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Evaluation of Reliability of Safety Instrumented System (SIS) and Safety Valves of Crude Oil Separators in an Oil Field

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ABSTRACT

A crude oil separator is a pressure vessel used to separate oil and gas in an oil well stream. The separators are provided with a Basic Process Control System (BPCS) and a protection system which consists of a Safety Instrumented System (SIS) and a Pressure Relief System (PRS). Failure of the crude oil separator might result in fire, explosion, and toxic dispersions. The world has witnessed several fire and explosion incidents due to the operation of crude oil separators. The reliability of crude oil separators' control and protective systems is very important to verify their abilities to perform their functions. This technical article presents an overview of the layers of protection of crude oil separators and the reliability of protective systems. The article also evaluates the reliability of SIS and safety valves of crude oil separators in an oil field. The crude oil separators are arranged in the form of three parallel trains of separators, each divided into three stages. The first stage consists of two separators and each stage of the second and third stages consists of one separator. The reliability of the different configurations of the SIS and safety valves of a train of production separators has been estimated and found to be acceptable.

Keywords: Crude oil separator, Reliability, Safety instrumented system, Safety valve

تقييم إمكانية الاعتماد على نظام السلامة الآلي وصمامات الأمان لخزانات فصل الزيت الخام في حقل نفطي

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ملخـــــــص البحــــــث

الزيت الخام المنتج من آبار النفط يتكون من زيت وغاز وماء وللاستفادة من الزيت والغاز كمصدران رئيسيان للطاقة يجب فصل الزيت والغاز عن المكونات الأخرى. خزانات فصل الزيت تستخدم في أماكن استخراج الزيت بالقرب من رؤوس الآبار ومراكز تجميع ومعالجة الزيت الخام وهي عبارة عن أوعية معدنية تعمل عند ضغط مرتفع وتستخدم لفصل الزيت عن الغاز عن الماء ومزودة بأنظمة تحكم وتشغيل آلي وكذلك مزودة بأنظمة حماية آلية (أوتوماتيكية) وصمامات أمان. وبالرغم من أن خزانات فصل الزيت مزودة بأنظمة التحكم والحماية وخطط الطوارئ إلا أن خزانات فصل الزيت تعرضت للعديد من

الحرائق والانفجارات في العديد من دول العالم. هذا المقال يقدم ملخص لأنظمة التحكم الآلي وأنظمة الحماية الآلية وصمامات الأمان وإمكانية الاعتماد على هذه الأنظمة. المقال كذلك يقدم دراسة لتقييم أداء عمل أنظمة الحماية الآلية وصمامات الأمان لخزانات فصل الزيت بحقل نفطي. الخزانات بهذا الحقل مصممة على هيئة ثلاث قطارات من خزانات الفصل متصلة على التوازي وكل قطار من هذه الخزانات يتكون من ثلاث مراحل متصلة على التوالي، المرحلة الأولى تتكون من خزانين وكل من المرحلة الثانية والثالثة تتكون من خران واحد. لقد تبين من هذه الدراسة أن تصميم أنظمة السلامة الآلية والتي تتكون من حساسات وأنظمة معالجة وصمامات طوارئ لخزانات فصل الزيت لها إمكانية اعتمادية عالية بشرط أن تتم الاختبارات الدورية لأنظمة السلامة حسب الجدول الزمني المحدد لها.

الكلمات الدالة: خزانات فصل الزيت الخام، الاعتمادية، أنظمة السلامة الآلية، أنظمة تشغيل الخزانات، صمامات الأمان.

1. Introduction

Crude oil produced from oil wells is a mixture of oil, gas and water. Oil and gas are the most important energy sources therefore they should be separated from other material as soon as they are produced from oil wells. Oil and gas separators are used in the upstream sector of the oil and gas industry, which is concerned with the exploration, extraction, and processing of hydrocarbons. The separator is a pressure vessel used to separate oil and gas from a well stream. The mixture of oil, gas and water that it is in emulsion form enters to a static vessel so that gas is lighter than the liquid and will move to the topside and the liquid itself is water and oil settle in the bottom. Water is heavier than oil, water will settle down and oil will be in the middle. The separated oil and water are drained off through the bottom outlet, while the gas is routed through the top outlet.

