Ballot ID: 6209

Title:	API 581 Part 5, Section 7 and Appendix 5.B
Purpose:	Propose changes from Fall 2022 ballot 5909 resolution
Impact:	Minor technical changes and editorial changes only
Rationale:	API 581 Task Group resolved ballot comments from Ballot 5909 in the fall of 2022. This ballot addresses those comments which were mostly editorial.
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Submitted to Task Group		**Submitted to SCI**		**Submitted to Master Editor**	
Date	*Resolution*	*Date*	*Resolution*	*Date*	*Added*

Proposed Changes and/or Wording *{attach additional documentation after this point}*

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7   STEAM SYSTEM

7.1   Overview

7.1.1   General Background

Steam systems account for approximately 30% of the total energy used in a typical petroleum refinery [17] based on US Department of Energy figures. Steam systems are utilized 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.

Steam system specialists work with plants to identify opportunities to reduce the amount of energy consumed by steam systems to stay competitive. Steam system maintenance costs should also be optimized and to protect health and safety issues as well as avoid unplanned downtime. The integrity and efficiency of steam-using equipment is critical to the operation and productivity of petrochemical industry. In addition, steam distribution systems and steam tracing systems which provide the heat necessary to maintain flow rates in product distribution ~~lines~~piping, vessels and reactors [18].

Routine inspection and testing of steam ~~using~~ systems consisting of steam traps, associated ~~lines~~piping, and steam equipment is required to avoid failures of the traps, associated ~~lines~~ piping or equipment, leading to failure of the system. 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 and testing interval or possible mitigation actions. The scope of this section includes steam traps, associated steam distribution ~~lines~~piping, and equipment using steam. 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 POF from plant-specific data if available, or to be determined from industry default data. These inputs are used to generate a POF as a function of time via a Weibull statistical approach. The consequence of device failure is calculated using methods outlined in Part 3, modified to include different failure scenarios. The combination of consequence and time-based POF provides a risk value which increases with time between inspections/tests. This allows inspection and test intervals to be determined based on risk targets. Figure 7.1 illustrates the basic methodology required for the determination of POF and is the basis for setting up inspection and test intervals or any mitigation actions.

7.1.2   Steam Application Types

Steam is essential for heating, mechanical drives and several other applications in process plants and 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 [19]. 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~~piping, and drive-power equipment such as turbines. Each of these applications may require the steam trap to perform a slightly different role.

In general, there are five major steam application groups that use steam traps: steam distribution ~~lines~~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) [20].

Examples of equipment used in steam systems, illustrating the importance of their application to the refining process, are listed in Table 7.1 [20].

7.2 The Definition of Steam System

7.2.1 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 is quickly and efficiently removed through steam traps to the correct condensate discharge location (CDL). Therefore, steam systems are an integral part of the process plant. A steam system is defined as one piece of steam-using equipment and its associated piping and traps. ~~A steam system consists of a combination of a steam-using equipment and its associated lines with steam traps.~~ Figure 7.2 shows multiple steam ~~using~~ systems with the following components:

a) Steam traps

b) Associated steam ~~lines~~ piping (distributing and condensate)

c) Equipment (steam-using equipment)

Depending on the system design, mechanical pumps or control valves may be installed in place of steam traps (as shown in Figure 7.2).

COF is a key driver for a Risk-Based Inspection (RBI) approach in steam-using/distribution systems, for assessment of steam traps, associated steam ~~lines~~piping, and steam-using equipment (as described in Section 7.~~2~~4).

7.2.2 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 7.2 describes different types of steam traps for each of the above categories.

7.2.3 Steam ~~Lines~~Piping

Steam ~~lines~~ piping supply steam to the steam-using equipment. As described, condensate is removed through steam traps installed at CDLs. The steam flow rates are typically higher in steam distribution ~~lines~~ piping than in other equipment, reaching velocities of > 100 ft/s (30 m/s). At these speeds, when the cross-sectional area of a ~~line~~ pipe section is liquid full, slugs of condensate can be carried through the piping at high velocities, causing water hammer. Potentially, this may cause failures of piping, valves, and equipment as well as personal injuries. The higher velocities in steam ~~lines~~ piping should be considered during design when the location of trap installations is being decided.

7.2.4 Steam-Using Equipment

As described in Section 7.1.2, there are many applications for steam and, depending on the application, various types of steam-using equipment are used. Table 7.1 provides examples of five steam application groups.

7.2.5 Steam System Damage Mechanism Equipment and Failure Modes

7.2.5.1 Background

The role of steam distribution lines piping is to reliably supply high quality steam to steam-using equipment. Condensate Is quickly and efficiently removed through steam traps installed in proper CDL installations. CDLs are susceptible to failures due to blockage (cold) or leakage (described in Section 7.2.5.3.1 and Section 7.2.5.3.2). This methodology currently does not cover freeze protection of CDLs.

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.

7.2.5.2 Damage Mechanism

7.2.5.2.1 Water hammer

A sudden release of steam or scalding water can occur due to the consequences of water hammer, a common damage mechanism affecting steam systems. 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 [2021] as the primary problem in steam systems and is sometimes referred to as Condensate Induced Water Hammer. Water Hammer occurs 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.

Water hammer generated in steam and condensate recovery systems is ordinarily classified via two main causes:

a) High-speed condensate slamming into, for example piping

b) 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 1450 psi (10 MPa) 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 to gaskets and valve flanges or the valves themselves. Water hammer in steam distribution piping interrupts service and can cause failures leading to personal injury and property damage. According to historical failures, 82% of steam systems experience some type of water hammer. In a typical steam-using system, water hammer causes 67% of premature steam system component failures [17].

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

a) Failure to ensure water (condensate) has been removed using steam traps and drains prior to admitting steam into the piping system.

b) Failure to correctly maintain steam traps, drain, and to blowdown valves (in order to preserve operable condition).

c) Failure to ensure an adequate number of steam traps and drains have been installed at locations conducive to condensate removal.

d) Failure to operate system valves correctly as well as failure to use bypass valves to safely warm system piping downstream of isolation valves.

7.2.5.3 Failure Modes

7.2.5.3.1 Steam Trap Blockage Leading to Water Hammer

Condensate cannot be discharged when the steam trap is blocked, often resulting in water hammer contributing to potential equipment damage.

7.2.5.3.2 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 7.4.2

7.3 Probability of Failure Methodology

7.3.1 Use of Weibull Curves

The POF for steam systems is calculated using a two parameter Weibull distribution as expressed in Equation (5.122) as shown in Part 1, Section 4.1.3. Use of Weibull curves for establishing POF is further described in Part 1, Section 4.1.3.

$$P_f = 1 - exp\left(-\left(\frac{t}{\eta}\right)^{\beta}\right)$$

(5.122)

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

7.3.2 Required data

The basic data required for the evaluation of POF for steam systems are listed in Table 7.3.

7.3.3 Overview

This section presents a procedure to calculate the POF for a steam system. Figure 7.2 provides an overview of the POF calculation framework for ~~steam~~ 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~~ piping is then derived and combined with the steam-using equipment generic failure frequencies to calculate a system POF. Final POF values are obtained by tailoring the POF for steam traps and equipment to local conditions by customized probability factors.

As described in Section 7.2, a steam system is defined as one piece of steam-using equipment and its associated piping and traps~~a steam system consists of a combination of steam-using equipment and its associated lines with steam traps~~. The POF of each system will be considered as the combined effect of individual equipment with its associated traps for both leakage and blockage, i.e.:

$$P(t)_{f,final,leak\ (steam\ \text{--}using\ system)} = P(t)_{f\ (equ)} \cdot P(t)_{f,final,leak(ST,MP\ or\ CV)}$$

(5.123)

$$P(t)_{f,final,cold\ (steam\ \text{--}using\ system)} = P(t)_{f\ (equ)} \cdot P(t)_{f,final,cold(ST,MP\ or\ CV)}$$

(5.124)

The procedure for calculation of $P(t)_{f,final,leak(ST,MP\ or\ CV)}$ and $P(t)_{f,final,cold(ST,MP\ or\ CV)}$ is provided in Section 7.3.4 and Section 7.3.5 . $P(t)_{f(equ)}$ is the POF calculated for the ~~steam~~ steam-using equipment as explained in Section 7.3.6.

7.3.4   Probability of Failure (Steam ~~Line~~Piping)

7.3.4.1   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 7.3.1, 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 (5.122) 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 characteristic life parameter ~~scale~~ $\eta_{def,ST}$ (for leak and blockage) and shape β_{ST} parameters are obtained from Table 7.4. (from historical data analysis), the POF of the steam trap is calculated using Equation (5.125) for leakage and (5.126) for blockage.

$$P(t)_{f,def,leak} = 1 - exp\left[-\left(\frac{t}{\eta_{def,leak,ST}}\right)^{\beta_{ST}}\right] \qquad (5.125)$$

$$P(t)_{f,def,cold} = 1 - exp\left[-\left(\frac{t}{\eta_{def,cold,ST}}\right)^{\beta_{ST}}\right] \qquad (5.126)$$

The data presented in Table 7.4 are based on the best available sources and experience to date from owner-operators. Table 7.4 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-operator where more accurate data for default shape/ characteristic life parameters ~~scale parameters~~ are available. The default parameters in Table 7.4 are suggested for use when data is unavailable.

