Quantitative Safety Analysis of a Laboratory-Scale Bioreactor for Hydrogen Sulfide Biotreatment Using Fault Tree Analysis

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Numerous research activities are conducted all over the world to study biological treatment of H_2S in laboratory-scale bioreactors. Important hazards associated with these bioreactor systems include the escape of H_2S gas and leakage of chemical/biological liquids, which have severe adverse effects on the involved labors, equipment, and materials. The objective of this article is to present a quantitative safety analysis of a laboratory-scale continuous bioreactor system for H_2S gas biotreatment using the fault tree analysis approach. Three unwanted top events were determined as the most hazardous events, being H_2S leakage inside the laboratory, H_2S leakage to outdoor from bioreactor outlet, and leakage of liquid chemical/biological solutions. The minimal cut sets and the probability of the occurrence of each top event were determined. The importance of cut sets and basic events were calculated, and priorities for control measures were determined. The analysis allows better decision on priority of control measures, and maintenance or replacement schemes of the system components in an endeavor to minimize the probability of failure or hazard occurrence. The presented analysis proves the usefulness of fault tree analysis in making quantitative risk assessment and safety analysis, which are important elements in laboratory safety management system. © 2013 American Institute of Chemical Engineers Process Saf Prog 32: 376–386, 2013

Keywords: laboratory-scale bioreactor; hydrogen sulfide; safety analysis; process safety; fault tree analysis

INTRODUCTION

The emission of hydrogen sulfide is found in many industrial activities. Today, several physicochemical processes have been in application to remove H_2S from waste gas. However, these processes require a large energy input and high capital and operating costs and produce secondary wastes that must be disposed [1–7]. For these reasons, biological processes for the removal of H_2S are more attractive, because they are believed to be inexpensive and cause no environmental pollution [3]. Currently, due to its attractiveness and fertility as a research field, numerous laboratory-scale research activities are conducted to study various aspects related to biological treatment of H_2S. Many of these research activities are conducted using continuous laboratory-scale bioreactor systems fed with H_2S gas as the target pollutant. For many reasons, these bioreactor systems are subjected to frequent or occasional failure events. One of the most dangerous outcomes of these failures is the escape of H_2S gas from the system, either in the form of leakage or in the outlet gas stream of the bioreactor. Leakage of chemical liquids (e.g., nutrients, pH adjusting agents, and various sulfur compounds) and bacterial cell suspensions is another probable event.

H_2S is a very toxic gas with a smell of rotten eggs and odor threshold as low as about 0.5 ppb. Inhalation of low concentrations of H_2S can cause headache, dizziness, nausea, cramps, staggering, excitability, and drowsiness. Levels higher than 10 ppm can affect human health. However, at 100 ppm, it can no longer be smelled. Breathing H_2S at a concentration higher than 500 ppm can be fatal after a few breaths, due to its broad spectrum toxicity [8]. The NIOSH recommends a ceiling value (10 min) of H_2S as 10 ppm, whereas the OSHA permissible exposure limit is 20 ppm at the workplace and the ceiling concentration (10 min) is 50 ppm [9]. In addition to health effects, H_2S is highly corrosive, and its release can cause damage to equipment, particularly sensitive analytical equipment. It reacts with other chemicals in the laboratory causing change in their chemical properties and may cause severe catalyst poisoning in laboratories involving catalytic applications. On the other hand, chemical/biological liquid leaks may have severe effect on human through skin contact and on equipment and materials in the laboratory.

The above-mentioned facts imply that labors, equipment, and material in laboratories involving this type of research bioreactors are at high risk of exposure to variable H_2S gas

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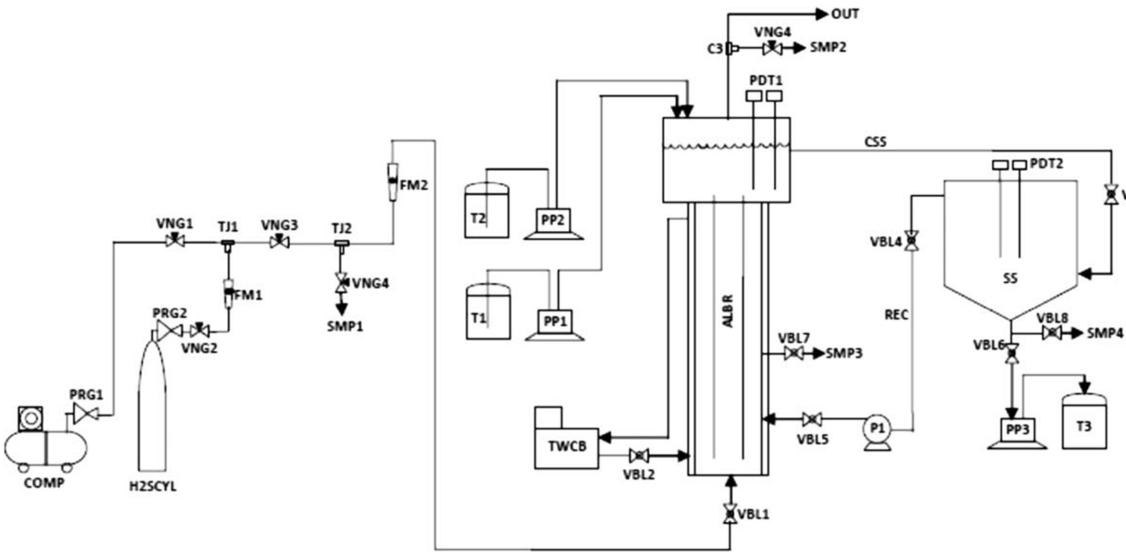


Figure 1. Schematic of the studied laboratory-scale H2S biotreatment process. CSS: cell and sulfur suspension; OUT: outlet air to hood; P: circulation pump; PDT: pH/DO/temp sensors; PRG: pressure reducer and pressure gauge; REC: recycled cell suspension; SMP: gas/liquid sampling; T: tanks (1: nutrient, 2: HCl, and 3: sulfur sludge); TJ: Tee joint; VNG: gas needle valve; and VBL: liquid ball valve.

concentrations and liquid chemical/biological contact during failure events. Therefore, it is highly recommended to pay attention for aspects related to safety and reliability of such bioreactor systems that have potentially dangerous outcomes of failure.

