Vulnerability Analysis for Risk Zones Boundary Definition to Support a Decision Making Process at CBRNE Operations

Aliaksei Patsekha, Michael Hohenberger and Harald Raupenstrauch

Abstract**—**An effective emergency response to CBRNE accidents that represent highly dynamic situations needs immediate actions within limited time, information and resources. The aim of the study is to provide the foundation for division of unsafe area into risk zones according to the impact of hazardous parameters (heat radiation, thermal dose, overpressure, chemical concentrations). A decision on the boundary values for three risk zones is based on the vulnerability analysis that covered a variety of accident scenarios containing the release of a toxic or flammable substance which either evaporates, ignites and/or explodes. Critical values are selected for the boundary definition of the Red, Orange and Yellow risk zones upon the examination of harmful effects that are likely to cause injuries of varying severity to people and different levels of damage to structures. The obtained results provide the basis for creating a comprehensive real-time risk map for a decision support at CBRNE operations.

Keywords**—**boundary values, CBRNE threats, decision making process, hazardous effects, vulnerability analysis, risk zones

I. INTRODUCTION

EMERGENCY response is the stage of the disaster management process that needs immediate actions and attracts the most attention and resources. The way it has been planned and the way the hazardous situation is managed will have a significant influence on post-disaster recovery and future development possibilities [1]. An effective emergency response and evacuation management plans are meant to save people's lives, protect public and private property, keep the environment safe and meet basic human needs after an emergency has occurred.

The CBRNE, natural, or human caused threats and accidents are still urgent at present, though they usually do not occur often; however, the civil defence system always has to be ready for a rapid response [2]. The focus of the research is mainly on CBRNE threats that refer to hazardous incidents caused by chemical substances (C), biological pathogens (B), radioactive material (R), nuclear weapons (N) and explosives (E) as well as by the misuse of expertise related to these (e.g. structural failures, releases of toxic substances, leaks of flammable materials, terrorist attacks, etc.).

CBRNE agents can often cause mass destruction, but this is not necessarily the case despite many of them have the potential to do so. The CBRNE classification based on the time of the incident, the impact magnitude and the availability of the materials [3] proves that CBRNE incidents represent highly dynamic situations where every minute counts and where there is a need for rapid and effective measures to save lives, protect health and stabilize the situation. These actions are in the field of duty of first responders (usually firefighters, police officers, paramedics or emergency medical technicians) for whom operations with CBRNE substances represent an enormous challenge with regard to the decision-making processes. For example, CBRNE accidents oblige emergency personnel to evacuate masses that necessitate the sudden movement of many people. But the work on informing the area residents and providing them with a safety evacuation plan is a far complicated matter and needs both broader and more specific skills than emergency plans normally needed even in the largest buildings. A place for people's relocation from an exposed area should be determined within an adequate vision of the threat evolution, especially in a case of fast-approaching hazards [4]. Or we can mention another difficulty for rescue operations and its phases (e.g. victims' treatment, control or containment of fire and other hazards) when responders should consider the possibility of the site contamination with CBRNE agents that pose an immediate threat to the health and safety of the emergency personnel [5].

The time is another obvious factor which provides additional pressure on decision makers. Though, even in an acute emergency, an assessment, however brief, is needed to ensure that any action undertaken is effective [1]. Usually, in cities the average response time is between five and ten minutes [6]. The opening time span (up to 15-20 min) after the initial hazardous occurrence are considered of paramount importance that results in a situation where emergency personnel have only a few minutes to find the most effective way to limit casualties generated by CBRNE hazards [7], [8]. Accidents such as an ammonium nitrate explosion occurred at the West Fertilizer Company facility in West (Texas, US) on April 17, 2013 where 15 people were killed (12 of them were emergency responders unprepared for an accident of such magnitude), 260 were injured, make clear that a suitable risk assessment is of central importance, especially in the first response phase.

Summing things up, we can conclude that first responders and their advisors should possess the right qualifications and comprehensive knowledge that is key to managing CBRNE

The authors would like to thank the Austrian Federal Ministry of Agriculture, Regions and Tourism and the Austrian Research Promotion Agency (FFG) with their Security Research Program (KIRAS) for the funding support of the ERIMAPS project.

