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RISK ANALYSIS OF CRYOGENIC AMMONIA STORAGE TANK IN IRAN BY FAULT TREE METHOD

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من أهم المخاطر المتعلقة بتنكات تخزين الأمونيا هو تسرب كميات كبيرة من هذه المادة بسبب أعطال الخزانات. في الآونة الأخيرة، تم بناء العديد من خزانات الأمونيا في إيران وهو الأمر الذي يتطلب دراسة عميقة حول مخاطر الفشل المرتبطة بها. في هذه الورقة، تم استخدام أسلوب fault tree كأسلوب للتقييم الكمي للمخاطر وذلك لتحديد وتقييم المخاطر ذات الصلة بأحد خزانات الأمونيا سعة 20000 طن. وقد تم تحديد خمسة أسباب رئيسية للإنبعاثات الكبيرة من الأمونيا كأحداث عليا. بناء على هذه الأحداث العليا، تم تحديد جميع الأحداث الفرعية واجراء التحليل باستخدام fault tree. تم اعداد نموذج (MECHREL) لتقييم المخاطر المرتبطة بخزان الأمونيا قيد الدراسة. بالاضافة لذلك تم دراسة حساسية كل حدث. ويمكن استخدام نتائج هذه الدراسة بشكل سريع لتحديد المسارات الأكثر أهمية من أجل اتخاذ قرارات على أساس المخاطر المحتملة.

The most important concern about an atmospheric ammonia storage tank is the release of the large amount of ammonia due to the loss of tank integrity. Recently, several ammonia storage tanks have been built in Iran which necessitates a deep study about the failure risk associated with them. In this paper, fault tree analysis as a quantitative risk assessment has been applied to specify and evaluate the related risks of ammonia storage tank with the capacity of 20,000 tons. Five major causes for the ammonia large release are specified as the top events. Based on these top events, all possible sub-events therefore are recognized and the fault tree analysis is performed. In-house software, MECHREL, is prepared to evaluate the risks related to the specified storage ammonia tank. Moreover, the sensitivity of each event is investigated in the following. These results can be used to identify the most critical paths quickly to have reasonable risk-based decisions.

1. INTRODUCTION

The cold storage tank is the equipment that can be found mostly in all industries. The necessity of the storing a large amount of liquefied gas at atmospheric pressure beside the inverse proportionality of the construction cost with the tank dimension[1], instigate the construction and design of storage tanks with capacity of 10,000 to 120,000 m^3. Apparently, an increase in tank dimensions would be accompanied by an increase in tank failure probability. Therefore, the risk assessment and elucidating the causal relations to optimize the design as well as prediction of failure modes seems inevitable.

In this paper, the fault tree method, which is a systematic risk assessment tool, is employed for an ammonia storage tank with the capacity of 20,000 tons in Lordegan petrochemical plant (Iran) to identify and evaluate the potential hazards leading to release of a large amount of ammonia liquid or vapor from the body or inlet/outlet lines to the environment as a final undemanding top event and based on this analysis, the critical failure modes are discovered. The results are a good guide in condition monitoring and make it possible to identify critical paths. This assessment is focused only to the internally-induced events which lead to catastrophic failure. These events are highly dependent upon human error or equipment failure. So, the external events (e.g., earthquakes, sabotage etc.) are not considered.

Generally, there are four common types of ammonia storage tanks, namely, ‘single’, ‘double’, ‘full’ and ‘membrane’ containments that the economical, environmental considerations, acceptable safety level and system reliability are the effective parameters in type selection. Single containment double wall type is a common type in ammonia industries in Iran. Recently, several high capacity tanks of this type have been built or are under construction to store the liquid ammonia at -40 ^oC. In the single containment system, a carbon steel main wall, primary container, is used to contain the liquid ammonia and the outer wall retains the thermal insulation. This wall, which is covered by a dome roof, plays also the role of a vapor barrier. A concrete dike wall must be foreseen around it to support the ammonia leakage in the case of tank failure. A schematic configuration of single containment double wall tank is depicted in Figure1[2].

