The application of risk-based inspections on furnace high-pressure cooling systems incorporating proportional hazards and steam explosion consequence modelling

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1

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Abstract

Purpose – Steam explosions are a major safety concern in many modern furnaces. The explosions are sometimes caused by water ingress into the furnace from leaks in its high-pressure (HP) cooling water system, coming into contact with molten matte. To address such safety issues related to steam explosions, risk based inspection (RBI) is suggested in this paper. RBI is presently one of the best-practice methodologies to provide an inspection schedule and ensure the mechanical integrity of pressure vessels. The application of RBIs on furnace HP cooling systems in this work is performed by incorporating the proportional hazards model (PHM) with the RBI approach; the PHM uses real-time condition data to allow dynamic decision-making on inspection and maintenance planning.

Design/methodology/approach – To accomplish this, a case study is presented that applies an HP cooling system data with moisture and cumulated feed rate as covariates or condition indicators to compute the probability of failure and the consequence of failure (CoF), which is modelled based on the boiling liquid-expanding vapour explosion (BLEVE) theory.

Findings – The benefit of this approach is that the risk assessment introduces real-time condition data in addition to time-based failure information to allow improved dynamic decision-making for inspection and maintenance planning of the HP cooling system. The work presented here comprises the application of the newly proposed methodology in the context of pressure vessels, considering the important challenge of possible explosion accidents due to BLEVE as the CoF calculations.

Research limitations/implications – This paper however aims to optimise the inspection schedule on the HP cooling system, by incorporating PHM into the RBI methodology, as was recently proposed in the literature by Lelo *et al.* (2022). Moisture and cumulated feed rate are used as covariate. At the end, risk mitigation policy is suggested.

Originality/value – In this paper, the proposed methodology yields a dynamically calculated quantified risk, which emphasised the imperative for mitigating the risk, as well as presents a number of mitigation options, to quantifiably affect such mitigation.

Keywords Risk based inspection (RBI), Proportional hazards model (PHM), High pressure (HP), Pressure vessel, Probability of failure (PoF), Consequence of failure (CoF)

Paper type Case study

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1. Introduction

Industry decision-makers frequently utilise a risk-based methodology for strategising inspection and maintenance schedules in order to effectively mitigate the risk associated with pressure vessels. This approach is formalised within risk-based inspection (RBI) standards and guidelines like API RP 581. The evaluation of risk comprises primarily of the probability of failure (*PoF*) and the consequence of failure (*CoF*). Through the RBI procedure, both the likelihood and severity of failure are pinpointed and measured to establish an inspection policy.

Qualitative risk assessment often relies on expert judgement and plant-specific knowledge, whereas quantitative risk assessment, mandated for high-risk pressure vessels, utilises statistical calculations derived from historical data. Improvements in the accuracy of quantitative assessment for both the *PoF* and *CoF* components are obvious benefits, given the potential consequences of catastrophic failure in such high-risk pressure vessels.

This study proposes enhancements to the quantitative risk assessment for the *PoF* and the *CoF* through the utilisation of valuable suggested methodologies.

The scenario being addressed involves a leaking pipe within the high pressure (HP) cooling system, resulting in the sudden infiltration of water into molten matte (which denotes the molten metal sulphide phases formed during the smelting of base metal), within the furnace of a converter plant located in a smelter (Taskinen, 2017). We examine a scenario in which water accumulates on the slag crust, preceding the crust's failure, leading to the infiltration of water into the molten matte. This could potentially trigger a boiling liquid-expanding vapour explosion (BLEVE) within the converter. In order to mitigate such incidents, the RBI process was proposed, enhanced by the application of advanced methodologies for precise calculation and analysis of *PoF* and *CoF*.

According to Zeng and Zio (2018), the underlying assumption of the RBI approach is that risk remains acceptable between two planned inspection or maintenance intervals. This assumption is however not always true for complex degrading systems (Bhatia *et al.*, 2019) and an innovative dynamic risk assessment (DRA) methodology is required for risk assessment of dynamically changing systems.

The literature presents diverse methodologies (both qualitative and quantitative) for assessing *PoF*, a crucial parameter in risk evaluation. Quantitative approaches are required for assessing critical vessels. Ideally, quantitative approaches will be based on a failure model to determine the remaining useful life (RUL). In cases where the failure model is not known or accurate, the next best practice would be to use failure statistical methods and supplement this with Bayesian methods when data is scarce. Since RBI implies that inspections are performed and therefore that condition parameters will be available, it is argued in this paper that in these cases, a need exists for the *PoF* estimation method, which uses both the statistical failure statistics, as well as the condition data, to estimate the *PoF*.

The main objective of this work is that by the incorporation of PHM (which uses both statistical and condition data) into RBI, the inspection decision is not only defined in terms of frequency but the decision-making process becomes dynamic because real-time condition data are used to update the *PoF*. Another objective of this work is that the CoF is not defined based on acceptability criteria and expert opinion, but rather by calculating it using BLEVE theory.

The paper is organised as follows. Section 2 describes the methodology, starting with the problem description, followed by the RBI approach and consequence of a BLEVE. Section 3 addresses the case study and discusses the results. Finally, section 4 concludes the paper.

2. Methodology

2.1 Problem description

Water coming in contact with liquid metal is a well-documented hazard within the metallurgical field and has been implicated in numerous fatal incidents globally (Kennedy *et al.*, 2013a). In the process of converting platinum group metals (PGMs), the presence of water leaking from a cracked pipe within the HP cooling system may gather on top of the slag crust covering a pool of molten matte. This scenario has the potential to trigger a BLEVE as water accumulates gradually over time.

To overcome such safety challenges, RBI is suggested in this work to integrate PHM into RBI for the *PoF* computation, as was recently proposed by Lelo *et al.* (2022).

Figure 1 schematically depicts water leaking from an HP pipe, at a mass flow rate $\dot{m}_1$, and then accumulating on the slag crust at a mass flow rate $\dot{m}_2$, before the slag fails under the weight of the accumulated water, the water penetrates the matte and then flashes.

2.2 Risk based inspection

2.2.1 Introduction. RBI is a methodology of risk analysis that allows the management of inspection programmes in an industry (Martínez *et al.*, 2009). RBI is focused towards preventing loss of containment of a HP system, and the RBI methodology utilises equipment failure to determine inspection regimes (Simpson, 2007).

In industry three common approaches are followed for risk assessment: (1) qualitative, (2) semi-quantitative and (3) quantitative. Although different organisations and companies promote the use of the RBI approach, the most established is that of the American Petroleum

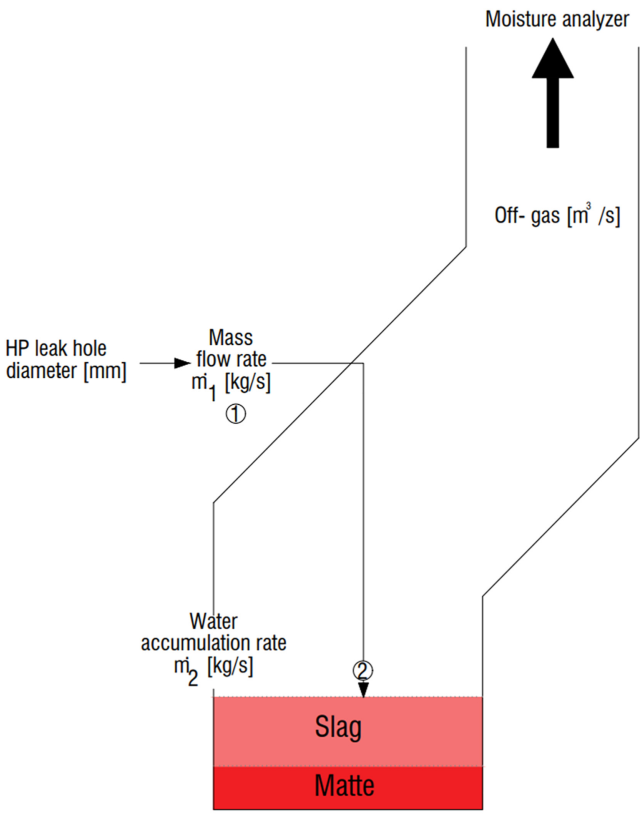

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Figure 1.
Overview of the model describing the HP water leak accumulation on the slag

Institute (API). The API follows a quantitative approach to risk assessment and is widely used in the oil and gas industries.

The launching of the first edition of the API 581 standard in 2000 brought significant advances to the industry. A complete rewrite of API 581 was released in September 2008, and a third edition in 2016, providing a step-by-step procedure that enables practitioners to better understand and implement the methodology (Shishesaz *et al.*, 2013).

Besides the API for the petrochemical industry, there is also the European Committee for Standardisation Workshop Agreement (CWA 15740), a guideline for the power generation industry. Both API 581 and CWA 15740 define risk as the product of the probability of an event occurring and the consequences. Risk can therefore be written as:

$$Risk = PoF \times CoF$$

2.2.2 Probability of failure estimation in the CWA 15740 guideline.

(1) Qualitative assessment (screening level)

Singh and Pretorius (2017) describe the basic steps of the European methodology, which addresses the risk analysis on multiple levels, progressing from the initial screening step to a detailed quantitative assessment.

During the screening stage, the assessment of risk consists of screening the components. The *PoF* estimation is performed by determining several specific criteria that could influence the *PoF*.