Although the U.S. OSHA Laboratory Standard and Hazard Communication Standard have improved safety management in laboratories and pilot plants, incidents that result in injuries and property loss continue to occur in these research and teaching locations [10]. It was reported that academic laboratories experience an accident rate 10–50 times higher than that seen in industrial laboratories [11]. This was frequently attributed to the absence of a hazard identification or risk analysis as a root cause factor [12]. A successful laboratory-scale process safety management system is expected to minimize these high accident rates. An important element in this management system is "process safety and reliability analysis."

Evaluation of process safety and reliability can be performed using several methods, such as hazard operability (HAZOP) studies, failure modes and effects analysis (FMEA), what-if analysis, fault tree analysis (FTA), and others [13,14]. While other methods are qualitative [13], FTA is a quantitative method. It is useful and easily possible to integrate results from applying methods such as the "what-if" approach, FMEA, or HAZOP into FTA [15].

FTA is a logical and diagrammatic method used to describe accident failure modes. FTA interprets the relationship between the malfunction of system components and observed symptoms and evaluates the probability of an accident resulting from sequences and combinations of faults and failures. Probabilistic FTA is a quantitative analysis tool used to calculate the probability of a top event from given failure probabilities of system components [13].

FTA is extensively and very successfully applied to safety studies in nuclear, chemical, and aerospace industries [16]. However, application to potentially hazardous laboratory-scale systems is rarely found in the literature, although occurrence of hazardous events is very likely due to many reasons, such as congested space, using frangible material of construction (i.e., plastic or glass), frequent changes in operating conditions and layout, excessive manual work, and lack of knowledge about the process performance.

The objective of this article is to present a quantitative safety analysis of a laboratory-scale continuous bioreactor system for H_2S gas biotreatment using the FTA approach as an important element in laboratory-scale process safety management system.

METHODS

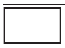
Process Description

The bioreactor system used in this study is almost similar in operation to many other laboratory-scale systems found in the literature. The process diagram of the laboratory-scale bioreactor system is shown in Figure 1. The acrylic airlift bioreactor (ALBR) is 80% filled with a suspension of sulfide oxidizing bacteria (SOB). The SOB is fed with mineral nutrient solution, including the inorganic carbon source, from the nutrient tank T1 by a peristaltic pump (PP1) adjusted to a predetermined flow rate. The temperature of the bioreactor is controlled by circulating heated water through the bioreactor jacket using a thermostated water circulation bath (TWCB).

The air–H_2S mixture is prepared by joining a stream of compressed air coming from the air compressor (COMP) to a stream of H_2S coming from the gas cylinder (H2SCYL). The pressure reducers PRG1 and PRG2 control the pressure of the air stream and H_2S gas stream, respectively. Furthermore, the needle valves VNG1 and VNG2 insure more control on the flow rates of air and H_2S, respectively. The gas flow rates are measured using flow meters FM1 (for H_2S) and FM2 (for air–H_2S mixture) before being introduced to the bottom of the ALBR through a gas distribution perforated plate (GDIST) with 1-mm holes. The gas is sampled for measurement at the inlet and outlet sample points SMP1 and SMP2, respectively.

Important parameters such as pH, dissolved oxygen, and temperature are monitored using the PDT1 and PDT2 sensors in the ALBR and the sulfur settler (SS), respectively. Other parameters are measured by sampling at SMP3 and SMP4 by applying the appropriate analyses. Elevated pH values are controlled by adding HCl from the tank T2 using the peristaltic pump PP2.

Table 1. Symbols used in fault trees.

Symbol	Stands for
	Intermediate event
	Basic event
	OR gate
	AND gate
	External event (expected event)
	Transfer (the tree is continued elsewhere)

The mixed sulfur-cell suspension is withdrawn from the top of the ALBR to the SS for separation of elemental sulfur particles. The settled sulfur in the form of slurry is withdrawn from the bottom of the SS using a peristaltic pump PP3 adjusted to the same flow rate as that of the nutrient pump (PP1). The supernatant cell suspension containing lower sulfur content is recycled to the ALBR using a circulation pump (P1) operating at a predetermined flow rate that is controlled by the valves VBL4 and VBL5.

Development of Fault Trees

Once the process is described in details and the components of the system are identified, FTA can be conducted by applying the following steps:

1. *Top event identification*: This is the undesired or hazardous event resulting from the failure of system components or procedures. In our case, the top events considered are H_2S leakage inside the laboratory, H_2S leakage to outdoor from ALBR gas outlet, and leakage of liquid chemical/biological solution.
2. *Fault trees construction*: This is performed by identifying all possible scenarios that lead to each of the top events, such as system component failures, process variable changes, and human failures. These scenarios are presented in the form of failure logic diagrams using "AND" and "OR" gates to express relations that combine events so as to identify the Boolean expression relative to the top event. AND gate means that all the input events are necessary for producing the output event, whereas OR gate means that at least one of the input events is necessary for producing the output event. The lower event in each scenario is the basic event. Diagrams expressing these elements are defined in Table 1.
3. *Determination of minimal cut sets (MCSs)*: The MCS is defined as the smallest combination of basic events which, if they all take place, cause the top event. The identification of the MCSs of a fault tree enables the system's potential weak points to be highlighted [17]. They form the basis for deriving the structure function, which is appropriate for the quantification of the fault tree in terms of the probability or expected frequency of occurrence of the undesired event [18]. In general, there exist several MCSs for a technical system; each of them constitutes a possible mode of its failure [16].
4. *Quantitative analysis of fault tree*: This step aims to calculate the probability or frequency of the top event. This can be performed using reliability data (failure rates) of system components and operators by applying Boolean or gate-by-gate approach. Also, cut set importance and basic event importance can be analyzed.

