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Use of hazardous event frequency to evaluate safety integrity level of subsea blowout preventer

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Abstract

Generally, the Safety Integrity Level (SIL) of a subsea Blowout Preventer (BOP) is evaluated by determining the Probability of Failure on Demand (PFD), a low demand mode evaluation indicator. However, some SIL results are above the PFD's effective area despite the subsea BOP's demand rate being within the PFD's effective range. Determining a Hazardous Event Frequency (HEF) that can cover all demand rates could be useful when establishing the effective BOP SIL. This study focused on subsea BOP functions that follow guideline 070 of the Norwegian Oil and Gas. Events that control subsea well kicks are defined. The HEF of each BOP function is analyzed and compared with the PFD by investigating the frequency for each event and the demand rate for the components. In addition, risk control options related to PFD and HEF improvements are compared, and the effectiveness of HEF as a SIL verification for subsea BOP is assessed.

Keywords: Subsea blowout preventer (BOP); Safety instrumented system (SIS); Demand rate; Probability of failure on demand (PFD); Hazardous event frequency (HEF)

1. Introduction

Following the Deepwater Horizon accident in the Gulf of Mexico, attention has focused on subsea Blowout Preventers (BOP). The subsea BOP is a safety-related instrumented system used during well drilling and well intervention operations. Management of well bore pressures to control well kicks is important because of the potential damage of such kicks to the environment. Moreover, kick control is essential to prevent kick-related accidents that may harm people and well assets. The subsea BOP plays a vital role in the mitigation of damages and the prevention of accidents.

Safety Instrumented Systems (SIS) have been used in the oil and gas industry for years in order to control and mitigate risks. The SIS, as defined by standard 61508 of the International Electrotechnical Commission (IEC 61508, 2010), is an instrumented system that can be used to implement one or more Safety Instrumented Functions (SIF). Establishment of Safety Integrity Levels (SIL) is a fundamental concept within the IEC 61508 standard. A SIL consists of four possible discrete probabilistic levels that are used to specify the safety integrity requirements of SIF, which are allocated to Safety-Related Systems (SRS). In order to allocate SIL to SRS, the IEC 61508 standard classifies SRS into those with low demand or high demand/continuous modes of operation. Based on the definitions within IEC 61508-4 (2010), the boundary between the low and high demand modes for a SIF is determined by a demand rate of one per year. The IEC 61508-4 (2010) classification is an improvement over the previous definition (IEC 61508-4, 1997), which categorized the operational mode based on both demand rate and proof test rate.

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Nomenclature

AP	Annular Preventer
A/PR	Annular and Pipe Ram
BOP	blowout preventer
BSR	Blind Shear Ram
CCF	Common Cause Failure
CV	Choke Valve
DV	Diverter Valve
DS	Diverter System
EUC	Equipment Under Control
HEF	Hazardous Event Frequency
HPU	Hydraulic Power Unit
KV	Kill Valve
MDD	Mean Demand Duration
MooN	M-out-of-N
MTBK	Mean Time Between Kicks
NOG	the Norwegian Oil and Gas
OREDA	Offshore REliabilityDAta
PDS	reliability of computer-based safety systems, Norwegian acronym
PFD	Probability of Failure on Demand
$PFD_{MooN\text{-}system}$	Probability of Failure on Demand of a system having MooN voting logic Probability of
PFH	Failure per Hour
PRP	Pipe Ram Preventer
PV	Pilot Valve
RBD	Reliability Block Diagram
SIF	Safety instrumented function
SIL	Safety Integrity Level
SIS	Safety instrumented system
SRS	Safety-Related System
SV	drill string Safety Valve
TCS	Topside Control System
TPB	Topside Push Button
$\lambda_{component}$	failure rate of a component
λ_{de}	demand rate
$(\lambda_{de})_{system}$	demand rate of a system
λ_{DU}	rate of Dangerous Undetected failure
λ_{kick}	frequency of a subsea well kick
τ	test interval
$\tau_{interval}$	test interval having an ‘interval’ period

As a result of this definition change, categorization of a SIS became easier. However, the validity of SIS evaluating parameters over the demand rate range remained unclear. The SIS evaluating parameters give single representative values for low and high demand mode, regardless of the actual demand rate; thus, if a SIS is classified as in the low or high demand mode, then its demand rate is not considered during evaluation; moreover, demand rate effects are not reflected within that evaluation. In addition, different evaluation approaches for the two modes may lead to distinct SIL results at the boundary between the two demand rates. A slight gap in the demand rate near a SIS boundary can result in a markedly different evaluation. Moreover, how well industry representatives comply with applying such evaluations is unclear. For example, industry representatives may just follow rules or guides without analyzing the SIS demand rate during field development.

The subsea BOP is a SIS employed during drilling of a subsea well and is comprised of multiple redundant components that perform the same task. The subsea BOP is considered to function in the low demand rate mode and is evaluated by using the Probability of Failure on Demand (PFD) method, a standard SIS evaluation method for equipment in the low demand mode. Recent research (Cai et al., 2012a, b) has evaluated the performance of subsea BOP under the premise that they are in the low demand mode. Kim et al. (2014) applied demand rates when evaluating BOP performance by using a Markov model, but that study did not include a SIS evaluation of BOP function. According to guideline 070 of the Norwegian Oil and Gas (NOG 070, 2004), the SIL evaluation method proposes a standard that provides minimal satisfaction for two subsea BOP functions. However, a more realistic method of analysis is necessary because some BOP components that operate different functions are not independent. Moreover, some BOP components that undergo repetitive usage for different function operate in the high demand rate mode. Thus, the subsea BOP's demand rate is mostly within the PFD's effective range, but some components have a demand rate that is outside the PFD's effective range.

Even though there is a demarcation point between low and high demand modes for a SIS, the SIS evaluation parameters PFD and Probability of Failure per Hour (PFH) may not reflect the actual situation, especially near the borderline between the two modes. To overcome this limitation, Misumi and Sato (1999) proposed using a Hzardous Event Frequency (HEF) evaluation method, which considers both demand rate and demand duration when evaluating a SIS. Bukowski (2006) suggested a relatively simple SIS model that incorporated a process demand into a fail dangerous state (PFDPRS; i.e., the probability of being in a state of fail that is dangerous and at which the process requires to be shut down), an approach that showed the effect of process demand on SIS performance. Innal et al. (2010) researched the characteristics of PFH, which lies in the same domain as HEF. Liu and Rausand (2011) researched on reliability assessment of SIS to different demand modes with concept of hazardous events. Jin et al. (2011) stated that a scenario-based formula (i.e., an analytic solution of HEF) for a single component supported the HEF results obtained from PFD for the low demand mode and the HEF results obtained from PFH for the high demand mode. They also showed that a Markov model, which considered demand rate and demand duration, produced results that supported the results from a scenario-based formula. However, further HEF research is needed because industry representatives have become familiar with the PFD and PFH concepts, but not with the use of HEF.

In this paper, the use of HEF as a SIS evaluation parameter is proposed as an alternative to using PFD at demand rates near the boundary between the low and high demand modes. The comparison of HEF and PFD results required confirmation that the SIL range for PFH could be used as a HEF-based SIL range. The validity of HEF as the SIS evaluation parameter was examined by assessing two subsea BOP functions that are defined in NOG 070 (2004).

The remaining portions of this paper are organized as follow. In section two, equations presenting various voting logics for PFD, PFH, and HEF are defined. A range for HEF is proposed for each SIL. Section three defines two functions of an NOG 070 subsea BOP, and the components used in the analyses are clarified. The events occurring from a subsea well kick during the drilling operation are defined by using event tree analysis. Section four evaluates and compares two subsea BOP functions by using PFD and HEF analyses. Moreover, PFD is investigated for all events. The demand rate of the events and the components of the subsea BOP are derived from the PFD results of the two events and are used to assess the HEF results. In addition, the PFD, HEF, and PFH results for two subsea BOP functions are compared and there is a discussion of their limitations. In section five, risk control options related to both PFD and HEF are proposed. Also, configurations that assign a pod to each function are discussed in section six. Finally, section seven concludes the paper.

2. SIS evaluation

2.1. PFD and PFH for MooN voting logic (PDS method)

A SIS can operate in two modes depending on the demand rate. If the demand rate is less than one per year, the SIS is in the low demand mode and PFD can be used to evaluate the SIS. For a system that incorporates the MooN (M-out-of-N) voting logic, the use of PFD as an evaluation tool falls within the PDS method (a Norwegian acronym indicating the reliability of computer-based safety systems, Hauge et al., 2010), which was developed for quantification of the reliability and availability of the SIS. Based on the MooN voting logic,

$$PFD_{MooN} = C_{MooN} \cdot \beta \cdot \lambda_{DU} \cdot \tau/2 + N!/ \times \{(N-M+2)! \cdot (M-1)!\} \cdot (\lambda_{DU} \cdot \tau)^{N-M+1}, \quad (1)$$

where λ_{DU} is the dangerous undetected failure rate, τ is the test interval, and the MooN voting ($M < N$) indicates that at least M modules of N components should be operated normally. When considering the common cause failure for the various voting, the modifier C_{MooN} is in Table 1.

A SIS demand rate of more than one per year is indicative of the high demand mode, and in that case, PFH is used to evaluate the SIS. The PDS method defines PFH which is used as the high demand mode's standard method of evaluation for the MooN voting logic as

Table 1
C_{MooN} factors for different voting logics (Hauge et al., 2010).

