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SCAP: a new methodology for safety management based on feedback from credible accident-probabilistic fault tree analysis system

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Abstract

As it is conventionally done, strategies for incorporating accident — prevention measures in any hazardous chemical process industry are developed on the basis of input from risk assessment. However, the two steps — risk assessment and hazard reduction (or safety) measures — are not linked interactively in the existing methodologies. This prevents a quantitative assessment of the impacts of safety measures on risk control.

We have made an attempt to develop a methodology in which risk assessment steps are interactively linked with implementation of safety measures. The resultant system tells us the extent of reduction of risk by each successive safety measure. It also tells based on sophisticated maximum credible accident analysis (MCAA) and probabilistic fault tree analysis (PFTA) whether a given unit can ever be made 'safe'. The application of the methodology has been illustrated with a case study. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: Probabilistic hazard assessment; Risk assessment; Safety evaluation; Fault tree analysis

1. Introduction

We have recently introduced a new methodology termed as analytical simulation [1,2] which enables, one to conduct probabilistic fault tree analysis (FTA) in a chemical process industry with much more quickness, accuracy, and precision than is possible with the

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conventional fault tree evaluation techniques. We have also, earlier, introduced the concept of rapid risk assessment (RRA) based essentially on maximum credible accident analysis (MCAA; [3–7]). We have now integrated analytical simulation and MCAA, and have further introduced fault tree-safety measure feedback loops into the system to come up with a safety management options presented here. The technique tells us where the hazards exit in an industry, quantifies the hazard, forecasts probability of accidents in the hazardous components of the industry, suggests safety measure, and then loops back to reassess the hazards. In this manner, it enables one to work out exactly what safety measures, of what sophistication, can bring down the hazard to acceptable levels. It is also able to distinguish for the analyst the units that cannot be made safe even after installing all conventional safety measures. The technique thus isolates units for which the industry must put in position special emergency preparedness and disaster management plans. We have given the acronym SCAP to this technique; ‘S’ denotes safety, ‘C’ and ‘A’ denote credible accidents, and ‘P’ is for probabilistic FTA.

2. The steps involve in SCAP

The SCAP algorithm is depicted in Fig. 1. The features of each of the steps are summarized below.

2.1. Hazard identification using FEDI and TDI

This step utilizes the hazard identification and ranking analysis system developed earlier by us [8,9]. HIRA enables computation of fire and explosion damage index (FEDI) and toxic damage index (TDI). The distinguishing features of these are the followings.

2.1.1. Fire and explosion damage index (FEDI)

For the purpose of developing FEDI, the various units of an industry are classified as follows:

1. storage units;
2. units involving physical operations such as heat transfer, mass transfer, phase change, pumping and compression;
3. units involving chemical reactions;
4. transportation units;
5. other hazardous units such as furnace, boilers, direct-fired heat exchangers, etc.

Estimation of FEDI involves the following steps:

1. classification of the various units in an industry into the five categories mentioned above;
2. evaluation of energy factors;
3. assignment of penalties;
4. estimation of damage potential;
5. estimation of FEDI.

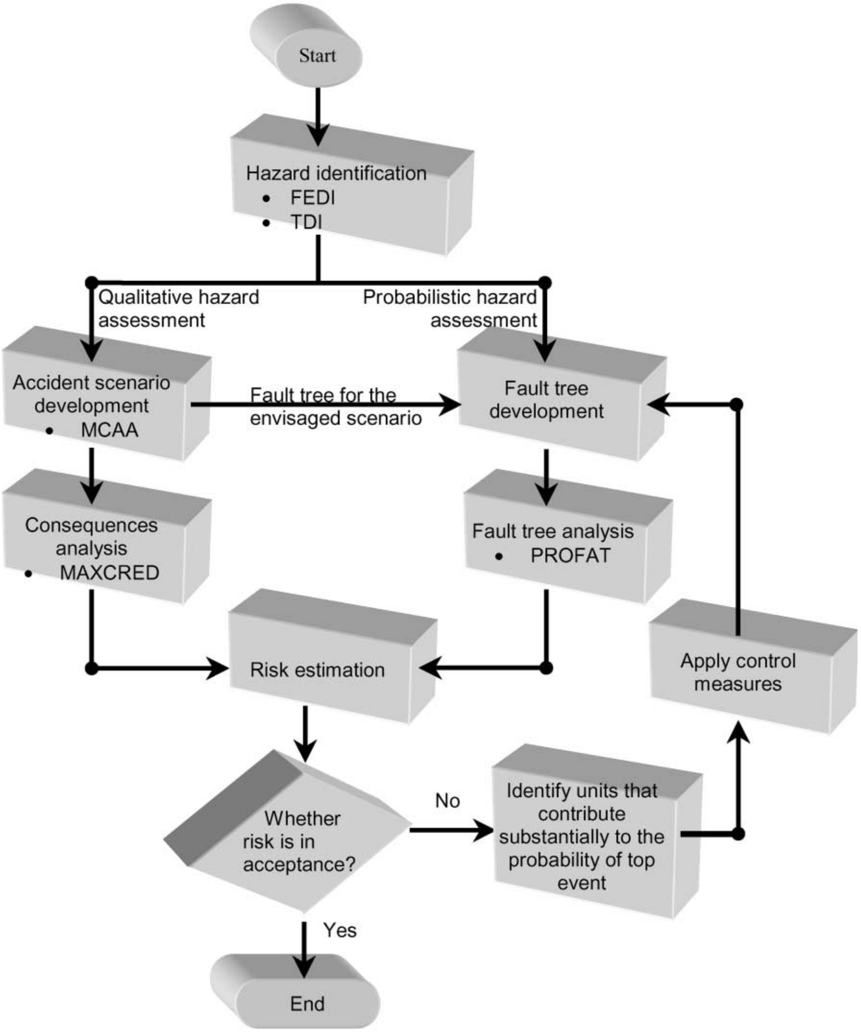
Start
Hazard identification
• FEDI
• TDI
Qualitative hazard assessment
Probabilistic hazard assessment
Accident scenario development
• MCAA
Fault tree for the envisaged scenario
Fault tree development
Consequences analysis
• MAXCRED
Fault tree analysis
• PROFAT
Risk estimation
Apply control measures
Whether risk is in acceptance?
No
Identify units that contribute substantially to the probability of top event
Yes
End

Fig. 1. The SCAP algorithm.

2.1.2. Toxic damage index

Toxic damage index (TDI) is a representation of lethal toxic load over an area. It is measured in terms of radius of the area (in meters) getting affected lethally by toxic load (50% probability of causing fatality). This index is derived by using transport phenomena and empirical models based on the quantity of chemical(s) involved in the unit, the physical state of the chemical(s), the toxicity of the chemical(s), the operating conditions, and the site characteristics [10,11]. The dispersion is assumed to occur under slightly stable atmospheric conditions. We have opted for ‘slightly stable atmospheric conditions’ as these represent a median of high instability and high stability. Furthermore, such conditions are often prevalent during accidents — as had happened at Bhopal, Basel, Panipat and other places [3,8,9,12–14].

The estimation of TDI is done with one core factor named as 'G factor' and several penalties. The G factor takes into account the following:

1. during the accidental release of super-heated liquid (liquid stored or processed above its normal boiling point) from the unit, a part of the liquid would flash to vapors and the remaining part would form a liquid pool which would subsequently evaporate;
2. the release of gases would directly lead to dispersion in the atmosphere and would cause build-up of lethal toxic load;
3. liquefied gases would have two-phase release, followed by dispersion and build-up of toxic load;
4. pyrophilic solids would give toxic vapors which would generate toxic load in the air.

2.1.3. HIRA

When combined in HIRA, TDI and FEDI serve the following purpose:

1. it takes into consideration impact of various process operations, and the associated parameters for hazard identification;
2. it provides quantitative results of good reliability;
3. most of the penalties used in computing FEDI and TDI (on which HIRA is based) are derived from the well-tried and tested models of thermodynamics, transport phenomena, heat transfer, and fluid dynamics [15–17]. A few penalties are quantified with the help of empirical models and hazard ranking procedures such as NFPA [18] and EHS [19];
4. it does not need case-to-case calibration as its magnitude directly signifies the level of hazard;
5. it may be used for very rapid reconnaissance of risk.

2.2. Quantitative hazard assessment branch: MCAA and MAXCRED

The essence of conducting hazard assessment of a unit lies in forecasting the probability of one or more types of accidents occurring in the unit and the damage likely to be caused by the accidents.

Maximum credible accident analysis (MCAA) is one of the most widely used concepts in risk assessment of process industries. Central to this concept is the aspect of 'credibility' of envisaged accident scenarios and their consequences. We have developed a computer-automated tool, MAXCRED [6,20], and its higher versions and MAXCRED-III [7] which perform MCAA as inputs to risk assessment. The features of MAXCRED-III are

1. The package enables simulation of accidents and estimation of their damage potential. MAXCRED-III has been developed with an intention to provide a more versatile and accurate tool for rapid risk assessment than is possible with existing packages. It may be seen that earlier version of MAXCRED-III has significantly greater capabilities than other commercial packages whereas MAXCRED-III further improves its sophistication by incorporating domino/cascading effect, and implementation of advance concept of software engineering [7].

2. MAXCRED-III has five main modules (options): scenario generation, consequence analysis, domino, documentation, and graphics.
3. In the scenario generation module credible accident scenario(s) are generated for the unit under study. It is an important input for the subsequent steps. More realistic the accident scenario, more accurate is the forecast of the type of accident, its consequences, and associated risks; consequently more appropriate and effective the strategies for crisis aversion and management. Each accident scenario is basically a combination of different likely accidental events that may occur in an industry. Such scenarios are generated based on the properties of chemicals handled by the industry, physical conditions under which reactions occur or reactants/products are stored, geometries and material strengths of vessel and conduits, in-built valves and safety arrangements, etc. External factors such as site characteristics (topography, presence of trees, ponds, rivers in the vicinity, proximity to other industries or neighborhoods, etc.) and meteorological conditions are also considered.
4. The consequence analysis module involves assessment of likely consequences if an accident scenario does materialize. The consequences are quantified in terms of damage radii (the radii of the area in which the damage would readily occur), damage to property (shattering of window pans, caving of buildings), and toxic effects (chronic/acute toxicity, mortality). The assessment of consequence involves a wide variety of mathematical models. For example, source models are used to predict the rate of release of hazardous material, the degree of flashing, and the rate of evaporation. Models for explosions and fires are used to predict the characteristics of explosions and fires. The impact intensity models are used to predict the damage zones due to fires, explosion and toxic load. Lastly, exposure-response models are used to predict human response to different levels of exposures to toxic chemicals.
5. Domino module analyzes the damage potential of the primary event at the point of location of the secondary unit and checks for the likelihood of the occurrence of the secondary accident. If the probability of the secondary accident is sufficiently high than the appropriate accident scenarios are developed and analyzed for consequences.
6. The graphics module enables visualization of risk contours in the context of the site of accidents. The option has two facilities: (i) site drawing, and (ii) contour drawing. The site drawing option enables the user to draw any industrial site layout using freehand drawing or using any already defined drawing tool. The contour drawing option has the facility for drawing various damage/risk contours over the accident site. The contours can be drawn in different shapes and sizes as per the requirement of the user.
7. The documentation module of MAXCRED-III mainly deals with handling of different files such as: data file, scenario file, output file and information flow. This object works as ‘information manager’: it provides the necessary information to each module and sub-module to carry out desired operations, and stores the results in different files.
8. All-in-all MAXCRED-III is a versatile tool for risk assessment and is envisaged to be self contained in the sense that it does not need other packages for data analysis or graphics support.

