ELSEVIER

Journal of Hazardous Materials A137 (2006) 1–7

Journal of Hazardous Materials

www.elsevier.com/locate/jhazmat

Statistical analysis of major accidents in petrochemical industry notified to the major accident reporting system (MARS)

Zoe Nivolianitou [a,*], Myrto Konstandinidou [a], Christou Michalis [b]

[a] Institute of Nuclear Technology-Radiation Protection, National Center for Scientific Research "Demokritos", 15310 Ag. Paraskevi, Greece
[b] Major Accident Hazard Bureau (MAHB), Institute for Systems Engineering and Informatics, JRC Ispra 21020, Italy

Received 4 May 2004; received in revised form 22 December 2004; accepted 27 December 2004
Available online 2 May 2006

Abstract

The European major accident reporting system (MARS) was created within the framework of European Union (EU) directive 82/501, the so-called "SEVESO" directive, and in order to register all the major industrial accidents notified to the European Union authorities from the member states. Statistical analysis of these accidents offers significant data to the understanding and prevention of industrial accidents. This paper makes an analysis of some characteristics of major accidents in the petrochemical sector included in MARS. The statistical analysis focused on the main categorization fields of the MARS short reports and additionally a refinement of the immediate causes of major accidents with focus on the organizational factors was attempted through the details provided in the full reports of the database.

Keywords: Major accidents; SEVESO directive; MARS; Statistical analysis; Petrochemical industry

1. Introduction

The major accident reporting system (MARS) has been developed and operated since 1984 by the Major Accident Hazard Bureau (MAHB) at the Institute for Systems Engineering and Informatics (ISEI) of the European Commission (EC) Joint Research Centre (JRC) in Ispra, Italy, within the framework of the SEVESO regulatory directives [1].

Major accidents have been defined in the SEVESO I regulatory environment for the chemical process industry, as "an occurrence such as a major emission, fire or explosion resulting from uncontrolled developments in the course of an industrial activity, leading to a serious danger to man, immediate or delayed, inside or outside the establishment, and/or to the environment, and involving one or more dangerous substances" [2].

The SEVESO II Directive, which replaced and strengthened SEVESO I, includes a more succinct definition of what constitutes a major accident based on precise quantitative threshold criteria, which result in an overall lowering of the criteria for notification. It also demands for notification of accidents or near misses, which member states regard as being of particular technical interest for preventing major industrial accidents and limiting their consequences [3].

The criteria for the notification of an accident to the Commission as provided for in Article 15 (and annex VI) of the SEVESO II Directive are:

1. Substances involved (quantity of dangerous substance discharged)
2. Injury to persons and damage to real estate
3. Immediate damage to the environment (terrestrial, freshwater, marine habitat and groundwater)
4. Damage to property
5. Cross-border damage

Both SEVESO I and SEVESO II Directives require that competent authorities of the European Union (EU) member states notify major accidents involving dangerous substances which occur in their own countries to the European Commission, except for those related to nuclear, military, mining, transport or waste land-fill sites.

Section 2 of this paper makes an overview of MARS database, while Section 3 presents the statistical analysis of major accidents in the petrochemical industry included in it. Section 4 makes a refinement of general causes, with respect to, the

* Corresponding author. Tel.: +30 210 6503744; fax: +30 210 6503744.
E-mail address: zoe@ipta.demokritos.gr (Z. Nivolianitou).

0304-3894/$ – see front matter
doi:10.1016/j.jhazmat.2004.12.042

underlying ones. Finally, Section 5 discusses the results of the authors working experience with MARS.

2. MARS structure

The way of reporting accidents in MARS comprises two forms: the 'short report' which is intended for use in the immediate notification of an accident, and the 'full report', which is prepared when the accident has been fully investigated, and its causes, evolution, and consequences are fully understood. In certain cases, further information becomes available as, for example in the course of judicial proceedings. There is also provision for the 'full report' information to be further modified [1].

