RISK-BASED ANALYSIS FOR STEAM SYSTEM

Contents

1 Introduction and Background

1.1 Overview

1.1.1 General background

Based on US Department of Energy figures, steam systems account for approximately 30% of the total energy used in a typical petroleum refinery(1). Steam systems are utilised throughout the plant for motive, heating and process purposes, such as in the steam turbine driver for the recycle gas compressor, the re-boiler for the depropanizer column, and for stripping steam for crude distillation.

Driven by the need for increased competitiveness, steam system specialists work regularly with plants identifying opportunities to reduce the amount of energy consumed by their steam systems. At the same time, steam system maintenance costs should be optimized and most importantly, health and safety issues and unplanned downtime avoided. The integrity and efficiency of steam-using equipment is critical to refinery productivity. This is also true for steam distribution systems (which deliver the steam), and steam tracing systems which provide the heat necessary to maintain flow rates in product distribution lines, vessels and reactors(2).

Routine inspection and testing of steam-using systems consisting of steam traps, associated lines and equipment is required due to the possibility that the trap or associated lines/equipment may fail leading to failure of the system. In the past, such failures have resulted in a significant loss of steam and have led to personal injury..

A risk-based approach to evaluate the criticality of equipment in steam-using systems is covered here to set inspection/testing frequency or any possible mitigation actions. Included in the scope are all steam traps, associated steam distribution lines and equipment using steam. In particular, the methodology involves the use of reliability data for steam trap types in the form of Weibull parameters.

It is assumed that devices have been designed in accordance with specific design standards and sized, selected, and installed appropriately. It is also assumed that the devices are included in inspection plans. The fundamental approach is to determine the probability of failure from plant-specific data if available, or to be determined from default data (provided here). These inputs are used to generate a Probability of Failure (POF) as a function of time via a Weibull statistical approach. The consequence of device failure is determined based on methods outlined in Part 3, but modified to include different failure scenarios. The combination of consequence with time-based POF, results in a risk value which increases with time between inspections/tests. This allows inspection/test intervals to be determined based on risk targets. The flow chart shown in section 2.1 illustrates the basic methodology required for the determination of POF and hence the basis for setting up inspection and test schedules or any mitigation actions.

1.1.2 Steam application types

In process plants, steam is essential for heating, mechanical drives and several other applications. In each case, steam traps are commonly used to ensure that steam is not wasted. A steam trap is a type of automatic valve which filters out condensate (for example condensed steam) and non-condensable gases such as air without letting steam escape. As described in ANSI/FCI 69-1-1989, a steam trap is a self-contained valve which automatically drains the condensate from a steam-containing enclosure while remaining tight to live steam, or if necessary, allows steam to flow at a controlled or adjusted rate(3). Most steam traps will also pass non-condensable gases while remaining tight to live steam. Various types

of steam trap mechanisms (operating principles) have been developed to automatically discharge condensate and non-condensable gases. The most widely used mechanisms are those reliant on differences in temperature, specific gravities, and pressure. Each of these types of steam traps has its own advantages and applications.
Steam traps are usually required to drain condensate from steam piping, steam-using process and comfort heating equipment, tracer lines, and drive-power equipment such as turbines. Each of these applications may require the steam trap to perform a slightly different role.

In summary, there are five major steam trap application groups: steam distribution piping; steam-heated equipment; steam-driven equipment; steam tracing; and direct steam applications. These systems can be indispensable in delivering the energy needed for operating an industrial plant; including process heating (e.g. heat exchangers) and steam tracing systems, as well as mechanical drives (e.g. steam turbines).

Examples of equipment used in steam systems, illustrating the importance of their application to the refining process, are listed in Table 1.

1.2 The definition of steam system

1.2.1 Overview

The role of the steam system is to reliably supply steam of the highest quality to the steam-using equipment. In order for this to be achieved, condensate must be removed quickly and efficiently through steam traps installed in the correct condensate discharge location (CDL). Therefore steam systems are an integral part of the process plant. A typical steam system is shown in Figure 1 with the following hierarchy:

1. Steam traps
2. Steam lines (distributing and condensate)
3. Associated equipment (steam-using equipment)

In some cases, depending on the design, mechanical pumps or control valves may be installed in place of steam traps (as shown in Figure 1 above).

Failure consequences are key drivers for a Risk-Based Inspection (RBI) approach in steam-using/distribution systems, starting with assessment of steam traps, followed by steam lines and finally, the steam-using equipment (as described in Section 2

1.2.2 Steam trap

Steam traps are a type of automatic valve which filters out condensate (i.e. condensed steam) and non-condensable gases, such as air, without letting steam escape. In industry, steam is used regularly for heating or as a driving force for mechanical power. Steam traps are used in such applications to ensure steam is not wasted. Based on the operating principles of steam traps, they can be classified as mechanical, thermostatic or thermodynamic. Table 2 describes different types of steam traps for each of the above categories.

1.2.3 Steam line

Steam lines supply steam to the steam-using equipment. As described, condensate must be removed through steam traps installed at CDLs.
The flow of steam is typically much faster in steam distribution piping than in other equipment and can reach speeds of over 30m/s (100ft/s). At these speeds, when the cross-sectional area of a pipe section is completely filled by water, slugs of condensate can be carried through the piping at high velocity causing water

hammer, which may cause failures through damage to piping, valves and equipment and may result in personal injuries. . The higher flow velocities in steam lines must therefore be taken into account during decisions regarding location and design of trap installations.

1.2.4 Steam-using equipment

As described in Section 1.1.2, there are many applications for steam and, depending on the application, various types of steam-using equipment are used. Table 1 provides examples for five (5) steam application groups.

1.2.5 Steam system equipment and failure modes

1.2.5.1 Background

The role of steam distribution lines is to reliably supply steam of the highest quality to the steam-using equipment. In order for this to be achieved, condensate must be removed quickly and efficiently through steam traps installed in proper CDL installations. CDLs are locations where condensate is removed from steam systems; they are susceptible to failures as the result of the following steam trap failure modes: blockage (cold) or leakage (described in 1.1.3.2 and 1.1.3.3).

A sudden release of steam or scalding water can occur due to failure modes such as water hammer. Water hammer has been cited by Paffel[4] as the 'number one' problem in steam systems. Water hammer is a known vulnerability in steam systems, and is sometimes referred to as 'Condensate Induced Water Hammer'. This most commonly occurrs when steam is introduced into cold pipework which has not been drained sufficiently. As the steam cools, it turns into condensate, taking up a smaller volume in the pipework than steam. This produces a vacuum or pocket into which the water flows rapidly, creating an impact against the pipework.

The failures described in this section will also result in equipment failure consequences such as industrial steam turbine erosion failures, flooding of heat exchangers, failures in steam tracing systems, failures in flare systems (loss of steam will prevent atomizing of gases prior to burning), distillation towers and strippers.

1.2.5.2 Steam trap blockage leading to water hammer

When a steam trap is blocked, the condensate cannot be discharged. The steam trap loses its basic function, resulting in problems including water hammer which can lead to equipment damage, etc. Water hammer generated in steam and condensate recovery systems is ordinarily classified via two main causes:

- High-speed condensate slamming into, for example piping
- Sudden condensation of steam, which produces walls of condensate that crash into each other.

When water hammer occurs, a momentary abrupt pressure change of over 10MPa (1450psi) may occur inside the piping. The change in pressure may result in an impact and can cause pipe rupture, severely jarring piping, equipment or machinery housings, possibly resulting in damage, not only to gaskets in junctions, but also to valve flanges or the valves themselves. Water hammer in steam distribution piping interrupts service and can cause failures leading to serious personal injury and property damage. According to historical failures, 82% of steam systems experience some type of water hammer[1]. In a typical steam-using system, water hammer causes 67% of premature steam system component failures [1].

Water hammer events are commonly caused by the following systemic failures:

- Failure to ensure water (condensate) has been removed using steam traps and drains prior to admitting steam into the piping system.
- Failure to correctly maintain steam traps, drain, and to blowdown valves (in order to preserve operable condition).
- Failure to ensure an adequate number of steam traps and drains have been installed at locations conducive to condensate removal.
- Failure to operate system valves correctly as well as failure to use bypass valves to safely warm system piping downstream of isolation valves.

1.2.5.3 Steam trap leakage

Leakage is another mode of steam trap failure resulting in energy waste and poor environmental compliance. The failure consequence of leakage is described in Section 5.2.

1.3 Use of Weibull curves

The POF for steam systems is computed using a two parameter Weibull distribution as expressed in Equation [1) as shown in Part 1 Section 4.1.3. Use of Weibull curves for establishing POF is further described in Part 1 Section 7.1.4.

$$\boldsymbol{PoF = 1 - exp\left[-\left(\frac{t}{\eta}\right)^{\beta}\right]} \qquad [1]$$

Where β is the Weibull Shape Parameter, η is the Weibull characteristic life parameter, in years, and t is the independent variable time, also in years.

The POF of the specific trap is related to identifiable process and installation conditions. Such conditions may be related to design, operational and maintenance/inspection history conditions. Also associated with failure are conditions such as poor manufacturing and installation and excessive piping vibration. Improper installations or poor operational and maintenance condition may also increase the POF.

1.4 Required data

The basic data required for the evaluation of POF for steam systems are listed in Table 3.

2 Probability of Failure Methodology

2.1 Overview

This section presents a procedure to calculate the POF for a steam system. Figure 2 provides an overview of the POF calculation framework for steam using systems. POF is a function of time for a range of steam trap types and properties, using Weibull fitting of steam trap failure data. The POF of the associated lines is then derived and combined with the steam-using equipment generic failure frequencies to compute the POF for the system. Final POF values are obtained by tailoring the POF for steam traps and equipment to local conditions by customized probability factors.

As described in Section1.2 above a steam system consists of a combination of equipment and its associated lines. The POF of each system will be considered as the combined effect of individual equipment with its associated traps, i.e.:

$$\boldsymbol{POF_{Steam\ using\ System} = F_{MS} \times PoF(t)_{final\ (equ)} \times PoF(t)_{final\ (ST,\ MP\ or\ CV)}} \qquad [2]$$

Where F_{MS} is the Management Systems Factor calculated following the guidelines given in Part 2, Annex 2.A and section 3.5.4, $\boldsymbol{PoF(t)_{final\,(ST,\ MP\ or\ CV)}}$ is the Probability of Failure calculated for the associated lines (combined POF), consisting of multiple steam traps, mechanical pumps and control valves. The procedure for calculation of $\boldsymbol{PoF(t)_{final\,(ST,\ MP\ or\ CV)}}$ is given in Section 2.2 and 2.3. $\boldsymbol{PoF(t)_{final\,(equ)}}$ is the Probability of Failure calculated for the steam using equipment as explained in Section 2.4..

2.2 Models for assessing POF (steam line level)

2.2.1 POF for steam traps, mechanical pumps and control valves

Analysis has been carried out on the historical time to failure data (for various failure types) and a Weibull distribution has been fitted. As described in section 1.3, Weibull functions are suitable for such analysis with the added advantage of having the ability to evaluate large populations of data to seek trends. In the absence of large sets of failure data, the functions are still useful as a starting point.

Equation [1] is the cumulative failure density function of a two parameter Weibull distribution, also referred to as the Probability of Failure (POF) for a steam trap. In this equation, t is the in-service life of the steam trap (in years), η is the characteristic life (also in years) and β is the shape parameter.

Once the scale η_{defaul_ST} and shape β_{ST} parameters are obtained (from historical data analysis), the POF of the steam trap $PoF_{default}$ is calculated using equation [1] and Table 4. The data presented in Table 4 are based on the best available sources and experience to date from owner-users. Table 4 introduces default Weibull parameters for the different steam trap types in both failure modes. However, it is recommended that both Weibull parameters be used by the owner/user where more accurate data for default shape/scale parameters are available. The default parameters in Table 4 are suggested for use when data is unavailable.

2.2.2 Adjusted POF for steam traps, mechanical pumps and control valves

Adjustments are made to the η parameter to increase or decrease POF as a result of condition of design/installation, operation or maintenance history factors. POF is then adjusted based on the adjustment multiplier for each design/installation (F_D), operational (F_O) or maintenance history (F_M) conditions. The default, $PoF_{default}$, needs to be adjusted by the adjustment multipliers given in Table 5 to 13.

$$\boldsymbol{\eta_{adjusted\,(ST,MP\ or\ CV)} = \eta_{default} \times (F_{D(ST,MP\ or\ CV)} \times F_{O(ST,MP\ or\ CV)} \times F_{M(ST,MP\ or\ CV)})} \quad [3]$$

$$\boldsymbol{PoF(t)_{final\,(ST,\ MP\ or\ CV)} = 1 - exp\left[-\left(\frac{t}{\eta_{adjusted\,(ST,MP\ or\ CV)}}\right)^{\beta_{ST}}\right]} \quad [4]$$

Then, $\eta_{adjusted}$ will be used to calculate the final (tailored) POF (Equation [4]) for each steam trap, mechanical pump or control valve operating within the steam system. The shape factor β_{ST} used in equation [4] is the same shape factor generated from Table 4. PoF_{final} is the final PoF of each steam trap, mechanical pump or control valve.