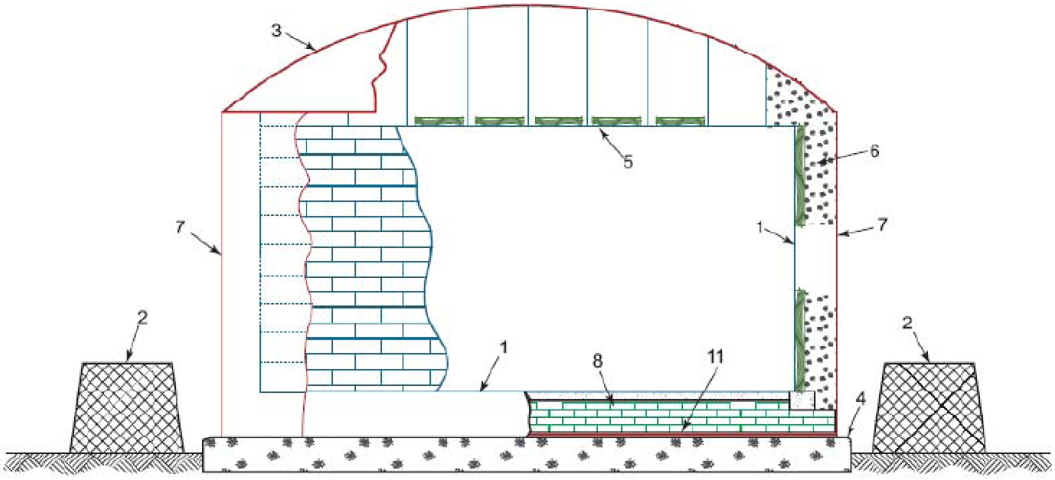

Figure 1. A schematic configuration of single containment double wall tank [3]

1) Primary liquid container (low temperature steel)	2) Secondary liquid container (dike)	3) Warm vapor container (roof)
4) Concrete foundation	5) Suspended deck with insulation	6) Insulation (Annular space)
7) Warm vapor container (outer shell)	8) Bottom insulation	9) Warm vapor container (outer bottom)

In the following, a detailed description of safety systems of a specific ammonia storage tank is expressed and then, the fault tree is modeled based on the specified storage tank. Finally, by identifying the cut sets, critical paths will be discovered. A sensitivity analysis is then performed to investigate the importance of each event and cut set.

2. AMMONIA TANK SPECIFICATIONS

The ammonia storage tank which is under study is a single containment, double wall type tank. It is designed to store 20,000 tons of liquid ammonia at -33 ^{o}C. The minimum and maximum design temperature is equal to -40 ^{o}C and +48 ^{o}C, respectively. The inner wall of the tank diameter is 44m and the diameter of the outer wall is 45.4m with a height of 21m. The minimum and maximum tank design pressure is set equal to -9.8 mbarg and 98 mbarg, respectively. Figure 2 shows a schematic view of tank safety systems. The abbreviation of each component has been brought in nomenclatures. To setup the fault tree analysis, the first step is to discover all top events, which lead to catastrophic release of ammonia to the environment.

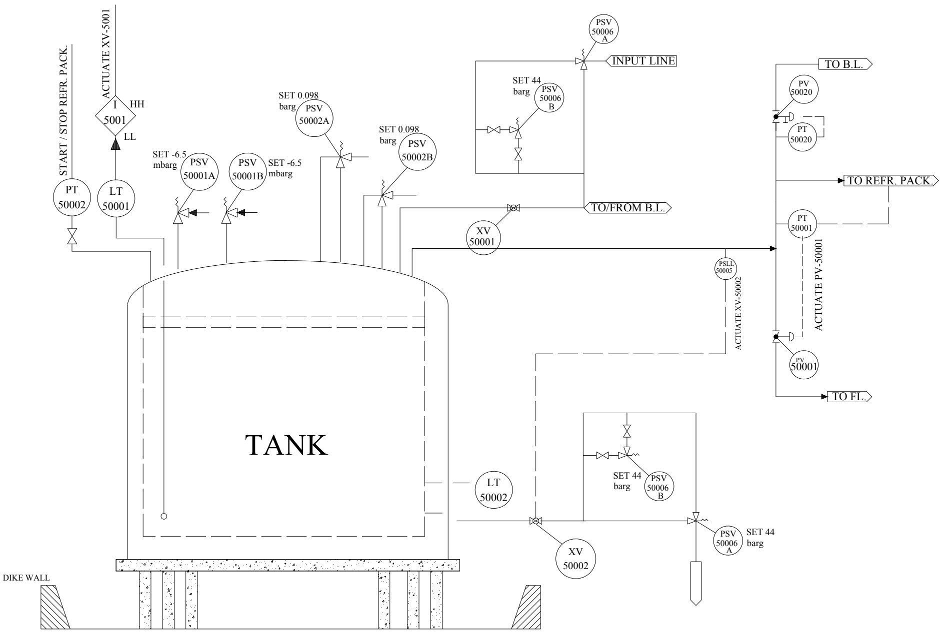

Figure 2. A schematic sketch of tank safety diagram

For the specified tank, five internal events, which may be under control, are discovered:

- Ammonia release due to overfilling.
- Ammonia release due to over pressurization.
- Ammonia release due to under pressurization.
- Ammonia release due to rupture of the inlet loading line.
- Ammonia release due to rupture of the outlet loading line.

These five events are asserted to be the major reasons of tank failure.

3. FAULT TREE ANALYSIS

Fault tree is a logical and diagrammatic tool to interpret the relationship between the malfunction of components. It is used to evaluate the probability of an accident resulting from sequences or combinations of faults and failures. In this method, by means of Boolean algebra, all the events resulting to accident of hazards will be discovered. "AND" and "OR" are the two gates which are used mostly in Boolean algebra. The AND logic function is used whenever the simultaneous happening of input events triggers the output event, while, the logic function OR shows that events are related in series and happening of one input will lead to top event occurrence[4].

