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Effect of Equipment Component Generic Frequency Data on Probability of Failure Calculations for Risk-Based Inspection

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Keywords

Major Accident Scenario Frequency

Probability of Failure

Risk Based Inspection

Corrosion

Abstract

A software was developed to use equipment component frequency data specific to the facility or provided from different sources in lost event probability calculations for risk-based inspection. Corrosion causes equipment aging and loss events in which hazardous substances are released uncontrollably. The API RP 581 Recommended Practise of the American Petroleum Institute is widely used in the calculation of corrosion-based loss event risks for static pressure equipment such as atmospheric tanks, heat exchangers, columns, reactors, and used for basis of the developed software. In API RP 581, the risk of loss event is defined as the product of the probability of failure and the severity of consequence. Equipment component generic failure frequencies are a variable at the probability of failure calculation. Current software use only equipment component generic failure frequencies given at API RP 581. For this reason, establishment-specific equipment component failure frequency data or data that can be obtained from other sources cannot be used. To solve this problem, a software based on API RP 581 methodology has been developed and provided with the opportunity for the user to enter equipment component failure frequency data from different sources. The findings showed that when using data from different literature sources, there are different results up to 1491% in the probability of failures. Since the increase in the probability of the failures will increase the risk, that creates results such as pulling the equipment inspection dates forward, performing more effective and therefore more costly inspections, increasing the precautions and costs to be taken. Therefore, software which are based on API RP 581 methodology should be developed in such a way that different generic frequency data can be used.

Cite

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1. INTRODUCTION

According to the Regulation on Prevention of Major Industrial Accidents And Lessening Their Adverse Impacts (2019) major industrial accident is defined as a major spread, fire or explosion event during the operation of an establishment caused by one or more dangerous substances. Those events may cause immediate or later serious danger to human and/or environmental health inside or outside the establishment, resulting from uncontrolled developments (URL1, 2019).

Corrosion is one of the main causes of major industrial accidents (Wood et al., 2013; Baybutt, 2015). Loss of containment due to disruption of the integrity of the equipment component may result not only from the corrosive properties of hazardous materials, but also from the properties of the material from which the equipment is manufactured, operating environment, operating conditions, or their interaction (API RP 581, 2016).

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Concepts such as the prevention of process safety in major industrial accidents caused by corrosion and aging have become a subject of process safety in various legislations around the world. For the manufacturers and users of these equipment, starting from the design, the inspection, maintenance and repairs, evaluations and various reasons in terms of the number, variety, costs, effectiveness and focus of the equipment have revealed the need for a risk-based corrosion management strategy.

There are guides, standards, codes and similar various documents have been published by both non-profit organizations and various private sector organizations on corrosion damage mechanisms, estimation of major industrial accident risk, development of risk-based inspection (RBI) methodology and risk management. ASME PCC-3:2007, EN 16991:2016, DNV-RP-G101:2002, EEMUA206:2006, EEMUA 159:2017 and API RP 581:2016 are the most widely known among these documents (EN 16991, ASME-PCC-3, EEMUA 206, EEMUA 159, DNV-RP-G101). There are different qualitative and quantitative approaches in the published documents for the estimation of corrosion based damage mechanisms' risks. Documents are being updated due to reasons such as the need to evaluate the effects of various variables such as the chemical substance, equipment and components, corrosion mechanism, inspection and control techniques, differences in management system evaluation in the estimation of risk.

The American Petroleum Institute has two recommended practices which are API RP 580 and API RP 581, for guidelines on risk-based inspection. Since the 1990s, the issue of risk-based inspection on static pressure equipment has come to the fore in chemical processes where toxic, flammable and explosive dangerous chemicals are processed and stored, especially in petroleum refineries. With the sponsorship of some of the leading international companies in the refining, petrochemical and chemical industries, first the American Petroleum Institute (API) published the Basic Resource Document, which revealed the risk-based inspection (RBI) methodology, and then the risk-based inspection recommended practice in 2000 (Revie, 2015)

API RP 580 sets out the basic requirements for risk-based inspection, but does not go into methodology and details. API RP 581 allows detailed quantitative analyzes to be made on different corrosion-based damage mechanisms with its unique formulas, tables and graphics (API RP 581). For this reason, it is widely used all over the world compared to other standards, guides or norms and contributes to the development of software.

However, there are some problems and limitations both in the API RP 581 recommended practice and software which are based on API RP 581. One of them is to use only the equipment component failure frequency values based on corrosion damage mechanisms in equipment components given in the API RP 581 instead of the facility's own data or the values given in different references.

There are various studies in the literature regarding the effects of differences in generic equipment component failure frequency values (GFF) on risk in terms of equipment components. Considering the differences between failure frequency data in industry and the need to improve data quality, Keeley et al. (2011) conducted a study on the work program conducted by the UK Health and Safety Laboratory (HSL), which brought together and updated existing failure frequency data sources and reviewed new sources that were not previously available (Keeley et al., 2011).

Pittiglio et al. (2014) found that in the process industries, decisions such as equipment inspection, maintenance, and change management have become more "risk-based" over time, but the differences in the failure frequency data used in risk calculations and their differences from major systematic studies in the 1960s-1970s stated that new studies are necessary for these reasons (Pittiglio et al., 2014).

In this study it' s aimed to reveal the effect of equipment component generic failure frequency (GFF) data on probability of failure (POF) calculations based on API RP 581 methodology. To do that, a flexible software is developed which has capability of data input from user. That kind of software flexibility provides opportunity to use establishment specific and/or literature GFF values for the user. The developed software calculates POF value using GFF values given at API RP 581 as default and at the same time another POF can be calculated if the user inputs another GFF value.