2.3. The probabilistic fault tree analysis branch and PROFAT

Fault tree analysis (FTA) is an analytical tool that uses deductive reasoning to determine the occurrence of an undesired event. FTA, along with component failure data and human reliability data, can enable determination of the frequency of occurrence of an accidental event.

In this branch of SCAP, fault trees are constructed of various likely initiating events, which may eventually lead to the 'top' event or the accident. In order to develop probabilistic fault trees and analyze them swiftly we have developed a methodology termed by us 'analytical simulation' [2]. A complete automated tool called PROFAT (PRObabilistic FAult Tree analysis; [1]) has also been developed by us to perform analytical simulation. The key steps are

1. *Fault tree development* — based on the detailed study of the process, control arrangement, and behavior of components of the unit/plant the top event (most undesirable situation) is identified. Further, a logical dependency between the causes leading to the top event is developed and represented in terms of a fault tree. Such a fault tree can be developed for an individual unit or a combination of units, depending upon the convenience of the user.
2. *Boolean matrix creation* — the fault tree developed as above is transformed to a Boolean matrix. If the dimension of the Boolean matrix happens to exceed the processing ability of the computer available with the user, structural moduling technique may be applied [21,22]. This technique proposes moduling of the fault tree into a number of smaller sub-modules with a dependency relation among them. This reduces the memory allocation problem as well as makes the computation faster [23].
3. *Finding of minimum cutsets and optimization* — the Boolean matrix is then solved using analytical method for minimum cutsets [24–26]. If the problem has been structurally moduled, than each module is solved independently, and the results thus occurred are combined. The minimum cutsets, which result, may be optimized using any appropriate technique. Optimization is necessary in order to eliminate the unimportant paths (cutsets).
4. *Probability analysis* — the already optimized minimum cutsets are processed for probability estimation. These authors recommend the use of Monte-Carlo simulation method [27–29] for this purpose instead of direct estimation because, simulation method not only gives the probability of the top event but it also provides information on the sensitivity of the results. Further, simulation is helpful in studying the impact of each of the initiating events. To increase the accuracy of the computations and reduce the margin of error due to inaccuracy involved in the reliability data of the basic events (initiating events), we recommend the use of fuzzy probability set [30–34].
5. *Improvement index estimation* — an added advantage of the simulation method is that it enables study of the importance of each component; in other words each cause (initiating event) which leads to the top event. The contribution of each cause is estimated by repeating the step IV while that particular cause is absent. Subsequently, the contribution of each cause is transformed into an index termed 'improvement index'. This index signifies percent contribution of each cause in leading to the top event. Thus, from the

improvement index one can easily deduce what are the events most likely to cause an accident and need immediate care.

2.3.1. PROFAT

The methodology summarized above was resolved into a computer-automated tool PROFAT. The tool has been coded in C++ and consists of five main modules: DATA, minimum

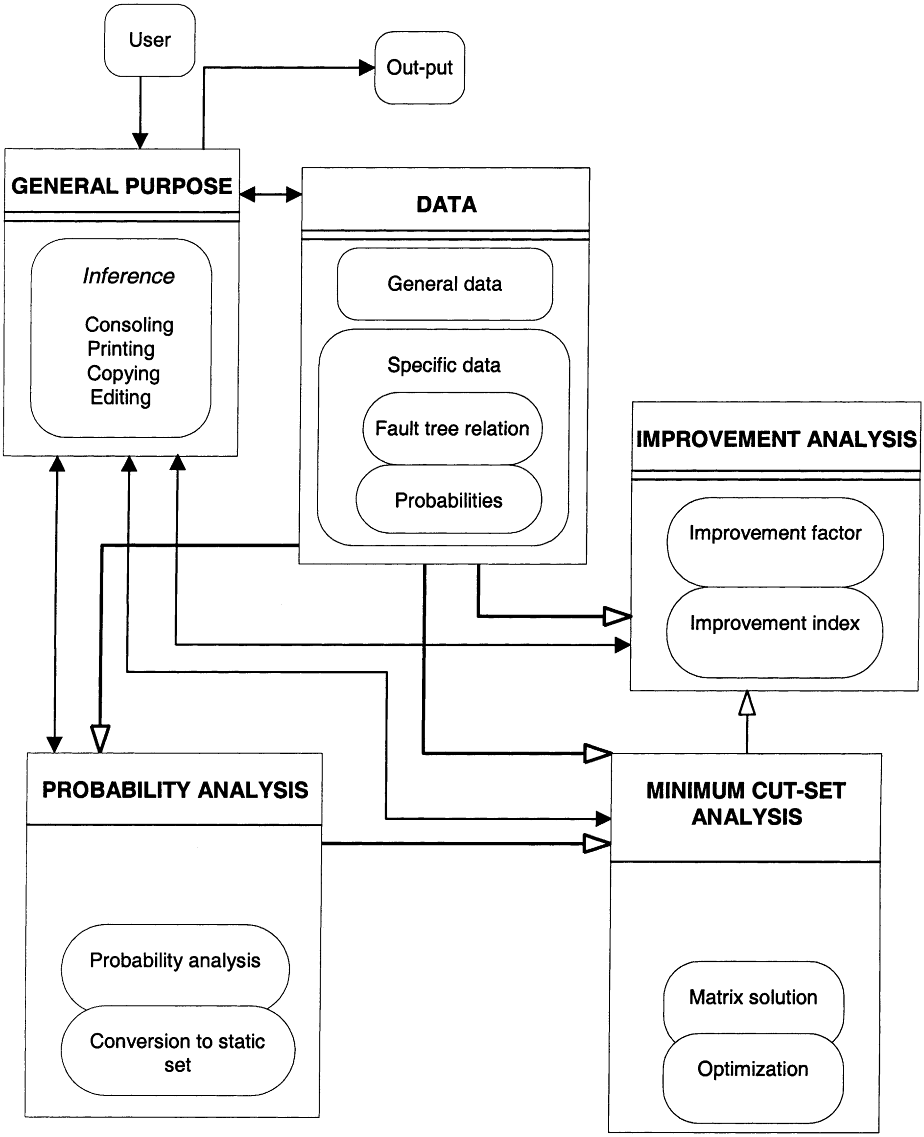

Fig. 2. Architecture and message flow sequence of PROFAT.

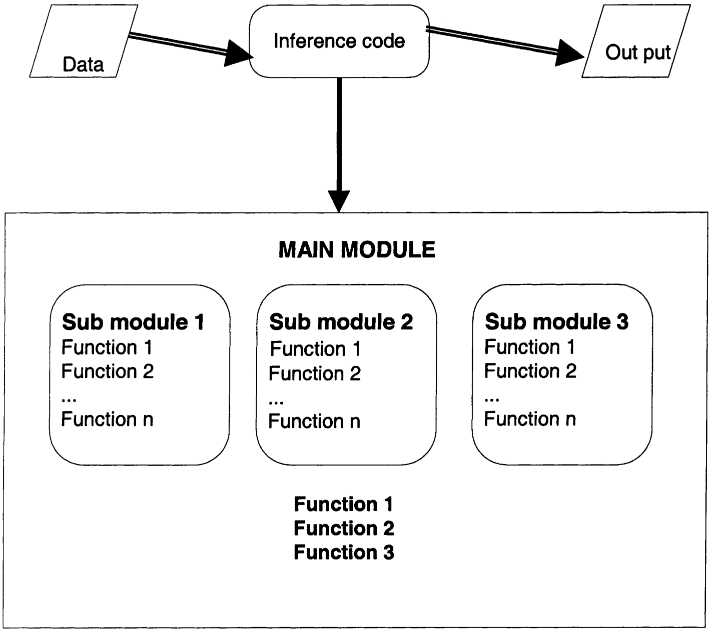

Fig. 3. Internal architecture of a typical module.

cutsets analysis, probability analysis, improvement factor analysis, and general-purpose modules.

Each module performs specific task, and is linked with the other modules. For example, the minimum cutsets analysis module uses data provided in the form of Boolean relation (fault tree relation) by the DATA module, to generate minimum cutsets. The architecture and message flow sequence of PROFAT are given in Fig. 2.

Each module of PROFAT comprises of two or more submodules. For example, matrix formulation, matrix solution, and cutsets optimization are subordinates (derived classes) to the main minimum cutsets analysis module (main minimum cutsets analysis class). These submodules (derived classes) inherit functions defined in main module (main class) to serve specific applications as well as comprise of some ‘friends’ functions (functions not part of the class but otherwise useful). The architecture of a typical module is shown in Fig. 3.

