Second Annual Symposium, Mary Kay O'Connor Process Safety Center
"Beyond Regulatory Compliance: Making Safety Second Nature"
Reed Arena, Texas A&M University, College Station, Texas
October 30-31, 2001

Quantitative Risk Assessment for Refinery Industry

Adam Markowski
Technical University of Lodz
90-924 Lodz ul. Wolczanska 213
POLAND

Email: markows@wipos.p.lodz.pl

ABSTRACT

A quantitative risk assessment is widely accepted methods for safety assurance in process industry. The methods is continuosly improving by introduction of new approaches both to hazards identification and risk evaluation.

This paper adresses two important aspects:

1. Selection of creditable inicidents after qualitative hazards identification which subsequently are used in individual and group risk evaluation

2. "Domino effects" understood as a subsequent chain of accidents after single hazard event.

The first aspect is developed by the application of multilayer risk matrix where each layer represents risk reduction level according to typical prevention, protection and response layers met in a particular refinery installation. The second aspect is presented by guidelines on a particular chain of events occuring for the most often refinery types of the equipment (storage tanks, loading and unloading areas, reactors, pipe networks and other types of process equipment). The above aspects are illustrated by the case sudy of a HF Alkylatian Plant.

QUANTITATIVE RISK ASSESSMENT FOR REFINERY INDUSTRY

Adam S. Markowski
Faculty of Process and Environmental Engineering
Technical University of Lodz,
90-024 Lodz, Wolczanska 213, Poland
Phone:+48 42 631 37 45, Fax: +48 42 636 26 45, E-mail:markowski@wipos.p.lodz.pl

Abstract

Risk analysis for installations containing large amounts of flammable substances is fundamental to ensure safety and to meet legal requirements. The paper deals with a quantitative risk assessment of a typical isobutane storage installation so frequently met in refineries which, due to its location, may cause the domino effect. Based on the proposed methodology individual and social risk curves were calculated. It was proved that a standard installation did not meet acceptable risk criteria and that possible domino effect only slightly increased the individual and societal risk. The proposed adequate safety and protection measures can ensure tolerable risk.

1. Introduction

Refineries with numerous dangerous substances and processes represent high potential of extraordinary hazards. Large majority of refinery industry facilities are located in the vicinity of densely populated, urban residential and industrial areas and ecosystems. Hence the analysis of the possibility of the occurrence and the scale of such events is so important to be able to undertake adequate precaution, protection and preventive measures. Quantitative risk assessment (QRA) serves this task [1].

This paper deals with quantitative risk assessment of a typical LPG storage facility frequently met in refineries. The assessment was performed using the SafetiM software which enables a calculation of both potential consequences of the release of flammable substances and the individual and social risk curves. The calculations were performed for various options taking into account existing protection layers, the impact of possible domino effects and proposed risk reducing measures.

2. LPG storage in refineries

Liquefied petroleum gases (LPG) are produced in many refining processes starting from atmospheric distillation, vacuum distillation, hydrocracking, catalytic cracking, reforming and isomerization. These gases usually appear in the light stage (so called wet gas) and after purification and separation are collected in storage tanks as separate fractions C3 and C4. Then they can be used to obtain propane-butane mixture or for further petrochemical processes.

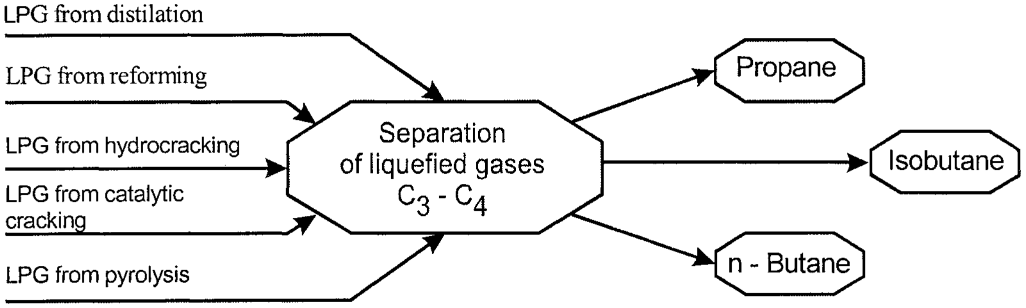

Fig. 1. LPG sources in refinery installations

Storage tanks within an installation, linked with one another by a piping system and pumps and connected to the installation itself, are used for temporary storage purposes or as supply sources for the production lines. They are of 200-400 m^3 capacity, often situated within several dozen meters from the production installation and from control room. These may provoke the domino effect in the surrounding if unexpected developments occur.

It is also worth stressing that chemical composition of LPG obtained as a result of refining processes varies largely from simple alkanes, alkenes, small molecule olefins and other cyclical and aromatic hydrocarbons. After various processes of separation and purification, the gases used for further petrochemical syntheses contain a given dominant compound, e.g. isobutane for alkylation or propane - butane for propylene pyrolysis. Considering all these, modelling of releases and dispersion of such mixtures need to be taken into account.

3. Risk management concept in chemical plants

Risk management consists in decision making process in the risk area based on the assessment of relations between existing hazards and applied safety and protection systems. It is illustrated in Fig. 2.