There are many types of separators used successfully in the field, but most often, depending on the environment in which they are housed, separators are classified based on orientation into horizontal, vertical, and spherical and can be divided based on phase into gas/liquid two-phase and oil/gas/water three-phase separators. The separators are provided with Basic Process Control System (BPCS) and a protection system which consists of a Safety Instrumented System (SIS) and Pressure Relief System (PRS). Failure of the crude oil separator might result in fire, explosion, and toxic dispersions.

Separators in the oil and gas industry can be vulnerable to disasters and accidents if they are not designed, constructed, and maintained properly. In 1989 separation facilities in France was not equipped with relief device exposed to fire incident resulting in 4 fatalities and significant damage [1]. In 2010, an oil spill occurred at an offshore platform in the Gulf of Mexico when a failure in an oil-water separator led to a release of oil into the ocean. The spill resulted in significant environmental damage and was one of the worst offshore oil spills in history. In 2014, an explosion occurred at an oil refinery in Washington State, USA, when a failure in an oil-water separator led to a release of flammable vapors. The explosion caused several fires and resulted in the evacuation of thousands of people. In 2018, a fire broke out at an oil refinery in California, USA, resulting in several injuries and significant damage to the refinery [2]. Abolfazl Naemnezhad et al. [3] highlighted that due to the critical role of an oil production separator on the old Iranian Nowrooz oil production platform, the corrosion inspection has been delayed for ten years. The Consequence assessment of the separator explosion highlighted that the risk of thermal radiation damage to humans and structures reaches a radius of 21m, and the explosion impacts reach a radius of 30m. In 2019, an explosion occurred at an oil refinery in Texas, USA, The explosion resulted in several injuries and significant damage to the refinery.

This technical article presents an overview of the layers of protection of crude oil separators and the reliability of the protective systems. The article also presents an evaluation of the reliability of SIS and safety valves of crude oil separators in an oil field. The crude oil separators are arranged in the form of three parallel trains of separators each train divided into three stages. The first stage consists of two separators and each stage of the second and third stages consists of one separator. The reliability of different configurations of the SIS and safety valves of one train of production separators has been estimated.

2. System protection layers

Safeguard systems are an important part of the process plant and equipment, which protects personnel, plant, and the environment from abnormal operating conditions. The safeguarding system consists of layers of protection. The layers of protection are independent measures that reduce the likelihood of undesirable adverse events or the consequence of that event if it were to happen by process control, prevention or mitigation. Generally, all process facilities have more than one protection layer hierarchically performing its function to maintain the safe state of the facility if the previous protection layer has failed to protect. The layers of protection are depicted in Figure 1.

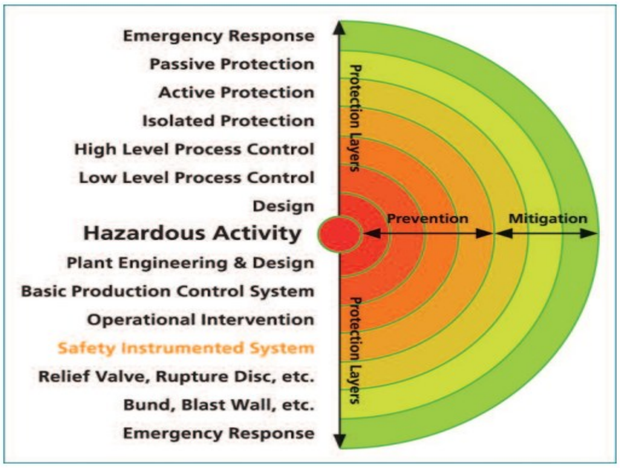

Figure 1. Layers of hazard protection [4].