Suggested adjustment multiplier categories that need to be considered for steam traps, mechanical pumps and control valves are given in tables 5 to 13. It should be noted that the value of each 'adjustment multiplier' depends on engineering judgement.

2.3 Multiple steam trap installations

For any steam using equipment, there are several associated lines with steam traps installed. The lines usually have steam traps installed in parallel or series. When there are multiple steam traps installed, the calculated POF for any one specific steam trap in the multiple installation will remain the same. However, the overall combined POF of multiple traps (parallel or series) must be considered for each line.

For example, Figure 3 is the sample arrangement of the traps showing their capacity. Calculation of the POF for each line is given by equations [5] or [6] which allow calculation of the total POF for the lines. In addition, if the capacity of Trap 1 and Trap 2 are not sufficient for the equipment requirement individually, these two traps must be treated as series configurations (Figure 4b).

$$\boldsymbol{PoF}_{\boldsymbol{series\ steam\ traps}} = \max(\boldsymbol{PoF}_{\mathbf{1}}, \boldsymbol{PoF}_{\mathbf{2}}) \quad [5]$$

$$\boldsymbol{PoF}_{\boldsymbol{Parallel\ steam\ traps}} = \boldsymbol{PoF}_{\mathbf{1}} \times \boldsymbol{PoF}_{\mathbf{2}} \quad [6]$$

2.4 PoF for equipment

As discussed in Section 1.1.2, there are different types of equipment used in steam-using systems. Examples of some of these types were given in Table 1. In this section, the POF calculation due to steam related failure will be covered. Equipment consists of the following:

- Heat exchanger
- Distillation tower/column
- Stripper
- Flare
- Steam turbine
- Piping (steam main or condensate piping)
- Tracing (instrumentation/relief valve)

The POF of equipment is considered as the combined effect of individual equipment (e.g. heat exchanger, tracing, and steam turbine) with its associated lines (section 2.2). Calculation of the POF of equipment takes into account the effect of both equipment and its associated lines. It is also important to note that the calculation assumes that each individual item of equipment is independent.

The equations below are used in estimating the POF for the equipment listed above and each equipment is considered independent and assessed separately.

$$\boldsymbol{\eta}_{\boldsymbol{adjusted\_equ}} = \boldsymbol{\eta}_{\boldsymbol{default\_equ}} \times (\boldsymbol{F}_{\boldsymbol{D}_{\boldsymbol{equ}}} \times \boldsymbol{F}_{\boldsymbol{O}_{\boldsymbol{equ}}} \times \boldsymbol{F}_{\boldsymbol{M}_{\boldsymbol{equ}}}) \quad [7]$$

$$\boldsymbol{PoF}(\boldsymbol{t})_{\boldsymbol{final\ (equ)}} = \mathbf{1} - \boldsymbol{exp}\left[-\left(\frac{\boldsymbol{t}}{\boldsymbol{\eta}_{\boldsymbol{adjusted\_equ}}}\right)^{\boldsymbol{\beta}_{\boldsymbol{equ}}}\right] \quad [8]$$

The default scale parameter, η_{defaul_equ} and shape parameter, β_{equ} are obtained from historical data analysis. Table 14 shows default Weibull parameters for the different types of steam-using equipment. The data presented in Table 14 are based on the best available sources and experience to date from owner-users. However, it is recommended that other Weibull parameters be used by the owner/user where more accurate data (plant specific) for default shape/scale parameters are available. The default parameters in Table 14 are suggested for use when data is unavailable. The generic values provided in Table 14 are based on failure of steam systems. The POF of the steam-using equipment, $PoF_{default\_equ}$ is calculated using Equation [1] and Table 14.

Similar to the approach for steam traps discussed in Section 2.2.2, $\eta_{adjusted\_equ}$ is used to calculate the final (tailored) POF (Equation [8]) for steam-using equipment. The shape factor β_{equ} used in equation [8] is the shape factor from table 14. $PoF_{final\,(equ)}$ is the final POF of the steam-using equipment. The adjustment multiplier categories for each design/installation ($F_{D_{equ}}$), operational ($F_{O_{equ}}$) or maintenance history ($F_{M_{equ}}$) factors are given in Table 15 to Table 17, and are used to modify the default scale parameter, $\eta_{default\_equ}$. It should be noted that the value of each 'adjustment multiplier' depends on engineering judgement.

2.5 POF for steam-using systems

The total POF for steam-using systems is calculated following Equation [2]

$$\boldsymbol{POF_{Steam\,using\,System} = F_{MS} \times PoF(t)_{final\,(equ)} \times PoF(t)_{final\,(ST,\ MP\,or\,CV)}}$$

[2]Where, $\boldsymbol{PoF(t)_{final\,(ST,\ MP\,or\,CV)}}$ will be calculated from Equation 5 or 6 if there are multiple steam traps.

3 POF after Inspection

As discussed earlier, Weibull parameters for the failure on demand curves are determined based on the analysis of a sample set of data (see section 1.3). However, as inspection data is collected, these parameters may be adjusted for each device based on the inspection results. The Bayesian updating approach to problems of this type is common, in order to adjust probabilities as new information is collected.

This approach assumes that the Weibull shape parameter (β parameter) remains constant based on the historical data, and adjusts the characteristic life η parameter), as inspection data are collected.

3.1 POF after Cleaning

The steam trap POF will be updated if the trap is periodically cleaned. The POF will be reduced to a certain level after each clean. For example, if the periodic cleaning is done at 0.5 years then, at 0.6 years, the POF will be reduced to the same POF value as at 0.1 year. At 1.1 years, the POF will be equal to the POF at 0.1 years, and so on.

4 POF calculation procedure

The following calculation procedure may be used to determine the probability of failure due to leak and blockage for steam traps and steam using equipment.

Step 1: Identify the steam traps, mechanical pumps and control valves in the system. Also, establish if there is any associated steam using equipment in the steam system. Gather data as defined in Table 3.

Step 2: Calculate the POF for the steam traps, mechanical pumps and control valves:

Step 2.1: Determine the default values of the Weibull parameters based on the appropriate failure mode from Table 4.

Step 2.2: Using the appropriate Tables (Table 5 to 13), determine the design, operating and maintenance condition adjustment for each item (steam trap, mechanical pump and control valve).

Step 2.3: Using equation [3], adjust the Weibull parameter $\boldsymbol{\eta_{default}}$ based on the values in Step 2.2.

Step 2.4: Using equation [4], calculate the $\boldsymbol{PoF(t)_{final\,(ST,\ MP\ or\ CV)}}$ for the items based on the adjusted Weibull parameter $\boldsymbol{\eta_{adjusted\,(ST,MP\ or\ CV)}}$.

Step 3: Inspection POF updating for steam traps

Step 3.1: Identify the effectiveness of the inspection and testing method using Table 18.

Step 3.2: Using Equation [9], calculate the probability of not failing the inspection prior to inspection.

$$\boldsymbol{P_{prior} = 1 - PoF_{adjusted}} \qquad [9]$$

Step 3.3: Identify the confidence factor (CF) associated with the inspection effectiveness and inspection result using Table 19.

Step 3.4: Use Equation [10] if the inspection results do not show the expected failure, and use Equation [11] if the inspection confirms the expected failure. Calculate PoF_{after} for blockage and leakage failures.

$$\boldsymbol{PoF_{after} = \left(1 - CF_{pass}\right) \times P_{prior}} \qquad [10]$$

$$\boldsymbol{PoF_{after} = \left(1 - CF_{pass}\right) \times P_{prior} + PoF_{adjusted} \times CF_{fail}} \qquad [11]$$

Step 3.5: Look up the appropriate equation for updating the POF after inspection using Table 20, and calculate the PoF_{wgt}, based on the inspection effectiveness and inspection results.

Step 3.6: Using equation [12], update the characteristic life $\boldsymbol{\eta_{adjusted\,(ST)}}$, with using the same β_{ST} shape factor established earlier and $\boldsymbol{t}$ is the inspection interval.

$$\boldsymbol{\eta_{upd} = \frac{t}{\left(-\ln\left[1 - PoF_{wgt}\right]\right)^{\frac{1}{\beta_{ST}}}}} \qquad [12]$$

Step 3.7: Using equation [13] calculate the POF at year in service.

$$\boldsymbol{PoF_{upd} = 1 - exp\left[-\left(\frac{t}{\eta_{upd}}\right)^{\beta_{ST}}\right]} \qquad [13]$$

Step 3.8: Based on the steam trap arrangement, calculate the POF using equation [5] or [6] for both failure modes, at $\boldsymbol{t_{service\,(ST)}}$.

Step 4: Calculate the POF for the steam using equipment:

Step 4.1: Identify the default Weibull parameters for the steam using equipment from Table 14.

Step 4.2: Using Table 15, determine the design condition adjustment ($\boldsymbol{F_{D_{equ}}}$) for the steam using equipment.

Step 4.3: Using Table 16, determine the operation condition adjustment ($\boldsymbol{F_{O_{equ}}}$) for the steam using equipment.

Step 4.4: Using Table 17, determine the maintenance history/inspection condition adjustment ($\boldsymbol{F_{M_{equ}}}$) for the steam using equipment.

Step 4.5: Using equation [7], adjust the Weibull parameter $\boldsymbol{\eta_{default\,(equ)}}$ based on the values in Steps 4.2, 4.3 and 4.4.

Step 4.6: Using equation [8], calculate the $\boldsymbol{PoF(t)_{final\,(equ)}}$ for the steam using equipment based on the adjusted Weibull parameter $\boldsymbol{\eta_{default\,(equ)}}$.

Step 5: Using equation [2], estimate the POF for the steam using system.

5 Consequence of Failure Methodology

5.1 Background

This section presents a procedure to calculate consequence of failure (COF) for a steam system.

5.2 Models for assessing COF

5.2.1 Overview

In summary, the calculation of the COF is carried out by evaluating costs involved in different failure consequences, such as the cost of the loss of inventory, regulatory cost, environmental costs, cost of downtime and cost of repairs. Failure will result in a consequence, i.e. potential impact on both the environment and people, as well as product loss and component damage in some cases.

The COF varies with different equipment and failure modes; below is a list of potential costs due to failures, and calculation methods for COF.

5.2.2 Cost of steam loss due to leakage

$$Cost_{loss} = {leakage\ rate\ (kg/hr) \times 8760(hrs) \times cost\ of\ the\ steam\ (\$/kg)}/_{1000} \qquad [14]$$

The leakage rate is based on historical inspection data.

5.2.3 Cost of condensate loss due to downstream equipment rupture

$$Cost_{loss,DS} = condensate\ mass\ (kg) \times cost\ of\ the\ condensate\ (\$/kg)/_{1000} \qquad [15]$$

The condensate mass is calculated following the procedure recommended in Part 3 Section 4.7.2 Equation 3.14.

5.2.4 Cost of component damage due to rupture caused by water hammer

The temporary default component damage cost uses the recommended values from Part 3 Section 4.12.2 for heat exchangers and steam tracing main pipes, and the North American Electric Reliability Corporation (NERC) Generating Availability Data System (GADS) for steam turbines. The default values are able to be customized by the user.

5.2.5 Cost of production loss due to shut down or reduced service efficiency

The value of production loss can be either input directly by the user or determined using Equation (1.65) in Part 1 Section 8.

$$\boldsymbol{Cost_{prod} = Unit_{prod} \times (\frac{Rate_{red}}{100}) \times D_{sd}} \qquad [16]$$

Where, $Unit_{prod}$ is the daily profit margin on the unit (\$/day). This will be input by the user. $Rate_{red}$ is the production rate reduction on a unit as a result of the equipment being out of service (%), which will also be user input. D_{sd} is the number of days required to shut down a unit in order to repair the equipment during an unplanned shutdown (days).

5.2.6 Cost of safety impact to personnel and environment due to rupture and leakage

The steam released through leakage or rupture will result in a safety impact on personnel and the environment. This is calculated as the total personnel injury cost within a certain area, i.e. the consequence area (CA_{inj}).

$$COF_{inj} = CA_{inj} \times popdens \times injcost \quad [17]$$

The consequence area (CA_{inj}) is calculated by modifying the procedure in Part 3 Section 4.10.

For rupture (blockage), the hole size 'A' will default to the inlet/connection size to ensure a conservative assessment and result. The inlet size is used in Equation 3.70 to calculate the consequence area (CA_{inj}) due to rupture. For leakage, the hole size of 25mm is used in Equation 3.69 to calculate the consequence area (CA_{inj}) (i.e. the medium hole size).