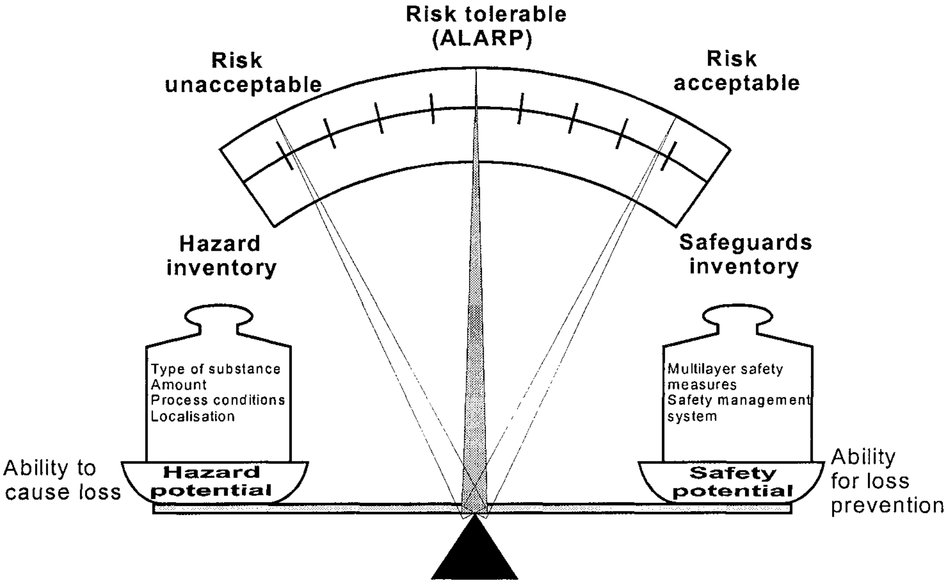

Fig. 2. Risk management - safety assurance principle [2].

In refining processes there is a very broad spectrum of different hazards which represent mostly a certain fire & explosion potential. They are measurable by any semi-quantitative techniques (e.g. DOW or MOND Index) or full consequences analysis [1,2,3].

On the other hand all hazards are guarded by variety of safety system. According to CCPS guidelines [4] those system are organized into a multi-layer system where the following main layers can be distinguished:

1. Prevention layer which is responsible for the minimisation of chemical releases; that layer consists of the basic controls (BPCS), process alarms, operator supervision and its response. This layer mainly affects a likelihood of chemical releases.
2. Protection layer comprises the automatic protection of installation after releases or after critical alarms. It includes safety instruments systems (PSV, trips, interlocks, ESD), blow-down systems, emergency cooling, fire fighting and explosion protection. That layer affects the likelihood and consequences of chemical releases.

3. Response layer is acting as the mitigation of the consequences of chemical release and includes the action of fire brigade and rescue services.

This concept is illustrated in Fig. 3.

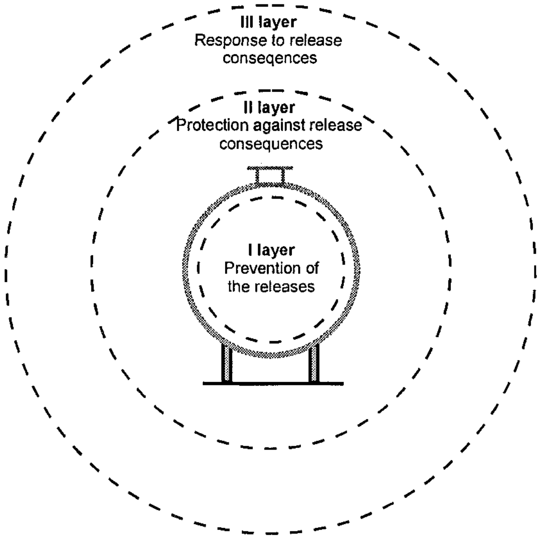

Fig. 3. Layers of protection in chemical plant.

It can be noticed that characteristic features of multilayer safety systems are following:

1. Sequential, serial and independent activity of each safety layer.
2. Each safety layer is a barrier to develop hazards and may consist of some subsequent sublayers.
3. Initiating event for the release incident used to be failure of elements acting in the prevention layer.
4. Risk reduction level can be calculated separately for each layer based on Bayes theorem.
5. Effectiveness of each layer depends on the quality of safety management system and applicability of BAT (best available techniques).

The relation between existing hazards and safeguards system represents risk level adequate to each installation. Therefore in risk evaluation and assessment the detailed analysis of hazards and connected safety measures, especially layer of protection is necessary.

4. Selection of most representative set of incidents for QRA

In starting part of QRA the most representative set of incidents (RSI) need to be selected. As it is known the use of hazard identification techniques can lead to the identification of a wide range of incidents which are the basis for selection. However a possible accidental releases of substance and/or energy can be infinitive due to variety of possible ruptures or leaks taking place in different location and size of the piping or vessels. Each release incident can expand into so called incident outcomes (RIO) depending on the propagation, safeguards and mitigation measures. These outcomes need to be taken into account in risk evaluation. In fact there is no well grounded methodology which may satisfy the above requirements of the study and adequately represent the spectrum of all hazards and safeguards.

In our approach so called "multi-layer risk matrix" (MRM), presented in Fig. 4 was applied [5].