2. MATERIAL AND METHOD

2.1. API RP 581 Risk-Based Inspection Methodology Overview

API RP 581 risk-based inspection is a method in which the frequency values of the loss of containment that may occur due to corrosion of pressure equipment and the areal and financial severity of the results of fire, explosion or toxic release that may occur as a result of loss of containment are evaluated as the two basic elements of risk (Figure 1).

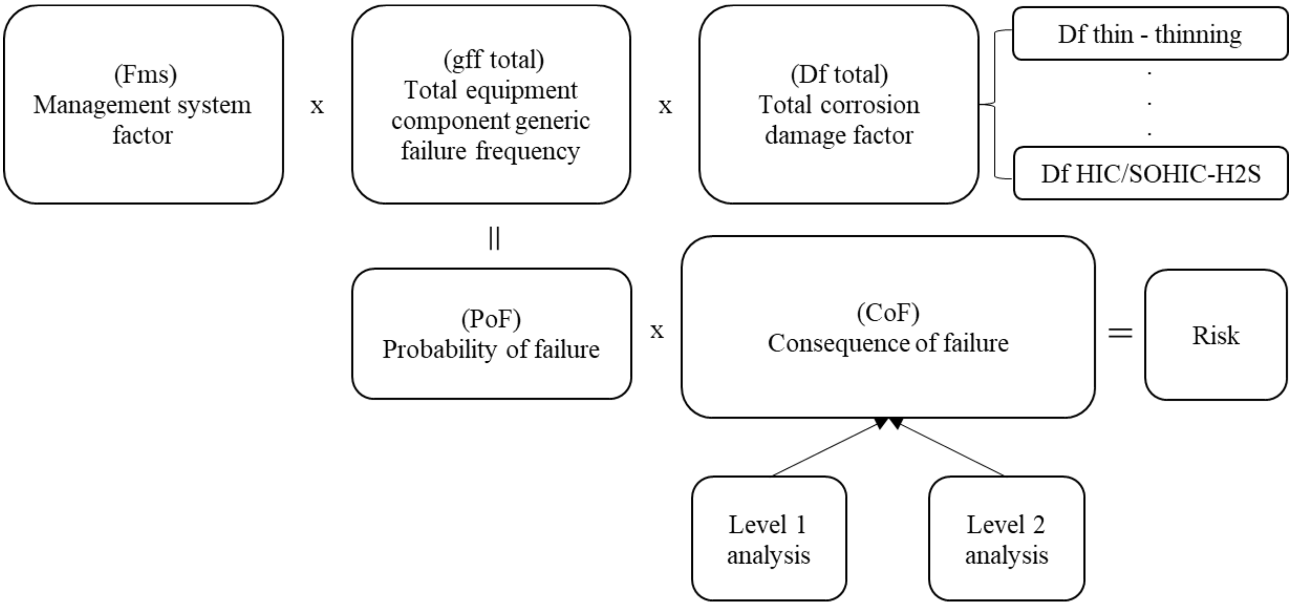


Figure 1. *Risk estimation general components for risk-based inspection according to API RP 581*

It is expressed as the annual potential occurrence frequency (Pf (t) since it depends on time) of different degrees of failure frequency that occur in the equipment due to the corrosion mechanism depending on the hazardous chemical substance in the equipment, and the working conditions, and the working environment. The expression "failure" used by API RP 581 means "loss of containment/integrity" that causes loss events. Failure sizes are represented by representative hole diameters of a given diameter in varying range (Table 1). Generic failure frequency (GFF) data for equipment component types can not be used alone for POF calculations without corrosion mechanism and management system adjustment factors because those obtained GFF values from industry are not specific to the failure mechanism and establishment. Some of the GFF values given for equipment components in API RP 581 are given in Table 2.

A correction is made in the POF calculation by multiplying the GFF values by the management system factor (F_{ms}) of the establishment where the risk is evaluated and the sum of the time-dependent damage factors (Df(t)) of the damage mechanisms caused by the corrosion in the equipment. Accordingly, PoF calculation is made according to equation 1.

$$P_f(t) = GFF_{total}\ x\ F_{ms}\ x\ D_f(t) \qquad (1)$$

Correction factors with a value greater than 1.0 will increase the POF and those with a value less than 1.0 will decrease it. Both correction factors are always positive numbers.

2.1.1. Equipment Component GFF Values in API RP 581

In API RPI 581, GFF values are differentiated according to both the equipment and its component and the representative hole diameters of a certain diameter in a geometrically varying range of damage size. In this regard, different GFF values in each different categorical equipment component are given as different numerical values according to the damage size in 4 different hole diameters. These diameters and some of the equipment component GFF values are given in Table 1 (API RP 581).

Table 1. *Hole sizes used in level 1 and 2 consequence analysis (COF) in API RP 581*

Release Hole Number	**Release Hole Type**	**Range of Release Hole Diameter (mm)**	**Release Hole Diameter, d_n (mm)**
1	Small	0 - 6.4	$d_1 = 6.4$
2	Medium	>6.4 to 51	$d_2 = 25$; $d_2 =$ minimum [D,25]
3	Large	>51 to 152	$d_3 = 102$; $d_3 =$ minimum [D,102]
4	Rupture	>152	$d_4 =$ minimum [D,406]

Table 2. *GFF values for the some of the equipment components given in API RP 581*