7.3.4.2   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 adjusted based on the adjustment multiplier for each design/installation, F_D, operational, F_O, or maintenance history, F_M, conditions. The default POF ($P(t)_{f,def,leak}$ and $P(t)_{f,def,cold}$), needs to be adjusted by the adjustment multipliers given in Table 7.5 to Table 7.13.

$$\eta_{adj,leak(ST,MP\ or\ CV)} = \eta_{def,leak,ST} \cdot F_{D(ST,MP\ or\ CV)} \cdot F_{O(ST,MP\ or\ CV)} \cdot F_{M(ST,MP\ or\ CV)} \qquad (5.127)$$

$$\eta_{adj,cold(ST,MP\ or\ CV)} = \eta_{def,cold,ST} \cdot F_{D(ST,MP\ or\ CV)} \cdot F_{O(ST,MP\ or\ CV)} \cdot F_{M(ST,MP\ or\ CV)} \qquad (5.128)$$

$$P(t)_{f,final,leak(ST,MP\ or\ CV)} = 1 - exp\left[-\left(\frac{t}{\eta_{adj,leak(ST,MP\ or\ CV)}}\right)^{\beta_{ST}}\right] \qquad (5.129)$$

$$P(t)_{f,final,cold_{(ST,MP\ or\ CV)}} = 1 - exp\left[-\left(\frac{t}{\eta_{adj,cold_{(ST,MP\ or\ CV)}}}\right)^{\beta_{ST}}\right] \qquad (5.130)$$

The adjusted η parameter ($\eta_{adj,leak_{(ST,MP\ or\ CV)}}$ and $\eta_{adj,cold_{(ST,MP\ or\ CV)}}$) is used to calculate the final (tailored) POF using Equation (5.129) for leakage and Equation (5.130) for blockage for each steam trap, mechanical pump or control valve operating within a steam system. The shape factor β_{ST} used in Equation (5.129 and 5.130) is the same shape factor generated from Table 7.4. Equation (5.129) and Equation (5.130) provides the final POF for each steam trap, mechanical pump or control valve in a steam ~~using~~ system.

Suggested adjustment multiplier categories that need to be considered for steam traps, mechanical pumps and control valves are given in Table 7.5 to Table 7.13. It should be noted that the value of each adjustment multiplier depends on engineering judgement.

7.3.5 Multiple Steam Trap or Mechanical Pumps or Control Valves Installations

For any ~~steam~~ steam-using equipment, there are several associated ~~lines~~ piping with steam traps (or mechanical pumps or control valves) installed. The ~~lines~~ piping usually have steam traps installed in parallel or series. When there are multiple steam traps (or mechanical pumps or control valves) installed, the calculated POF for any one specific steam trap in the multiple installation will remain the same. However, the overall combined POF for leakage and blockage of multiple traps (in parallel or series) should be considered for each ~~line~~ piping using Equations (5.131 and 5.132) for traps in series and Equations (5.133 and 5.134) for traps in parallel.

$$P(t)_{f,final\ series,leak_{(ST,MP\ or\ CV)}} = 1 - \left(1 - P(t)_{f1,leak}\right) \cdot \left(1 - P(t)_{f2,leak}\right) \cdot ... \cdot \left(1 - P(t)_{fn,leak}\right) \qquad (5.131)$$

$$P(t)_{f,final\ series,cold_{(ST,MP\ or\ CV)}} = 1 - \left(1 - P(t)_{f1,cold}\right) \cdot \left(1 - P(t)_{f2,cold}\right) \cdot ... \cdot \left(1 - P(t)_{fn,cold}\right) \qquad (5.132)$$

$$P(t)_{f,final\ parallel,leak_{(ST,MP\ or\ CV)}} = P(t)_{f1,leak} \cdot P(t)_{f2,leak} \cdot ... \cdot P(t)_{fn,leak} \qquad (5.133)$$

$$P(t)_{f,final\ parallel,cold_{(ST,MP\ or\ CV)}} = P(t)_{f1,cold} \cdot P(t)_{f2,cold} \cdot ... \cdot P(t)_{fn,cold} \qquad (5.134)$$

For example, Figure 7.3 is the sample arrangement of the traps showing their capacity. Calculation of the POF for each ~~line~~ piping is given by Equation (5.133) and Equation (5.134) which allow calculation of the total POF for the ~~lines~~ piping in parallel configuration. In addition, if the capacity of Trap 1 and Trap 2 are not sufficient for the equipment requirement individually, these two traps (or mechanical pumps or control valves) are treated as series configurations (Figure 7.3b) using Equation (5.131) and Equation (5.132).

7.3.6 POF for Equipment

As discussed in Section 7.1.2, there are different types of equipment used in steam-using systems. Examples of some of these types were given in Table 7.1. In this section, the POF calculation due to steam related failure will be covered. Equipment consists of the following:

a) Heat exchanger

b) Distillation tower/column

c) Stripper

d) Flare

e) Steam turbine

f) Piping (steam main or condensate piping)

g) Tracing (instrumentation/relief valve)

The calculation of the POF of equipment takes into account the effect of both equipment and its associated ~~lines~~piping. It is also important to note that the calculation assumes that each individual item of equipment is independent.

For example, Figure 7.4(a) shows an arrangement of a steam turbine with traps. ~~A b~~Block diagram~~s~~ for combining the POF calculation for the same system in parallel and series is provided in Figure 7.4(b) and (c) respectively.

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

$$\eta_{adj,equ} = \eta_{def,equ} \cdot \left(F_{D_{equ}} \cdot F_{O_{equ}} \cdot F_{M_{equ}} \right) \tag{5.135}$$

$$P(t)_{f,final(equ)} = 1 - exp\left[-\left(\frac{t}{\eta_{adj,equ}} \right)^{\beta_{equ}} \right] \tag{5.136}$$

The default characteristic life ~~scale~~ parameter, $\eta_{def,equ}$ and shape parameter, β_{equ} are obtained from historical data analysis. Table 7.14 shows default Weibull parameters for the different types of steam-using equipment. The data presented in Table 7.14 are based on the best available sources and experience to date from owner-operators. However, it is recommended that other Weibull parameters be used by the owner-operator where plant specific data for default shape/ characteristic life ~~scale~~ parameters are available. The default parameters in Table 7.14 are suggested when plant specific data is unavailable and are based on failure of steam systems. The POF of the steam-using equipment, $P(t)_{f,def(equ)}$ is calculated using Equation (5.122) and parameters from Table 7.14.

Similar to the approach for steam traps discussed in Section 7.3.4.2, $\boldsymbol{\eta_{adj,equ}}$ is used to calculate the final (tailored) POF (Equation (5.~~129~~136)) for steam-using equipment. The shape factor β_{equ} used in Equation (5.~~129~~136) is the shape factor from Table 7.14. $\boldsymbol{P(t)_{f,final(equ)}}$ 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 7.15 to Table 7.17, and are used to modify the default characteristic life ~~scale~~ parameter, $\eta_{def,equ}$. It should be noted that the value of each adjustment multiplier depends on engineering judgement.

7.3.7   POF for Steam-Using Systems

The total POF for one piece of steam-using systems is calculated using Equation (5.123) and Equation (5.124) where, $\boldsymbol{P(t)_{f,final,leak(ST,MP\ or\ CV)}}$ and $\boldsymbol{P(t)_{f,final,\text{~~leakcold~~}(ST,MP\ or\ CV)}}$ is calculated from Equation (5.129) ~~or~~ and Equation (5.130) for individual steam traps and for multiple steam traps the procedure in Section 7.3.5 is used

7.3.8   POF after Inspection

Weibull parameters for the failure on demand curves are determined based on the analysis of a sample set of data (Section 7.3.1). However, as inspection data is collected, these parameters may be adjusted for each device based on the actual inspection results. This approach assumes that the Weibull shape parameter, β, remains constant based on the historical data and adjusts the characteristic life, η, as inspection data are collected.

The effectiveness of inspection and testing is provided in Annex 2.F, Section 2.F.11.2, Table 2.F.11.1. The probability of succeeding the inspection prior to inspection is given by Equation (5.137) and Equation (5.138).

$$P(t)_{f,prior,leak} = 1 - P(t)_{f,final,leak_{(ST,MP\ or\ CV)}} \tag{5.137}$$

$$P(t)_{f,prior,cold} = 1 - P(t)_{f,final,cold_{(ST,MP\ or\ CV)}} \tag{5.138}$$

After inspection, the POF is updated based on the results. Use Equation (5.139) and (5.140) if the inspection results do not show the expected failure.

$$P(t)_{f,after,leak} = \left(1 - CF_{pass}\right) \cdot P(t)_{f,prior,leak} \tag{5.139}$$

$$P(t)_{f,after,cold} = \left(1 - CF_{pass}\right) \cdot P(t)_{f,prior,cold} \tag{5.140}$$

Use Equation (5.141) and (5.142) if the inspection confirms the expected failure.

$$P(t)_{f,after,leak} = \left(1 - CF_{pass}\right) \cdot P(t)_{f,prior,leak} + \left(P(t)_{f,final,leak_{(ST,MP\ or\ CV)}} \cdot CF_{fail}\right) \tag{5.141}$$

$$P(t)_{f,after,cold} = \left(1 - CF_{pass}\right) \cdot P(t)_{f,prior,cold} + \left(P(t)_{f,final,cold_{(ST,MP\ or\ CV)}} \cdot CF_{fail}\right) \tag{5.142}$$

Based on the outcome of the inspection and its effectiveness the updated probability of failure after inspection is calculated using equations in Table 7.19. The characteristic life $(\eta_{adj,leak_{(ST,MP\ or\ CV)}}$ and $\eta_{adj,cold_{(ST,MP\ or\ CV)}})$ is updated based on the outcome of the inspection using Equation (5.143) and Equation (5.144).

$$\eta_{upd,leak} = \frac{t}{\left(-\ln(1-P(t)_{f,wgt,leak})\right)^{\frac{1}{\beta_{ST}}}} \tag{5.143}$$

$$\eta_{upd,cold} = \frac{t}{\left(-\ln(1-P(t)_{f,wgt,cold})\right)^{\frac{1}{\beta_{ST}}}} \tag{5.144}$$

Where, β_{ST} is shape factor established earlier and t is the inspection interval. The updated characteristic life is then used in the calculation of the POF using equation (5.145) and (5.146).

$$P(t)_{f,upd,leak} = 1 - exp\left[-\left(\frac{t}{\eta_{upd,leak}}\right)^{\beta_{ST}}\right] \tag{5.145}$$

$$P(t)_{f,upd,cold} = 1 - exp\left[-\left(\frac{t}{\eta_{upd,cold}}\right)^{\beta_{ST}}\right] \tag{5.146}$$

7.3.8.1   POF after Cleaning

The steam trap POF will be reduced after each cleaning. For example, if the periodic cleaning is done every 0.5 years, the POF at 0.6 years will be reduced to the same POF value as at 0.1 year and at 1.1 years the POF will also be equal to the POF at 0.1 years.

