24th ABCM International Congress of Mechanical Engineering
December 3-8, 2017, Curitiba, PR, Brazil

COBEM-2017-1364
RISK ANALYSIS IN CHEMISTRY LABORATORY

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Abstract. *Technical systems inside a research laboratory represents risks for users and for the population around. This work presents a risk analysis study about a chemistry laboratory in Federal University of Santa Catarina using risk analysis methodology based in New Product Development (NDP) has developed by Núcleo Integrado de Desenvolvimento de Produtos (NEDIP). The results obtained clearly show the main sources of risks: fire, delayed evacuation of the laboratory, explosion and intoxication by handling. Therefore, the risk management in hazard environment is important to protect the users and the equipments. This approach also aims the reflection about safety in educational environment.*

Keywords: *risk analysis, risk management, CNEA, FTA*

1. INTRODUCTION

Chemistry laboratories are unhealthy and dangerous environments, technicians, professors and students handle with chemical reagents and equipments (sources of heat and electricity) and then, they are exposed to many potential sources of risks. Risk, according to Dias et al., (2011), is understood as a probability of occurrence of an incident or as consequences of it. Therefore, it is important to characterize the future states and their respective relevancies in order to manage the risks, i.e., to identify actions to avoid or reduce the chance of an incident occurring again or mitigate its consequences. In this context, the use of multi-causal theory suggests that the causes of the occurrence of an incident are systematized by factors that integrate the human behavior, the environment and the technical system.

Educational centers as universities are environments that are prone to integrate these factors and to offer risks to the population. Müller and Mastroeni (2004) indicate that, in research laboratories, the most accident-prone group are academics, scholars or trainees, that are individuals who participate in projects and share these environments. Within this aspect, the importance of risk analysis in chemistry laboratories is highlighted. According to Verga Filho (2008), if working conditions or equipment fulfilling high safety conditions and if workers perform proper training, accidents can be avoided. To develop the risk analysis, the primary focus was to identify the main risk conditions that can offer danger for the users of the Laboratory of Bioinorganic and Crystallography located in Federal University of Santa Catarina. In order to achieve the intended objective, the project was based on specific objectives: a) Obtain information through questionnaires, interviews and laboratory visits; b) Determine barriers according to risk analysis techniques such as Fault Tree Analysis (FTA) and Causal Network Events Analysis (CNEA); c) Elaborate emergency response plans; d) Analysis of results and proposals; e) Present how risk management in hazard environment can be integrated in the under-graduation level.

The structure of the article presents a flow to the understanding of the activities developed during the risk analysis. Primary Sections: Bibliographic Review, which details the main concepts and techniques used; Methodology, present the methodology used for risk management analysis; Results, shows the analysis of the main potential incidents using the tools for risk analysis and present how to integrated the risk analysis techniques on the under-graduation level.

2. RISKS INTO RESEARCH LABORATORIES

According to Gimenez (2009) there is a diverse number of risks into chemistry laboratories due to the presence of dangerous, toxic, corrosive, irritant and flammable substances, use of equipment that assign certain risks (alteration in temperature and pressure) and manipulate biological and pathogenic agents. Some causes of the laboratory accidents are unsuitable instructions, insufficient supervision of the executor, incorrect use of equipment or materials with unknown characteristics and emotional state changes.

According to the interview (2017) with users of the Laboratory of Bioinorganic and Crystallography located in Federal University of Santa Catarina, the accidents that come from these causes are usually intoxications, thermal burns, electric shocks, fires, explosions, contamination by biological agents and interactions with radiation.

The “Table 1” represents the total number of accidents in research laboratories in Brazil and the number of accidents between the periods from 2008 to 2011, according to Brandalize (2013). It is shown a significant value of accidents in laboratories and how there is a latent field for development of studies about to reduce this condition.

Table 1. Accidents in laboratories and total national accidents between 2008 a 2011.

Year	Accidents into laboratories	Total accidents Brazil	% in relation to total
2008	703	755980	0,093
2009	696	733365	0,095
2010	751	709474	0,106
2011	751	711164	0,106

2.1 Technical Definitions

Primarily, it is necessary to define some concepts about what risk, incident and danger, and then, introduce the methodology of analysis and risk management. According to Kumamoto and Henley (1996), risk is formally defined as a combination of five factors: Probability, Result, Significance, Causal Scenario and Affected Population, these are the determining factors for generating the risk profile.

