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Quantified Risk Assessment of Fire Incidence inside Hyperbaric Chamber: A Case Study

P. K. CHATTOPADHYAYA*[1], S. K. BASU[2], and M. C. MAJUMDER[3]

[1] *Scientist, Research & Development Establishment (Engineers), DRDO, Alandi Road, Dighi, Pune - 411015, India*
[2] *Professor Emeritus, Department of Production Engineering and Workshop, College of Engineering, Wellesely Road, Shivaji Nagar, Pune-4411005, India*
[3] *Professor, Department of Mechanical Engineering, National Institute of Technology, Durgapur-713209, West Bengal, India*

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Abstract: An enclosed human occupancy chamber is commonly known as hyperbaric chamber system (HCS). The medical treatment to divers suffering from decompression sickness is administered inside a hyperbaric chamber. The hazards inherent inside the chamber include sudden loss of pressure, fire and rapid loss of life-supporting gases. Fire can be catastrophic inside the oxygen-enriched confined space of a hyperbaric chamber. The fire protection system (FPS), a hazard barrier against fire is designed to respond to the true demand of the initiating event (fire incidence) which can happen at any time. The paper is devoted to the risk assessment of fire incidence inside a hyperbaric chamber and gives a methodology for risk assessment for incident of fire using fault tree and event tree analyses. The mean proportion of time the system is not functioning upon demand is a measure of safety for the fire protection system, which is estimated using the mean fractional dead time (FDT). The minimum mean time between hazards (MTBH) of a life-safety system, indicates the minimum performance level of hazard barriers designed to provide protection against hazards, can be considered as design matric for risk analysis. The MTBF of FPS is calculated and its usefulness is discussed.

Keywords: *Quantified risk assessment, hyperbaric chamber system, fire protection system, mean time between hazards (MTBF), fractional dead time*

1 Introduction

An enclosed human occupancy chamber is commonly known as hyperbaric chamber system (HCS). The medical treatment to divers suffering from decompression sickness is administered inside a hyperbaric chamber. The hazards inherent inside the chamber include sudden loss of pressure, fire and rapid loss of life-supporting gases. Hence, the facility is evaluated and certified by certification authority before the facility is placed in operation [1]. Fires in hyperbaric chambers have been described as explosive in nature due to severity of the burning and the speed at which the fire propagates inside the oxygen-enriched confined space. As a hazard barrier a fire protection system (FPS) is installed to put out the fire incidence occurring in the hyperbaric chamber. There are reported 77 fatalities and 13 injuries inside 35 hyperbaric chambers in 73 years [2]. Most of these chambers are found to be operational in Asian countries. The fire protection system (FPS), a protective layer against fire is designed to respond to the true demand against the initiating event (fire incidence) which can happen at any time. The efficacy of

*Corresponding author’s email: pk_chatto@yahoo.com

fire protection system (FPS) or for that matter the design weaknesses could not be ascertained for those chambers as information is not easily accessible. On-time deployment with desired output is the critical function for a FPS, which is the barrier against hazards. The reliability estimation (for on-time deployment) of hybrid inflator which is used to inflate airbag in case of automotive collision has been reported in [3], where the items are taken in series for reliability estimation. The reliability estimation of sprinkler system installed in high-rise building has been reported in [4].

System risk evaluation methods fall into three broad categories [5]. Qualitative Risk Assessment in which numbers and probabilities are not used extensively or at all. This is simplest approach with subjective assessment of risk and to rank them in a subjective manner. Quantified Risk Assessment (QRA) in which element performance (or event outcomes) and system risk are given as numerical point estimate (deterministic). Probabilistic Risk Assessment (PRA) in which system element performance is given as a random variable so that variability and the uncertainty of variables are propagated through the analysis leading to the system risk being represented as a probability distribution. The level of operational risk for hyperbaric chamber against loss to personnel and damage to system can be qualitatively evaluated using risk assessment code for ASME certified pressure vessel systems, which is a numerical expression of comparative risk [6]. The detail of such methodology is available in [7]. However, it does not cover risk assessment against fire hazards; as such quantitative risk assessment for hyperbaric chamber against fire has not been reported much.