C_{MooN}	N = 1	N = 2	N = 3	N = 4	N = 5	N = 6
M = 1	–	1.0	0.5	0.3	0.21	0.17
M = 2	–	–	2.0	1.1	0.7	0.4
M = 3	–	–	–	2.9	1.8	1.1
M = 4	–	–	–	–	3.7	2.4
M = 5	–	–	–	–	–	4.3

$$PFH_{MooN} = C_{MooN} \cdot \beta \cdot \lambda_{DU} + N!/ \times \{(N-M+1)! \cdot (M-1)!\} \cdot \left\{(\lambda_{DU} \cdot \tau)^{N-M+1}/\tau\right\}. \quad (2)$$

2.2. HEF

The HEF is calculated as the average frequency of hazardous events per hour (Rausand, 2014). Hazardous events occur when a SIS fails to deliver its function at the moment that function is demanded. When a SIS has failed and the SIS is demanded or when a SIS is demanded and the SIS does not actuate, a hazardous event occurs. However, if a SIS has failed, but there is no actuation demand, then no hazardous event occurs.

To estimate HEF accurately, situations that can happen to a SIS have to be identified, and equations must be developed that represent each situation, as suggested by Misumi and Sato (1999); however, their approach is cumbersome. The Markov model, which can be used to express various states of a system, can also be used to determine HEF (Jin et al., 2011; Kim et al., 2014; Liu and Rausand, 2011). However, further researches into various voting logics are needed if the Markov model is to be used for a complicated system. Rausand (2014) defined HEF where demand has no duration in a low demand SIF as

$$HEF_{MooN} = PFD_{MooN} \cdot \lambda_{de}. \quad (3)$$

This equation determines the frequency of dangerous situation from a SIS failure when a safety-critical system with PFD_{MooN} is required to perform its function at a demand rate of λ_{de}. Rausand (2014) also introduced a method to obtain HEF by considering Mean Demand Duration (MDD) as represented by

$$HEF \approx \left(PFD_{avg} + \overline{\lambda}^{*}_{SF} \cdot MDD\right)\lambda_{de}, \quad (4)$$

where $\overline{\lambda}^{*}_{SF}$ is the average dangerous failure rate of a SIF during a function-demanded situation and can be regarded as PFH. This failure rate is usually higher than the normal condition failure rate, λ, because the SIS is being exposed to a more severe condition. However, in this paper, this term is not considered due to an absence of information on $\overline{\lambda}^{*}_{SF}$ and the MDD of the subsea BOP components.

2.2.1. SIL range for HEF

As the demand rate increases, it is more likely that the system is under demand when a SIS failure occurs and the PFH is therefore a good measure for HEF (Rausand, 2014). In such a case, SIS failure in the high demand mode will lead to an immediate hazardous event. The boundary of both low and high demand modes is less than one per year or not, and a demand rate of one per year is equivalent to a demand rate of approximately 1.14e−4 per hour. Therefore, the SIL range for PFD becomes equal to the SIL range for PFH when the SIL range for PFD is multiplied by the demand rate of approximate 1e−4 per hour (Fig. 1).

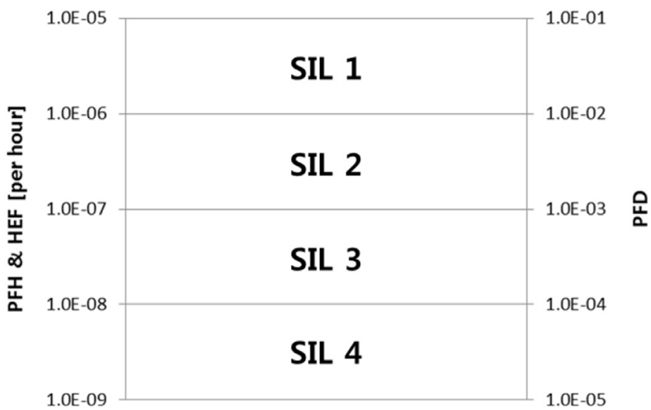


Fig. 1. SIL range for PFH, PFD and HEF.

Thus, the frequency of hazardous events due to failure of a low demand mode SIS component is similar to the frequency obtained by multiplying the PFD and the demand rate (Jin et al., 2011). In addition, HEF has a range of values similar that of PFH. Therefore, it is reasonable to evaluate HEF by applying the SIL range for PFH, as shown in Fig. 1, since HEF is derived by multiplying the PFD and the demand rate.

3. Subsea BOP configuration and input data

The subsea BOP functions as well-controlling equipment with an important role as a safety barrier when a subsea well is being explored or developed. According to NOG 070 a subsea BOP has two SIF and they require a minimum SIL 2 safety approach (Table 2).

The NOG 070 also indicates that to set the requirement level at SIL 3 for two SIF of a subsea BOP would result in the need to change the existing control system, and it would be necessary to include additional rams in the standard BOP assembly. Because of challenges associated with such additional requirements, the two SIF of a subsea BOP should meet the minimum SIL 2 requirements.

In this section, the SIL of the Annular and Pipe Ram (A/PR) function and the Blind Shear Ram (BSR) function of a subsea BOP were evaluated through the application of both PFD and HEF in order to determine whether the HEF approach would meet NOG 070 requirements.

3.1. Subsea BOP configuration and well control procedure

A subsea BOP selected for the analysis is the Class VI BOP stack which has two annular preventers, one BSR preventer, and three pipe ram preventers (Fig. 2 (a)). It is usually designed for well operations requiring 10–15,000 psi pressure containing capabilities and tapered work strings (WEST E. S., 2009). Above sea level, there is an annular diverter system that can seal the well annulus and a diverter valve that can release hydraulic pressure to keep the internal pressure of the drilling riser under normal conditions. Above the drill string, there is a safety valve that can seal the drill string annulus. Moreover, on the topside there are push buttons on the driller's and tool pusher's consoles that can send input commands to all components (Cai et al., 2012a). The driller and tool pusher consoles have the same roles, but they may send commands differently. Input commands.usually installed redundantly because that system should guarantee high system reliability. Thus, the control system is deemed redundant in this paper.

Table 2
Minimum SIL requirements – drilling related safety functions (NOG 070, 2004).

Safety function	SIL	Functional boundaries for given SIL requirement/comments
Drilling BOP function	2	Annular/pipe ram (A/PR) function
Closing of relevant		- Seal around drill pipe
BOP valve(s)	2	Blind shear ram (BSR) function
in order to prevent blowout		- Seal an open hole
and/or well leak		- Shear drill pipe and seal off well

Fig. 2 (b) shows the components and component routing related to the A/PR and BSR functions. The push-button system, the control system, and the two pods are used in common for those two functions even though they are SIS elements that are usually functionally independent.

In general, when a subsea well kick occurs during drilling, the events and procedures shown in Fig. 3 (Hauge et al., 2012) are undertaken to control the well kick. Table 3 provides details for each event shown in Fig. 3.

The subsea BOP A/PR function seals the annulus around the drill pipe and is event 2 in Table 3 (events 2A and 2B). The BSR function covers the hole and seals the well by cutting the drill pipe and is event 5 in Table 3 (events 5A and 5B). Event 2 is subdivided into 2A and 2B depending on the location of the hydrocarbons, whereas event 5 is subdivided depending on whether there is flow inside the BOP. However, these subsea BOP functions, as described in NOG 070, are the same regardless of hydrocarbon location or flow inside the BOP.

3.2. Input data for SIL evaluation

The input data used for the analyses are listed in Table 4. WEST E. S. (2009) mentioned that there were no correlations between failure rates and water depth. The failure rate data for the safety valve and the diverter valve installed topside exclude data for the pilot valve (Hauge and Onshus, 2010). The failure rate of the pilot valve is used during evaluation of the safety and diverter valves. The annular preventer is generally used as part of the diverter system, and the diverter system's failure rate is assumed to be the same as that of the annular preventer. The failure rate of the pod is based on a Multiplex Electro-Hydraulic (MUX) type controller that receives an electric signal from topside and activates a hydraulically powered actuator valve.

The common cause failure was considered using the beta factor model. The most important thing of using the beta factor model is what value is used for the beta factor. Hauge et al. (2015) suggested the beta factor based on field experience for several SIS components. However, the research on the beta factors for the subsea BOP components has not developed well, so the well-known existing methods were used to obtain the beta factors. The beta factors for the topside push button