Dias et al., (2011) defines risk as “[…] the chance of a future state “x”occur, given the occurrence of an initial state that can be expressed by the conditional probability P (Future State “x” | initial state) -, being necessary for its complete characterization, the demarcation of the two states, beyond the scenarios that allow this transition” (DIAS, et al., 2011).

Calil (2009) defines incident as any event that has negative consequences, hence, incident contains the concept of an accident - which is restricted to events that cause damage.

Mosleh et al., (2004) define danger as any act (omission or action), condition or state of the system - or a combination of these - with the potential to result in an accident or more comprehensively, in an incident.

Risk management, in its broadly definition “Is the science, the art and the function that aims at the protection of human resources, material and financial resources of an organization, either by eliminating or reducing their risks, either by financing the remaining risks, while it is economically more viable " (De Cicco and Fantazzini, 1985) *apud* (Brandalize, 2013).

The “Fig. 1” (CATAI, 2012) presents a sequence of actions, evaluations, that make up the risk management process.

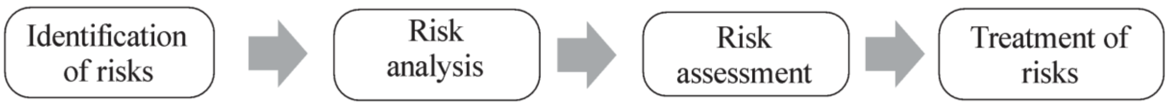


Figure 1. Risk management process flow.

2.2 Methodology for Risk Management

According to Dias et al., (2011), the risk management methodology consists of a set of procedures and organized techniques, whose aims is to manage technical systems, people and environments, with a objective to developing a process of analysis, treatment, acceptance and communication of risk.

The methodological procedures for this research were delineated from the illustration of the “Fig. 2” adapted from Acires et al., (2011) e Calil (2009) which illustrates a roadmap divided into five stages, designing, implementation, use, review and deactivation. However, the stages of implementation, use, review and deactivation are not included in the context of this work will not be described.

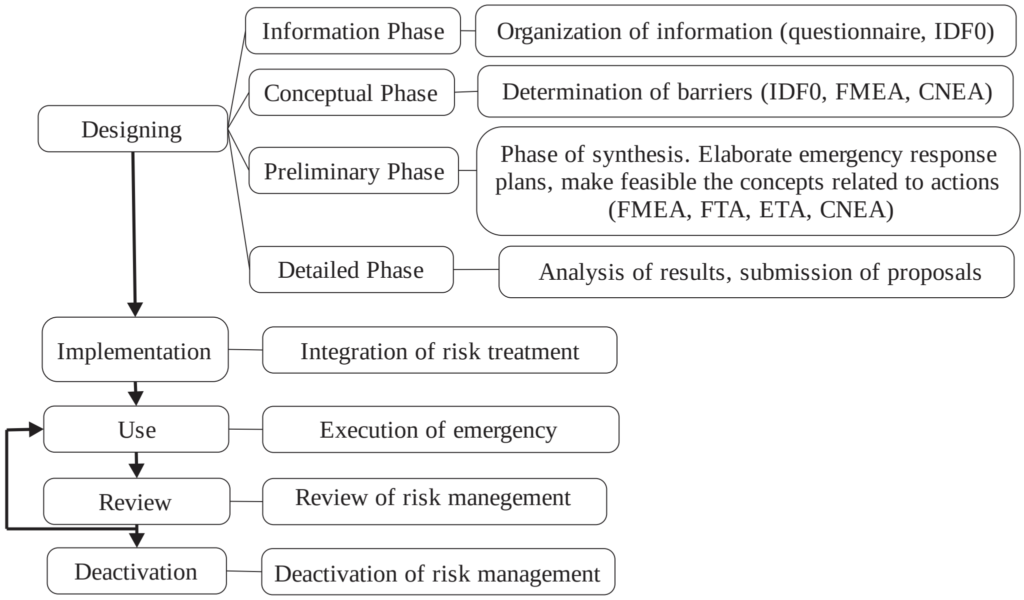


Figure 2. Stages of the Risk Management Methodology

According to Dias et al., (2011), in the design stage, a plan is elaborated to be able to manage it later. This stage is composed by the phases described below.