Probability Analysis

Assuming the failure rate of a component (λ_i) is constant [19], the probability of an event (P_i) is calculated using the following Poison expression

$$P_i = 1 - e^{-\lambda_i t} \tag{1}$$

If $\lambda_i t$ is small (i.e., <0.1), the expression may be simplified to

$$P_i = \lambda_i t \tag{2}$$

The mean time before failure (MTBF) of a component is the reciprocal of failure rate [20] and is calculated as

$$(\mathrm{MTBF})_i = \frac{1}{\lambda_i} \tag{3}$$

With an assumption that the basic events are independent [21], the probability (P_k) of a given MCS k with n_k basic events is the product of the probabilities of its basic events as in Eq. (4).

$$P_k^n = \prod_{i=1}^{n_k} P_i \tag{4}$$

The probability of a top event (P_T) with N MCSs can be finally calculated using the expression

$$P_\mathrm{T} = 1 - \prod_{k=1}^{N} (1 - P_k) \tag{5}$$

The importance of a MCS (I_k) and that of a basic event (I_i) can, therefore, be calculated using the following equations [22]

$$I_k = \frac{P_k}{P_\mathrm{T}} \tag{6}$$

$$I_i = \sum_{k=1}^{M} I_k \tag{7}$$

where M is the number of MCSs containing the basic event i. Failure contribution of a basic event F_i can also be calculated by the expression

$$F_i = \sum_{k=1}^{M} P_k \tag{8}$$

Component Failure Data

Most of the failure data used in this study were extracted from many sources [23–28]. In the case where failure rate of a given component differs from one source to another, the highest one was selected. This was applied for more safety, and because laboratory-scale components are less durable than full-scale ones. The remaining failure data were calculated from the bioreactor performance history, such as SOB failure, ALBR leakage, perforated gas distribution blockage,

Table 2. Basic events and failure modes description.

Abbreviation	Description
Basic events	
ALBR	Airlift bioreactor
COMP	Air compressor
FM	Flow meter
GDIST	Gas distributer
GTUBE	Gas tubing
H2SCYL	H_2S cylinder
HUM	Human error
LTUBE	Liquid tubing
OPV	Operational variables
P	Pump
POWER	Power supply
PP	Peristaltic pump
PRG	Pressure regulator
SOB	Sulfide oxidizing bacteria
SS	Sulfur settler
T	Tank
TJ	Tee joint
VBL	Liquid ball valve
VNG	Gas needle valve
WBP	Water bath pump
WBTC	Water bath temp. controller
Failure modes	
_B	Blocked
_F	Failure/fails running
_L	Leaks
_OS	Over-speed
_PF	Component power fails
_R	Rupture
_STUD	Study
_US	Under-speed

peristaltic pump leakage, and so forth. The majority of human failures were considered to be skill-based errors (e.g., slips of actions and lapses of memory) with almost the same error contribution conditions. Furthermore, all system components and variables were adjusted manually by the same laboratory technician. Therefore, a constant probability of 0.005 was calculated by HEART technique [29] for all kinds of human failure involved in this study. Similar value was reported and used in other applications [30].

The failure rates of system components were converted to probabilities of failure using Eq. (1) or (2). The descriptions of basic events and failure modes are presented in Table 2. The information of each basic event (e.g., ID name, description, and probability) is presented in the constructed fault trees shown in the subsequent figures.

It should be noticed that the basis for calculating the probabilities of failure of basic events and top events is 1 h. This implies that the probability shown for a given basic event is the probability that this component fails within a period of 1 h. Usually, the basis for probability calculation is one year (or 8760 h) in industrial applications. However, in laboratory-scale and pilot-scale applications, the process is not operated in steady-state all the time (i.e., variations are many), and the available space is limited. This increases the rates of components failure and human errors. Furthermore, the permissible human exposure levels for a chemical hazard are based on 8-h exposure duration, or even minutes (e.g., short-term exposure limit and ceiling value) such as the case with H_2S. This makes the basis of 1 h for the probability of failure in this study more reasonable than longer periods.

RESULTS AND DISCUSSION

The Top Event "H_2S Leakage Inside the Laboratory"

The fault tree of the top event "H_2S leakage inside the laboratory" is shown in Figure 2. The tree involves a total of 30 basic events, of which six events are repeated. The unrepeated events are, therefore, 24 basic events. The MCSs for this top event are 30 MCSs. Table 3 presents the probability and importance of each of the 30 MCSs as calculated using Eqs. (4) and (6). Table 3 shows that the most important MCSs are GDIST_B (importance: 18.25%), followed by PRG2_L, VNG2_L, VNG3_L, and VNG4_L (importance: 14.60% each), and then ALBR_L, FM1_L, and FM2_L (importance: 7.31% each). Also, there are seven MCSs with importance in the range 0.04–0.73%, whereas the remaining 15 MCSs are of minor importance.

Based on the determined MCSs and using Eqs. (7) and (8), the failure contribution and importance of the 24 basic events involved in the occurrence of the top event were calculated and presented in Table 4. A basic event that is, also, a MCS has the same importance. For instance, the event GDIST_B has an importance of 18.25% both as a basic event and as a MCS (Tables 3 and 4). The basic event HUM_F (human failure) has an importance of 0.15% in the occurrence of the top event "H_2S leakage inside the laboratory."

Using a simple decision making tool, such as Pareto analysis or ABC analysis, the system components GDIST (gas distributer inside the bioreactor), the regulator PRG2, and the valves VNG2, VNG3, and VNG4 should be given a first priority in the form of periodical maintenance or even replacement before failure to minimize the likelihood of the top event. These components had a total importance of about 77%. The second priority is given to the components ALBR assembly and the flow meters FM1 and FM2, which have a collective importance of about 22%.

The relatively high importance of the basic event GDIST_B is attributed to the fact that elemental sulfur particles are a major product of the biological oxidation of H_2S. A portion of these particles gradually settle and stick by the SOB on the gas distributer and cause blocking of the GDIST holes. Unless an appropriate maintenance and cleaning scheme is established, this causes bioreactor rupture due to increased pressure (intermediate event E3 in Figure 2). On the other hand, the pressure regulator PRG2 and the gas needle valves (VNG) contain metallic parts in their construction that might be affected by the corrosive H_2S, resulting in their failure and leakage (intermediate events E4 and E5 in Figure 2).

The maintenance scheme of these components can be determined by taking into account the MTBF of each component as calculated by Eq. (3). For instance, the calculated MTBF for GDIST is 2,000 h (or 83 days). This necessitates periodic maintenance within time intervals sufficiently shorter than 83 days (say every 2 months), keeping in mind that this interval might be shortened in case of extra formation of elemental sulfur due to excessive H_2S loads applied to the bioreactor. Besides proper maintenance, a pressure gauge should be fixed to the gas stream entering the bioreactor for detecting the increased back pressure at early stages of GDIST blocking. This may help taking the right decision on GDIST maintenance before failure.