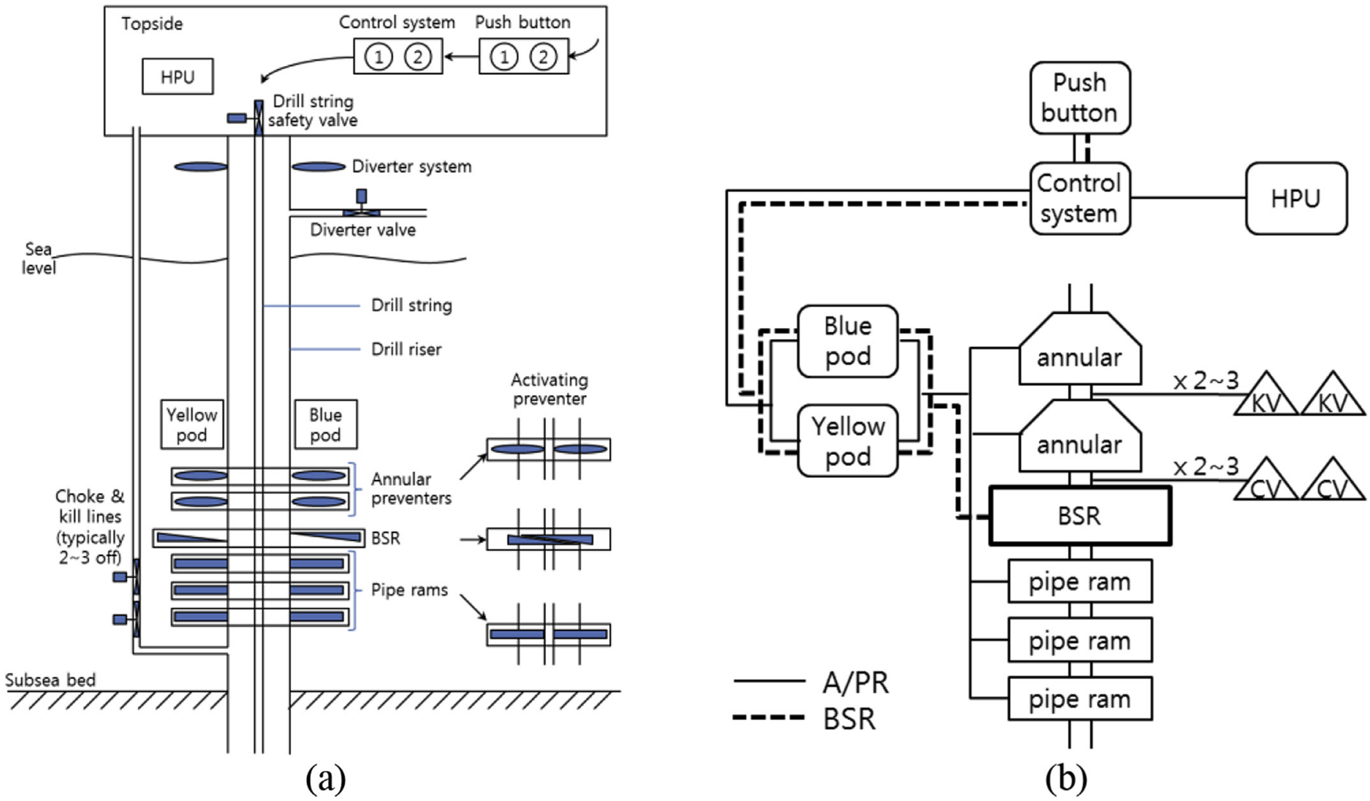


Fig. 2. Subsea BOP components classification. (a) schematic subsea BOP configuration; (b) functional classification of simplified subsea BOP structure (the solid line is the function of the annulus and the pipe ram preventer (referred as A/PR) and the dash line is the function of the blind shear ram preventer (referred as BSR)).

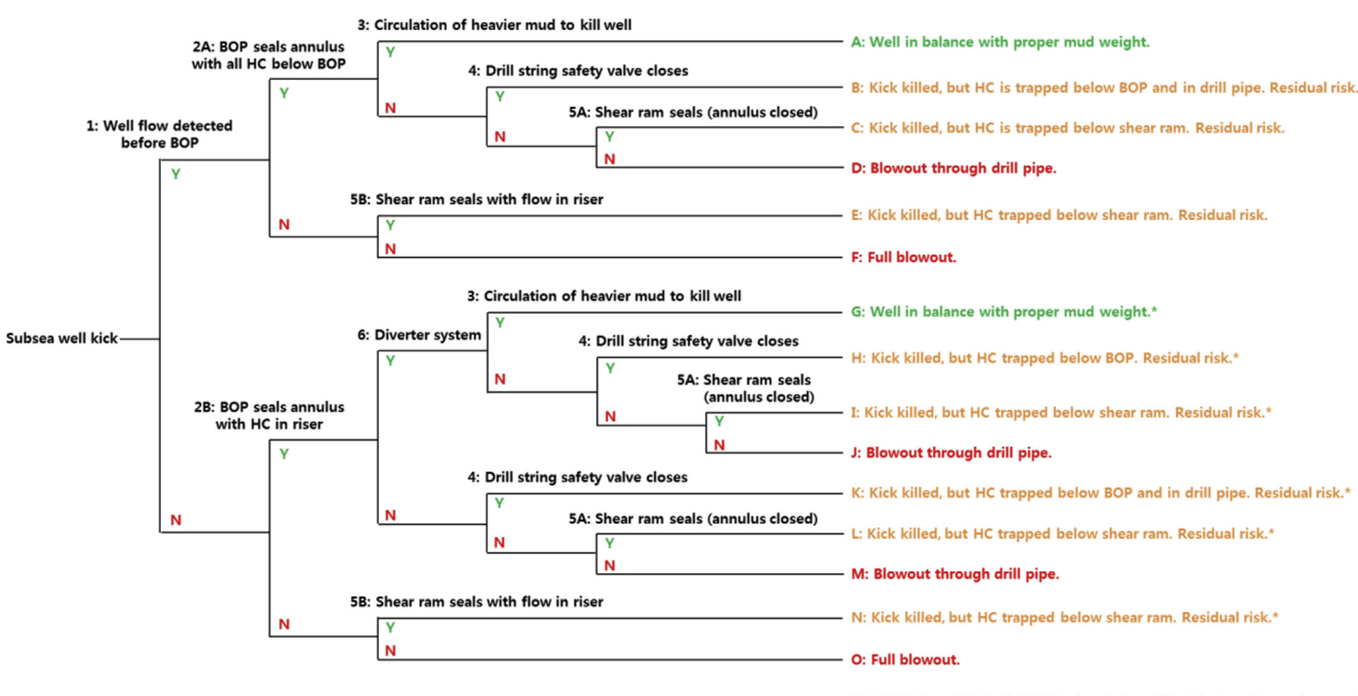


Fig. 3. Event tree for subsea well kick control (Hauge et al., 2012).

and the topside control system were referred by Hauge and Onshus (2010). The beta factors for the pod, the annular/pipe ram preventer and the choke and kill valve were estimated by IEC 61508-6 Annex D (2010).

The function test is based on NORSOK D-010 Annex A (2004). In the case of the pod and A/PR preventer, a test at 70% of working pressure is performed every 6 months. A working pressure test of the BSR preventer is performed every

Table 3
Event description of Fig. 3 (Hauge et al., 2012).

No.	Event
1	Hydrocarbon inflow is detected before it reaches BOP (early kick detection)
2A	BOP seals annulus with all hydrocarbons(HC) below BOP (i.e. given successful kick detection)
2B	BOP seals annulus with flowing hydrocarbons in riser (i.e. early kick detection has failed)
3	Mud with appropriate weight is pumped into well and the choke lines vent gas and light mud from well
4	Drill string safety valve closes drill string
5A	Shear ram cuts and seals well − no flow through BOP
5B	Shear ram cuts and seals well − flow through BOP
6	The diverter valve opens to vent gas and mud away from installation

Table 4
Input data for PFD calculation.

Component	Failure rate, λ [per 10^f hour]	CCF beta factor, β [%]	Test interval, τ[a]
Topside push button	0.4[b]	3[b]	Each 6 months (perfect test)
Topside control system	4.9[b]	7[b]	
Drill string safety valve (ex. pilot)	2.1[b]	−	
Diverter system	11.2[f]	−	
Diverter valve (ex. pilot)	2.1[b]	−	
Pilot valve	0.8[b]	−	
Hydraulic power unit	0.9[c]	−	
Choke and kill valve	0.4[d]	5[e]	
Pod (MUX)	104.7[d]	5[e]	
Annular preventer	11.2[d]	5[e]	
Pipe ram preventer	6.5[d]		
BSR preventer	5.4[d]	−	

[a] Hauge et al. (2012).
[b] Hauge and Onshus (2010).
[c] OREDA (2009).
[d] WEST E. S. (2009).
[e] IEC 61508-6 Annex D (2010).
[f] Assumption from annular preventer[d].

6 months. It is assumed that all components used in analysis are tested every 6 months regularly and the test is the perfect test which means all failure are detected during the 6 months interval test.

4. PFD and HEF of subsea BOP

4.1. PFD calculation

The PFDs of events 1 and 3 were obtained from previously reported data (Hauge et al., 2012), whereas the PFDs of events 2, 4, 5, and 6 were derived from input data. Operational failure for events 2 and 5 also used previously reported data (Hauge et al., 2012). To evaluate the PFD for events 2, 4, 5, and 6, Reliability Block Diagrams (RBD) were constructed for each event. The CCF block is belonging to the following redundant components. The RBD for event 2 is shown in Fig. 4. To control well kick, a command is inputted by push buttons on topside. The command is delivered through control systems and final elements are activated. The pods receive the signal from the control system and activate annular preventers or pipe ram preventers. Two annular preventers can be used at the same time according to circumstances. However, one pipe ram preventer is usually used to perform the A/PR function even though three pipe rams are installed in the subsea BOP. Two variable bore ram preventers which can be used for various diameters of pipes and one fixed ram preventer which can be used for only one pipe diameter are generally equipped in the subsea BOP. The lowest pipe ram preventer is used for the subsea BOP test and the middle and upper pipe ram preventers are used for the well kick control. However, the pipe ram preventers seldom activate at the same time because the sealing bore size ranges of preventers are different even though they are the variable bore ram preventers. The hydraulic power unit supplies the hydraulic power to the annular preventers to keep sealing the annulus when the annular preventers activate. The choke and kill valves are equipped to depressurize or to pressurized the annulus pressure.