In this paper, an attempt is made to study the risk scenarios due to occurrence of fire inside an enclosed human occupancy chamber and assess the risk level using quantified risk assessment (QRA) methodology with the hazard barrier as fire protection system (FPS).

2 System Risk Assessment

The total risk of a system is usually calculated from multiple risk scenarios consisting of failure events, processes, human errors *etc*. The hazard barriers prevent and control of occurrences of hazards. Hence, the failures of hazard barriers facilitate occurrences of hazards. The system (hazard barrier) representation techniques are fault tree (FT), event tree (ET) *etc*., which are used to represent the sequence that may lead to failure of the system. Typically in applications, a combination of FT and ET is used for the system representation. The objective of fault tree analysis is to find systematically all possible failure modes of the occurrence of the top event which are undesirable system failure. It is a top-down logic model and at the bottom of each failure path reside the basic failure events. Basic failure rates advance through logic gates to result in the failure rates of intermediate events and finally to determine the top event (TE) failure rate. The event tree method is used to depict the cause and effect relationship between initiating events and the progression of events by the way of failure to function or successful functioning of sub-systems following the occurrence of initiating event. The system modeling steps are proposed as follows.

a) The initiating event is identified as fire incidence and other sources of risk, which may be present, are ignored. The models of failures of hazard barrier (FPS) are developed and amount of exposure is estimated.
b) Initiating event forms the starting point for the modeling of the risk scenarios *i.e.*, the combination of events leading to various end states of the system [8]. The fault tree and event tree are integrated and their events are quantified to determine the

frequencies of scenarios with the help of Boolean representation of scenarios. We identify in logic modeling all failures that lead to failure of the event tree headings.

c) Then fatality risk [8] for each scenario is calculated by multiplying scenario frequency with scenario fatality as given in (1). Then total fatality risk level is calculated by summation of risks pertaining to all the scenarios.

$$\mathrm{Risk} = \sum_i f_i c_i \tag{1}$$

where f_i and c_i are frequency and consequence of the hazard scenario i.

d) The criteria of severity of consequences are categorized as catastrophic, critical, marginal and negligible based on MIL-STD-882D classification. The varying degrees of severity of consequences are quantified based on past data on fire incidences inside HCS. The estimated total fatality risk against fire incidences inside HCS is compared with assigned acceptable risk criteria and an appropriate decision can be taken on future course of actions.

e) The incident of fire occurs very infrequently and therefore the FPS remains in passive state for long periods of time. Such a system may fail in passive state and the failure may remain hidden until a demand for execution occurs or until the system is tested. The mean fractional dead time (FDT) is the fraction of time that the system is dead *i.e.*, the mean proportion of time the system is not functioning upon demand is a measure of safety for FPS [3]. That means that for uncontrolled hazards to happen, both fire incident and mean fractional death time are to occur simultaneously. Assuming fires occur randomly according to a homogeneous Poisson process (HPO) with intensity (FR) which is the mean number of fires per year, a critical scenario occurs for a fire incidence while the fire protection system is in a failed state. For a constant failure rate, λ for a system and τ, the test interval of the system, the mean fractional dead time (FDT) is given by [4],

$$FDT = \lambda . \tau/2 \tag{2}$$

A critical situation may happen if a fire occurs while the system is in failed state. The mean time between critical situations is in effect the mean time between failures (MTBF) and is the reciprocal of multiplication of fire incidence rate (FR) and FDT. The above MTBF can be taken as the mean time between hazards (MTBH), which is the reciprocal of the probability of the overall hazards (fire with no detection/activation) [9].

$$MTBH = \frac{1}{FR.FDT} \tag{3}$$

The minimum mean time between hazard (MTBH) of a life-safety system, indicates the minimum performance level of hazard barriers designed to provide protection against hazards, can be taken as design matric for risk analysis.