The 'short report' gives essential information concerning the accident, in a free-text format, under the following headings:

- accident type
- substances directly involved
- immediate sources of accident
- immediate causes
- immediate effects
- emergency measures taken
- immediate lessons learnt

The 'full report' is much more analytic, and involves more work in its preparation. It still contains free-text fields to describe facts connected with an accident, but it also contains the definition of descriptive codes, for the accident itself and for associated information, so as to enable the MARS database to be searched under almost 200 different headings (data variables). Some of them are listed below:

- type of accident
- industry where accident occurred
- activity being carried out
- components directly involved
- causative factors (immediate and underlying)
- ecological systems affected
- emergency measures taken

MARS does not constitute the only database in European level. Other databases concerning industrial accidents in fixed installations do exist, such as national databases in some European countries: ZEMA in Germany; ARIA in France; AEA technology MHIDAS database in UK; TNO FACTS database in The Netherlands; the World Offshore Accident Data (WOAD), and the Loss Prevention bulletin of UK IChemE. Additionally, to that, there also exist also many non-public sources for data collection from industries and insurance companies.

Concerning MARS, it is very important to mention the following:

1. MARS is the mandatory major industrial accidents database and reporting scheme within the European Union.
2. It includes major industrial accidents but also 'unusual' major technological events with serious social impact (e.g. damage in an amusement park).
3. It has the purposes of the rapid dissemination of the information supplied by member states pursuant to Article 15(1) of the SEVESO II Directive among all competent authorities with an analysis of the causes of major accidents and the lessons learned from them.
4. It supplies information to competent authorities on the occurrence, prevention and mitigation of major accidents [3].

Thus, apart from information distribution, the main purpose of MARS is to analyse the data reported by the member states to the Commission with aiming at generation of lessons learned from accidents. This is being done within the overall objectives of the SEVESO Directive:

1. prevention of major accidents involving dangerous substances;
2. limitation of their consequences on man and the environment, with a view to ensuring high levels of protection throughout the community in a consistent and effective manner.

Lessons learned from major industrial accidents should help to identify significant areas of concern. This could also help into setting of priorities for further improvements and into undertaking more research or/and regulatory intervention for industry, where necessary. Those lessons could also be used as input to qualitative and quantitative risk analyses either as relevant top events, or initiating events, or even as accident sequence scenarios.

MARS currently includes 498 accident events (status 6/2003), each consisting of 200 data variables, 30 of which are free-text fields. In other words, 100,000 individual categorical (selection lists, click boxes) and numerical data values define together with 15,000 free-text fields the total amount of information included in the database events.

3. Data analysis

3.1. Type of industry

For the above-mentioned 498 accidents and according to the data provided both from the short and the full reports, statistical analysis can be made of the fields mentioned in paragraph 2. This has been extensively done by Kirchsteiger, Kawka and Kirchsteiger, and Drogaris [4–7].

The present analysis, however, is concentrated on the accidents that happened exclusively in petrochemical installations and refineries which sum up to 85 (status 6/2003) in the MARS database. Petrochemical installations are characterized by very high levels of risk because of the nature of processed flammable substances and of the gravity of consequences, in case of a major accident in these establishments. Many specific accident types are closely related to the petrochemical installations (e.g. BLEVEs, fireballs, UVCEs) whose consequences can affect many people inside and outside these establishments, but also the surrounding environment as mentioned by Papazoglou et al. [8,9].

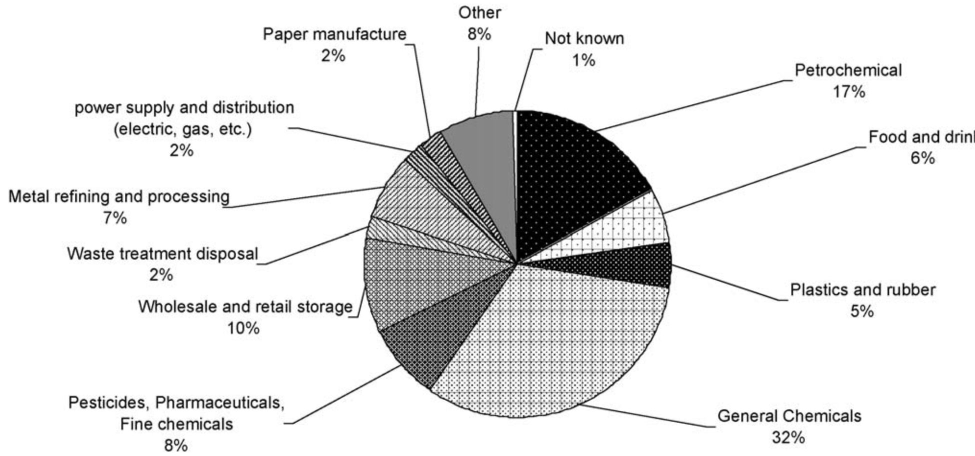

Fig. 1. Percentage of major accidents notified in MARS per type of industry for the period 1985–2002.