Popdens and injcost used in the above equation is defined in Part 3 Section 4.12.5.The required input parameters are listed in Table 21..

Note: for multiple traps, the following scenario is used for calculating COF.

Blockage: $COF_{inj} = max(COF_{inj\_1}, COF_{inj\_2}, \dots . COF_{inj_n})$
[18]

Leak: $COF_{inj} = (COF_{inj\_1} + COF_{inj\_2}, \dots \dots COF_{inj\_n})$
[19]

5.3 Cost models for different equipment

5.3.1 Overview

The COF varies for different equipment and failure modes. A list of potential costs due to failure and calculation methods was introduced in Section 5.2. For freshly added applications, the various potential failure consequences are added to the 'event tree' as the starting point for COF model development. In addition, for steam distribution, depending on the type of equipment connected, the COF is estimated differently. Currently, 'type of connected equipment' is one of the inputs for steam distribution COF estimation. In Sections 5.3.2 to 5.3.10, the algorithm for estimating COF for different equipment is explained.

5.3.2 COF model for heat exchanger and steam turbine

The failure modes for heat exchanger and steam turbines can be either blockage or leakage, which are calculated separately. When 'blockage' happens, it must be established whether there is an opening bypass for the steam system. If no opening bypass exists, any blockages will cause the steam system to shut down and possibly water hammer inside the equipment. The outcome of which could result in main equipment production loss and rupture respectively. As stated previously, a rupture will give rise to a cost due to component damage and safety impact (personnel injury). In summary, the COF due to blockage without an opened bypass for heat exchanger and turbine can be calculated as:

$$CoF_{cold}^{HEX,Turbine} = Cost_{prod} + Cost_{comp} + COF_{inj} \quad [20]$$

If the bypass is opened, the consequence will be the same as the consequence of leakage.

For leakage, as well as blockage , with an open bypass, the total steam loss is calculated first. It must then be established whether the outlet is open or closed. If it is open, the safety impact is considered in addition to the loss of steam. It is not, however, considered for internal leakage.

If the outlet is closed while the traps are leaking, there will be a subsequent consequence of water hammer occurring to the downstream equipment/pipe in addition to steam loss from leaking traps. In the worst case, the downstream pipe will be ruptured. This will result in production loss due to downstream equipment shutdown, downstream pipe component damage, loss of condensate and associated safety impacts. In summary, the COF due to leakage as well as blockage with an open bypass for the heat exchanger and turbine can be calculated as:

$$\boldsymbol{CoF^{HEX,Turbine}_{leak,open} = Cost_{loss} + Cost_{loss,D/S}} \quad [21]$$

$$\boldsymbol{CoF^{HEX,Turbine}_{leak,closed} = Cost_{loss} + (\, Cost_{prod,D/S} + Cost_{comp,D/S} + COF_{inj,D/S} + Cost_{loss,D/S})} \quad [22]$$

5.3.3 COF model for general steam tracing

The failure modes for steam tracing equipment can be either blockage or leakage, which are calculated separately. Unlike a heat exchanger or turbine (as described in Section 5.3.2), the COF for tracing is considered for the main pipe and tracing line respectively. When 'blockage' happens, it must be established whether there is an opened bypass for the system or the trap is disconnected. If the bypass is closed or the trap is not disconnected, the blockage will cause the steam system to shut down or the content to cool down and possibly water hammer inside the tracing line. In one case, the steam system shut down and content sub-cooling will result in production loss in addition to the cost of main pipe cut-off (component damage). In another case, the water hammer inside the tracing line will cause the tracing line to rupture (worst case scenario), which will result in costs of the tracing line component damage in addition to associated safety impacts.

In summary, the COF due to blockage without opened bypass or trap disconnection for high temperature steam tracing can be calculated as:

$$\boldsymbol{CoF^{Tracing,HT}_{cold} = Cost_{prod} + Cost_{comp,main} + Cost_{comp,line} + COF_{inj}} \quad [23]$$

If the bypass is opened or the trap disconnected, the consequence will be the same as the consequence of leakage.

For leakage, as well as blockage, with an open bypass or trap disconnection, the estimation is the same as the consequence of leakage for a heat exchanger or turbine. In summary, the COF for both, leakage and blockage, with an open bypass or trap disconnection for high temperature steam tracing is calculated as:

$$\boldsymbol{CoF^{Tracing,HT}_{leak,open} = Cost_{loss} + COF_{inj}} \quad [24]$$

$$\boldsymbol{CoF^{Tracing,HT}_{leak,closed} = Cost_{loss} + (\, Cost_{prod,D/S} + Cost_{comp,D/S} + COF_{inj,D/S})} \quad [25]$$

5.3.4 COF model for low temperature steam tracing

The failure modes can be either blockage or leakage, which will be calculated separately. The COF for tracing is considered for main pipe and tracing lines separately.

Similarly to the high temperature tracing (Section 5.3.3), when blockage happens, the COF can be summarised as:

$$\boldsymbol{CoF^{Tracing,LT}_{cold} = Cost_{prod} + Cost_{comp,main} + Cost_{comp,line} + COF_{inj}} \quad [26]$$

For leakage as well as blockage with open bypass or trap disconnection, the common failure consequence for both an open and closed system is as follows: Firstly, the steam leaking will result in costs from steam loss; if multiple traps are leaking, the sum of steam loss costs should be reported. Secondly, leakage causes equipment shut down or overheating, which gives rise to costs from production loss. Finally, water hammer may occur inside the process line due to leakage; in the worst case, it will cause a rupture of the process line and result in costs from process line component damage and safety impact. The fluid within the process line must be identified; it may be flammable or toxic or flammable and toxic. The quantitative model to estimate safety COF is developed based on Part 3. If the fluid is both flammable and toxic, the worst case will be used for the subsequent calculation.

In addition to costs listed above, for an open system (i.e. the outlet is opened), there are further safety impacts caused by leaking steam. If the outlet is closed, there is a subsequent consequence of water hammer occurring to the downstream equipment/pipe. The evaluation approach for this subsequent consequence is the same as the heat exchanger, turbine and high temperature tracing.

In summary, the COF due to leakage as well as blockage with open bypass or trap disconnection for low temperature steam tracing is calculated as:

$$\boldsymbol{CoF^{Tracing,LT}_{leak,open}} = \boldsymbol{COF_{inj}} + (\boldsymbol{Cost_{loss}} + \boldsymbol{Cost_{comp,process}} + \boldsymbol{Cost_{prod,process}} + \boldsymbol{COF_{inj,process}}) \quad [27]$$

$$\boldsymbol{CoF^{Tracing,LT}_{leak,closed}} = (\boldsymbol{Cost_{loss}} + \boldsymbol{Cost_{comp,process}} + \boldsymbol{Cost_{prod,process}} + \boldsymbol{COF_{inj,process}}) + (\boldsymbol{Cost_{prod,D/S}} + \boldsymbol{Cost_{comp,D/S}} + \boldsymbol{COF_{inj,D/S}}) \quad [28]$$

5.3.5 COF model for steam tracing with relief valve

The relief valve is a type of valve used to control or limit the pressure in the steam tracing system. Pressure can build up as a result of a process, instrument or equipment failure. However, if the relief valve fails, there is the possibility the high pressure of the fluid within the pipe is raised further and causes leakage through the joints. In this case, the failure consequence is the sum of the cost of fluid loss and injury costs due to the leakage where the relief valve is installed (see, Part 1.7). The COF calculation follows the COF equations for low temperature steam tracing.

5.3.6 COF model for steam tracing with flow meter

A flow meter is an instrument used to measure linear, non-linear, volumetric or the mass flow rate of fluids, which can be found on both general tracing and low temperature applications. If the flow meter fails, the fluid is transported without measurement. This will not cause any safety consequence or financial loss in terms of product loss or component damage. However, without measurement, there may be a certain amount of business loss, which will be assessed by the user. In summary; the total COF is the same as for general tracing on a low temperate tracing system, with modified business loss which will be assessed by the user directly.

5.3.7 COF model for distillation columns with stripping steam

The steam trap failure modes considered for distillation columns are leakage and blockage . For the failure mode of leakage, if the outlet is open, COF is the sum of steam loss and cost of the safety impact due to condensate / steam discharge into the open air (Equation 21). Otherwise, if the outlet is closed, steam loss is the only leakage COF (Equation 22). In terms of failure due to blockage when the bypass is not open, there is the possibility of condensate carry-over and/or water hammer, and the COF is calculated as the sum of component damage, production loss and the cost of safety impact (Equation 20). If the bypass is open, the COF of due to blockage is the same as the COF of leakage.

5.3.8 COF model for flare

The steam trap failure modes considered for flare are leakage and blockage . Similar to distillation columns (Section 5.3.7), if the steam trap of the flare leaks and its outlet is open, COF is the sum of steam loss and the cost of the safety impact due to condensate / steam discharge to the open air (Equation 21). Otherwise, if the outlet is closed, steam loss is the only leakage COF (Equation 22). In terms of failure due to blockage when the bypass is not open, there is the possibility of condensate carry-over and/or water hammer, and the COF is calculated using Equation 20 as the sum of component damage, production loss, the cost of safety impact due to pipe rupture and environmental costs due to reduced burning efficiency which will be assessed by the user directly using Equation 29. If the bypass is open, the COF of due to blockage is the same as the COF of leakage.

$$COF_{inj} = MAX(COF_{inj,nfnt}, COF_{inj,flam}, COF_{inj,toxic}) \quad [29]$$

5.3.9 COF model for steam distribution piping

The failure modes considered for steam distribution piping are leakage and blockage. Similarly to distillation columns (Section 5.3.7), if the steam trap of the main line leaks and its outlet is open, COF is the sum of steam loss and cost of the safety impact due to condensate/steam discharge to open air (Equation 21). Otherwise, if the outlet is closed, steam loss is the only leakage COF (Equation 22). In terms of failure due to blockage when the bypass is not open, there will be the possibility of water hammer; the COF is calculated as the sum of component damage (main line), production loss, and the cost of any safety impact (Equation 20). If the bypass is open, the COF due to blockage is the same as the COF of leakage.

5.3.10 COF model for condensate recovery line

The failure mode considered for the steam recovery line is leakage only. This is because blockage steam traps related to the recovery line are not discharging into the line, so they do not have any effect. When the recovery line fails due to a steam trap leakage, the condensate pipe may rupture due to water hammer. The COF is calculated as the sum of any component damage (pipe), cost of safety impact, condensate loss and downstream equipment production loss (Equation 25).

6 COF calculation procedure

The following calculation procedure may be used to determine the consequence of failure (COF) for a steam system. The COF needs to be calculated for both failure modes.

Step 1: Calculate the cost of steam loss due to leakage using Equation 14.

Step 2: Calculate the cost of condensate loss due to downstream equipment rupture using Equation 15. Go to Step 3, if no downstream equipment is connected or if the system is open i.e. the condensate is discharged to open.

Step 3: Calculate the cost of production loss due to shut down or reduced service efficiency using Equation 16.

Step 4: Calculate the cost of safety impact to personnel and environment due to rupture and leakage using Equation 17. If there are multiple steam traps use equations 19 or 20.

Step 5: Calculate the COF of component damage based on the type of steam using equipment as given in Section 5.3.2 to 5.3.10.

7 Risk Based Analysis

The risks to be considered are business loss, injury to people and damage to the environment, which is calculated using Equation [30]:

$$\boldsymbol{Risk}(\boldsymbol{t}) = \boldsymbol{PoF}_{\boldsymbol{Steam\ using\ system}} \times \boldsymbol{CoF} \quad [30]$$

Where $\boldsymbol{PoF}_{\boldsymbol{Steam\ using\ system}}$ is obtained from Equation 2.

For the output, the risk is calculated as a function of time on a risk matrix. All of the post-assessment analysis are conducted based on this; this will be discussed in detail in the following sections.

8 Inspection and Risk Mitigation Planning

8.1 Risk mitigation plan

8.2 Overview

The mitigation plan comprises risk mitigation suggestions/actions to assist asset users/owners managing their steam system through the identification of the influence of each mitigation action on the system. The method for illustration of the risk target is the 'Iso-risk target'. the Iso-risk target is defined as 'A line of constant risk and a method of graphically showing POF and COF values in a log-log, two dimensional plot where risk increases toward the upper right-hand corner' The value of the target risk will be determined by the user.

The possible mitigation actions listed in Sections 8.2.2 to 8.2.3 are suggestions only and may not be applicable in all situations.

8.2.1 Configuration of steam system

The risk can be modified by changing the configurations of the steam system, either by adding spare equipment or extra steam traps to the line or changing the type of the existing steam traps. The influence will depend on the number and location of the extra steam traps. Specifically, if extra steam traps are added, the arrangement of the steam system will be changed. The value of POF will be amended accordingly. Meanwhile, different steam traps will have a different $PoF_{adjsuted}$, which will affect the POF of the steam system (Equation [2]).