7.3.9 POF Calculation Procedure

The following calculation procedure is used to determine the POF due to leak and blockage for steam traps and ~~steam~~ steam-using equipment. The POF of each system is calculated as the combined effect of individual equipment with its associated traps for both leak and blockage.

a) STEP 1: Identify the steam traps, mechanical pumps and control valves and associated ~~steam~~ steam-using equipment item in the steam system. Provide required data defined in Table 7.3.

b) STEP 2: Calculate the POF for each steam traps, mechanical pumps and control valves for both failure modes:

   1. STEP 2.1: Determine the default values of the Weibull parameters for both failure modes from Table 7.4.

   2. STEP 2.2: Using Table 7.5 to Table 7.13, determine the design, operating and maintenance condition adjustment for each item (steam trap, mechanical pump and control valve).

   3. STEP 2.3: Using Equation (5.127) and Equation (5.128), adjust the Weibull parameter $\eta_{def,leak,ST}$ and $\eta_{def,cold,ST}$ based on the values in STEP 2.2 for both failure modes.

   4. STEP 2.4: Calculate $P(t)_{f,final,leak(ST,MP\ or\ CV)}$ and $P(t)_{f,final,cold(ST,MP\ or\ CV)}$ using Equation (5.129) and Equation (5.130) based on the adjusted Weibull parameter $\eta_{adj,leak(ST,MP\ or\ CV)}$ and $\eta_{adj,cold(ST,MP\ or\ CV)}$ using Equation (5.127) and Equation (5.128). Repeat for each steam trap, mechanical pump and control valve.

   5. STEP 2.5: For steam traps, mechanical pumps and control valves installed in parallel or series use Equations (5.131) to (5.134) for both failure modes to calculate POF.

c) STEP 3: Inspection POF updating for each steam trap, mechanical pump and control valve for both failure modes. Repeat the following steps in case of multiple steam traps, mechanical pumps and control valves

   1. STEP 3.1: Identify the effectiveness of the inspection and testing method using Annex 2.F, Section 2.F.11.2, Table 2.F.11.1.

   2. STEP 3.2: Using Equations (5.137) and (5.138), calculate the probability of not failing the inspection prior to inspection for both failure modes.

   3. STEP 3.3: Identify the confidence factor (CF) associated with the inspection effectiveness and inspection result using Table 7.18.

   4. STEP 3.4: Calculate $P(t)_{f,after}$ for blockage and leakage failures using Equations (5.139) and (5.140) if the inspection results do not show the expected failure and Equations (5.141) and (5.142) if the inspection confirms the expected failure.

   5. STEP 3.5: Calculate $P(t)_{f,wgt}$ using the appropriate equation for inspection using Table 7.19 and based on the inspection effectiveness and inspection results.

   6. STEP 3.6: Calculate the updated characteristic life, using Equations (5.143) and (5.144).

7. STEP 3.7: Calculate the POF at year in service using Equations (5.145) and (5.146).

8. STEP 3.8: Calculate the POF for both failure modes, at $t_{service(ST)}$ based on the steam trap arrangement using Equations (5.131) and (5.132) for series or Equations (5.133) and (5.134) for parallel configuration.

d) STEP 4: Calculate the POF for one piece of steam-using equipmenteach steam using equipment in the steam system:

1. STEP 4.1: Using the default Weibull parameters for the steam steam-using equipment from Table 7.14.

2. STEP 4.2: Using Table 7.15, determine the design condition adjustment, $F_{D_{equ}}$, for the steam steam-using equipment.

3. STEP 4.3: Using Table 7.16, determine the operation condition adjustment, $F_{O_{equ}}$, for the steam steam-using equipment.

4. STEP 4.4: Using Table 7.17, determine the maintenance history/inspection condition adjustment, $F_{M_{equ}}$, for the steam steam-using equipment.

5. STEP 4.5: Using Equation (5.135), adjust the Weibull parameter, $\eta_{def,equ}$, based on the values in STEPS 4.2, 4.3 and 4.4.

6. STEP 4.6: Using Equation (5.136), calculate the, $P(t)_{f,final(equ)}$, for the steam steam-using equipment based on the adjusted Weibull parameter, $\eta_{adj,equ}$.

e) STEP 5: Calculate the final POF for the steam using system using Equations (5.123) and (5.124) for both failure modes.

7.4 Consequence of Failure Methodology

7.4.1 Background

This section presents a procedure to calculate consequence of failure (COF) for a steam system. Equipment can be connected to either an open system or a closed system and have COF due to leakage and blockage. An open system will allow the steam/condensate to escape into the environment while a closed system circulates the steam/condensate to be reused.

7.4.2 Models for Assessing COF

7.4.2.1 Overview

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

COF varies with different equipment and failure modes. The following sections provide the potential costs due to failures and outlines the COF calculation steps.

7.4.2.2 Cost of Steam Loss Due to Leakage

$$FC_{loss} = \left(\frac{lrate \cdot 8760 \cdot FC_{steam}}{1000}\right)$$ (5.147)

The leakage rate ($lrate$) is based on historical inspection data.

7.4.2.3 Cost of Condensate Loss Due to Downstream Equipment Rupture

$$\cancel{FC_{condensate} = \left(\frac{mass_{condensate} \cdot 8760 \cdot FC_{steam}}{1000}\right)}$$

$$FC_{loss,D/S} = mass_{condensate} \cdot FC_{condensate}$$ (5.148)

The condensate mass ($mass_{condensate}$) is calculated following the procedure recommended in Part 3, Section 4.7.2, Equation (3.14). The cost of condensate ($FC_{condensate}$) is user specified.

7.4.2.4 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~~ process 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.

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

The production loss value can be manually assigned or calculated using Equation (5.149).

$$FC_{prod} = Unit_{prod} \cdot \left(\frac{rate_{red}}{100}\right) \cdot D_{sd}$$ (5.149)

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.

7.4.2.6 Cost of safety impact to personnel due to rupture and leakage

The steam released through leakage or rupture may result in a safety impact on personnel. The total personnel injury cost, FC_{inj} ~~$CA_{f,inj}$~~, within a certain area is calculated using Equation (5.150).

$$FC_{inj} = CA_{f,inj} \cdot popdens \cdot injcost$$ (5.150)

Where $CA_{f,inj}$ is calculated by using the procedure in Part 3, Section 4.10.2.

The hole size used to calculate the $CA_{f,inj}$ due to rupture from blockage is the inlet/connection size using Part 3, Equation (3.70). ~~For leakage, the~~ A medium hole size of 1 in. (25 mm) is used to calculate $CA_{f,inj}$ due to leakage using in Part 3, Equation (3.69). The *popdens* and *injcost* used in Equation (5.150) is defined in Part 3, Section 4.12.5. The required input parameters are listed in Table 7.20.

The cost of safety impact to personnel due to rupture and leakage of downstream equipment ($FC_{inj,D/S}$), is calculated by using water as model fluid.

Financial consequence as a result of serious injury to personnel due to process ($FC_{inj,process}$), is calculated using Equation (5.151) based on the hole size in Part 3, using the product in the process pipe.

$$FC_{inj,process} = max(FC_{inj,nfnt} + FC_{inj,flam} + FC_{inj,toxic}) \qquad\qquad\qquad (5.151)$$

For multiple traps, use Equations (5.~~154~~152) and Equation (5.~~152~~153) to calculate COF.

Blockage:

$$FC_{inj,cold} = max(FC_{inj,cold_1}, FC_{inj,cold_2}, ..., FC_{inj,cold\_n}) \qquad\qquad (5.~~151~~152)$$

Leak:

$$FC_{inj,leak} = (FC_{inj,leak_1} + FC_{inj,leak_2} + \cdots + FC_{inj,leak\_n}) \qquad\qquad (5.~~152~~153)$$

7.4.3   Cost Models for Different Equipment

7.4.3.1   Overview

The financial COF varies for different equipment and failure modes. A list of potential costs due to failure and calculation methods was introduced in Section 7.4.2. For freshly added applications, the various potential failure consequences are added to the 'event tree' as the starting point for financial COF model development. The financial COF is calculated differently for steam distribution system depending on the type of equipment connected. Currently, 'type of connected equipment' is one of the data requirements for steam distribution COF calculation. Section 7.4.3.2 through Section 7.4.3.10 outline the calculation methodology for estimating financial COF for different equipment.

7.4.3.2   COF model for heat exchanger and steam turbine

The failure modes for heat exchanger and steam turbines can be either blockage or leakage and are calculated separately. The presence of an opening bypass for the steam system should be determined in the case of a blockage. If no opening bypass exists, a blockage could cause the steam system to shut down and may result in water hammer inside the equipment, causing a production loss and/or rupture. A rupture may cause a financial loss due to component damage and safety impact (personnel injury). The financial COF due to blockage without an opened bypass for heat exchanger and turbine is calculated using Equation (5.~~153~~154).

$$FC_{cold}^{HEX,Turbine} = FC_{prod} + FC_{comp} + FC_{inj} \qquad\qquad\qquad (5.~~153~~154)$$

The blockage consequence is calculated the same as a leakage consequence (Equation (5.155)) in an open system if ~~a~~ the bypass is opened.