As shown in Fig. 1, accidents in petrochemical installations represent the 17% of the total number in industrial accidents, which is the second more important sector in industrial installations behind general chemicals with 32%. Pharmaceutical and pesticides follow with 9% along with wholesale and retail storage with 10% (including LPG bottling and bulk distribution and tank storage farms). The category *other* (12%) includes smaller and less dangerous industrial activities such as: ceramics, timber and furniture, textiles and clothing, electronics and electrical engineering, amusement and transportation centers. The smallest percentage belongs to the paper manufacture industry, the waste treatment disposal and the power supply and distribution industry (2% in all cases). This percentage does not mean that accidents do not happen in these industrial installations. Accidents do happen, but they do not fall within the category of major accidents as this is given by the EC [7]. In 1% of the events, the information given was not sufficient so as to permit classification of the accident in a certain type of industrial activity.

Regarding the analysis of major accidents in the petrochemical field, the following observations have been made in the various classification criteria.

3.2. Year of occurrence

The distribution of accidents in the petrochemical sector per year in the period of 1985–2002 is shown in Fig. 2.

The overall slight increase in the beginning of the 1990s in numbers of accidents reported to MARS per year does not mean necessarily increase in actual accident occurrences in the EU member states but could also be explained as a consequence of an increased acceptance of the MARS which led to reporting of "any interesting" accidental events by the competent authorities, as commented by Kirchsteiger [4].

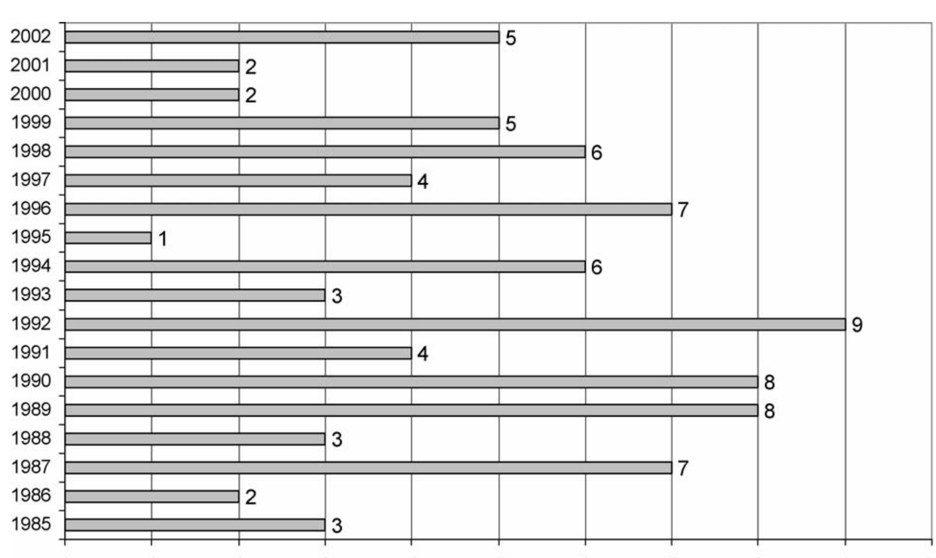

Fig. 2. Number of major accidents in the petrochemical industry per year of occurrence.

Table 1
Number of cases of substances involved in major accidents in the petrochemical industry

Substance involved	Number of accidents
Hydrogen	13
Crude oil	5
Heavy H/C	12
Gas oil	21
Natural gas	13
LPG	21
Ethylene	12
Sulfuric products	7
HF	2

3.3. Substances involved

Table 1 shows the substances that were more involved in accidents of the petrochemical field directly or indirectly. In most cases (21 major accidents), gasoline and its products were involved, while LPG contributes with 21 accidents as well. Natural gas (LNG, methane, ethane) was present in 13 cases. Heavy hydrocarbons and crude oil were the hazardous substance involved in 13 and 5 cases, respectively. Hydrogen and ethylene were involved in 13 and 12 accidents each. Sulfuric products (SO_2 and H_2S) were involved in seven major accidents, human factors (HF) in two major accidents and mineral oils in one major accident. It is obvious that in some cases more than one substance were involved in the accident.