Control systems are important to all process equipment to make sure each piece of equipment works safely and efficiently. A Basic Process Control System (BPCS) is a system that responds to input signals and generates an output signal which causes the equipment or process under control to operate in a particular manner. BPSC is to assist or replace the operator in maintaining normal process operations despite deviations.

3. Protective System

Protective systems are the barriers that are put in place to prevent incidents from happening, escalating or causing harm. A protective system is to protect for personnel, environment, and assets during abnormal conditions, usually resulting from control system failures or external events. Protective systems can be divided into a Safety Instrumented System (SIS) and a Pressure Relief System (PRS).

3.1 Safety Instrumented Systems (SISs)

SISs are frequently used in the petroleum industry to detect hazardous events e.g. high levels and high pressures. The standard IEC 61508 defines SIS, as “SIS is a system composed of sensors, logic solvers, and final control elements to take a process to a safe state when predetermined conditions are violated” [5]. The sensor is the subsystem that detects and relays a process parameter to the SIS. The logic solver is the subsystem that executes the logic to take safety action. The final element is the subsystem that takes action to place the process in a safe state. There are many other names for SIS, for example, safety shutdown system, emergency shutdown system, safety interlock, trip system, protective instrumented system, or safety critical system.

3.2 Pressure Relief System (PRS)

The active protective layer consists of safety relief or rupture disc. The primary purpose of a pressure relief valve (PRV) is the protection of life and property by venting fluid from an over pressurized vessel. Safety valves are primarily used with compressible gases and in particular for steam and air services. Relief valves are commonly used in liquid systems, especially for lower capacities and thermal expansion duty. A safety relief valve is a PRV that may be used either as a safety or a relief valve, depending on the application. Safety relief valves are classified as (1) conventional type, (2) pilot operated, (3) balanced bellows, (4) power actuated, and (5) temperature actuated. The most common operating problems with all types of relief valves are (i) Fail to open at a set pressure (ii) failure to close (failure to reseat) (open above set pressure, (iv) failure to relieve required capacity, (v) open below set pressure, (vi) Leakage, (vii) Chattering [6]. Many codes and standards are published throughout the world which address the design and application of pressure relief valves. The most widely used and recognized of these is the ASME Boiler and Pressure Vessel Code, commonly called ASME Code [7].

4. Reliability of protective systems

Reliability presents the ability of an item or system to perform its intended function. Reliability is defined as “the probability of a component or system to perform its intended function during a specific period time and under a given set of conditions” [8].

Safety Instrumented Systems (SIS) are responsible for operational safety and guarantee emergency stops within limits considered safe whenever the operation exceeds these limits. There are two basic ways for the SIS to fail. The first way is commonly called a nuisance or spurious trip, which usually results in an unplanned but relatively safe process shutdown. While there is minimal danger associated with this type of SIS failure, the operational costs can be enormous. The second type of failure does not cause a process shutdown or nuisance trip. Instead, the failure remains undetected, permitting continued process operation in an unsafe and dangerous manner. If an emergency demand occurred, the SIS system would be unable to respond properly. These failures are known as covert or hidden failures and contribute to the probability (PFD) of the system failing in a dangerously on demand.

The reliability or unreliability of the safety systems is quantified by the average probability of failure on demand (PFDavg) [9]. PFD is an adequate indicator of reliability for safety systems [1]. If it is not tested, the probability of failure tends to be 1.0 with time. Periodic tests keep the probability of failure within desirable limits. To verify that an SIS performs its safety functions and to reveal any failures, proof tests, which are offline periodic inspection tests should be carried out. The proof tests are performed to detect the hidden undetected failures of a system in operation. After detecting the hidden failures, the system can be restored in a condition “as good as new” or as close as practical to this condition [10].