Equation (5) results in a top event probability of 2.737×10^{-3}, which is the probability of H_2S gas leakage from the system inside the laboratory within a given hour. Using Eq. (1), this probability is equivalent to a gas leakage frequency (λ) of 2.74×10^{-3} per hour or about two leakage events per month. At first glance, this frequency may be thought in as small. However, this is untrue knowing that the

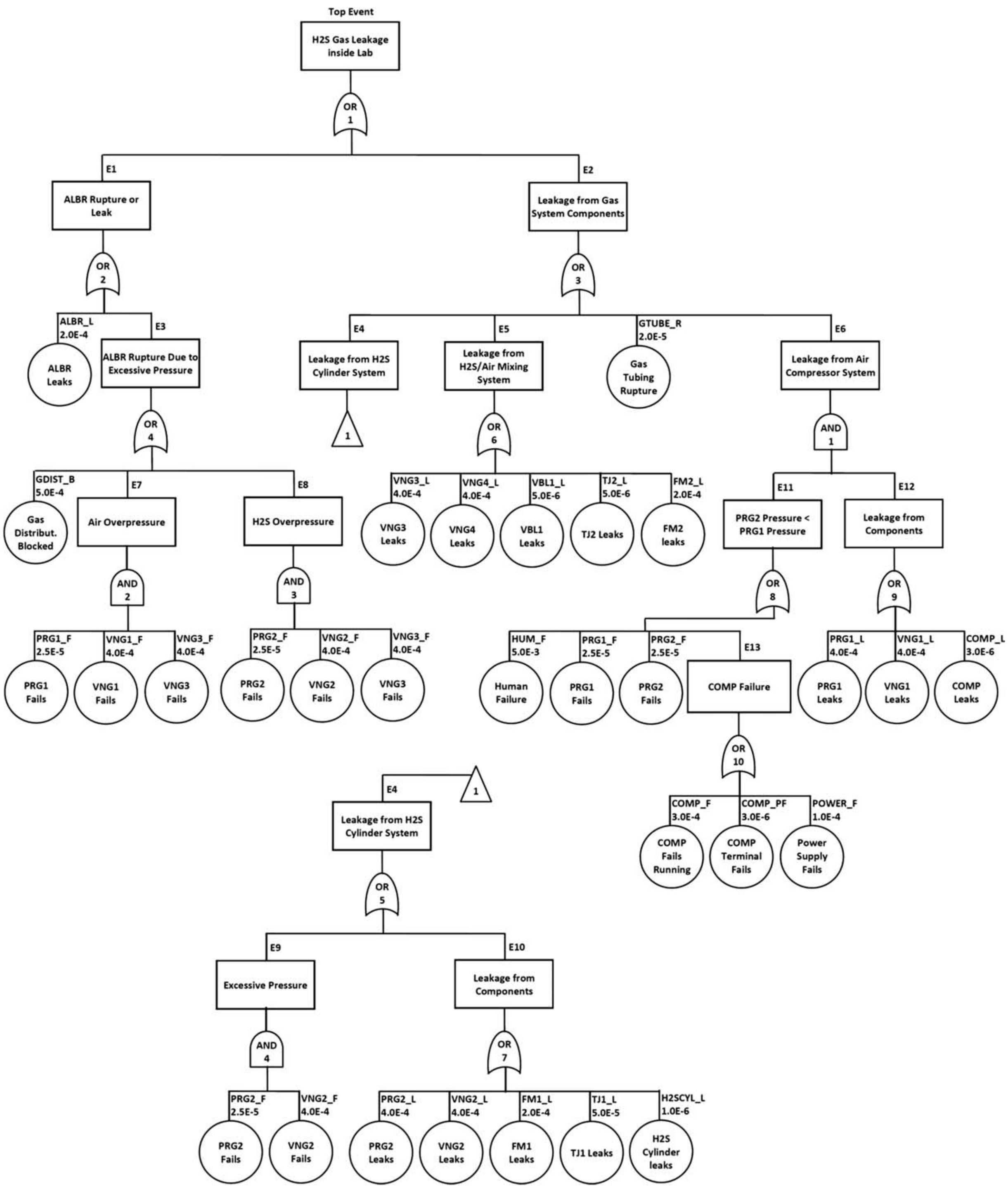


Figure 2. Fault tree for the top event "H_2S leakage inside the laboratory."

concentration and duration of H_2S leakage can be, unexpectedly, very hazardous.

The calculated probability and frequency of the top event "H_2S leakage inside the laboratory" can be minimized by controlling the most important basic events leading to its occurrence. For instance, if the basic event GDIST_B is completely controlled (e.g., by good maintenance scheme), its contribution to failure will be zero and the top event probability will be reduced to 2.238×10^{-3} (frequency: 1.6 per month). On the other hand, if all the above-mentioned first priority components are appropriately controlled, the top event probability will be reduced to 6.4×10^{-4} (frequency: 0.5 per month). Similarly, further reduction of top event probability to 4.04×10^{-5} (frequency: 0.03 per month), if the second priority components are properly controlled.

The Top Event "H_2S Leakage to Outdoor from ALBR Gas Outlet"

Figure 3 shows the fault tree for the top event "H_2S leakage to outdoor from ALBR gas outlet," which have 22 contributing basic events and one external event (operational

Table 3. MCSs for the top event "H_2S gas leakage inside the laboratory."

No.	Cut Set	Probability	Importance (%)
1	GDIST_B	5.0 E − 04	18.25
2	PRG2_L	4.0 E − 04	14.60
3	VNG2_L	4.0 E − 04	14.60
4	VNG3_L	4.0 E − 04	14.60
5	VNG4_L	4.0 E − 04	14.60
6	ALBR_L	2.0 E − 04	7.30
7	FM1_L	2.0 E − 04	7.30
8	FM2_L	2.0 E − 04	7.30
9	GTUBE_R	2.0 E − 05	0.73
10	TJ1_L	5.0 E − 06	0.18
11	TJ2_L	5.0 E − 06	0.18
12	VBL1_L	5.0 E − 06	0.18
13	HUM_F PRG1_L	2.0 E − 06	0.07
14	HUM_F VNG1_L	2.0 E − 06	0.07
15	H2SCYL_L	1.0 E − 06	0.04
16	COMP_F PRG1_L	1.2 E − 07	0.00
17	COMP_F VNG1_L	1.2 E − 07	0.00
18	POWER_F PRG1_L	4.0 E − 08	0.00
19	POWER_F VNG1_L	4.0 E − 08	0.00
20	COMP_L HUM_F	1.5 E − 08	0.00
21	PRG1_F PRG1_L	1.0 E − 08	0.00
22	PRG1_F VNG1_L	1.0 E − 08	0.00
23	PRG1_L PRG2_F	1.0 E − 08	0.00
24	PRG2_F VNG1_L	1.0 E − 08	0.00
25	PRG2_F VNG2_F	1.0 E − 08	0.00
26	COMP_F COMP_L	9.0 E − 10	0.00
27	COMP_L POWER_F	3.0 E − 10	0.00
28	COMP_L PRG1_F	7.5 E − 11	0.00
29	COMP_L PRG2_F	7.5 E − 11	0.00
30	PRG1_F VNG1_F VNG3_F	4.0 E − 12	0.00

Table 4. Basic event analysis for the top event "H_2S gas leakage inside the laboratory."