3. Application of SCAP: a case study

We present below an illustrative example of the application of SCAP to a petrochemical industry

3.1. Step I: reconnaissance with HIRA

All the units of the petrochemical industry are screened by HIRA. The results are summarized in Fig. 4 (the legends used in the figure are illustrated in Table 1). As may be seen,

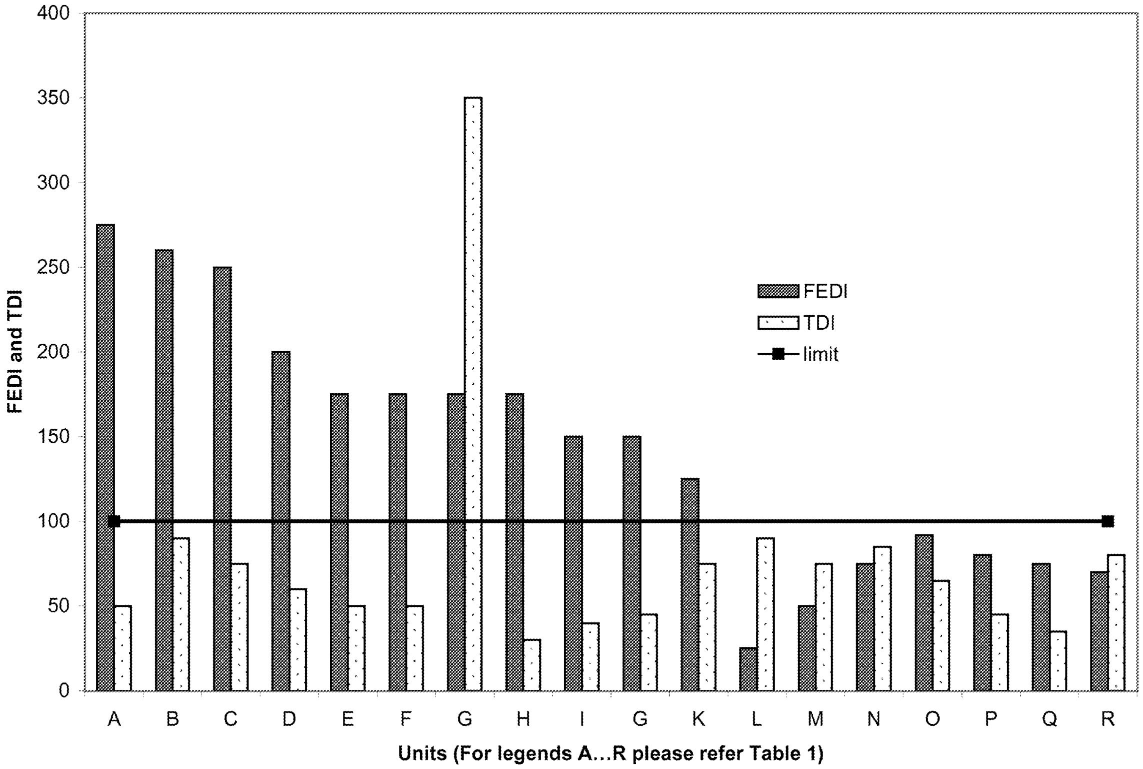

Fig. 4. Fire and explosion damage index (FEDI) and toxic damage index (TDI) for different units of the plant.

Table 1
Different units of a petrochemical industry

Plant process unit	Identifier for Fig. 4
Chlorohydrin storage	A
Propylene oxide (chlorohydrin) reactor	B
Reactor holding tank	C
Propylene storage tank	D
Propylene oxide storage tank	E
MPG storage tank	F
Chlorine storage tank	G
Ethylene oxide storage tank	H
Nitrogen storage tank	I
DPG storage	J
Solvent recovery unit	K
PO neutralization tank	L
De-hydrochlorination tank	M
PG distillation unit	N
Propylene glycol reactor	O
Polyol reactor	P
Stripping unit	Q
PO distillation unit	R

propylene storage, chlorohydrin reactor, chlorine storage. Propylene oxide storage units were identified as highly hazardous, warranting more detailed studies, which we did. For the sake of brevity, we are presenting the study of propylene oxide reaction unit (chlorohydrin reactor) as an illustrative example.

3.1.1. Process summary

The process involves the generation of propylene oxide by saponification of propylene chlorohydrin with lime and recovery by distillation. The process is carried out in the following stages:

- production of chlorohydrin;
- saponification;
- purification of propylene oxide (PO);
- purification of dichloropropane (DCP).

3.1.2. Production of chlorohydrin

The main reactions are

$$\mathrm{Cl_2 + H_2O \rightarrow ClH + ClOH}$$

$$\mathrm{ClOH + C_3H_6 \rightarrow ClC_3H_6OH}$$

Simultaneously, side reactions take place, especially DCP is formed

$$\mathrm{C_3H_6 + Cl_2 \rightarrow C_3H_6Cl_2}$$

as well as dichloroisopropyl-ether (DCIPE) is formed

$$C_3H_6 + ClOH + ClC_3H_6OH \rightarrow (C_3H_6Cl)_2O + H_2O$$

The reaction is slightly exothermic and takes place in aqueous solution. Chlorine is dissolved in water to give hypochlorous acid; propylene reacts with the latter to form chlorohydrin.

Direct contact between propylene and chlorine in gaseous phase produces essentially DCP, so it is important to perform total dissolution of chlorine before the propylene injection. On the other hand, the solubility of DCP in water or in chlorohydrin solution is very low. If chlorine and propylene react in DCP phase, they produce mainly DCP. Thus, it is imperative that the appearance of DCP phase must be avoided. This is achieved by using excess of propylene which eliminates DCP from the chlorohydrin solution by stripping.

It is, of course, desirable to operate at as high a chlorohydrin concentration as possible, in order to reduce the volume of make-up water added to the chlorohydrin reactor, and also volume of waste effluent from the downstream saponifier. To achieve these ends (minimizing DCP, and DCIPE formation, and consumption of make up water) the system is usually operated to produce a propylene chlorohydrin concentration of about 4%. At temperature over 60–65°C chlorohydrin yield decreases and by-products yield increase.

In order to facilitate DCP stripping, the temperature of the reactor can be maintained as high as possible, but the solubility of propylene in chlorohydrin solution is greater at lower temperature, and chlorohydrin solution is more corrosive at high temperature. In practice, the reactor temperature is kept between 50 and 60°C. The propylene concentration at the top of the reactor may be as little as possible taking into account the necessity to maintain the concentration of chlorine in recycled gas at zero. The reactor works at slightly over atmospheric pressure. A higher pressure would increase propylene and chlorine solubility, but the equipment cost would also increase, mainly for the reactor.

Excess of propylene and inert from chlorine and propylene feed are recycled with fresh propylene feed, after soda washing and cooling which condenses the stripped DCP. For eliminating inert (propane, CO_2, O_2, N_2, etc.) a purge is made from the recycle gas. The chlorine consumption depends on the quantity of the side products (DCP and DCIPE) obtained in the reactor. The propylene consumption also depends on the quantity of side products and on the inert content of chlorine and propylene fresh feed.

3.1.3. Saponification of chlorohydrin

Propylene chlorohydrin is saponified with lime as follows:

$$2ClC_3H_6OH + Ca(OH)_2 \rightarrow 2C_3H_6O + CaCl_2 + 2H_2O$$

Sufficient alkali must be added to the saponifier to neutralize the hydrochloric acid formed in the chlorohydrin reactor and also to hydrolyse the chlorohydrin to propylene oxide. A 15–20 wt.% lime slurry is introduced to the chlorohydrin solution upstream of the saponifier to ensure good mixing. An excess of 10% of lime is used so that the concentration of hydroxyl ion remains constant throughout the course of the reaction. The rate of solubility of the lime is in fact the rate-limiting step of the reaction.

The saponifier is also a stripper for the propylene oxide; the former is achieved by steam injection. The reaction must be completed rapidly to avoid excessive stripping of un-reacted chlorohydrin and a high yield loss as propylene glycol. The lime used for milk of lime preparation should contain less than 1% magnesium (Mg) to minimize the formation of aldehydes by isomerization of propylene oxide. Stripping from the solution must do removal of the propylene oxide by stripping from the solution quickly to drive the equilibrium to the right and to minimize the formation of propylene glycol.

3.1.4. Purification of PO

The PO extracted by stripping from the saponifier contains water, DCP, DCIPE and other impurities as aldehydes. It is sent to the distillation column in which aldehydes are dimerized by injection of caustic soda solution as catalyst. PO is recovered at the top of the column and condensed; it is sent to a stripping column in which the lighter fractions are separated.

3.1.5. Purification of DCP

DCP and other chlorinated organic derivatives are removed from aqueous effluent by decantation; the organic phase is dried by azeotropic distillation and DCP is separated from DCIPE and heavier ones by distillation. The present study is focused on the reaction section of the plant, which is considered to be among the most hazardous of the process units.

3.2. Step II: accident scenarios development with MAXCRED-III

Based on past accident analysis of mishaps occurring in process industries and the authors' experience, following scenarios have been visualized for accidents in different units.

Scenario 1: propylene transportation line. Instantaneous release of propylene from the pipeline generates a vapor cloud which, on ignition cause a fire ball.

Scenario 2: chlorine transportation line. Continuous release of chlorine from the pipeline causes building of toxic load.

Scenario 3: chlorohydrin reactor. This is a BLEVE followed by fire ball. Burned/unburned chemical on dispersion causes building of toxic load.

Scenario 4: recycle line. Release of chemical causes generation of vapor cloud, which on meeting an ignition source burns as flash fire.

3.3. Step III: consequence analysis

The forecasts for scenario 1 (instantaneous release followed by fire ball) are presented in Table 2. The vapor cloud generated by instantaneous release on ignition would cause a fire ball, which would generate heat radiation effect. It is clear from table that an area of ∼90 m radius faces 50% probability of being damaged due to heat load. The shock wave and heat radiation may cause fatality as well as second order accidents by seriously damaging other units/accessories. The worst affected would be propylene oxide reactor, and storage of chlorine.

Scenario 2 envisages a continuous release of chlorine followed by dispersion (Table 3). Toxic level with the potential to cause (50% probability) fatality would occur over an area

Table 2
Results of consequence analysis for scenario 1; accident in propylene transportation line

Parameters	Values
Unit: propylene transportation line	
Scenario: fire ball	
Fire ball	
Radius of the fire ball (m)	14.2
Duration of the fire ball (s)	5.7
Energy released by fire ball (kJ)	1.80E+06
Radiation heat flux (kJ/m^2)	1165.4
Damage radii (DR) due to thermal load	
DR for 100% fatality/damage (m)	56
DR for 50% fatality/damage (m)	87
DR for 100% third degree of burn (m)	115
DR for 50% third degree of burn (m)	145

of ∼2000 m radius. For another 300 m the harmful concentration shall persist though of lesser propensity to cause fatality.

The forecasts based on detailed calculations for scenario 3 are presented in Table 4. BLEVE, followed by fire ball, would cause intensive damage. It is evident from the table that damage of high degree of severity would be likely over an area of 125 m radius while moderate damage (50% probability of lethality) would occur over an area of 175 m radius. The released unburned propylene, chlorine, and also the burned product would disperse into the atmosphere. The toxic level of these chemicals with the potential to cause (50% probability) fatality would occur over an area of ∼800 m radius. For another 400 m the harmful concentration shall persist.