- Informational Phase: It seeks to organize all information of modes of failure, causes, effects, dangerous technical conditions, people and environmental, the fault scenarios and fault studies. In this phase the survey of norms, regulations and laws, analysis of the concerned parties involved. Examples of techniques used in this phase are: Questionnaires in order to obtain information, IDEF0 to organize the analysis of processes and to help in communication between the various process agents.
- Conceptual Phase: The objective of the conceptual phase is to develop risk analysis and define the barriers. In this stage strategies are developed to isolate the dangerous condition of the trigger event. We use techniques such as FMEA to organize the language relating systems and their functions and CNEA to relate the most likely causes and barriers to inhibit failure mode.
- Preliminary Phase: Its objective is to make feasible the concepts related to the actions to eliminate, mitigate or accept the risks, being elaborated plans of emergency response. It is a phase of synthesis and techniques such as FMEA, FTA, ETA, CNEA can be used.
- Detailed Phase: Analysis phase of results, submission of proposals, socialization of results with stakeholders.

2.2.1 Causal Network Event Analysis (CNEA)

According to Dias et al., (2011), the CNEA tool structures the risk analysis identifying the event, their causes and effects and the barriers that act in the causal chain. The CNEA can be used even when the analyst does not have sufficient knowledge to establish relationships between the causes and effects of an incident. This technique facilitates the understanding of these relationships and allows in the process of risk analysis the delineation of causal chain barriers in order to prevent or mitigate the effects of the incidents studied.

According to Dias et al., (2011) in the modeling of CNEA from people's experiences, it is possible to raise scenarios and risk controls. The CNEA model technique is based in seven steps as will be discussed in the following sections.

2.2.2 Fault Tree Analysis (FTA)

The FTA tool was developed by H. A. Watson in 1962. It is a deductive technique in which, from an initial event, there are identified the intermediate events resulting from the logical association of the root causes that generated it.

In the development of the FTA, any relevant causes leading to the top event are considered, such as: equipment failures, human or software errors. However, it is important to realize fault analysis as a model, therefore, the analyst considers only the most significant causes, neglecting those considered irrelevant (Dias, et al., 2011). The logical associations are based on Boolean Algebra and through the representation of logical gates with standardized symbols for each conditional. For example, logic gates "AND" or "OR" (Kumamoto And Henley, 1996).

Through these associations, the identification of intermediate events follows until the root causes for the occurrence of the top event be identified, at the point where the FTA resolution limit is obtained. Hence, the application of FTA allows both a qualitative analysis (due to reasons of cause and effect) and a quantitative analysis, when determining the probability of occurrence of events.

2.2.3 Importance of risk analysis for undergraduate students into laboratories

According Hill, R. and Finster (2010), for decades, the topic of chemical safety was included at the margins of lab courses, mostly taught in a small way as a footnote to various lab experiments and procedures. And now, in the twenty-first century, for a variety of legal, ethical, and educational reasons, the topic of chemical safety it has been more teaching, but it is still not considered as priority content of chemistry area. “chemistry faculty simply do not consider instruction in laboratory and chemical safety to be very important or at least important enough to devote a whole course to the topic” (Hill, R. and Finster, 2010).

According Osang et al., (2013) scientist, engineers, laboratory or workshop users have lost their lives and the lives of others due to accidents in the workshop caused by ignorance, neglect or carelessness.

According with International Labour Organization (OIT) the convention n170 approved on 77a meeting of the International Conference of the work (Genebra - 1990) is necessary "provide to workers information about chemicals products used in workplaces, as well as the measures of the prevention that allows them participated of effective protection programs".

According Hill, R. and Finster (2010) “Chemical companies now understand, better than many colleges and universities, that being safe is the soundest financial practice a company can adopt. And as more laws and regulations have been developed over the past several decades, employers and employees really have no choice about many aspects of laboratory safety”. Developing such knowledge and habits in safety is what will make today's student a valuable professional in the future.