8.2.2 Inspection

If an inspection is performed, or a condition monitoring device installed, the risk categories will also be shifted as the tailored characteristic life $\eta_{adjusted}$ will be updated accordingly. The procedure proposed in Section 3 will be followed. For sensors, the Confidence Factor (CF) value will be defaulted to 'usually effective'.

Cleaning of the steam trap has a significant impact on the POF; the more frequent the cleaning, the lower the POF over time.

8.2.3 Spare equipment

If any 'spare' equipment is included in one steam system, this may help to reduce the consequential cost of production loss. The POF can also be mitigated by intentionally releasing steam, e.g. via 'bypass open'. However, this action is not recommended due to environmental and safety viewpoints. In addition, it not only causes an increment of COF due to loss of steam, but could also lead to local corrosion damage i.e. $Cost_{Loss}$ and $Cost_{comp}$.

9 Nomenclature

A	Hole size, defaulted to inlet size
CoF_{LOSS}	The consequence of failure due to the product (steam) loss
CoF_{rup}	The consequence of failure due to rupture
$CoF_{cold}^{HEX,Turbine}$	The consequence of failure of heat exchanger and turbine due to blockage
$CoF_{leak,open}^{HEX,Turbine}$	The consequence of failure of heat exchanger and turbine due to leakage (open system)
$CoF_{leak,closed}^{HEX,Turbine}$	The consequence of failure of heat exchanger and turbine due to leakage (closed system)
$CoF_{cold}^{Tracing,HT}$	The consequence of failure of high temperature tracing due to blockage
$CoF_{leak,open}^{Tracing,HT}$	The consequence of failure of high temperature tracing due to leakage (open system)
$CoF_{leak,closed}^{Tracing,HT}$	The consequence of failure of high temperature tracing due to leakage (closed system)
$CoF_{cold}^{Tracing,LT}$	The consequence of failure of low temperature tracing due to blockage
$CoF_{leak,open}^{Tracing,LT}$	The consequence of failure of low temperature tracing due to leakage (open system)
$CoF_{leak,closed}^{Tracing,LT}$	The consequence of failure of low temperature tracing due to leakage (closed system)
COF_{inj}	The consequence of personnel injury
$COF_{inj,D/S}$	The consequence of personnel injury (downstream)
$COF_{inj,process}$	The consequence of personnel injury (process line)
$\boldsymbol{COF_{inj,nfnt}}$	The consequence of injury due to non-flammable, non-toxic
$\boldsymbol{COF_{inj,flam}}$	The consequence of injury due to flammable release
$\boldsymbol{COF_{inj,toxic}}$	The consequence of injury due to toxic release
$Cost_{prod}$	The cost of production loss
$Cost_{comp}$	The cost of component damage
$Cost_{prod,D/S}$	The cost of production loss (downstream)
$Cost_{compD/S}$	The cost of component damage(downstream)
$Cost_{comp,main}$	The cost of component damage (main pipe)
$Cost_{loss}$	The cost of steam
$Cost_{loss,D/S}$	The cost of condensate loss (downstream)
$Cost_{comp,line}$	The cost of component damage(tracing line)
$Cost_{prod,process}$	The cost of production loss (process line)
$Cost_{compprocess}$	The cost of component damage(process line)
CF_{pass}	Confidence factor for the inspection result not in failure
CF_{fail}	Confidence factor for the inspection result in failure
$F_{D_{ST}}$	Design adjustment multiplier for steam traps

$F_{O_{ST}}$	Operational adjustment multiplier for steam traps
$F_{M_{ST}}$	Maintenance/inspection history adjustment multiplier for steam traps
$\boldsymbol{F_{MS}}$	Management System Factor
$F_{D_{MP}}$	Design adjustment multiplier for mechanical pump
$F_{O_{MP}}$	Operational adjustment multiplier for mechanical pump
$F_{M_{MP}}$	Maintenance/inspection history adjustment multiplier for control valve
$F_{D_{CV}}$	Design adjustment multiplier for control valve
$F_{O_{CV}}$	Operational adjustment multiplier for mechanical pump
$F_{M_{CV}}$	Maintenance/inspection history adjustment multiplier for control valve
$F_{D_{equ}}$	Design adjustment multiplier for steam using equipment
$F_{M_{equ}}$	Maintenance/inspection history adjustment multiplier for steam using equipment
$F_{O_{equ}}$	Operational adjustment multiplier for steam using equipment
injcost	The cost of personnel injury per individual
$PoF_{adjusted-parallel}$	Tailored probability of failure for one steam trap in parallel
$PoF_{adjusted-series}$	Tailored probability of failure for one steam trap in series
$\boldsymbol{PoF(t)_{final\,(equ)}}$	Tailored probability of failure calculated for the steam using equipment
$POF_{steam\,using\,system}$	Probability of failure for steam using system
$\boldsymbol{PoF(t)_{final\,(ST,\ MP\ or\ CV)}}$	Tailored probability of failure calculated for the associated lines (combined POF), consisting of multiple steam traps, mechanical pumps and control valves
PoF_{after}	Probability of failure after inspection depending on the results
PoF_{prior}	The probability of not failing the inspection prior to inspection
PoF_{wgt}	The updated probability of failure after inspection
popdens	is the population density of personnel or employees in the unit, personnel/m^2 (personnel/ft^2)
t	The time at which the risk is to be calculated
t_i	Time to failure from historical data
$Unit_{prod}$	Daily production margin on the unit ($/day)
$Rate_{red}$	Production rate reduction on a unit as a result of the equipment being out of service (%)
η	Weibull parameter
$\eta_{adjusted}$	Tailored characteristic life (scale factor)
η_{defaul}	Scaled parameter estimated using Weibull AFT model

β	Shape factor estimated using AFT model

11 References

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Table 1 Steam-using application groups and equipment examples

Application Group	Equipment Example	Process Application Examples
Steam heated equipment	Process Heat Exchanger	Alkylation, distillation, gas recovery, isomerisation, visbreaking, coking, storage tank heating
Direct steam application	Distillation Tower	Distillation, fractionation
	Stripper	Crude and vacuum distillation, catalytic cracking, catalytic reforming, asphalt processing, lube oil processing, hydrogen treatment
	Flare	Air-assisted flares, pressure-assisted flares, enclosed ground flares,
Steam driven equipment	Steam Turbine	Power generation, compressor mechanical drive, hydrocracking, naphtha reforming, pump mechanical drive
Steam distribution piping	Piping	Piping to distribute steam and condensate recovery
Steam tracing	Tracing	Utility stations, steam and condensate piping

Table 2 Steam trap types for each of three categories of steam trap

Steam trap category	Common applications	Steam trap type
Mechanical steam traps	The mainstream of traps used today on equipment that requires large discharge capacities. Temperature / pressure controlled applications with fluctuating loads	Free float
		Lever float
		Inverted bucket
Thermostatic steam traps	Where condensate back-up can be tolerated or is required in order to remove excess enthalpy, e.g. non-critical tracing	Bimetal
		Balanced pressure trap
Thermodynamic steam traps	Tracing, drip, and certain light process steam applications	Thermodynamic Disc
		Thermodynamic Piston

Table 3 Basic data needed for POF calculation of steam-using system

Data	Description	Data Source

Steam trap type	Type of steam trap:
	• Mechanical steam traps
	  ○ Free float
	  ○ Lever float
	  ○ Inverted bucket
	• Thermostatic steam traps
	  ○ Bimetal
	  ○ Balanced pressure trap
	• Thermodynamic steam traps
	  ○ Thermodynamic Disc
	  ○ Thermodynamic Piston
		User Specified

Steam trap/ mechanical pump or control valve design, operational and maintenance/ inspection history conditions	Data required on whether the following conditions apply: • Design conditions exceed maximum allowable pressure or maximum allowable temperature (PMA/TMA); • Steam trap configuration and capacity of individual steam traps; • Possibility of steam locking; • Any line bundling (i.e. inlet tracing line is heated by other bundled pipes); • No protection from weather; • Poor installation environment (i.e. higher than average failure rate at this location or area); • No strainer exists; • Trap is made of stainless steel (any grade); • Internal and/or external strainer upstream of steam trap is installed; • ; • Operation conditions do not exceed maximum operating pressure or maximum operating temperature (PMO/TMO); • Operational stability is high, i.e. pressure/temperature/flow rate does not vary during normal operation; • Water hammer near the trap is recorded; • Disassembly preventive maintenance exists ; • Built-in integral/self-cleaning exists.	User Specified
Steam system inspection history	• Date of testing • Type of test (Effectiveness) • Results of test/inspection • Overhauled?	User Specified
Steam-Using Equipment	Steam-using equipment: • Steam Turbine • Heat Exchanger • Tracing – General • Tracing – Low Temperature (lower than 80ºC / 176ºF) • Tracing – Instrumentation • Tracing – Relief Valve • Steam Main Line • Condensate Line (Recovery) • Flare • Distillation Column	Fixed Equipment
Equipment Details	Operating conditions Design conditions Dimensions Other damage mechanisms and Damage Factors (as per Part 2)	User Specified

Table 4 Default Weibull parameters for different steam trap types

Steam Trap Category	Steam Trap Type	Failure Mode	Default β_{ST}	Default η_{defaul_ST}
Mechanical steam traps	Free Float	Blocked	1.8	13.8
		Leak		16.1
	Inverted bucket	Blocked	1.6	13.8
		Leak		16.1
	Lever Float	Blocked	1.7	8.5
		Leak		11.7
Thermostatic steam traps	Bimetal	Blocked	1.8	7.5
		Leak		8
	Balanced Pressure	Blocked	2	5.2
		Leak		5.3
Thermodynamic steam traps	Disc	Blocked	2	5
		Leak		9.4
	Impulse	Blocked	2	5
		Leak		9.4

Table 5 Design condition adjustment ($F_{D_{ST}}$) for steam trap

Design Condition	Description	Adjustment Multiplier for design conditions ($F_{D_{ST}}$)
Poor	If all of the below criteria are true: a. Design conditions exceed PMA / TMA b. Possibility of steam locking c. If any line bundling d. No protection from weather e. Poor installation environment f. No strainer exists	0.5
Average	If any of the following criteria are true: a. Design conditions exceed PMA / TMA b. Possibility of steam locking c. If any line bundling d. No protection from weather e. Poor installation environment f. No strainer exists	0.85
Good	If none of the following criteria are true AND the trap is not made of Stainless Steel (any grade) AND internal or external strainer is installed: a. Design conditions exceed PMA / TMA b. Possibility of steam locking c. If any line bundling d. No protection from weather e. Poor installation environment f. No strainer exists	1.0
Very Good	If none of the following criteria are true AND the trap is made of Stainless Steel (any grade) AND both internal and external strainer is installed: a. Design conditions exceed PMA / TMA b. Possibility of steam locking c. If any line bundling d. No protection from weather e. Poor installation environment f. No strainer exists	1.15
Steam locking: equipment configuration causing steam-condensate mixture entering the trap or piping configuration causing steam to move ahead of condensate into the trap. Line bundling: inlet tracing line is heated by other bundled pipes. Poor installation environment: higher than average failure rate at this location or area.		

