Methodological framework for assessment of overall hazard of an accident - a Serbian experience

Evica Stojiljkovic*, Miroljub Grozdanovic and Srdjan Glisovic
University of Nis, Faculty of Occupational Safety, Carnojevica 10a, 18000 Nis, Serbia

Received 27 September 2010; revised 10 February 2011; accepted 14 February 2011

This study presents an integrating methodological framework for assessment of overall hazard of an accident by achieving synergism in application of methods for technical system reliability assessment, human reliability assessment and accident analysis. Case study performed at a company (M/s Tehnogas AD, Nis, Serbia) has confirmed that new methodological framework for assessment of level of overall hazard, is highly applicable, comprehensive and simple to perform.

Keywords: Human error, Hazard analysis, Industrial accident, Industrial environment

Introduction
An accident is an uncontrolled event, occurring during manufacturing, transport or storage, in which certain quantity of hazardous substances released into air, water or land jeopardize human lives and health, damage material goods and cause undesired environmental outcomes1. Major accident means an occurrence (major emission, fire, or explosion) resulting from uncontrolled developments in the course of operation of particular establishment, and leading to serious danger to human health and/or environment, inside or outside the establishment, and involving one or more dangerous substances2. Initiators and/or links of occurrence of accidents most often are human errors, technology failures and/or unforeseen external influences3.

Main components of a risk assessment are evaluation of probability and evaluation of possible consequences on safety, health and environment. For study purpose, methods for risk assessment are classified into four categories (technology oriented methods, human oriented methods, management oriented methods, and accident analysis methods). However, certain areas of application overlap and some methods belong to more than one group4-13. Among several methods for accident analysis, some methods that can be used for both system analysis and accident investigations include Deviation Analysis (DA), Safety Function Analysis (SFA), Accident Evolution and Barrier Method (AEBM), Change Analysis (CA), Multilinear Events Sequencing (MES). However, use of any single method can not provide comprehensive evaluation of the risk of an accident because no method can independently achieve desired goals. For resolving practical problems, a synergistic effect of several mutually complementary methods is necessary4.

This study integrates methodological framework for assessment of overall hazard of an accident.

Proposed Method
Proposed method for assessment of level of overall hazard of an accident is based on some published studies14-16, and takes into consideration certain national regulations17-19 [Code of practice on methodology for risk assessment and mitigation of chemical and environmental accidents, Fire Safety Law (FSL) and Law on Emergency Situation Management (LESM) of the Republic of Serbia]. Proposed method is composed of following steps: i) Assessment of hazards caused by technology and manufacturing process (TP); ii) Assessment of hazards caused by human factor (HF); iii) Assessment of hazards caused by environmental impact (E); and iv) Assessment of level of overall hazard of an accident (A). TP, HF, E and A are given as
A = TP \cdot E - HF \cdot \frac{TP}{30} \quad \ldots(1)

TP = CA \cdot ER \cdot PP \cdot PM \quad \ldots(2)

where CA – magnitude of possible consequences of an accident (1 - negligible, 2 - significant, 3 - serious, 4 - very serious, 5 - extreme); ER – exposure to risk of an accident (1 - small, 2 - medium, 3 - large); PP – possibilities of prevention (1 - poor, 1.5 - acceptable, 2 - good); and PM – preparedness measures level (1 - low, 1.5 - medium, 2 - high).

HF = QL + RA + RL \quad \ldots(3)

where QL – level of skillfulness of operators supposed to act in case of an accident(1 - poor -, 1.5 - medium, 2 - good); RA – adequacy of response to an accident (1 - inadequate, 1.5 - semi-adequate, 2 - adequate); RL – evaluation of remediation likelihood (1 - poor, 2 -good, 3 - excellent).

E = EC + CPS + OI \quad \ldots(4)

where EC – arrangement of surroundings of an industrial complex (1 - poor, 1.5 - satisfactory, 2 - excellent); CPS – compatibility of operators and response systems (1 - poor, 1.5 - medium, 2 - good); and OI – other influences (0.5 - almost negligible, 1 - little, 1.5 - great).

Assessment of A (Table 1) is in the range between minimal value (A=2.4) and maximum value (A=316). So far, there is no recorded attempt to simultaneously apply different methods united in one common methodological framework. This study aims to achieve synergism in application of methods for technical system reliability assessment, human reliability assessment and accident analysis (Table 2).