To enhance the reliability of an SIS against failures, redundancy is often implemented in the system configuration. However, redundancy introduced a subclass of dependent failures called common-cause failure (CCF). IEC 61508 [10] defines a CCF as a failure that is the result of one or more events, causing concurrent failures of two or more separate channels in a multiple channel system, leading to system failure. CCF only affects subsystems with redundant components. It is referred to as the CCF fraction. β is a parameter with a value between 0 and 1 that represents the fraction of failures that result in all redundant components within a subsystem being disabled. Conservative β values are 0.1 for sensors and 0.05 for final elements. Common Cause Failures can be eliminated, or substantially reduced, by using not only redundant architectures but by diverse types of equipment within a redundant architecture [11].

Calculation of the overall PFDavg begins with the use of one of the equations shown in Table 1 below for each subsystem – sensor, logic solver, and final element. Mirek Generowicz [12] summarized the derivation of the SIS configuration equations. The equations used consider the specific failure rates of the analyzed device and the proposed test interval of the subsystem.

The overall PFD_{avg} is obtained by summing the individual components [13].

$$PFD_S + PFD_L + PFD_{FE} = PFD_{SYSTEM} \qquad (1)$$

Where:

PFD_{SYSTEM} is the probability of failure on demand of the system

PFD_S is the probability of failure on demand of the sensors

PFD_L is the probability of failure on demand of the SIS logic solver

PFD_{FE} is the probability of failure on demand of the final control elements.

Table 1: Equations of the probability of failure on demand [12].

SIS configuration	PFD_{avg}
$1oo1$	$\left[\lambda_{DU} \times \frac{TI}{2}\right]$
$1oo2$ *(Identical)*	$\left[(\lambda_{DU})^2 \times \frac{(TI)^2}{3}\right]$
$1oo2$ *(Identical with CCF)*	$\left[(\lambda_{DU})^2 \times \frac{(TI)^2}{3}\right] + \left[\beta \times \lambda_{DU} \times \frac{TI}{2}\right]$
$1oo2$ *(Non-Identical)*	$\left[\frac{(\lambda_{DU,1} \times \lambda_{DU,2})TI^2}{3}\right]$
$2oo2$ *(Identical)*	$[\lambda_{DU} \times TI]$
$1oo3(Identical\ without\ CCF)$	$\left[(\lambda_{DU})^3 \times \frac{(TI)^3}{4}\right]$
$1oo3(Identical\ with\ CCF)$	$\left[(\lambda_{DU})^3 \times \frac{(TI)^3}{4}\right] + [\beta \times \lambda_{DU} \times TI]$

5. Crude oil Separators in an Oil Field

The crude oil produced from oil wells in an oil field is distributed on test and production separators through a manifold. The production separators are divided into three trains, each train consists of three stages, the first stage consists of two separators, the second stage consists of one separator and finally third stage consists of one separator. Figure 2 shows a train of production separators.

The main process variables in the separators are pressure and level. Pressure is controlled by a Pressure Control Valve (PCV) installed in the gas outlet and liquid level is controlled by Level Controlled Valves (LCV) installed in the liquid outlet lines.

The separators are protected from overpressure by SIS and safety valves. SIS consists of high pressure switches and high level switches on the separators operate on 16inch shutdown valves on the crude oil manifold.

The hydrocarbon mix at 725 Psi in manifold (oil 37323 bopd, water 10679 bwpd) inlet to the first stage separators. First stage separators are used to separate liquids (oil and water) from gas. The gas is sent to the NGL plant, and in case of emergency is diverted to let-down flares. Every separator in the first stage is protected by SIS (HLS, HPS, logic solver, and trip valve) and three safety valves. The outlet crude oil from the first stage separators is diverted to one separator in the second stage at 165psi. In the second stage, three phase separation takes place oil from gas from water. The water is sent to the disposal pit. The separator is protected by SIS and two safety valves. The outlet crude oil from the second stage separator is sent to the third stage separator at 30psi, in the third stage separator three phase separation takes place. The third stage separator is protected by SIS and two safety valves. The separated gas from the second and third stages is sent to a gas compression plant. Table 2 shows the separator's design and operating pressures, as well as alarms triggering pressures, the safety valves set pressures, and shutdown pressure [14].