3.4. Substances characteristics

Substances are categorized in MARS by means of their hazardous characteristics (toxic, flammable and explosive) and their relative percentage in the major accidents bulk. As expected from the type of industry, we are focusing on and the type of accidents that usually take place in this industry; most of the substances are flammable (48%), explosive (1%) or both (35%). Purely toxic was the 12% of the substances involved in major accidents, while the ecotoxic and the corrosive substances represent together the 4% of the total percentage of substances involved.

3.5. Type of accident

Fig. 3 shows the number of accidents notified per type of accident.

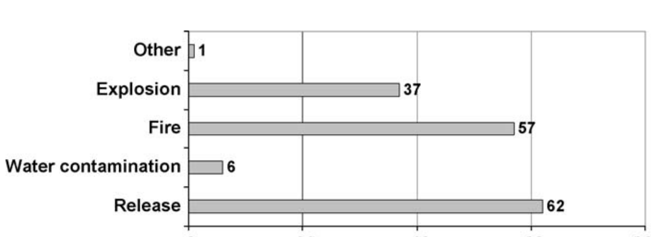

Fig. 3. Type of major accidents in the petrochemical industry.

In 62 cases, a release on the ground or in the air was notified and only in 6 cases release had taken place in the water. Fire was ignited in 57 cases and explosion phenomena (either as fireball or VCE confined and unconfined) took place in 37 cases. As it is evident, in major accidents, these types of accidents may co-exist and overlap.

3.6. Operating status

In most of the cases (70%), the plant was under normal operation when a major accident took place. Phases more critical to the life of plant are shutdown, restart and start up. From the point of view of major accidents, these phases represent the 3%, 1% and 6%, respectively. Maintenance and testing have a percentage of 13% and 4% in major accident occurrence each.

3.7. Immediate causes

The graph in Fig. 4 presents the immediate causes of accidents notified to Major Hazards Bureau and shows that 40% of the major accidents notified have causes either exclusively (19%) or partially (21%) attributed to human factor. Equipment failure was the 44% of the causes of major accidents in the petrochemical sector in the period from 1985 to 2001; natural phenomena like floods or thunderstorms and environment conditions like low temperature or humidity were the 7% of causes either directly (3%) or in combination with equipment failure (4%). "Other" notifies rare and random events. In 9% of the cases, immediate causes have not yet been defined.

3.8. Consequences

In Fig. 5, the immediate consequences of the accidents notified in the petrochemical sector are presented. As for the accident type categories, there is significant overlap among the consequence categories. It is evident that in most accidents with fatalities and/or injuries, there is also material loss involved, while in cases with bigger number of fatalities, a significant community disruption is also likely.

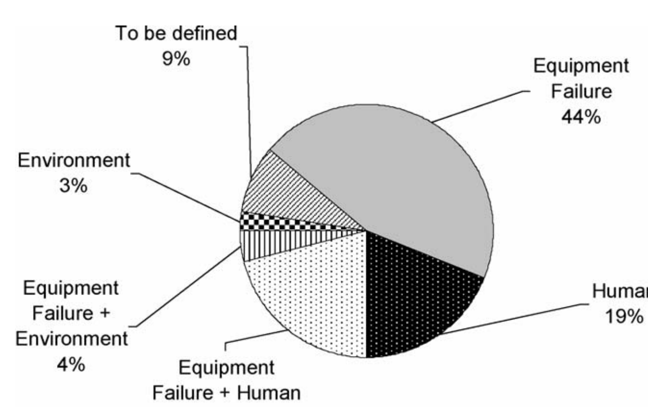

Fig. 4. Immediate causes of accidents in the petrochemical industry for the period 1985–2002.

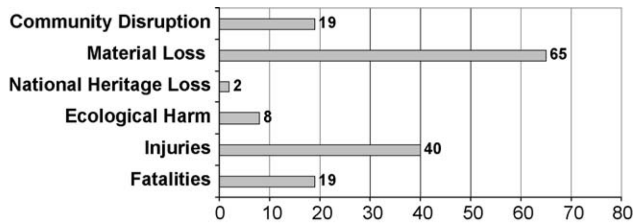

Fig. 5. Serious consequences of major accidents in the petrochemical industry.