Synergism in Application of Methods

New method for assessment of the level of overall hazard of an accident is based on synergistic application of presented methods as well as on expert evaluation. Six experts gave their judgement on the most probable outcomes of elementary events, on correlations between them and on their impact on overall level of hazard of an accident. Expert evaluation is based on knowledge, experience, intuition, as well as on knowledge on behavior of particular system elements in the same or similar conditions. In order to identify hazards caused by the technology, human factor and environment and to determine exposure of people and assets to hazard of an accident, a detailed analysis of technical data, process information and environmental conditions has been performed. For this, all necessary documentation available at the analyzed industrial complex (technical description of the system, equipment layout, staff activity plans, blueprint of the facility, etc.) was collected. On-site survey was performed as well.

Preliminary Hazard Analysis (PHA)

PHA was used for identification of hazard, creation of list of undesirable events, as well as for description of sources of hazard, hazard factors, conditions of occurrence and development of an accident. In PHA procedure, Preliminary Hazard List (PHL) was created to identify hazard using following methods: Energy Analysis (EA), Hazard and Operability Studies (HAZOP), Failure Mode and Effects Analysis (FMEA) and Reliability Analysis (RA). However, as these methods
are mainly related to hardware, it was also necessary to perform Operating and Support Hazard Analysis (OHA), which supplements PHA using Human Error Analysis (HEA), Job Safety Analysis (JSA), and Management Oversight and Risk Tree (MORT). As human is main cause of most accidents, a well known theoretical framework was used to quantify compatibility of human operator and related response system. To provide all necessary data before performing assessment of a specific case, following methods were also used: Cause-Consequence Diagram (CCD), Consequence Analysis Models (CAM), JSA, DA, SFA, etc.

Preparedness measures, level of skillfulness of operators supposed to act in case of an accident, evaluation of remediation likelihood, and adequacy of response to an accident, were estimated on the basis of code of practice on methodology for risk assessment and mitigation of chemical and environmental accidents and compliance with legislation of the Republic of Serbia (FSL, LESM). Although the portion of described methodology relies on provisions set by one specific jurisdiction, it would become universally applicable just by applying appropriate regulations of any other legislative entity.

### Results and Discussion

Proposed method was applied at a company (M/s Tehnogas AD, Nis, Serbia). Production site comprised oxygen, nitrogen and crude argon manufacturing units; distribution centers for oxygen and carbon dioxide, and warehouses for these gases. Proposed method consisted of $TP$, $HF$, $E$ and $A$.

#### Assessment of Hazard Caused by Technology and Manufacturing Process ($TP$)

Work activities at M/s Tehnogas AD Nis, consist of operating specific manufacturing technology / storage facilities and filling portable, hermetic steel containers with fluids for mass consumption. Storage rooms are of particular concern, since oxygen stored (> 200 t) belongs to category of hazardous materials. Applied technology also comprises complex processing equipment and pressurized containers.

Taking into account all circumstances at observed company premises, it has been estimated that possible accidents could occur in the form of mechanical explosions at particular segments of equipment and local installations, or in the form of fires ignited by explosions due to contact with organic materials and due to gas

---

Table 2—Synergetic application of methods for hazard assessment of an accident

<table>
<thead>
<tr>
<th>Methods / Procedures and Regulations</th>
<th>CA</th>
<th>ER</th>
<th>PP</th>
<th>PM</th>
<th>QL</th>
<th>RA</th>
<th>RL</th>
<th>EC</th>
<th>CPS</th>
<th>OI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy Analysis (EA)</td>
<td>X</td>
<td></td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Deviation Analysis (DA)</td>
<td></td>
<td></td>
<td></td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hazard and Operability Studies (HAZOP)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Safety Function Analysis (SFA)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Failure Mode and Effects Analysis (FMEA)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Event Tree Analysis (ETA)</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Absolute Probability Judgement (APJ)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Change Analysis (CA)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Technique for Human Error Rate Prediction (THERP)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Cause-Consequence Diagram (CCD)</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Consequence Analysis Models (CAM)</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Job Safety Analysis (JSA)</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Management Oversight and Risk Tree (MORT)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Code of Practice on Methodology for Risk Assessment and Mitigation of Chemical and Environmental Accidents</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fire Safety Law</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Law on Emergency Situation Management</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
leakage. For presented hazard estimation, it was necessary to determine level of possible consequences of hypothetical accidents (CA). Possible causes of supposed accidents at M/s Tehnogas AD production site could be human factor, mechanical failures, disruptions in transport of products, natural disasters, war situations or sabotage, fires and explosions. Critical locations with estimated higher probability of possible accident occurrences are: i) fire on transport vehicle in vicinity of the tank; ii) significant damage of any of the tanks due to sabotage; iii) oxygen leaking through a tank valve that remained open due to negligence; iv) crack / rupture at flexible hoses while filling reservoirs and containers; v) mechanical damage of heat exchangers at facilities for production of liquid gases; vi) breakdown of devices for measuring and control at any of the tanks; and vii) breakdown of main pump engine. Data collected during identification of sources of potential hazards and obtained from analysis of critical locations where increased potential hazard of an accident was noticed, allow for estimation of the effects on human health, assets and environment. If an accident has occurred, consequences on health and lives of workers under worst case scenario might be characterized as serious, while damage of natural and material resources would depend on the type and scope of the accident. In case of the most unfavorable development of events (damage of oxygen tank during summer), possible consequences on the nature and assets would reach the level of significant to serious. On the basis of performed analysis and by applying described method (Table 2), quantitative expert assessment on the consequences of potential accidents provides the value of 3 (CA=3).