3.3 Reliability of crude oil separator SIS

The reliability of protective systems is determined by the fractional dead time (FDT). FDT is a fraction of the time that a protective system is inactive, or the probability that it will fail to operate when required. Calculation of the FDT which is the overall PFDavg of SIS begins with use of the equations shown in Table 1. The failure rate data, CCF β factor, and the test interval used for the calculation of SIS are collected from the literature [13, 15] and summarized in Table 3.

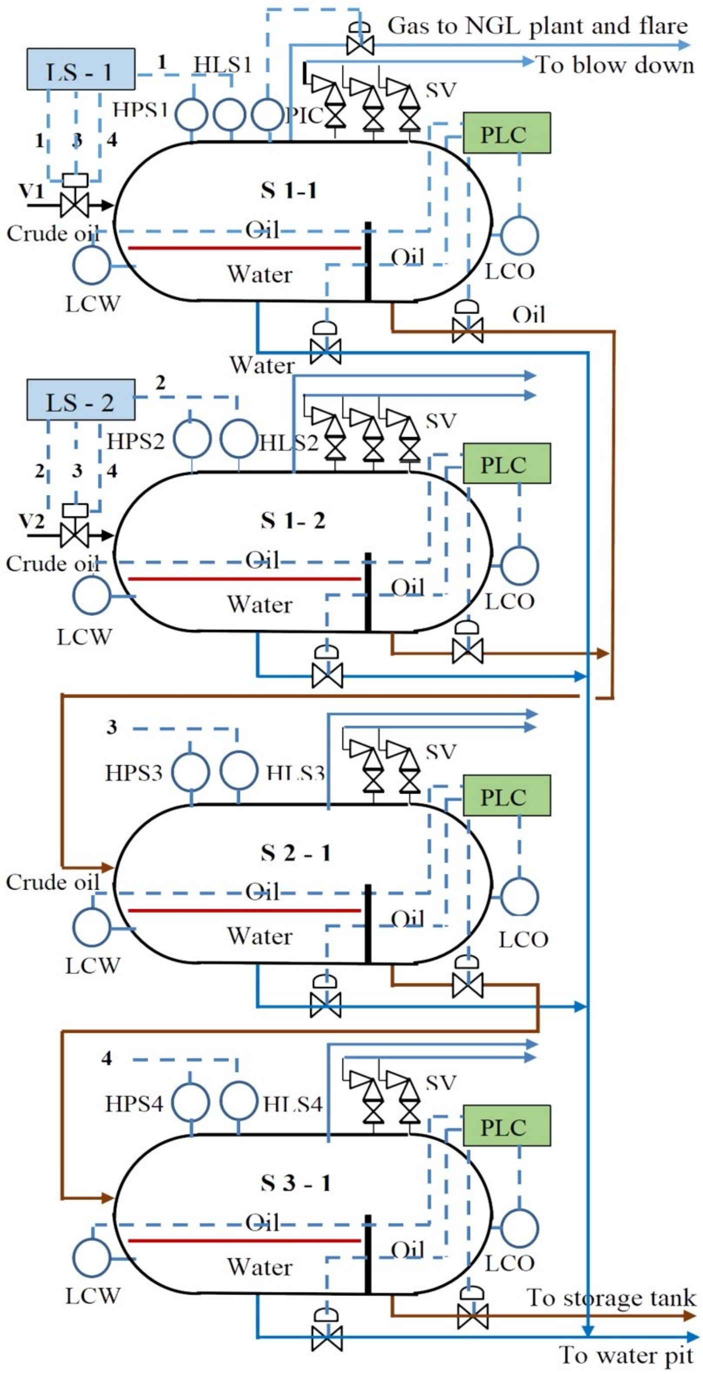

Figure 2: Train of crude oil production separators [14].