In analyzing a fault tree, top event may occur by various combinations of events, called cut sets. By omitting all repetitive events from cut sets, the resulting sets are called minimal cut sets which show the smallest combination of components failure which, if they happen simultaneously, the top event will happen. Classification of all cut sets will result in the valuable information to specify investment plan to improve the reliability and safety of system.

After setting up the fault tree, by specifying the failure rate or occurrence probability of basic events, the occurrence probability of undesired top event will be found out. Moreover, classifying of cut sets based on the number of components and their occurrence probability is the consequence of the analysis.

To set up a fault tree, one needs to know the valid historical data from the identical components of equipments in the same application. But unfortunately, most of the time, these data are unavailable and there is no choice but to rely on the other documents such as Process Equipment Reliability Data published by the Center for Chemical Process Safety (CCPS) of the American Institute of Chemical Engineers (AIChE)[5], or the information of other similar projects, if available.

However, it is not necessary to be concerned about the uncertainty of generic data because, the risk analysis method, inherently, has some uncertainties, furthermore, hierarchy of the events which lead to the undesirable event, is the major advantage[6]. Moreover, a sensitivity analysis helps in deciding about the components for which more data should be collected.

4. CALCULATION METHOD

To perform the fault tree analysis, quantitatively method, two types of failure probability values for equipments must be taken into consideration [7]:

- Unavailability: the probability of a component failure to response when it is on demand.
- Unreliability: probability that a component fails during mission time, though it has been successfully started.

In-house software, MECHREL[8], which is prepared by the authors, is used to simulate the fault tree. Modeling the fault tree, cut sets classification and finding out the minimal cut sets, all are performed by that software. Five major hazards that may lead to the final undesired accident are shown in Figure 3.

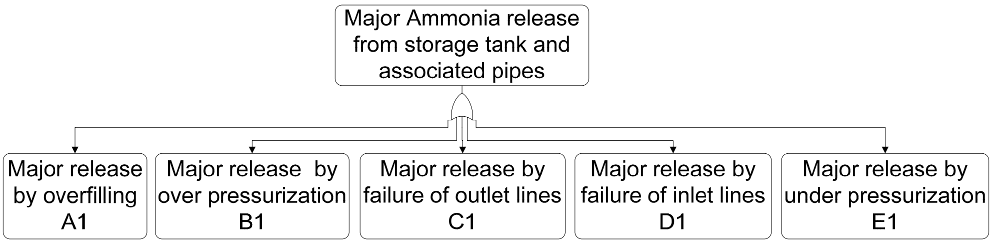

Figure 3. Fault tree diagram for major accidents that may lead to major release of ammonia

In the following, the fault tree of each major accident is described and the method of estimating the probability of the over pressurization is explained in detail. The failure rates or occurrence probabilities used to calculate failure probabilities are brought in Table 1. Based on these values, the cut sets for present fault tree are found out and sorted in Table 2.

Table 1. The failure rates used for the calculation of failure probabilities

Name	**Description**	**Failure rate**	**Unit**	**Ref.**
LT-50001 I	Fails to indicate liquid level correctly	$8.76x10^{-3}$	Per year	[12]
LT-50002 I	Fails to indicate liquid level correctly	$8.76x10^{-3}$	Per year	[12]
LT-50002 AL	Fails to alarm in H.L	$8.76x10^{-3}$	Per year	[12]
LT-50001 AC	Fails to actuate inlet valve in H.L.L.	$8.76x10^{-3}$	Per year	[12]
XV-50001 C	Fails to get closed	$6.62x10^{-3}$	-	[12]
PT-50020 AC	Fails to actuate PV-5002 in the pressure more than mbarg	$3.8x10^{-4}$	Per year	[5]
PV-50020 OP	Fails to open in pressure more than 50mbarg	$6.62x10^{-3}$	-	[5]
PT-50002 AC	Fails to run refrigerating package ate 70mbarg	$3.8x10^{-4}$	Per year	[5]
REFRIG.RUN	Fails in refrigeration package operation (Compressor)	$4x10^{-1}$	-	[5]
PT-50001 AC	Fails to load refrigerating package at 80mbarg	$3.8x10^{-4}$	Per year	[5]
REF.LOAD	Fails to condense ammonia in refrigeration package (Compressor)	$4x10^{-1}$	-	[5]
PSV-50002A/B OP	Fails to open at 98mbarg	$18.2x10^{-3}$	-	[5]
PV-50001 OP	Fails to open at 80mbarg	$6.62x10^{-3}$	-	[5]
PSLL-50005 AC	Fails to actuated at 10 mbarg	$2.5x10^{-4}$	Per year	[12]
XV-50002 CL	Fails to get closed automatically	$6.62x10^{-3}$	-	[5]
PSV-50001A/B OP	Fails to get opened completely at -6.5mbarg	$8x10^{-4}$	Per year	[5]
PSV-50006A/B OP	Fails to get opened completely when the pressure is going under 44mbarg	$18.2x10^{-3}$	Per year	[5]
PSV-50005A/B OP	Fails to get opened completely when the pressure is going under 3.5mbarg	$18.2x10^{-3}$	Per year	[5]
HUMAN ERROR	Operator fails to observe correctly	$1x10^{-3}$	-	[6]
HUMAN ERROR	Operator fails to response to alarm	$5x10^{-2}$	-	[6]