Table 6 Operation condition adjustment ($F_{O_{ST}}$) for steam trap

Operation Condition	Description	Adjustment Multiplier for design conditions ($F_{O_{ST}}$)
Poor	If operation conditions exceed PMO / TMO AND operational stability is low (i.e. > 50% operation load variations expected)	0.77
Average	If operation conditions do not exceed PMO / TMO AND operational stability is medium (i.e. ≤ 50% operation load variations expected)	0.85
Good	If operation conditions does not exceed PMO / TMO AND operational stability is high (i.e. no operation load variations expected)	1

Table 7 Maintenance history/inspection condition adjustment ($F_{M_{ST}}$) for steam trap

Maintenance Condition	Description	Adjustment Multiplier for design conditions ($F_{M_{ST}}$)
Poor	If water hammer near the trap (i.e. within 10 metres) is recorded in the past AND no disassembly preventive maintenance exists.	0.65
Average	If water hammer near the trap (i.e. within 10 metres) is recorded in the past AND disassembly preventive maintenance exists	0.72
Good	If water hammer near the trap (i.e. within 10 metres) is not recorded AND disassembly preventive maintenance does not exist AND built-in manual cleaning exists	1.0
Very Good	If water hammer near the trap (i.e. within 10 metres) is not recorded AND disassembly preventive maintenance exists AND built-in integral/self-cleaning exists	1.1

Table 8 Design condition adjustment ($F_{D_{MP}}$) for mechanical pump

Design Condition	Description	Adjustment Multiplier for design conditions ($F_{D_{MP}}$)
Poor	If all of the below criteria are true: a. Design conditions exceed PMA / TMA b. Possibility of steam locking c. Poor installation environment d. System installation is non-ideal	0.5
Average	If any of the following criteria are true: a. Design conditions exceed PMA / TMA b. Possibility of steam locking c. Poor installation environment d. System installation is non-ideal	0.8
Good	If none of the following criteria are true AND the trap is not made of Stainless Steel (any grade) AND system installation is average: a. Design conditions exceed PMA / TMA b. Possibility of steam locking c. Poor installation environment	1.0
Very Good	If none of the following criteria are true AND the trap is made of Stainless Steel (any grade) AND system installation is ideal AND strainer installed: a. Design conditions exceed PMA / TMA b. Possibility of steam locking c. Poor installation environment	1.25
System installation is non-ideal: functionality is affected by sizing or configuration		

Table 9 Operation condition adjustment ($F_{O_{MP}}$) for mechanical pump

Operation Condition	Description	Adjustment Multiplier for design conditions ($F_{O_{MP}}$)
Poor	If operation conditions exceed PMO / TMO AND operational stability is low (i.e. > 50% operation load variations expected) AND pump load is high (i.e. > 75% of pump capacity)	0.76
Average	If operation conditions do not exceed PMO / TMO AND operational stability is medium (i.e. ≤ 50% operation load variations expected) OR pump load is medium (i.e. 50 – 75% of pump capacity)	1.2
Good	If operation conditions do not exceed PMO / TMO AND operational stability is high (i.e. no operation load variations expected) AND pump load is low (i.e. < 50% of pump capacity)	1.6

Table 10 Maintenance history/inspection condition adjustment ($F_{M_{MP}}$) for mechanical pump

Maintenance Condition	Description	Adjustment Multiplier for design conditions ($F_{M_{MP}}$)
Poor	If water hammer near the pump (i.e. within 10 metres) is recorded in the past	0.65
Average	If water hammer near the pump (i.e. within 10 metres) is not recorded AND disassembly preventive maintenance does not exist	1
Good	If water hammer near the pump (i.e. within 10 metres) is not recorded AND disassembly preventive maintenance exists	2

Table 11 Design condition adjustment ($F_{D_{CV}}$) for control valve

Design Condition	Description	Adjustment Multiplier for design conditions ($F_{D_{CV}}$)
Poor	If all of the below criteria are true: a. Design conditions exceed PMA / TMA b. Possibility of steam locking c. Poor installation environment (i.e. higher than average failure rate at this location or area)	0.6
Average	If any of the following criteria are true: a. Design conditions exceed PMA / TMA b. Possibility of steam locking c. Poor installation environment (i.e. higher than average failure rate at this location or area)	0.75
Good	If none of the following criteria are true: a. Design conditions exceed PMA / TMA b. Possibility of steam locking c. Poor installation environment (i.e. higher than average failure rate at this location or area)	1.0
Very Good	If none of the following criteria are true AND the trap is made of Stainless Steel (any grade) AND strainer installed: a. Design conditions exceed PMA / TMA b. Possibility of steam locking	1.3

	c. Poor installation environment (i.e. higher than average failure rate at this location or area)	

Table 12 Operation condition adjustment ($F_{O_{cv}}$) for control valve

Operation Condition	Description	Adjustment Multiplier for design conditions ($F_{O_{cv}}$)
Poor	If operation conditions exceed PMO / TMO AND operational stability is low (i.e. > 50% operation load variations expected) AND load is high (i.e. > 75% of valve capacity)	0.77
Average	If operation conditions do not exceed PMO / TMO AND operational stability (i.e. ≤ 50% operation load variations expected) is medium OR load is medium (i.e. 50 – 75% of valve capacity)	0.9
Good	If operation conditions do not exceed PMO / TMO AND operational stability is high (i.e. no operation load variations expected) AND load is low (i.e. < 50% of valve capacity)	1.0

Table 13 Maintenance history/inspection condition adjustment ($F_{M_{cv}}$) for control valve

Maintenance Condition	Description	Adjustment Multiplier for design conditions ($F_{M_{cv}}$)
Poor	If water hammer near the trap (i.e. within 10 metres) is recorded in the past	0.65
Average	If water hammer near the trap (i.e. within 10 metres) is not recorded AND disassembly preventive maintenance does not exist	1
Good	If water hammer near the trap (i.e. within 10 metres) is not recorded AND disassembly preventive maintenance exists	1.1

Table 14 Default Weibull parameters for steam-using equipment

Equipment	Default $\eta_{default\_equ}$	Default β_{equ}
Steam Turbine	34.48	3
Heat Exchanger	22.73	3
Tracing – Instrumentation	52.63	3
Tracing – Relief Valve	55.56	3
Steam Line	25.1	3
Condensate Line (Recovery)	21.5	3
Distillation Column	37	3
Flare	13.3	3

Table 15 Design condition adjustment ($F_{D_{equ}}$) for steam-using equipment

Design Condition	**Description**	**Adjustment Multiplier for design conditions ($F_{D_{equ}}$)**
Poor	If all of the below criteria are true: a. No inlet steam separator b. No appropriate steam trap (type and capacity) is installed c. Major reduction in number of steam traps (as per design) d. No automatic/manual start function e. One or more locations on steam supply that require condensate drainage cannot discharge continuously	0.5
Average	If any of the following criteria are true: a. No inlet steam separator b. No appropriate steam trap (type and capacity) is installed c. Major reduction in number of steam traps (as per design) d. No automatic/manual start function e. One or more locations on steam supply that require condensate drainage cannot discharge continuously	0.7
Good	If none of the below criteria are true AND steam traps are not equipped with by-pass: a. No inlet steam separator b. No appropriate steam trap (type and capacity) is installed c. Major reduction in number of steam traps (as per design) d. No automatic/manual start function e. One or more locations on steam supply that require condensate drainage cannot discharge continuously	1.0
Very Good	If none of the below criteria are true AND all steam traps equipped with by-pass a. No inlet steam separator b. No appropriate steam trap (type and capacity) is installed c. Major reduction in number of steam traps (as per design) d. No automatic/manual start function e. One or more locations on steam supply that require condensate drainage cannot discharge continuously	1.1

Table 16 Operation condition adjustment ($F_{O_{equ}}$) for steam-using equipment

Operation Condition	Description	Adjustment Multiplier for design conditions ($F_{O_{equ}}$)
Poor	If all of the below criteria are true: a. Superheat rate <10°C (18°F) b. Cyclic operation c. Exceed PMO/TMO/Steam Mass d. In the case of turbine: superheat rate < 15ºC (27°F) AND (for condensing turbine only) operating vacuum > 25% weaker than design e. In the case of heat exchanger: superheat rate is ≥ 10° C (18°F) AND steam passing through outlet control valve (if existing) AND > 50% operation load variations expected AND stall condition exists (i.e. insufficient different pressure)	0.45
Average	If minimum of 4 criteria from the below are true: a. Superheat rate <10°C (18°F) b. Cyclic operation c. Exceed PMO/TMO/Steam Mass d. In the case of turbine: superheat rate < 15ºC (27°F) AND (for condensing turbine only) operating vacuum > 25% weaker than design e. In the case of heat exchanger: superheat rate is ≥ 10°C (18°F) AND steam passing through outlet control valve (if existing) AND > 50% operation load variations expected AND stall condition exists (i.e. insufficient different pressure)	0.7
Good	If minimum of 2 criteria from the below are true: a. Superheat rate <10°C (18°F) b. Cyclic operation c. Exceed PMO/TMO/Steam Mass d. In the case of turbine: superheat rate < 15°C (27°F) AND (for condensing turbine only) operating vacuum > 25% weaker than design e. In the case of heat exchanger: superheat rate is ≥ 10°C (18°F) AND steam passing through outlet control valve (if existing) AND > 50% operation load variations expected AND stall condition exists (i.e. insufficient different pressure)	0.85
Very Good	If none of the below criteria is true: a. Superheat rate <10°C (18°F) b. Cyclic operation c. Exceed PMO/TMO/Steam Mass d. In the case of turbine: superheat rate < 15°C (27°F) AND (for condensing turbine only) operating vacuum > 25% weaker than design e. In the case of heat exchanger: superheat rate is ≥ 10°C (18°F) AND steam passing through outlet control valve (if existing) AND > 50% operation load variations expected AND stall condition exists (i.e. insufficient different pressure)	1.0

Table 17 Maintenance history/inspection condition adjustment ($F_{M_{equ}}$) for steam-using equipment

Maintenance Condition	Description	Adjustment Multiplier for design conditions ($F_{M_{equ}}$)
Poor	Ongoing likelihood of water hammer AND damage/repair AND trips reported previously AND no maintenance conducted as recommended	0.4
Average	Low likelihood of water hammer AND damage/repair AND trips reported previously AND no maintenance conducted as recommended	0.6
Good	No likelihood of water hammer AND damage/repair AND trips not reported previously in previous AND maintenance recommendations are all conducted	1.0

Table 18 Inspection and testing effectiveness for steam traps

Inspection Effectiveness	Failure Mode	Description of Inspection or Testing
Highly effective	Leakage Blockage	Certified* tools and certified* inspector and comprehensive data collection as per Table 3 (e.g. including related valves, piping and location data)
Usually effective	Leakage Blockage	On-line monitoring with diagnostic function
Fairly effective	Leakage Blockage	Non-certified tools and/or non-certified inspector, OR Certification unknown, OR On-line monitoring without diagnostic function
Ineffective	Leakage Blockage	No inspection, OR Incorrect inspection method

* The tool and inspector should be certified to relevant standard or code.

Table 19 Level of inspection Confidence Factor for steam traps

Inspection results	Confidence factor that inspection result determines the true damage state, CF			
	Ineffective	Fairly effective	Usually effective	Highly effective
Leak detected, CF_{fail}	No credit	0.6	0.85	0.95
Leak not detected, CF_{pass}	No credit	0.6	0.75	0.9
Blocked, CF_{fail}	No credit	0.6	0.85	0.95
Not Blocked, CF_{pass}	No credit	0.6	0.85	0.95

Table 20 Equations for updating the POF after inspection

Inspection effectiveness and results	Inspection results	Equation for updating the POF after inspection
Highly effective	No leakage or blockage detected	$\boldsymbol{PoF_{wgt} = PoF_{adjusted} - 0.2 \times PoF_{adjusted}\left(\frac{t}{\eta_{adjusted\_ST}}\right) + 0.2 \times PoF_{after}\left(\frac{t}{\eta_{adjusted\_ST}}\right)}$
Usually effective		
Fairly effective		
Highly effective	Leakage or blockage detected	$\boldsymbol{PoF_{wgt} = PoF_{after}}$
Usually effective		
Fairly effective		$\boldsymbol{PoF_{wgt} = 0.5 \times PoF_{adjusted} + 0.5 \times PoF_{after}}$

Table 21 Required user input parameters for COF assessment

Cost	Input data
Steam loss, $Cost_{LOSS}$	Cost of steam
	Inspection interval, 8760 hours IF not defined by user
Production loss, $Cost_{prod}$	$Unit_{prod}$, Daily production margin on the unit ($/day)
	$Rate_{red}$, Production rate reduction on a unit as a result of the equipment being out of service (%)
	D_{sd}, The number of days required to shut a unit down to repair the equipment during an unplanned shutdown (days)
Component Damage cost, $Cost_{comp}$	User direct input
Safety impact of rupture, COF_{rup}	Pipe inside diameter, mm (inches)
	Operating pressure, MPa (psi)
	Leak duration (optional), otherwise default to 3 minutes
	Injury cost per person
	Population density, number of people per square meter
COF of leakage, COF_{leak}	Release hole size, otherwise defaulted to inlet size
	Pipe inlet diameter, mm (inches)
	Storage pressure, MPa (psi)
	Injury cost per person
	Population density, number of people per square meter
COF of rupture of process line	Pipe inlet diameter, mm (inches)
	Absolute storage pressure, MPa (psi)
	Leak duration (Optional), otherwise default to 3 minutes
	Injury cost per person
	Population density, number of people per square meter
	Fluids (select from list)

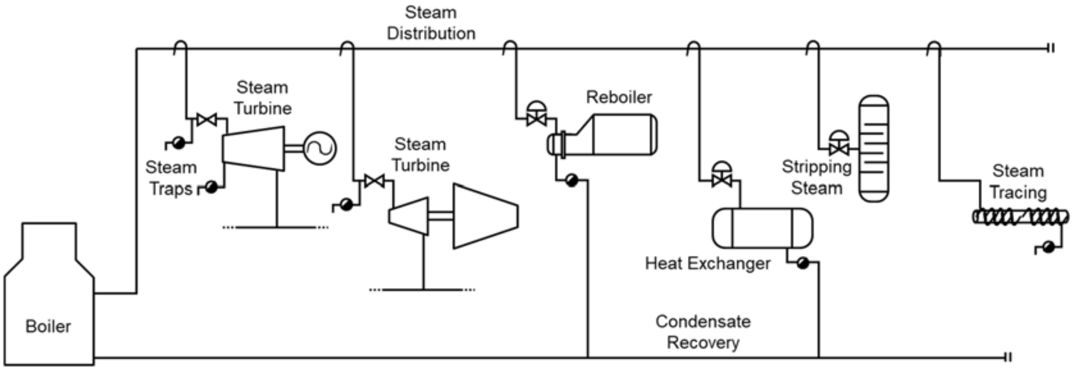

Figure 1 A typical steam system containing steam traps, steam lines and associated equipment