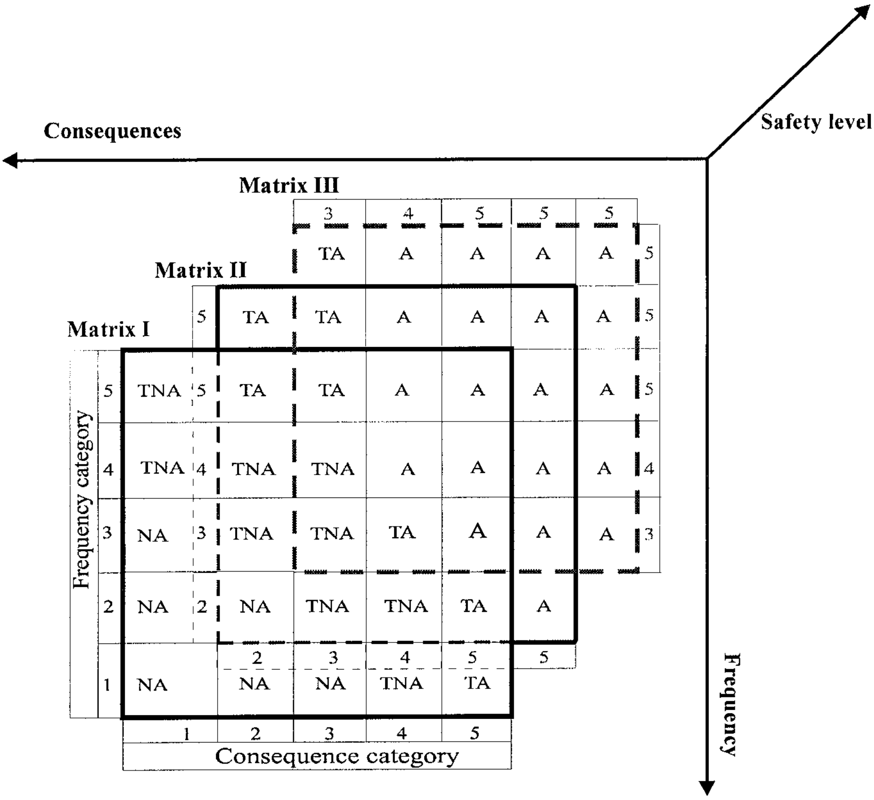

Fig. 4. Multi-layer risk matrix .

In that matrix each layer of protection is represented by a separate risk matrix with a specific categorisation of risk component.

The frequency, consequences and risk level were categorised as follows:

- the frequency categorisation - 5 categories from very frequent ($10^{-1}\cdot 1$/year) to very rare (above 10^{-4} 1/year)
- the consequences severity categorisation - 5 categories, from catastrophic to negligible
- the risk level- 4 categories:
  A - low acceptable risk, no need for further action,
  TA - low-tolerable risk, action based on ALARP principle,
  TNA - tolerable risk, indication for improvements in medium notice,
  NA - unacceptable risk, must reduce immediately.

The following steps accomplish evaluation of risk level using multi-layer risk matrix:

1. Identification of safety systems (safety layers).
2. Determination of an initiating event and its frequency (generic).
3. Determination of initial consequence, C_0 (generic).
4. Evaluation of risk reduction level for 1st layer.
5. Evaluation of risk reduction level for 2nd layer.
6. Evaluation of risk reduction level for 3rd layer.
7. Evaluation of risk level, RL.

$$RL = f_0 \cdot C_0 \cdot \prod_{1}^{n} RL_n$$

5. Incident scenario for LPG releases

The development of incidents and types of hazards accompanying gas releases depend upon the characteristics of the source of outflow and external conditions in the release area. The following can be listed:

- presence of immediate source of ignition or late ignition,
- LPG leakage point, i.e. above the LPG surface (vapour phase of the tank) or in the liquid phase
- size of the leakage,
- nature of the leakage: continuous or instantaneous.

In storage installations there are numerous leakage possibilities (through small openings in the wall or faulty seals) as well as those of catastrophic ruptures, i.e. breakage of the pipeline or an opening in the tank of the diameter at least equal to that of the largest connection. Standard hole size guidelines can be found in publication of IChemE [6].

Release incident (RI) for flammable substance may be developed in different incidents outcomes (RIO) presented by the event tree in Fig.5.

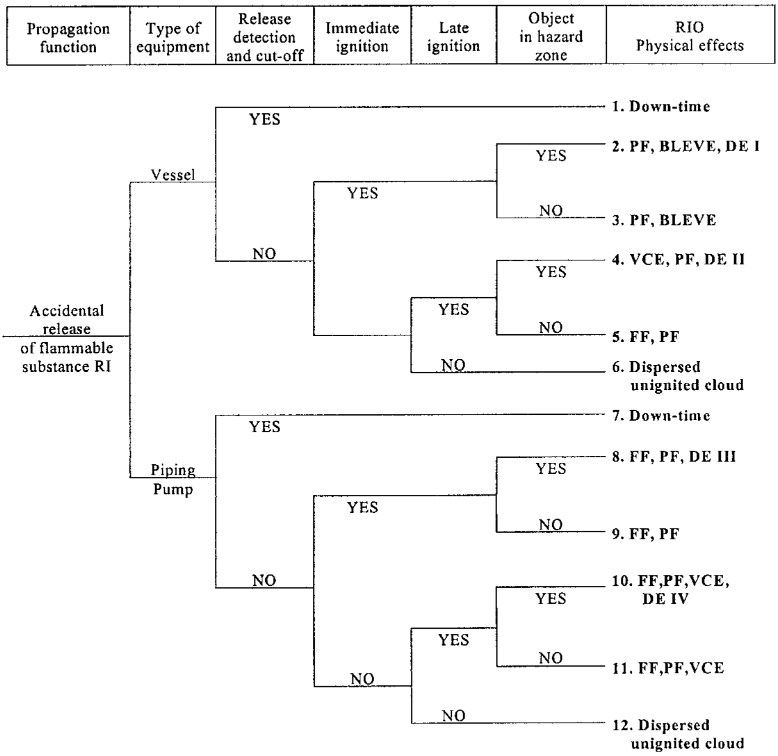

Fig. 5. General event tree for LPG releases.

The above event tree shows that some outcome cases may be further developed into different domino events. It may happen if only the hazard zone, where particular physical effects exceed threshold value, envelopes the adjacent vulnerable objects.

6. Methodology to assess the significance of domino effects from major hazards plants

The domino effects are part of legal requirements then it is important to be included in final results of QRA [7]. In that work domino effect means the effect of major accident in basic plant causing on the adjacent plant or nearby site a release of a dangerous substance as a result of direct or indirect interrelation. "Domino" implies escalation of an accident to another plant and it is a wider definition than "escalation" which may refer to one particular plant only. There are two types of domino events:

1. direct domino event caused by interaction of the top loss of containment events,
2. indirect domino event caused by small leak due to failure of the equipment, loss of utilities, human error or ineffective mitigation system.

A typical feature of the domino is multiplication and chain of incidents which may be in series or parallel. Fig. 6. shows a characteristic pattern of domino effects in a chemical plant.