No.	Event	Failure Contribution	Importance (%)
1	GDIST_B	5.000 E − 04	18.25
2	PRG2_L	4.000 E − 04	14.60
3	VNG2_L	4.000 E − 04	14.60
4	VNG3_L	4.000 E − 04	14.60
5	VNG4_L	4.000 E − 04	14.60
6	ALBR_L	2.000 E − 04	7.30
7	FM1_L	2.000 E − 04	7.30
8	FM2_L	2.000 E − 04	7.30
9	GTUBE_R	2.000 E − 05	0.73
10	TJ1_L	5.000 E − 06	0.18
11	TJ2_L	5.000 E − 06	0.18
12	VBL1_L	5.000 E − 06	0.18
13	HUM_F	4.015 E − 06	0.15
14	PRG1_L	2.180 E − 06	0.08
15	VNG1_L	2.180 E − 06	0.08
16	H2SCYL_L	1.000 E − 06	0.04
17	COMP_F	2.409 E − 07	0.01
18	POWER_F	8.030 E − 08	0.00
19	PRG2_F	3.008 E − 08	0.00
20	PRG1_F	2.008 E − 08	0.00
21	COMP_L	1.635 E − 08	0.00
22	VNG2_F	1.000 E − 08	0.00
23	VNG1_F	4.000 E − 12	0.00
24	VNG3_F	4.000 E − 12	0.00

variable study, OPV_STUD). This event is called "expected event," that is, it is planned to occur. In this study, it represents the immediate effect of changing the value of an operational parameter (as part of the research plan) on SOB activity, such as H_2S load, temperature, pH, and so forth. At this stage, this event is given a probability of 1.0. Thereafter, when the SOB acclimatizes to the new condition and the bioreactor operates in steady-state condition, this event is given a probability of zero. Precautions are normally followed during occurrence of the external event due to expected gas release, such as scrubbing the outlet stream by lead acetate solution to capture H_2S gas prior to discharge to the atmosphere. However, in steady-state operation and during the absence of that event, gas leakage to outdoor will happen due to other failure events. Therefore, our main interest in the following discussion is operational variables control failure due to system components or human error (event E2 in Figure 3).

The top event probability at steady-state conditions (i.e., OPV_STUD probability = 0.0) is calculated as 1.22×10^{-3}. However, in transient conditions (i.e., OPV_STUD probability = 1.0), the probability of the top event is sharply increased to 0.101.

The MCSs for the top event "H_2S leakage to outdoor from ALBR gas outlet" are presented in Table 5. There are 19 MCSs for this top event. Out of these, 18 are second-order cut sets (i.e., involve two basic events) and only one is fourth-order cut set (i.e., involves four basic events). The reason for this is that there must be at least two basic events for the top event to occur, illustrated by the AND gate number 1 in the first level of the fault tree (Figure 3). The basic event SOB_F must be one of these events, because the top event will not happen if SOB can withstand the variations in operational parameters. This is why the importance of the basic event SOB_F is 100% (Table 6). It should be noticed that SOB_F is a conditional event (i.e., not independent). It happens only if at least one of the other basic events in the fault tree occurs.

Table 5 shows that the most important MCS is HUM_F SOB_F (40.89%), indicating high contribution of human failure to the occurrence of the top event. In line with this, Table 6 shows that the importance of the basic event HUM_F is 40.89%. This is attributed to the role of manual work in the adjustment and control of bioreactor operational variables, such as opening/closing valves, adjusting pump flow rates, pH and chemical formulations, and observing flow meters and other meter displays. Measures to minimize human failure are many, including training, raising safety awareness, using suitable quality assurance techniques (such as standard procedures, checklists, double checks, etc.), better ergonomic design, and automation. On the other hand, the total importance of the two basic events PP1_L and PP2_L is 40.9% (Table 6). The type of peristaltic pumps PP1 and PP2 is that depending on squeezing a stretched silicone tube to enforce chemical solution flow. Continuous stretching and squeezing leads to silicone tube rupture with time. This event results in either nutrient supply deficiency (event E4 in Figure 3) or improper pH adjustment (event E5 in Figure 3), depending on the leaking pump. To control this type of basic events, regular replacement of the silicone-tubing part is necessary. This can be determined by the MTBF of this component, as calculated using Eq. (3), being 400 h or 16.7 days (say replacement every 15 days). If all of the first priority basic events (HUM_F, PP1_L, and PP2_L) are controlled, the top event probability will be reduced to 7.71×10^{-4}.

The Top Event "Leakage of Liquid Chemical/Biological Solution"

The fault tree of the top event "leakage of liquid chemical/biological solution" is illustrated in Figure 4. There are 32