The screening analysis is relatively fast, simple, and cost-effective. During the screening, component risks are ranked using criteria like "high", "medium" and "low" risk levels. After screening the components, semi-quantitative analysis can be performed for components that fall into high and medium-risk categories, while components in the low-risk category continue to be subjected to the required maintenance.

The PoF at the screening stage is assessed by considering criteria such as:

(1) Presence of degradation

(2) Year of the last inspection

(3) The component ages

(4) Rate of degradation

(5) Design concerns

(6) Previous repairs of damage

(7) Rate of degradation

with each criterion having an associated weighting. The weight of each criterion is assigned according to the level of influence it has on the probability of causing failure. Furthermore, each criterion is scored relative to a qualitative measure of its influence on the component.

To produce a precise *PoF*, the score criterion expressed by *C* is multiplied by the weighting of the criterion expressed by *W*. The sum of that product for different components is then multiplied by the generic failure frequency, *GFF*, which is a factor used based on experience to identify failure frequencies of different components. *GFF* is typically developed using expert judgement and a history of component failure.

$$PoF = \{[(C1 \times W1) + (C2 \times W2) + (C3 \times W3)] \times (GFF)\} \quad (1)$$

(2) Semi-quantitative assessment (level two risk assessment)

Once the low-risk components have been screened out as described in the previous paragraph, the high and medium-risk components go to the semi-quantitative assessment (Singh and Pretorius, 2017).

The purpose of the level two *PoF* assessment is to determine the detailed factors that may affect the identified damage mechanisms for a given component. The *GFF* is once again used, but for this level, actual failure frequencies obtained from industry experience, are used where available. In instances where no industrial *GFF* data are available, the RBI team will revert to the *GFF* values that were used in the previous *PoF* determination. The level two risk calculation is performed in the same manner as the level one risk calculation. However, in the level two *PoF* assessment the number of criteria for the component under analysis is greater than the previous assessment level.

These criteria could be:

(1) Component age

(2) Total starts per year

(3) Time since the last inspection

(4) Rate of degradation

(5) Presence of hot spot

(6) Nominal operating temperature

(7) Corrosion susceptibility

(8) Frequency of temperature excursions

(9) The severity of temperature excursions

(10) Design concerns

(3) Quantitative assessment (level three risk assessment)

The fully quantitative or detailed approach is essentially based on calculating the RUL for the component under analysis. No further calculation is required when the calculation indicates that there is an acceptable period before failure. Otherwise, even more, detailed calculations are performed.

In the CWA standard, the detailed risk assessment follows almost the same rules as in the screening level, although in greater detail. For most critical components, the CWA procedure suggests a more detailed analysis where the damage mechanism can be identified, and the degradation rate obtained. The *PoF* can then be estimated (Jovanovic, 2014).

The quantitative methods for determining the *PoF* described above can be divided into two discernible approaches. In the case where an accurate failure model is available and expected loading and environmental conditions are quantifiable, the life expectancy for an identified failure mode is calculated. In this calculation, the ageing damage accumulation is estimated and forms the basis of risk-based decisions in terms of inspection schedules. Such inspections monitor the damage parameters, such as crack sizes or corrosion damage and are essentially a condition monitoring activity. Depending on the observed damage found during these inspections compared to the failure model results, RUL calculations are performed to trigger repair/replacement decisions or updated future inspection schedules. This includes the case where RBI implementation is done on existing equipment, which would already have accumulated damage. Again, future inspection schedules are based on a calculated RUL, with a failure model being available and pre-existing damage parameters having been measured.

In the case where an accurate failure model is not available, inspection schedules are based on historical or generic failure statistics, to estimate failure rates and probabilities. In this second approach, the inspections, or condition monitoring, are also aimed at finding damage (e.g. cracking or corrosion damage), but since a failure model is not available to estimate an RUL, any indication of damage would typically lead to repair/replacement actions.

2.2.3 Others risk assessment techniques. Quantitative Risk Analysis (QRA) pertains to the quantitative evaluation of risk through the application of mathematical methodologies grounded in engineering assessments, aiming to integrate estimations of incident probabilities and consequences (Song, 2018). A variety of methodologies have been devised for conducting quantitative risk analyses, with the traditional approaches such as Fault Tree (FT), Event Tree (ET) and Bow-tie (BT) standing out as the most prominent. These analyses play a crucial role in risk assessment by assessing the effectiveness of safety measures in avoiding or minimising accident repercussions. For instance, FT, which is widely utilised, delineates the logical connections from root causes to the top event qualitatively through gates, while quantitatively revealing the potential impact of a failure. However, these traditional risk assessment techniques are recognised for their static nature, failing to adapt to evolving operational circumstances or modifications (Khan and Abassi, 1998). Besides, conventional risk assessment techniques, in addition to generic failure data utilisation, are characterised by their non-case-specific nature, thereby introducing uncertainty into the outcomes. The limitations associated with these techniques have spurred the emergence of DRA methods, which aim to provide a more refined evaluation. These methods focus on the continual reassessment of risk by updating the initial failure probabilities of events and safety barriers as new information becomes available during a specific operation. The revision of prior failure probabilities is currently accomplished through two primary approaches. Firstly, Bayesian strategies involve the utilisation of new data in the form of likelihood functions to update prior failure rates using Bayes' theorem. Secondly, non-Bayesian updating approaches rely on real-time monitoring of parameters, inspection of process equipment and the application of physical reliability models to supply new data (Abimbola *et al.*, 2014).

The DRA presented in the previous paragraph by Abimbola *et al.* (2014) relies on the Bayesian approach, which includes expert opinion. However, this paper suggests a full quantitative approach without expert input in the computation. A condition-based approach would resolve the shortcomings related to the non-quantitative and time-based approaches by tracking the condition of a component. Being able to estimate the RUL of a component allows inspection and replacement to be planned. However, the condition-based approach relies on the availability of an accurate failure model. When this is not available, the time-based approach would be the only option, even though the inspections performed because of the RBI assessment will continuously add information, which will be under-utilised, only being used to inform replacement/repair decisions based on conservative acceptance criteria. Hence, this research proposes to combine the condition-based approach with component age, using a proportional hazard model (PHM).

2.3 Introduction to the proportional hazards model

The proportional hazards model (PHM) is based on work done by Cox to estimate the risk of human mortality. The PHM incorporates the effects of covariates or explanatory variables on the distribution of lifetimes. Covariates are any measured parameters that are thought to be related to the lifetimes of components. For each given time, the covariate provides an increase or decrease in the hazard, proportional to the baseline hazard rate (Lelo *et al.*, 2019).

The PHM is now one of the most popular statistical models used for survival analysis. Its popularity arises from the fact that the PHM is part of a broader class of survival analysis models which provide information on the duration of time between the identifiable start and the occurrence of an event (Lelo *et al.*, 2019). A key feature when using a PHM is that it can utilise time-series variation in the covariates. The information can be provided based on the change in explanatory variables over time that influence the probability of the event occurring.

The PHM is often presented in terms of the hazard model formula:

$$h[t, Z(t)] = \frac{\beta}{\eta}\left(\frac{t}{\eta}\right)^{\beta-1} exp\left\{\sum_{i=1}^{m} \gamma_i Z_i(t)\right\}$$

where $Z_i(t)$ is the explanatory variable expressing the hazard at the time t for an item or a component with a given specification of a set of predictor variables denoted by covariate. The $h_0(t)$ part is the baseline hazard; it includes time but not covariates, the second part $e^{\sum_i^p \gamma_i Z_i}$ which is the exponential part that includes covariates but not time. Therefore, the Cox model equation says that the hazard at a given time is the product of two important quantities, the baseline hazard function and the exponential part expressing the linear sum of $\gamma_i Z_i$.

2.4 Risk assessment based on API approach

The API RBI methodology may be used to manage the overall risk of a plant based on the inspection of the process equipment with the highest risk (Henry and Osage, 2014). API 581 provides quantitative procedures to establish an inspection programme using risk-based methods for pressurised fixed equipment including pressure vessels, piping, tankage, pressure relief devices, heat exchanger tube bundles, etc. In contrast to CWA 15740 which is essentially a framework for risk assessment, API 581 offers a quantitative approach in terms of empirical equations. It also addresses questions such as how to qualify and quantify risks, as well as how to plan and execute an inspection programme (Martínez *et al.*, 2009). These are important reasons why we follow the API 581 approach in this work.

2.4.1 Probability of failure according to API 581. The notion of failure can have several meanings, such as:

(1) When components lose their legal or technical integrity due to a failure mechanism such as cracking or loss of thickness, this can be called a failure by loss of integrity or compliance.

(2) Failure by loss functionality is when a component no longer meets the performance standard. Failure by loss of containment is when tanks or pressure-containing parts are leaking or worse.

The PoF by loss of containment is an important part of risk assessment. To run an RBI implementation, a credible assessment of the PoF must be performed. Once the degradation processes and their probable rates are known, the PoF is rather low since the safe life of the equipment can be evaluated and monitored properly. In the opposite case, when degradation processes are not known, incidents can go unnoticed until it is too late.

API 581 proposes two methods of computing the PoF. The first is the GFF method and the second is the two parameters Weibull method. The GFF method is utilised to predict the loss of containment PoF of pressure boundary equipment. The second method addressed by API 581 is the Weibull distribution method used to predict the PoF.