3. RESEARCH METHODOLOGY

The risk analysis methodology developed by Dias et al., (2011) was used as one of the main references for the accomplishment of this work, therefore, presents a cohesive structure and with significant results when applied in an energy generation and distribution company.

The methodology adopted to develop this work was appropriate from the Product Development Process (PDP), which was combined with technical study activities. After the informational search about the activities, structure, personnel and other routines of the laboratory, it was developed a spreadsheet of potential incidents, its conditions and hazards. This relationship was then classified according to the risk concept of Kumamoto and Henley (1996), being revised in terms of Probability of occurrence, Result, Significance, Causal Scenario and Affected Population.

The main related conditions were: fire due to product storage, intoxication by handling of chemicals products, explosion by handling and delayed evacuation by emergency situations. A number of existing barriers were cataloged on the same worksheet and others were listed according to existing standards. The information contained in the worksheet provided the basis for the preparation of CNEA and FTA. For the sequencing of the work and structuring of the analyzes were followed the steps:

a) Prior study of the standards of a chemistry laboratory;
b) Visits to the chemistry laboratory under study;
c) Questionnaire to agents who attend the chemistry laboratory;
d) Use of the CNEA technique (adopting the five steps recommended by Dias et al., (2011, p.192);
e) Use of the FTA technique;
f) Discussion of results;
g) Conclusion and suggestions.

3.1 Application of Techniques into Laboratory

The modeling by CNEA is adequate to model incidents with grouped causal chain in which the resulting effects are identical. According to the CNEA methodology, seven main steps are followed as described below:

1) Definition and scope of analysis

The analysis by CNEA is delighted to be comprehensive enough to reach the causes of the dangerous conditions, primarily those involved in the organizational issue, cultural behavior and follow-up of the regulative norms. From the point of view of effects, they were analyzed until the second level.

2) Identification of the incident

At this stage, the main incidents reported by laboratory users were identified, such as: explosion, fire, intoxication, evacuation and electric shock. The conditions of the incidents are related in: storage, handling, panic and dead circuit. Among these conditions, four critical incidents for the analysis were selected, being the decision-making criteria based on the information gathering and planning of the activities. The incident in the risk analysis in a laboratory environment is characterized as operating out of the standard conditions. That is, an undesirable situation under experiment in point of view of operator safety and the laboratory population.

3) Identification of the causes

The immediate causes and roots causes of each incident were obtained with the informational survey and deepening the questions about causal chains, respectively. There are common root causes among various incidents such as: incorrect references, imprudence, unfamiliarity. Other specifics root causes of evacuation incident are: unprepared, disorganization and physical space structure.

4) Identification of effects

In this approach, the analysis of effects triggering continues until a second level for explosion and intoxication and only one level for fire and delayed evacuation. The work focus going to be based in studies about the laboratory environment and its population.

5) Identification of barriers

The identification and new barriers proposals are illustrated in CNEA. In the condition of the environment, there is a substantial lack in contingency barriers for evacuation and preventive function barriers such as laboratory practices and safety training, in order to reduce the transmission of behavioral vices and notions of danger in this ambience.

6) Identification of trigger event

The most common trigger events in the analyzed incidents are related to human responsibilities such as storage failures, exposure of energy sources, contact between substances or between substances and operator. Moreover, there is the emergency situation, associated as trigger event in delayed evacuation incident.

7) Identification of hazardous state

The dangerous condition is present in every technical system and in certain cases, it can be attenuating by barriers or nullifying your contact with the trigger event. In the case of potential chemical energy, the dangerous condition is the amount of energy contained in the reagents released as heat, in this way barriers suggest control in the quantity of chemicals.

The CNEA technique has a user-friendly interface for non-specialized system knowledge level, however, to get to know the logical relationship between the events is necessary develop the Fault Tree Analysis (FTA).

The FTA modeling, accompanies the same depth of CNEA technique, focusing into determine the cause effect relationship. As well as CNEA, in FTA, the root causes about organization and culture behavior aspects are shown, classification another intermediate cause in parallel studies, due to lack of information or analysis strategy

4. RESULTS

In the following sections, the results of the risk analysis of the four prioritized events will be exposed, such as: fire due to improper product storage, intoxication by incorrect handling of products, explosion by incorrect handling of products or delayed evacuation by emergency situations.