The total steam loss is calculated for both leakage and blockage with an open bypass. If the bypass is open, the safety impact is considered in addition to the loss of steam. ~~Safety impact is not included 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. The financial COF due to both leakage and blockage with an open bypass for a heat exchanger and turbine is calculated using Equation (5.~~154~~155) and Equation (5.~~155~~156)~~.~~ If the bypass is closed or if there is no bypass then $FC_{inj} = 0$ in equation 5.155.

$$FC_{leak,open}^{HEX,Turbine} = FC_{loss}$$

$$FC_{leak,open}^{HEX,Turbine} = FC_{loss} + FC_{inj} \tag{5.~~154~~155}$$

$$FC_{leak,closed}^{HEX,Turbine} = FC_{loss} + FC_{loss,D/S} + (FC_{prod,D/S} + FC_{comp,D/S} + FC_{inj,D/S}) \tag{5.~~155~~156}$$

7.4.3.3 COF model for general steam tracing

The failure modes for general steam tracing equipment (tracing with steam temperatures above 180°C) can be either blockage or leakage, which are calculated separately. Unlike a heat exchanger or turbine (as described in Section 7.4.3.2), the COF for tracing is considered for the ~~main~~ process pipe and tracing ~~line~~piping. When 'blockage' happens, it shall 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~~piping. In one case, the steam system shut down and content sub-cooling will result in production loss in addition to the cost of ~~main~~ process pipe cut-off (component damage). In another case, the water hammer inside the tracing ~~line~~ piping will cause the tracing ~~line~~ piping to rupture (worst case scenario), which will result in costs of the tracing ~~line~~ piping component damage in addition to associated safety impacts.

The COF due to blockage in an open and closed system without opened bypass or trap disconnection for ~~high temperature~~ general steam tracing is calculated using Equation (5.~~156~~157).

$$FC_{cold}^{Tracing,HT} = FC_{prod} + FC_{comp,main} + FC_{comp,line} + FC_{inj}$$

$$FC_{cold}^{Tracing,HT} = FC_{prod} + FC_{comp,process} + FC_{comp,line} + FC_{inj} + FC_{inj,process} \tag{5.~~156~~157}$$

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

~~For both leakage and blockage with an open bypass or trap disconnection, the calculation is the same as the consequence of leakage for a heat exchanger or turbine. The COF for both leakage and blockage with an open bypass or trap disconnection for high temperature steam tracing is calculated using Equation (5.157) or Equation (5.158).~~

For leakage, in an open system the COF is calculated using Equation (5.155). For a closed system, the leakage COF is calculated using Equation (5.156).

$$FC_{leak,open}^{Tracing,HT} = FC_{loss} + FC_{inj} \tag{5.157}$$

$$FC_{leak,closed}^{Tracing,HT} = FC_{loss} + (FC_{prod,D/S} + FC_{comp,D/S} + FC_{inj,D/S}) \tag{5.158}$$

7.4.3.4 COF Model for Low Temperature Steam Tracing

Low temperature steam tracing is used in applications that require low flow or needs to be kept warm due to low ambient conditions. The temperature of steam used in low temperature steam tracing is between 150-180°C. The failure modes can be either blockage or leakage, which will be calculated separately. The COF for tracing is considered for ~~main~~ process pipe and tracing ~~lines~~piping separately.

Similar to the ~~high temperature~~ general steam tracing (Section 7.4.3.3), when blockage occurs, the COF is calculated using Equation (5.~~159~~157) for both open and closed system without bypass.

$$FC_{cold}^{Tracing,LT} = FC_{prod} + FC_{comp,main} + FC_{comp,line} + FC_{inj} \qquad\qquad\qquad (5.159)$$

For both leakage and blockage with open bypass or trap disconnection, the common failure consequence for both an open and closed system is as follows:

a) The steam leaking will result in costs from steam loss; if multiple traps are leaking, the sum of steam loss costs should be reported.

b) Leakage causes equipment shut down or overheating, which gives rise to costs from production loss.

Water hammer may occur inside the process ~~line~~ piping due to leakage may results in a rupture of the process ~~line~~ piping and costs from process ~~line~~ piping component damage and safety impact. The fluid within the process ~~line~~ piping is assigned as flammable or toxic or flammable and toxic. The semi-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.

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 it is a ~~the outlet is~~ closed system, there is a subsequent consequence of water hammer occurring to the downstream equipment/pipe, use Equation 5.158 with $FC_{inj} = 0$. ~~The evaluation approach for this subsequent consequence is the same as the heat exchanger, turbine and high temperature tracing.~~

The COF due to both leakage and blockage with open bypass or trap disconnection for low temperature steam tracing is calculated using Equation (5.~~160~~158) for open system and Equation (5.~~161~~159) for closed system.

$$FC_{leak,open}^{Tracing,LT} = FC_{inj} + \left(FC_{loss} + FC_{comp,process} + FC_{prod,process} + FC_{inj,process} \right) \qquad (5.\cancel{160}158)$$

$$FC_{leak,closed}^{Tracing,LT} = \left(FC_{loss} + FC_{comp,process} + FC_{prod,process} + FC_{inj,process} \right)$$
$$+ \left(FC_{prod,D/S} + FC_{comp,D/S} + FC_{inj,D/S} \right)$$

$$FC_{leak,closed}^{Tracing,LT} = \left(FC_{loss} + FC_{loss,D/S} + FC_{comp,process} + FC_{prod,process} + FC_{inj,process} \right) + \left(FC_{prod,D/S} + FC_{comp,D/S} + FC_{inj,D/S} \right) \qquad (5.\cancel{161}159)$$

Where, $FC_{inj,process}$ is calculated using Equation 5.151.

7.4.3.5 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 Section 6.1.7). The financial COF calculation follows the COF equations for low temperature steam tracing.

7.4.3.6 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 financial COF is the same as for general tracing on a low temperature tracing system, with modified business loss which will be assessed by the user directly.

7.4.3.7   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 in open system when the ~~outlet~~ bypass is open, financial COF is the sum of steam loss and cost of the safety impact due to condensate/steam discharge into the open air (Equation (5.~~154~~155)). If the outlet is closed, steam loss is the leakage financial COF (Equation (5.~~155~~156)). 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 financial COF is calculated as the sum of component damage, production loss and the cost of safety impact using Equation (5.~~153~~154). If the bypass is open, the financial COF of due to blockage is the same as the COF of leakage.

7.4.3.8   COF model for flare

The steam trap failure modes considered for flare are leakage and blockage. Similar to distillation columns (Section 7.4.3.7), if the steam trap of the flare leaks and its outlet is open, financial COF is the sum of steam loss and the cost of the safety impact due to condensate / steam discharge to the open air (Equation (5.~~154~~155)). Otherwise, if the outlet is closed, steam loss is the only leakage financial COF (Equation (5.~~155~~156)). 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 financial COF is calculated using Equation (5.~~153~~160) 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 (5.162)~~. If the bypass is open, the financial COF of due to blockage is the same as the COF of leakage.

$$FC_{Cold}^{Flare} = FC_{loss} + FC_{comp} + FC_{inj} + FC_{comp,process} + FC_{prod,process} + FC_{inj,process} + FC_{env} \underline{\hspace{2cm}} \quad (5.160)$$

Where, $FC_{inj,process}$ is calculated from Equation 5.151.

$$FC_{inj} = max\left(FC_{inj,nfnt}, FC_{inj,flam}, FC_{inj,toxic} \right) \quad \text{(5.162)}$$

7.4.3.9   COF model for steam distribution piping

The failure modes considered for steam distribution piping are leakage and blockage. Similar to distillation columns (Section 7.4.3.7), if the steam trap of the main steam distribution piping ~~line~~ leaks and its outlet is open, financial COF is the sum of steam loss and cost of the safety impact due to condensate/steam discharge to open air using Equation (5.~~154~~155). ~~Otherwise, if~~ If the outlet is closed, the leakage financial COF due to steam loss ~~is the only leakage financial COF~~ is calculated by using Equation (5.155) with $FC_{inj} = 0$. In terms of failure due to blockage when the bypass is not open, there will be the possibility of water hammer; the financial COF is calculated as the sum of component damage (steam distribution piping ~~main line~~), production loss, and the cost of any safety impact (Equation (5.~~153~~154). If the bypass is open, the financial COF due to blockage is the same as the financial COF of leakage.

7.4.3.10   COF model for condensate recovery ~~line~~piping

The failure mode considered for the steam recovery ~~line~~ piping is leakage only. This is because ~~blockage~~ blocked steam traps are not discharging into ~~related to~~ the condensate recovery ~~line~~ piping~~are not discharging into the line~~, so they do not have any effect. When the recovery ~~line~~ piping fails due to a steam trap leakage, the condensate pipe may rupture due to water hammer. The financial COF is calculated as the sum of any component damage (pipe), cost of safety impact, condensate loss and downstream equipment production loss using Equation (5.~~158~~161).

$$FC_{leak}^{Recovery} = FC_{loss,D/S} + FC_{prod,D/S} + FC_{comp,D/S} + FC_{inj,D/S} \qquad\qquad (5.161)$$

7.4.4 COF calculation procedure

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

a) STEP 1: Calculate the cost of steam loss due to leakage using Equation (5.147).

b) STEP 2: Calculate the cost of condensate loss due to downstream equipment rupture using Equation (5.148). Go to STEP 3, if no downstream equipment is connected or if the system is open i.e. the condensate is discharged to open.

c) STEP 3: Calculate the cost of production loss due to shut down or reduced service efficiency using Equation (5.149).

d) STEP 4: Calculate the cost of safety impact to personnel ~~due to rupture and leakage~~ due to steam and process release using Equation (5.150) and Equation (5.151) respectively. If there are multiple steam traps use Equation (5.~~151~~152) and Equation (5.~~152~~153).

e) STEP 5: Establish if the system is open or closed, ~~Calculate~~ calculate the financial COF of component damage based on the type of ~~steam~~ steam-using equipment using Table 7.21 and table 7.22 ~~as given in Section 7.4.3.2 to Section 7.4.3.10~~.