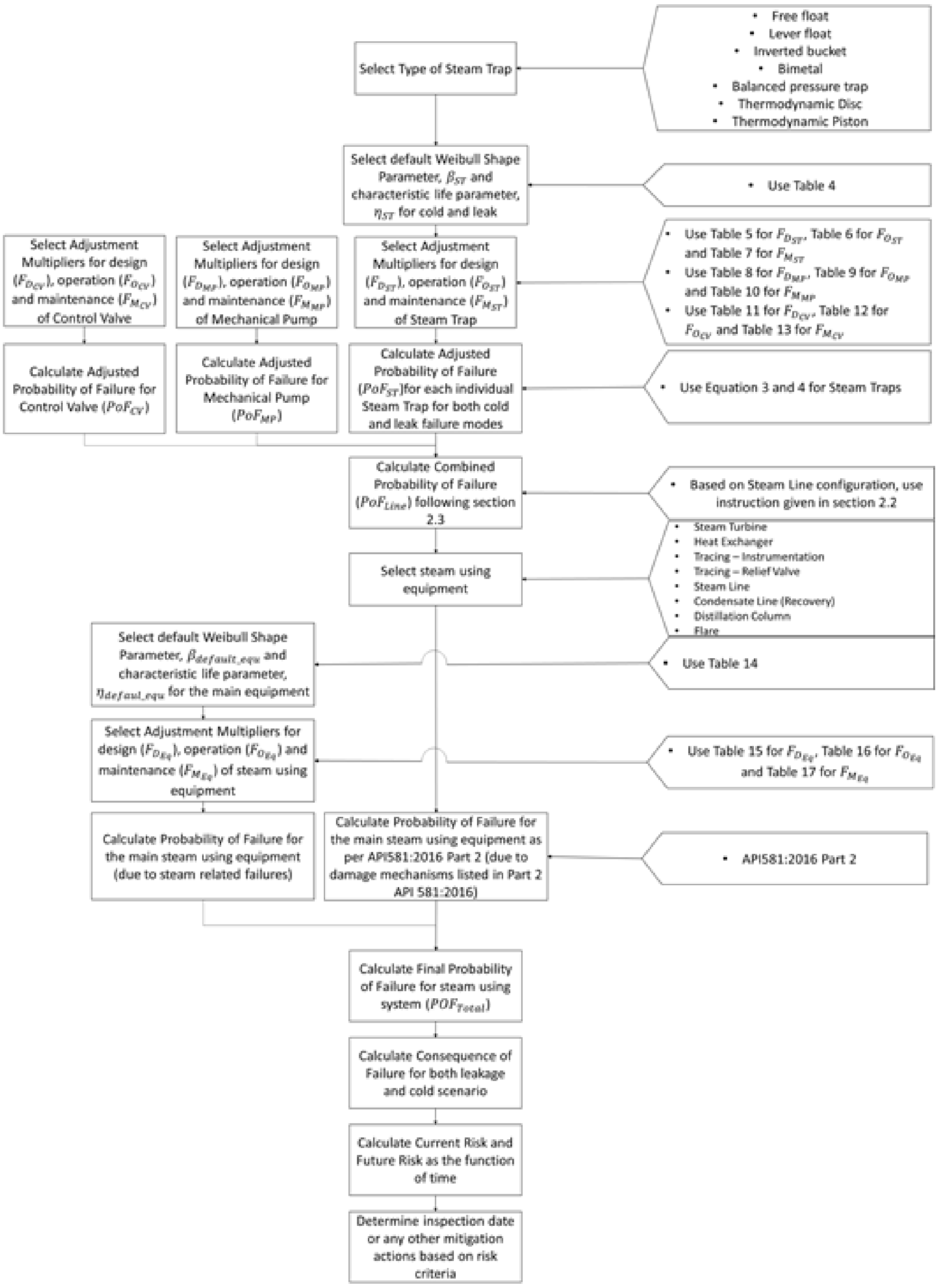

Figure 2 Overview of POF calculation framework for steam systems.

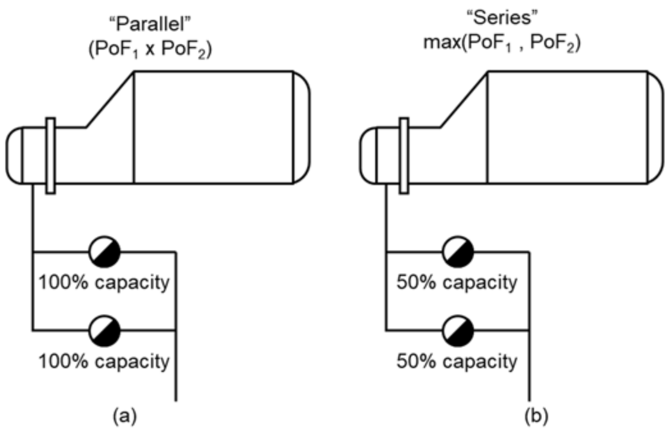

Figure 3 Sample configuration of multiple steam traps.

Worked Examples

Worked Example: 1

To illustrate the calculation for risk of steam line application, the following data is supplied:
Table 1: Data provided by client

Parameter	Value
In-service duration of steam line, $t_{service\ (equ)}$	15 years
Arrangement of steam traps	Series
Capacity of steam traps	Relief in full capacity
Design condition for the steam line	Very Good
Operating condition for the steam line	Average
Maintenance condition for the steam line	Good
Management system factor	1
Closed system	No
Unit cost of steam (USD/1000kg)	20
Leakage rate (kg/hr)	8
Safety impact cost due to steam trap blockage (USD)	287,000
Safety impact cost due to steam trap leakage (USD)	10,000
Component damage (USD)	20,000
Environmental cost (USD)	0
Daily production margin on the unit (USD/day)	100,000
Production rate reduction on a unit as a result of equipment being out of service	100%
Days required to shut the unit down to repair the equipment during an unplanned shutdown	3

Table 2: Data gathered for steam traps

Parameter	Trap 1 ($ST1$)	Trap 2 ($ST2$)	Trap 3 ($ST3$)	Trap 4 ($ST4$)
Type of Steam Trap	Free Float	Free Float	Free Float	Free Float
In-service Duration, $t_{service\ (ST)}$	6 years			
Design Condition	Good	Average	Average	Average
Operating Condition	Average	Good	Good	Poor
Maintenance Condition	Very Good	Good	Average	Good
Year of Last Inspection, t_{insp}	5			
Inspection Effectiveness	Highly Effective	Highly Effective	Highly Effective	Highly Effective
Inspection Result	Good	Good	Good	Good

Establishing POF:

Step 1: Identify the type, configuration and number of steam traps, mechanical pumps and control valves in the system. Also, establish if there is any associated steam using equipment in the steam system. Gather data as defined in Table 3.

Steam system consists of 4 steam traps and a steam line. The data has been provided in Table 1 and 2.

Step 2: Calculate the POF for the steam traps

Step 2.1: Determine the default values of the Weibull parameters based on the appropriate failure modem from Table 4.

Steam Trap Type	Failure Model	Default β_{ST}	Default η_{defaul_ST}
Free Float	Blocked	1.8	13.8
	Leak		16.1

Step 2.2: Using Table 5, determine the design, operating and maintenance condition adjustment for each steam trap.

Adjustment Factors	Trap 1 ($ST1$)	Trap 2 ($ST2$)	Trap 3 ($ST3$)	Trap 4 ($ST4$)
$F_{D_{ST}}$	1.0	0.85	0.85	0.85
$F_{O_{ST}}$	0.85	1.0	1.0	1.0
$F_{M_{ST}}$	1.1	1.0	0.72	1.0

Step 2.3: Using equation [3], adjust the Weibull parameter $\boldsymbol{\eta_{default}}$ based on the values in Step 2.2.

$$\boldsymbol{\eta_{adjusted\,(ST)} = \eta_{default\,(ST)} \times \left(F_{D_{ST}} \times F_{O_{ST}} \times F_{M_{ST}}\right)}$$

$$\eta_{adjusted\,(ST\,1\_blockage)} = 13.8 \times (1 \times 0.85 \times 1.1) = 12.90$$

$$\eta_{adjusted\,(ST\,1\_leakage)} = 16.1 \times (1 \times 0.85 \times 1.1) = 15.05$$

The values of the adjusted $\boldsymbol{\eta_{adjusted\,(ST)}}$ based on the equation:

Steam trap	$\eta_{adjusted\,(ST)}$ for blocked	$\eta_{adjusted\,(ST)}$ for leakage
Trap 1 ($\boldsymbol{ST1}$)	12.9	15.05
Trap 2 ($\boldsymbol{ST2}$)	11.73	13.69
Trap 3 ($\boldsymbol{ST3}$)	8.45	9.85
Trap 4 ($\boldsymbol{ST4}$)	11.73	13.69

Step 2.4: Using equation [4], calculate the POF for the steam traps based on the adjusted Weibull parameter $\boldsymbol{\eta_{adjusted\,(ST)}}$

$$\boldsymbol{PoF(t_{insp})_{adjusted\,(ST)} = 1 - exp\left[-\left(\frac{t_{insp}}{\eta_{adjusted\,(ST)}}\right)^{\beta_{ST}}\right]}$$

$$PoF(t_{insp})_{adjusted\ (ST1)\_blockage} = 1 - exp\left[-\left(\frac{5}{12.9}\right)^{1.8}\right] = 0.1661$$

$$PoF(t_{insp})_{adjusted\ (ST1)\_leakage} = 1 - exp\left[-\left(\frac{5}{15.05}\right)^{1.8}\right] = 0.1285$$

Summarising the values of the adjusted $\boldsymbol{PoF(t_{insp})_{adjusted\ (ST)}}$ based on the equation:

Steam trap	$PoF_{adjusted\ (ST)}$ for blocked	$PoF_{adjusted\ (ST)}$ for leakage
Trap 1 ($\boldsymbol{ST1}$)	0.1661	0.1285
Trap 2 ($\boldsymbol{ST2}$)	0.1938	0.1505
Trap 3 ($\boldsymbol{ST3}$)	0.3222	0.2555
Trap 4 ($\boldsymbol{ST4}$)	0.1938	0.1505

Step 3: Inspection POF updating for steam traps:

Step 3.1: Identify the effectiveness of the inspection and testing method using Table 18. Inspection effectiveness and outcomes are provided in Table 2.

Step 3.2: Using Equation [9], calculate the probability of not failing the inspection prior to inspection:

$$\boldsymbol{P_{prior} = 1 - PoF_{adjusted\ (ST)}}$$

$$P_{prior\_ST1\_blockage} = 1 - 0.1661 = 0.8339$$

$$P_{prior\_ST1\_leakage} = 1 - 0.1285 = 0.8715$$

Steam trap	P_{prior} for blocked	P_{prior} for leakage
Trap 1 ($\boldsymbol{ST1}$)	0.8339	0.8715
Trap 2 ($\boldsymbol{ST2}$)	0.8062	0.8495
Trap 3 ($\boldsymbol{ST3}$)	0.6778	0.7445
Trap 4 ($\boldsymbol{ST4}$)	0.8062	0.8495

Step 3.3: Identify the confidence factor (CF) associated with the inspection effectiveness and inspection result using Table 19.