Table 2. Critical paths or cut sets which results in the release of ammonia, sorted based on the event frequency per year

Major accidents	**Rank**	**Sensitivity analysis**	**Frequency / year**	**Cut sets**
Ammonia release due to overfilling (A1)	1	$9.45x10^{1}$	$2.76x10^{-3}$	A8-A14-A15
	4	$5.39x10^{-1}$	$1.58x10^{-5}$	A8-A14-A11-A13
	5	$4.07x10^{-1}$	$1.19x10^{-5}$	A8-A7-A11-A13
	6	$7.14x10^{-2}$	$2.09x10^{-6}$	A8-A7-A15-A13
Ammonia release due to over pressurization (B1)	9	$2.85x10^{-7}$	$8.33x10^{-12}$	B6-B18-B8-B15
	10	$1.89x10^{-7}$	$5.52x10^{-12}$	B11-B18-B8-B15
	13	$2.85x10^{-8}$	$8.33x10^{-13}$	B5-B18-B8-B15
	14	$1.08x10^{-8}$	$3.17x10^{-13}$	B10-B18-B8-B15
Ammonia release due to under pressurization (C1)	7	$4.51x10^{-6}$	$1.32x10^{-10}$	C17-C3-C14-C15
	8	$3.42x10^{-6}$	$1.00x10^{-10}$	C17-C3-C8
	11	$1.13x10^{-7}$	$3.30x10^{-12}$	C11-C3-C14-C15
	12	$8.55x10^{-8}$	$2.50x10^{-12}$	C11-C3-C8
	15	$4.27x10^{-9}$	$1.26x10^{-13}$	C16-C3-C14-C15
	16	$3.25x10^{-9}$	$9.50x10^{-14}$	C16-C3-C8
Ammonia release due to rupture of the inlet loading line (D1)	2	2.27	$6.62x10^{-05}$	D2-D4-D5
Ammonia release due to rupture of the outlet loading line (E1)	3	2.27	$6.62x10^{-05}$	E2-E4-E5

4.1 Ammonia release due to overfilling

The first event, which is described here, is overfilling. Referring to Figure 2, when the tank is being filled to high level (H.L.) and and level transmitters LT-50001/LT-50002 do not show the correct liquid level or the operator does not observe the indicated level correctly, the liquid level exceeds the H.L. In this stage, if the operator does not respond correctly to high level alarm or if LT-50002 fails to indicate liquid level correctly, liquid level exceeds the H.H.L. In this case, LT-50001 should close the inlet valve, automatically. If LT-50001 does not perform its duty correctly or if the inlet valve XV-50001 does not respond, liquid ammonia will be vastly released to the environment. The fault tree shown in Figure 4 depicts graphically, the above described events which lead to overfilling. Overfilling frequency is evaluated to be equal to 2.8×10^{-3}/year.