3 Brief Description of FPS

The FPS installed inside the hyperbaric chamber is designed fulfilling the requirements stipulated in NFPA-99 Handbook [10]. The extinguishing agent (water) is discharged in sprays forming fine droplets to reduce the heat in the fuel thereby inhibiting ignition and combustion. The schematic diagram for the system structure of hyperbaric chamber system relevant to FPS is shown in Figure 1 which is established in terms of functions of items for successful operation of system.The list of abbreviations used for items is given in Table 1. All abbreviations have three letters with prefixes A, X and F denoting items pertaining to air, oxygen and fire systems respectively. For example, ABP indicates the item ‘pneumatically operated ball valve’ in air system. The generic failure rates in terms of failure per million hours (FPMH) are taken from NPRD-95 (Category NSWC-07).

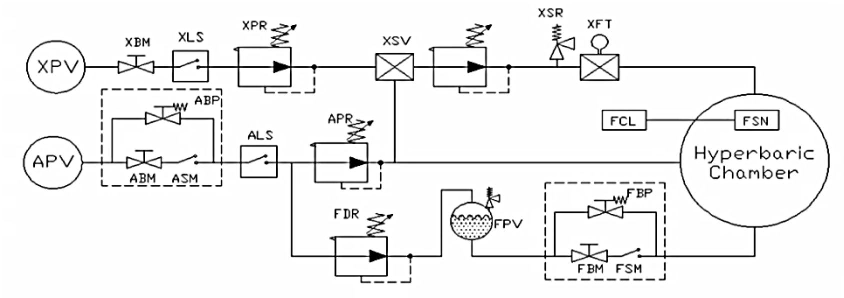


Figure 1: Schematic Diagram for FPS

Table 1: List of the Items with Failure Rates

Abbre-viation	Item Name	Failure rate (FPMH)
BP	Ball Valve Pneumatic	2.3979
PV	Energy storage Cylinder	18.635
BM	Ball Valve Manual	0.7559
PR	Pressure Regulator	20.0024
DR	Differential Pressure Regulator	15.456
TR	Filter	0.0413
SN	Fire Sensor	0.444
CL	Fire controller	62.3716
BV	Valve Standby System	0.5747
SV	Solenoid Valve	0.5
LS	Low Pressure Switch	9.0431
SM	Manual Switch	1.0
SR	Safety Reliable Valve	1.6879

Three critical sub-systems *viz.*, air and oxygen and fire protection systems are required to be analyzed. The air system is functional continuously during operation and oxygen system is working intermittently as per need.The Compressed air stored in APV is led to pressurize the HCS. The air-line is normally opened by remote operation of ABP. The stored pressure of air is reduced to the desired pressure with the help of APR. The lower pressure switch, ALS gives indications as and when the vessel pressure, falls below some pre-set pressure. The ball valve ABM is kept in passive redundancy and the operation of switch ASM is considered as 100% reliable. The oxygen gas is stored in XPV and is fed into HCS by operation of manual valve, XBM. In case of accidental fire taking place inside the chamber, the fire protection system (FPS) shall function on demand and there shall be conditional supply of air through oxygen line in place of oxygen. As soon as fire is sensed by the fire sensor (FSN) housed inside the chamber, automatic ball valve (FBP) opens up the gust of stored water under pressure in energy storage vessel (FPV) into the hyperbaric chamber. The functional operation of the chamber is aborted and slowly de-pressurized back to ambient. All the subsystems along with important constituent items are given below.

a) Air supply system (A) : APV, ABP, ABM, ASM, ALS, APR
b) Oxygen supply system (X) : XPV, XBM, XLS, XPR, XSR, XFT
c) Fire protection system(FPS)
   i) Detection System (DS) : XSN, XCL
   ii) Suppression system(SS) : APV, ABV, ALS, FDR, FSR, FPV, FBV
   iii) Air-in-mask system(AS) : APV, ABV, ALS, APR, XSV, XPR, XSR, XFT