The SIS of the first stage separators S 1-1 consists of HPS1 and HLS1 sensors installed in parallel and in series with the logic solver (LS1) and actuated valve (v1). The reliability block diagram of SIS of the first stage separator is shown in Figure 3. In case the pressure or the level exceeds the design limit in the first stage separator S 1-1, the HPS-1 or HLS-1 will shut off the trip valve v1 through the LS-1. The FDT of the SIS is summarized in Table 3. The reliability of the first stage separator S 1-2 is the same as the S 1-1.

Table 2: Separators design and operating pressures

Separator	Operating pressure psi	Safety valve set pressure psi	Vessel design pressure psi	Alarm pressure psi	Shutdown pressure psi
1st stage	710	770	780	730	745
2nd stage	165	220	256	185	200
3rd stage	30	80	85	50	65

Table 3: The failure rate data.

Parameter	Pressure Transmitter	Level Transmitter	Logic solver	Actuated valve
Dangerous undetected failure rate, λ_{DU} $(hr)^{-1}$	3.4×10^{-8}	2.5×10^{-8}	8.6×10^{-8}	2.8×10^{-7}
Common cause factor, β	10%	10%	10%	5%
Proof Test Interval, *TI*	1yr (8760 hr.)	1yr (8760 hr.)	1yr (8760 hr.)	1yr (8760 hr.)

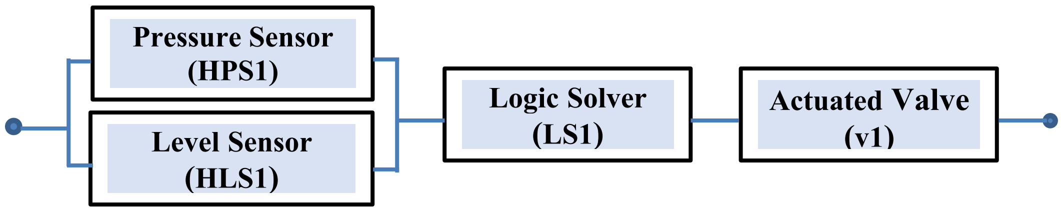

Figure 3: Reliability block diagram for SIS of first stage separator.

The level and pressure might be built up in the second and third stage separators through two cases:

In case - 1 the pressure or the level exceeds the design limit in the second stage separator S 2-1 which resulted in both first stage separators S 1-1, and S 1-2, the HPS-3 or HLS-3 will shut off the trip valves v1 and v2 through the LS-1 and LS-2. The reliability block diagram of SIS of the second stage separator is shown in Figure 4. The FDT of the SIS is summarized in Table 3.

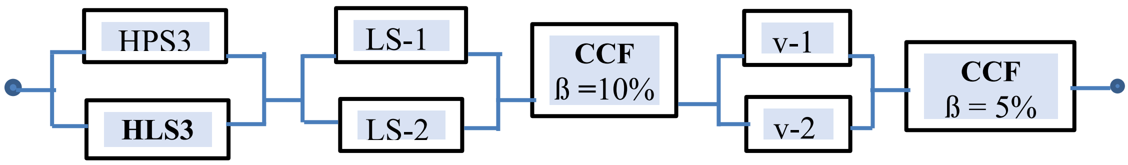

Figure 4: Reliability block diagram for SIS of second stage separator.

In case - 2 the pressure or the level exceeds the design limit in the second stage separator S 2-1 which results in either first stage separators S 1-1, or S 1-2, the HPS-3 or HLS-3 will shut off v1 or v2 through the LS-1 or LS-2. The FDT of the SIS is summarized in Table 4.

3.4 Reliability of crude oil separator safety valves

Pressure relief valves must be tested based on a regular schedule and according to a strict set of requirements. Those requirements and schedules can vary based on industry, but they can also vary depending on which organization governs the safety regulations within that industry. American Society of Mechanical Engineers (ASME) sets one of the most well-known pressure relief valve testing standards. ASME recommends that every pressure relief valve must be tested at some interval of regularity. Testing ensures valves function normally, from opening at the appropriate pressure to releasing fully when they are actuated. Typical testing frequencies are annual, every three years, every five years, and per inspection history [16].