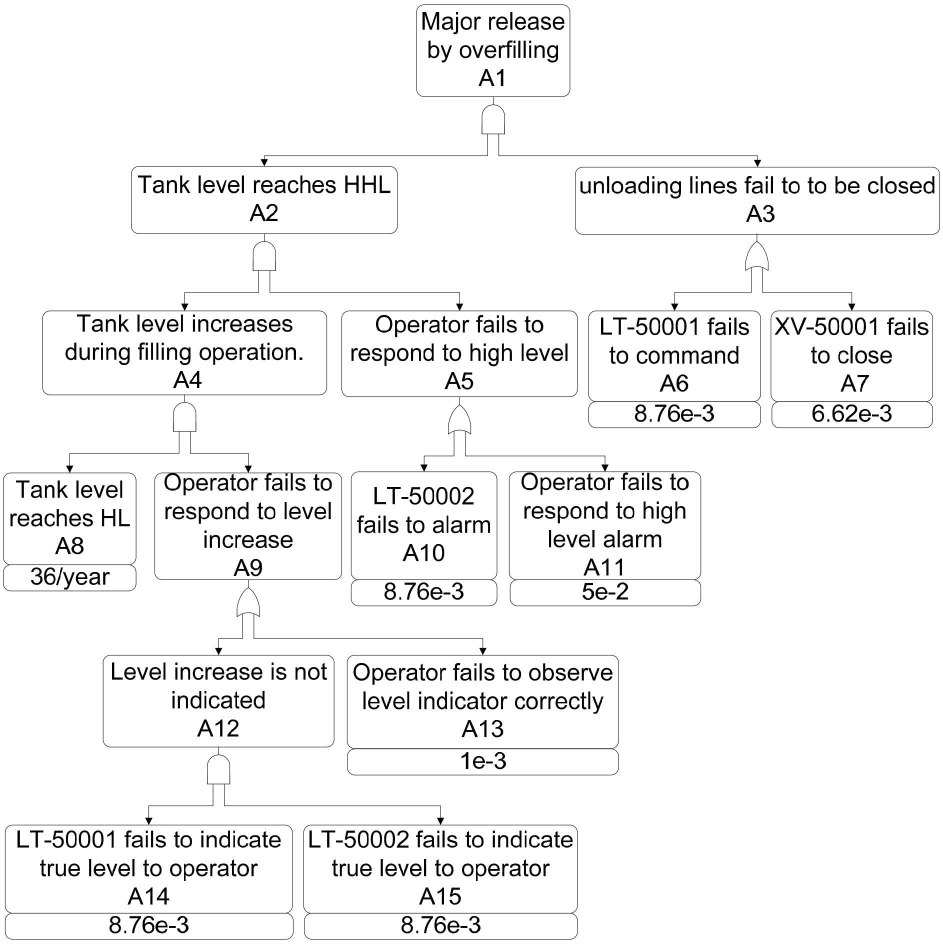

Figure 4. Fault tree diagram for tank overfilling

It is worthwhile to mention that two duties are considered for LT-50001 and LT-50002; Indicating liquid level and closing the inlet valve. With the assumption of Common Cause Failure, CCF [9], which means each valve does not perform its duties because of same cause (for example LT-50001 may not perform its duties because of electrical shock) , then the event A14 will be same as A6 and A15 will be same as A10. This assumption reduces the number of cut sets because some repeated event will be in some cut sets; for example without assuming CCF, two of cut sets will be A6-A8-A10-A14-A15 and A6-A10-A8-A13 and by considering CCF (A14=A6 , A10=A15) then the first one will be eliminated. Such as these two cut sets, total number of cut sets for this event will diminished from 8 to 4, table 3, which is very helpful in recognition of critical points and sensitivity analysis.

Table 3. Diminishing cut sets of event A1 because of CCF

Original cut sets	CCF	Minimal Cut sets
A8-A14-A15-A10-A6	A14 = A6 A10 = A15	A8-A13-A10-A6
A8-A13-A10-A6		
A8-A14-A15-A11-A6		A8-A13-A11-A6
A8-A13-A11-A6		
A8-A14-A15-A10-A7		A8-A13-A10-A7
A8-A13-A10-A7		
A8-A14-A15-A11-A7		A8-A13-A11-A7
A8-A13-A11-A7		

4.2 Ammonia release due to over pressurization

Over pressurization in tank may lead to the rapture of tank body. This over pressurization can be as a result of blockage of vapor outlet line, sudden drop in barometric pressure or rollover. The allowable working pressure is between -6.5mbarg up to +98mbarg while it works normally at 50mbarg. An increase in the working pressure beyond 50mbarg triggers a controller, PT-50001, to run the refrigerating package. However, up to 70mbarg, the ammonia vapor does not direct to the package. When the inside pressure reaches 80mbarg, this controller lets the vapor to be condensed in the package. If the pressure increases more, the controller opens the valve, PV-50001, and conducts the ammonia vapor to the flare. If none of those methods can stop increasing the pressure, PSV-50002A/B will vent the extra ammonia vapor to the safe zone. The fault tree for over pressurization is shown in Figure 5. Referring to Table 2, there are four cut sets in over pressurization events which may be named CSi, i = [1, 2, 3, 4]. For this major accident, the probability of over pressurization, P, may be evaluated as follows [7]:

$$
\begin{aligned}
&\text{Probability of over pressurization} = P = P(CS_1 \cup CS_2 \cup CS_3 \cup CS_4) \\
&= P(CS_1) + P(CS_2) + P(CS_3) + P(CS_4) - P(CS_1)P(CS_2) - P(CS_1)P(CS_3) \\
&- P(CS_1)P(CS_4) - P(CS_2)P(CS_3) - P(CS_2)P(CS_4) + P(CS_1)P(CS_2)P(CS_3) \\
&+ P(CS_1)P(CS_2)P(CS_4) + P(CS_2)P(CS_3)P(CS_4) - P(CS_1)P(CS_2)P(CS_3)P(CS_4)
\end{aligned}
$$