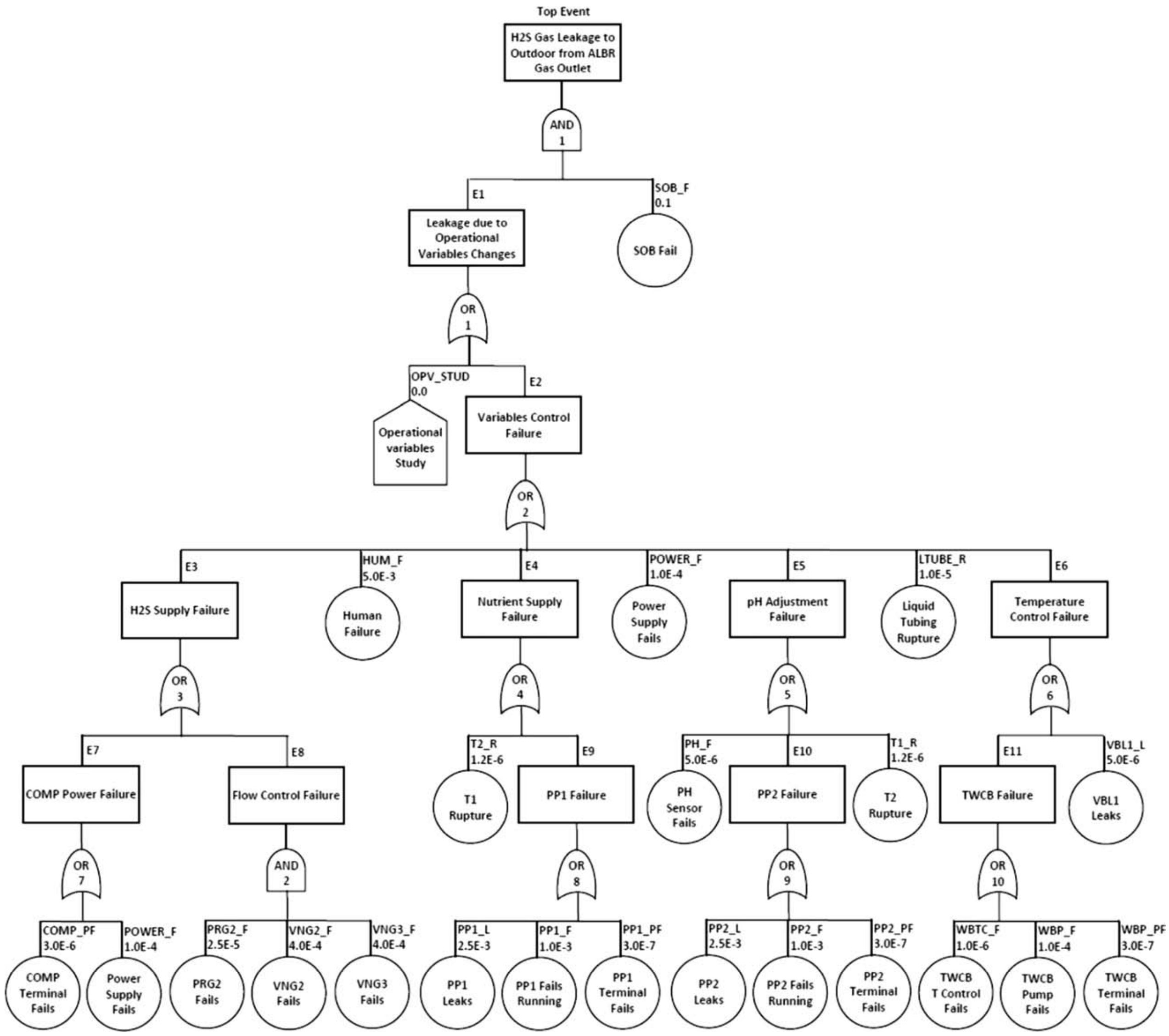


Figure 3. Fault tree for the top event "H_2S leakage to outdoor from ALBR gas outlet."

different basic events that might contribute to this top event. The number of MCSs for this top event is 28, as presented in Table 7. Two MCSs are third-order, whereas the majority (26 MCSs) are first-order cut sets. This is mainly because the AND gates are in the lower levels of the fault tree. This explains, also, the similar importance values for those 26 MCSs when presented as basic events in Table 8.

Priority analysis reveals that the four basic events human failure (HUM_F), PP1 over-speed (PP1_OS), PP3 over-speed (PP3_OS), and PP3 under-speed (PP3_US) are considered first-priority events to be controlled, where their importance is 68.16%, collectively. The control of human failure is discussed in the previous section. Over-speeding and under-speeding of the peristaltic pumps might be controlled by accurate and regular calibration and by proper replacement scheme of the silicone-tubing component of the pumps, because relaxation of the tube with extended use will change the pump speed. It was mentioned in the previous section that the replacement of the silicone tube of the peristaltic pump to control pump leakage due to silicone tube rupture should be at intervals shorter than 16.7 days. However, the MTBF of the basic events involving over-speeding or under-speeding of the peristaltic pumps is 200 h (or 8.3 days), which is half the MTBF of the pump leakage. This necessitates replacement of the silicone-tubing component before 8.3 days rather than the previously proposed 15-day interval.

Interestingly, the second-priority basic events to be controlled are PP1_L, PP2_L, and PP3_L, which have a total importance of 25.56%. Furthermore, the basic event PP3_F is one of the third-priority events with an importance of 3.41% (Table 8). This implies that the peristaltic pumps of the system are responsible for 80.1% of the chances of the top event occurrence due to leakage, over-speeding, under-speeding, or failure. The high contribution of the peristaltic pumps to system failure necessitates a good maintenance scheme of these pumps. Successful maintenance of the pumps will decrease the probability of the top event from 2.898×10^{-2} down to 5.843×10^{-3}. Further decrease to 8.469×10^{-4} may be achieved by minimizing human errors.

Table 8 shows that the importance of the basic event GDIST_B is 1.7%, being much lower than its importance to the top event "H_2S leakage inside the laboratory," which is 18.25% (Table 3). This situation raises the awareness that all possible top events of a given process should be looked at

Table 5. MCSs for the top event "H_2S gas leakage to outdoor from ALBR gas outlet."

No.	Cut Set	Probability	Importance (%)
1	HUM_F SOB_F	5.0 E − 05	40.89
2	PP1_L SOB_F	2.5 E − 05	20.45
3	PP2_L SOB_F	2.5 E − 05	20.45
4	PP1_F SOB_F	1.0 E − 05	8.18
5	PP2_F SOB_F	1.0 E − 05	8.18
6	POWER_F SOB_F	1.0 E − 06	0.82
7	SOB_F WBP_F	1.0 E − 06	0.82
8	LTUBE_R SOB_F	1.0 E − 07	0.08
9	PH_F SOB_F	5.0 E − 08	0.04
10	SOB_F VBL1_L	5.0 E − 08	0.04
11	COMP_PF SOB_F	3.0 E − 08	0.02
12	SOB_F T1_R	1.2 E − 08	0.01
13	SOB_F T2_R	1.2 E − 08	0.01
14	SOB_F WBTC_F	1.0 E − 08	0.01
15	PP1_PF SOB_F	3.0 E − 09	0.00
16	PP2_PF SOB_F	3.0 E − 09	0.00
17	SOB_F WBP_PF	3.0 E − 09	0.00
18	PRG2_F SOB_F VNG2_F VNG3_F	4.0 E − 14	0.00
19	OPV_STUD SOB_F	0.0 E + 00	0.00

Table 6. Basic event analysis for the top event "H2S gas leakage to outdoor from ALBR gas outlet."