~~e)~~f) STEP 6: To calculate the financial consequence for leakage (FC_{leak}) and blockage (FC_{cold}), combine the leakage COF of steam trap (control valve or mechanical pump) from STEP 4 with the leakage COF of component damage in STEP 5 and the blockage COF of steam trap (control valve or mechanical pump) from STEP 4 with the blockage COF of component damage in STEP 5.

7.5 Risk Based Analysis

The risks due to leakage and blockage ~~is~~ are calculated using Equations (5.~~163~~162) and (5.~~164~~163). Where the POF of steam system is calculated from Equations (5.123) and (5.124) for both leakage and blockage.

$$R(t)_{leak} = P(t)_{f,final,leak\ (steam\ \sim\!\!using\ system)} \cdot FC_{leak} \qquad\qquad (5.\sim\!\!163 162)$$

$$R(t)_{cold} = P(t)_{f,final,cold\ (steam\ \sim\!\!using\ system)} \cdot FC_{cold} \qquad\qquad (5.\sim\!\!164 163)$$

The total risk $R(t)$ is the sum of the risk due to blockage and leakage and is calculated from Equation (5.~~165~~164).

$$R(t) = R(t)_{leak} + R(t)_{cold} \qquad\qquad (5.\sim\!\!165 164)$$

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 the following sections.

7.6 Inspection and Risk Mitigation Planning

7.6.1 Risk mitigation plan

7.6.2 Overview

The mitigation plan comprises risk mitigation suggestions/actions to assist asset owner-operator 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 Section 7.6.2.1 to Section 7.6.2.3 are suggestions only and may not be applicable in all situations.

7.6.2.1 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~~ piping 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 $P(t)_{adjusted}$, which will affect the POF of the steam system (Equations (5.123) and (5.124)).

7.6.2.2 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 7.3.9 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.

7.6.2.3 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. FC_{loss} and FC_{comp}.

7.7 Nomenclature

$CA_{f,inj}$	is the final personnel injury consequence area, ft^2 (m^2)
CF_{pass}	is the confidence factor for the inspection not to result in failure
CF_{fail}	is the confidence factor for the inspection results in failure
$mass_{condensate}$	is the condensate mass used in the consequence calculation associated with the nth release hole size, lb (kg)

$cost\ of\ steam$ ~~is the cost of steam, $/lb ($/kg)~~

D_{sd} is the time required to shut down a unit to perform a repair, days

$F_{D_{CV}}$ is the design adjustment multiplier for control valve

$F_{D_{equ}}$ is the design adjustment multiplier for ~~steam~~ steam-using equipment

$F_{D_{MP}}$ is the design adjustment multiplier for mechanical pump

$F_{D_{ST}}$ is the design adjustment multiplier for steam traps

$F_{O_{CV}}$ is the operational adjustment multiplier for control valve

$F_{O_{equ}}$ is the operational adjustment multiplier for ~~steam~~ steam-using equipment

$F_{O_{MP}}$ is the operational adjustment multiplier for mechanical pump

$F_{O_{ST}}$ is the operational adjustment multiplier for steam traps

$F_{M_{CV}}$ is the maintenance/inspection history adjustment multiplier for control valve

$F_{M_{equ}}$ is the maintenance/inspection history adjustment multiplier for ~~steam~~ steam-using equipment

$F_{M_{MP}}$ is the Maintenance/inspection history adjustment multiplier for mechanical pump

$F_{M_{ST}}$ is the maintenance/inspection history adjustment multiplier for steam traps

FC is the final financial consequence, $

FC_{env} is the cost of environmental damage, $

FC_{comp} is the cost of component damage, $

$FC_{comp,D/S}$ is the cost of component damage(downstream), $

$FC_{comp,line}$ is the cost of component damage (tracing ~~line~~ piping), $

$FC_{comp,main}$ is the cost of component damage (main pipe), $

$FC_{comp,process}$ is the cost of component damage(process ~~line~~ piping), $

$FC_{condensate}$ is the cost of condensate, $/lb ($/kg)

$FC_{cold}^{HEX,Turbine}$ is the financial consequence of failure of heat exchanger and turbine due to blockage, $

$FC_{leak,open}^{HEX,Turbine}$ is the financial consequence of failure of heat exchanger and turbine due to leakage (open system), $

$FC_{leak,closed}^{HEX,Turbine}$ is the financial consequence of failure of heat exchanger and turbine due to leakage (closed system), $

FC_{inj} is the financial consequence as a result of serious injury to personnel, $

$FC_{inj,cold}$ is the financial consequence due to blockage as a result of serious injury to personnel, $

$FC_{inj,leak}$ is the financial consequence due to leakage as a result of serious injury to personnel, $

$FC_{inj,D/S}$ is the financial consequence as a result of serious injury to personnel (downstream), $

$FC_{inj,flam}$ is the financial consequence of as a result of serious injury to personnel due to flammable release, $

FC_{inj_n} is the financial consequence as a results of serious injury to personnel, $ for steam trap n

$FC_{inj,nfnt}$ is the financial consequence as a result of serious injury to personnel due to non-flammable, non-toxic, $

$FC_{inj,process}$ is the financial consequence as a result of serious injury to personnel (process ~~line~~ piping), $

$FC_{inj,toxic}$ is the financial consequence of as a result of serious injury to personnel due to toxic release, $

FC_{loss} is the cost of steam loss, \$

$FC_{loss,D/S}$ is the cost of condensate loss (downstream), \$

FC_{prod} is the cost of production loss, \$

$FC_{prod,D/S}$ is the cost of production loss (downstream), \$

$FC_{prod,process}$ is the cost of production loss (process ~~line~~ piping), \$

FC_{steam} is the cost of steam production, \$/lb (\$/kg)

$FC_{cold}^{Tracing,HT}$ is the financial consequence of failure of ~~high temperature~~ general steam tracing due to blockage, \$

$FC_{leak,open}^{Tracing,HT}$ is the financial consequence of failure of ~~high temperature~~general steam tracing due to leakage (open system), \$

$FC_{leak,closed}^{Tracing,HT}$ is the financial consequence of failure of ~~high temperature~~ general steam tracing due to leakage (closed system), \$

$FC_{cold}^{Tracing,LT}$ is the financial consequence of failure of low temperature tracing due to blockage, \$

$FC_{leak,open}^{Tracing,LT}$ is the financial consequence of failure of low temperature tracing due to leakage (open system), \$

$FC_{leak,closed}^{Tracing,LT}$ is the financial consequence of failure of low temperature tracing due to leakage (closed system), \$

FC_{steam} ~~is the cost of steam, \$/lb (\$/kg)~~

$lrate$ Leakage rate is based on historical inspection data, lb/hr (kg/hr)

$injcost$ is cost of personnel injury per individual, \$

$P(t)_{f,final,leak\ (steam\ \sout{using}\ system)}$ is the probability of failure for steam ~~using~~ system due to leakage, failure/year

$P(t)_{f,final,cold\ (steam\ \sout{using}\ system)}$ is the probability of failure for steam ~~using~~ system due to blockage, failure/year

$P(t)_{f,final,leak(ST,MP\ or\ CV)}$ is the tailored probability of failure due to leakage calculated for the associated ~~lines~~ piping (combined POF), consisting of multiple steam traps, mechanical pumps and control valves, failure/year

$P(t)_{f,final,cold(ST,MP\ or\ CV)}$ is the tailored probability of failure due to blockage calculated for the associated ~~lines~~ piping (combined POF), consisting of multiple steam traps, mechanical pumps and control valves, failure/year

$P(t)_{f,def,leak}$ is the probability of failure due to leakage of steam traps mechanical pumps and control valves based on default values for Weibull parameters, failure/year

$P(t)_{f,def,cold}$ is the probability of failure due to leakage of steam traps mechanical pumps and control valves based on default values for Weibull parameters, failure/year

$P(t)_{fn,leak}$ is the probability of failure due to leakage of steam traps mechanical pumps and control valves, n in series or parallel configurations, failure/year

$P(t)_{fn,cold}$ is the probability of failure due to blockage of steam traps mechanical pumps and control valves, n in series or parallel configurations, failure/year

$P(t)_{f,final\ series,leak(ST,MP\ or\ CV)}$ is the probability of failure due to leakage for multiple steam traps, mechanical pumps and control valves in series, failure/year

$P(t)_{f,final\ series,cold(ST,MP\ or\ CV)}$ is the probability of failure due to blockage for multiple steam traps, mechanical pumps and control valves in series, failure/year

$P(t)_{f,final\ parallel,leak(ST,MP\ or\ CV)}$ is the probability of failure due to leakage for multiple steam traps, mechanical pumps and control valves in parallel, failure/year

$P(t)_{f,final\ parallel,cold(ST,MP\ or\ CV)}$ is the probability of failure due to blockage for multiple steam traps, mechanical pumps and control valves in parallel, failure/year

$P(t)_{f,prior,leak}$ is the probability of not failing due to leakage the inspection prior to inspection, failure/year

$P(t)_{f,prior,cold}$ is the probability of not failing due to blockage the inspection prior to inspection, failure/year

$P(t)_{f,after,leak}$ is the probability of failure due to leakage after inspection depending on the results, failure/year

$P(t)_{f,after,cold}$ is the probability of failure due to blockage after inspection depending on the results, failure/year

$P(t)_{f,upd,leak}$ is the probability of failure due to leakage used for inspection updating, failure/year

$P(t)_{f,upd,cold}$ is the probability of failure due to blockage used for inspection updating, failure/year

$P(t)_{f,wgt,leak}$ is the updated probability of failure due to leakage after inspection, failure/year

$P(t)_{f,wgt,cold}$ is the updated probability of failure due to blockage after inspection, failure/year

$P(t)_{f,final(equ)}$ is the tailored probability of failure calculated for the ~~steam~~ steam-using equipment, failure/year