The PFD of each of the components is

$$PFD_{1oo2\text{-}TPB} = \beta_{TPB}\cdot\lambda_{TPB}\cdot\tau/2 + (\lambda_{TPB}\cdot\tau)^2/3 = 2.730e-5, \quad (5)$$

$$PFD_{1oo2-TCS} = \beta_{TCS}\cdot\lambda_{TCS}\cdot\tau/2 + (\lambda_{TCS}\cdot\tau)^2/3 = 9.047e-4, \quad (6)$$

$$PFD_{1oo1-HPU} = \lambda_{HPU}\cdot\tau/2 = 1.971e-3, \quad (7)$$

$$PFD_{1oo2-Pod} = \beta_{Pod}\cdot\lambda_{Pod}\cdot\tau/2 + (\lambda_{Pod}\cdot\tau)^2/3 = 8.157e-2, \quad (8)$$

$$PFD_{1oo3-A/PR} = C_{1oo3}\cdot\beta_{A/PR}\cdot\lambda_{A/PR}\cdot\tau/2 + \left(\lambda_{A/PR}\cdot\tau\right)^3/4 = 5.286e-4, \quad (9)$$

$$\lambda_{A/PR} = \left((\lambda_{AP})^2\cdot(\lambda_{PRP})\right)^{(1/3)}, \quad (10)$$

and

$$PFD_{1oo2-CV} = PFD_{1oo2-KV} = \beta_{CV}\cdot\lambda_{CV}\cdot\tau/2 + (\lambda_{CV}\cdot\tau)^2/3 = 4.381e-5, \quad (11)$$

where $PFD_{1oo2\text{-}TPB}$, β_{TPB} and λ_{TPB} are the PFD, the beta factor and the failure rate, respectively, of the redundant topside Push-Button System (TPB), and $PFD_{1oo2\text{-}TCS}$, β_{TCS} and λ_{TCS} are the PFD, the beta factor and the failure rate, respectively, of the redundant Topside Control System (TCS). $PFD_{1oo1\text{-}HPU}$ and λ_{HPU} are the PFD and the failure rate, respectively, of the Hydraulic Power Unit (HPU). $PFD_{1oo2\text{-}Pod}$, β_{Pod} and λ_{Pod} are the PFD, the beta factor and the failure rate, respectively of a pod system having blue and yellow pods. $PFD_{1oo3\text{-}A/PR}$, C_{1oo3},

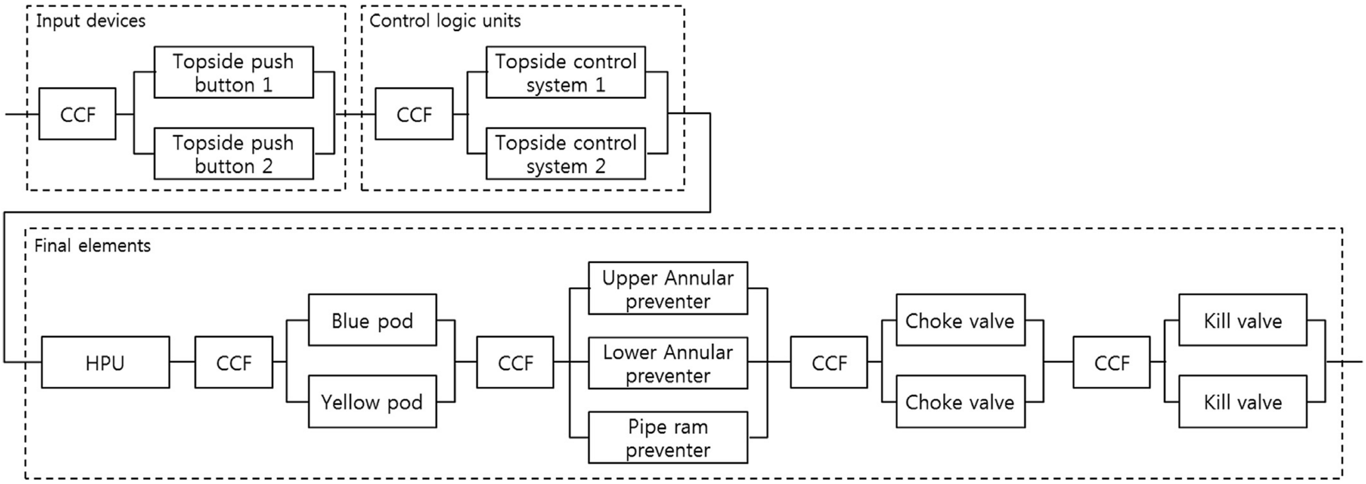


Fig. 4. Reliability block diagram for event 2 (A/PR function).

$\beta_{A/PR}$ and $\lambda_{A/PR}$ are the PFD, the modifier, the beta factor and the failure rate, respectively, of the two annular preventers and the one pipe ram preventers, whereas λ_{AP} and λ_{PRP} are the failure rates of an annular preventer and a pipe ram preventer, respectively. Considering that the system is composed of different components, which are performing the same function, the representative failure rate in Eq. (10) can be obtained from the work reported by Hauge et al. (2012). $PFD_{1oo2\text{-}CV/KV}$, β_{CV} and λ_{CV} are the PFD, the beta factor and the failure rate, respectively, of the redundant choke and kill valves (CK, VK). By adding each of the PFD values, the PFD_{E2} for sealing annulus of event 2 (E2) is

$$PFD_{E2} = PFD_{1oo2-TPB} + PFD_{1oo2-TCS} + PFD_{1oo1-HPU} + PFD_{1oo2-Pod} + PFD_{1oo3-A/PR} + PFD_{1oo2-CV} + PFD_{1oo2-KV} = 8.508e-2. \quad (12)$$

The RBD for event 4, that is, the closing of the drill string annulus via the safety valve, is shown in Fig. 5. After the annulus is sealed by A/PR function, the safety valve is activated to seal the inside of the drill pipe. The command from the topside push buttons is delivered through the topside control system to the safety valve.

The PFD of event 4, PFD_{E4}, is given by

$$PFD_{1oo1-PV} = (\lambda_{PV} \cdot \tau)/2 = 1.752e-3, \quad (13)$$

$$PFD_{1oo1-SV} = (\lambda_{SV} \cdot \tau)/2 = 4.599e-3, \quad (14)$$

and

$$PFD_{E4} = PFD_{1oo2-TPB} + PFD_{1oo2-TCS} + PFD_{1oo1-PV} + PFD_{1oo1-SV} = 7.283e-3, \quad (15)$$

where $PFD_{1oo1\text{-}PV}$ and λ_{PV} are the PFD and the failure rate, respectively, of the Pilot Valve (PV) of the drill string safety valve, and $PFD_{1oo1\text{-}SV}$ and λ_{SV} are the PFD and the failure rate, respectively, of the drill string Safety Valve (SV).

The RBD for event 5 is shown in Fig. 6. The BSR preventer acts a role as the last safety barrier when all of the primary safety measures fail. The BSR preventer cuts the drill sting and seals the well bore. The command from the topside push buttons is delivered through the topside control system to the pods to make BSR preventer activate.

Herein, the PFD for event 5 (PFD_{E5}), that is, cutting the drill string and sealing the well with a BSR preventer, is

$$PFD_{1oo1-BSR} = (\lambda_{BSR} \cdot \tau)/2 = 1.183e-2, \quad (16)$$

and

$$PFD_{E5} = PFD_{1oo2-TPB} + PFD_{1oo2-TCS} + PFD_{1oo2-Pod} + PFD_{1oo1-BSR} = 9.432e-2, \quad (17)$$

where $PFD_{1oo1\text{-}BSR}$ and λ_{BSR} are the PFD and the failure rate, respectively, of the BSR preventer.

The RBD for event 6 is shown in Fig. 7. The diverter system releases the hydrocarbon inside the riser to depressurize before the hydrocarbon reaches the topside. When the command from the topside push buttons delivered through the topside control.system to the diverter system, the diverter seals the annulus and the diverter valve is open to release the hydrocarbon through the bypass.

The PFD for activation of the diverter system for the event 6, PFD_{E6}, is

$$PFD_{1oo1-DS} = (\lambda_{DS} \cdot \tau)/2 = 2.453e-2, \quad (18)$$

$$PFD_{1oo1-DV} = (\lambda_{DV} \cdot \tau)/2 = 4.599e-3, \quad (19)$$

and

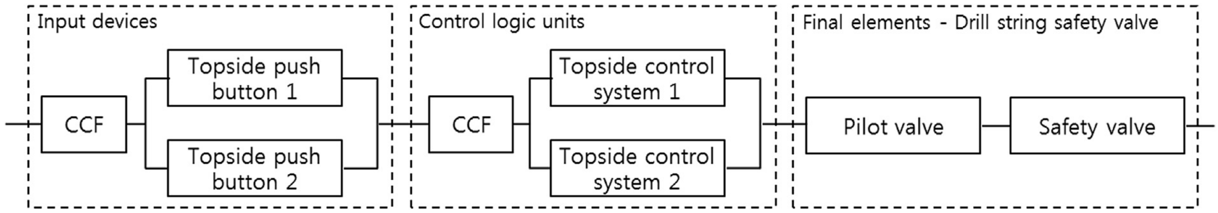


Fig. 5. Reliability block diagram for event 4.