Inspection results	Confidence factor that inspection result determines the true damage state, CF			
	Trap 1 (ST1)	Trap 2 (ST2)	Trap 3 (ST3)	Trap 4 (ST4)
Leak not detected, $CF_{pass,leak}$	0.9	0.9	0.9	0.9
Not Blocked, $CF_{pass,blocked}$	0.95	0.95	0.95	0.95

Step 3.4: Inspection has not reported any failure, therefore by using Equation [10], PoF_{after} was calculated for both blockage and leakage failure:

$$\boldsymbol{PoF_{after} = (1 - CF) \times P_{prior}}$$

$$PoF_{after\_ST1\_blockage} = (1 - 0.95) \times 0.8339 = 0.04170$$

$$PoF_{after\_ST1\_leakage} = (1 - 0.9) \times 0.8715 = 0.08715$$

Steam trap	PoF_{after} for blocked	PoF_{after} for leakage
Trap 1 ($ST1$)	0.04170	0.08715
Trap 2 ($ST2$)	0.04031	0.08495
Trap 3 ($ST3$)	0.03389	0.07445
Trap 4 ($ST4$)	0.04031	0.08495

Step 3.5: Look up the appropriate equation for updating the POF after inspection using Table 20, and calculate the PoF_{wgt}, based on the inspection effectiveness and inspection results.

$$\boldsymbol{PoF_{wgt} = PoF_{adjusted} - 0.2 \times PoF_{adjusted\,(ST)}\left(\frac{t_{insp}}{\eta_{adjusted\,(ST)}}\right) + 0.2 \times PoF_{after}\left(\frac{t_{insp}}{\eta_{adjusted\,(ST)}}\right)}$$

$$PoF_{wgt\_ST1\_blockage} = 0.1661 - 0.2 \times 0.1661\left(\frac{5}{12.9}\right) + 0.2 \times 0.04170\left(\frac{5}{12.9}\right) = 0.1565$$

$$PoF_{wgt\_ST1\_leakage} = 0.1285 - 0.2 \times 0.1285\left(\frac{5}{15.05}\right) + 0.2 \times 0.08715\left(\frac{5}{15.05}\right) = 0.1258$$

Steam trap	PoF_{wgt} for blocked	PoF_{wgt} for leakage
Trap 1 ($ST1$)	0.1565	0.1258
Trap 2 ($ST2$)	0.1807	0.1457
Trap 3 ($ST3$)	0.2881	0.2371
Trap 4 ($ST4$)	0.1807	0.1457

Step 3.6: Using equation [12], update the characteristic life $\eta_{adjusted\,(ST)}$, with using the same β_{ST} shape factor established earlier:

$$\boldsymbol{\eta_{upd} = \frac{t_{insp}}{\left(-\ln[1 - PoF_{wgt}]\right)^{\frac{1}{\beta_{ST}}}}}$$

$$\eta_{upd\_ST1\_blockage} = \frac{5}{\left(-\ln[1 - 0.1565]\right)^{\frac{1}{1.8}}} = 13.37$$

$$\eta_{upd\_ST1\_leakage} = \frac{5}{\left(-\ln[1 - 0.1258]\right)^{\frac{1}{1.8}}} = 15.24$$

Steam trap	η_{upd} for Blocked	η_{upd} for Leakage
Trap 1 ($ST1$)	13.37	15.24
Trap 2 ($ST2$)	12.25	13.96
Trap 3 ($ST3$)	9.11	10.34
Trap 4 ($ST4$)	12.25	13.96

Step 3.7: Using equation [13] calculate the POF at year in service.

$$\boldsymbol{PoF_{upd} = 1 - exp\left[-\left(\frac{t_{service\,(ST)}}{\eta_{upd}}\right)^{\beta_{ST}}\right]}$$

$$PoF_{upd\_ST1\_blockage} = 1 - exp\left[-\left(\frac{6}{13.37}\right)^{1.8}\right] = 0.2105$$

$$PoF_{upd\_ST1\_leakage} = 1 - exp\left[-\left(\frac{6}{15.24}\right)^{1.8}\right] = 0.1704$$

Steam trap	PoF_{upd} for Blocked	PoF_{upd} for Leakage
Trap 1 ($ST1$)	0.2105	0.1704
Trap 2 ($ST2$)	0.2417	0.1964
Trap 3 ($ST3$)	0.3760	0.3130
Trap 4 ($ST4$)	0.2417	0.1964

Step 3.8: Using equation [5], calculate the $\boldsymbol{PoF(t)_{final\,(ST,\;MP\,or\,CV)}}$ for the steam traps based on series arrangement for both failure modes, at $\boldsymbol{t_{service\,(ST)}}$:

$$\boldsymbol{PoF\left(t_{service\,(ST)}\right)_{series\,(ST)} = max\left(PoF_{(ST1)}, PoF_{(ST2)}, PoF_{(ST3)}, PoF_{(ST4)}\right)}$$

$$PoF\left(t_{service\,(ST)}\right)_{series\,(ST\_blockage)} = max\,(0.2105, 0.2417, 0.3760, 0.2417) = 0.3760$$

$$PoF\left(t_{service\,(ST)}\right)_{series\,(ST\_leakage)} = max\,(0.1704, 0.1964, 0.3130, 0.1964) = 0.3130$$

	Blocked	Leakage
$\boldsymbol{PoF(t_{service\,(ST)})_{lines}}$	0.3760	0.3130

Step 4: Calculate the POF for the steam line:

Step 4.1: Identify the default Weibull parameters for the steam line from Table 14.

$$\boldsymbol{\eta_{default\,(equ)} = 25.1}$$

$$\boldsymbol{\beta_{equ} = 3}$$

Step 4.2: Using Table 15, determine the design condition adjustment ($\boldsymbol{F_{D_{equ}}}$) for the steam line.
The design condition adjustment ($\boldsymbol{F_{D_{equ}}}$): Very Good

$$\boldsymbol{F_{D_{equ}} = 1.1}$$

Step 4.3: Using Table 16, determine the operation condition adjustment ($\boldsymbol{F_{O_{equ}}}$) for the steam line.
The operation condition adjustment ($\boldsymbol{F_{O_{equ}}}$): Average

$$\mathbf{F_{O_{equ}} = 0.7}$$

Step 4.4: Using Table 17, determine the maintenance history/inspection condition adjustment ($\boldsymbol{F_{M_{equ}}}$) for the steam line.
The maintenance history/inspection condition adjustment ($\boldsymbol{F_{M_{equ}}}$): Good

$$\mathbf{F_{M_{equ}} = 1}$$

Step 4.5: Using equation [7], adjust the Weibull parameter $\boldsymbol{\eta_{default\,(equ)}}$ based on the values in Steps 4.2, 4.3 and 4.4.

$$\boldsymbol{\eta_{adjusted\,(equ)} = \eta_{default\,(equ)} \times (F_{D_{equ}} \times F_{O_{equ}} \times F_{M_{equ}})}$$

$$\eta_{adjusted\,(equ)} = 25.1 \times (1.1 \times 0.7 \times 1) = 19.33$$

Step 4.6: Using equation [8], calculate the POF for the steam line based on the adjusted Weibull parameter $\boldsymbol{\eta_{default\,(equ)}}$

$$\boldsymbol{PoF(t_{service})_{final\,(equ)} = 1 - exp\left[-\left(\frac{t_{service}}{\eta_{adjusted\,(equ)}}\right)^{\beta_{equ}}\right]}$$

$$PoF(t_{service})_{final\,(equ)} = 1 - exp\left[-\left(\frac{15}{19.33}\right)^{3}\right] = 0.3733$$

Step 5: Using equation [2], estimate the POF for the steam using system.

$$\boldsymbol{POF_{Steam\ using\ System} = F_{MS} \times\ PoF(t)_{final\,(equ)} \times PoF(t)_{final\,(ST,\ \ MP\ or\ CV)}}$$

$$POF_{Steam\ using\ System\_blockage} = 1 \times\ 0.3733 \times 0.3760 = 0.1404$$

$$POF_{Steam\ using\ System\_leakage} = 1 \times\ 0.3733 \times 0.3130 = 0.1168$$

	Blocked	Leakage
$\boldsymbol{POF_{Steam\ using\ System}}$	0.1404	0.1168

Establishing COF:

Step 1: Calculate the cost of steam lost from equation [14]:

$$\boldsymbol{Cost_{steam\_loss} = \frac{leakage\ rate\ \times 8760 \times cost\ of\ steam}{1000} = \$1402}$$

$$Cost_{steam\_loss} = \frac{8\ \times 8760 \times 20}{1000} = \$1402$$

Step 2: The system is open hence go to step 3.

Step 3: Calculate the cost of production loss from equation [16]:

$$\boldsymbol{Cost_{production\ loss} = Unit_{prod}\ \times \frac{Rate_{red}}{100} \times D_{sd}}$$

$$Cost_{production\ loss} = 100{,}000\ \times \frac{100}{100} \times 3 = \$300{,}000$$

Step 4: Cost of safety impact:

$$\boldsymbol{Cost_{safety\ impact,blockage} = \$287{,}000}$$

$$\boldsymbol{Cost_{safety\ impact,leakage}} = \$\mathbf{10,000}$$

Step 5: Cost of component damage:

$$\boldsymbol{Cost_{component\ damage}} = \$\mathbf{20,000}$$

For leakage, the COF:

$$\boldsymbol{COF_{leakage}} = \boldsymbol{Cost_{steam\_loss}} + \boldsymbol{Cost_{safety\ impact,leakage}} = \$\mathbf{11,402}$$

$$COF_{leakage} = 1402 + 10{,}000 = \$11{,}402$$

For blockage, the COF:

$$\boldsymbol{COF_{blockage}} = \boldsymbol{Cost_{component\ damage}} + \boldsymbol{Cost_{production\ loss}} + \boldsymbol{Cost_{safety\ impact,blockage}} + \boldsymbol{Cost_{environment}}$$

$$COF_{blockage} = 20{,}000 + 300{,}000 + 287{,}000 + 0 = \$607{,}000$$

Risk:

The risk associated with the failure of the steam equipment is calculated using equation [30] for blocked and leakage. The total risk is the summation of both.

$$\boldsymbol{Risk\left(t_{service\ (equ)}\right)} = \left[\boldsymbol{PoF_{blockage}\left(t_{service\ (equ)}\right)} \times \boldsymbol{COF_{blockage}}\right] + \left[\boldsymbol{PoF_{leakage}\left(t_{service\ (equ)}\right)} \times \boldsymbol{COF_{leakage}}\right]$$

$$Risk\left(t_{service\ (equ)}\right) = [0.1404 \times 607{,}000] + [0.1168 \times 11{,}402] = 86554.55$$

For the output, the risk is calculated as a function of time on a risk matrix.

Worked Example: 2

Calculate the risk of failure for a 20 inch flare service by a steam line with 3 steam traps.

To illustrate the calculation for risk of flare application, the following data is supplied:

Parameter	Value
In-service duration of flare, $t_{service\,(equ)}$	10 years
Arrangement of steam traps	Series
Capacity of steam traps	Relief in full capacity
Design condition for the flare	Good
Operating condition for the flare	Good
Maintenance condition for the flare	Very Good
Management system factor	1
Closed system	No
Unit cost of steam (USD/1000kg)	10
Leakage rate (kg/hr)	15
Safety impact cost due to steam trap blockage (USD)	160,000
Safety impact cost due to steam trap leakage (USD)	9,000
Component damage (USD)	100,000
Environmental cost (USD)	0
Daily production margin on the unit (USD/day)	300,000
Production rate reduction on a unit as a result of equipment being out of service	100%
Days required to shut the unit down to repair the equipment during an unplanned shutdown	5

Parameter	Trap 1 ($ST1$)	Trap 2 ($ST2$)	Trap 3 ($ST3$)
Type of Steam Trap	Free Float	Disc	Disc
In-service Duration, $t_{service\,(ST)}$	8 years	3 years	
Design Condition	Good	Very Good	Good
Operating Condition	Average	Average	Good
Maintenance Condition	Good	Good	Good
Year of Last Inspection, t_{insp}	7	2	
Inspection Effectiveness	Highly Effective	Highly Effective	Highly Effective
Inspection Result	Good	Good	Good

Establishing POF:

Step 1: Identify the type, configuration and number of steam traps, mechanical pumps and control valves in the system. Also, establish if there is any associated steam using equipment in the steam system. Gather data as defined in Table 3.

Steam system consists of 3 steam traps and a flare line. The data has been provided in Table 3 and 4.

Step 2: Calculate the POF for the steam traps

Step 2.1: Determine the default values of the Weibull parameters based on the appropriate failure modem from Table 4.

Steam Trap Type	Failure Model	Default β_{ST}	Default η_{defaul_ST}
Free Float	Blocked	1.8	13.8
	Leak		16.1
Disc	Blocked	2	5
	Leak		9.4

Step 2.2: Using Table 5, determine the design, operating and maintenance condition adjustment for each steam trap.