(1) Generic failure frequency method

The PoF function of time is calculated by equation (2):

$$P_f(t) = gff_{total} \times D_f(t) \times F_{ms} \quad (2)$$

where $P_f(t)$ is the PoF as a function of time. This is obtained by multiplying the generic failure frequency gff_{total}, the damage factor $D_f(t)$ and the management system factor $F_{ms.}$

The GFF is the failure frequency preceding any specific damage happening from exposure to the operating environment and is given for many discrete hole sizes for the different types of processing equipment.

In the API 581 standard, the damage factor is obtained through a value which is defined as the component wall thickness factor, which is calculated using the most recent inspection data ("Development of Dynamic Models, 2018").

The management systems factor Fm_s adjusts for the management system on the mechanical integrity of the plant, which is valid for the entire system. The Fm_s evaluation method comprises responding to many questions, and the answers produce a score for the quality of the management system (Helle, 2012).

(2) Two Parameters Weibull distribution method

According to API RP 581 (2016), the PoF is calculated from the equation:

$$PoF = 1 - \exp\left[-\left(\frac{t}{\eta}\right)^{\beta}\right] \quad (3)$$

Where, the Weibull shape parameter β is dimensionless and the Weibull characteristic life parameter η is defined as the time at which 63.2 per cent of the units have failed. The β parameter shows the failure rate development over time. The failure modes associated with infant mortality have a $\beta < 1$ with a decreasing failure rate as the system matures. A β equal to 1 implies a mature system or component with a steady-state, constant failure rate and a $\beta > 1$ implies the wear-out stage, where the failure rate is increasing over time.

For $\beta = 1$ the mean time to failure and η are equal.

For this research, we apply the second method because it is a quantitative approach compared to the first, which is more qualitative.

2.5 Consequence of failure according to the API 581

The *CoF* is presented into two categories. These are the consequences based on the area affected by a failure (Syawalina *et al.*, 2020).

The *CoF* analysis in RBI (API 581) consists of allowing one to rank the equipment items based on risk and providing a suitable inspection schedule. According to API 581, the computation of the consequences is based on empirical equations.

Loss of containment of dangerous fluids from pressurised processing equipment may result in damage to surrounding equipment, serious injury to personnel, production losses and undesirable environmental impact (Henry and Osage, 2014). The consequences of failure are calculated using well-known consequence analysis methods and are presented as an affected impact area (Shishesaz *et al.*, 2013).

The impact areas from incident outcomes such as pool fires, fireballs and vapour cloud explosions are quantified based on the outcome of thermal radiation or overpressure on surrounding equipment and personnel. For this case study, consequence modelling is based on the impact of blast overpressure on structure and human beings.

API 581 provides two levels of consequences analysis:

(1) Level 1 consequence analysis for this research evaluates the affected impact area due to overpressure for a specific reference fluid. Generally, the reference fluid that closely

matches the normal boiling point (NBP) and molecular weight (MW) of the fluid contained within the process equipment should be used. Water, steam, acid, ammonia, chlorine, hydrogen and hydrogen fluoride are some reference fluids for the level 1 consequence analysis (Henry and Osage, 2014). The first step to determine the CoF is to select a reference fluid that most closely matches the NBP and MW of the fluid contained within the process equipment. Subsequent steps consist of calculating the release rate that depends on the physical properties of the material, the phase of the fluid and the process operating conditions (Prayogo *et al.*, 2016).

(2) Level 2 consequence analysis provides a detailed approach to determine the consequences of loss of containment of dangerous fluids from pressurised equipment. This research will not use level 2 consequences because we are dealing with steam and water which require a level 1 analysis.

2.6 Consequence analysis based on a BLEVE

2.6.1 Introduction. Current furnace designs often integrate extensive use of cooling elements to accomplish long service lives at high operating intensities. However, contact between water and high-temperature fluids can provoke boiling liquid expanding vapour explosions (BLEVEs) (Kennedy *et al.*, 2013b). However, for the purposes of this paper, CoF modelling refers to the impact or consequences of BLEVE. Contact between water and high-temperature fluids can result in a powerful BLEVE.

BLEVEs are important due to their severity and the fact that they simultaneously involve diverse effects which can cover a large area: overpressure, thermal radiation and missiles ejection (Planas-Cuchi *et al.*, 2004).

2.6.2 Impact or consequence of BLEVE. The evaluation of the consequences of a BLEVE pivots on two parameters:

(1) The burst energy determines the severity of the blast overpressure generated by the BLEVE (Abbasi and Abbasi, 2007)

(2) The impact of the blast on structures and injuries on persons

The calculation of a BLEVE incident severity consists of a stepwise procedure. One of the first steps is to calculate the energy associated with the BLEVE. According to the trinitrotoluene (TNT) equivalency method, the energy or the effects of physical explosion can be expressed as TNT equivalent mass by using the appropriate energy conversion factor (Approximately $4680 \frac{\mathrm{J}}{\mathrm{kg}}$ of TNT$\big)$ where M_{TNT} is the equivalent mass of TNT (kg). The formula is provided by the API 581 document:

$$M_{TNT} = C_{30} n_v R T_s \ln\left[\frac{P_s}{P_{atm}}\right] \tag{4}$$

with T_s the storage or normal operating temperature, R is the universal gas constant which is 8.314 J/(kg-mol), n_v is the moles (kg-mol) that flash from liquid to vapour upon release at t_0 atmosphere, P_s (kPa) is the storage or normal operating pressure, and P_{atm} is the atmospheric pressure.

Abbasi and Abbasi (2007) proposed equation (5) to calculate the energy associated with the BLEVE, if the flashing fraction of the liquid and the pressurised gas expand isentropically as an ideal gas.

$$M_{TNT} = \frac{2.4 \times 10^{-4} \times PV^*}{k-1} [1 - \left[\left[\frac{101}{P}\right]^{k-1/k}\right] \tag{5}$$

with P (kPa) the pressure in the vessel at the time of burst, V^* (m^3) is the total vapour volume k ratio of specific heat at constant volume, M_{TNT} is the equivalent mass (kg) of TNT of the explosion energy.

(1) Overpressure

Once the explosion energy of a BLEVE is estimated, overpressure can be determined by employing the correlations available in literature which link overpressure with explosion energy, and the distance from the accident epicentre.

Overpressure (or blast overpressure) is the pressure caused by shock waves over and above a normal atmosphere. Kumar Malviya and Rushaid (2018) suggested an equation to calculate the overpressure:

Assume the equivalent TNT mass (kg):

$$M_{TNT} = \frac{f_E \Delta H_c M_G}{\Delta H_{TNT}} \tag{6}$$

with M_G (kg) the mass of the gas that participates in the explosion, ΔH_c is the heat of combustion of the gas (kJ/kg), ΔH_{TNT} the heat of combustion of TNT (kJ/kg).

The scaled distance (m/ $kg^{1/3}$):

$$Z = \frac{x}{{M_{TNT}}^{1/3}} \tag{7}$$

where M_{TNT} is the equivalent TNT mass, and x is the distance from the centre of the explosion.

The overpressure of the shock wave is given by:

$$PS = \frac{80.800\left[1+\left[\frac{Z}{4.5}\right]^2\right]}{\sqrt{1+\left[\frac{Z}{0.045}\right]^2}\sqrt{1+\left[\frac{Z}{0.32}\right]^2}\sqrt{1+\left[\frac{Z}{1.35}\right]^2}} \tag{8}$$

(2) Impact modelling

After defining the reference fluid, which is steam in our case, the next step is to assess the consequences of incident outcomes on workers and structures utilising impact modelling.

It is well known that overpressure, thermal radiation, etc. cause damage according to the exposure level; however, mathematical modelling is needed to predict the impact and risk associated with the BLEVE (Ahumada, 2016).

As stated in the previous paragraph, to assess the consequences of an accident on people and structure, a function relating to the magnitude of the impact is used. Usually, the method utilised is the probit analysis, which relates the probit (from "probability unit") variable to the probability (Mustapha and El-Harbawi, 2016).

The probit variable Y is a measure of the percentage of a population submitted to effect with a given intensity (V), this variable follows a normal distribution, with an average value and a standard deviation of 1.

The probit function is usually of the form:

$$Y = a + b \ln V \tag{9}$$

where Y represents the probit function or variable, a and b are constants obtained from best-fitting response data or are experimentally determined from information on accidents, etc. V is the causative factor whose definition changes according to the associated hazard, it is also a measure of the intensity of the damaging effect. It can be overpressure, thermal radiation, or any other parameter (Mustapha and El-Harbawi, 2016). For this research, overpressure is used as a measure of the damaging effect.

The relationship between the probit variable (Y) and the probability of fatality P.

$$P = 50\left[1 + \frac{Y-5}{|Y-5|}\operatorname{erf}\left(\frac{|Y-5|}{\sqrt{2}}\right)\right] \tag{10}$$

with P the probability of fatalities due to BLEVE, and erf the error function.

2.7 Analysis of risks of pressure vessel

(1) Introduction

A pressure vessel is intended for the production, manufacturing, storage or implementation of vapour or a gas, compressed, liquefied or dissolved, under a pressure higher than the atmosphere pressure (Wyckaert *et al.*, 2017). Pressure vessels exist habitually in all shapes (spherical, cylindrical, conical, elliptic, etc.).