Table 4: FDT of the SIS of crude oil separator

	First stage separators			
	Sensors	**Logic solvers**	**Isolation valves**	**Total system**
S 1-1	FDT HPS1, HLS1(1oo2)	FDT LS1(1oo1)	FDT v1(1oo1)	FDT_{system}
	2.17×10^{-8}	3.8×10^{-4}	1.2×10^{-3}	1.6×10^{-3}
S 1-2	FDT HPS2, HLS2(1oo2)	FDT LS2(1oo1)	FDT v2(1oo1)	FDT_{system}
	2.17×10^{-8}	3.8×10^{-4}	1.2×10^{-3}	1.6×10^{-3}
	Case -1 Pressure from S 1-1 & S 1-2			
S 2-1	FDT HPS3,HLS3(1oo2)	FDT LS1 &2(2oo2)	FDT v1&2(2oo2)	FDT_{system}
	2.17×10^{-8}	8×10^{-4}	2×10^{-3}	2.8×10^{-3}
S 3-1	FDT HPS4,HLS4(1oo2)	FDT LS 1&2(2oo2)	FDT v1&2(2oo2)	FDT_{system}
	2.17×10^{-8}	8×10^{-4}	2×10^{-3}	2.8×10^{-3}
	Case - 2 Pressure from S 1-1 or S 1-2			
S 2-1	FDT HPS3,HLS3(1oo2)	FDT LS 1or LS2(1oo2)	FDT v1or v2(1oo2)	FDT_{system}
	2.17×10^{-8}	3.8×10^{-5}	6.3×10^{-4}	1×10^{-4}
S 3-1	FDT HPS3,HLS3(1oo2)	FDT LS 1or LS2(1oo2)	FDT v1or v2(1oo2)	FDT_{system}
	2.17×10^{-8}	3.8×10^{-5}	6.3×10^{-4}	1×10^{-4}

Periodical test certificates have been collected and analyzed for 308 safety valves in an oil field. Visual inspection and pre-over haul test have been carried out. When a valve is first removed from the equipment, it should be given a visual inspection to check (i) the condition of flanges, for pitting, roughening, and decreases in the width of the seating surface. (ii) Springs for evidence of corrosion or cracking, and for correctness at the pressure and temperature conditions under which the valve operates. (iii) Bellows, if the valve is of the bellows type. (iv) inlet and outlet nozzles, for evidence of deposits of foreign material and corrosion.

Pre-overhaul tests have been carried out to verify the in-service performance of the safety valves. The setup used for the testing of safety valves consisted of a clamp down table suitable for several safety valve sizes. It is connected to compressed air cylinders (52 litre, 330 bar) and three high quality gauges by ½ inch tubing. The gauges are accurate and regularly calibrated. The gauges are mounted on a panel separated from the test station to eliminate inaccuracies caused by shock. The records of the pre-overhauled tests are classified and analyzed to obtain the failure rate of the safety valves. Table 5 summarizes the production separator's safety valve failure rate.

The failure rate of safety valves also has been obtained from the literature. Table 6 presents the failure rate of safety valves from internationally recognized sources.

The reliability of safety valves can be calculated using the fractional dead time (FDT) method. The reliability of safety valves may be reduced due to common cause failure. The CCF resulted from the oil deposit in the valves, human error during testing, etc. The beta factor model has been used to calculate the CCF. Stien et al [18] suggested that the beta factor for safety valves is 11%. The reliability of safety valves has been calculated with and without common cause failure. The results are summarized in Table 7.

Table 5: Production separators safety valve performance and failure rate.

Separator	Safety valves	Faults per year	Safety valve performance	
			Acceptable (+/- 10%)	Not acceptable (more than 10%)
1st stage	18	0.054	88%	12%
2nd stage	6	0.018	97%	3%
3rd stage	6	0.019	96%	4%

Table 6: Failure rate of safety valves [17].