Adjustment Factors	Trap 1 ($ST1$)	Trap 2 ($ST2$)	Trap 3 ($ST3$)
$F_{D_{ST}}$	1.0	1.15	1.0
$F_{O_{ST}}$	0.85	0.85	1.0
$F_{M_{ST}}$	1.1	1.0	1.0

Step 2.3: Using equation [3], adjust the Weibull parameter $\eta_{default}$ based on the values in Step 2.2.

$$\eta_{adjusted\,(ST)} = \eta_{default\,(ST)} \times \left(F_{D_{ST}} \times F_{O_{ST}} \times F_{M_{ST}}\right)$$

$$\eta_{adjusted\ (ST1\_blockage\ )} = 13.8 \times (1 \times 0.85 \times 1.1) = 12.09$$

$$\eta_{adjusted\ (ST1\ \_leakage)} = 16.1 \times (1 \times 0.85 \times 1.1) = 15.05$$

The values of the adjusted $\boldsymbol{\eta_{adjusted\ (ST\ )}}$ based on the equation:

Steam trap	$\eta_{adjusted\ (ST\ )}$ for blocked	$\eta_{adjusted\ (ST\ )}$ for leakage
Trap 1 ($\boldsymbol{ST1}$)	12.90	15.05
Trap 2 ($\boldsymbol{ST2}$)	4.89	9.19
Trap 3 ($\boldsymbol{ST3}$)	5.0	9.4

Step 2.4: Using equation [4], calculate the POF for the steam traps based on the adjusted Weibull parameter $\boldsymbol{\eta_{adjusted\ (ST\ )}}$

$$\boldsymbol{PoF(t_{insp})_{adjusted\ (ST)} = 1 - exp\left[-\left(\frac{t_{insp}}{\eta_{adjusted\ (ST)}}\right)^{\beta_{ST}}\right]}$$

$$PoF(t_{insp})_{adjusted\ (ST1\_blockage)} = 1 - exp\left[-\left(\frac{7}{12.9}\right)^{1.8}\right] = 0.2830$$

$$PoF(t_{insp})_{adjusted\ (ST\_leakage)} = 1 - exp\left[-\left(\frac{7}{15.05}\right)^{1.8}\right] = 0.2229$$

Summarising the values of the adjusted $\boldsymbol{PoF(t_{insp})_{adjusted\ (ST)}}$ based on the equation:

Steam trap	$PoF_{adjusted\ (ST)}$ for blocked	$PoF_{adjusted\ (ST)}$ for leakage
Trap 1 ($\boldsymbol{ST1}$)	0.2830	0.2229
Trap 2 ($\boldsymbol{ST2}$)	0.1540	0.0463
Trap 3 ($\boldsymbol{ST3}$)	0.1479	0.0443

Step 3: Inspection POF updating for steam traps:

Step 3.1: Identify the effectiveness of the inspection and testing method using Table 18.

Step 3.2: Using Equation [9], calculate the probability of not failing the inspection prior to inspection:

$$\boldsymbol{P_{prior} = 1 - PoF_{adjusted\ (ST)}}$$

$$P_{prior\_ST1\_blockage} = 1 - 0.2830 = 0.7170$$

$$P_{prior\_ST1\_leakage} = 1 - 0.2229 = 0.7771$$

Steam trap	P_{prior} for blocked	P_{prior} for leakage
Trap 1 ($\boldsymbol{ST1}$)	0.7170	0.7771
Trap 2 ($\boldsymbol{ST2}$)	0.8460	0.9537
Trap 3 ($\boldsymbol{ST3}$)	0.8521	0.9557

Step 3.3: Identify the confidence factor (CF) associated with the inspection effectiveness and inspection result using Table 19.

Inspection results	Confidence factor that inspection result determines the true damage state, CF		
	Trap 1 (ST1)	Trap 2 (ST2)	Trap 3 (ST3)
Leak not detected, $CF_{pass,leak}$	0.9	0.9	0.9
Not Blocked, $CF_{pass,blocked}$	0.95	0.95	0.95

Step 3.4: Inspection has not reported any failure, therefore by using Equation [10], PoF_{after} was calculated for both blockage and leakage failure:

$$\boldsymbol{PoF_{after} = (1 - CF) \times P_{prior}}$$

$$PoF_{after\_ST1\_blockage} = (1 - 0.95) \times 0.7170 = 0.03585$$

$$PoF_{after\_ST1\_leakage} = (1 - 0.9) \times 0.7771 = 0.0777$$

Steam trap	$\boldsymbol{PoF_{after}}$ for blocked	$\boldsymbol{PoF_{after}}$ for leakage
Trap 1 ($\boldsymbol{ST1}$)	0.03585	0.07771
Trap 2 ($\boldsymbol{ST2}$)	0.04230	0.09537
Trap 3 ($\boldsymbol{ST3}$)	0.04261	0.09557

Step 3.5: Look up the appropriate equation for updating the POF after inspection using Table 20, and calculate the PoF_{wgt}, based on the inspection effectiveness and inspection results.

$$\boldsymbol{PoF_{wgt} = PoF_{adjusted} - 0.2 \times PoF_{adjusted\,(ST)}\left(\frac{t_{insp}}{\eta_{adjusted\,(ST)}}\right) + 0.2 \times PoF_{after}\left(\frac{t_{insp}}{\eta_{adjusted\,(ST)}}\right)}$$

$$PoF_{wgt\_ST1\_blockage} = 0.2830 - 0.2 \times 0.2830 \times \left(\frac{7}{12.90}\right) + 0.2 \times 0.03585\left(\frac{7}{12.90}\right) = 0.2562$$

$$PoF_{wgt\_ST1\_leakage} = 0.2229 - 0.2 \times 0.2229 \times \left(\frac{7}{15.05}\right) + 0.2 \times 0.07771\left(\frac{7}{15.05}\right) = 0.20935$$

Steam trap	$\boldsymbol{PoF_{wgt}}$ for blocked	$\boldsymbol{PoF_{wgt}}$ for leakage
Trap 1 ($\boldsymbol{ST1}$)	0.25622	0.20935
Trap 2 ($\boldsymbol{ST2}$)	0.14490	0.04840
Trap 3 ($\boldsymbol{ST3}$)	0.13943	0.04644

Step 3.6: Using equation [12], update the characteristic life $\eta_{adjusted\,(ST)}$, with using the same β_{ST} shape factor established earlier:

$$\boldsymbol{\eta_{upd} = \frac{t_{insp}}{(-\ln[1 - PoF_{wgt}])^{\frac{1}{\beta_{ST}}}}}$$

$$\eta_{upd\_ST1\_blockage} = \frac{7}{(-\ln[1 - 0.25622])^{\frac{1}{1.8}}} = 13.77$$

$$\eta_{upd\_ST1\_leakage} = \frac{7}{(-\ln[1-0.20935])^{\frac{1}{1.8}}} = 15.65$$

Steam trap	η_{upd} for Blocked	η_{upd} for Leakage
Trap 1 ($ST1$)	13.77	15.65
Trap 2 ($ST2$)	5.06	8.98
Trap 3 ($ST3$)	5.16	9.17

Step 3.7: Using equation [13] calculate the POF at year in service,

$$\boldsymbol{PoF_{upd} = 1 - exp\left[-\left(\frac{t_{service\,(ST)}}{\eta_{upd}}\right)^{\beta_{ST}}\right]}$$

$$PoF_{upd} = 1 - exp\left[-\left(\frac{8}{13.77}\right)^{1.8}\right] = 0.3136$$

$$PoF_{upd} = 1 - exp\left[-\left(\frac{8}{15.65}\right)^{1.8}\right] = 0.2583$$

Steam trap	PoF_{upd} for Blocked	PoF_{upd} for Leakage
Trap 1 ($ST1$)	0.3136	0.2583
Trap 2 ($ST2$)	0.2969	0.1056
Trap 3 ($ST3$)	0.2867	0.1015

Step 3.8: Using equation [5], calculate the $\boldsymbol{PoF(t)_{final\,(ST,\ MP\,or\,CV)}}$ for the steam traps based on series arrangement for both failure modes, at $\boldsymbol{t_{service\,(ST)}}$:

$$\boldsymbol{PoF\left(t_{service\,(ST)}\right)_{series\,(ST)} = max\left(PoF_{(ST1)}, PoF_{(ST2)}, PoF_{(ST3)}\right)}$$

$$PoF\left(t_{service\,(ST)}\right)_{series\,(ST\_blockage)} = max\,(0.3136, 0.2969, 0.2867) = 0.3136$$

$$PoF\left(t_{service\,(ST)}\right)_{series\,(ST\_leakage)} = max\,(0.2583, 0.1056, 0.1015) = 0.2583$$

	Blocked	Leakage
$\boldsymbol{PoF(t_{service\,(ST)})_{lines}}$	0.3136	0.2583

Step 4: Calculate the POF for the flare:

Step 4.1: Identify the default Weibull parameters for the flare from Table 14.

$$\boldsymbol{\eta_{default\,(equ)} = 13.3}$$

$$\boldsymbol{\beta_{equ} = 3}$$

Step 4.2: Using Table 15, determine the design condition adjustment ($F_{D_{equ}}$) for the flare.

The design condition adjustment ($F_{D_{equ}}$): Good

$$F_{D_{equ}} = 1.0$$

Step 4.3: Using Table 16, determine the operation condition adjustment ($F_{O_{equ}}$) for the flare.

The operation condition adjustment ($F_{O_{equ}}$): Good

$$\mathrm{F}_{\mathrm{O}_{\mathrm{equ}}} = 0.85$$

Step 4.4: Using Table 17, determine the maintenance history/inspection condition adjustment ($F_{M_{equ}}$) for the flare.

The maintenance history/inspection condition adjustment ($F_{M_{equ}}$): Very Good

$$\mathrm{F}_{\mathrm{M}_{\mathrm{equ}}} = 1.0$$

Step 4.5: Using equation [7], adjust the Weibull parameter $\eta_{default\,(equ)}$ based on the values in Steps 4.2, 4.3 and 4.4..

$$\eta_{adjusted\,(equ)} = \eta_{default\,(equ)} \times \Pi(F_{D_{equ}}, F_{O_{equ}}, F_{M_{equ}})$$

$$\eta_{adjusted\,(equ)} = 13.3 \times (1 \times 0.85 \times 1) = 11.31$$

Step 4.6: Using equation [8], calculate the $PoF(t)_{final\,(equ)}$ for the flare based on the adjusted Weibull parameter $\eta_{default\,(equ)}$

$$PoF(t_{service})_{final\,(equ)} = 1 - exp\left[-\left(\frac{t_{service}}{\eta_{adjusted\,(equ)}}\right)^{\beta_{equ}}\right]$$

$$PoF(t_{service})_{final\,(equ)} = 1 - exp\left[-\left(\frac{10}{11.31}\right)^{3}\right] = 0.4990$$

Step 5: Using equation [2], estimate the POF for the steam using system.

$$POF_{Steam\ using\ System} = F_{MS} \times PoF(t)_{final\,(equ)} \times PoF(t)_{final\,(ST,\ MP\ or\ CV)}$$

$$POF_{Steam\ using\ System\_blockage} = 1 \times 0.499 \times 0.3136 = 0.1565$$

$$POF_{Steam\ using\ System\_leakage} = 1 \times 0.499 \times 0.2583 = 0.1289$$

	Blocked	**Leakage**
$POF_{Steam\ using\ System}$	0.1565	0.1289

Establishing COF:

Step 1: Calculate the cost of steam lost from equation [14]:

$$\boldsymbol{Cost_{steam\_loss}} = \frac{\boldsymbol{leakage\ rate\ \times 8760 \times cost\ of\ steam}}{\mathbf{1000}}$$

$$Cost_{steam\_loss} = \frac{15\ \times 8760 \times 10}{1000} = \$1314$$

Step 2: The system is open hence go to step 3.

Step 3: Calculate the cost of production loss from equation [16]:

$$\boldsymbol{Cost_{production\ loss} = Unit_{prod}\ \times \frac{Rate_{red}}{100} \times D_{sd}}$$

$$Cost_{production\ loss} = 300{,}000\ \times \frac{100}{100} \times 5 = \$1{,}500{,}000$$

Step 4: Cost of safety impact:

$$\boldsymbol{Cost_{safety\ impact,blockage}} = \$\mathbf{160,000}$$

$$\boldsymbol{Cost_{safety\ impact,leakage}} = \$\mathbf{9,000}$$

Step 5: Cost of component damage:

$$\boldsymbol{Cost_{component\ damage}} = \$\mathbf{100,000}$$

For leakage, the COF:

$$\boldsymbol{COF_{leakage} = Cost_{steam\_loss} + Cost_{safety\ impact,leakage}}$$

$$COF_{leakage} = 1314 + 9{,}000 = \$10{,}314$$

For blockage, the COF:

$$\boldsymbol{COF_{blockage} = Cost_{component\ damage} + Cost_{production\ loss} + Cost_{safety\ impact,blockage} + Cost_{environment}}$$

$$COF_{blockage} = 100{,}000 + 1{,}500{,}000 + 160{,}000 + 0 = \$1{,}760{,}000$$

Risk:

The risk associated with the failure of the steam equipment is calculated using equation [30] for blocked and leakage. The total risk is the summation of both.

$$\begin{aligned}\boldsymbol{Risk(t_{service\ (equ)})} &= \left[\boldsymbol{PoF_{blockage}(t_{service\ (equ)}) \times COF_{blockage}}\right] \\ &+ \left[\boldsymbol{PoF_{leakage}(t_{service\ (equ)}) \times COF_{leakage}}\right] \\ &= [\mathbf{0.1565 \times 1,760,000}] + [\mathbf{0.1289 \times 10,314}] \\ &= \mathbf{276768.54}\end{aligned}$$

For the output, the risk is calculated as a function of time on a risk matrix.