Table 3
Results of consequence analysis for scenario 2; accident in chlorine transportation line

Parameters	Values
Unit: chlorine transportation line	
Scenario: release and dispersion of toxic gas	
Toxic release and dispersion	
Box continuous model: elevated source	
Wind speed (m/s)	3.0
Concentration at distance of 200 m (kg/m^3)	3.58E−02
Heavy gas plume characteristics	
Ground level concentration of plume at axis (kg/m^3)	7.207E−02
Ground level concentration on puff at border (kg/m^3)	7.107E−03
Cloud radius (m)	2.509E+02
Maximum ground level concentration (kg/m^3)	9.929E−02
Damage radii (DR) for various degree of damage	
DR for 100% lethality (m)	1125
DR for 50% lethality (m)	1942
DR for 10% lethality (m)	2342

Table 4
Results of consequence analysis for scenario 3; accident in chlorohydrin reactor

Parameters	Values
Unit: propylene oxide reactor	
Scenario: BLEVE followed by fire ball and dispersion of toxic gas	
Explosion: BLEVE	
Total energy released (kJ)	4.06E+07
Peak over pressure (kPa)	1292.23
Variation of over pressure in air (kPa/s)	2442.56
Shock wave velocity (m/s)	1134.74
Duration of shock wave (ms)	21
Missile characteristics	
Initial velocity of fragment (m/s)	452.2
Kinetic energy of fragment (kJ)	2.52E+06
Penetration ability at 50 m from the location of tertiary accident	
Concrete structure (m)	0.16
Brick structure (m)	0.23
Steel structure (m)	0.00
Damage radii (DR) for various degree of damage due to overpressure	
DR for 100% lethality (m)	125
DR for 50% lethality (m)	175
DR for 10% lethality (m)	205
Fire ball	
Radius of the fire ball (m)	81.79
Duration of the fire ball (s)	33.42
Energy released by fire ball (kJ)	2.55E+08
Radiation heat flux (kJ/m^2)	9759.5
Damage radii (DR) due to thermal load	
DR for 100% fatality/damage (m)	117
DR for 50% fatality/damage (m)	146
DR for 100% third degree of burn (m)	168
DR for 50% third degree of burn (m)	216
Toxic release and dispersion	
Box instantaneous model: elevated source	
Concentration at distance of 200 m (kg/m^3)	2.56E−03
Heavy gas puff characteristics	
Ground level concentration of puff (kg/m^3)	1.631E−04
Ground level concentration on puff axis (kg/m^3)	1.631E−03
Cloud radius (m)	5.511E+03
Maximum distance traveled by the cloud (m)	6.567E+02
Maximum ground level concentration (kg/m^3)	1.453E−02
Damage radii (DR) for various degree of damage	
DR for 100% lethality (m)	587
DR for 50% lethality (m)	774
DR for 10% lethality (m)	1254

Table 5
Results of consequence analysis for scenario 4; accident in recycle line

Parameters	Values
Unit: recycle line	
Scenario: flash fire	
Flash fire	
Volume of vapor cloud (m^3)	5.65
Effective time of fire (s)	54
Radiation heat flux (kJ/m^2)	776.39
Damage radii (DR) due to thermal load	
DR for 100% fatality/damage (m)	27
DR for 50% fatality/damage (m)	38
DR for 100% third degree of burn (m)	65
DR for 50% third degree of burn (m)	101

The study of the consequences of scenario 4 (release and burning of recycled gases) reveals that the likely damage due to this event in terms of heat load would be less intense than forecast by scenarios 1–3. However, it is evident (Table 5) that at a distance of ∼40 m from the accident epicenter the intensity of heat load would be severe enough to cause secondary accident and fatality.

3.4. Step IV: probability estimation and risk computation

3.4.1. Fault tree development for propylene line

The top event was identified as instantaneous release, which on meeting an ignition source would lead to fire ball. There are 12 basic events, which may contribute directly and/or indirectly to the accident scenario. The identified basic events with their frequency of failure are given in Table 6. Most of the data are obtained from the industry, however, values of some parameters were obtained from the literature, as industry specific data were

Table 6
Elements of the fault tree developed for a probable accident in propylene transportation line

Number referred in figure	Elements	Failure frequency (per year)
1	Ignition source	2.1E−01
2	Leak from pipe joints	36.0E−04
3	Leak from valve — 1	216.0E−03
4	Leak from flange and/or gasket	50.40E−04
5	Leak from valve — 2	216.0E−03
6	Leak from valve — 3	216.0E−03
7	Excess heat duty in kettle	288.0E−03
8	Temperature controller fails	2.0E−01
9	Excess heating by the heater	158.4E−03
10	Orifice/pipe line choked	216.0E−06
11	Pressure controller failed	2.5E−01
12	Mechanical failure of pipe	8.0E−06

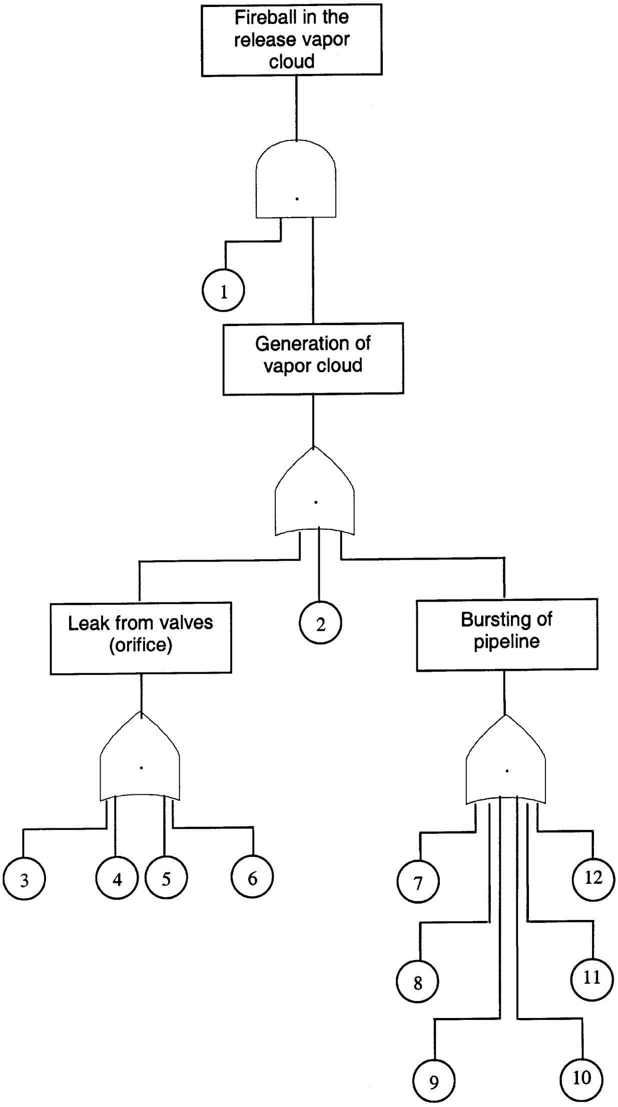
Fireball in the release vapor cloud
1
Generation of vapor cloud
Leak from valves (orifice)
2
Bursting of pipeline
3
4
5
6
7
12
8
11
9
10

Fig. 5. Fault tree diagram for an accident in propylene transportation line.

not available for these events [12]. Based on the process description and the detailed study of the reactor, fault tree was developed as shown in Fig. 5.

3.4.2. Fault tree analysis

The result of FTA (output of PROFAT) is presented in Table 7. The total probability of occurrence of the undesired event when all the initiating events occur is estimated is as 0.2998.

Table 7
Results of PROFAT for a probable accident scenario in propylene transportation line

Event not-occurring	Probability	Improvement	Improvement index
0	2.998600E−01	0.000000E+00	0.000000
1	0.000000E+00	2.998600E−01	56.19616
2	2.993580E−01	5.020201E−04	0.094083
3	2.674781E−01	3.238183E−02	6.068615
4	2.991569E−01	7.030964E−04	0.131766
5	2.674781E−01	3.238183E−02	6.068615
6	2.674781E−01	3.238183E−02	6.068615
7	2.555297E−01	4.433030E−02	8.307854
8	2.700481E−01	2.981189E−02	5.586987
9	2.765931E−01	2.326685E−02	4.360395
10	2.998299E−01	3.007054E−05	0.005635
11	2.619158E−01	3.794417E−02	7.111042
12	2.998588E−01	1.162291E−06	0.000218

The improvement factor analysis (fifth step of ASM) suggested that event 1 would have largest contribution (about 56%) to the probability of the eventual accident. Table 7, which summarizes the results of improvement analysis indicate that events which would have the lowest contribution towards the undesired event are 2, 10 and 12.

The study concludes that particular attention must be paid to the events 1, 7, 11, 3, 5 and 6 which are most likely to cause the eventual accident (top event).

3.5. Fault tree development for chlorine transportation line

Chlorine transportation line deals with chlorine at the temperature 35°C, pressure 300 kPa, and flow rate 0.289 kg/s. The probable accident scenario for this envisaged as continuous release followed by dispersion. There are seven basic events that contribute directly to cause accident. The likely sequence of events involved is depicted in Fig. 6. The probability of occurrence of these basics event are presented in Table 8. It is evident that event 5 has considerably high rate of failure.