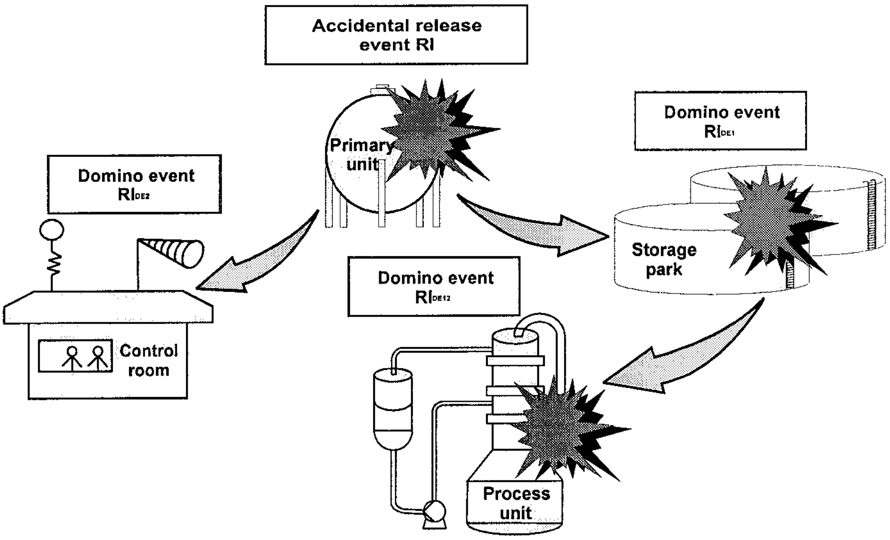

Fig. 6. Typical pattern of domino events.

The release incident (RI) may be escalated into three different physical effects: shock wave, thermal radiation and missiles projection. Each of these physical effects generates a hazard zone where the values of particular effects exceed threshold values and due to that a particular domino event may take place. It depends on many different influencing factors relevant to that escalation process, specifically for each type of the event. The most important are the following :

- the type of equipment,
- the type of the substance involved,
- the adjacent equipment and its vulnerability,
- the distance from RI and between subsequent equipment,
- propagation conditions like ignition sources, wind direction and mitigation means.

The level of damages due to the domino event depends on the distance involved, propagation conditions and vulnerability of the adjacent equipment. The literature on the subject quotes many, though different, data concerning the impact of various physical effects upon humans, buildings and industrial installations [3,8,9]. Table 1 presents the most convincing threshold criteria.

Table 1. Threshold criteria for physical effects of fire and explosion hazards.

Type of object	Thermal radiation [kW/m^2]	Overpressure for total damage [kPa]	Overpressure for partial damage [kPa]
Pressure vessel	37.5	48	38
Atmospheric tank	37.5	---	---
Fixed roof tank	37.5	21	7
Floating roof tank	37.5	45	45
Pipelines	37.5	40	24
Ordinary plant buildings	12.5	7	---
Central rooms	25	Depends on the design	Depends on the design
People	1000[(kW/m^2)$^{3/4}$·sec]	14-16	---

There is no universal threshold value for missiles projection. The calculation procedure on the missile range prediction is provided in Yellow Book [10].

As can be concluded the additional scenarios of the domino event should be considered in QRA. To this aim two values have to be identified:

1. Probability of domino events P_{DE}.
2. Consequences of the domino events.

Probability of domino event, P_{DE}, used to be calculated as follows [3]:

$$P_{DE} = F_{RI} \times P(RI/DE)$$

where: F_{RI} is the frequency of accidental event in basic plant,

$$P(RI/DE) = \sum_{k=1}^{3} P(RI/DE)_k$$ is propagation probability,

k=1 for thermal radiation effect (TR),
k=2 for overpressure effect (ΔP),
k=3 for missile projection effect (MISS).

The estimation of P(RI/DE) should take into account the mechanisms of the propagation and can be done for particular type of the physical effect using three different approaches:

1. based on Probit functions,
2. based on empirical data,
3. "worst case" approach.

In that work the last approach was assumed that means the propagation probability is equal 1 if the vulnerable target is inside the hazard zone for the particular physical effect.

The consequences of domino events were assumed catastrophic and calculated similarly to release incidents considering appropriate conditions: type of the substance, amount, conditions before release and external propagation conditions. Outside the impact area of a critical physical effect (hazard zone), a domino event may also occur but a probability and consequence of those events would be significantly smaller and they were not taken into account.

The methodology of considering domino top events in calculating of individual and societal risk is shown in Fig. 7.

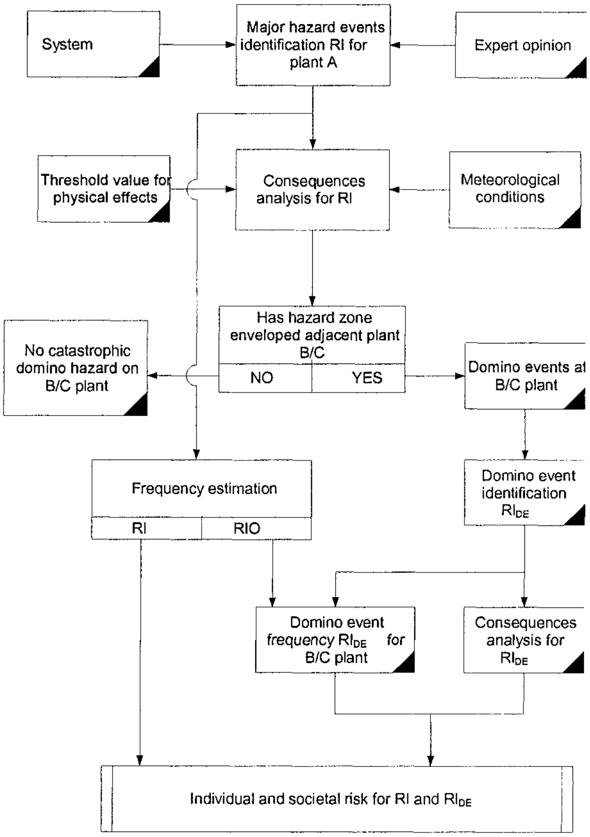

Fig. 7. General methodology of calculating risk considering domino effects.