Sources	Failure rate per yr.
OREDA (2002)	2.4E-2
OREDA (2009)	1.4E-2
OREDA (2015)	1.12E-2
Parry	4.9E-2
SINTEF	8.76E-3
UKAEA	3.72E-2

Table 7: Safety valve reliability

Test interval year	FDT of safety valve (1oo3) for Separators S 1-1, S 1-2		FDT of safety valve (1oo2) for Separators S 2-1, S 3-1	
	FDT without CCF	FDT with CCF	FDT without CCF	FDT with CCF
1	3.9E-4	5.4E-3	1.1E-4	1.0E-3
2	3.1E-4	1.1E-2	4.3E-4	2.2E-3
3	1.1E-3	1.7E-2	9.7E-4	3.7E-3
4	2.5E-3	2.4E-2	1.7E-3	5.3E-3
5	4.9E-3	3.2E-2	2.7E-3	7.2E-3
6	8.5E-3	4.1E-2	3.9E-3	9.2E-3

6. Discussion

In case of the control systems of the separators are failed to control the level and pressure this would lead to liquid carryover and overpressure of the separator. The liquid carryover from the separator has not just an impact on the flare but also jeopardizes the safety of the oil center facilities to danger due to the rain of burning droplets of crude oil. Therefore the crude oil separators should be provided with an SIS capable of isolating the source of building up of the level and pressure. The separators are provided with SIS and safety valves designed and maintained to fulfill their function when it is required. The reliability of the SIS and safety valves has been estimated. If the level or the pressure in S 1-1 exceeds the design limit, the HPS1 or HLS1 can respond and shut off the isolation valve (v1) through the logic solver (LS-1) with a reliability 0.9977 provided the system is tested every year. The same result has been obtained for S 1-2.

In case -1 the pressure or level exceeds the design limit in second stage separator S 2-1 and third stage separator S 3-1 due to the failure of control and SIS of both S 1-1 and S 1-2, the SIS of each stage S 2-1 and S 3-1 will respond to isolate the trip valves with reliability 0.9972.

In case -2 the pressure or level exceeds the design limit in second stage separator S 2-1 and third stage separator S 3-1 due to the failure of control and SIS of either S 1-1 or S 1-2, the SIS of each stage S 2-1 and S 3-1 will respond to isolate the trip valves with reliability 0.999.

Safety valves are the last line of defence to protect the separator from overpressure. First stage separators are provided with three parallel safety valves, and second and third stages separators are provided with two safety valves. The safety valves are duplicated to avoid any interruption to the process of maintenance or replacement which could be costly or unsafe. Duplicating safety valves to provide process continuity implies the use of valves to isolate one device while putting the other online.

The reliability of safety valves of first stage separators S 1-1 and S 1-2 without CCF was estimated to be 0.9996 and with CCF was 0.9946 provided the safety valves are tested every year. The reliability of safety valves of second and third stage separators without CCF was estimated to be 0.9996 and with CCF was 0.9946.

The crude oil separators were provided with reliable protection systems provided that the systems were tested regularly.

7. Conclusions

Crude oil separator plays a vital role in the separation process of the crude oil mixture in the upstream oil industry. Crude oil separator work at high pressure therefore it has to be provided with reliable control and protection systems. In this case study the crude oil separators were provided with SIS and a pressure relief system. The reliability of the SIS and safety valves has been estimated. The SIS of the separators has been designed to be redundant and diverse to meet the reliability objectives and protect the separators in case of the failure of the control system. The reliability of the SIS was found to be 0.997 provided the system is tested every year.

Although a redundant system is more reliable however the redundant system is subjected to common cause failure (CCF). The reliability of the safety valves of the separators was estimated with and without CCFs. The reliability of safety valves without CCF was found to be 0.9996 and with CCF was 0.9946. CCF can be overcome by adopting and adapting the Belt and Brace strategy.

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