Table 8
Elements of the fault tree developed for a probable accident in chlorine transportation line

Number referred in figure	Elements	Failure frequency (per year)
1	Leak from pipe joints	36.0E−04
2	Leak from valve	216.0E−03
3	Valve choked	900.0E−04
4	Mechanical failure of pipe	216.0E−06
5	Flow controller failed	2.5E−01
6	Excess flow from the tank	288.0E−03
7	Orifice/pipe line choked	144.0E−06

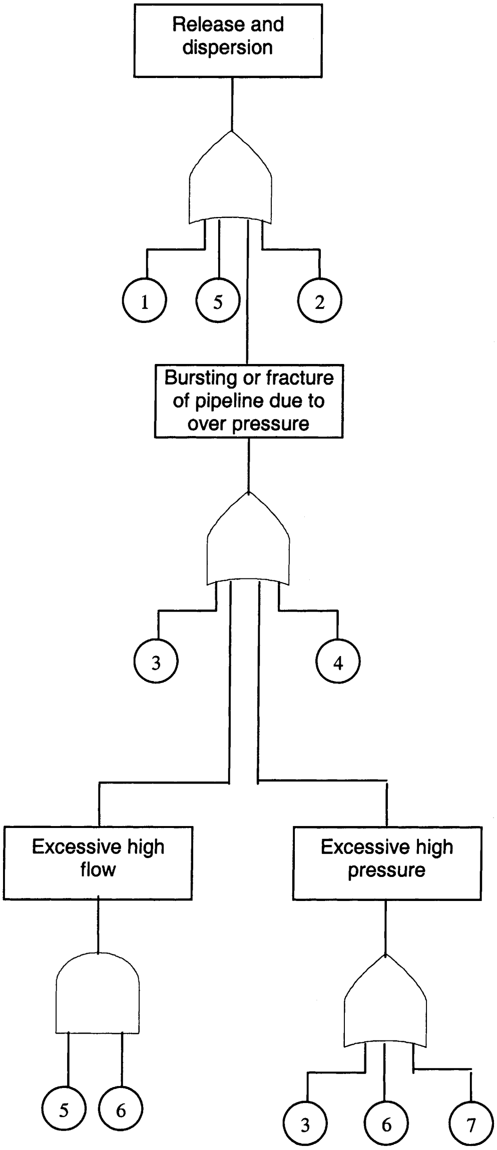

Fig. 6. Fault tree diagrams for an accident in the chlorine line.

3.5.1. Fault tree analysis

The developed fault tree (as depicted in Fig. 6) has been analyzed using PROFAT. The result of the analysis is presented in Table 9. The overall probability of occurrence of this particular scenario is estimated to be 0.618 per year. It is evident from the table that events 2, 5, and 6 may contribute to the extent of 20, 33 and 39%, respectively, in causing this

Table 9
Results of PROFAT for a probable accident scenario in chlorine transportation line

Event not-occurring	Probability	Improvement	Improvement index
0	6.184552E−01	0.000000E+00	0.000000
1	6.173319E−01	1.123369E−03	0.266844
2	5.325158E−01	8.593947E−02	20.41397
3	5.877467E−01	3.070849E−02	7.294466
4	6.183881E−01	6.717443E−05	0.015957
5	4.796692E−01	1.387861E−01	32.96711
6	4.541411E−01	1.643141E−01	39.03101
7	6.184105E−01	4.476309E−05	0.010633

accident. Control of these events would reduce the overall probability of occurrence of the top event.

3.6. *Fault tree development for the reactor*

The reactor unit involves propylene and chlorine dissolved in water to give chlorohydrin. As mentioned in previous section, the most credible accident scenario for this unit has been forecast as BLEVE followed by fire ball and dispersion of released gases. Detailed diagnostic analysis of the unit revealed that there are 17 basic events that would constitute directly to the realization of the forecasted event (Table 10). Among these, event numbers

Table 10
Elements of the fault tree developed for a probable accident in the chorohydrin reactor

Number referred in figure	Elements	Failure frequency (per year)
1	Ignition source	2.1E−01
2	Mechanical failure of the vessel	4.3E−05
3	Level controller fails	2.5E−01
4	Flow controller fails	2.5E−01
5	Over run of the pump	3.0E−02
6	High flow rate of the recycle stream	9.0E−02
7	High flow of water at up stream	9.0E−02
8	Temperature controller fails	2.0E−01
9	Upstream of propylene is high	1.7E−01
10	Heating medium flow rate in heater is high	1.7E−01
11	Flow rate is low	3.17E−01
12	Overfilling of the tank	1.5E−03
13	Uncontrolled side reaction	2.5E−01
14	Temperature of recycle stream is high	1.7E−01
15	High heat duty at exchanger E0117	1.44E−01
16	High flow rate of steam in kettle vaporizer	9.0E−02
17	Pressure of the steam in the vaporizer is high	1.7E−01
Details for event no. 11 (low flow rate)		
1′	Flow controller fails	2.5E−01
2′	Valve is choked	4.0E−03
3′	Low flow rate at upstream	9.0E−02

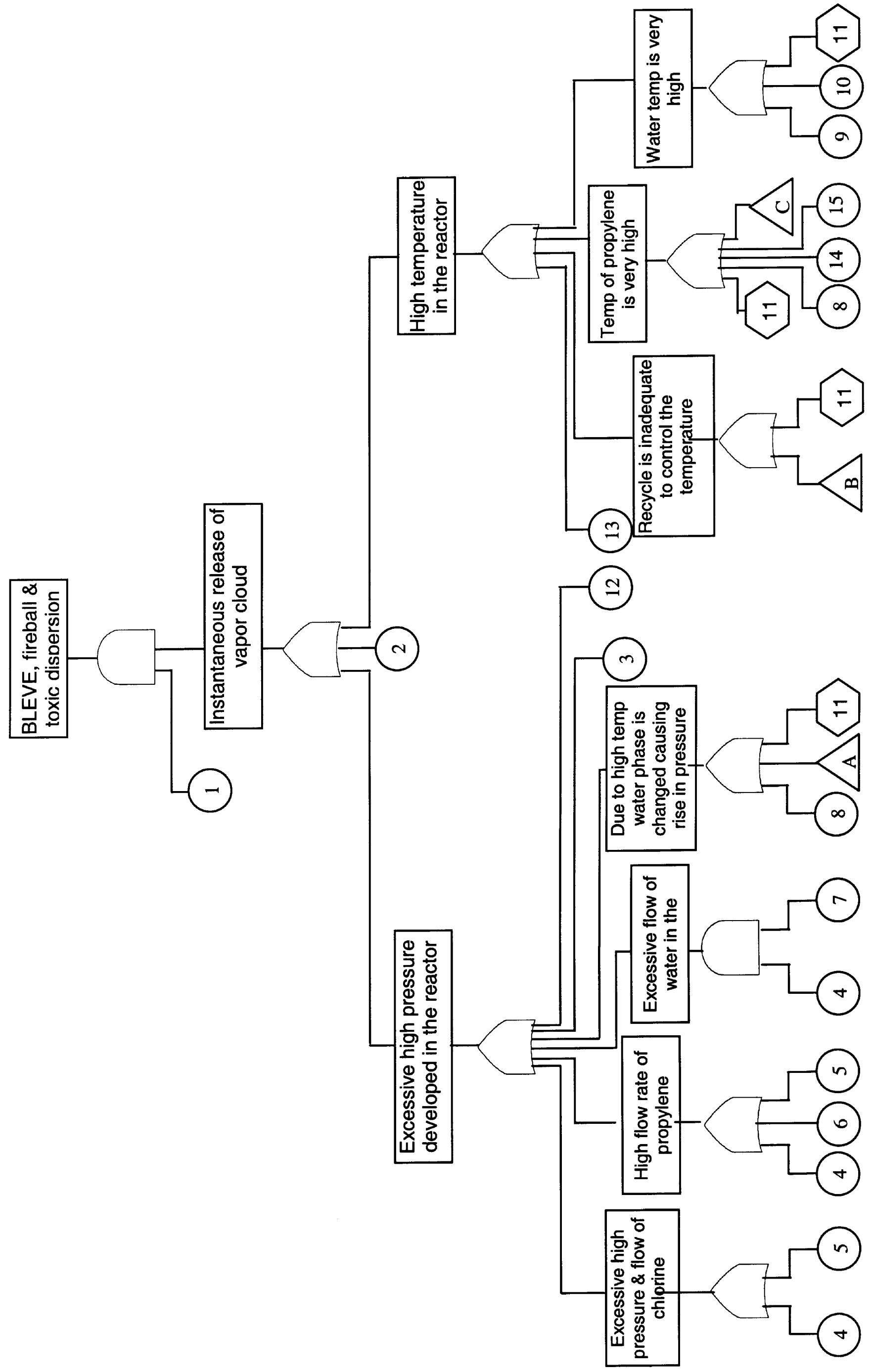
BLEVE, fireball & toxic dispersion
1
Instantaneous release of vapor cloud
2
Excessive high pressure developed in the reactor
High temperature in the reactor
Excessive high pressure & flow of chlorine
4
5
High flow rate of propylene
4
6
5
Excessive flow of water in the
4
7
Due to high temp water phase is changed causing rise in pressure
8
A
11
3
12
13
Recycle is inadequate to control the temperature
B
11
Temp of propylene is very high
11
8
14
15
C
Water temp is very high
9
10
11

Fig. 7. Fault tree diagrams for an accident in chlorohydrin reactor.

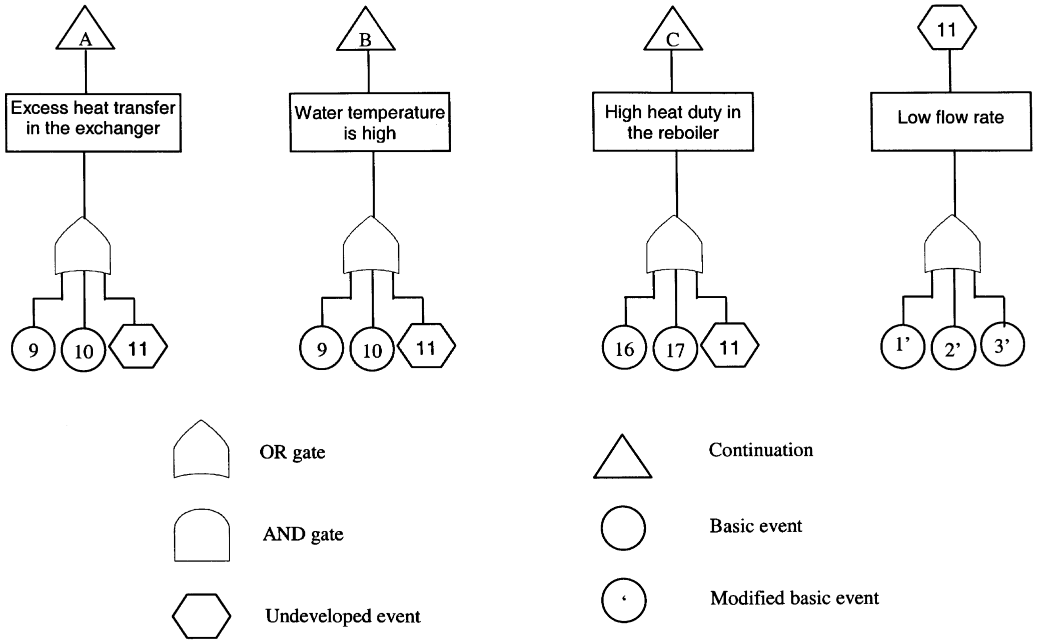

Fig. 7. (*Continued*).