Aliaksei Patsekha is with the Montanuniversitaet Leoben, Franz-Josef-Strasse 18, 8700 Leoben (e-mail: aliaksei.patsekha@unileoben.ac.at).

Michael Hohenberger is with the Montanuniversitaet Leoben, Franz-Josef-Strasse 18, 8700 Leoben (e-mail: michael.hohenberger@unileoben.ac.at).

Harald Raupenstrauch is with the Montanuniversitaet Leoben, Franz-Josef-Strasse 18, 8700 Leoben (e-mail: harald.raupenstrauch@unileoben.ac.at).

events. The information on propagation of hazardous effects is of a great importance as it is used to define the borders of "risk zones" which determine the behavior and decisions of the emergency personnel.

Within the "ERIMAPS – Real-time risk maps for decision support at CBRNe operations" project, an attempt is made to develop the foundation for creating a comprehensive real-time risk map that will be based on simple impact calculations, available with a minimum of input parameters and reckon with spatial demographic data to provide assistance in a decision making process.

II. Main part

There are different methods to divide an incident adjacent area to zone types according to their threat rate. For this reason qualitative and quantitative approaches are mainly used [9]-[11]. For the purpose of this work it was decided to make a combined classification for zoning of hazardous areas, according to the values of defined during planned impact modelling characteristics.

A distinctive feature of the carried-out vulnerability analysis is a joint risk-based assessment of hazardous impacts on people on the one hand, and buildings and facilities – on the other. This approach provides an opportunity to consider a wide range of threats which occur in a case of a CBRNE accident in an urban environment.

Hazardous consequences and impact analysis are addressed from the point of the final result of the ERIMAPS project that is to develop the background for creating a software solution for the representation of a real-time risk map and to investigate the applicability of a risk-based assessment of the hazardous area. This includes implementation of a completely new approach to simplify the calculation process of hazardous impacts and linking it with the data from geographic information systems (GIS) as well as atmospheric information. Cross light of this research scope is described in [12], [13] with the main specific feature in using various modelling software to estimate the consequences of a hazardous incident. But generally applied models (CFD, ALOHA, HAMS-GPS, MET, etc.) are not fully suited for the purpose of the project because of their complicity, computational power and time demands, limited access, need in validation or reconfiguration from industrial to the urban environment and so on [14], [15].

Risk zones. Expected output parameters for the vulnerability analysis are decided on the chosen calculation models where hazardous impacts are estimated by heat radiation, thermal dose, overpressure and toxic concentration values. Those to be defined values are used to divide the hazardous area and specify it in certain risk zones which should be presented in a graphic form for more convenient use by emergency personnel during the operation.

It was suggested to implement commonly recommended colour scheme for zones marking-out when a hazard is going to reach the defined dangerous level. So the Red – Orange – Yellow colours are used to give some natural feeling of being in an unsafe or risky area.

The 'Red zone' marks the most dangerous area and is the closest to the initial hazardous occurrence (fire, explosion, toxic release). It is in the circumference where fatal injuries and collapsed structures can be expected. The 'Orange zone' is still dangerous, the people there are likely to be hospitalized, but it is rather unlikely that a healthy person gets fatally injured there. However, more vulnerable people are still at risk of dying in this zone. The 'Yellow zone' is primarily dangerous for vulnerable population and risk groups, such as children or people who are unable to flee. But if the evacuation is conducted within a certain time frame, fatalities are unlikely. If necessary, green colour could be used to mark clearly safe areas, where no hazardous impacts are expected. General approach to divide a hazardous area into the risk zones considering the resulted impact on people and structures is summarized in Table I.

TABLE I
APPROACH TO THE RISK ZONE CATEGORIZATION

Risk zone colour	Grade of hazardous impact on people	Grade of hazardous impact on structures and buildings
Red	Possibility of fatality	Heavy damage
Orange	Irreversible consequences	Moderate damage
Yellow	Reversible consequences	Minor damage

Hazardous effects. There are three main group effects due to fires, explosions and toxic releases: heat radiation, pressure waves and exposure to toxic substances. Besides the process conditions and source terms, they are dependent on the type and amount of the substance involved and are distance and duration sensitive.