4 Functioning of FPS

Three protective measures as hazard barriers such as fire detection, fire suppression and air through mask are in place and have following distinct functions to perform to successfully extinguish fire and safely take out occupants after de-pressurization of chamber. Now, the functioning of FPS is explained as under.

a) Fire detection system (DS): Three Duel IR flame detectors (FSN) are positioned suitably on the top of chamber (Figure 1)

b) Fire suppression system (SS): Once fire is detected by fire detection system, the fire suppression system shall function on demand and is activated through opening of automatic ball valve (FBP).The water is instantly released under pressure (air pressure is acting as driving pressure) and surges down-stream of the valve through the arrangement of fixed piping before being discharged through open orifice of fixed discharge nozzle. As per operational requirements, the internal pressure in the chamber is variable up to a maximum pressure of 5 bar (equivalent to 50 m sea water depth). A differential pressure regulator (FDR) which senses the chamber pressure (reference pressure) and adjusts the driving pressure in excess of 3 bar (to chamber pressure) in the closed tank (FPV). Figure 2 shows a schematic diagram.

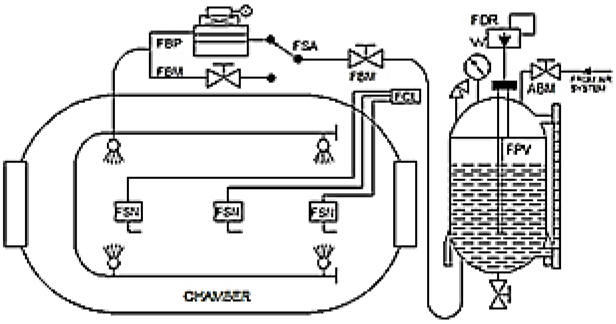


Figure 2: Fire Suppression System

c) Air through mask (AS): Once a fire is identified by a fire detector, a solenoid valve (XSV) placed in oxygen line first disconnects oxygen supply to chamber and then connects to air supply line. Immediately, breathable air is supplied in to the chamber through XBM.Thus, conditional supply of air through oxygen system in place of oxygen is provided as breathing gas.The chamber occupants inhale air through mask till they are rescued from the chamber.

5 Risk Assessment of Fire incidence inside Hyperbaric Chamber (HCS)

A case study on risk assessment of fir incidence inside hyperbaric chamber system (HCS) has been reported in this paper. It is assumed that at least 0.1 hr of operation is needed for the fire to be completely extinguished.

5.1 Risk Acceptance Criteria

The safety risk analysis estimates potential harms caused by accidents occurring during work exposures and the consequences from becoming seriously injured or dying would determine a basis for measuring risk. It could be measured in terms of money, which may not be ethical [8]. The fatality is also taken as a measure of losses. The fatal accident rate (FAR) is sometimes used measure for personal risk and is defined as the expected number of fatalities per 10^8 hours of exposures [11]. It may be noted that the off-shore work, however has just above 30 fatalities per year for work exposures of 3000 hour a year which is based on upper limit of tolerability for risk to individual as 1 x 10^{-3} per year (1 in 1000) in the context of ALARP (as low as reasonably possible) [12]. The motivating example of hyperbaric chamber has similar work environment, as off-shore work also include under sea work. We focus our discussion on the fatality risk to the occupants of hyperbaric chambers, which include patients, divers and medical supervisors. The risk acceptance criterion is based on the assumption that the probability that a person is died due to mishap during one year should not exceed 0.1% of the individual tolerability limit [13]. Then, the risk acceptance criteria can be taken as 1×10^{-6} per person per year.