A main observation in the present analysis is that 20% of the accidents (19 accidents), led to human fatalities while in 50% of the accidents (40 accidents), human injuries were registered. The hazard potential of this specific industrial domain along with the propagation of the consequences, in case of an accident, beyond the industrial establishment barriers may explain these elevated numbers. Unfortunately, the exact number of injured person inside and outside of the establishment is not known.

Furthermore in 10% of the accidents (eight accidents), environmental consequences were registered. Again, no information is given on the magnitude or the severity of the consequences in the ecosystem.

3.9. Emergency measures taken

Table 2 presents the emergency measures taken during the evolution of the accident in the petrochemical sector. In almost all cases (89%), the internal fire brigade forces of the establishment had to interfere in order to suppress the accident. This was done in combination with external forces (42%), with evacuation of nearby communities (10%) and with sheltering of the population (6%) or decontamination of the surroundings (6%). In 3% of the cases, only decontamination of ground and waters took place, and in 4% of the cases, there was no need for intervention.

3.10. Post accident measures

The measures taken after the conclusion of the accident are either measures of prevention (52%), or measures of mitigation (3%), or both (18%). There are still cases that the after accident measures are not yet defined.

In Table 3, the most common post accident measures taken are presented. In most cases, changes in the design (39%) or development of new procedures (22%) were decided. As lack of inspection and/or adequate maintenance is crucial, inspection (21%) and maintenance (8%) were defined as post accident measures. The use of a safety manager (8%) and the organization of a safety audit (3%) were also notified to the Major Hazards Bureau.

Table 2
Emergency measures taken for major accidents in the petrochemical industry

Emergency measures taken	Percentage of accidents
On site	25
On site + external	42
On site + external + sheltering	3
On site + external + decontamination	6
On site + external + sheltering + evacuation	3
On site + external + evacuation	10
External + evacuation	4
Decontamination	3
Nothing	4
Total	100

Table 3
Post accident measures taken for major accidents in the petrochemical industry

Post accident measures	Number of accidents
Design change	28
Procedures	16
Inspection	15
Safety audit	2
Maintenance	5
Safety manager	6

4. Refinement of immediate causes in the full reports

After examination of the full reports, it has been realized that many causes initially classified as equipment failure in the short reports description, were actually due to organizational factors. On the other hand, in many cases, equipment failure due to corrosion was caused by faulty maintenance, which is a pure organizational matter.

Fig. 6 depicts the specific causes attributed to human/organizational factors in the accidents of the petrochemical sector. Human error is mainly caused either by design deficiency or by lack of procedures (22% and 17%, respectively). Lack of procedures does not only mean that there are no procedures for the specific task. Indeed, procedures might exist but they are inadequately or incomprehensively written. Other causes that are incorporated in the human and organizational factor notion are: lack of training or inadequate training (11%), management-organization (9%), inappropriate maintenance (4%) and inspection (3%) and operator error (11%).

The specific causes for equipment that contributed to accidents in the petrochemical sector are presented in Fig. 7. In most of the cases, malfunction or corrosion was the specific causes for equipment failure (28% and 18%, respectively). Other causes related to equipment failure are: unexpected or runaway reaction (11%), control and monitoring failure (5%), electrostatic accumulation (4%) and blockage (7%).

Another case of latent organizational failure is the inadequate material; cause identified in short reports as equipment failure, which, however, is further categorized as a design deficiency (22%) in full reports.

In 25% of the petrochemical major accidents (22 out of 85 in total), the initial cause in the short report was mentioned as equipment failure but from the details provided in the full reports, the real cause turned out to be organizational factor, with most frequently the design deficiency and the lack of training and procedures. The reader must keep in mind that not every petrochemical major accident has a full report and that even in full reports there are cases where the accident causes are not yet identified.