Equipment Type	**Component Type**	**Small Hole GFF**	**Medium Hole GFF**	**Large Hole GFF**	**Rupture GFF**	**GFF Total (failure/year)**
Compressor	Compressor R	8.00E-06	2.00E-05	2.00E-06	6.00E-07	3.06E-05
Heat Exchanger	ID SS	8.00E-06	2.00E-05	2.00E-06	6.00E-07	3.06E-05
	ID TS	8.00E-06	2.00E-05	2.00E-06	6.00E-07	3.06E-05
Pipe	Pipe-1	2.80E-05	0	0	2.60E-06	3.06E-05
	Pipe-2	2.80E-05	0	0	2.60E-06	3.06E-05
Pump	Pump2S	8.00E-06	2.00E-05	2.00E-06	6.00E-07	3.06E-05
Atmospheric Storage Tank	Tank bottom	7.20E-04	0	0	2.00E-06	7.22E-04
	Shell-1-10	7.00E-05	2.50E-05	5.00E-06	1.00E-07	1.00E-04
Vessel/FinFan	Codrum	8.00E-06	2.00E-05	2.00E-06	6.00E-07	3.06E-05
	Drum	8.00E-06	2.00E-05	2.00E-06	6.00E-07	3.06E-05
	FinFan	8.00E-06	2.00E-05	2.00E-06	6.00E-07	3.06E-05
	Reactor	8.00E-06	2.00E-05	2.00E-06	6.00E-07	3.06E-05

2.1.2. Equipment Component GFF Values in Other Literature

Within the scope of Seveso II Directive studies in Europe, the Purple Book (CPR 18E, 2005) published by the Ministry of Housing, Spatial Planning and the Environment to guide quantitative risk assessment includes the release frequencies of hazardous materials for equipment. The release frequency data was based on various government-sponsored projects, expert opinions and other known sources, and sources were addressed for each equipment type. The events that cause the release frequency are named as loss of containment. Loss events are categorized with the G lettering. According to this;

G.1: Sudden release of entire inventory

G.2: Discharge of the entire inventory within 10 minutes by continuous release at a constant release rate

G.3: Continuous release through a hole with an effective diameter of 10 mm

As an example, the release frequencies given in the Purple Book on constant pressure vessels on an annual basis are given in Table 3.

Table 3. *Pressure vessel failure frequency examples from Purple Book*

Equipment	**G1.**	**G2.**	**G3.**
Pressure vessel	5×10^{-7}	5×10^{-7}	1×10^{-5}
Process vessel	5×10^{-6}	5×10^{-6}	5×10^{-4}
Reactor vessel	5×10^{-6}	5×10^{-6}	5×10^{-4}

Quantitative risk assessment data has been provided to the chemical process industries by the American Center for Chemical Safety (CCPS) since the 1980s. CCPS published the "CCPS Guidelines for Process Equipment Reliability Data" in 1989 and "Guidelines for Improving Plant Reliability through Data Collection and Analysis" in 1998. Subsequent enhancements in this information-gathering effort have allowed the creation of the Process Equipment Reliability Database (PERD), which provides deeper and more specific analysis of equipment availability, reliability, design improvements, maintenance strategies, and life-cycle cost determination (AIChE PERD, 2020).

In the Guidelines For Initiating Events And Independent Protection Layers In Layer of Protection Analysis book, the frequency of catastrophic integrity loss for pressure vessels is stated as 1 x 10^{-5} per year (CCPS, 2014).

The International Oil and Gas Producers Association (IOGP) publishes the "process release frequencies" report at regular intervals. The current data presented in the 2019 IOGP Process release frequencies report is based on the analysis of data from the United Kingdom Health and Safety Executive (HSE) Hydrocarbon Release Database (HCRD) from 1992 to 2015. The data sheets to be used for the equipment are grouped separately from each other in accordance with the explanations above, unlike API RP 581. As an example, generic failure frequency data for process (pressurized) equipment is given in Table 4 (IOGP, 2019).

Table 4. *IOGP process release frequencies report process equipment leak frequency data*

Hole Diameter Range (mm)	Inlets 50 to 150 mm Diameter	Inlets >150 mm Diameter
1 to 3	5.0E-04	5.0E-04
3 to 10	2.6E-04	2.6E-04
10 to 50	1.4E-04	1.4E-05
50 to 150	7.4E-05	3.8E-05
>150	---	3.6E-05
Total	9.8E-04	9.8E-04

Det Norske Veritas (DNV) process release frequency data are also frequently used in the industry. Like IOGP, DNV data are based on HCRD and some other data sources. DNV, derives data from HCRD data, but with a different equation than IOGP. There is derived equation is used in the DNV Leak software to generate the release frequencies for the lost event. The release frequency data of the process vessel calculated by the software are given as an example in Table 5 (DNV, 2013).

Table 5. *DNV Leak process vessel release frequency data*

Proses vessel Frequency data				
Equipment Size	Category	Total	Full Pressure	Zero Pressure
	3 - 10 mm	5.946E-04	4.093E-04	1.393E-04
	10 - 50 mm	4.379E-04	2.236E-04	1.408E-04
	50 - 150 mm	1.652E-04	6.181E-05	7.316E-05
	> 150 mm	2.736E-04	5.930E-05	2.977E-04
	Total	2.360E-03	1.540E-03	8.110E-04

2.1.3. POF Algorithm and Calculation

In this study, like as other existing software used in industrial applications, API RP 581 RBI methodology is followed for the POF calculation and algorithm is given in Figure 2.