5.2 Criteria of Severity of Consequences

As per MIL-STD-882D, if we categorise severity of consequences as catastrophic, critical, marginal and negligible, we can estimate the consequences in terms of work-place fatalities due to fire incidents depending on the hazard scenarios envisaged. Taking a cue from [2], let us assume that there are 77 fatalities and 13 injuries inside hyperbaric chambers in 73 years due to fire incidents, where the occurrences of deaths are more than injuries. Considering an estimated world population of 2000 chambers where on an average 3 persons work, the individual probability of fatality for catastrophic severity and injury for critical severity are estimated as 1.76×10^{-4} and 2.95×10^{-5}.The marginal and negligible severity categories are assumed as 2.95×10^{-6} and 2.95×10^{-7}, respectively.

5.3 Fault Tree Model

The failure to function against fire incidence is defined as a top event (TE) of the fault tree, which is built on three hazard barriers, *e.g.*, failure to detect fire, failure to suppress fire and failure to supply of air to masks. Hence, the reliability evaluation of FPS is essential and can be carried out from the fault tree. It is now required to calculate the probabilities of the basic failure events described in the event tree and fault tree. The cut sets for the failure of DS, SS and AS are obtained from the respective fault trees shown in Figure 3.Then the probabilities of each scenario is calculated based on the occurrence of one of its cut sets.

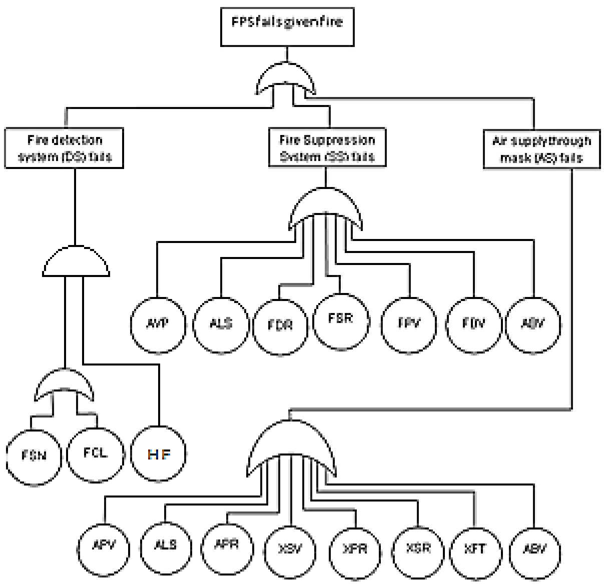


Figure 3 Fault Tree Model for FPS

The human error event is a function of work place factors and operator characteristics. For a chamber, most issues related to human factors are already addressed during design and human-related hazard are reduced. The probability of 1 x 10^{-2} can be taken for human factors related operational error [14].The exponential distribution is widely used distribution in reliability evaluation of system, due to its constant failure rate, λ.The generic failure rates in terms of failures per million hours (FPMH) taken from NPRD-95 (Category NSWC-07) are used for all the items and are given in Table 1.The fault trees for DS, SS and AS are solved for top event failure rates separately. Then they are added to obtain the failure rate of fire protection system. The values are given in Table 2. Then frequency of occurrence is obtained from FDT of the subsystem and calculated using equation (2). Considering maintenance and testing schedule of FPS as three months operation time, 8 hours repair time and τ as 380 hours, the FDT of FPS is calculated as given in Table 2.

5.4 Event Tree Model

The event tree models scenarios of successive events that lead to exposure of hazards and ultimately to the undesirable consequences. Each scenario in the event tree consists of a unique sequence of occurrences and non-occurrences of pivotal events (Table 3). The event tree heading events are assumed to be binary and are represented by fault tree logic modeling technique which determines the probability of the occurrence of the top events if a protective barrier fails. The upper (success) branches are represented by over bar of an event (*e.g.,* $\overline{DS}$) and the lower (failure) branches are represented by a regular event (*e.g.*, DS). The overall outcome of each of the scenario of events is shown at the end of each sequence. The logical representation of each sequence is also shown in the form of a Boolean expression, for example, for Scenario-2 in Table 3, events DS and SS have occurred *i.e.*, they properly worked. The functioning or non-functioning of combinations of these measures would lead to different damage states.