7. Case study

7.1. Description of the object

A typical isobutane storage installation was analysed. It is situated within a production installation in a refinery and consists of three spherical tanks of the volume of 300 m^3 each, a system of pumps, heat exchanger and appropriate linking pipelines. The scheme of the installation is presented in Fig. 8.

The location of the storage installation is shown in Fig. 9.

The following meteorological conditions were assumed: air humidity: 70%, dominating class of atmospheric stability: F and D, wind velocity: 2 and 5 m/sec respectively, dominating wind direction: S-W.

At the distance of 34 m, in the immediate vicinity of the installation there are 2 cylindrical floating roof tanks of gasoline of the volume of 2000 m^3 each, a central room and a production installation which are 44 m from it. Flask furnace is the direct source of ignition situated at the distance of 100 m and traffic on internal routes.

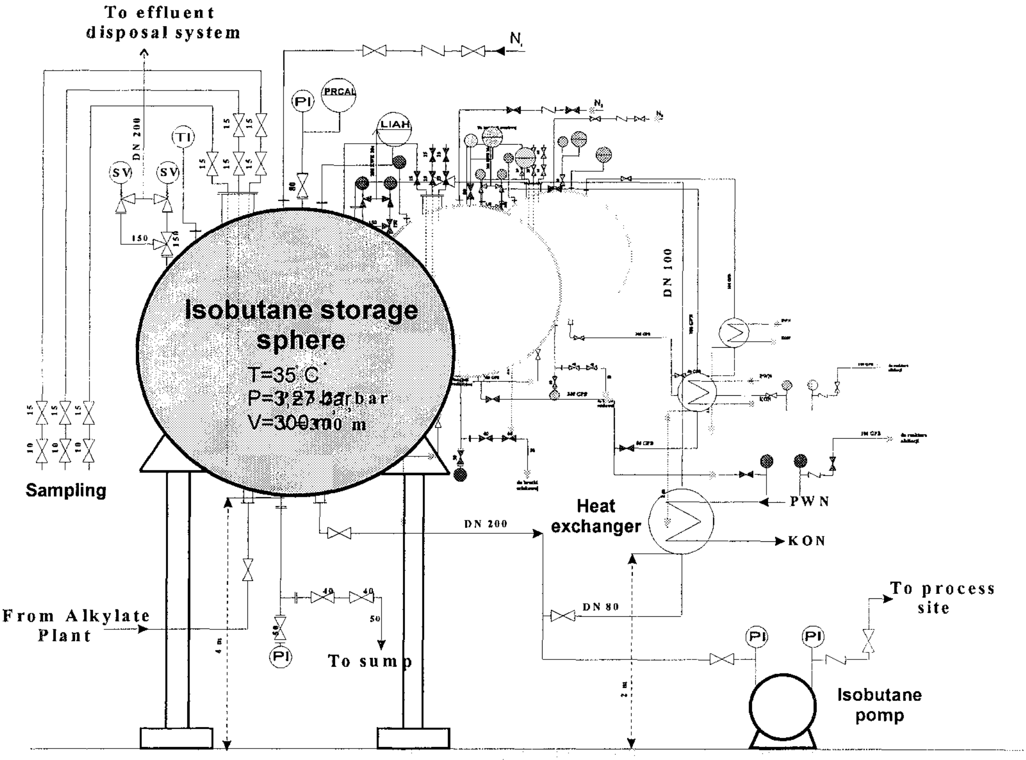

Fig. 8. Scheme of isobutane storage installation.

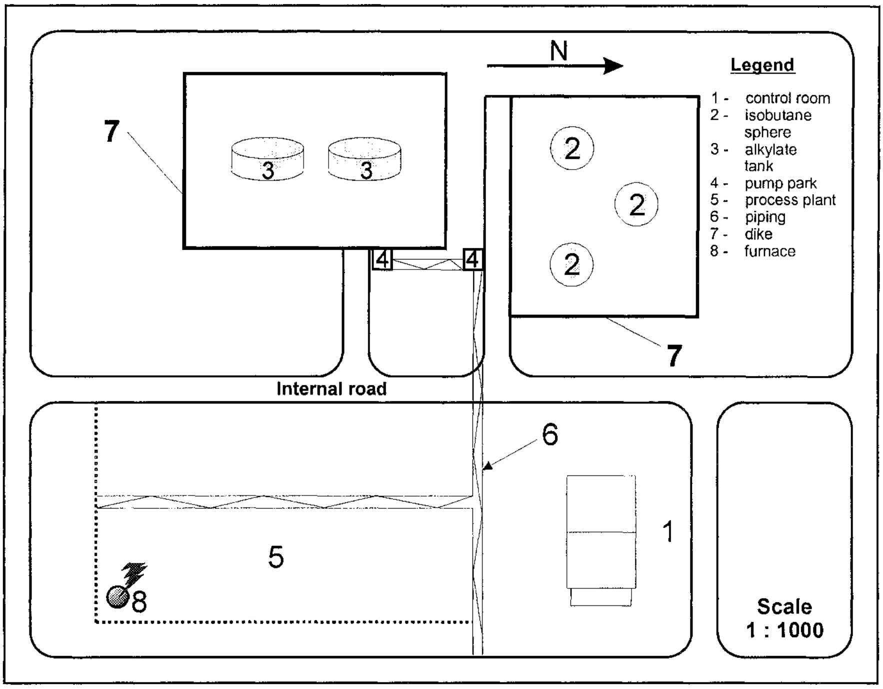

Fig. 9. Location of isobutane storage installation.