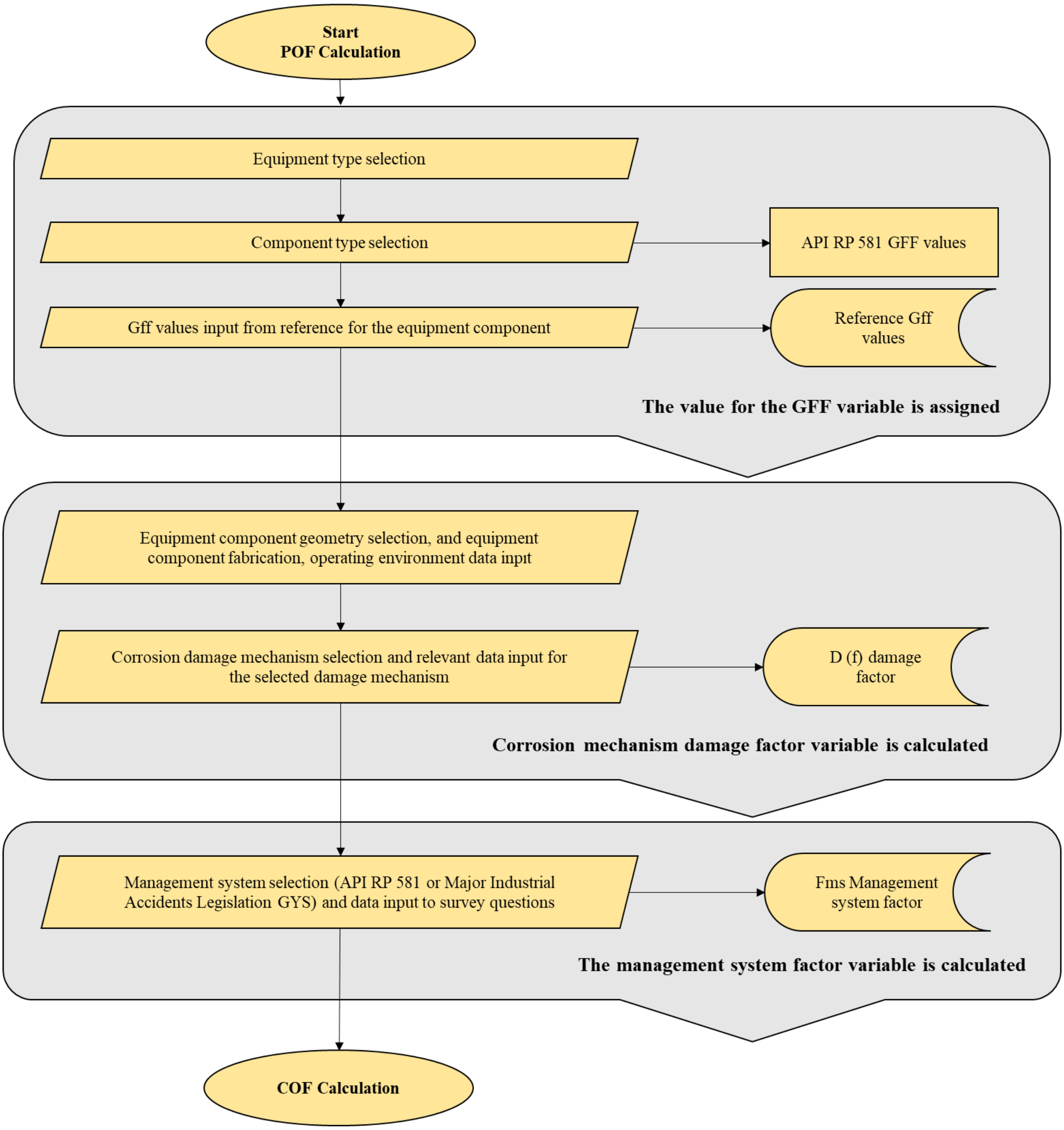


Figure 2. *POF calculation algorithm*

3. CASE STUDY

The case study is RBI calculation on a drum. Operating temperature, T, is 49˚C and pressure, P, 0.696 MPa. In drum the fluid is a mixture of propane and butane with 0.11% H_2S. Operating conditions allow aqueous conditions, general corrosion is inspected. Measured corrosion rate of 0.29 mm per year. Also, stress corrosion cracking caused by wet H_2S is possible with a susceptibility of Low. B effectiveness level inspection results on 04.04.2003 revealed some general corrosion and thickness is measured as 19.05 mm. There is no history of inspection for wet H_2S cracking. The management system is evaluated and was found to be 0.5. Mechanical design parameters of the drum, operating conditions, some properties related to the fluid it limits and inspection values are given in Table 6, 7 and 8.

The values of the case studies were entered into the software developed according to the formulas and tables in the sections on POF calculation in the current edition of API RP 581 in 2016. Since the features of the software such as management systems evaluation and result analysis are out of the scope of this study, only the screenshots of the data inputs of the user interface of the developed software related to this study are given in Figures 3, 4 and 5. The user interface for equipment component data of the developed software screenshot given in Figure 3. The user selects the equipment and component type which is intended to be evaluated for RBI study and the GFF values given at API RP 581 are automatically assigned to the calculations at backend of the software which are stored and called from Microsoft SQL Database. If the user wants to use other GFF value from other references than API RP 581 those data shall be entered by manually. For the calculation POF and Risk the user inputs are categorized as equipment component fabrication values such as yield / tensile strength, allowable stress load; component geometry such as cylindirical (CYL), inside diameter, and working environment such as working temperature which are all given at Table 6. Those data shall be entered by manually from the user. The user interface for corrosion mechanism data of the developed software screenshot given in Figure 4. The user interface for consequence of failure (COF) and risk evaluation at Figure 5, which are all user input data and leaved as constant values just for this study.