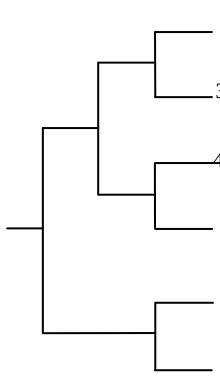
Table 2: Failure Rates and FDT of Sub-systems of FPS

λ_{DS} = 63.7036 x10^{-6} per hour
λ_{SS} = 64.6064 x 10^{-6} per hour
λ_{AS} = 70.4868 x10^{-6} per hour
λ_{FPS} = 1.99 x10^{-4} per hour
$FDT_{FPS} = 0.0378$

5.5 Risk Assessment

The Scenario-1 indicates functioning of entire FPS system and effective against putting out fire. Scenarios-2, 3 and 4 indicate partial functioning of FPS and their efficacy in totality are not met with. As shown in Table 3, if the fire detection system (DS) fails then none of the other two systems *viz*., fire suppression system (SS) and air supply to mask (AS) are activated as DS shall not send signal to FCL for activation of SS and AS. In case, DS does not operate and fire is noticed by the operator, the operator manually executes the operations of SS and AS by actuation of FBM and XSV respectively. There are remote chances of not operating either or both of the valves and hence both the probable scenarios are neglected. The sequence logic for Scenarios-5 and 6 are included with probability of success/failure of human factors respectively [14]. The operator is active in Scenario-5, but in the Scenario-6, the operator fails to operate resulting in fatal scenario. Fire is only one initiating event (cause) considered in this analysis and scenarios (effects) are developed through even tree analysis as shown in Table 3.

Table 3: Event Tree Analysis and Estimated Risk per Person per Year

Fire (FR)	DS	SS	AS	HF	Scenario	Sequence Logic	Frequency Per year	Category of Severity consequences	Consequences in fatality	Risk person per year
						1. FR.DS.SS.AS	0.5399	No death, no injury Negligible	2.96×10^{-7}	1.59×10^{-7}
						2. FR.$\overline{DS}$.$\overline{SS}$.$\overline{AS}$	3.89×10^{-5}	Injury, Marginal	2.96×10^{-6}	1.15×10^{-10}
						3. FR.$\overline{DS}$.$\overline{SS}$.AS	3.48×10^{-5}	Injury, Critical	2.96×10^{-5}	1.03×10^{-9}
						4. FR.$\overline{DS}$.SS.$\overline{AS}$	2.51×10^{-9}	Fatal, Catastrophic	1.76×10^{-4}	4.41×10^{-13}
						5. FR.$\overline{DS}$.SS.AS.HF	3.35×10^{-7}	Injury, Marginal	2.96×10^{-6}	9.91×10^{-13}
						6. FR.DS.$\overline{SS}$.$\overline{AS}$.$\overline{HF}$	3.39×10^{-9}	Fatal, Catastrophic	1.76×10^{-4}	5.96×10^{-13}
									TOTAL	1.60×10^{-7}

The frequency of occurrence of each scenario is calculated and given in Table 3. The rate of incidence of fire (FR) is assumed as 0.54 per year as 39 reported fire incidence in 73 years of operations [2]. The estimated high rate of incidence of fire (in about every second year) is based on fire incidence occurred in old (under-designed) chambers. The DS and manual backup HF have failed in Scenario-6, then the activation of SS and AS is also failed. Then, the failure probabilities of AS and SS are considered as one in the calculation of the frequency of Scenario-6. The frequency of Scenario-6, which is most undesired, is very low. The severity consequence for Scenario-1 is negligible, as the fire protection system functions as desired. For Scenario-2, the severity consequence is marginal as fire is put out and breathable air is available to masks for the chamber occupants. In Scenarios-3 and 4, fire situation is known due to operation of DS and appropriate actions deemed to have initiated by outside operators. As AS functions in Scenario-3, the oxygen supply is cut-off and excess oxygen may not be present inside the chamber, which accelerates the fire burning rate. Hence critical injury to occupants is expected during Scenario-3. The severity consequence for Scenario-4 is catastrophic as the presence of oxygen increases the fire burning rate. In Scenario-5, although DS did not function, the fire is put out due to operation of manual back-up HF and severity consequence could be marginal. In the Scenario-6, even manual back-up HF fails and a catastrophic situation is generated.