The installation is equipped with safety and protection systems presented in Table 2.

Table 2. Safety and protection systems

Safety layer	Measures
Layer I- prevention systems	Good engineering practice-GEP(standards ASEM and ANSI/ASME, execution EX) Local measurements: PI, TI, LI Measurements with indications and alarm in central room: PRCAL, LIAH
Layer II - protection systems	Safety valves SV connected to discharge installation Tray under the tank (outflow) Safety nitrogen
Layer III - respond systems	Sprinklers system Fire Brigade

7.2. Identification of representative set of incidents - RSI

Analysis of 21 historical data collected in The Accident Database [11] indicates the principal possible causes of failures of LPG tanks with isobutane and butane. Overfilling, overpressure, mechanical failure, human error and external events can be named as the most frequent ones. From among various physical effects BLEVE explosions account for 14%, vapor cloud explosions for 43%, pool and flash fires for 19% and in 24% of cases only the release and gas dispersion in the air without ignition were reported.

As a result of Primary Hazard Assessment (PHA) 17 incidents were identified for which then the risk was assessed using a typical 4-level risk matrix. Thus we could obtain 3 representative incidents RI representing tolerable risk at the best and at the same time belong to the same group of releases. Having developed these events for two types of seal failure (rupture and leakage) six of RI were finally obtained and they are presented in Table 3.

Table 3. Set of representative incidents RSI.

RSI	Incident scenario	Failure frequency, 1/year
RI 1	Leakage on the tank wall (d_{Hole}=25mm) or on connections due to overfilling, overpressure or wall destruction	$9\cdot10^{-5}$
RI 2	Storage tank rupture due to the break down of the lower connection	$1\cdot10^{-5}$
RI 3	Transport pipeline rupture (d_{Hole}=200mm, L=50m) between the tank and the pump	$5\cdot10^{-5}$
RI 4	Transport pipeline leakage (d_{Hole}=10% cross section, L=50m) between the tank and the pump	$5\cdot10^{-4}$
RI 5	Rupture of pump body	$3\cdot10^{-5}$
RI 6	Leakage at the pump seal	$3\cdot10^{-3}$
RI_{DE} 7	Rupture of a neighboring isobutane tank due to domino effect relating to BLEVE in RI 2	$0.16\cdot10^{-5}$
RI_{DE} 8	Rupture of adjacent atmospheric tank and release of gasoline due to VCE in RI 2	$0.36\cdot10^{-5}$
RI_{DE} 9	Rupture of adjacent piping and release of gasoline due to VCE in RI 2	$0.36\cdot10^{-5}$
RI_{DE}10	Destruction of control room due to VCE in RI 2	$0.36\cdot10^{-5}$

As can be seen additionally, there were included the domino event incidents because, as later calculation proves, hazard zone enveloped the neighboring objects shown in Fig. 9.
Outcome incident frequency for $RI_{DE}7$-10 was calculated using the event tree (Fig. 5. Data concerning the frequency of certain RI were based on generic data quoted in literature [3,6,12,13]. The following propagation functions were assumed:

Table 4. Propagation probabilities functions [6,13].

Immediate ignition	0.2
Late ignition	0.5
Detection of a leakage and its cut off	0.3
Object in hazard zone	1

7.3. Analysis of the results

7.3.1. Identification of domino events.

The calculations were performed using the SafetiM v.5.22 software by Det Norske Veritas [14] which enables the calculation of both the potential consequences of releases of flammable substances and individual and societal risk curves. The first part of calculations has identified the range of hazard zone for the release incidents taking into account the following physical effects threshold criteria:

for thermal radiation: 37.5 kW/m^2
for overpressure: 45 kPa

The circle based on the distance from release source to the threshold value forms hazard zone (impact area where domino effects may occur). The calculated range of hazard zones for all release incidents is given in Table 5. Inside the impact area there are the following objects which are considered as a possible target for domino effects:

1. the spherical izobutane neighboring tank,
2. the atmospheric gasoline tank,
3. the piping at process plant,
4. the control room where four operators are employed.

Therefore all these targets were included as a sources of subsequent domino events ($RI_{DE}7$-$RI_{DE}10$) and underwent similar the probabilities and consequences calculations. The results of calculation were added to the Table 5. Since the domino incidents $RI_{DE}8$ and $RI_{DE}9$ do not form hazard zone they will not contribute to the individual and societal risk estimate.

Table 5. Range of hazard zone.

RI	37.5 kW/m^2		45 kPa		Physical effect
	F2	D5	F2	D5	
RI1	65	54	59	no effect	JF, VCE or FF
RI2	209	209	288	480	PF, BLEVE, VCE, Missiles
RI3	234	194	314	289	JF, FF or VCE
RI4	34	36	140	119	PF, FF or VCE
RI5	234	194	314	289	JF, FF or VCE
RI6	117	98	140	119	JF, FF or VCE
$RI_{DE}7$	209	209	288	480	BLEVE, FF orVCE, Missiles
$RI_{DE}8$	no effect	no effect	23	no effect	PF
$RI_{DE}9$	no effect	no effect	23	no effect	PF
$RI_{DE}10$	-	-	-	-	Destruction of control room

PF- pool fire, JF- jet fire, FF- flash fire, VCE- vapour cloud explosion

7.3.2. Selection of the option for calculation

In order to show the impact of domino effects as well as selection of representative set of incident on individual and social risk the further calculations concerned 6 different options:

1. Option 1 included 6 identified release incidents RI1-RI6.
2. Option 2 eliminated incident RI2 leading to the BLEVE - as a result of the proposal presented in Fig. 10.
3. Option 3 similar to Option 1 plus additional domino incident $RI_{DE}7$.
4. Option 4 included all identified RI1-RI6 and all domino events $RI_{DE}7$ to $RI_{DE}10$.
5. Option 5 is identical with Option 2 plus additional domino incident $RI_{DE}8$ due to possible missile projection.
6. Option 6 as Option 4 but when calculating societal risk the population density was changed from 0.002 to 0.0005 people per 1 square meter.