Thermal radiation harmful effects on the human body and structures are the most frequent threats during CBRNE accidents. The impact analysis to identify peoples' vulnerabilities has been primarily conducted to determine the boundary values for the risk zones. Effects of heat radiation and thermal dose were examined to decide these zones specification. During the process, injuries caused by heat radiation and thermal dose (from redness or blister formation on the skin to charring, heat inhalation trauma) and pain limits from the thermal radiation intensity were discussed as well as indirect effects of thermal radiation (effect of clothing, smoke inhalation, structural effects). In Table II the heat radiation and thermal dose critical values to define the risk zones that were adopted considering recommendations [11], [16], [17] are presented.

Thermal radiation intensity of 1.5 kW/m² for the 'Yellow zone' is chosen as a pain threshold value whereas thermal dose here is based on the high probability of getting first degree burns. The limits of 3 kW/m² and 200 kJ/m2 for the 'Orange zone' are set up on the possibility that people there are likely to be hospitalized (onset of serious injury and second degree burns are expected), but lethal outcome for a healthy person is rather unlikely (escape time to avoid serious consequences is about 60 seconds). The heat radiation and thermal dose for the 'Red zone' are for a 1% chance of fatality (type of injury – third-degree burns) for continuous (up to 90 seconds) exposure. Also specific values of the heat radiation are added in Table II to manage the safety and health of on the scene disaster responders that is critical for obvious reasons [18].

Analysis of thermal radiation harmful effects on structures allowed to define values to corresponding risk zones (Table II). The expected damages were addressed from the point of their possible threat to people in the surroundings and a time span for which they are relevant (e.g. pool and jet fires can last for hours and fireballs and vapour cloud explosions are usually finished within seconds) [16]. So for the 'Red zone' critical heat flux value is compliant with heavy damage to housing (e.g. auto-ignition of textiles and wood) or process equipment. The 'Orange zone' boundaries were decided on the damage type that is related to ignition of surfaces and rupture or other type of failure of structural elements (for exposure durations more than 30 min). Less severe damage level (serious discolouration of the material surfaces, peeling-off of paint and/or substantial deformation of constructional elements) is accepted for the 'Yellow zone'. In addition, it was decided to use a supplementary scale of heat radiation values to anticipate indirect injuries which can occur through structural damage (from distortion of substructure components and glass breakage to plastic melting and fuel ignition) to people who stay indoors or in close proximity to buildings (see "humans (indirect effect)" option in Table II).

TABLE II
CRITICAL VALUES SELECTED FOR THE DEFINITION OF THE RISK ZONES (FOR FIRES AND EXPLOSIONS)

Hazardous parameter	Hazard targets	Zone colour Yellow	Orange	Red
Heat radiation [kW/m^2]	- humans	1.5	3	6.3
	- responders (EN469 clothing)	3	4.6 [a]	6.3 [b]
	- responders (EN1486 clothing)	4.6	6.3 [a]	10 [b]
	- structures	2	12	35
	- humans (indirect effect) [c]	2	4	12
Thermal dose [kJ/m^2]	- humans	125	200	375 / 250 [d]
Overpressure [kPa]	- humans	2	5	14
	- structures	3.5	17	35
	- humans (indirect effect) [c]	0.5	5	8

[a]It is possible to perform incident related activities depending on the firefighter's clothing with a maximum time set at 3 min (EN469) and 5 min (EN1486).

[b]It is possible to escape from a heat radiation contour (not allowed to perform incident related activities).

[c]Probability of indirect injuries to people indoors or in direct proximity to buildings or structures.

[d]Thermal dose for exposure to fireballs.

Another assessed scenario of hazardous events is related to explosions. The main direct harmful effect to humans (and surrounding facilities) is the sudden increase in pressure that occurs as a blast wave passes. The most vulnerable human organs are ears and lungs because of their high sensitivity to jump-in pressure (blast lung is the most common fatal injury). Despite there are various consequences of an explosion (pressure waves, missile flight, heat radiation, crater formation, earth shocks) for the differentiation of the risk zones the peak overpressure is used as the key parameter.