Wyckaert *et al.* (2017) conducted a study on the health and safety risk assessment of pressure vessels. They reviewed literature from the past ten years and analysed accident reports from Quebec and the United States over the past sixteen years. Despite advanced technologies and standards regulating pressure vessels and piping, serious accidents can still occur. According to Wyckaert *et al.* (2017), the study highlighted two major risks related to the use of pressure vessels:

(1) An increase of the internal fluid pressure above the burst pressure of the vessel

(2) A decrease in the resistance of the vessel material due to the operating conditions which in turn causes a decrease in the burst pressure

Majid and Ghorba (2015) noted that technical issues are not the only factors leading to the rupture of pressure vessels. Human and organisational factors are also significant parameters to consider.

Leroux *et al.* (2010) conducted a study on the transport of dangerous materials. They identified the main risks related to the transport and storage of dangerous materials, such as explosion, fire and emission of toxic products. The study highlighted that human error is identified as the principal causal factor in these types of accidents.

As for the material of the enclosure of the vessel, the environment has a great impact on the fragile parts of the vessel (Barbosa *et al.*, 2006). Leaks are prone to fragile components of the pressure vessel and piping, making them more sensitive to wear, fatigue and human error.

According to Wyckaert *et al.* (2017), the impact of accidents involving pressure vessels can be severe, including explosion, domino effects due to fragments, fire, creation of slick of products or gas clouds or toxic or flammable vapours and the projection of fragments.

(2) Risk quantification and classification of pressure vessels based on failure modes.

The establishment of the Risk Quantification and Grading Method Based on Failure Mode (RBFM) is a noteworthy innovation. This method is highly suitable for the surface static equipment of oil and gas gathering and processing stations. It functions by analysing each failure mode and its corresponding consequences to obtain the risk grade under each respective failure mode. The present study aims to assess various failure modes and their associated risks to equipment based on field production parameters. In conjunction with API 581 Risk-Based Inspection and Statistical Summary pipeline transportation occurrences in 2018, typical failure modes include leakage, combustion, explosion and the like. The primary damage mechanisms are thinning, environmental cracking, and functional or mechanical failure. The failure reasons are analysed and classified into four categories and 19 subcategories (Baru, 2016).

Of significance, the process failure mechanism of pressure vessels is innovatively introduced in the functional or mechanical failure damage mechanism, such as overpressure, gas and liquid channelling, flooding and so forth. The corresponding risk factors gradually deteriorate the equipment over time and ultimately lead to equipment failure. The risk factors that affect pressure vessels mainly include media, operation, design, environment and man-machine factors (Singh and Pokhrel, 2018). Based on accident statistics (Pipeline Performance in Alberta, 1990–2005), the most common damage mechanism of equipment in the station is thinning, including internal corrosion and external corrosion. Internal corrosion hazards include medium components, operating parameters and design, which ultimately affect the internal corrosion rate and lead to internal corrosion perforation (Liao *et al.*, 2023). External corrosion is divided into soil corrosion, corrosion under the insulation layer and joint coating corrosion, among others. Therefore, the risk factors are related to soil, insulation layer, environmental parameters and pipeline materials, which affect the external corrosion rate or potential (Shi *et al.*, 2021). In the functional or mechanical failure damage mechanism, there are several failure reasons. Blocking hazards can be divided into three types, which are mainly related to the properties of sand gravel, wax evolution of oil products and formation temperature of natural gas hydrate (Ke and Chen, 2019). Overpressure is related to the maximum allowable operating pressure and operating pressure. Gas and liquid channelling, and tank deflection are closely related to operating parameters (temperature, pressure, flow rate, etc.). The hazards of mis-operation in improper operation are closely related to the operators' skills and knowledge (to management and persons).

In this work, we investigate only the scenario of a leaking pipe in the HP cooling system which leads to water suddenly penetrating molten matte in the furnace of a converter plant in a smelter, despite the generalisation that might have been obtained from also considering all the other possible accident scenarios, such as coal explosions.

We consider the case where water accumulates on the slag crust before the crust fails, and the water penetrates the molten matte. This may lead to a BLEVE in the converter. To prevent such accidents, the RBI process is suggested, enhanced by the application of sophisticated techniques to calculate *PoF* and *CoF*.

3. Case study for HP cooling system

A case study is presented in this section to illustrate the RBI implementation leading to the inspection optimisation for the HP cooling system.

We consider the closed-circuit HP cooling system on a Wheeler converter plant. The system is constructed out of SA-192 boiler tubes with a total surface area of 628 square metres in contact with the converter off-gas. The system is designed to cool the converter plant off-gas from the processing temperature of approximately 1,400 ℃ degrees down to less than 800 ℃.

The operating parameters of the HP system are:

(1) System temperature: 220–250$°C$

(2) System pressure: 50–70 bar

(3) Circ. Water flow: 1,600 (m^3/hr)

(4) Inlet gas temperature: 1,200–1400°C

(5) Outlet gas temperature: 600–800 °C

(6) Exit water temperature limit: 275°C

The downtime hours experienced due to HP leaks from 2017 until 2020 have been recorded. The moisture of the off-gas and the cumulative feed rate corresponding to the cumulative operating times (age) have also been recorded as condition and usage indicators. It is argued that increasing moisture in the off-gas would indicate the development of leaks in the cooling system.

Table 1 presents a sample of data with moisture and cumulative feed rate as covariates for the HP cooling system (the standardisation of the measured covariate values is done to ease the computational burden during parameter fitting, of having values of vastly different magnitudes):

3.1 Simulation and results for quantitative risk assessment based on failure data (Weibull Time-based approach)

3.1.1 Probability of failure estimation for time-based approach. The *PoF* calculation is an important step in the RBI process. The risk assessment process based on the API 581 standard uses the Bayes theorem, which is based on expert opinion as a qualitative approach, and it uses the Weibull Time-based approach to estimate the PoF as a quantitative method.

This section addresses the time-based approach for RBI which involves determining the PoF related to the HP cooling system failure data. The failure data employed for this purpose was recorded over a period of three years and consisted of leaking incidents due to cracking of the piping at various locations in the cooler system. It was assumed that each such incident represented a new independent failure of the cooler, therefore allowing it to consider to be one non-repairable system, with one Weibull failure distribution, for our purposes. Even though the leaks causing the various incidents had been repaired, it was assumed that no repeat failures occurred at the same location, making this assumption viable.

We first estimate the regression coefficients required to build a time-to-failure two-parameter Weibull equation. Equation (11) below, which is the log-likelihood function for the two parameters Weibull distribution, is maximised to determine the regression parameters.

$$\Lambda = Nln(\beta) - N\beta \ln(\eta) + (\beta - 1)\sum_{i=1}^{N} \ln(t_i) - \sum_{i=1}^{N} \left(\frac{t_i}{\eta}\right)^{\beta} \tag{11}$$

The maximum likelihood of the log-likelihood function given by equation (11) leads to the following outcome:

Inspection time (h)	Moisture	Feed rate	Standardised moisture	Standardised feed rate
50	3,200	2,066,500	10,917	−1,864
100	0.073	4,321,678	−0.312	−1,821
450	−0.019	11,576,624	−0.648	−1,681
500	−0.019	13,724,506	−0.648	−1,640

Source(s): Table 1 created by authors

Table 1. History 2 taken out of Campaign 1 histories

$$\frac{1}{\beta} = \frac{\sum_{i=1}^{N} t_i^{\beta} ln\, t_i}{\sum_{i=1}^{N} t_i^{\beta}} - \frac{1}{N}\sum_{i=1}^{N} ln\, t_i \tag{12}$$

The estimation of the shape parameter β in equation (12) is performed numerically using a MATLAB code, the result found for the shape parameter $\beta = 1.5$ for the HP cooling system.

Differentiation of equation (11) gives the regression parameter $= 1.5$ *and* η:

$$\eta = \left(\frac{1}{N}\sum_{i=1}^{N} t_i^{\beta}\right)^{1/\beta} = 5180.4\, hours \tag{13}$$

With β and η known, the hazard rate for the time-based approach is:

$$h(t) = \frac{1.5}{5180.4}\left(\frac{t}{5180.4}\right)^{1.5-1} \tag{14}$$

Since the HP cooling system is complex and has multiple failure modes, it is to be expected that the shape parameter of close to unity. This would indicate a near-constant failure rate and hazard rate. Figure 2 below depicts the actual hazard rate related to the failure data for the HP cooling system (see Figure 3).