4.1 Fire due to improper product storage

For the analysis of the causal chain, identification and proposals of preventive barriers that aim to avoid the occurrence of the central event or to mitigate its effects The CNEA technique was used in the fire like analysis as an incident caused by the storage condition of chemical product.

As shown in “Figure 4” the fire is presented to the center, the root causes being incorrect reference, imprudence and unfamiliarity on the left and the injurious and blasting effects on the right. The trigger event allocated are described as “TE”, the barriers already allocated are described as “BA” and proposed preventive barriers as “BP” according to “Tab. 2” and “Fig. 3”.

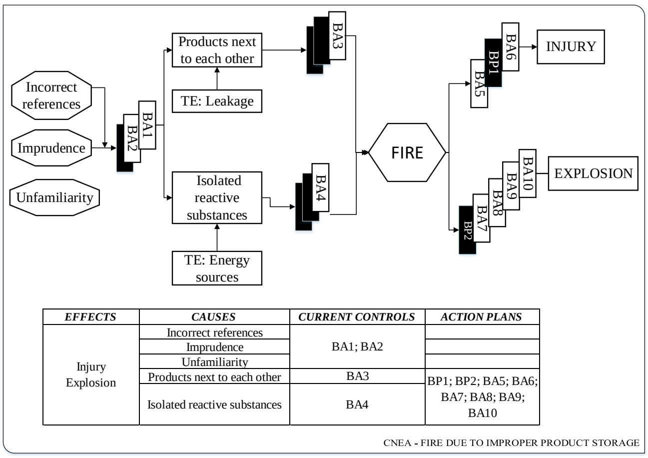


Figure 3. CNEA - Fire due to improper products storage.

Table 2. Fire barriers

Barriers	BA7 Quantities of laboratory-controlled products
BA1 Identification of products	BA8 Protection against projectiles
BA2 Orientation	BA9 Proper storage of cylinders
BA3 Storage in categories	BA10 Fire extinguishers
BA4 Temperature controlled enviroments	BP1 Escape routes
BA5 Alarms	BP2 Inventory control
BA6 Fire extinguishers	

Also in the analysis of the fire due to improper products storage, the FTA was performed to analyze the logical relations between the events, as shown in “Fig. 4”, being in this study fire as top event and root causes as incorrect reference, imprudence and unfamiliarity.

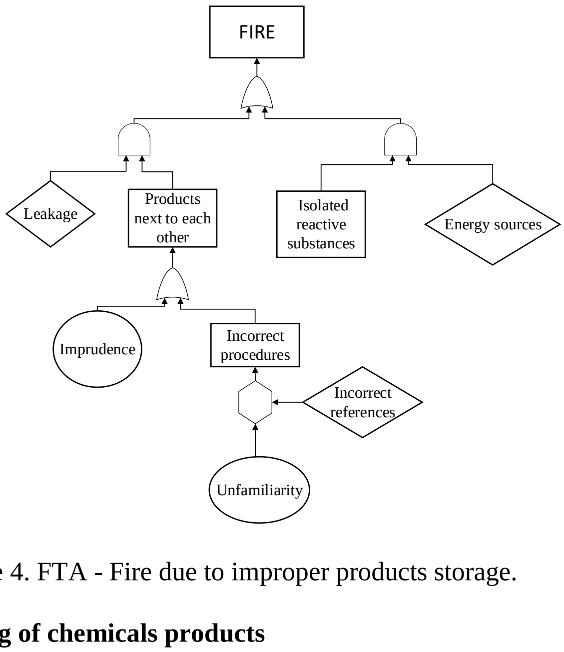
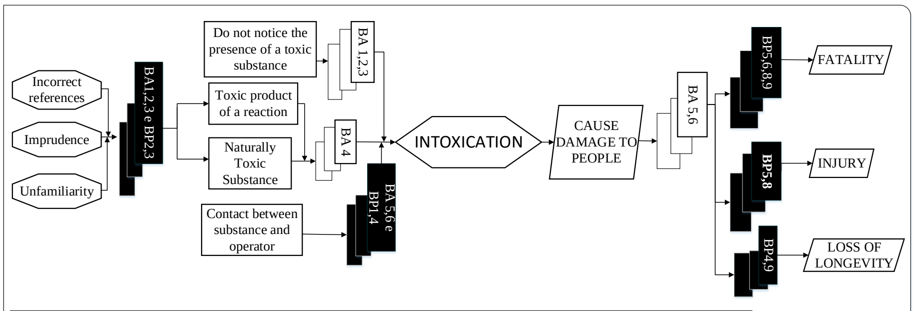


Figure 4. FTA - Fire due to improper products storage.