$popdens$ is the population density of personnel or employees in the unit, personnel/ft^2 (personnel/m^2)

$Rate_{red}$ is the production rate reduction on a unit as a result of the equipment being out of service (%)

$R(t)_{leak}$ is the risk due to leakage as a function of time, $/year

$R(t)_{cold}$ is the risk due to blockage as a function of time, $/year

$R(t)$ is the risk as a function of time, $/year

t is the time at which the risk is to be calculated, years

$Unit_{prod}$ is the unit production margin ($/day)

β is the Weibull shape parameter estimated using AFT model

β_{equ} is the shape factor for equipment from Table 7.14

β_{ST} is the shape factor for steam traps, mechanical pumps and control valves from Table 7.4

η is the Weibull characteristic life parameter, years

$\eta_{def,leak,ST}$ is the scaled parameter for leakage estimated using Weibull AFT model from Table 7.4, years

$\eta_{def,cold,ST}$ is the characteristic life ~~scaled~~ parameter for blockage estimated using Weibull AFT model from Table 7.4, years

$\eta_{adj,leak(ST,MP\ or\ CV)}$ is the tailored characteristic life ~~(scale factor)~~ for leakage based on condition of design/installation, operation or maintenance history factors for equipment, years

$\eta_{adj,cold(ST,MP\ or\ CV)}$ is the tailored characteristic life ~~(scale factor)~~ for blockage based on condition of design/installation, operation or maintenance history factors for equipment, years

$\eta_{adj,equ}$ is the tailored characteristic life ~~(scale factor)~~ based on condition of design/installation, operation, or maintenance history factors for equipment, years

$\eta_{def,equ}$ is the <u>characteristic life</u> ~~scaled~~ parameter for equipment estimated using Weibull AFT model from Table 7.14, years

$\eta_{upd,leak}$ is the updated characteristic life for leakage after inspection results, years

$\eta_{upd,cold}$ is the updated characteristic life for blockage after inspection results, years

7.8 Tables

Table 7.1 – Steam-Using Application Groups and Equipment Examples

Application Group	Equipment Example	Process Application Examples
Steam heated equipment	Process Heat Exchanger	Alkylation, distillation, gas recovery, isomerization, 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 7.2 – 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 7.3 – Basic Data Needed for POF Calculation of Steam-Using System

Data	Description	Data Source

Steam trap type	Type of steam trap:
	• Mechanical steam traps
	  o Free float
	  o Lever float
	  o Inverted bucket
	• Thermostatic steam traps
	  o Bimetal
	  o Balanced pressure trap
	• Thermodynamic steam traps
	  o Thermodynamic Disc
	  o 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~~ pipe bundling (i.e. inlet tracing ~~line~~ pipe 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 176°F (80°C)) • Tracing – Instrumentation • Tracing – Relief Valve • Steam Main ~~Line~~piping • Condensate ~~Line~~ piping (Recovery) • Flare	Fixed Equipment

Data	Description	Data Source
	• Distillation Column	
Equipment Details	Operating conditions Design conditions Dimensions	User Specified

Table 7.4 – Default Weibull Parameters for Different Steam Traps, Control Valve and Mechanical Pump

Steam Trap Category	Steam Trap Type	Default β_{ST}	Default value for Leakage failure mode $\eta_{def,leak,ST}$	Default value for Blockage failure mode $\eta_{def,cold,ST}$
Mechanical steam traps	Free Float	1.8	16.1	13.8
	Inverted bucket	1.6	16.1	13.8
	Lever Float	1.7	11.7	8.5
Thermostatic steam traps	Bimetal	1.8	8	7.5
	Balanced Pressure	2	5.3	5.2
Thermodynamic steam traps	Disc	2	9.4	5
	Impulse	2	9.4	5
Control valve		1.8	61.5	61.5
Mechanical Pump		1.2	3.1	3.1

Table 7.5 – Design Condition Adjustment 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~~ pipe 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~~ pipe 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~~ pipe 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~~ pipe 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~~ Pipe bundling: inlet tracing ~~line~~ pipe is heated by other bundled pipes. Poor installation environment: higher than average failure rate at this location or area.		

Table 7.6 – Operation Condition Adjustment 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 7.7 – Maintenance History/Inspection Condition Adjustment 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 m) is recorded in the past AND no disassembly preventive maintenance exists.	0.65
Average	If water hammer near the trap (i.e. within 10 m) is recorded in the past AND disassembly preventive maintenance exists	0.72
Good	If water hammer near the trap (i.e. within 10 m) 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 m) is not recorded AND disassembly preventive maintenance exists AND built-in integral/self-cleaning exists	1.1

Table 7.8 – Design Condition Adjustment 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 7.9 – Operation Condition Adjustment 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 7.10 – Maintenance History/Inspection Condition Adjustment 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 m) is recorded in the past	0.65
Average	If water hammer near the pump (i.e. within 10 m) is not recorded AND disassembly preventive maintenance does not exist	1
Good	If water hammer near the pump (i.e. within 10 m) is not recorded AND disassembly preventive maintenance exists	2

Table 7.11 - Design Condition Adjustment 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 c. Poor installation environment (i.e. higher than average failure rate at this location or area)	1.3

Table 7.12 – Operation Condition Adjustment 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 7.13 – Maintenance History/Inspection Condition Adjustment 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 m) is recorded in the past	0.65
Average	If water hammer near the trap (i.e. within 10 m) is not recorded AND disassembly preventive maintenance does not exist	1
Good	If water hammer near the trap (i.e. within 10 m) is not recorded AND disassembly preventive maintenance exists	1.1

Table 7.14 – Default Weibull Parameters for Steam-Using Equipment

Equipment	Default $\eta_{def,equ}$	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 header	25.1	3
Condensate recovery ~~Line~~ piping ~~(Recovery)~~	21.5	3
Distillation Column	37	3
Flare	13.3	3

Table 7.15 – Design Condition Adjustment 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 7.16 – Operation Condition Adjustment 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 < 18°F (10°C) b. Cyclic operation c. Exceed PMO/TMO/Steam Mass d. In the case of turbine: superheat rate < 27°F (15°C) AND (for condensing turbine only) operating vacuum > 25% weaker than design e. In the case of heat exchanger: superheat rate is ≥ 18°F (10°C) 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 < 27°F (15°C) AND (for condensing turbine only) operating vacuum > 25% weaker than design e. In the case of heat exchanger: superheat rate is ≥ 18°F (10°C) 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 < 18°F (10°C) b. Cyclic operation c. Exceed PMO/TMO/Steam Mass d. In the case of turbine: superheat rate < 27°F (15°C) AND (for condensing turbine only) operating vacuum > 25% weaker than design e. In the case of heat exchanger: superheat rate is ≥ 18°F (10°C) 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 < 18°F (10°C) b. Cyclic operation c. Exceed PMO/TMO/Steam Mass d. In the case of turbine: superheat rate < 27°F (15°C) AND (for condensing turbine only) operating vacuum > 25% weaker than design e. In the case of heat exchanger: superheat rate is ≥ 18°F (10°C) 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 7.17 – Maintenance History/Inspection Condition Adjustment 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 7.18 – Level of Inspection Confidence Factor for Steam Traps, Mechanical Pumps and Control Valves

Inspection results	Confidence Factor that Inspection Result Determines the True Damage State, CF				
	Ineffective	**Poorly Effective**	**Fairly Effective**	**Usually Effective**	**Highly Effective**
Leak detected, CF_{fail}	No credit	0.3	0.6	0.85	0.95
Leak not detected, CF_{pass}	No credit	0.3	0.6	0.75	0.9
Blocked, CF_{fail}	No credit	0.3	0.6	0.85	0.95
Not Blocked, CF_{pass}	No credit	0.3	0.6	0.85	0.95

Table 7.19 – Equations for Updating POF After Inspection

Inspection Effectiveness	Inspection results	Equation for updating the POF after inspection
Highly effective	No leakage or blockage detected	$P(t)_{f,wgt,leak} = P(t)_{f,final,leak_{(ST,MP \text{ or } CV)}} - 0.2$ $\cdot P(t)_{f,final,leak_{(ST,MP \text{ or } CV)}} \left(\dfrac{t}{\eta_{adj,leak_{(ST,MP \text{ or } CV)}}} \right)$ $+ 0.2$ $\cdot P(t)_{f,final,leak_{(ST,MP \text{ or } CV)}} \left(\dfrac{t}{\eta_{adj,leak_{(ST,MP \text{ or } CV)}}} \right)$
Usually effective		
Fairly effective		
Poorly Effective		

		$$P(t)_{f,wgt,cold} = P(t)_{f,final,cold(ST,MP\ or\ CV)} - 0.2$$ $$\cdot P(t)_{f,final,cold(ST,MP\ or\ CV)} \left(\frac{t}{\eta_{adj,cold(ST,MP\ or\ CV)}} \right)$$ $$+ 0.2$$ $$\cdot P(t)_{f,final,cold(ST,MP\ or\ CV)} \left(\frac{t}{\eta_{adj,cold(ST,MP\ or\ CV)}} \right)$$
Highly effective		$$P(t)_{f,wgt,leak} = P(t)_{f,after,leak}$$ $$P(t)_{f,wgt,cold} = P(t)_{f,after,cold}$$
Usually effective	Leakage or blockage detected	
Fairly effective		$$P(t)_{f,wgt,leak} = \left(0.5 \cdot P(t)_{f,final,leak(ST,MP\ or\ CV)} \right)$$ $$+ \left(0.5 \cdot P(t)_{f,after,leak} \right)$$ $$P(t)_{f,wgt,cold} = \left(0.5 \cdot P(t)_{f,final,cold(ST,MP\ or\ CV)} \right)$$ $$+ \left(0.5 \cdot P(t)_{f,after,cold} \right)$$
Poorly Effective		