Table 11
Results of PROFAT for a probable accident scenario in chlorohydrin reactor

Event not-occurring	Probability	Improvement	Improvement index
0	3.770728E−01	0.000000E+00	0.000000
1	0.000000E+00	3.770728E−01	58.58161
2	3.770679E−01	4.947186E−06	0.000769
3	3.459893E−01	3.108358E−02	4.829111
4	3.426628E−01	3.441003E−02	5.345903
5	3.736045E−01	3.468335E−03	0.538837
6	3.664676E−01	1.060525E−02	1.647619
7	3.740458E−01	3.026992E−03	0.470270
8	3.747678E−01	2.305090E−03	0.358116
9	3.565070E−01	2.056587E−02	3.195090
10	3.565070E−01	2.056587E−02	3.195090
11	3.367733E−01	4.029950E−02	6.260886
12	3.769009E−01	1.719296E−04	0.026711
13	3.459893E−01	3.108358E−02	4.829111
14	3.565069E−01	2.056590E−02	3.195095
15	3.598026E−01	1.727027E−02	2.683089
16	3.664676E−01	1.060522E−02	1.647614
17	3.565070E−01	2.056587E−02	3.195090

1, 3, 4, 5, 8 and 17 have a high frequency of occurrence. The logical dependency of these basic events is shown in Fig. 7. It is clear from the figure that events 11, 4, 9 and 10 repeat frequently.

3.6.1. Fault tree analysis

The results of FTA for the reactor units are presented in Table 11. It is evident that the basic event contributes 58% to the actual happening of the accident, whereas other events such as 11, 4, 3, 13, 14, 9, 10, and 17 are contributing to a lesser degree. Controlling of the event 1 and events 11, 4 and 3 would substantially reduce the probability of occurrence of the accident.

3.7. Fault tree development for recycle line

The gases that are removed from the top of the reactor and recycled back mainly comprise of propylene, water vapor and traces of chlorine. The accident scenario for this unit is release

Table 12
Elements of the fault tree developed for a probable accident in recycle line

Number referred in figure	Elements	Failure frequency (per year)
1	Ignition source	2.1E−01
2	Leak from pipe joints	36.0E−04
3	Mechanical failure of pipe	8.0E−06
4	Orifice/pipe line choked	144.0E−06
5	Valve choked	900.0E−04
6	Excess flow rate at upstream	288.0E−03

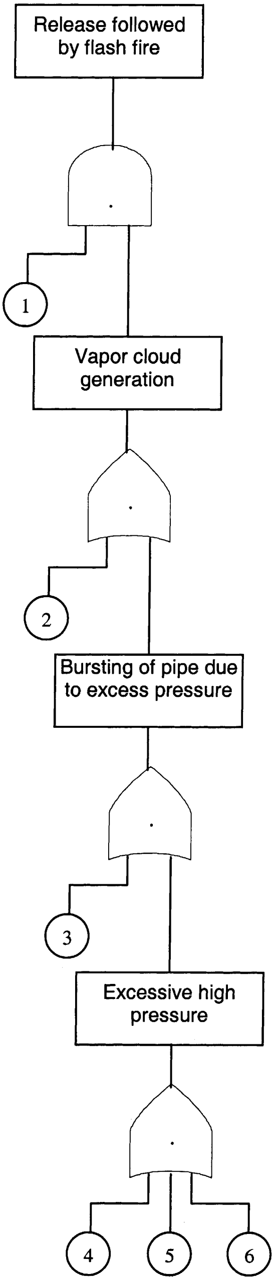
Release followed by flash fire
1
Vapor cloud generation
2
Bursting of pipe due to excess pressure
3
Excessive high pressure
4
5
6

Fig. 8. Fault tree diagrams for an accident in the recycle line.

Table 13
Results of PROFAT for a probable accident scenario in recycle line

Event not-occurring	Probability	Improvement	Improvement index
0	9.032172E−02	0.000000E+00	0.000000
1	0.000000E+00	9.032172E−02	50.66435
2	8.956252E−02	7.591993E−04	0.425859
3	9.031998E−02	1.743436E−06	0.000978
4	9.029133E−02	3.039092E−05	0.017047
5	7.074708E−02	1.957464E−02	10.98004
6	2.273473E−02	6.758699E−02	37.91171

of flammable chemicals eventually turning to a fire ball on meeting an ignition source. Six basic events may cause such an accident. A detailed study of this scenario indicates that ignition source has the maximum probability of occurrence as compared to other events (Table 12). Fig. 8 gives the likely pattern of events leading to the final event.

3.7.1. Fault tree analysis

The output of PROFAT for this accident is presented in Table 13. The total probability of occurrence of the top vent when all events occur is estimated as 0.09032, it is clear that events 1 and 6 are the major factors which if controlled would lead to a significant fall in the probability of occurrence of the top event. It is also evident from the table that events 3, 4 and 2 have minimum contribution to the top event.

3.8. Step V: risk estimation

Based on the results of the consequence analysis and probabilistic FTA, the risk posed by each of the unit was estimated. As the risk is related, inter alia, to the number of persons likely to be harmed, the population distribution in and around the likely accident points (Fig. 9) was also taken into account. The resultant FN (frequency of occurrence — number of fatalities) curves are presented in Figs. 10–14. It may be seen that in all the cases the risk posed is far above the acceptable limit (TNO acceptable risk criteria, as described in [12]).

3.9. The final step: risk reduction through safety measures — MCCA–PFTA controller system

A list of the possible control options to reduce the risk is listed in Table 14. From these, various combinations of the control measures were selected to reduce the risk potential of a unit. When these measures were accounted for, the fault tree for the unit got modified, as shown in Fig. 15 the list of the control measures for propylene transportation line. On analysis of the new fault tree (Fig. 15), the frequency of occurrence of the top event (envisaged accident) was seen changed to the 6.7502E−05, which is ~4500 times lesser than the previous value. The risk profile (FN curve) after implementation of control measures is shown in Fig. 10, revealing that after the safety measures were taken into account, the risk profile has come down to well within the acceptable limits. When SCAP was applied

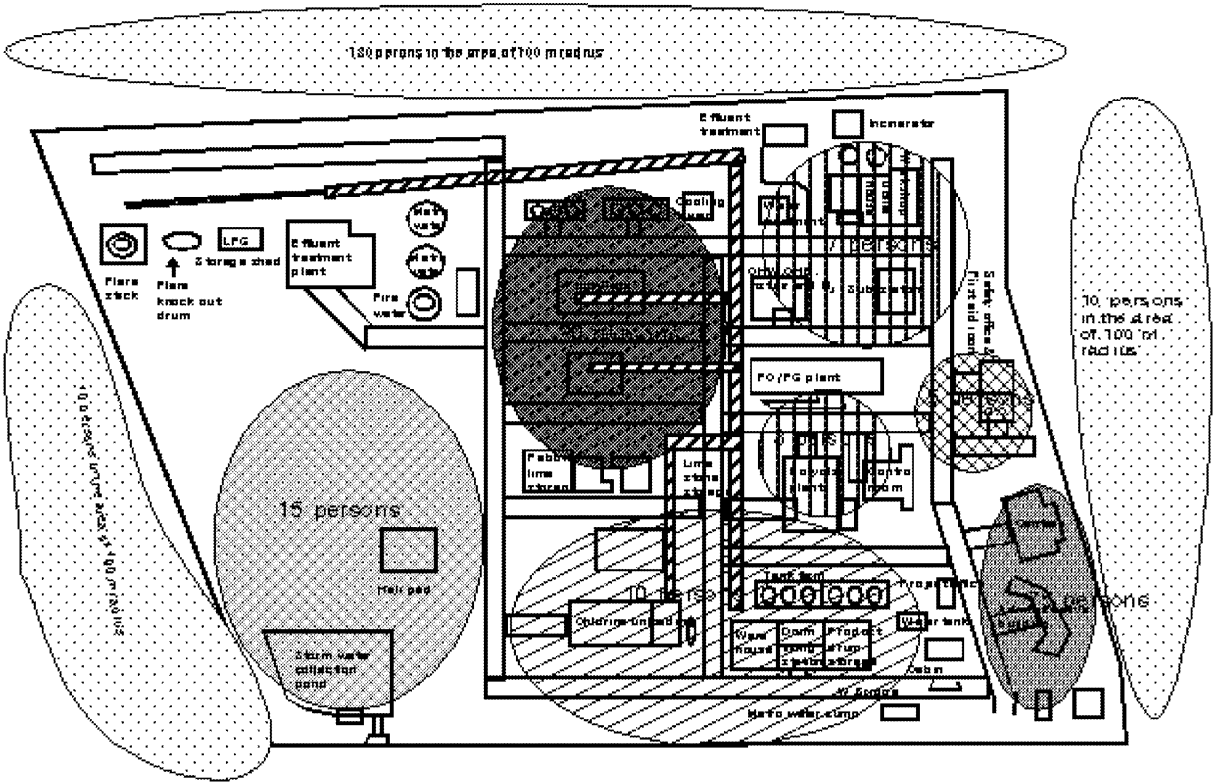

Fig. 9. The layout of the industry and distribution of population in and around the industry.