Table 6. *Drum design, operating conditions, fluid-related data*

Design data		**Equipment Component type**	Cylindrical shell-CYL
Design code	EN ISO	Inside diameter, mm	2479.675
Material of construction	Carbon steel	Length, mm	9144
Yield / Tensile strength, MPa	205 / 380	Volume, m^3	44.136
Allowable stress load, MPa	94.8	**Process fluid**	
Weld joint efficiency (0.7-1)	0.85	Name	mixture of propane and butane
Post weld heat treatment	Yes	Liquid ratio (0-1)	0.5
Design temperature, °C	232	Gas ratio (0-1)	0.5
Design pressure, MPa	1.138	Type	Type 0
Furnished thickness, mm	20.637	Phase in the equipment	2 phase (liquid-gas)
Corrosion allowance, mm	3.175	Molecular weight, MA, kg/kmol	51
Cladding/weld overlay	-	Liquid phase density, p_l, kg/m^3	538.379
Thickness of weld cap, mm	0	Gas phase density, p_g, kg/m^3	5.97
Equipment type	Pressure vessel	Normal boiling point, °C	-21
Component type	Drum	Physical state outside	Gas
Fabrication date	1.01.1972	Autoignition temprature, °C	369
Service date	1.01.1972	Ideal Gas Specific Heat Capacity Ratio, k (unitless)	1.13

Table 7. *Thinning inspection results*

D_f thin (General and local D_f) Inspection 1		
Date	04.04.2003	
Damage mechanism	D_f^{Thin}	
Effectiveness	D_f^{thin} – Inside - B: Usually effective	
Measured thickness, t_{rdi}, mm	19.05	
Corrosion rate, mm/year	Measured	0.29
Corrosion Rate Confidence Levels	High Confidence	3
Thinning type	General	1
F_{om} – Online monitoring	-	
F_{ip}- Adjustment for Injection/Mix Points	-	
F_{dl} - Adjustment for Dead-legs	-	

Table 8. *HIC/SOHIC-H_2S inspection results*

$D_f^{HIC\ SOHIC\ H2S}$ Hydrogen-induced Cracking and Stress-oriented Hydrogen-induced Cracking in Hydrogen Sulfide Services (HIC/SOHIC-H_2S) Inspection 1	
Date	1.01.1972
Damage mechanism	$D_f^{HIC\ SOHIC\ H2S}$
Effectiveness	Df HIC/SOHIC-H_2S - Inside - E: Ineffective
Sensitivity (Low, Medium, High)	Low
Water present (yes/no)	Yes
H_2S in water ppm	< 50 ppm
pH value	5.5 – 7.5
Cyanide (yes, no)	Yes
Steel product form (plate or pipe) and Sulfide content of plate steel	Product Form— Seamless/Extruded Pipe
Post weld heat treatment	Yes
F_{om} – Online monitoring	-