Table 7.20 – Required Data for COF Assessment

Cost Description	Data Source
Cost of steam, \$/~~kg~~ lb (FC_{steam})	User specified ~~User required~~
Cost of condensate, \$/lb ($FC_{condensate}$)	User specified
Leakage rate is based on historical inspection data, lb/hr (kg/hr) (lrate)	User specified ~~User required~~
Cost of personnel injury per individual as per Part 3, Section 4.12.5, \$ ($injcost$)	User specified ~~User required~~
Population density of personnel or employees in the unit as per Part 3, Section 4.12.5, personnel/ft^2 ($popdens$)	User specified ~~User required~~
Inspection interval, 8760 hours IF not defined by user	User specified ~~User required~~
Daily production margin, $Unit_{prod}$, on the unit (\$/day)	User specified ~~User required~~
Production rate reduction, $Rate_{red}$, on a unit as a result of the equipment being out of service (%)	User specified ~~User required~~
The number of days, D_{sd} , required to shut a unit down to repair the equipment during an unplanned shutdown, days	User specified ~~User required~~
The cost of production loss from downstream equipment, \$ ($FC_{prod,D/S}$)	User specified ~~User required~~
The cost of production loss in process ~~lines~~ piping, \$ ($FC_{prod,process}$)	User specified ~~User required~~
Component damage costs, applies to the cost of all downstream equipment as in Table 7.14, \$. (FC_{comp} , $FC_{comp,line}$, $FC_{comp,main}$, $FC_{comp,process}$, $FC_{comp,D/S}$)	User specified ~~User required~~

Table 7.21 – COF equations for blockage in steam-using equipment.

Equipment	Open/Closed System	Bypass (Open)	Bypass (Close)
Steam Turbine	Open	5.155	
	Closed	5.156	5.154
Heat Exchanger	Open	5.155	
	Closed	5.156	
Tracing - General	Open	5.155	
	Closed	5.156	
Tracing - Low Temperature	Open	5.158	
	Closed	5.159	
Tracing - Instrumentation	Open (General)	5.155	
	Open (Low-Temp)	5.158	
	Closed (General)	5.156	5.157
	Closed (Low-Temp)	5.159	
Tracing - Relief Valve	Open (General)	5.155	
	Open (Low-Temp)	5.158	
	Closed (General)	5.156	
	Closed (Low-Temp)	5.159	
Steam Header	Open	5.155	
	Closed	5.156	5.154
Condensate Recovery	Open	Not Applicable	
	Closed		
Distillation Column	Open	5.155	
	Closed	5.156	5.154
Flare	Open	5.155	
	Closed	5.156	5.16

Table 7.22 – COF equations for leakage in steam-using equipment.

Equipment	Open/Closed System	Bypass (Open)	Bypass (Close)
Steam Turbine	Open	5.155	5.155[1]
	Closed	5.156	
Heat Exchanger	Open	5.155	
	Closed	5.156	
Tracing - General	Open	5.155	
	Closed	5.156	
Tracing - Low Temperature	Open	5.158	5.158[1]
	Closed	5.159	
Tracing - Instrumentation	Open (General)	5.155	5.155[1]
	Open (Low-Temp)	5.158	5.158[1]
	Closed (General)	5.155	5.155[1]
	Closed (Low-Temp)	5.159	5.158[1]
Tracing - Relief Valve	Open (General)	5.155	5.155[1]

	Open (Low-Temp)	5.158	5.158[1]
-	Closed (General)	5.155	5.155[1]
-	Closed (Low-Temp)	5.159	5.158[1]
Steam Header	Open	5.155	5.155[1]
-	Closed	5.156	
Condensate Recovery	Open	Not Applicable	
-	Closed	5.161	N/A
Distillation Column	Open	5.155	5.155[1]
-	Closed	5.156	
Flare	Open	5.155	
-	Closed	5.156	
Note 1: For leakage with a closed bypass in an open or closed system, use $FC_{inj} = 0$ in appropriate equations.			

7.9   Figures

```
                                                    ┌─────────────────────────┐
                                   ┌─────────────┐  │ • Free float            │
                                   │ Select Type │◄─┤ • Level float           │
                                   │ of Steam    │  │ • Inverted bucket       │
                                   │ Trap        │  │ • Bimetal               │
                                   └─────────────┘  │ • Balanced pressure trap│
                                          │         │ • Thermodynamic Disc    │
                                          ▼         │ • Thermodynamic Piston  │
                                   ┌─────────────┐  └─────────────────────────┘
                                   │ Select      │
                                   │ default     │
                                   │ Weibull     │
                                   │ Shape       │
                                   │ Parameter,  │
                                   │ and         │
                                   │ characteristic
                                   │ life param. │
                                   └─────────────┘
```

Select Type of Steam Trap
- Free float
- Level float
- Inverted bucket
- Bimetal
- Balanced pressure trap
- Thermodynamic Disc
- Thermodynamic Piston

Select default Weibull Shape Parameter, and characteristic life parameter, for blockage and leak

Select Adjustment Multipliers for design, operation and maintenance, of Control Valve

Select Adjustment Multipliers for design, operation and maintenance, of Mechanical Pump

Select Adjustment Multipliers for design, operation and maintenance, of Steam Trap

Calculate Adjusted Probability of failure for Control Valve

Calculate Adjusted Probability of failure for Mechanical Pump

Calculate Adjusted Probability of failure for each individual Steam Trap for both blockage and leak failure modes

Calculate Combined Probability of Failure
- Based on Steam Line configuration

Select steam using equipment
- Steam Turbine
- Heat Exchanger
- Tracing – Instrumentation
- Tracing – Relief Valve
- Steam Line
- Condensation Line (recovery)
- Distillation Column
- Flare

Select default Weibull Shape Parameter, and characteristic life parameter, for main equipment

Select Adjustment Multipliers for design, operation and maintenance, of steam using equipment

Calculate Probability of failure for the main steam using equipment (due to steam related failures)

Calculate final Probability of Failure for steam using system

Calculate Consequence of Failure for both leakage and blockage scenario

Calculate Current Risk and Future Risk as the function of time

Determine inspection date or any other mitigation actions based on risk criteria

Draft - For Committee Review

```
                                                                    • Free float
                                                                    • Level float
                                   ┌──────────────────┐             • Inverted bucket
                                   │ Select Type of   │◄────────    • Bimetal
                                   │ Steam Trap       │             • Balanced pressure trap
                                   └──────────────────┘             • Thermodynamic Disc
                                            │                       • Thermodynamic Piston
                                            ▼
                                   ┌──────────────────┐
                                   │ Select default   │
                                   │ Weibull Shape    │
                                   │ Parameter, and   │
                                   │ characteristic   │
                                   │ life parameter,  │
                                   │ for blockage     │
                                   │ and leak         │
                                   └──────────────────┘
                                            │
  ┌───────────────┐   ┌───────────────┐   ┌──────────────────┐
  │ Select        │   │ Select        │   │ Select           │
  │ Adjustment    │   │ Adjustment    │   │ Adjustment       │
  │ Multipliers   │   │ Multipliers   │   │ Multipliers      │
  │ for design,   │   │ for design,   │   │ for design,      │
  │ operation and │   │ operation and │   │ operation and    │
  │ maintenance,  │   │ maintenance,  │   │ maintenance, of  │
  │ of Control    │   │ of Mechanical │   │ Steam Trap       │
  │ Valve         │   │ Pump          │   │                  │
  └───────────────┘   └───────────────┘   └──────────────────┘
          │                   │                    │
          ▼                   ▼                    ▼
  ┌───────────────┐   ┌───────────────┐   ┌──────────────────┐
  │ Calculate     │   │ Calculate     │   │ Calculate        │
  │ Adjusted      │   │ Adjusted      │   │ Adjusted         │
  │ Probability   │   │ Probability   │   │ Probability of   │
  │ of failure for│   │ of failure for│   │ failure for each │
  │ Control Valve │   │ Mechanical    │   │ individual       │
  │               │   │ Pump          │   │ Steam Trap for   │
  │               │   │               │   │ both blockage    │
  │               │   │               │   │ and leak failure │
  │               │   │               │   │ modes            │
  └───────────────┘   └───────────────┘   └──────────────────┘
          │                   │                    │
          └───────────────────┴────────────────────┤
                                                    ▼
                                   ┌──────────────────┐
                                   │ Calculate        │◄──────  • Based on Steam Line configuration
                                   │ Combined         │
                                   │ Probability of   │
                                   │ Failure          │
                                   └──────────────────┘
                                            │
                                            ▼                        • Steam Turbine
                                   ┌──────────────────┐              • Heat Exchanger
                                   │ Select steam     │◄──────       • Tracing – Instrumentation
                                   │ using equipment  │              • Tracing – Relief Valve
                                   │                  │              • Steam Line
                                   └──────────────────┘              • Condensation Line (recovery)
                                            │                        • Distillation Column
                                            ▼                        • Flare
                                   ┌──────────────────┐
                                   │ Select default   │
                                   │ Weibull Shape    │
                                   │ Parameter, and   │
                                   │ characteristic   │
                                   │ life parameter,  │
                                   │ for main         │
                                   │ equipment        │
                                   └──────────────────┘
                                            │
                                            ▼
                                   ┌──────────────────┐
                                   │ Select           │
                                   │ Adjustment       │
                                   │ Multipliers for  │
                                   │ design,          │
                                   │ operation and    │
                                   │ maintenance, of  │
                                   │ steam using      │
                                   │ equipment        │
                                   └──────────────────┘
                                            │
                                            ▼
                                   ┌──────────────────┐
                                   │ Calculate        │
                                   │ Probability of   │
                                   │ failure for the  │
                                   │ main steam using │
                                   │ equipment (due   │
                                   │ to steam related │
                                   │ failures)        │
                                   └──────────────────┘
                                            │
                                            ▼
                                   ┌──────────────────┐
                                   │ Calculate final  │
                                   │ Probability of   │
                                   │ Failure for      │
                                   │ steam using      │
                                   │ system           │
                                   └──────────────────┘
                                            │
                                            ▼
                                   ┌──────────────────┐
                                   │ Calculate        │
                                   │ Consequence of   │
                                   │ Failure for both │
                                   │ leakage and      │
                                   │ blockage         │
                                   │ scenario         │
                                   └──────────────────┘
                                            │
                                            ▼
                                   ┌──────────────────┐
                                   │ Calculate        │
                                   │ Current Risk and │
                                   │ Future Risk as   │
                                   │ the function of  │
                                   │ time             │
                                   └──────────────────┘
                                            │
                                            ▼
                                   ┌──────────────────┐
                                   │ Determine        │
                                   │ inspection date  │
                                   │ or any other     │
                                   │ mitigation       │
                                   │ actions based on │
                                   │ risk criteria    │
                                   └──────────────────┘
```

Figure 7.1 – Overview of POF Calculation Framework for Steam Systems.