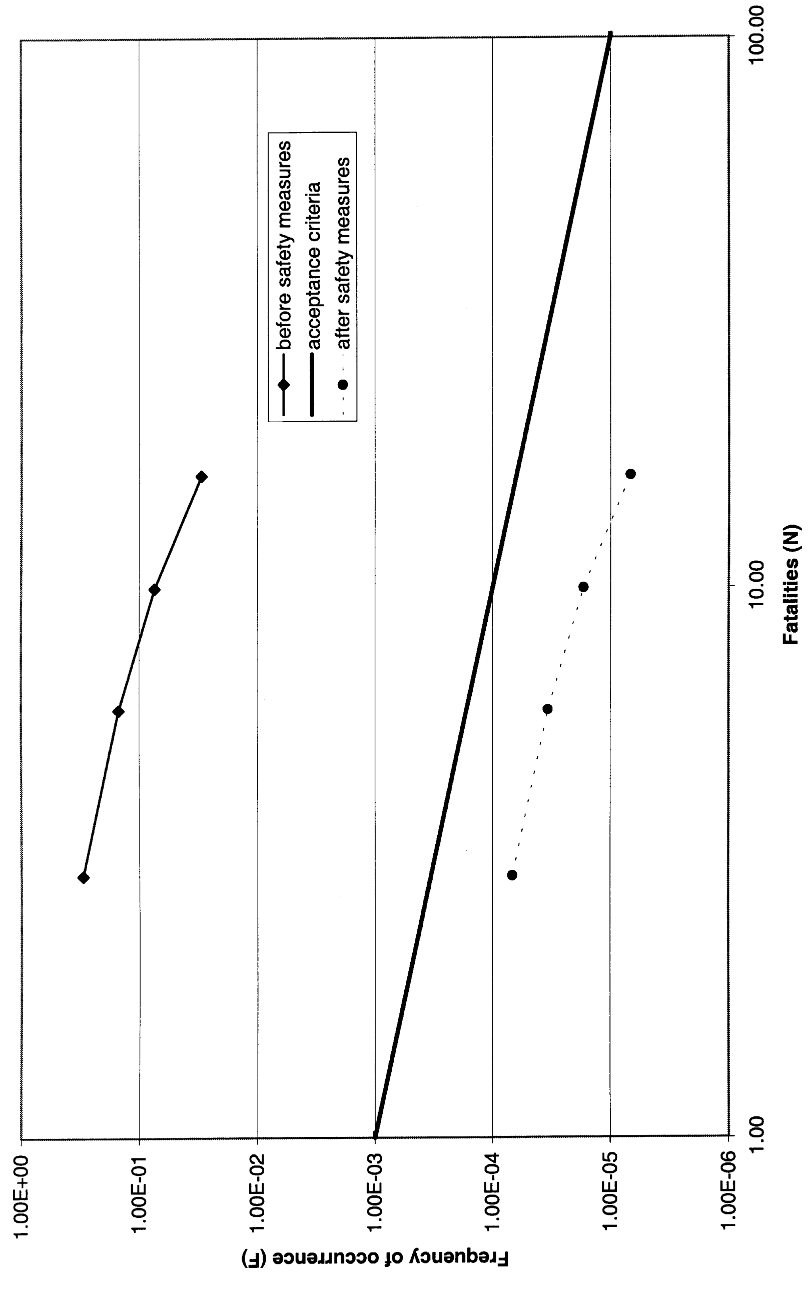

Fig. 10. FN curves for a propylene transportation pipeline.

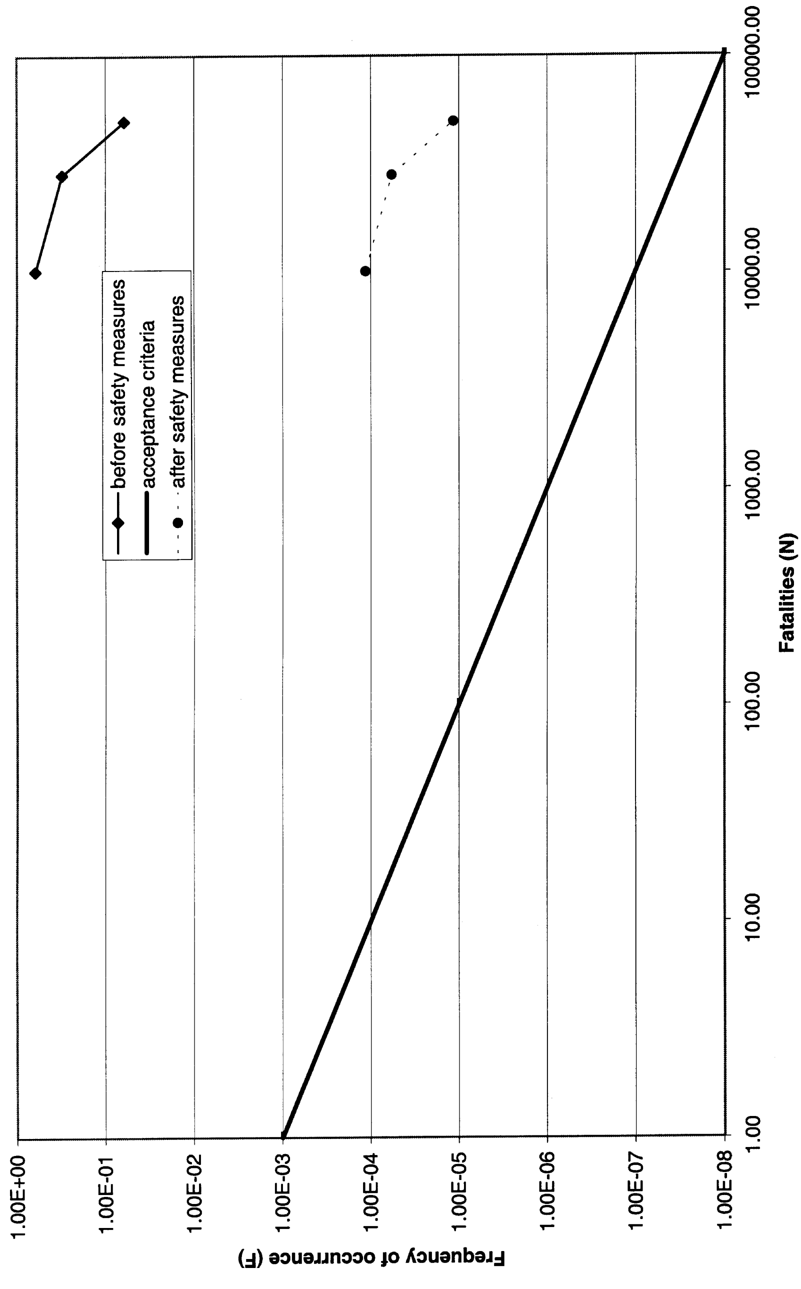

Fig. 11. FN curve for a chlorine transportation line.

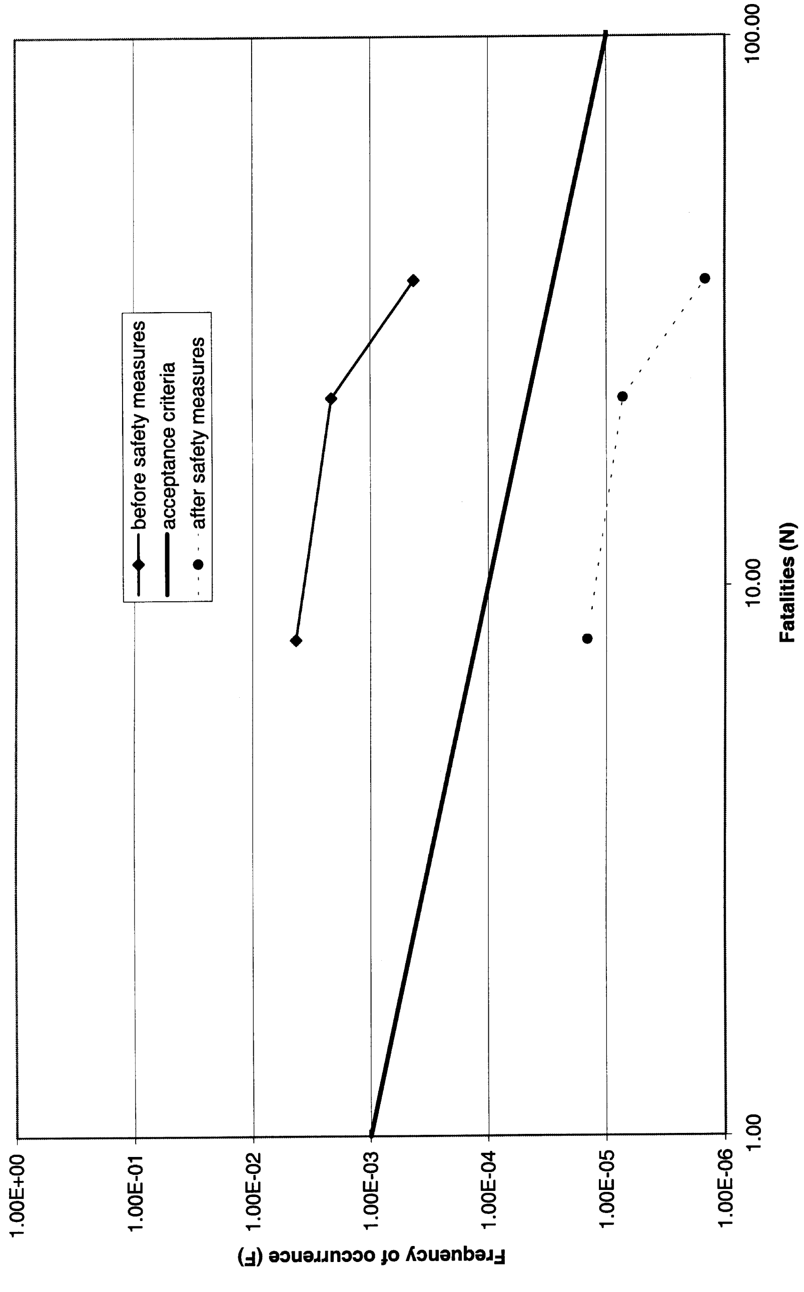

Fig. 12. FN curve for a chlorohydrin reactor due to heat and overpressure effect.