4.2 Intoxication by incorrect handling of chemicals products

The intoxication caused by handling of chemicals products was analyzed by CNEA in “Fig. 5”. The causes are positioned on the left and include incorrect references, imprudence and unfamiliarity, generating intermediate causes such as do not notice the presence of toxic substance, toxic product of a reaction, naturally toxic substance and also contact between substances and operators. If none of the preventive barriers detailed in “Tab. 3” can be activated, the intoxication incident and all sequences represented in its right side can be started as: fatality, injury and shortened longevity.



INCIDENT	EFFECTS	CAUSES	CURRENT CONTROLS	ACTION PLANS
INTOXICATION	CAUSE DAMAGE TO PEOPLE FATALITY INJURY LOSS OF LONGEVITY	INCORRECT REFERENCES	BA1; BA2; BA3	BP2; BP3
		IMPRUDENCE		
		UNFAMILIARITY		
		TOXIC PRODUCT OF A REACTION	BA4	
		NATURALLY TOXIC SUBSTANCE		
		DO NOT NOTICE THE PRESENCE OF THE TOXIC SUBSTANCE	BA1; BA2; BA3	
		CONTACT BETWEEN SUBSTANCE AND OPERATOR	BA5; BA6	BP1; BP4
				BA5; BA6; BP5; BP6; BP7; BP8; BP9

CNEA – INTOXICATION BY INCORRECT HANDLING OF CHEMICALS PRODUCTS

Figure 5. CNEA - Intoxication by incorrect handling of chemicals products.

Table 3. Intoxication barriers

Barriers

BA1 Study of reaction conditions of products
BA2 Look for relevant and reliable articles and materials on the reaction
BA3 Orientation of teachers and experienced members about the experiment
BA4 Use of neutralizing substances
BA5 Equipments for individual protection
BA6 Equipment for collective protection
BP1 Loading and transporting the reagent bottle cartridge into wooden trays
BP2 Camera monitoring
BP3 Create basic material for good laboratory practice and procedures
BP4 Circulation of air in a common environment between people and chemicals
BP5 Quick access to eye wash and showers
BP6 Marked escape routes
BP7 Appropriate organization
BP8 Contact and referral procedures for specialized first aid centers
BP9 Health monitoring program

The FTA was also used to analyze the logical relations between the event in intoxication by handling of chemicals products, as shown in "Fig. 6". In this study, intoxication is the top event and the root causes are imprudence and ignorance due to incorrect references.

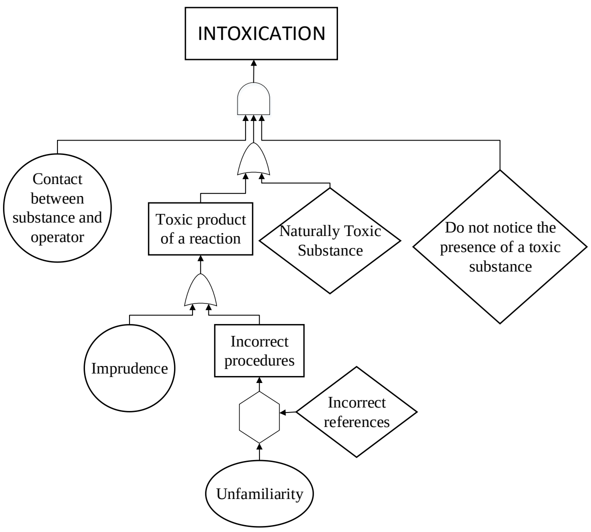
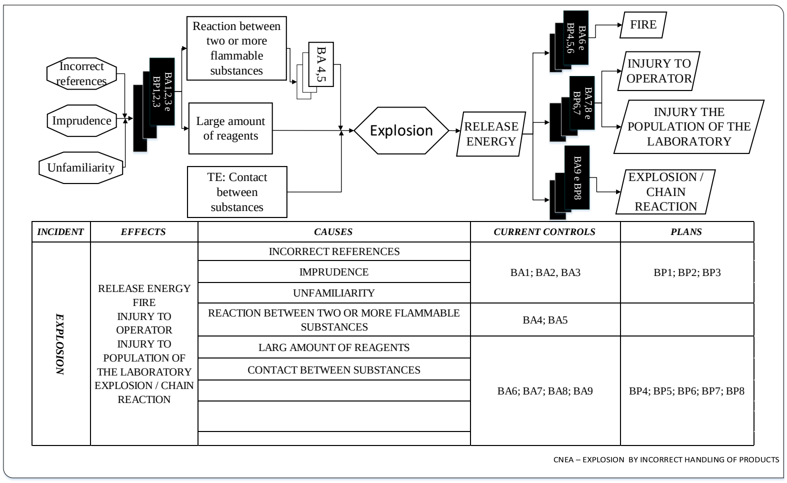