The hazard rate in Figure 2 is increasing, but trending to a constant rate. The mean time between failure (MTBF) is given by:

$$MTBF = \frac{\text{Operating time}}{\text{Number of failures}} = \frac{8850}{32} = 276 \text{ hours}$$

This means that at each 276 h or at each 11–12 days there is an expectation of having a leak into the HP cooling system. The PoF corresponding to the time-based approach for the HP

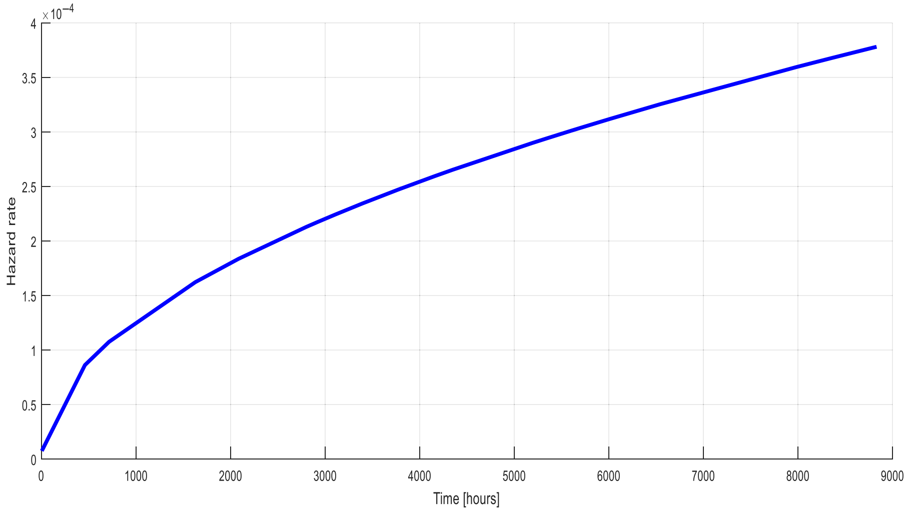
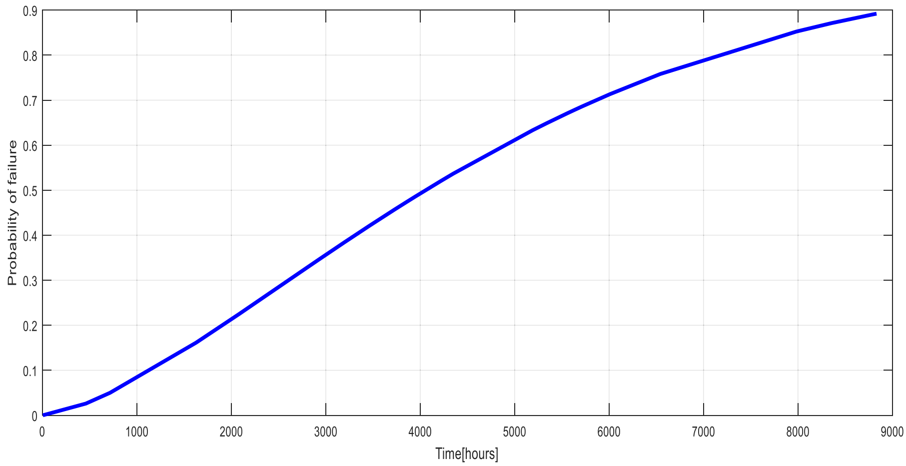


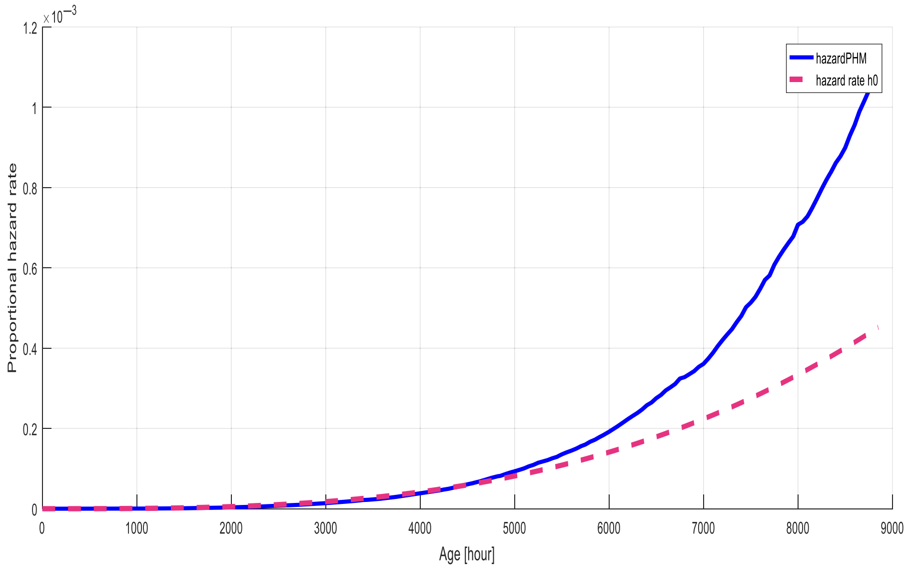
Figure 2. Hazard rate time based on the HP cooling system

Source(s): Figure 2 created by authors



Source(s): Figure 3 created by authors

Figure 3. Probability of failure for the HP cooling system (Time-based)



Source(s): Figure 4 created by authors

Figure 4. Proportional hazard rate for HP cooling system

cooling system is given in Figure 4 below. The hazard rate, MTBF and risk calculations are based on operating time and number of failures only and do not consider the covariates. From the data under analysis in this paper, the Laplace trend value being 0.2737 which is between -1 and $+1$. This means that the data are noncommittal and as a result, the data set is independent and identically distributed. Hence, the renewal theory is applicable (see Table 2).

3.2 Simulations and results for quantitative risk assessment based on the incorporation of covariates into the hazard computation using the PHM

3.2.1 Introduction to the proportional hazard model (PHM). The PHM is a statistical procedure that enables the estimation of the risk for a component or system to fail when its condition is monitored (Jardine and Tsang, 2013). PHM models are part of a broader class of survival analysis models that enable estimation of the risk of failure at a given time, given the period of operation (age), and any measured covariates that describe the state (condition or usage) of the component or system.

The PHM with a Weibull baseline hazard function is presented in the following formula (Jardine and Tsang, 2013):

$$h[t, Z(t)] = \frac{\beta}{\eta}\left(\frac{t}{\eta}\right)^{\beta-1} \exp\left\{\sum_{i=1}^{m} \gamma_i Z_i(t)\right\} \quad (15)$$

where $h[t, Z(t)]$ is the hazard function, $Z_i(t)$ are the covariates at time t, $\frac{\beta}{\eta}\left(\frac{t}{\eta}\right)^{\beta-1}$ is the baseline hazard function with β the shape parameter and η the scale parameter, which allow the construction of the baseline part of the model. These parameters are determined by maximising the likelihood function, based on the historical data.

3.2.2 Probability of failure for HP cooling system based on the PHM. The PHM model uses both the moisture and the cumulative feed rate as covariates. The moisture measurement in the off-gas is an early indicator of failure and the federate is a measure of the variability in usage of the system.

The first step of this investigation consists of estimating the regression coefficients β, η, γ required to build the PHM (Carstens and Vlok, 2013):

$$(\beta, \eta, \overline{\gamma}) = rln\left(\beta/\eta\right) + \sum_i ln\left[\left(T_i/\eta\right)^{\beta-1}\right] + \sum_i \overline{\gamma} \times \overline{Z_l}\,(T_i)\Bigg) - \sum_j \int_0^{T_j} \exp\left(\overline{\gamma}\overline{Z}_j(t)\, d\left(t/\eta\right)^{\beta}\right. \quad (16)$$

The result from the optimisation gives a shape parameter $\beta = 4$, a scale parameter $\eta = 8850$ hours the weight of the covariate $\gamma_1 = 0.0100$ (weight of the moisture parameter) and $\gamma_2 = 0.5281$ (weight of the cumulative feed rate parameter). The regression parameters are obtained from the maximum likelihood equation (16). The hazard rate equation corresponding to the above parameters with moisture and cumulative feed rate as the covariate is given by:

$$h[t, z(t)] = \frac{4}{8850}\left(\frac{t}{8850}\right)^{4-1} \exp\left[0.0100\,\text{Moisture} + 0.5281\text{Feedrate}\right] \quad (17)$$

Table 2. Summarized results corresponding to the time-based approach

Failure time	Hazard rate	Probability of failure
3.5	7.526e-06	1.756e-05
459.5	8.623e-05	0.0260
8,825	0.00037	0.891
8,832	0.00037	0.892

Source(s): Table 2 created by authors

A graphical representation of this equation for the PHM with moisture and cumulative feed rate as covariates is given in Figure 4 below.

Figure 4 shows both the proportional hazard rate, as well as the time-based component (factor h_0) of it. It may be observed that this time-based component h_0 is smoothly increasing with age to the power of three ($\beta - 1$). It is also important to observe that the trend of the time-based component h_0 means that covariates influence the proportional hazard rate.

The PoF corresponding to the proportional hazard approach for the HP cooling system is given in Figure 5 below:

3.2.3 Comparison between the time-based hazard rate and proportional hazards rate, for time-based and covariates, included. Figures 6 and 7 below display respectively the hazard rate related to the time-based and the proportional hazard rate and the PoF related to the time-based and PHM.

The hazard rate and PoF results obtained for the time-based and the proportional models are, respectively, plotted in Figures 6 and 7.

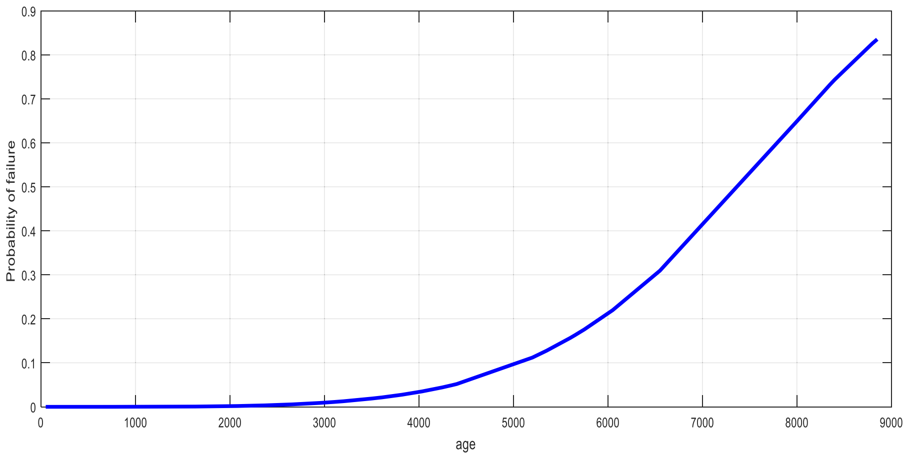
Generally, the hazard rate values are difficult to interpret, but the trends are insightful as the hazard rate expresses an instantaneous rate of failure. The time-based hazard rate h in Figure 6 is slightly increasing with time (age) to the power of 0.5 ($\beta - 1$). However, by inserting covariates in the hazard computation using the proportional model, both the proportional hazard rate, as well as the time-based component (factor h_0) of it, as plotted in Figure 6, are showing a significantly increasing hazard rate.