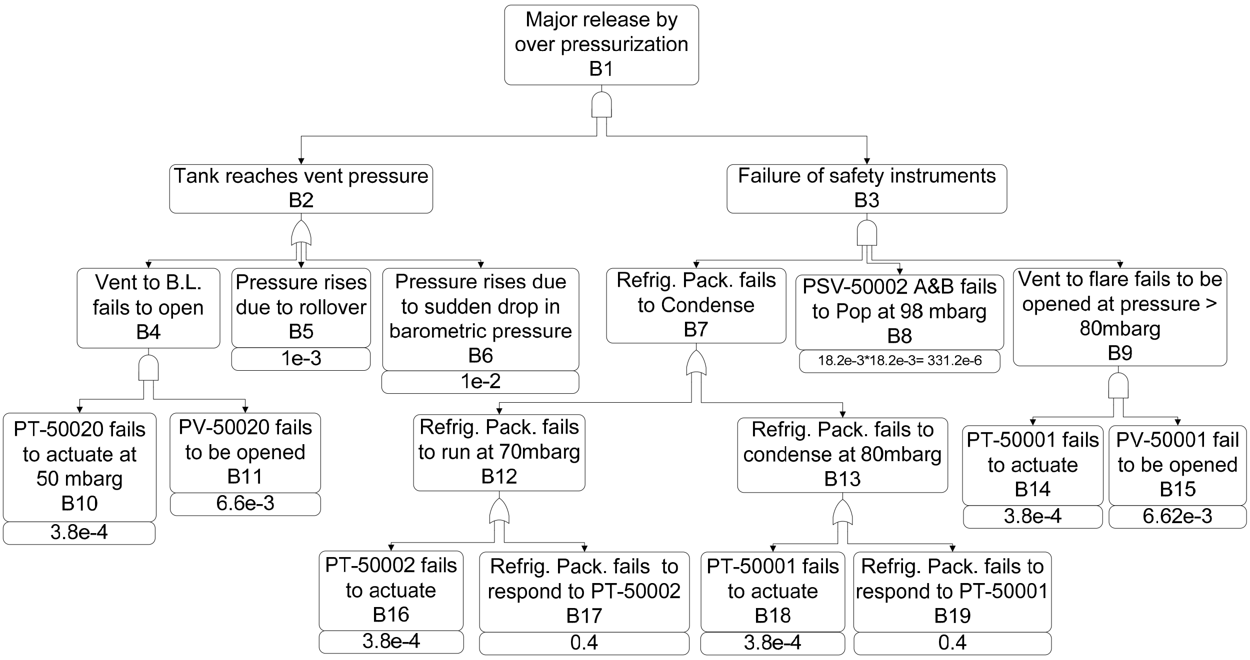

Figure 5. Fault tree diagram for over pressurization

Figure 6 shows evaluation of over pressurization in MECHREL software. Frequency of this event is $1.5x10^{-11}$/year.

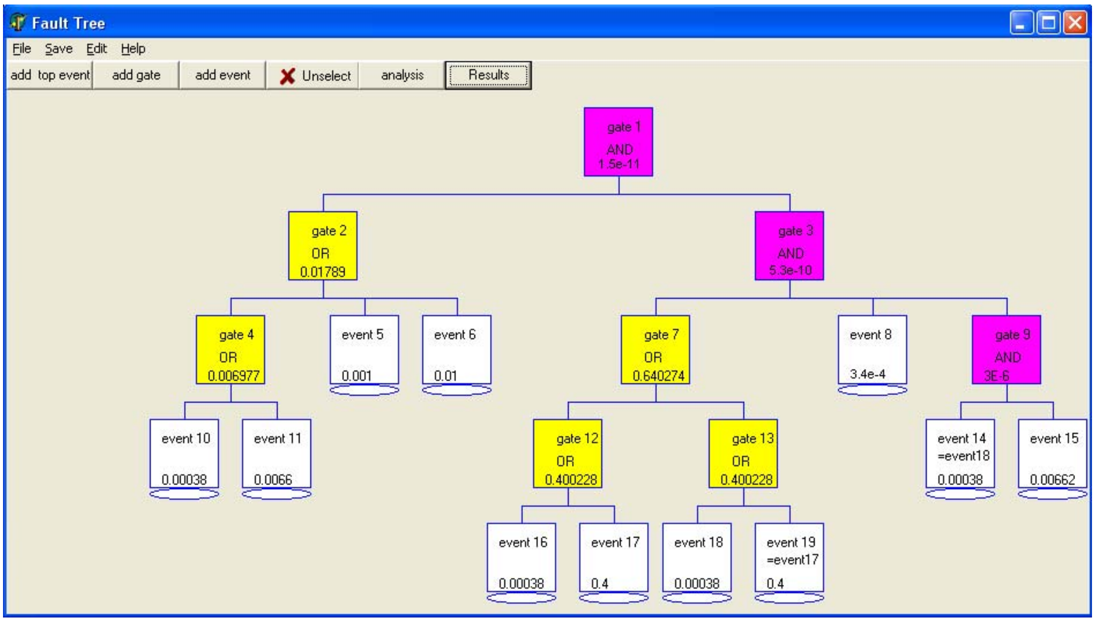

Figure 6. Set up the fault tree diagram for over pressurization in MECHREL

4.3 Ammonia release due to under pressurization

When the tank outflow is more than inflow, or barometric pressure gets increases abruptly, the ammonia tank may be subjected to vacuum which is very catastrophic for thin wall shell structures. In the present ammonia tank, whenever the working pressure drops below 30mbarg, PAL-50002 will turn off the refrigerating package. If the pressure decreases to 10mbarg, In this case, PSLL-50005 will actuate the valve XV-50002 to be closed. If this valve is not closed automatically, it is possible that operators located in site close it manually. If this valve, for any reason, fails to get closed, and the inside pressure reaches -6.5mbarg, two pressure switch valves, PSV-50001A/B, will open and let the tank breath to prevent buckling of the tank wall. The fault tree diagram for under pressurization can be observed in Figure 7. The evaluated result shows this event frequency to be $2.4x10^{-10}$/year.