Quantitative assessment of exposure to risk is performed based on following relevant conclusions: i) in case of leakage of any of technical gases (that has been assessed as possible scenario), it is probable to expect a minor material damage and minor injuries of operators (exposure to risk quantified by value of 1); ii) in case of fire on transport vehicle, there is a great hazard for lives of operators and possibility significant material damage to occur (exposure to risk quantified by value of 2); and iii) despite low probability of total damage of stored tanks to occur, consequences of such occurrence would be the most disastrous one (exposure to risk quantified by value of 3). Expert assessment on risk exposure due to hypothetical accidents, based on performed analysis and application of proposed method (Table 2), yields the value of 2 (ER=2). Analyses of some previous accidents caused by errors in technological process emphasize significance of both preventive measures and emergency procedures taken on the spot of an accident; a great deal of planning is needed in order to prevent possibility or reduce probability of an accident occurrence and to mitigate its consequences. Therefore, at least basic preventive measures and emergency response procedures should be in place, as follows: i) in order to protect built and natural environment, storage tanks with liquid gases ought to be placed inside concrete pools of adequate capacity, resistant to chemical reactions with applied fluids, and placed with a height of at least 1 m above the ground; ii) a system for collection and drainage of atmospheric waters, as well as an adequate wastewater treatment should be built, especially around area where liquid chemicals are being decanted; iii) adequate system monitoring and detection devices should be applied to control the process in real time; iv) regular check and monitoring of safety systems; v) timely analysis of safety systems reliability; and vi) due course informing stakeholders and the public about all significant safety issues. Quantitative expert assessment (Table 2) on possibilities for preventing accident in given circumstances is described by value of 2 (PP=2).

Preparedness (ability to provide most adequate response to a possible accident), is defined as interaction of competent subjects with available equipment while applying prescribed techniques. Level of preparedness could be increased by planning and designing appropriate safety systems based on hazard assessment and accident probability. Fire safety action plan of M/s Tehnogas AD is in compliance with municipal procedures and describes in detail the roles of all participants in a firefighting operation, available equipment the alarm system activation, and reporting procedures. Safety expert assessment value preparedness of the system comes 1.5 (PM=1.5).

According to Eq (2), hazard caused by a technological process is estimated as 18 (TP=18).

Assessment of Hazard due to Human Factor (HF)

Assessment of hazard due to HF refers to: i) skill level of operators, who are supposed to act in case of an accident (QL); ii) evaluation on adequacy of response to an accident (RA); and iii) evaluation on remediation likelihood (RL). Trainings for response in case of accidents are still performed in an old manner. However, accidental situations in industry occur out of a sudden
and unexpectedly, so that workers have to react immediately and under stress. Consequences of a wrong decision under an emergency situation can be immediate and disastrous. Considering that in present case only basic training was given to employees that are supposed to act in unpredictable situations, skill assessment provided the value of 1.5 (QL=1.5).

An adequate response to an accident starts when right information about accidents is received. However, accidents are usually preceded by certain warnings [appearance of a cloud of steam, unusual vibrations, warning sounds, leakage, mist, variations in process parameters (temperature, pressure), etc.]. Fast recognition of these signals and appropriate corrective actions could prevent further development of hazardous situations in many cases. In observed company (M/s Tehnogas AD), there was an appropriate scheme of responses to an accident that prescribed information flow among the most responsible workers, managers and services that take part in accident situation management. Therefore, quality of response to an accident has been assessed as satisfactory (RA=1.5).

Evaluation of remediation capacity and likelihood is greatly hypothetical because to judge on remediation measures that should compensate for consequences of an accident would mean monitoring post-accidental situation, restoration and remediation of environment. A comprehensive remediation would also mean overall facility recovery, as well as removal of the risk of accident recurrence. Therefore, estimated level of remediation capacity and likelihood is described with the value of 1 (RL=1).

