan date	30448.3875
Total generic failure frequency	0.0000306
Total factor management system	50%
Probability of failure (RBI date)	0.109471
Probability of failure (Plan date)	0.111739
Total consequence area for equipment damage	4.020049682 m^2
Total consequence area for personnel injury	9.720030412 m^2
Risk at RBI date	1.064058236 m^2/year
Risk at Plan Date	4.528176567 m^2/year
Risk target	3.71612 m^2/year
Next inspection date	07/06/2025
Risk Area with Inspection	0.56251 m^2/year

IV. CONCLUSION

According to the analysis of the research study, then some conclusion could be taken as explain below:

1. There are two damage factors obtained for the tube and header box. They are; thinning damage factor and CL-SCC damage factor and the result of the damage factor for the header box is 7154.95 at RBI date and 30448.4 at plan date. For the tube, the damage factor is 2720.62 at RBI date and 4158.99 at the plan date.
2. The risk area value for the tubes in the new inspection plan is 0.29248 m^2/year and for the header box the new inspection plan is 0.56251 m^2/year.
3. The inspection planning for the tubes could be generated on July 6, 2024 and inspection planning for the header box could be generated on July 6, 2025.
4. Remaining life for the asset is 8.696 years.

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