Steam traps for condensate discharge (or mechanical pumps or control valves)
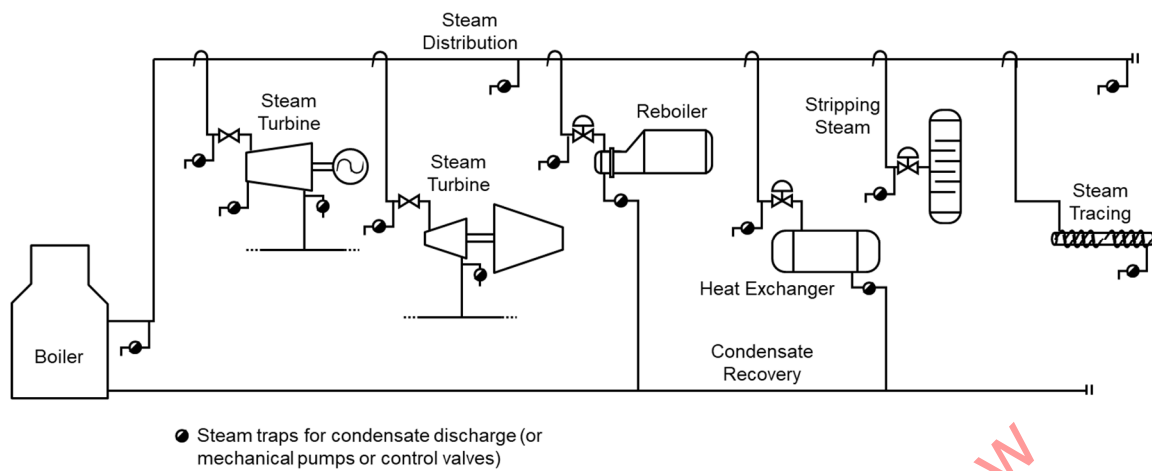
Figure 7.2 – A typical layout of multiple steam systems containing steam traps (or mechanical pumps or control valves), steam ~~lines~~ piping and associated equipment.
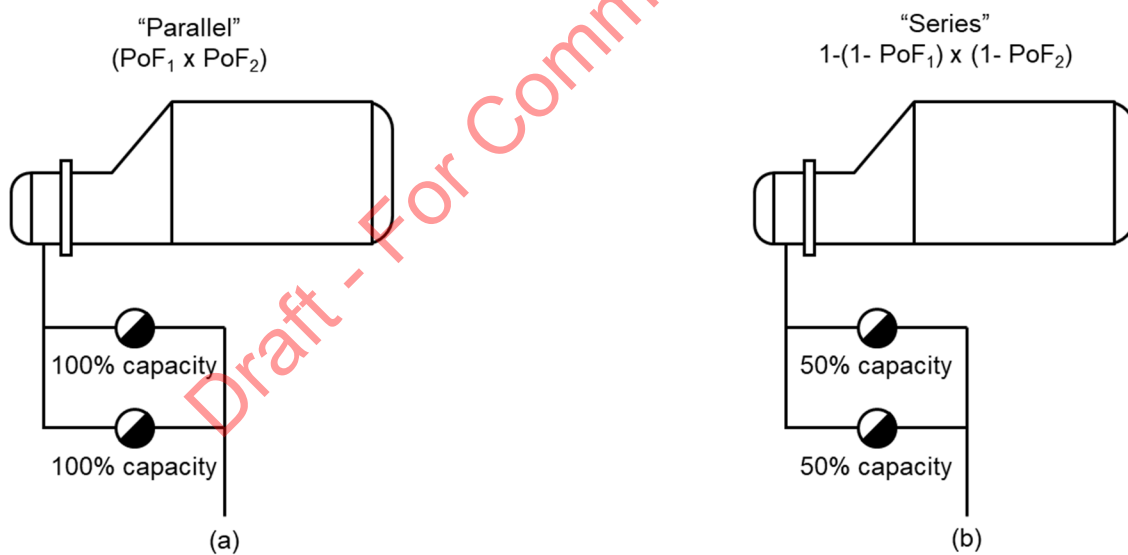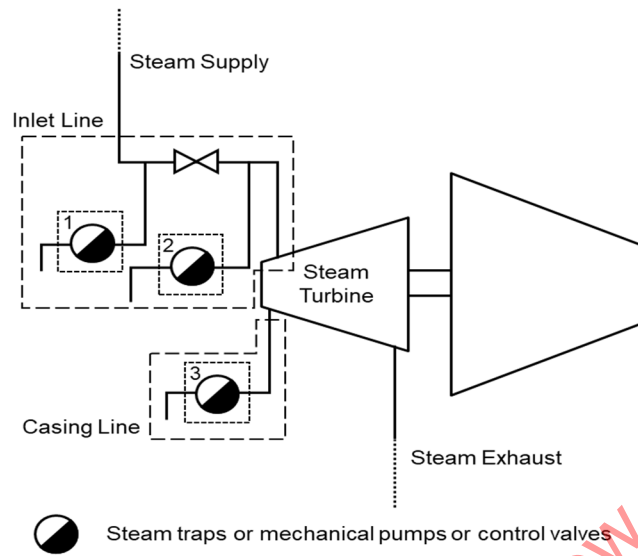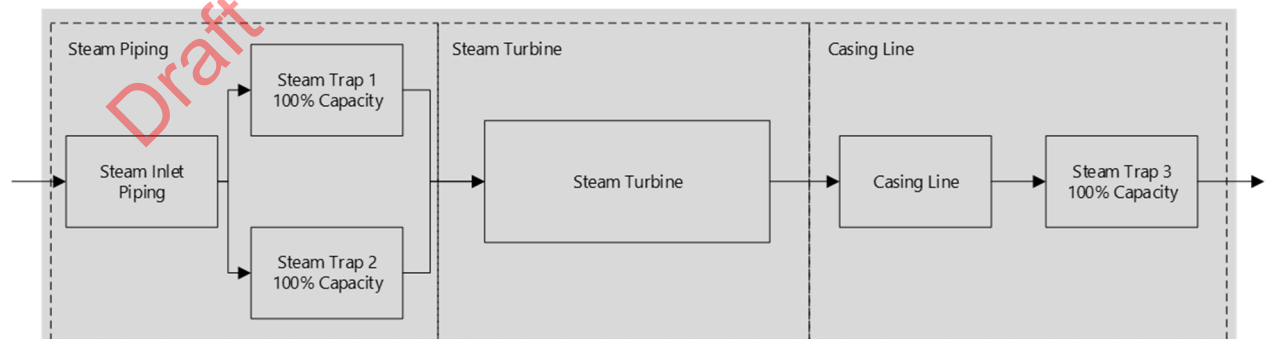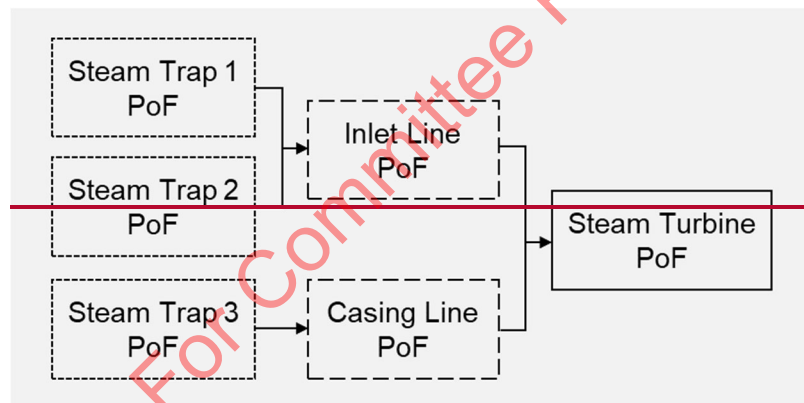

"Parallel"
$(PoF_1 \times PoF_2)$

100% capacity

100% capacity

(a)

"Series"
$1-(1- PoF_1) \times (1- PoF_2)$

50% capacity

50% capacity

(b)

Figure 7.3 – Sample Configuration of Multiple Steam Traps (or mechanical pumps or control valves).

(a) Configuration of a steam turbine with steam traps or mechanical pumps or control valves.

(b) <u>Reliability Block diagram when steam trap 1 and 2 are in parallel and operating at 100% capacity for the calculation of POF.</u> ~~Block diagram for the calculation of POF for steam turbine with steam traps or mechanical pumps or control valves.~~

(c) Reliability Block diagram when steam trap 1 and 2 are in series and operating at 50% capacity for the calculation of POF.

Figure 7.4 – Sample configuration of a steam turbine with steam traps or mechanical pumps or control valves.

Risk-Based Inspection Methodology
Part 5—Special Equipment
Annex 5.B Contents

Risk-Based Inspection Methodology
Part 5—Special Equipment
Annex 5.B—Bibliography

5.B.1 General

The references for Part 5 of this document are provided in Section 5.B.2 of this Annex.

5.B.2 Tables

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