This indicates that the incorporation of the covariate information yields a lower initial hazard rate that increases exponentially to a similar value than the time-based hazard rate towards the end of the period. The comparison of the cumulative distribution functions (PoF) shown in Figure 7 shows a similar result.

The proportional PoF curve is lower than the time-based *PoF* curve for a major part of the life of the HP cooling system. It reaches a *PoF* value of only 20% at 6,000 h, whereas the time-based *PoF* reached 20% already at 2000 h and are close to 70% at 6,000 h. This is a very significant demonstration of the benefit of the PHM method for more realistic *PoF* estimation, compared to the time-based model.

3.2.4 Consequence of failure for HP cooling system based on the BLEVE.

(1) Overpressure estimation



Source(s): Figure 5 created by authors

Figure 5. Probability of failure for HP cooling system (covariates included)

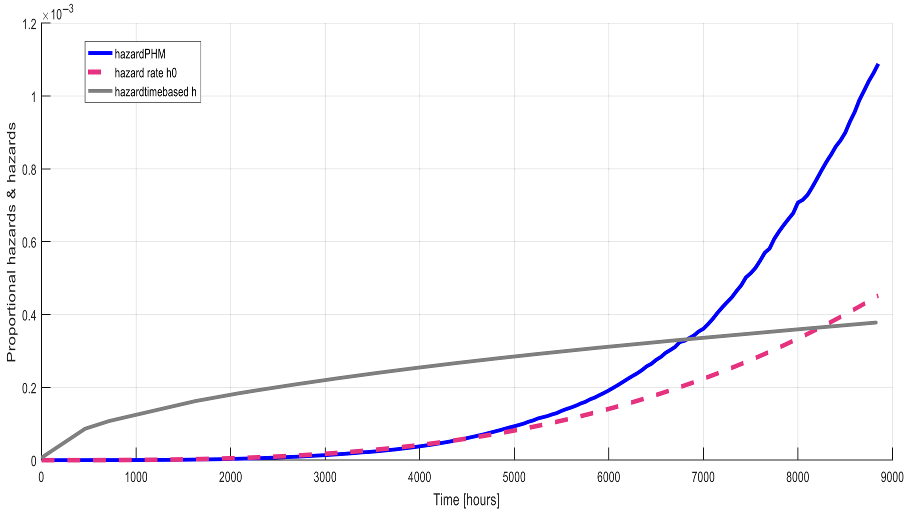


Figure 6. Comparison of hazard-rate

Source(s): Figure 6 created by authors

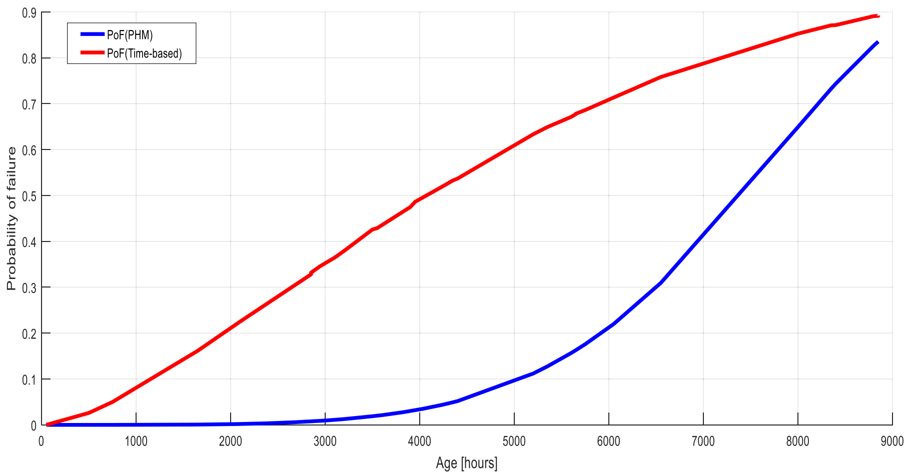


Figure 7. Comparison of time-based and PHM probability of failure results

Source(s): Figure 7 created by authors

CoF in this paper is related to the BLEVE effects. However, the literature describes three types of BLEVE effects: the shock wave or overpressure, the thermal radiation and the fragment projection (Shariff *et al.*, 2016). Here, we deal with overpressure as the causative factor of the damaging effect.

Overpressure is the pressure caused by a shock wave over and above normal atmospheric pressure (Kumar Malviya and Rushaid, 2018). To estimate the overpressure given in formula (8), the equivalent TNT mass formula (6) is first needed. However, formula (6) includes an important parameter M_G which is the mass of the explosive material which will be based on leak rate modelling. For the leak modelling purpose, we are using the Bernoulli equation for fluid flow through a pipe with a given diameter (Saqib *et al.*, 2017).

$$\dot{m} = \dot{V} \times \rho \tag{18}$$

with $\dot{V}$ the flow rate and ρ the water density.

The mass is the function of the flow rate $\dot{V}$ given by:

$$\dot{V} = C \times A\sqrt{\frac{2\Delta P}{S\rho}} \tag{19}$$

with C as the discharge coefficient. For an orifice in the pipe, it varies between 0.60 and 0.80.

A: The crack area

S: specific gravity = 1 for water

ρ: water density = 1000 kg/cube metre

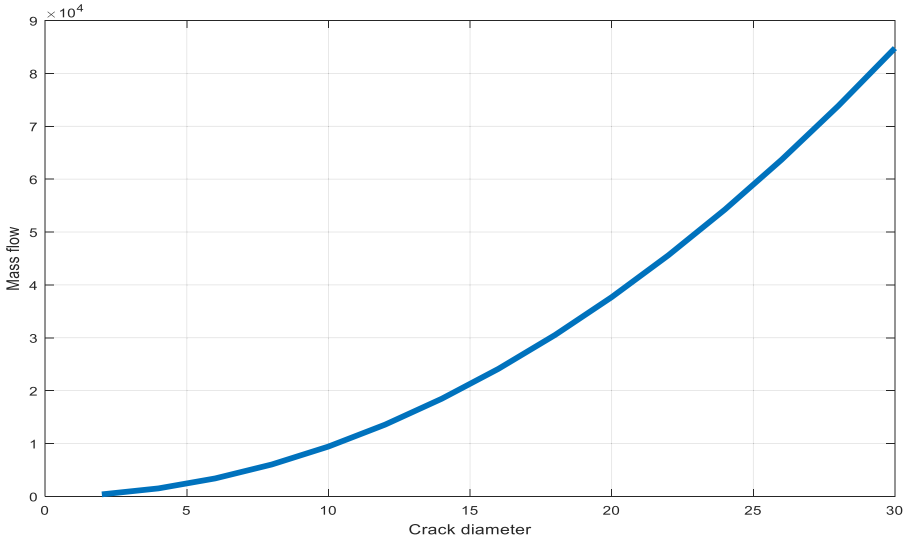
ΔP: Pressure drop

From equations (18) and (19), which compute respectively the mass and flow rate of the material flowing through the pipe crack to mix with the molten matte and slag in the furnace, the equivalent mass of the TNT given in equation (7) is obtained. Together with the scaled distance, the following graph is obtained:

The overpressure related to the explosion is given in Figure 9 below.

To estimate the consequences of an accident on people, we will refer to equation (9) which is the probit equation. The following section evaluates the effects of overpressure on humans and constructions (see Figure 10).