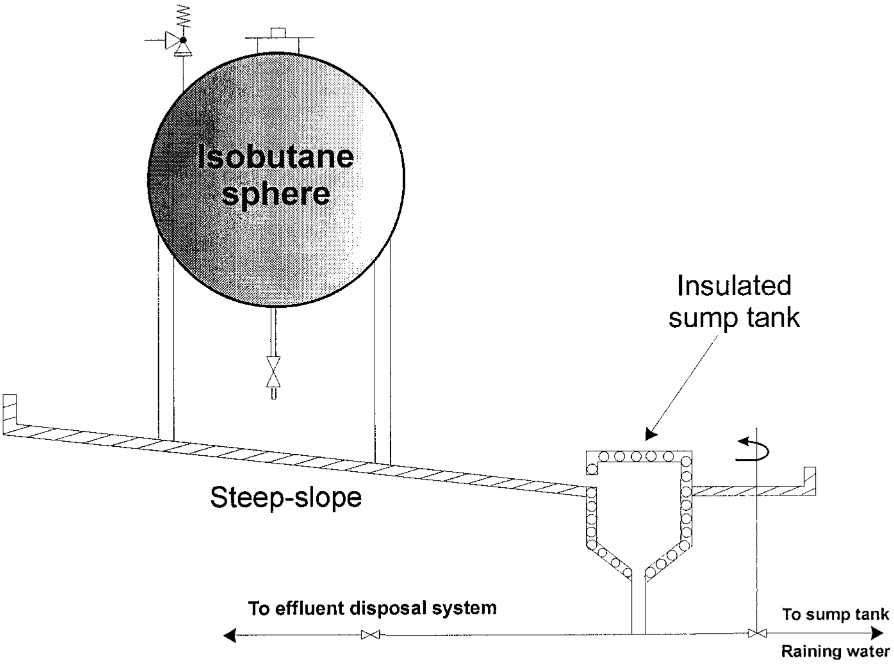

Fig. 10. Elimination of spilt liquid accumulation under the tank [15].

7.3.3. Results of risk calculation

The results of the calculations (for options 1,2, 4 and 6) are presented in Fig. 11 and Fig 12. As can be seen both individual and social risk are dependent upon the selection of representative set of incidents. Different set of release scenario generates different risk characteristics. This is a key point in risk analysis. The acceptable individual risk of 10^{-6}1/year (at the distance of 300 m which is a border of company) is only obtained for options 2 and option 5 at the distance of 110 m. This is because the BLEVE phenomenon was eliminated. For the rest of the options the acceptable individual risk level appeared at the distance of 350 m from the storage tanks. All domino events included in option 4 have a negligible effect on the individual risk.

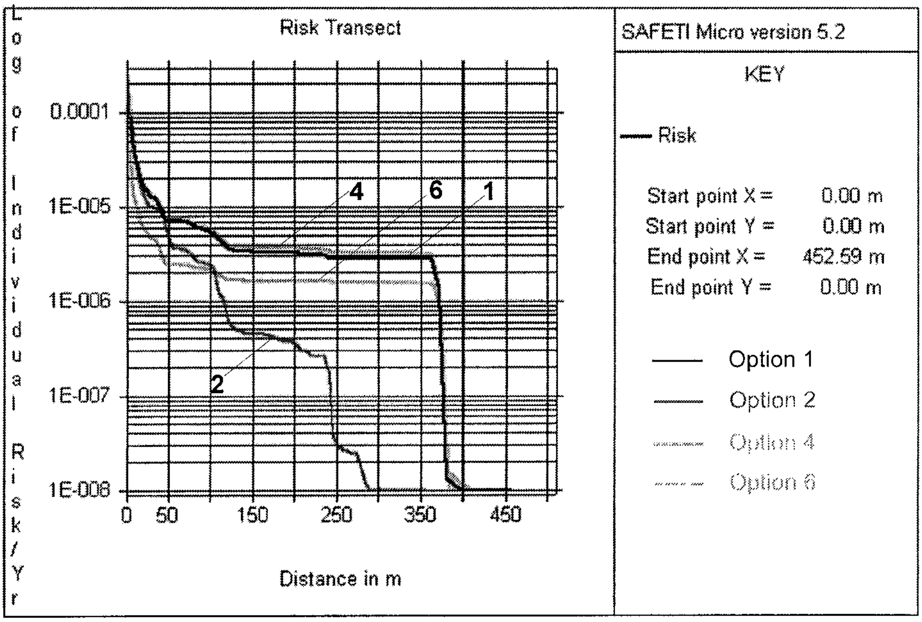

Fig. 11. Individual risk change with distance.

The societal risk is presented in the form of a graph giving the cumulative risk of multiple fatalities (frequency per year, F) as a function of the number of fatalities (N).