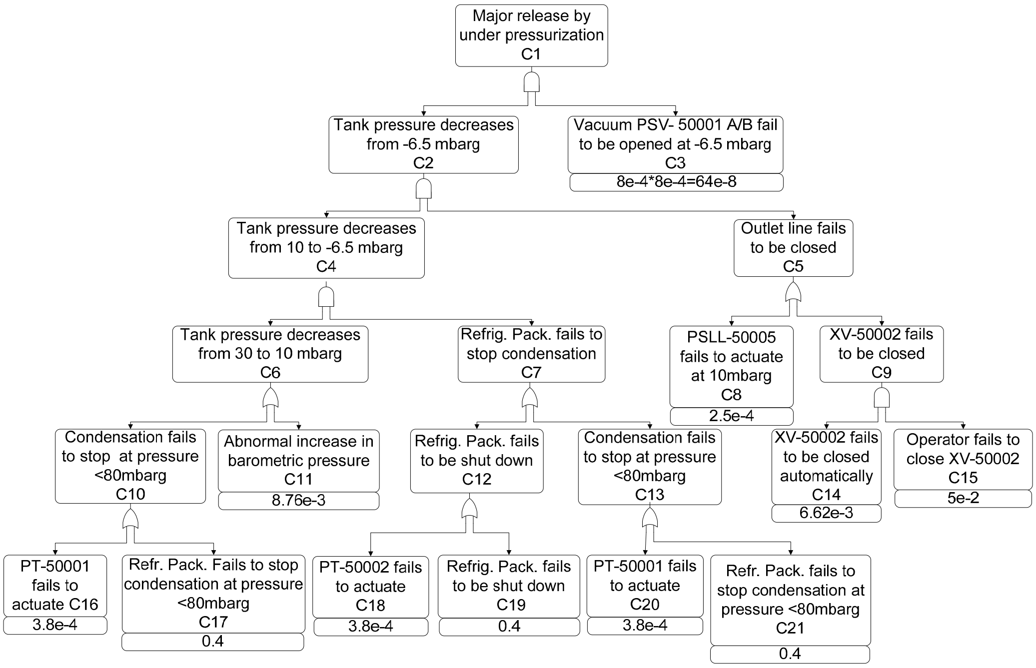

Figure 7. Fault tree diagram for under pressurization

4.4 Ammonia release due to rupture of the inlet/outlet loading line

The final assessed scenario is the release of ammonia due to rupture of the inlet or outlet loading lines. These lines work continually and if, for any reason, get blocked; ammonia gets confined in pipes, and will evaporate as the result of heat transfer with surroundings, so, the pressure of line will rise. The over pressurization in that part of pipe which is connected to the tank may be damped, but in other parts, it may lead to line rupture. In this condition, if the on-off valve XV-50001 be closed and the two pressure switches (relief valves), PSV-50006A/B do not open at line pressure of 44barg (44 barg is design criteria for inlet line and 3.5 barg is design criteria for outlet line), then, it has a potential to make damages to the pipe lines. The evaluated result shows these events frequency of $6.62\mathrm{x}10^{-5}$/year for both inlet and outlet line. The fault tree for rupture of inlet and outlet lines is shown in Figure 8 and Figure 9, respectively.