(2) Effects of overpressure on humans and constructions



Source(s): Figure 8 created by authors

Figure 8.
Mass flow versus crack diameter

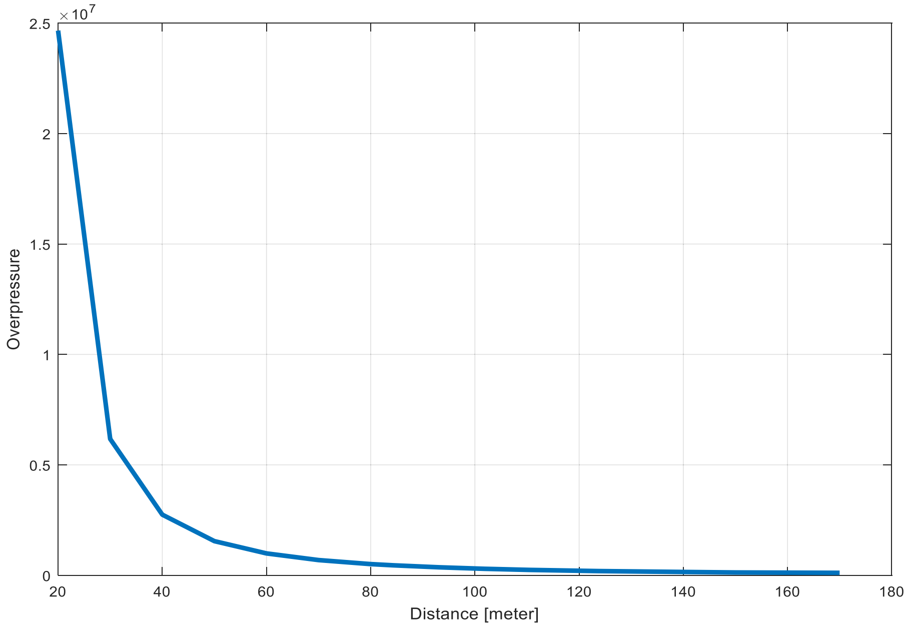


Figure 9. Overpressure in kPa versus distance in metre

Source(s): Figure 9 created by authors

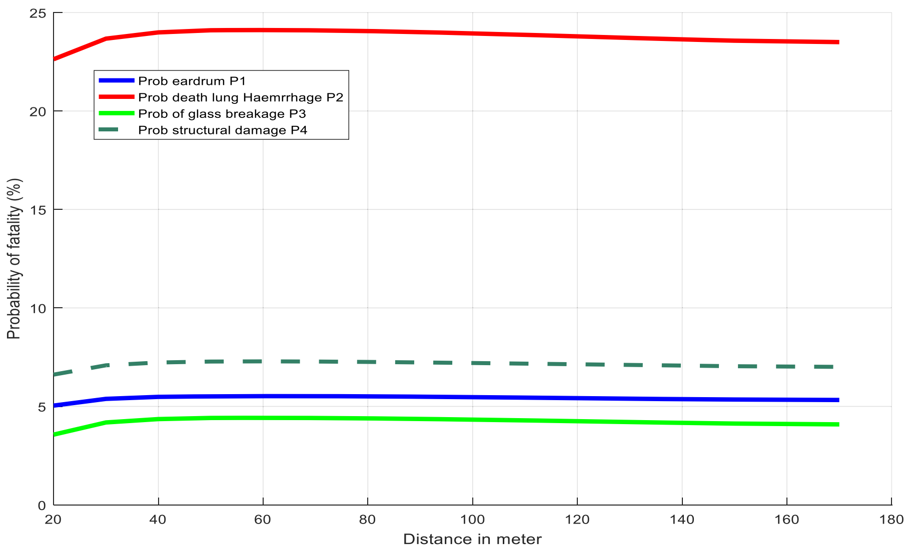


Figure 10. Probability of fatality versus distance

Source(s): Figure 10 created by authors

The direct effects of overpressure on humans are eardrum rupture, lung haemorrhage, whole-body displacement injury and injury from shattered glass. It is also important to notice that the most likely harm to people during the explosion comes also from the indirect effects of people being inside or close to the building when it collapses (Mustapha and El-Harbawi, 2016).

The typical causes of an explosion are burning, fragments hitting the people, buildings or structures failing down, people falling etc.

Sharrif *et al.* (2016) provide probit correlations for a variety of causes and effects:

The probit equation for eardrum to overpressure is given by:

$$Y1 = -15.6 + 1.93 ln\, P_{ovr} \tag{20}$$

The probit equation relating death from lung haemorrhage to overpressure:

$$Y2 = -77.1 + 6.91 ln\, P_{ovr} \tag{21}$$

There have been several experimental and theoretical studies of the behaviour of shattering and flying glass and studies of glass breakage following accidental explosions. The probit equation relating glass breakage to overpressure is given by:

$$Y3 = -18.1 + 2.79 ln\, P_{ovr} \tag{22}$$

and the probit equation relating structural damage to overpressure, by:

$$Y4 = -23.8 + 2.92 ln\, P_{ovr} \tag{23}$$

As stated previously, BLEVE effect investigation based on probit function (9) uses overpressure as a causative factor V in this research.

(3) Probability of fatalities

The probability of fatalities due to BLEVE can be obtained using equation (10), leading to the following curves:

3.2.5 Risk computation. This section consists of rating risks using the probability of occurrence and severity of consequence scale. Risk assessment consists of a series of procedures, including risk analysis, assessment of the degree of risk and judgement on whether the risk is acceptable or unacceptable (Embry *et al.*, 2014).

In this paper, the risk assessment will use the probability of occurrence and severity of consequence scales to rate risk associated with the BLEVE effect in the system under analysis.

(1) Probability of occurrence

The probability of occurrence in this work corresponds to the probability of having an explosion. PoF_{expl} denotes the likelihood that the risk could occur. Probability of occurrence uses a rating and value ranging from inconceivable (1) to very likely (5). For the purposes of this paper, the probability of occurrence includes two probabilities:

(1) The PoF causing a leak calculated from the history of failure – PoF_h

(2) The probability that the leak is at critical crack size – PoF_{cra}

Then, the probability of occurrence or the probability of having an explosion will be:

$$PoF_{expl} = PoF_h \times PoF_{cra} \tag{24}$$

The only data set available to estimate PoF_{cra}, is the fact that a catastrophic steam explosion has occurred twice during the twelve-year life of the system. We, therefore, estimate that the event of the crack failure large enough which cause water accumulation occurred twice in twelve years, i.e. ($\frac{1}{6}$ yearly). The probability of a crack, if it occurs, being large enough to cause a steam explosion hence is:

$$PoF_{cra} = \left(\frac{1}{6}\right) \Big/ PoF_h(at\ end\ of\ year) \quad (25)$$

From Figure 8, it can be seen that $PoF_h(at\ end\ of\ year) = 0.83$. This means that we can estimate $PoF_{cra} = \frac{\frac{1}{6}}{0.83} = 0.2 = 20\%$.

Applying these formulas to the data, results in the values listed in Table 5.

Failure probabilities of reactor pressure vessels have attracted significant attention in recent years. Extensive efforts have been dedicated to converting statistical evidence of conventional HP vessel integrity and findings from surveillance testing into failure probabilities specific to nuclear pressure vessels. Investigations on vessels comparable to nuclear vessels have been conducted both in the United Kingdom and in Germany. These investigations encompassed a total of approximately 100,000 and 1,000,000 vessel years, respectively. The overall number of failures relevant to nuclear vessel services corresponded to failure rates of 10^{-3} to 10^{-4} per year. Xiao *et al.* (2018) recently investigated the safety and reliability of pressure vessels considering various uncertain factors. The outcome of the investigation was that when the crack is shallow, the failure probability is less than 10^{-3}. For the case of this work considering the scenario of having cracks in the piping circuit of the HP cooling system and based on the experience on the ground, we assumed that failure happened twice every twelve years which justifies the incorporation of ⅙ in the probability calculation.

(2) Total probability of fatalities (likelihood)

Risk measures the likelihood and severity of the accident to evaluate the magnitude and prioritise the hazard as shown in Table 3 below. After the total probability of fatality and degree of harm is determined, the risk is assessed.

$$Total\ probability\ of\ fatality\ (Tpf) = PoF_h \times PoF_{cra} \times Probit\ (at\ end\ of\ year)$$

N.B: The result obtained from the total probability of fatality equation is considered as the likelihood or the *y*-axis in the risk matrix.

(3) Severity of Consequences

The severity of consequences assigns a rating based on the impact of an identified risk to safety, economic, persons and environment (Zakaria *et al.*, 2018). The severity of consequence assesses impacts in this paper under the form of:

- Single fatality (Lung haemorrhage)
- Multiple fatality (Structural damage)

(4) Risk matrix

Plotting PoF and CoF values on a risk matrix is a productive method of representing risk graphically. PoF is plotted across one axis, increasing in magnitude from the origin, while

Table 3. Probabilities of occurrence table (based on API 581)

Likelihood	Description	Rating value	Per cent
Very likely	The most likely result of the hazard	5	Above 0.1
Possible (likely)	Has a good chance of occurring and is not unusual	4	0.1
Conceivable	Might occur at some time in future	3	0.01
Remote	Has not been known to occur after many year	2	0.001
Inconceivable	Is practically impossible and has never occur	1	0.0001

Source(s): Table 3 created by authors

CoF is plotted across the other axis (API RP 581, 2016). It is important to notice that it is the responsibility of the owner-user to define and document the basis for PoF and CoF category ranges and risk targets used.

(1) *Risk matrix for single fatality*

For the lung haemorrhage, the likelihood (*y*-axis) is 0.040 (from Table 5) which is rated 5 (referring to Table 3), while the single fatality is rated D according to Table 4. To assess the risk for the lung haemorrhage, we are going to consider in the risk matrix the couple (D,5) means severity(consequence) rated at D and likelihood at 5(most likely). The following Section 3.2.6 explains the meaning (D,5).

For the structural damage**,** the likelihood value is 0.01 which is rated 4 in Table 3, which is likely, while the single fatality is rated D according to Table 4. The following Section 3.2.6 explains the meaning of (D,4) which is the coupled severity and likelihood, respectively.

(2) *Risk matrix for multiple fatality*

Multiple fatality analysis considers the number of persons exposed to the risk and how far they should be moved away. This will be the focus of further work is not addressed in this paper.