Based on above evaluations, and according Eq. (3), hazard due to human factor is 4 (HF=4).

Assessment of Hazard Caused by Environment (E)

Assessment of hazard caused by environmental influences is based on analysis of the arrangement of industrial premises and surroundings (EC); compatibility of people skills with available technological system (CPS) and existence of other harmful influences (OI). Analysis of immediate surroundings begins with the survey on disposition of objects in an industrial compound. As for described case study, all storage tanks were carefully designed and built of adequate materials, intended for this kind of structures. In design phase, statistical calculations were done for all reservoirs, taking into account, among other things, wind pressure and possible earthquakes. All thermal devices are designed for operation under pressure, and are subjected to regular inspection and tests. In the system observed, impact of materials from manufacturing process on structural elements, in case of accidental leakage, is reduced to a minimum. According to the method applied and data analysis on location layout, structure and material properties, value of expert assessment on arrangement of facilities and surroundings is found to be 1.5 (EC=1.5).

Assessment of compatibility between operators’ skills and response system features depend on system complexity (structure and interactions between a man and elements of the system). Human errors are often caused by negligence, disregard of guidelines, ignorance, use of substandard materials for overhaul, lack of compliance with prescribed procedures, etc. However, certain human wrongdoings are closely related to inadequate interactions with available equipment. In present case study, it was of particular interest to notice, identify, and predict possible human errors that might lead to an accident. Survey on work activities and manual handling of material and equipment at M/s Tehnogas AD, Nis, has revealed certain spots and actions that hypothetically might go wrong due to human factor under certain circumstances, such as: i) Filling storage tanks and decanting fluids from reservoirs into cistern trucks, while vehicles are disengaged; ii) Operating gaseous and liquid fuels dressed in working suits made of inflammable materials; and iii) Starting motor vehicle after filling tanker truck before required 30 min safety period has entirely elapsed, etc. In the company M/s Tehnogas AD, Nis there is a high level of the system complexity and a very low level of previously described kind of compatibility, which makes the system vulnerable and increases possibility of an accident to occur due to human factor. Using graph system for potential accidents, it has been assessed that compatibility level between operators and the system was 1.5 (CPS=1.5).

Assessment of hazard due to other, unpredictable, harmful impacts is based on probability that some form of natural or man-made disaster could happen (storm winds, thunder, impacts of flying objects, war situation and sabotage). A minor hazard of external impacts has been assessed at value 0.5 (OI=0.5).

Based on above quantitative assessments, and according to Eq. (4), value of hazard caused by external factors is estimated as 3.5 (E=3.5).

Assessment of the level of Overall Hazard of an Accident

Based on completed research, assessment results of the level of overall hazard of an accident to occur in
M/s Tehnogas AD is shown as: $TP = 18$ (CA, 3; ER, 2; PP, 2; and PM, 1.5); $HF = 4$ (QL, 1.5; RA, 1.5; and RL, 1); and $E = 3.5$ (EC, 1.5; CPS, 1.5; and OI, 0.5).

Level of overall hazard of an accident was calculated from Eq. (1) and is estimated as 60.6 ($A=60.6$), which suggests a level of hazard that would not endanger surroundings or consequences of hazard would not go beyond boundaries of industrial compound.

Conclusions

New methodological framework for a comprehensive risk assessment comprises estimates on hazards caused by technology, human factor and environment. Method is based on expert evaluation and combination of several well known methods (EA, HAZOP, FMEA, DA, SFA, JSA, etc.) as well as on Code of practice on methodology for risk assessment and mitigation of chemical and environmental accidents. Case study performed at a company (M/s Tehnogas AD, Nis, Serbia) has confirmed that new method is highly applicable, comprehensive and easy to perform. Applying newly proposed method for assessment of the level of overall hazard of an accident, all limitations and imperfections of used single methods have been successfully eliminated by an integrative, synergetic approach.

Acknowledgements

This study comprises a part of research project “Research and development of expert systems and methods for ergo-ecological risk assessment of accidents in Electric Power Company of Serbia”, TR 21030, 2008-2010., under auspices of Ministry of Science and Technological Development, Republic of Serbia.

References

3. Menshikov VB, The identification professional risks, in Proc Int Conf Professional Risk Assessment - Theory and Practice (Faculty of Occupational Safety, University of Nis, Nis) 2003, 9-12 (in Serbian).
16. Official Gazette of Republic of Serbia, No. 60/94, Code of Practice on Methodology for Risk Assessment and Mitigation of Chemical and Environmental Accidents (Govt. of Serbia, Serbia) (in Serbian).