Figure 6. FTA - Intoxication by incorrect handling of chemicals products.

4.3 Explosion by incorrect handling of products

An assumed incident of explosion caused by incorrect handling of chemicals products was analyzed using the CNEA technique according to "Fig. 7". The causes and barriers are located to the left side and include: incorrect references, imprudence and ignorance that generate intermediate events as: reaction between two or more unstable substances, a great number of reagents. These events when added to the trigger event (contact between substances) may occur in explosion situation if the barriers detailed in "Tab. 4" are not activated. As consequence, all events in the right side of the incident studied may be started such as fire, operator injury, population injury and chain explosion.



INCIDENT	EFFECTS	CAUSES	CURRENT CONTROLS	PLANS
EXPLOSION	RELEASE ENERGY FIRE INJURY TO OPERATOR INJURY TO POPULATION OF THE LABORATORY EXPLOSION / CHAIN REACTION	INCORRECT REFERENCES IMPRUDENCE UNFAMILIARITY	BA1; BA2, BA3	BP1; BP2; BP3
		REACTION BETWEEN TWO OR MORE FLAMMABLE SUBSTANCES	BA4; BA5	
		LARG AMOUNT OF REAGENTS CONTACT BETWEEN SUBSTANCES	BA6; BA7; BA8; BA9	BP4; BP5; BP6; BP7; BP8

Figure 7. CNEA - Explosion by incorrect handling of products.

Table 4. Anti-explosion barriers

Barriers

BA1 Study of reaction conditions and products
BA2 Look for relevant and reliable articles and materials on the reaction
BA3 Orientation of teachers and experienced members about the experiment
BA4 Use of neutralizing substances
BA5 Environment in neutralizing conditions
BA6 Fire extinguishers
BA7 Equipments for individual protection
BA8 Equipment for collective protection
BA9 Adequate protection of explosive substances
BP1 Prohibit a person from conducting experiments alone in laboratories
BP2 Camera monitored environment
BP3 Create basic material for good laboratory practice and procedures
BP4 Smoke Alarms
BP5 Fire extinguishers with higher capacity
BP6 Marked escape routes
BP7 Organization of materials
BP8 Storage of H2 cylinders within standards

In the analysis of explosion caused by incorrect handling of chemicals products, the FTA was used to logical relations between the events, as shown in "Fig. 8", being this study the intoxication as a top explosion event and root causes such as imprudence and ignorance due to incorrect references.