No.	Event	Failure Contribution	Importance (%)
1	SOB_F	1.223 E − 04	100.00
2	HUM_F	5.000 E − 05	40.89
3	PP1_L	2.500 E − 05	20.45
4	PP2_L	2.500 E − 05	20.45
5	PP1_F	1.000 E − 05	8.18
6	PP2_F	1.000 E − 05	8.18
7	POWER_F	1.000 E − 06	0.82
8	WBP_F	1.000 E − 06	0.82
9	LTUBE_R	1.000 E − 07	0.08
10	PH_F	5.000 E − 08	0.04
11	VBL1_L	5.000 E − 08	0.04
12	COMP_PF	3.000 E − 08	0.02
13	T1_R	1.200 E − 08	0.01
14	T2_R	1.200 E − 08	0.01
15	WBTC_F	1.000 E − 08	0.01
16	PP1_PF	3.000 E − 09	0.00
17	PP2_PF	3.000 E − 09	0.00
18	WBP_PF	3.000 E − 09	0.00
19	PRG2_F	4.000 E − 14	0.00
20	VNG2_F	4.000 E − 14	0.00
21	VNG3_F	4.000 E − 14	0.00
22	OPV_STUD	0.000 E + 00	0.00

together to decide all the basic events that should be given a first or second priority in control. A given basic event of low importance to one of the top events could be of high importance to another.

FTA Results Versus Observed Bioreactor Safety Performance

Frequencies of occurrence of the three top events in concern as calculated by FTA were compared to their observed occurrences before and after control of the most important basic events (Table 9). There is good agreement between the calculated and observed frequencies of the three top events, as described by the observed/FTA calculated frequency of occurrence. However, the observed number of H_2S gas leak events was relatively higher than the calculated frequency for the same event if the important basic events are to be controlled (Observed/FTA = 1.3). This might be attributed for a delay in replacement of a defective gas needle valve where it should have been replaced earlier.

It should be mentioned that the observed occurrence frequencies of the three top events were those recorded in a period of 4 months after applying the recommended corrective/preventive actions based on FTA. It is expected that the observed/FTA calculated ratio would be close to unity if longer period of observation was involved.

The good agreement between the observed and calculated occurrence probability and frequency of the three hazardous top events is an evidence of the effectiveness of using FTA method for safety and reliability analysis of laboratory-scale processes.

CONCLUSIONS

Laboratory-scale bioreactors treating H_2S may impose serious health and safety problems to the labors, equipment, and materials during failure events. In this article, we presented a quantitative safety and reliability analysis of a bioreactor system for H_2S biotreatment using FTA technique. Analysis of the most important hazardous top events (e.g., gas and liquid leakage) was considered. The presented analysis proves that this technique is an effective tool to quantitatively assess the risk of potential hazards of the process in terms of probability of these hazards (top events), probability and importance of each scenario that might lead to their occurrence (MCSs), and importance of each of the system components that initiate the occurrence of these hazards (basic events). These analyses allow better decision on priority of control measures, and maintenance or replacement schemes of the system components in an endeavor to minimize the probability of failure or hazard occurrence. For instance, the following basic events are considered first-priority events to be controlled for minimizing occurrence of the relevant top events:

- The basic events GDIST_B, PRG2_L, VNG2_L, VNG3_L, and VNG4_L for the top event "H_2S leakage inside the laboratory."
- The basic events HUM_F, PP1_L, and PP2_L for the top event "H_2S leakage to outdoor from ALBR gas outlet."
- The basic events HUM_F, PP1_OS, PP3_OS, and PP3_US for the top event "leakage of liquid chemical/biological solution."

In practice, all these important basic events should be equally treated, regardless of the variation of their importance to the three top events. A given basic event with minor importance to the occurrence of one top event might be of great importance to the occurrence of another top event. This is the reason of why the three top events were not integrated in one top event. Integration into one overall top event (i.e., leakage of any type) might cause changes in the importance of the basic events. For instance, the basic events that are important to the top event of the least probability of occurrence among others will certainly be much less important to the overall top event. This might result in improper decision taking. As an illustration of this case, probability of the top event "H_2S leakage inside the laboratory" is lower than that of the top event "leakage of liquid chemicals," although it might be more dangerous. The most important basic event of the former top event is GDIST_B (18.25%).