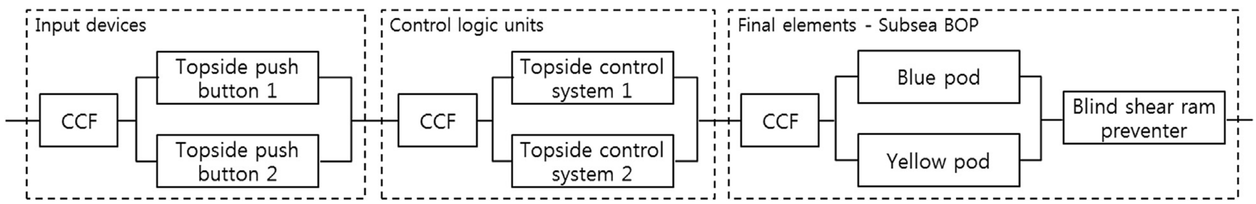


Fig. 6. Reliability block diagram for event 5.

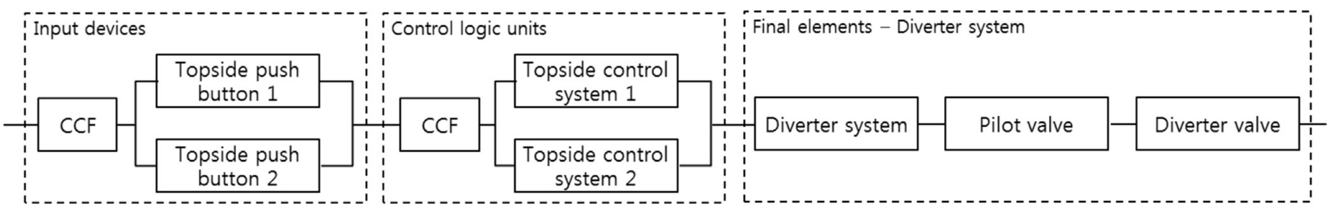


Fig. 7. Reliability block diagram for event 6.

$$\begin{aligned}PFD_{E6} &= PFD_{1oo2-TPB} + PFD_{1oo2-TCS} + PFD_{1oo1-DS} \\ &\quad + PFD_{1oo1-PV} + PFD_{1oo1-DV} \\ &= 3.181e-2,\end{aligned} \quad (20)$$

where $PFD_{1oo1\text{-}DS}$ and λ_{DS} are the PFD and the failure rate, respectively, of the diverter system (DS), and $PFD_{1oo1\text{-}DV}$ and λ_{DV} are the PFD and the failure rate, respectively, of the Diverter Valve (DV).

The PFD values for each event obtained through the above equations are listed in Table 5. A previously reported value (Hauge et al., 2012) was used for events 1 and 3. According to Hauge et al. (2012), operator failure was considered as the source of event 2. When hydrocarbons pass the riser through the BOP (i.e., event 2B), an operator's stress level may increase, which can result in a higher probability of failure. Similarly, it is difficult to undertake event 5 at the right location along the drill string if the flow is within the BOP (i.e., event 5B). As a result, the probability of operator failure is higher than when there is no flow in the BOP (i.e., event 5A). To determine the total PFD of all events, the PFDs of each event should be added (Table 5).

Table 5
PFD for events.

Event no.	PFD	Note (Hauge et al., 2012)
1	(0.05)	Statistically
2A	0.0851+(0.01) = 0.0951	operator failure
2B	0.0851+(0.05) = 0.1351	operator failure (more stressful)
3	(0.2)	Statistically
4	0.0073	
5A	0.0943+(0.05) = 0.1443	failure to hit a tool joint
5B	0.0943+(0.1) = 0.1943	failure to adjust the position (more stressful)
6	0.0318	

4.2. Demand rate and HEF of a subsea BOP

The frequency of occurrence of a kick taking place during development of an oil well is indicated by the Mean Time Between Kicks (MTBK). According to Holand (2001), in the US Gulf of Mexico and outer continental shelf area, one kick occurs every 111 days of BOP operation. Based on those data, the frequency of a subsea well kick, λ_{kick}, is

$$\lambda_{kick} = 1/MTBK = 1/(111 * 24) = 3.75e-4[\text{per hour}]. \quad (21)$$

The frequency of a subsea well kick and the PFD of each of the events presented in Table 5 were used to construct Fig. 8.

From the probabilities presented in Fig. 8, the demand rate of each event can be investigated. For example, the frequency of occurrence of event 2A can be obtained as following

$$\begin{aligned}(\lambda_{de})_{2A} &= \lambda_{kick}\cdot 1(Y) = \lambda_{kick}\cdot 0.95 = 3.56e-4[\text{per hour}] \\ &= 3.12[\text{per year}],\end{aligned} \quad (22)$$

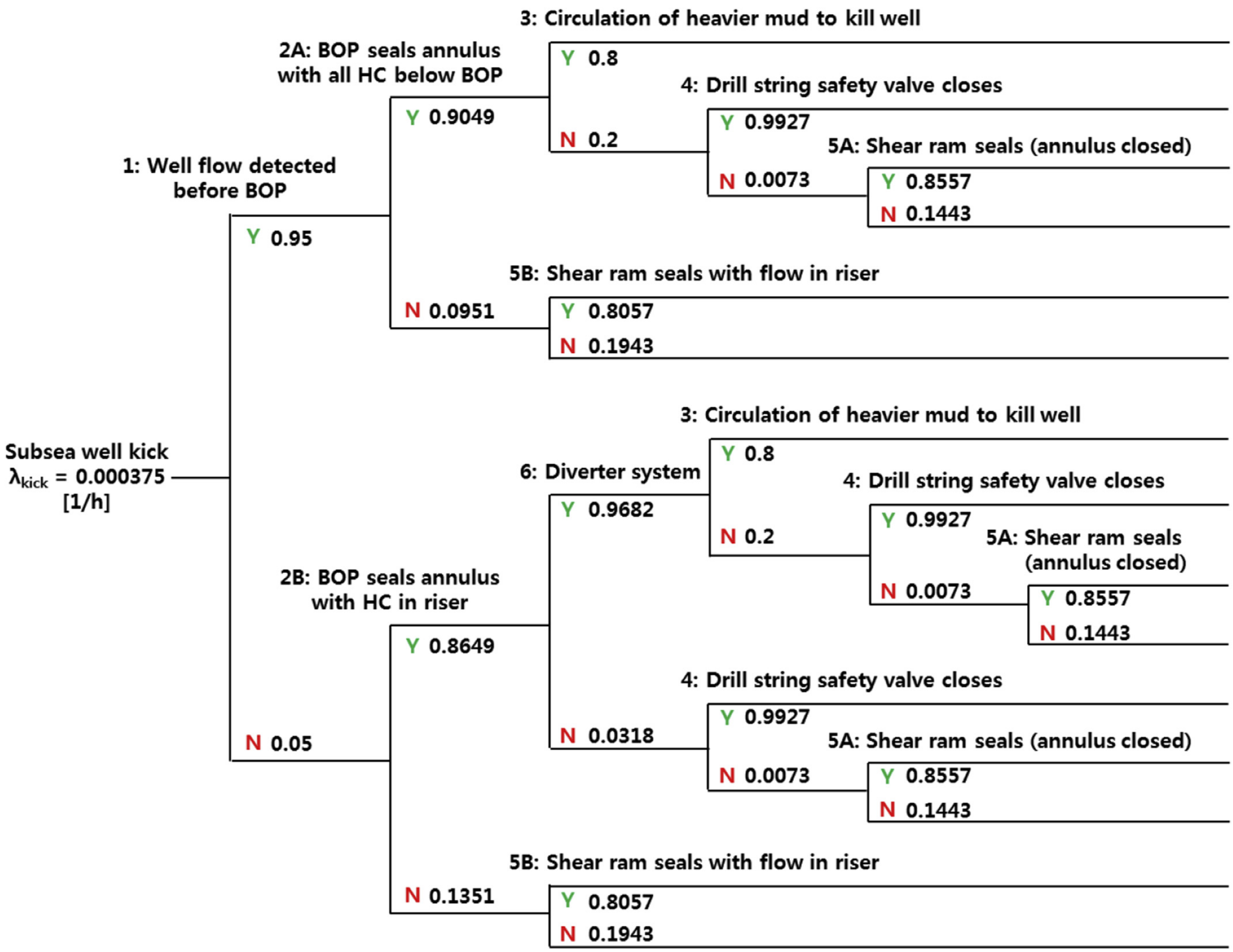


Fig. 8. Frequency of subsea well kick and probabilities of events for subsea well kick control.

where $(\lambda_{de})_{2A}$ is the demand rate for event 2A. The occurrence frequency of event 2A is equal to the demand rate of event 2A. Similarly, the demand rates for two functions of the subsea can be determined from the data in Fig. 8 and are shown in Table 6. Five scenarios were identified to require the A/PR function and BSR function together. The demand rate for each function was different for each scenario.

The scenarios no. 1 and 2 show that the demand rate of the A/PR function is bigger than one per year which is the boundary of the low and high demand mode in IEC 61508 (2010). It was found that the demand mode of the A/PR function was changed by the scenario.

The scenario no. 2 could be happened more frequently than other scenarios in Table 6. The demand rates of each of the components for the analysis were obtained from the scenario no. 2 of Table 6 and were listed in Table 7.

Based on the PFD and demand rate, the subsea BOP HEF values for the A/PR function (i.e., event 2) and the BSR function (i.e., event 5), are obtained by applying Eq. (3). The HEF results are thus obtained by

Table 6
Demand rate for BOP functions.