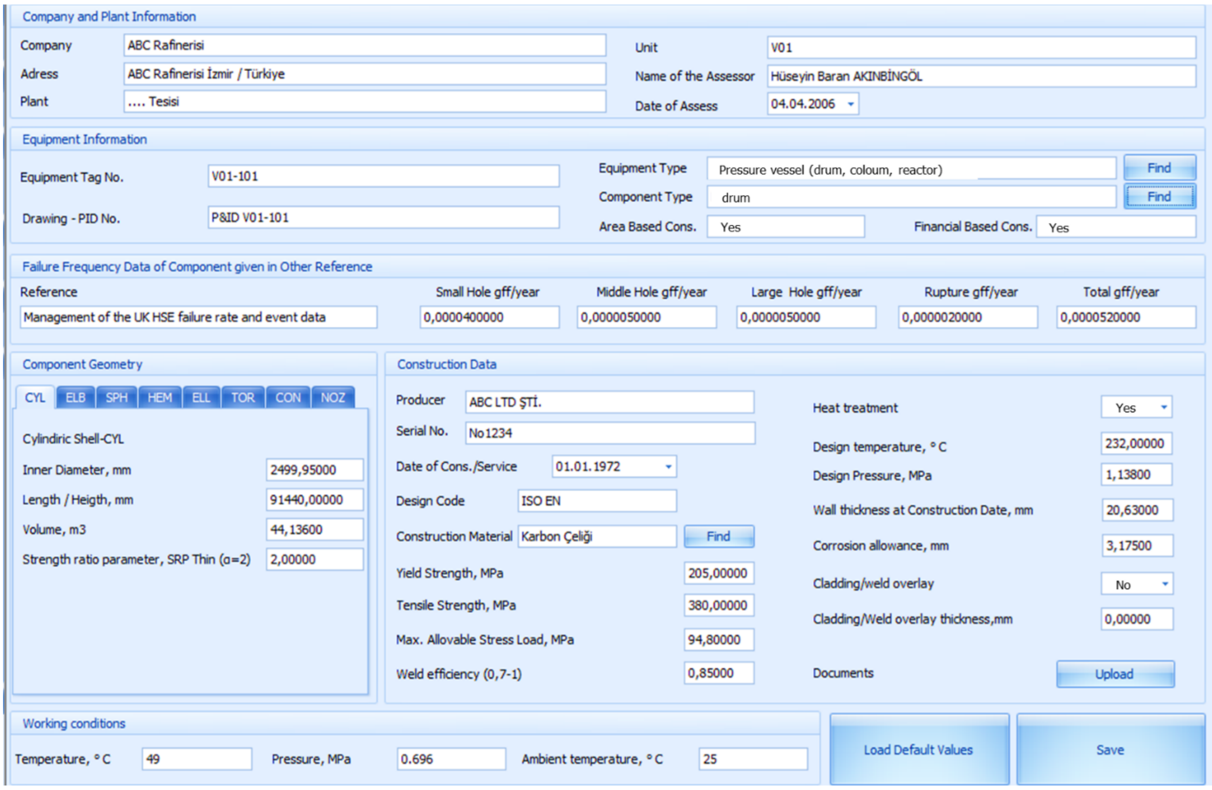


Figure 3. *Equipment and component data input to the software*

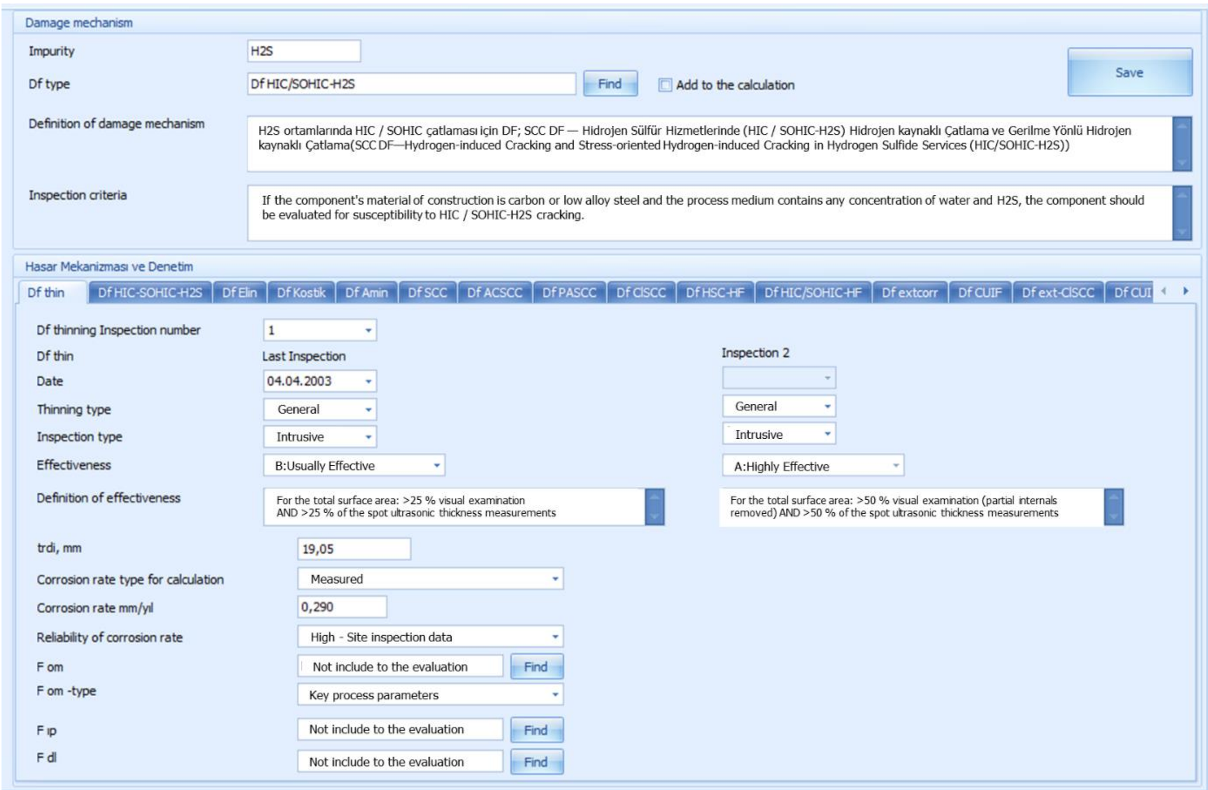


Figure 4. *Thinning corrosion mechanism data input to the software*

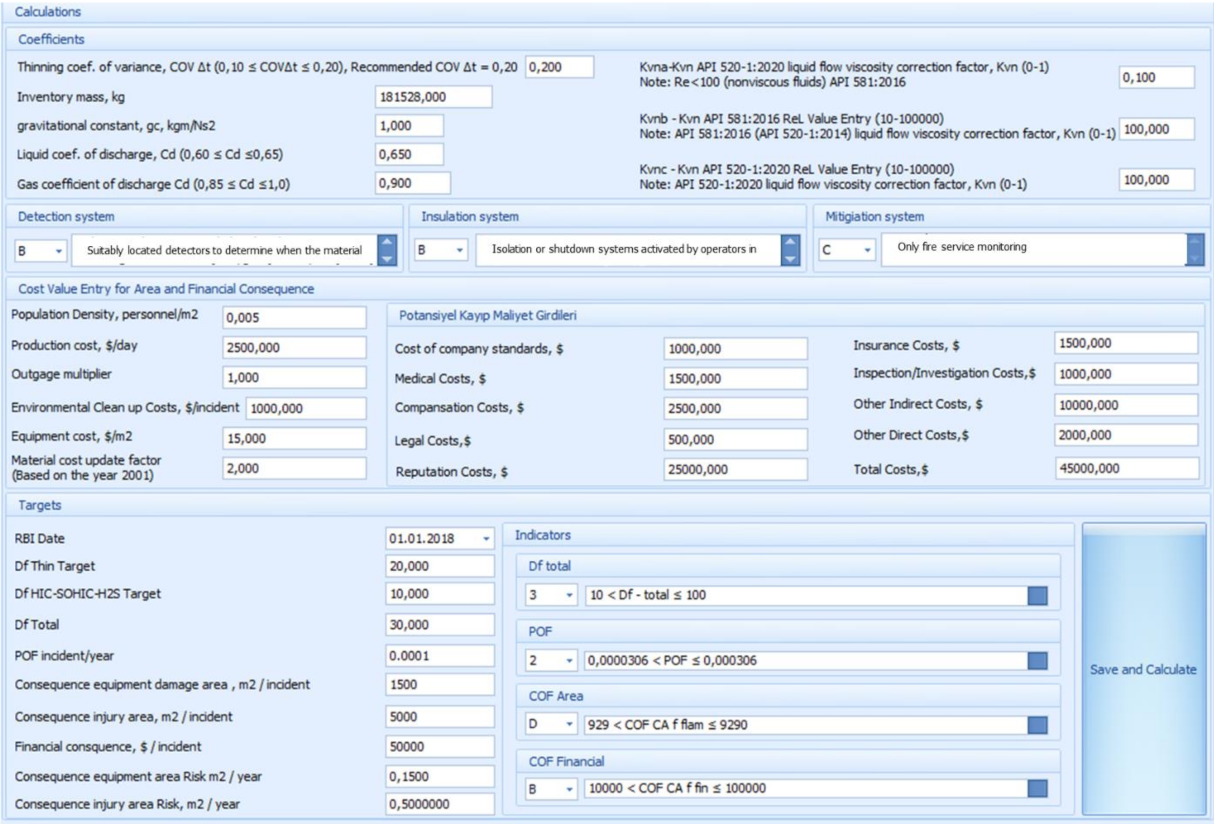


***Figure 5**. Result analysis data input to the software*

4. FINDINGS

As part of the case study, POF calculation was made for the date of 1.1.2018 over thinning and HIC/SOHIC-H_2S damage mechanisms. The GFF values taken from different references used in case study are shown at Table 9. The calculated POFs with equipment component generic failure frequencies taken from those references stated at Table 9 are given in Figure 6, and software screenshots are given in Figures 7 and 8.

***Table 9.** Probability of failure findings calculated with equipment component different GFF values*

Reference	Small Hole GFF	Medium Hole GFF	Large Hole GFF	Rupture GFF	Total GFF	POF