According to assumed method of the risk zone categorization, severe damage to structures and housing is present in a case of overpressure more than 35 kPa that provides a threshold value for the 'Red zone' (Table II). Moderate and light damage predefine criteria for the 'Orange' and 'Yellow' zones: 17 and 3.5 kPa, respectively. Similar to heat radiation effects, to consider a possibility of indirect trauma to people indoors due to overpressure, additional values are chosen to cover injuries occurring through damage to window frames, house ceilings, roofs and walls, etc.

Harmful effects of toxic action represent the third group of hazardous consequences during the CBRNE events that are assessed here. The damage degree a toxic chemical can inflict on its surroundings is determined by the toxicity of the material, the duration of exposure and the dose received due to its dispersion. Within the project scope it was decided to focus on the inhalation intoxication and its corresponding effects as the main threat to the majority of people present in the emergency area. The concentration of the substance for which it is still toxic as well as the impact duration affect exposure limits. Within the established goals of the project, as we were looking at short-term affecting in emergency cases, AEGLs (Acute Exposure Guideline Levels) and ERPG (Emergency Response Planning Guideline) were under consideration as emergency exposure limits. After conducting the comparative analysis, it was decided to use AEGLs as the focal and more flexible system in terms of exposure duration to define the risk zones.

Threshold three limit values in the AEGLs represent a different degree of toxic effects severity for five relatively short exposure periods – 10 min, 30 min, 1 hour, 4 hours, and 8 hours. These exposure levels are applicable to all members of the general population, including susceptible individuals. The following risk zone categorization based on AEGLs and corresponding severity of the toxic effects is accepted. Level 1 of AEGL is used for the 'Yellow' risk zone when notable discomfort, irritation, certain asymptomatic non-sensory effects are the main characteristic features. Irreversible or other serious, long lasting adverse health effects or an impaired ability to escape can be used for the description of the 'Orange zone' according to AEGL 2. Level 3 – for the 'Red zone' – is a case of life threatening health effects or death.

Individual AEGLs values for two of many major industrial gases that represent a toxic hazard through their manufacture, storage and transporting are given in Table III [19].

TABLE III
AEGLS VALUES FOR A SELECTION OF INDUSTRIAL TOXIC GASES

Gas	Risk zone colour	AEGLs	Concentration [ppm] for the exposure period of: 10 min	30 min	1 hour	4 hours	8 hours
Ammonia	Yellow	AEGL 1	30	30	30	30	30
	Orange	AEGL 2	220	220	160	110	110
	Red	AEGL 3	2700	1600	1100	550	390
Chlorine	Yellow	AEGL 1	0.50	0.50	0.50	0.50	0.50
	Orange	AEGL 2	2.8	2.8	2.0	1.0	0.71
	Red	AEGL 3	50	28	20	10	7.1

In terms of the research goals, AEGLs values for the exposure duration from 10 min to 1 hour are of great interest as they present useful information for first responders who should decide on immediate actions to deal with such dangerous situations like a release of toxic chemicals.

III. CONCLUSION

Following a disaster, initial assessments should be rapid and provide the information required to start an appropriate response aimed to save lives, protect health and stabilize the situation. Hazards definition plays the main part in this process. Several scenarios of CBRNE events which are related to the fire and/or explosion incidents or toxic releases are applied as a basis for main threats and hazard identification. Possible consequences due to the occurring heat radiation, blast wave and toxicity for people and facilities are used for the risk zones categorization. More specifically, the boundary values for these zones are based on the people's injury severity and the level of damage to structures or buildings.

The obtained results in the short-term in combination with data from geographic information systems provide necessary conditions for creating the injury pattern catalog and developing a building classification to support hazards impact assessment over the course of a CBRNE accident.

On a wider scale, the conducted research provides the foundation to develop a real-time risk map for decision support system during the CBRNE operations especially if an emergency occurs in an urban environment. A distinctive feature of the proposed approach is a multilayered map that covers different kinds of risks to humans and building structures which would definitely help to answer the central question from the ERIMAPS project: "What happens in an event in the next few minutes, who and how many will be affected, where is the focus and what resources are required?".

ACKNOWLEDGMENT

The ERIMAPS project is a cooperation between Montanuniversitaet Leoben, Die Johanniter Austria, the Austrian Federal Ministry of Defence, the Professional Fire Brigade Graz, the Professional Fire Brigade Vienna and Flammpunkt GmbH.