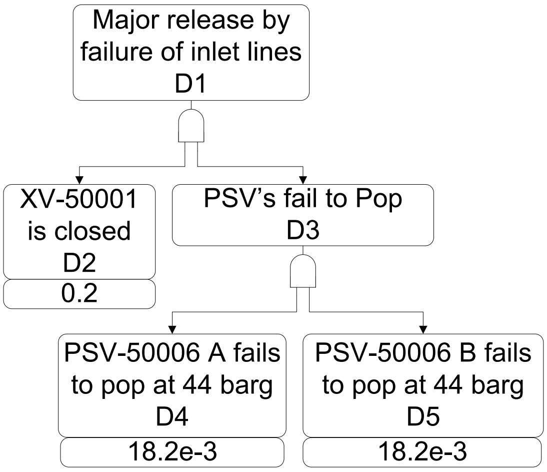

Figure 8. Fault tree diagram for rupture of inlet line

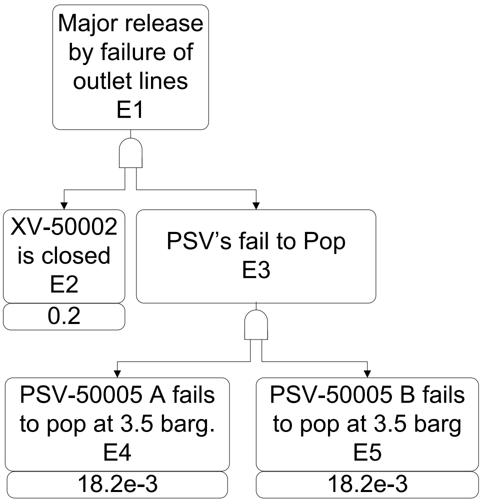

Figure 9. Fault tree diagram for rupture of outlet line

5. SENSITIVITY ANALYSIS

The final step in the analysis of a fault tree is to determine the importance of each cut set. The cut set importance is calculated as [10]:

$$I^{Ci} = \frac{Q_j}{Q_o} \times 100,$$

where I^{Ci} is the cut set importance, Q_j is the cut set frequency and Q_o is the top event frequency. All minimal cut sets are ranked in Table 2 based on their evaluated importance.

The other index in the fault tree analysis, which must be taken into consideration, is the improvement index which shows the criticality of a basic event and is determined by eliminating each basic event from the tree and evaluating its weight on the tree [11]. This index aids in deciding which events are most likely to cause an accident and would therefore require immediate attention.

$$I^{Ei} = Q_o - Q_{oj},$$

where I^{Ei} is the basic event improvement, Q_{oj} is top event frequency in the absence of j^th^ basic event and Q_o is the top event frequency. The improvement index for each basic event is calculated and presented in Figure 10.

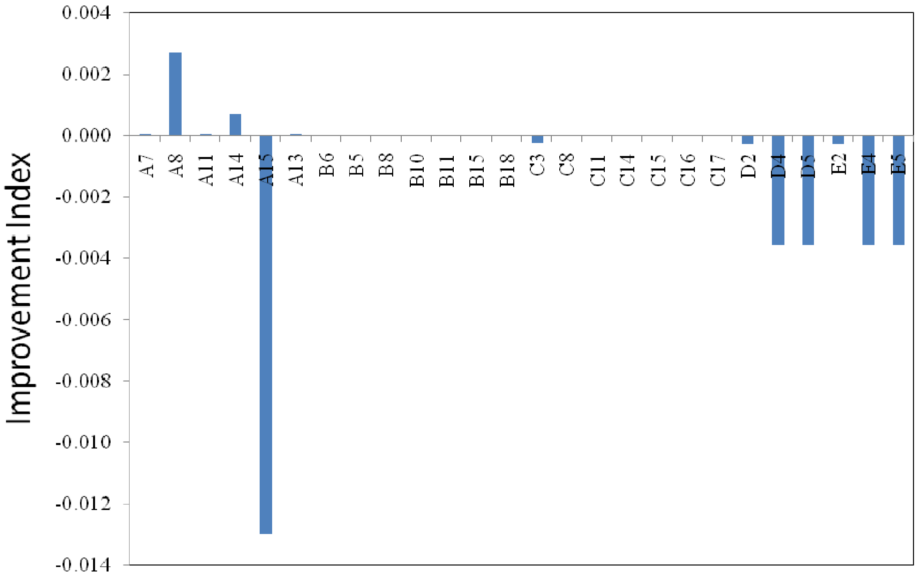

Figure10. Improvement index for each basic event

6. RESULTS AND DISCUSSION

The fault tree analysis is performed to estimate the probability of five major causes, which lead to the release of ammonia. As it can be deduced from Table 2, the most probable accident is overfilling with frequency of $2.8x10^{-3}$/year and after that, is the rupture of the inlet or outlet loading line with frequency of $6.62x10^{-5}$/year. Therefore, a basic step to improve the tank safety is to select level indictors with lower failure rate. So, it is recommended to replace the level indictors with SIL 2 (Safety Integrity Level 2) by the same one with SIL3. In the case of loading line improvement, it is also recommended to use safety valves with SIL 3. By those simple modifications, the frequency of overfilling decreases from $2.8x10^{-3}$/year to $4.1x10^{-5}$/year and the frequency of overfilling decreases from $6.62x10^{-5}$/year to $6.62x10^{-7}$/year, which shows a significant improvement in tank safety. It can be depicted from Figure 10, the events which are most likely to cause an accident, are A15, D4, D5, E4, E5, A8, and A14, which require immediate response in accidents.

7. CONCLUSION

In this paper, the quantitative fault tree analysis was performed for an ammonia tank with the capacity of 20,000 tons and the ability of this method in discovering the critical paths was proved. The sensitivity analysis showed also all potential hazards. Therefore, the results of this paper may be very vital to make the correct decisions in risky conditions. At the end, it is worthwhile to mention that the current calculations are based on the operation in first year and due to continual work of equipments, the failure rates will be increased.

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