IOGP	2.6E-04	1.4E-05	3.8E-05	3.6E-05	3.8E-04	1.19E-02
Management of the UK HSE failure rate and event data	4.0E-05	5.0E-06	5.0E-06	2.0E-06	5.2E-05	1.78E-03
DNV leak	4.09E-04	2.23E-04	6.18E-05	5.93E-05	7.54E-04	2.58E-02
API RP 581	8.00E-06	2.00E-05	2.00E-06	6.00E-07	3.06E-05	1.048E-03

As that can be seen from Table 9, the GFF values used in case study are not same which are taken from different references. In the case study, those GFF values are used and calculated POF values based on the different GFF values are shown at the cells under POF at Table 9 and Figure 6. As the POF value increases GFF value also increases which is naturally expected as per the equation 1.

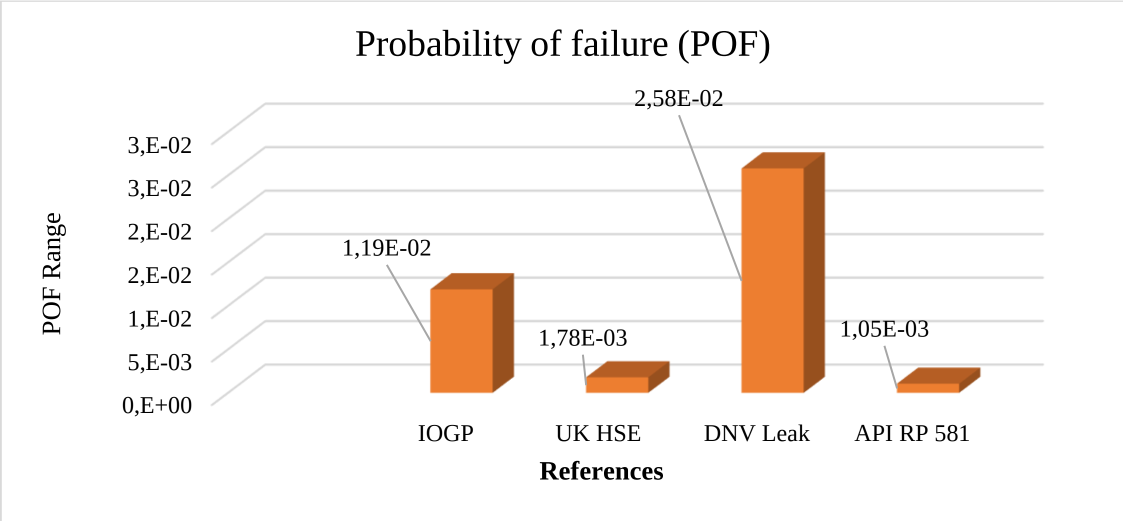
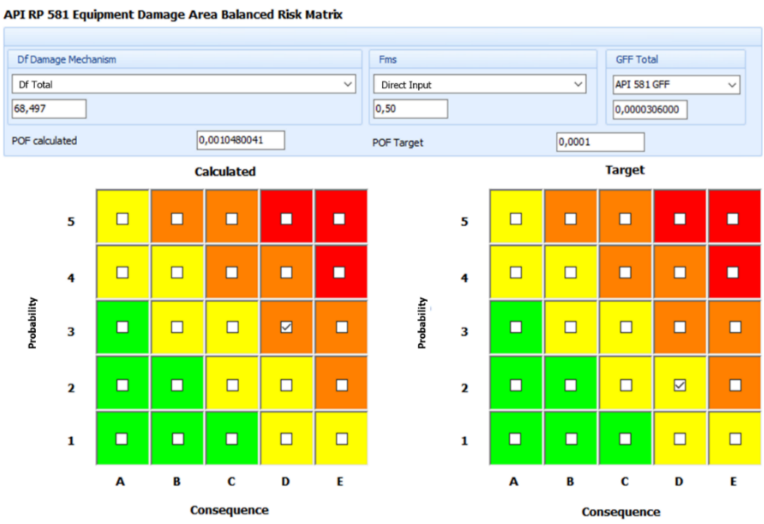