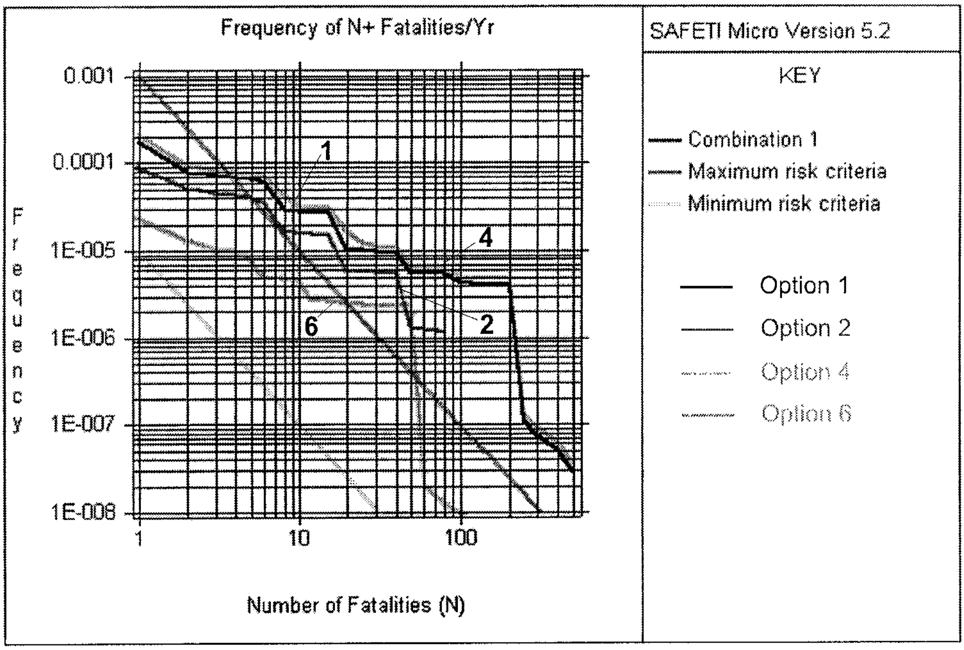

Fig. 12. Societal risk for selected options.

Most of the societal risk curves are beyond the recommended limits of maximum risk criteria. The best results are obtained for option 2 (5) and 6, where BLEVE scenario is eliminated (RI2). In that case no higher number of fatalities and the curve is almost between minimum and maximum risk criteria, in tolerable range.

The societal risk ranking analysis proves that the major contributors to the off-site societal risk have RI 2 and RI 6 accounting for over 75% of the fatalities. It helps to targeting areas for risk mitigation measures. Also the domino events do not have essential effect on level of the total societal risk. In fact, the increase is just by 18 % for Option 4 which includes all identified domino events, especially for higher number of fatalities N. The most important domino event is RI_{DE} 7 which ranking in social risk only in 8.8%. The participation of $RI_{DE}8$, $RI_{DE}9$, and RI10, both in terms of probabilities and consequences is negligible.

Table 6 presents total societal risk for the total hazard area resulting from identified RI incidents.

Table 6. Total societal risk index calculations

Option	Total risk - number of fatalities per year	Risk reduction level
Option 1	$1.96 \cdot 10^{-3}$	1
Option 2	$8.92 \cdot 10^{-4}$	0.46
Option 3	$2.02 \cdot 10^{-3}$	1.03
Option 4	$2.32 \cdot 10^{-3}$	1.18
Option 5	$1.03 \cdot 10^{-4}$	0.52
Option 6	$3.73 \cdot 10^{-4}$	0.19

The biggest risk reduction level is observed for option 6, where essential decrease of area population was assumed. Options 2 and 5 presents also essential reduction of total risk level as a result of the proposal presented in Fig. 10.

8. Conclusions

1. Safety assessment in the refinery plant may be accomplished by methodology based on the risk concept evaluated on the assessment of the dependence between the hazards potential and associated safeguards.
2. Safety systems in the process plant are consisting of multi-layers safeguard system where each layer represents an appropriate risk reduction level. Evaluation of the risk reduction level can be done by means of the semi-quantitative methods using multi-layer risk matrix.
3. Large storage of flammable LPG in a refinery represents major hazard which increases considerably if the installation is in a densly population area.
4. The general methodology to calculate individual and societal risk considering top domino effects is presented together with an example of calculation. The effect of top domino events was rather negligible (increase by 18%).
5. Quantitative risk assessment allows us to identify and rank incidents important for total risk.
6. The application of simple technical solution can significantly improve individual and societal risk respectively.

This paper constitutes a part of studies financed by the grant 7 T09C 022 20 of the Polish Committee for Scientific Research.

9. Bibligraphy

1. "Guidelines for chemical process quantitative risk analysis", AIChE, CCPS, New York, ISBN 0-8169-0720-X, 2000

2. "Zapobieganie Stratom w Przemysle- cz.III Zarzadzanie bezpieczenstwem procesowym" A. S. Markowski, ed., Wyd. Politechnika Lodzka, ISBN 83-87198-99-4 [Loss Prevention in Process Industry published by the Technical University of Lodz], 2000
3. Lees F.P. "Loss prevention in process industries", Butterworths, London, 1996
4. CCPS, "Guidelines for Engineering Design for Process Safety", AIChE, N.Y.,1993
5. Markowski A.S., "Wielowarstwowa matryca ryzyka dla instalacji procesowych", in Polish, Miedzynarodowa Konferencja Bezpieczenstwa i Niezawodnosci, KONBiN 2001, ITWL, T.4, 213-222 [Multi-layer risk matrix for process installations, International Conference on Safety and Reliability, KONBiN 2001], 2001
6. Cox A.W., Lees F.P., Ang M.L., "Classification of hazardous location" IChemE ISBN 0 85295 258 9, 1990
7. EU Directive, The control of major-accident hazards involving dangerous substances (COMAH), 96/82/EC, Official Journal of the European Communities,1997,No l, 10/13
8. TNO, "Method for the determination of possible damage to people and objects resulting from releases from hazardous materials",1979.
9. IChemE, "The effects of explosion in the process industries- overpressure monographs",1989
10. Yellow Book, " Methods for the calculation of physical effects", CPR14E, The Hague, The Committee for the prevention of Disasters,1997
11. The Accident Database, vers.4, IChem E, Rugby, UK, 2000
12. OREDA, "Offshore reliability data" 3rd edition, SINTEF IM, Norway,1997
13. "Purple Book", Guidelines for quantitative risk assessment, CPR 18E, The Hague, The Committee for the prevention of Disasters, 1999
14. "SafetiMicro, Software for assessment of fire &toxic impact", DNV, UK, 2001
15. "Guidelines for engineering design for process safety", CCPS, AIChE, 1993