3.2.6 Interpretation of the results for decision-making. For the fatality occurring due to lung haemorrhage, a total probability value of 0.04 was calculated (in Table 5). This could be understood to mean that, if there existed a hundred such identical plants, it is to be expected that every year 4 explosions which will cause a single fatality would occur, or alternatively, during a hundred years of operating one plant, there is an expectation of four fatalities caused by explosions, would occur. The assessed risk for this situation is at (D,5) on the risk matrix. The risk matrix in Figure 11, from which the results are interpreted, has four coloured zones and our lung haemorrhage result falls in the red zone. The red zone generally means that a high risk exists that management's objectives would not be achieved and that it therefore needs to be mitigated immediately.

For the **structural,** the total probability of fatality value is 0.01 which falls at 4 (likely) on the *y*-axis and the severity at D (a single fatality). The assessed risk of (D,4) in Figure 11 falls in the orange zone, which is called "medium high" in the API 581. At this level of risk, management's objectives may not be achieved and there is a need to mitigate the risk as soon as possible.

Possible risk-mitigating actions, to lower these risks to acceptable levels, include the following:

(1) Introducing inspections for cracks at frequencies sufficient to ensure repair actions are taken before leaks occur. This is the major objective of the RBI approach. The PHM method introduced in this paper ensures more accurate quantification of the risk as it evolves over time, which implies a less onerous schedule. To be able to implement the present mitigation strategy, it will be important to determine when each inspection

Severity	Description	Rate
Catastrophic	Numerous fatalities irrecoverable property damage and productivity	E
Fatal	Approximately one single fatality major property damage if the hazard is realised	D
Serious	Non-fatal-injury, permanent disability	C
Minor	Disabling but not permanent injury	B
Negligeable	Minor abrasions, bruises, cuts, first-aid type injury	A

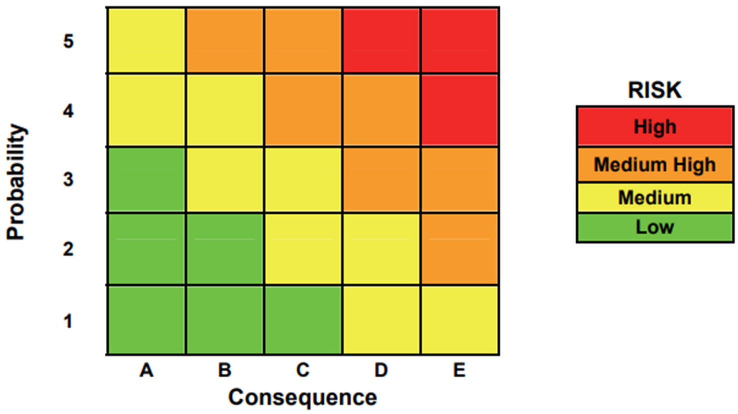
Source(s): Table 4 created by authors

Table 4. Severity of consequences table (based on the API581)

Table 5.
Risk comparison table

Age (h)	PoF (time-based TB)	PoF (PhM)	PoFexpl (TB)	PoF expl (Phm)	Lung haemorrhage	Structural	Lung haemorrhage Tpf (time-based)	Lung haemorrhage Tpf (Phm)	Structural Tpf (time-based)	Tpf (Phm)
3.5	1.76E-05	1.70E-09	3.51E-06	3.40E-10	0.241	0.074	8.46E-07	8.18E-11	2.60E-07	2.51E-11
459	0.026	5.02E-06	5.20E-03	1.00E-06	0.241	0.074	1.25E-03	2.42E-07	3.85E-04	7.42E-08
2.,083	0.225	0.002	4.50E-02	4.00E-04	0.241	0.074	1.08E-02	9.64E-05	3.33E-03	2.96E-05
3,519	0.429	0.02	8.58E-02	4.00E-03	0.241	0.074	2.07E-02	9.64E-04	6.35E-03	2.96E-04
4,220	0.521	0.044	1.04E-01	8.80E-03	0.241	0.074	2.51E-02	2.12E-03	7.71E-03	6.51E-04
5,191	0.633	0.112	1.27E-01	2.24E-02	0.241	0.074	3.05E-02	5.40E-03	9.37E-03	1.66E-03
5,559	0.671	0.156	1.34E-01	3.12E-02	0.241	0.074	3.23E-02	7.52E-03	9.93E-03	2.31E-03
6,542	0.758	0.309	1.52E-01	6.18E-02	0.241	0.074	3.65E-02	1.49E-02	1.12E-02	4.57E-03
7,985	0.852	0.648	1.70E-01	1.30E-01	0.241	0.074	4.11E-02	3.12E-02	1.26E-02	9.59E-03
8,798	0,89	0.826	1.78E-01	1.65E-01	0.241	0.074	4.29E-02	3.98E-02	1.32E-02	1.22E-02
8,825	0.892	0.835	1.78E-01	1.67E-01	0.241	0.074	4.30E-02	4.02E-02	1.32E-02	1.24E-02
8,832	0.892	0.835	1.78E-01	1.67E-01	0.241	0.074	4.30E-02	4.02E-02	1.32E-02	1.24E-02

Source(s): Table 5 created by authors



Source(s): Figure 11 from API 581 (2016)

Figure 11.
Risk matrix (figure taken from API 581)

should take place to keep the total PoF below a given value which is the medium acceptable PoF, arising from a calculated assessment of the integrity of high-quality fabrication such as pressure vessel.

(2) Shortening the duration of the campaigns of the furnace before swapping out and performing major rebuilds or replacements, whilst the assessed risk is still low enough. Again, the introduction of the PHM approach, makes this a viable mitigation action, since the risk increases rapidly towards the end of a campaign. It is important to note that the PoF results used to assess the risk, were end-of-campaign values. This strategy will be implemented as soon as the interval of time between inspections is determined. This is part of future work.

(3) Making the end-of-campaign decision risk-based, implying that the furnace would be taken out of operation at an acceptable risk level, which will be dynamically calculated, using the PHM introduction of the covariates as inputs.

Since the PHM method, used for calculating the *PoF*, can be updated during the campaign, using the monitored covariates as inputs, the risk assessment can also be dynamically updated. This implies that the end-of-campaign decision (and in fact, also the inspection frequencies), can be updated accordingly.

(4) Introducing controls, acting on the moisture measurement, to shut down the water feed to the HP system as soon as any indication of leaking is noticed, to avoid the accumulation of sufficient water to cause the major explosion (i.e., reducing the PoF_{cra} parameter).

Benefit of Incorporating the Proportional hazards model into risk-based model

Quantitative RBI decisions are time-based (having to decide on time-based inspection frequencies) and are therefore normally based on only time-based failure data to estimate the time progression of the PoF. RBI, also by definition, incorporates a condition-based approach, to guide decisions based on inspection (condition) results. These decisions may include keeping a component in operation, but changing future inspection frequencies or replacing/repairing the component.

The PHM approach offers significantly better insight into the progression of the PoF with age, than the time-based approach. No such insight is available when only observing the time-based PoF curve. It is therefore argued that the PHM approach would lead to both more economic and safer inspection frequency decisions.

Another important benefit of incorporating the PHM approach into RBI processes is derived from the fact that it allows the use of real-time condition monitoring data and therefore allows dynamic risk-based decisions, for inspection and maintenance planning. Again, this benefit will also be applicable only to cases where the condition monitoring results cannot be combined with an accurate RUL model.

4. Conclusion

The RBI is an ideal tool for asset management because of its ability to optimise the inspection schedule and extent of inspection, which contribute to the savings of cost and prioritise inspection on important components. This work suggested an approach based on the proportional hazard model to optimise risk which includes the *PoF* estimation as well as the *CoF*.

The PHM is used in this work as a prognostic model involved in the computation of *PoF* estimation which drives the risk computation. The incorporation of the PHM into the RBI enables the use of time-based failure data with real-time condition data, which could help the decision maker to make dynamic decisions on inspection schedule. Finally, the proposed approach is one of the suitable ways to optimise the quantitative approach for the RBI since the *PoF* is well determined by means of the PHM.

In this work, a case study was suggested using data from a closed-circuit HP cooling system on a Wheeler converter plant. It has been observed that the application of the RBI approach on a furnace HP cooling systems incorporating the PHM and steam explosion consequence modelling yielded the proposed methodology where risk was dynamically calculated and quantified, which emphasised the imperative for mitigating the risk, as well as present a few mitigation options, to quantifiably affect such mitigation.

We demonstrated the application of risk management of a HP cooling system for a metal smelting furnace, as water ingress into the furnace from leaks due to cracks, can cause a steam explosion. The risk management methodology incorporated a quantitative assessment of the *PoF*, based on PHM and the *CoF*, using BLEVE methods, of an explosion event. Finally, risk mitigation strategies, such as using the RBI principles to define the inspection frequency sufficient to ensure that repair actions are taken before leaks occur, or to shorten the furnace campaign duration before swapping out and performing major rebuild or replacement, to lower the risk to an acceptable level have been defined.

This article demonstrated the application of RBI approach on a furnace HP cooling systems, incorporating the PHM and steam explosion consequence modelling.

From the observations made during this paper, the following recommendations are made for future investigation:

(1) This study provides a foundation for the *PoF* computation for the DRA based on PHM. Future investigations must be focused towards aligning the proposed method to existing standards such as API 581 and the CWA 15740 guideline, to enable DRA.

(2) The estimation of PHM parameters requires enough lifetime data as well as condition monitoring data, which often is incomplete or missing, therefore, the use of knowledge elicitation (expert opinion) can be applied to determine Weibull parameters when there is not enough lifetime data.

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