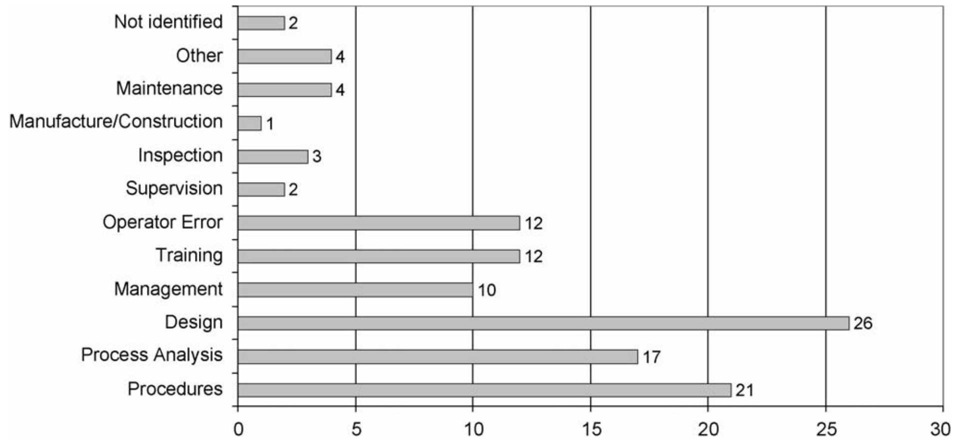

Fig. 6. Specific causes concerning human and organizational factors for major accidents in the petrochemical industry.

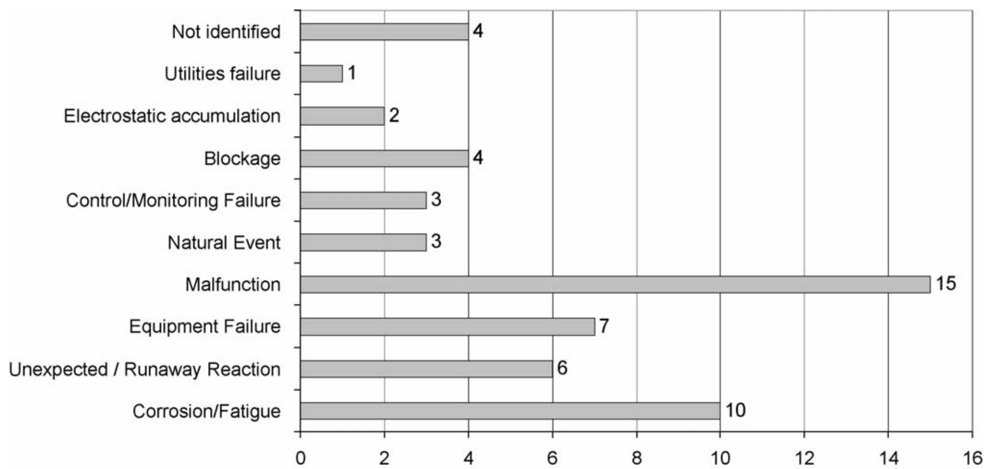

Fig. 7. Specific causes for equipment failure major accidents in the petrochemical industry.

Following this analysis, it becomes obvious that the overall percentage of human related causes has increased dramatically after the submission of the full reports, as organizational and management causes are incorporated into the human factor category causes supporting the finding of Cacciabue [10] that 80% of the accidents are due to human factor.

This observation is also supported by the fact that human factors are nowadays recognised as the most important issue in modern technology, with respect to, many related facets, such as usability, efficiency, effectiveness and especially safety [11]. Tackling HF and human–machine interaction (HMI) demands consideration for technical systems and working environments, together with the social and organizational context in which actual interactions take place. These factors must be integrated and considered in order to develop sustainable and effective design of systems and interfaces, effective training of operators and managers, and sound and accurate safety assessments and accident investigations.

5. Conclusions

The conclusions from several accident investigations and from studies on safety related issues in the petrochemical sector show that similar cases had already been registered in the past. As mentioned by Drogaris [7], this gives clear indication that, although the knowledge needed to prevent major accidents and minimize their consequences is often available, there is:

(a) lack of proper safety culture to enable effective use of this knowledge; and
(b) lack of a structured communication system to diffuse this knowledge.

Thus, the overall objective of the major accident reporting system to collect and diffuse knowledge on industrial accidents comes to fulfill the above gaps. With the use of the reporting system, competent authorities are able to exchange information and knowledge on the prevention, monitoring and post accident mitigation of severe incidents. The open form of the short reports to the public gives the possibility to spread out this knowledge.

The statistical analysis of the major accidents for the period 1985–2002 shows that the petrochemical industry is one of the most affected industrial fields with a high percentage (17%) of major accidents. However, the rate of major accidents in the petrochemical industry is constant in the last decade, with a slight decrease in 2000–2001 period (two accidents). The substances most frequently present in major accidents were gasoline (and its products) and LPG and as expected from the type of industry under focus in most of the cases substances were flammable and explosive. A fire that took place under normal operating status of the plant is the most frequent major accident notified to the MARS, which unfortunately is related to 50% of the cases with human injuries. The immediate causes of such major accidents are attributed to either the human factor (in 40% of the cases) or to equipment (in 44% of the cases). Natural phenomena and random events are also registered as immediate causes of major accidents.