No.	Scenario	A/PR function (Event 2) (2A or 2B)		BSR function (Event 5) (5A or 5B)		Percentage [%]
		Demand rate, λ_{de} [per hour]	Demand rate, λ_{de} [per year]	Demand rate, λ_{de} [per hour]	Demand rate, λ_{de} [per year]	
1	kick → 1(Y) → **2A**(Y) → 3(N) → 4(N) → **5A**	3.56E−04	3.12	4.71E−07	4.1E−03	1.3
2	kick → 1(Y) → **2A**(N) → **5B**	3.56E−04	3.12	3.39E−05	3.0E−01	91.8
3	kick → 1(N) → **2B**(Y) → 6(Y) → 3(N) → 4(N) → **5A**	1.88E−05	0.16	2.29E−08	2.0E−04	0.1
4	kick → 1(N) → **2B**(Y) → 6(N) → 4(N) → **5A**	1.88E−05	0.16	3.76E−09	3.3E−05	0.0
5	kick → 1(N) → **2B**(N) → **5B**	1.88E−05	0.16	2.53E−06	2.2E−02	6.9

$$\begin{aligned}HEF_{E2} &= PFD_{1oo2-TPB}\cdot(\lambda_{de})_{TPB} + PFD_{1oo2-TCS}\cdot(\lambda_{de})_{TCS} + PFD_{1oo1-HPU}\cdot(\lambda_{de})_{HPU} + PFD_{1oo2-Pod}\cdot(\lambda_{de})_{Pod} + PFD_{1oo3-A/PR}\cdot(\lambda_{de})_{A/PR}\\ &\quad + PFD_{1oo2-CV}\cdot(\lambda_{de})_{CV} + PFD_{1oo2-KV}\cdot(\lambda_{de})_{KV}\\ &= 9.727e-9 + 3.223e-7 + 7.022e-7 + 2.906e-5 + 1.883e-7 + 1.561e-8 + 1.561e-8 = 3.031e-5\end{aligned} \tag{23}$$

and

$$\begin{aligned}HEF_{E5} &= PFD_{1oo2-TPB}\cdot(\lambda_{de})_{TPB} + PFD_{1oo2-TCS}\cdot(\lambda_{de})_{TCS} + PFD_{1oo2-Pod}\cdot(\lambda_{de})_{Pod} + PFD_{1oo1-BSR}\cdot(\lambda_{de})_{BSR},\\ &= 9.727e-9 + 3.223e-7 + 2.906e-5 + 4.007e-7 = 2.979e-5\end{aligned} \tag{24}$$

Table 7
Demand rate for components.

Component	Demand rate, λ_{de} [per hour]
Topside push button, $(\lambda_{de})_{TSB}$	3.56e−4 (=$(\lambda_{de})_{E2}$)
Topside control system, $(\lambda_{de})_{TCS}$	3.56e−4 (=$(\lambda_{de})_{E2}$)
Hydraulic power unit, $(\lambda_{de})_{HPU}$	3.56e−4 (=$(\lambda_{de})_{E4}$)
Pod (MUX), $(\lambda_{de})_{Pod}$	3.56e−4 (=$(\lambda_{de})_{E2}$)
Annular/Pipe ram preventer, $(\lambda_{de})_{A/PR}$	3.56e−4 (=$(\lambda_{de})_{E2}$)
Choke and kill valve, $(\lambda_{de})_{CV}$ and $(\lambda_{de})_{KV}$	3.56e−4 (=$(\lambda_{de})_{E2}$)
BSR preventer, $(\lambda_{de})_{BSR}$	3.39e−5 (=$(\lambda_{de})_{E5}$)

where HEF_{E2} is the HEF of event 2 and HEF_{E5} is the HEF of event 5. Those results are compared with the PFD results in Table 8.

When the SIS of the subsea BOP was evaluated with the PFD calculations, two functions of the subsea BOP could not satisfy the SIL 2 requirement. Also, when the SIS was evaluated with the HEF calculations, neither the A/PR function nor the BSR function met the SIL 2 requirement. Sensitivity analysis was performed on each component's PFD and HEF values for event 2 (A/PR function) and event 5 (BSR function). The analyses considered that 70% of the PFD and HEF values of each component influenced their rank within the total PFD and HEF. During those analyses, an l_2-norm was used with the summation of the squares of the normalized differences being one.

Fig. 9 (a) shows that the pod component was dominant in both the PFD and HEF results for the A/PR function. Similarly, the pod component was also dominant in the BSR function. However, the BSR preventer was a large part of the PFD value because of a lack of redundancy, even though it had a low failure rate. The BSR preventer is an important component as it is the last component in the prevention of a kick-related accident; however, it does have a low demand rate, resulting in the lack of a BSR effect on HEF (Fig. 9 (b)). In contrast, the pod has a relatively high demand rate and its failure rate is much higher than that of the other components. When the pod is evaluated by PFD, there is a possibility of misinterpretation because the pod is more dangerous than suggested by the results.

4.3. Comparison of PFD, PFH, and HEF for two BOP functions

Fig. 10 shows a comparison of the PFD, PFH, and HEF of the A/PR and BSR functions of a subsea BOP. The PFH for the A/PR and BSR functions were obtained from Eq. (2) as follows

$$\begin{aligned}PFH_{E2} &= PFH_{1oo2-TPB} + PFH_{1oo2-TCS} + PFH_{1oo1-HPU}\\ &\quad + PFH_{1oo2-Pod} + PFH_{1oo3-A/PR} + PFH_{1oo2-CV}\\ &\quad + PFH_{1oo2-KV}\\ &= \{\beta_{TPB}\cdot\lambda_{TPB} + (\lambda_{TPB}\cdot\tau)^2/\tau\} + \{\beta_{TCS}\cdot\lambda_{TCS}\\ &\quad + (\lambda_{TCS}\cdot\tau)^2/\tau\} + \lambda_{HPU} + \{\beta_{Pod}\cdot\lambda_{Pod} + (\lambda_{Pod}\cdot\tau)^2/\tau\}\\ &\quad + \left\{C_{1oo3}\cdot\beta_{A/PR}\cdot\lambda_{A/PR} + (\lambda_{A/PR}\cdot\tau)^3/\tau\right\} + \{\beta_{CV}\cdot\lambda_{CV}\\ &\quad + (\lambda_{CV}\cdot\tau)^2/\tau\} + \{\beta_{CV}\cdot\lambda_{CV} + (\lambda_{CV}\cdot\tau)^2/\tau\}\\ &= 5.488e-5\end{aligned} \tag{25}$$

and

$$\begin{aligned}PFH_{E5} &= PFH_{1oo2-TPB} + PFH_{1oo2-TCS} + PFH_{1oo2-Pod} + PFH_{1oo1-BSR}\\ &= \{\beta_{TPB}\cdot\lambda_{TPB} + (\lambda_{TPB}\cdot\tau)^2/\tau\} + \{\beta_{TCS}\cdot\lambda_{TCS} + (\lambda_{TCS}\cdot\tau)^2/\tau\} + \{\beta_{Pod}\cdot\lambda_{Pod} + (\lambda_{Pod}\cdot\tau)^2/\tau\} + \lambda_{BSR}. = 5.911e-5\end{aligned} \tag{26}$$

Table 8
Comparison between the PFD and the HEF.

	PFD	SIL	HEF	SIL
Annular/pipe ram function (Event 2)	8.508E−02	1	3.031E−05	0
Blind shear ram function (Event 5)	9.432E−02	1	2.979E−05	0

The subsea BOP can be evaluated with PFD in a low demand mode SIS evaluation. However, in the present study the A/PR function could be demanded over three times per year (scenario no.1 and 2 of Table 6), and this is within the scope of the PFH. The PFD of the two subsea BOP functions didn't meet SIL 2 requirements, and the SIL from the PFH for those functions were lower than the SIL from the PFD. The PFD approach had tendency to underestimate the probability of failure, whereas the PFH approach tended to overestimate the probability of failure near the boundary between SIS demand modes.

For this investigation, the BSR function was demanded less than once per year (all scenarios of Table 6). However, the topside push button, topside control, and pod systems were demanded for the A/PR function over three times per year. The pod was the dominant system component related to BSR function failures. Moreover, the BSR function sequentially followed the A/PR function; thus, the pod should be used first to assess the A/PR function at the demand rate of the A/PR function. The PFD approach may not reflect the components used in other safety-critical systems. Moreover, the PFD assumes that all SIS components are demanded less than once per year and are operated independently. As a result, the PFD can underestimate the probability of failure. The PFH was not suitable for evaluating the BSR function, because the BSR preventer is low demand mode equipment.

The HEF analysis produced reasonable values for the A/PR and BSR functions. The HEF considers the demand rate and can be applied over the full demand rate range of the SIS. However, Eq. (3) is only valid for a zero-demand duration and in near-boundary demand mode cases. In addition, HEF

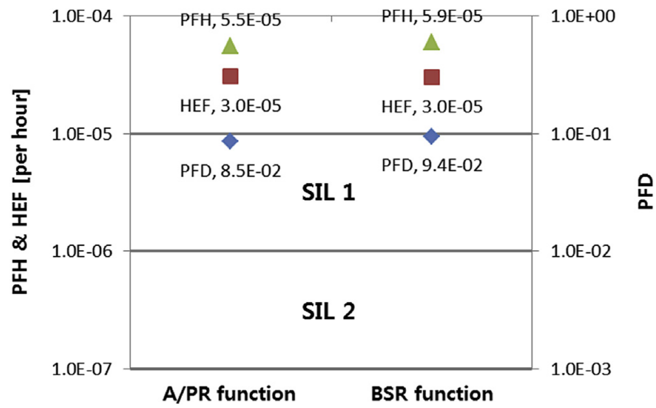


Fig. 10. Comparison of PFD, PFH and HEF for the A/PR function and the BSR function of the subsea BOP.