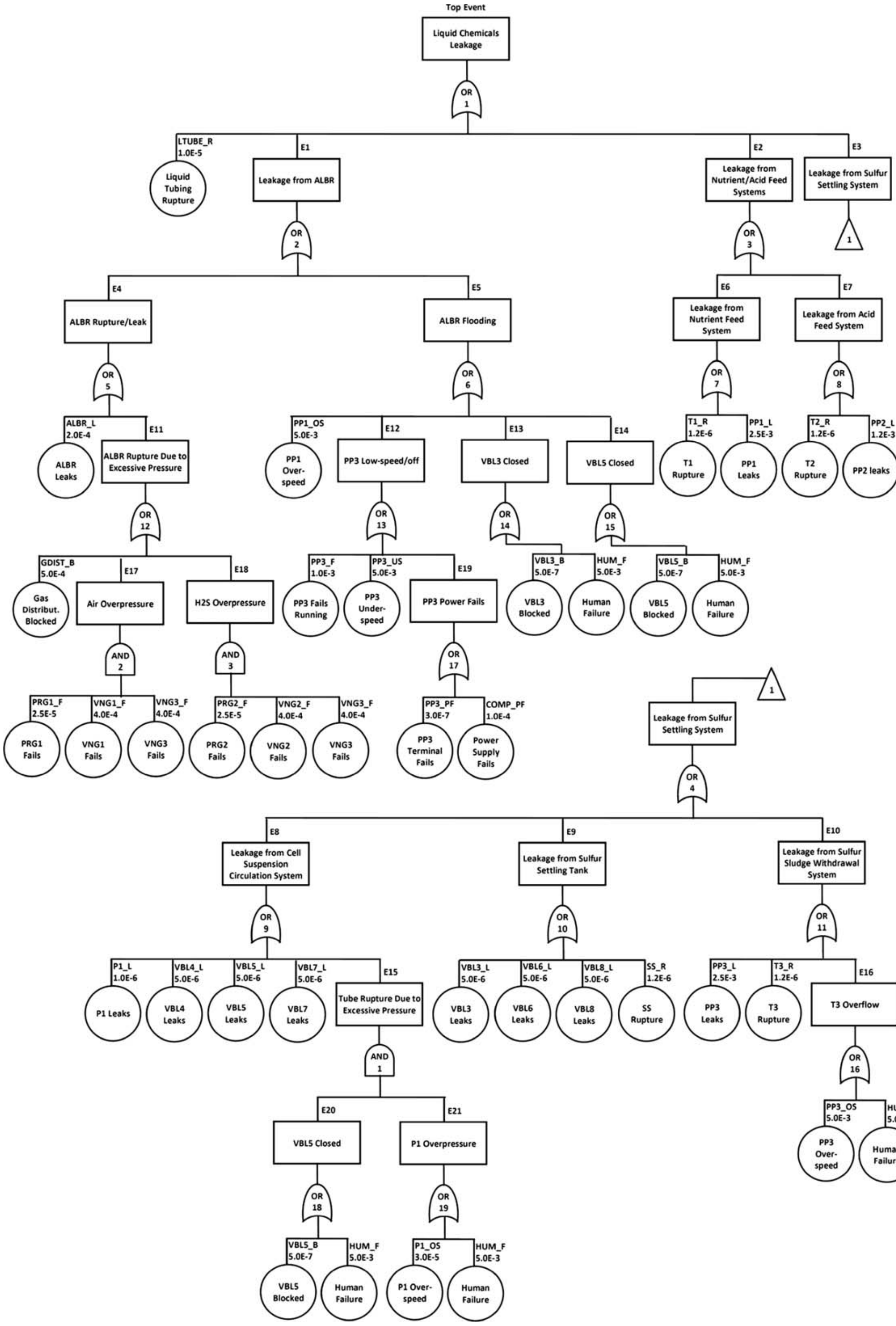


Figure 4. Fault tree for the top event “leakage of liquid chemical/biological solution.”

However, when integrating the three studied fault trees, the basic event will have an importance of 1.61% and will be classified as second-priority basic event. Therefore, careful determination of the top events is a key element in the success of safety analysis using FTA approach.

The reliability data used in this study were adopted from industrial-scale equipment databases. In contrast to industrial equipment, the reliability data of laboratory-scale equipment and auxiliaries are limited. This situation calls for an act to enforce laboratory equipment manufacturers to make

Table 7. MCSs for the top event "liquid chemical leakage."

No.	Cut Set	Probability	Importance (%)
1	HUM_F	5.0 E − 03	17.04
2	PP1_OS	5.0 E − 03	17.04
3	PP3_OS	5.0 E − 03	17.04
4	PP3_US	5.0 E − 03	17.04
5	PP1_L	2.5 E − 03	8.52
6	PP2_L	2.5 E − 03	8.52
7	PP3_L	2.5 E − 03	8.52
8	PP3_F	1.0 E − 03	3.41
9	GDIST_B	5.0 E − 04	1.70
10	ALBR_L	2.0 E − 04	0.68
11	POWER_F	1.0 E − 04	0.34
12	LTUBE_R	1.0 E − 05	0.03
13	VBL3_L	5.0 E − 06	0.02
14	VBL4_L	5.0 E − 06	0.02
15	VBL5_L	5.0 E − 06	0.02
16	VBL6_L	5.0 E − 06	0.02
17	VBL7_L	5.0 E − 06	0.02
18	VBL8_L	5.0 E − 06	0.02
19	SS_R	1.2 E − 06	0.00
20	T1_R	1.2 E − 06	0.00
21	T2_R	1.2 E − 06	0.00
22	T3_R	1.2 E − 06	0.00
23	P1_L	1.0 E − 06	0.00
24	VBL3_B	5.0 E − 07	0.00
25	VBL5_B	5.0 E − 07	0.00
26	PP3_PF	3.0 E − 07	0.00
27	PRG1_F VNG1_F VNG3_F	4.0 E − 12	0.00
28	PRG2_F VNG2_F VNG3_F	4.0 E − 12	0.00

Table 8. Basic event analysis for the top event "liquid chemical leakage."

No.	Event	Failure Contribution	Importance (%)
1	HUM_F	5.0 E − 03	17.04
2	PP1_OS	5.0 E − 03	17.04
3	PP3_OS	5.0 E − 03	17.04
4	PP3_US	5.0 E − 03	17.04
5	PP1_L	2.5 E − 03	8.52
6	PP2_L	2.5 E − 03	8.52
7	PP3_L	2.5 E − 03	8.52
8	PP3_F	1.0 E − 03	3.41
9	GDIST_B	5.0 E − 04	1.70
10	ALBR_L	2.0 E − 04	0.68
11	POWER_F	1.0 E − 04	0.34
12	LTUBE_R	1.0 E − 05	0.03
13	VBL3_L	5.0 E − 06	0.02
14	VBL4_L	5.0 E − 06	0.02
15	VBL5_L	5.0 E − 06	0.02
16	VBL6_L	5.0 E − 06	0.02
17	VBL7_L	5.0 E − 06	0.02
18	VBL8_L	5.0 E − 06	0.02
19	SS_R	1.2 E − 06	0.00
20	T1_R	1.2 E − 06	0.00
21	T2_R	1.2 E − 06	0.00
22	T3_R	1.2 E − 06	0.00
23	P1_L	1.0 E − 06	0.00
24	VBL3_B	5.0 E − 07	0.00
25	VBL5_B	5.0 E − 07	0.00
26	PP3_PF	3.0 E − 07	0.00
27	VNG3_F	8.00 E − 12	0.00
28	PRG1_F	4.0 E − 12	0.00
29	PRG2_F	4.0 E − 12	0.00
30	VNG1_F	4.00 E − 12	0.00
31	VNG2_F	4.00 E − 12	0.00
32	P1_OS	0.0 E + 00	0.00

Table 9. Comparison between calculated and actual failure frequency before and after FTA.

Top Event	Failure Rate (Per Hour) Before FTA Recommendations (Average of 2 Months)			Failure Rate (Per Hour) After FTA Recommendations (Average of 4 Months)		
	FTA Results	Observed	Observed/FTA	FTA Results	Observed	Observed/FTA
H_2S leakage indoor	2.74 E − 03	3.20 E − 03	1.20	6.40 E − 04	8.33 E − 04	1.30
H_2S leakage to outdoor	1.22 E − 03	1.40 E − 03	1.15	7.71 E − 04	6.94 E − 04	0.90
Liquid chemicals leakage	2.94 E − 02	2.45 E − 02	0.84	8.47 E − 04	8.33 E − 04	0.98

reliability data (e.g., rate of failure) available in their product catalogs.

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