Figure 6. *Probability of failure findings calculated with equipment component different GFF values*

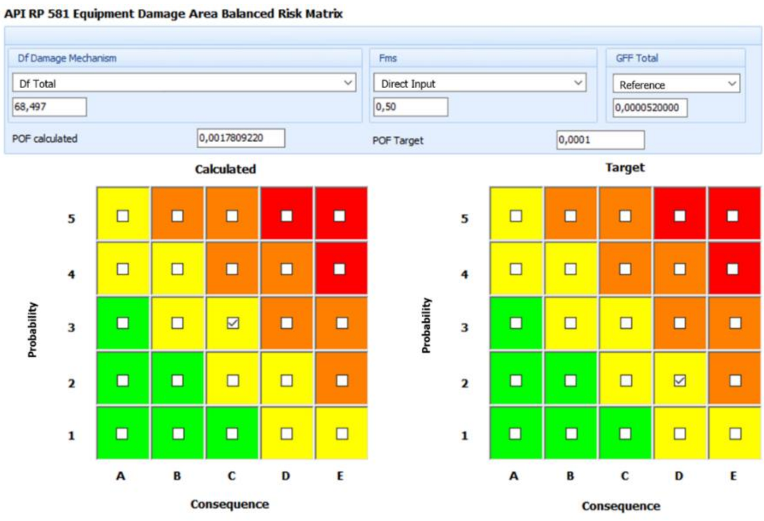
As that can be seen from Table 9, the GFF values used in case study are not same which are taken from different references. In the case study, those GFF values are used and calculated POF values based on the different GFF values are shown at Figure 6. The POF value increases as GFF value increases expected as per the equation 1.

The user interface for POF, COF and Risk calculation results are given at Figure 7 and 8. The POF results are given at Figure 7 based on GFF values taken from API RP 581 (see at Table 2 for drum and same as Table 9 for API RP 581). The POF results are given at Figure 8 based on GFF values taken from user input as from another reference (Keeley et al., 2011) (see Table 9 Management of the UK HSE failure rate and event data). The software also give POF, COF and risk results as matrix. At matrixes in Figure 7 and 8, the calculated risk category is found at orange area and in Figure 7 and found at yellow area in Figure 8. According to the results although the other values of variables are kept same for risk calculation except the GFF values, the different GFF values are effecting the calculated risk category which are important to decision making process for risk management.



Probability Category		Consequence Category	
Category	Probability Range	Category	Consequence Range
1	POF ≤ 0,0000306	A	COF CA f flam ≤ 9,29
2	0,0000306 < POF ≤ 0,000306	B	9,29 < COF CA f flam ≤ 92,9
3	0,000306 < POF ≤ 0,00306	C	92,9 < COF CA f flam ≤ 929
4	0,00306 < POF ≤ 0,0306	D	929 < COF CA f flam ≤ 9290
5	POF > 0,0306	E	COF CA f flam > 9290

Figure 7. *Screenshot of POF and other results calculated with API RP 581 GFF data*



Numerical Values Associated with POF and Area-based COF Categories

Probability Category		Consequence Category	
Category	Probability Range	Category	Consequence Range
1	POF ≤ 0,0000306	A	COF CA f flam ≤ 9,29
2	0,0000306 < POF ≤ 0,000306	B	9,29 < COF CA f flam ≤ 92,9
3	0,000306 < POF ≤ 0,00306	C	92,9 < COF CA f flam ≤ 929
4	0,00306 < POF ≤ 0,0306	D	929 < COF CA f flam ≤ 9290
5	POF > 0,0306	E	COF CA f flam > 9290

Figure 8. *Screenshot of POF and other results calculated with GFF data from the sample reference*

5. CONCLUSION

API RP 581 sets out a detailed methodology for risk-based inspection as compared to other standards. For that reason, that’s preferred for software developing. However, the data used for calculation within the methodology presented in API RP 581 are used directly in the software and different alternatives are not offered to the software users. In the literature, there are many studies on failure frequency data from different sources. In this study, it is focused on the POF value calculation results between the generic failure frequency data of the equipment component given in API RP 581 and the failure frequency values from other references are used. With a case study on the software developed in accordance with the methodology presented in API RP 581, findings on the POF values calculated when using different equipment component generic failure frequency data were obtained.

According to the findings, it was found that there was a difference of up to 1491% (14.91 times) between the POF value calculated based on the different generic failure frequency data used within the scope of the case study. Although the increase in the POF, increases the risk, requires more effective but more costly inspections, more effective detection, isolation and reduction systems in terms of result analysis, and increases in precautionary costs. This change in POF calculations, which can also be taken as the frequency of major industrial accidents, shows that the quality of the equipment component failure frequency data obtained from the experience in the industry is important.

Obtaining equipment component failure frequency data from industry from corrosion-induced integrity loss events and categorizing them according to not only the equipment component but also the corrosion damage mechanism type will increase the reliability of POF calculations. Software developed based on the methodology set forth in API RP 581 should be developed in a way that enables the use of equipment component generic failure frequency data, which can be obtained from different sources in the literature and in this study.

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CONFLICT OF INTEREST

No conflict of interest was declared by the authors.

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