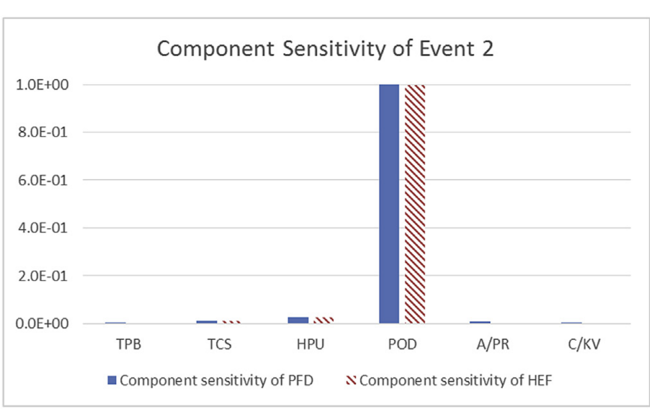
becomes cumbersome when building scenario-based equations due to the analytical solutions required for various situations. The Markov model has emerged as a good numerical solution, but it requires further development to enable it to be effective for various voting logics and complicated systems.

5. Control options

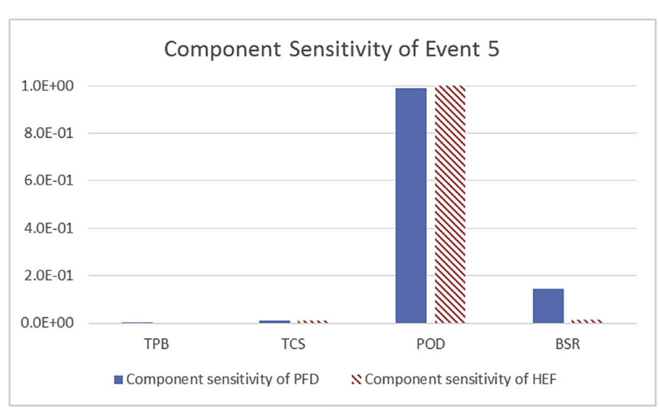
For the two subsea BOP SIF in this study to meet the minimum SIL 2 requirement (Table 2), a variety of control options related to the PFD and HEF evaluations were assessed.

5.1. Control option for PFD

The pod was the dominant component in both the A/PR and BSR functions (control option no. 0 in Fig. 11). To satisfy the minimum SIL 2 requirement, the pod could be controlled further in order to improve the A/PR function and the BSR function. One possible control option was the three pods system. The industry field has recognized the importance of the pod system, and there is a try to use three pods instead of two pods. The control option no. 1 in Table 9 was the result of the three pods system having 1oo3 voting logic. It showed that



(a)



(b)

Fig. 9. Sensitivity of components (blue block for the PFD and red comb pattern for the HEF). (a) component sensitivity of event 2; (b) component sensitivity of event 5.

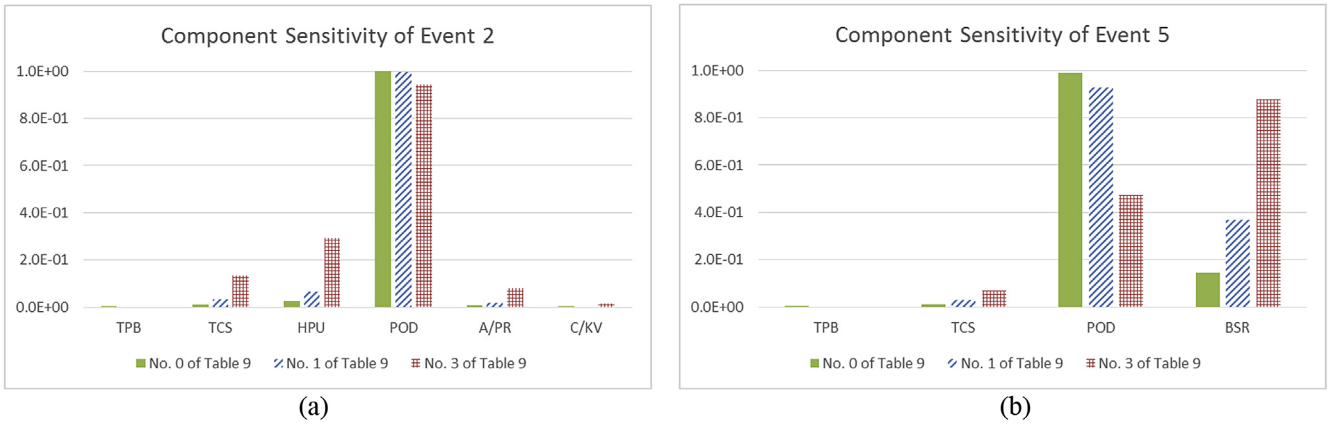


Fig. 11. Sensitivity of components (green block for no. 1, blue comb pattern for no. 1 and red check pattern for no. 3 of Table 9). (a) component sensitivity of event 2; (b) component sensitivity of event 5.

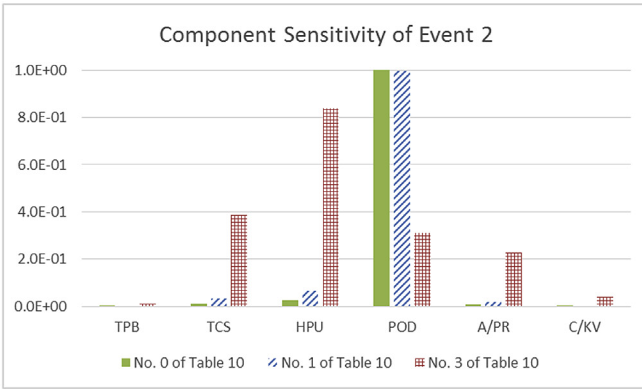
Table 9
Control options for PFD.

No.	Control option	A/PR function (event 2)			BSR function (event 5)		
		PFD	SIL	Reduction	PFD	SIL	Reduction
0	Origin	8.51E−02	1	0%	9.43E−02	1	0%
1	3 Pod system	3.34E−02	1	61%	4.26E−02	1	55%
2	23% Pod failure rate	9.86E−03	2	88%	1.91E−02	1	80%
3	3 Pod & 52% Pod failure rate	9.89E−03	2	88%	1.91E−02	1	80%
4	3 Pod & 52% Pod failure rate & 22% BSR failure rate	9.89E−03	2	88%	9.91E−03	2	89%

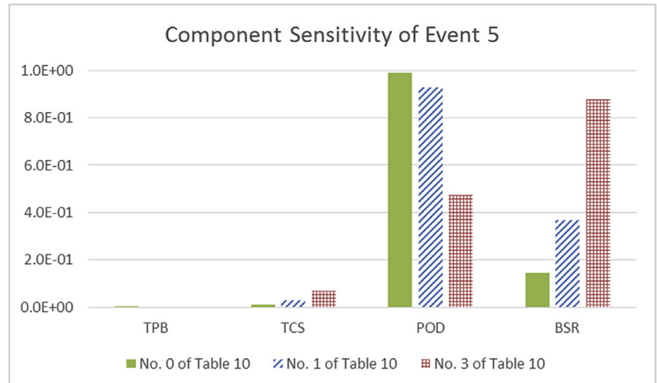
the three pods system could not meet the SIL 2 requirement for the A/PR and BSR functions. Another possible control option for the pod would be to enhance the performance of the pod and reduce its failure rate (control option no. 2 in Table 9). To meet the SIL 2 requirement, a pod failure rate should be reduced to 23% of the pod failure rate. Then, the PFD was reduced by 88% for the A/PR function and 80% for the BSR function. However, the BSR function could not meet the requirement. In the case of the three pods system (control option no. 1 of Table 9), the pod was still dominant to the PFD in Fig. 11. The failure rate should be reduced to 52% of the current failure rate to satisfy the SIL requirement (control option no. 3 of Table 9). However, to enhance the performance of the pod system was not enough to meet the SIL requirement of the BSR function. In the case of the control option no. 3 in Fig. 11 (b), the most dominant component is not the pod, but the BSR preventer. The PFD results for the BSR function indicate that the BSR preventer contributes a high portion of the total PFD value. Some subsea BOP are equipped with two BSR preventers (West E. S., 2009; five of thirty five subsea BOP operating in the Gulf of Mexico), but typically a single BSR preventer is used. Therefore, adding a redundant BSR preventer was not deemed a good control option, and this option was excluded from further consideration. BSR preventer performance enhancement was used as control option no. 3 (Table 9). To meet the SIL requirement, the BSR failure rate should be decreased to 22% of the current failure rate from the control option no. 3.