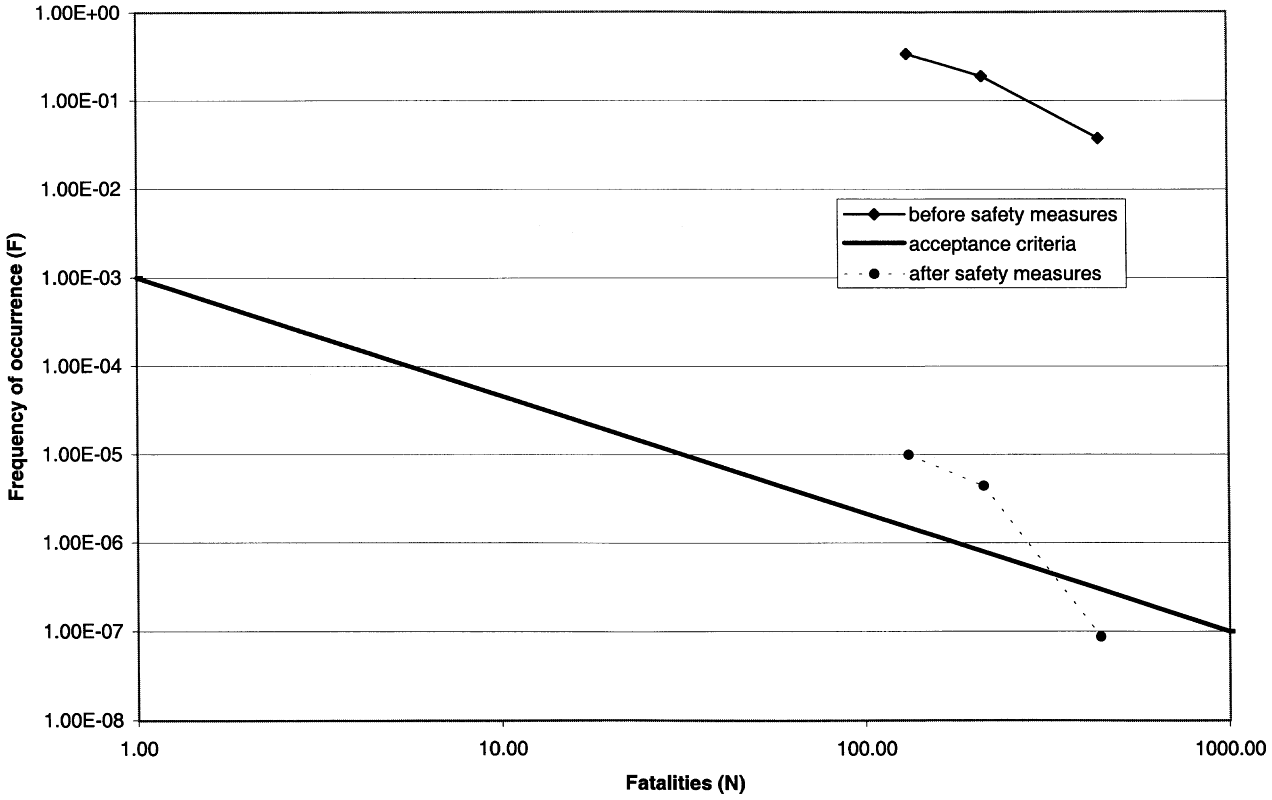

Fig. 13. FN curve for chlorohydrin reactor due to toxic effect.

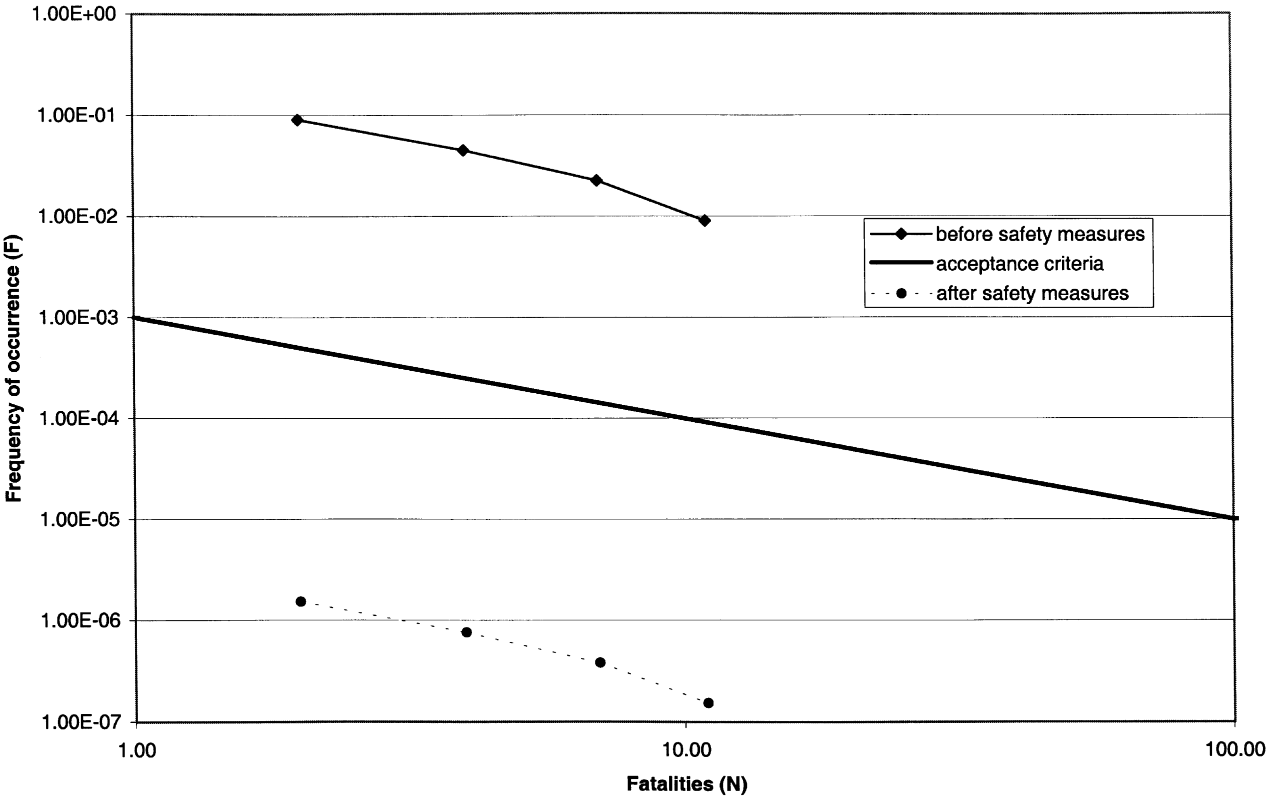

Fig. 14. FN curves for recycle line.

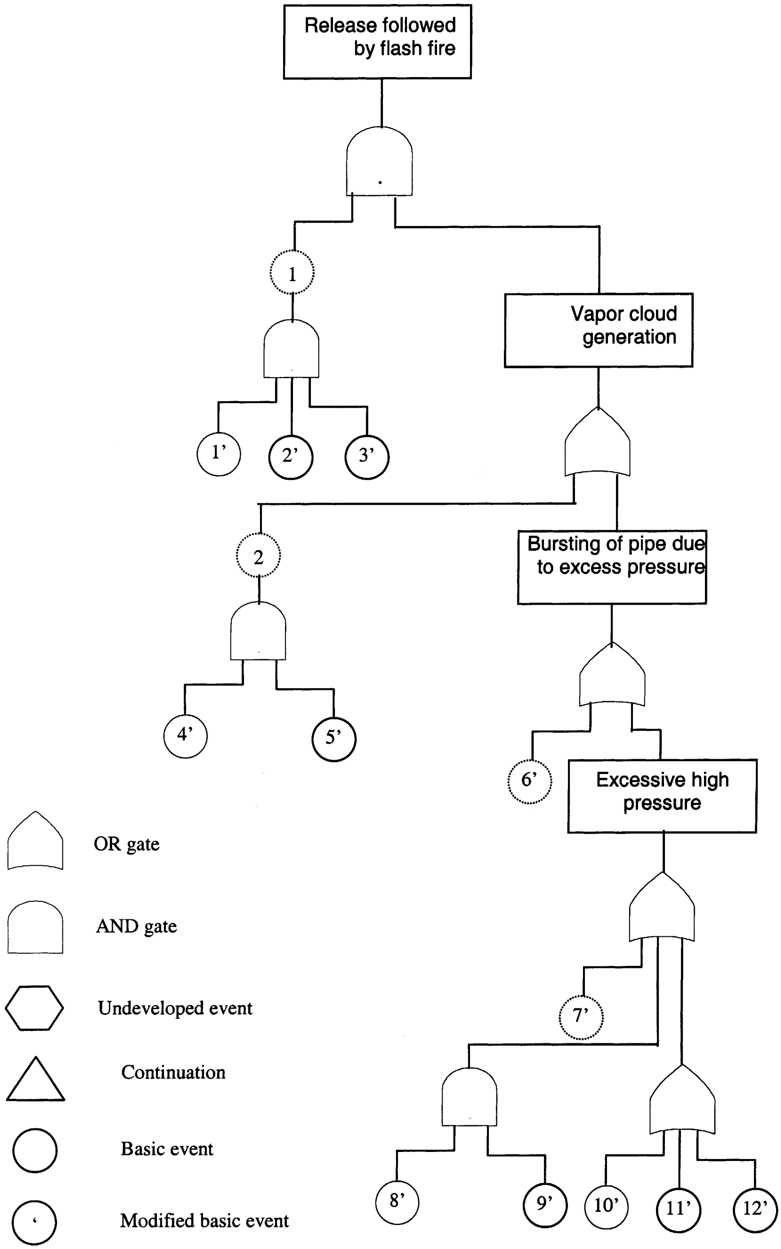

Fig. 15. The modified fault tree diagram for recycle line; the units marked (′) depicts the modified basic events (control measures).

Table 14
Various control options that have been suggested to be implemented over different units to bring risk factors to the acceptable values

Control option	Frequency of failure (per year)
Flame arrester	0.1080
Sprinkling system	0.0100
Flammable gas detector	0.0576
Advanced control mechanism, i.e. feed forward, cascade control, neural network based control, DDC	0.0050
Advanced final control element (digital controller)	0.0018
Installation of emergency relief valve	0.0150
Replacement of old valves with more reliable valves	0.0960
Check valve with relief provision	0.0300
Installation of controllers	0.0220
Installation of by pass line	0.0040
Leak detector	0.0576
Regular maintenance	0.0100
Safety relief valve	0.0100
Emergency relief valve evacuate the content to another vessel	0.0040
Inert gas purging to dilute released toxic gases	0.0090

in the same manner to the reactor unit and the recycle line (Figs. 12 and 14), significant lowering of the hazards was observed in these cases as well. However, in case of the fourth unit — involving chlorine — incorporation of safety measures failed to bring the FN curves down to acceptable levels. Thus, for this unit, the industry has to go for special emergency preparedness and disaster management plans. The industry would also have to treat this unit — and all such others, which do not respond favorably to SCAP treatment — as special red category or 'hot' units.

4. Summary and conclusion

The paper presents a new methodology in which safety management steps in a chemical process industry have been iteratively linked with the hazards contained in the industry. For a continuous assessment of the letter, as it is influenced by the former, a coupled system based on MCAA and PFTA techniques has been utilized. The resultant methodology enables a continuous and quantitative determination of impacts of safety measures on the risks posed by an industry. The methodology has been given an acronym SCAP where S stands for safety, C and A stand for credible accident, P stands for probabilistic FTA. The usefulness of the methodology has been demonstrated by a case study. When applied to the propylene oxide reaction unit of a petrochemical industry, SCAP was able to show how successive safety measures brought down the risks posed by three of the components of the unit to the levels defined 'safe'. It also brought out that a fourth constituent had such a fault tree that its risk potential could not be lowered significantly in spite of intensive inputs of accident controls.

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