The risk contributors are identified through event tree analysis. The risk associated with each scenario is given by the multiplication of frequency of occurrence of the scenario and consequence (*i.e.*, expected loss). The total fatality risk per person per year is estimated as 1.6×10^{-7}, whereas, the acceptable risk criteria level is 1.00×10^{-6}. Hence, it could be inferred that the risk level due to fire inside the hyperbaric chamber with fire protection system as hazard barrier seems to be safe and new risk mitigation strategy may not be needed for further reduction of risk level.

5.6 Estimation of MTBH

The failure rate and mean fractional dead time of FPS is estimated as 1.99×10^{-4} per hour and 0.0378 respectively. The MTBH of FPS is calculated using equation (3) and is obtained as 49 years, which means that the FPS is a highly reliable system. We may note that MTBH is analogous to the mean time between failures (MTBF), a reliability matric. The MTBH seems to be a prudent design assumption for the risk analysis and can be used as a design matric.

6. Conclusions

It is possible to summarize that the paper aims at deriving the following vital points:

a) The assessment of risk for fire incidence inside the hyperbaric chamber system is carried out to estimate quantified fatality risk where fault tree integrated with event tree diagrams are utilized. Total expected six scenarios are considered. The estimated fatality risk per person per year is 1.6×10^{-7} which is less than that of the acceptable fatality risk of 1.00×10^{-6}. Hence, there seems to be no requirement of further reduction of risk level inside the chamber.

b) The mean time between hazards (MTBH) can be used as a design matric for life-safety systems. The MTBH for the FPS under study is calculated as 49 years considering that the assigned maintenances have been carried out. This indicates that the FPS is a highly reliable system.

c) The safety risk reduction methodology as per IEC 61506 standard considers more than one independent protective layers like basic process control system, fire protection system, safety integrated instruments et cetera. Safety Integrity Level (SIL) seems to be a useful area of further work.

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P. K. Chattopadhyaya obtained his B.E. (Mechanical) from NIT, Silchar and M.E (Mechanical) from Pune University. He has been engaged in the design and development of defence equipment for last 25 years. He has published more than ten papers in international and national conferences. Email: pkchattopadhyaya@rde.drdo.in

S. K. Basu, B.E., Ph. D. (Moscow), D.Sc. (Engg); FNAE, F.I. Mech. E (London), F.I.E., F.O.R.S.I., is a Professor Emeritus in the Department of Production Engineering and Workshop at the College of Engineering, Pune. He is the former Chair-Professor (Tribology) IIT, Delhi; Director, Central Mechanical Engineering Research Institute, Durgapur; Professor of Prod. Engg., Jadavpur University; Head of the Department of Mechanical Engineering, R.E. College Durgapur; and Faculty member of IIT Kharagpur. He has approximately 200 technical papers to his credit in national and international journals and guided 26 Ph. D. students in the area of production and industrial engineering. He is a winner of the four prestigious awards of the Institution of Engineers, for the best papers. He also received Lifetime achievement award from AIMTDR in 2000. He has written six Engineering textbooks and has a number of patents to his credit. Email: skb.prod@coep.ac.in

M. C. Majumder obtained his Ph. D. in Mechanical Engineering from IIT, Kharagpur. He is presently working as Professor at NIT, Durgapur. He has 32 years of teaching and research experience. He has special interest in lubrication of artificial joints. He has guided six scholars for Ph. D. He has published 30 papers in international and national conferences. Email: manik.majumder@me.nitdgp.ac.in