5.2. Control option for HEF

The pod was the only component to be dominant within the HEF results for both the A/PR and BSR functions (control option no. 0 in Fig. 12). The selected PFD control options were performance improvement to reduce the failure rate because the PFD is evaluated based on both failure rate and test interval (Eq. (1)). However, the test interval shortening doesn't always lead to more reliable system inherently. The test is another demanding on a function, and more frequent tests mean more demanding the system functioning. Therefore, the control options for the test interval are excluded from the analysis. The HEF control options also deal with failure rate. To meet SIL 2 requirements for the two subsea BOP SIF, the HEF should decrease to approximately 3% of the current HEF for the A/PR function and the BSR function (control option no. 4 of Table 10). To that end, the 5% of the pod failure rate (control option no. 2 in Table 10) or the three pods system with the 12% of the pod failure rate (control option no. 3 in Table 10) should be guaranteed. However, these control options couldn't meet the SIL requirement of the A/PR function. Additional control option was needed to the most dominant component which was the HPU in control option no. 3 of Fig. 12 (a). To meet the SIL requirement, the HPU failure rate should be decreased to 26% of the current HPU failure rate. These HEF control options are more severe than those suggested as PFD control options, which assumed that the SIS demand rate is less than one per year (1.14e−4 per hour).



(a)



(b)

Fig. 12. Sensitivity of components (green block for no. 1, blue comb pattern for no. 1 and red check pattern for no. 3 of Table 10). (a) component sensitivity of event 2; (b) component sensitivity of event 5.

Table 10
Control options for HEF: aspect of the PFD.

No.	Control option	A/PR function (event 2)			BSR function (event 5)		
		HEF	SIL	Reduction	HEF	SIL	Reduction
0	Origin	3.03E−05	0	0%	2.98E−05	0	0%
1	3 Pod system	1.19E−05	0	61%	1.14E−05	0	62%
2	5% Pod failure rate	1.52E−06	1	95%	9.99E−07	2	97%
3	3 Pod & 12% Pod failure rate	1.51E−06	1	95%	9.93E−07	2	97%
4	3 Pod & 12% Pod failure rate & 26% HPU failure rate	9.94E−07	2	97%	9.93E−07	2	97%

However, the demand rate of the A/PR function was greater than one per year (3.75e−4 per hour) in Table 6. The pod is one component of the A/PR system, and it is treated as being in low demand mode even though it is not in that mode. Therefore, compared to the HEF, the PFD could underestimate the probability of failure of the two subsea BOP SIF.

6. Discussion

The HEF control options can consider the demand rate by applying Eq. (3). The pod is the dominant component within HEF and is applied in both the A/PR and BSR functions. However, the demand rates of those two functions are quite different (Table 6). A control option that separates the pod for each function that is being demanded at a different demand rate was investigated. Fig. 13 (a) shows the separated pod system. In that system, the additional pod is demanded only for the BSR function as, based on their function, the pods were separate. Fig. 13 (b) shows a combined pod system. If the separated BSR pod for the BSR function fails, then the blue and yellow pods of the A/PR function can be used to actuate the BSR preventer (such as is the case in the original subsea BOP in Table 10). Note that the A/PR function cannot use the separate BSR pod when the blue and yellow pods are broken.

The HEF results for the separated pod and the combined pod systems can be evaluated via Eq. (27) and Eq. (28), respectively.

$$HEF_{E5} = PFD_{1oo2-TPB}\cdot(\lambda_{de})_{TPB} + PFD_{1oo2-TCS}\cdot(\lambda_{de})_{TCS} + PFD_{1oo1-Pod}\cdot(\lambda_{de})_{BSR} + PFD_{1oo1-BSR}\cdot(\lambda_{de})_{BSR} \quad (27)$$

$$HEF_{E5} = PFD_{1oo2-TPB}\cdot(\lambda_{de})_{TPB} + PFD_{1oo2-TCS}\cdot(\lambda_{de})_{TCS} + PFD_{1oo2-Pod}\cdot\left(PFD_{1oo1-Pod}\cdot(\lambda_{de})_{BSR}\right) + PFD_{1oo1-BSR}\cdot(\lambda_{de})_{BSR} \quad (28)$$

The separate and combined pod systems produced no difference in HEF values for the A/PR function (Table 11) because the control options had the same pod configuration for the A/PR function (Fig. 2). However, the HEF of the BSR function reduced dramatically in both the separate and combined pod systems without performance improvement (Table 11). Note that the pod control options presented in Table 10 were still needed for the A/PR function.

The PFD evaluation could not utilize the suggested control options (Fig. 13). Moreover, the PFD when applied to a SIS demanded several times per year can underestimate the probability of SIS failure. Technically, in such a case the PFH should be used for that system's evaluation; regardless, PFD-based evaluations are adopted widely. A HEF-based evaluation can reflect demand rates near the boundary between low and high demand modes.

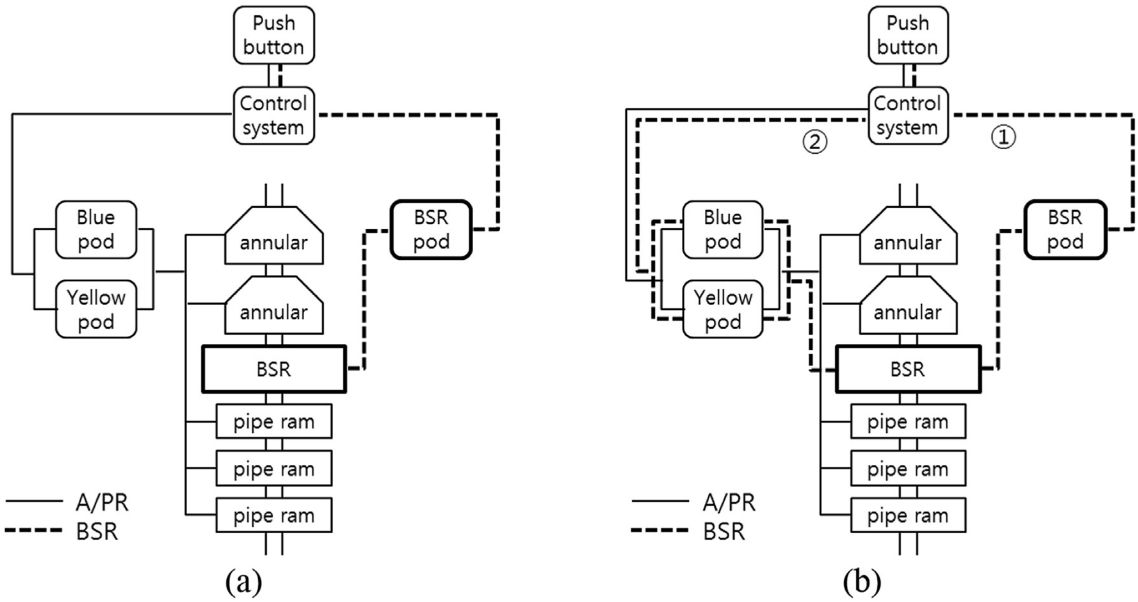


Fig. 13. BSR pod for BSR function. (a) separated pod system; (b) combined pod system (the solid line is the function of the annulus and the pipe ram preventer (referred as A/PR) and the dash line is the function of the blind shear ram preventer (referred as BSR)).

Table 11
Control options for HEF: aspect of the demand rate.

No.	Control option	A/PR function (event 2)			BSR function (event 5)		
		HEF	SIL	Reduction	HEF	SIL	Reduction
0	Origin	3.03E−05	0	0%	2.98E−05	0	0%
1	Separated pod system	3.03E−05	0	0%	8.50E−06	1	71%
2	Combined pod system	3.03E−05	0	0%	1.37E−06	1	95%

7. Conclusions

The conclusions of the study are as followings.

- The HEF was proposed as an alternative SIS evaluation indicator near the boundary of the PFD for the low demand mode and the PFH for the high demand mode. As an application, two functions of a subsea BOP were analyzed based on the definitions within NOG 070. The PFD which has been used as SIS evaluation indicator for the subsea BOP functions was compared with the HEF. The results of this study indicated the possibility of using HEF as a SIS evaluation indicator near the boundary of the PFD and the PFH applicability.
- It was found that evaluating a subsea BOP SIS via the existing PFD approach could underestimate the probability of failure of the subsea BOP SIS. The PFD, the probability of failure on demand, is used for the SIS evaluation of the low demand mode and it assumes that the SIF is required no greater than one per year. However, in the most frequently occurring scenario of well kick controlling procedure, the A/PR function was not a low demand mode operation. The BSR function was a low demand mode, but the pod, which was the most dominant equipment in the PFD evaluation of the BSR function, was used as the demand rate of the A/PR function. Those are out of the PFD range and the PFD may underestimate the probability of the failure at this demand rate range because the more frequent demand leads to more chance to be failed.
- Several control options were suggested from the perspective of PFD and HEF results. To meet the SIL requirement of NOG 070, control options to reduce 88% of the current PFD of the A/PR function and 89% of the current PFD of the BSR function were needed based on the PFD results. In the case of the HEF, 97% reductions from the current HEF were needed for both A/PR function and BSR function. The control option for the BSR preventer from the PFD evaluation and the control option for the HPU from the HEF evaluation should be delivered additional to control options for the pod systems.

Two research topics are suggested as future works. Firstly, it is to consider the effect of the circumstance to the technical systems. This study applied the effect of the different circumstance only on the operators (2A and 2B, 5A and 5B in Table 5) due to lack of data. However, the technical system could be affected by the circumstance and the failure rate could be changed. This can lead to the different PFD and the demand rate. The result will be closer to the real situation. Another topic is to consider the imperfect tests having the different test intervals. This study assumed that one kind of the test was performed every 6 months and the test was perfect to detect all faults of the system. However, several different tests are performed with different intervals in the industry. Also, sometimes some faults can't be found by the test. If these conditions can be applied to the analysis, the more realistic result can be obtained.

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