In major accidents, the interference of internal forces is absolutely necessary in almost all of the cases while the interference of external forces too was necessary in one third of the cases, sometimes in combination with other measures to protect the nearby communities such as sheltering, or evacuation. Decontamination of the surrounding environment resulted as necessary in only eight cases in total (as the only measure taken and in combination with other emergency measures). The post accident measures that took place after the termination of the major accidents were measures to prevent the accident of happening again in most of the cases, or measures to mitigate its consequences.

In the last decades, it has been cleared that human actions constitute a major source of vulnerability to the integrity of interactive systems, complex as well as simple ones. "Human errors" are inappropriate, incorrect or erroneous human actions and thus are causes of great concern as mentioned by Hollnagel [12]. However, the deeper analysis of major industrial accidents in diverse sectors revealed that the events leading to an accidental outcome had their origins in the organization and management of the system. For this reason, the focus of attention is moving away from the technical and human failures to the management activities [13].

The analysis of the specific causes of major accidents notified to the MARS database shows a latent contribution of management and organizational failure to the causation of major accidents. Even in cases where equipment failure was identified as the primary cause of the accidents, the more detailed study of full reports revealed organizational deficiencies that can be categorized either as inadequacies (design or procedures) or as insufficiencies (maintenance, inspection or training). The same is valid for cases where a human error was registered as immediate cause.

The combined percentage for human related causes – human errors, organizational and management issues – increases dramatically up to 64%.

The research and the analysis of the major accidents are of great importance for prevention of similar accidents and mitigation of the outcome. However, it is of crucial importance to expand this analysis to the near misses as those can reveal very important information about the status of the establishment and its potential to give rise to severe accidents. MARS has foreseen the notification and reporting of near misses too. It is up to the competent authorities to motivate industries to circulate this information too.

Acknowledgement

The financial support of the EU Commission through project "PRISM" GTC1-2000-28030 to this research is kindly acknowledged.

References

[1] MARS website:. http://mahbsrv.jrc.it/Activities-WhatIsMars.html.
[2] European Council, Council Directive 82/501/EEC on the major accident hazards of certain industrial activities ("SEVESO I"), Official Journal of the European Communities, Luxembourg, 1982.
[3] European Council, Council Directive 96/82/EC on the major accident hazards of certain industrial activities ("SEVESO II"), Official Journal of the European Communities, Luxembourg, 1997.
[4] C. Kirchsteiger, Trends in accidents, disasters and risk sources in Europe, J. Loss Prev. Process Ind. 12 (1999) 7–17.
[5] C. Kirchsteiger, Status and functioning of the European Commission's major accident reporting system, J. Hazard. Mater. 65 (1999) 211–231.
[6] N. Kawka, C. Kirchsteiger, Technical note on the contribution of sociotechnical factors to accidents notified to MARS, J. Loss Prev. Process Ind. 12 (1999) 53–57.
[7] G. Drogaris, MARS lessons learned from accidents notified, CDCIR, JRC, 1991.
[8] I.A. Papazoglou, Z. Nivolianitou, O. Aneziris, M. Christou, G. Bonanos, Risk-informed selection of a highway trajectory in the neighborhood of an oil-refinery, J. Hazard. Mater. 67 (1999) 111–144.
[9] I.A. Papazoglou, Z. Nivolianitou, O. Aneziris, M. Christou, Probabilistic safety analysis in chemical installations, J. Loss Prev. Process Ind. 5 (3) (1992).
[10] P.C. Cacciabue, Human factors impact on risks analysis of complex systems, J. Hazard. Mater. 71 (2000) 101–116.
[11] P.C. Cacciabue, Report on Research Activities, Human Factors Sector European Commission, Joint Research Centre, Institute for the Protection and Security of the Citizen, Technological and Economic Risk Management, 2001.
[12] E. Hollnagel, Cognitive Reliability Error Analysis Method, Elsevier Science Ltd., 1998.
[13] R. Kennedy, B. Kirwan, Development of a hazard and operability-based method for identifying safety management vulnerabilities in high risk systems, Saf. Sci. 30 (1998) 249–274.