REFERENCES

[1] Emergency response - World Health Organization. Available from https://www.who.int/water_sanitation_health/hygiene/emergencies/em2002chap4.pdf, accessed 01 March 2020.
[2] A. Baums, Response to CBRNE and human-caused accidents by using land and air robots. Automatic Control and Computer Sciences, 51(6) (2017) 410–416.
[3] CBRNE Health Information Resources - Section 1: Introduction to CBRNE Concepts. Available from https://www.nlm.nih.gov/dis_courses/cbrne/01-000.html, accessed 01 March 2020.
[4] S. Marsella, N. Sciarretta, CBRN Events and Mass Evacuation Planning. Enhancing CBRNE Safety & Security: Proceedings of the SICC 2017 Conference, (2018) 353–363.
[5] Introduction to CBRNE Terrorism: An Awareness Primer and Preparedness Guide for Emergency Responders. Available from http://jumpjet.info/Emergency-Preparedness/Disaster-Mitigation/NBC/Introduction_to_CBRNE_Terrorism.pdf, accessed 02 March 2020.
[6] Emergency medical services in Austria. Available from https://en.wikipedia.org/wiki/Emergency_medical_services_in_Austria, accessed 02 March 2020.
[7] J.-L. Vincent, E. Abraham, P. Kochanek, F.A. Moore, M.P. Fink, Textbook of Critical Care, seventh ed., Elsevier - Health Sciences Division, Philadelphia, United States, 2017.
[8] Initial operational response to a CBRN incident. Available from https://www.jesip.org.uk/uploads/media/pdf/CBRN%20JOPs/IOR_Guidance_V2_July_2015.pdf, accessed 03 March 2020.
[9] G.G. Noll, M.S. Hildebrand, G.D. Rudner, R. Schnepp, Hazardous materials: Managing the incident, fourth ed., Jones & Bartlett Learning, Burlington, MA, 2019.
[10] C.J.H. van den Bosch, R.A.P.M. Weterings (Eds.), Methods for the calculation of physical effects: due to releases of hazardous materials (liquids and gases) ('Yellow Book'), third ed., Committee for the Prevention of Disasters, The Hague, 2005.
[11] U. Hauptmanns, Process and Plant Safety, Springer Berlin Heidelberg, 2014.
[12] B. Yoo, S.D. Choi, Emergency Evacuation Plan for Hazardous Chemicals Leakage Accidents Using GIS-based Risk Analysis Techniques in South Korea. International Journal of Environmental Research and Public Health, 16(11) (2019) 1948.
[13] Y. Ghajari, A. Alesheikh, M. Modiri, R. Hosnavi, M. Abbasi, Spatial Modelling of Urban Physical Vulnerability to Explosion Hazards Using GIS and Fuzzy MCDA. Sustainability, 9(7) (2017) 1274.
[14] J. Burman, L. Jonsson, Issues when linking computational fluid dynamics for urban modeling to toxic load models: The need for further research. Atmospheric Environment, 104 (2015) 112–124.
[15] M. Ciccotti, F. Spagnolo, M. Palmery, Safety in the Transport of Hazardous Substances in Residential Areas: Cases of the Release of TIC (Chlorine, Propane, and Butane) at Low Temperatures. Enhancing CBRNE Safety & Security: Proceedings of the SICC 2017 Conference, (2018) 71–79.
[16] C.J.H. van den Bosch, L. Twilt, R.A.P.M. Weterings, et al., Methods for the determination of possible damage to people and objects resulting from releases of hazardous materials (Green Book), thirst ed., Committee for the Prevention of Disasters, Den Haag, 1992.
[17] S. Mannan (Ed.), Lees' Loss Prevention in the Process Industries, Hazard Identification, Assessment and Control, fourth ed., Elsevier, Amsterdam, 2012.
[18] Maximum allowable exposure to different heat radiation levels. Available from http://content.publicatiereeksgevaarlijkestoffen.nl/documents/PGS29/Raport%20IFV_20160509_Heat_radiation_contours_final.pdf, accessed 05 February 2020.
[19] Access Acute Exposure Guideline Levels (AEGLs) Values. Available from https://www.epa.gov/aegl/access-acute-exposure-guideline-levels-aegls-values, accessed 12 February 2020.