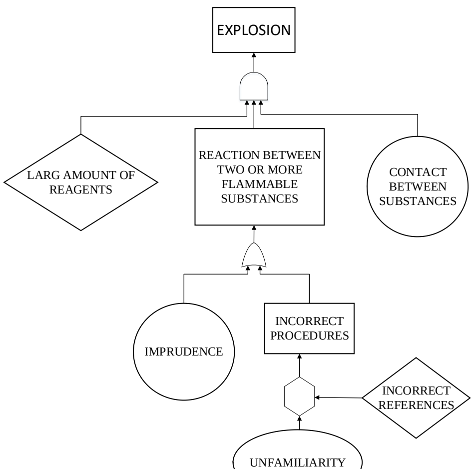
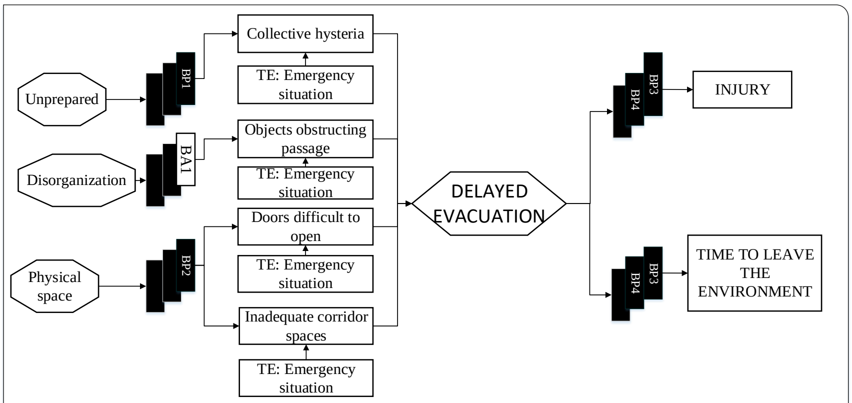


Figure 8. FTA- Explosion by incorrect handling of products.

4.4 Delayed Evacuation by emergency situation

As shown in “Figure 9”, the incident is the delayed evacuation. Its root causes are: unprepared users, disorganization of the environment and the physical space structure of the laboratory responsible by injurious effect and delay to get out of the room. This one may lead to a fatality occurrence. Current preventive barriers allocated are described as "BA" and the proposed preventive barriers as "BP", as shown in “Tab. 5”.



INCIDENT	EFFECTS	CAUSES	CURRENT CONTROLS	ACTION PLANS
DELAYED EVACUATION	Injury High response time	Unprepared		BP1
		Disorganization	BA1	
		Physical space		BP2
		Collective hysteria		BP3; BP4
		Objects obstructing passage		
		Doors difficult to open		
		Inadequate corridor spaces		

CNEA – DELAYED EVACUATION BY EMERGENCY SITUATION

Figure 9. CNEA - Delayed evacuation by emergency situation.

Table 5. Barriers against delayed evacuation

Barriers
BA1 Technical Standards
BP1 Trainings
BP2 Technical Standards
BP3 Risk map
BP4 Emergency exits

In the analysis of the delayed evacuation by emergency situation, the FTA analyzed the logical relations between the events, as shown in “Fig. 10”, in this study the delayed evacuation as top event and the causes of disorganization and structure.

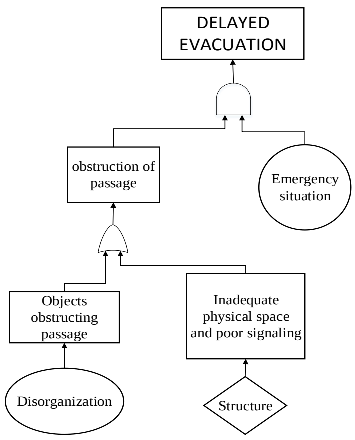


Figure 10. FTA - Delayed evacuation by emergency situation.

5. CONCLUSION

This work was able to identify the main risks about the chemistry laboratory investigated and some non-compliance situations. The risks founded were intoxication, delayed evacuation, explosion and fire. In sequence, some barriers and improvements were suggested. These priorities barriers suggested were defined by analyze the frequency of occurrence required, economic viability and implementation time. The barriers were identified, listed and classified as "BA" Current Allocated Barriers and "BP" Barriers proposed. Three barriers priority were suggested to be implement: new fire extinguishers, emergency exit signaling and safety training. This work based to alert and prevent the laboratory users about the latent existing risks. But, to propose some preventive barriers mentioned above, the causal scenario had been drafted and analyzed.

Research analysis of the existent risks in the laboratory of chemistry was carried out with the objective of finding solutions to alert, sensitize and to let the users aware of these kinds of risks. The culture of risk prevention must be disseminated in these types of environments. This paper addresses the need to view college laboratories as a workplace where there are risks and it cannot be ignored.

All of risks found need a constant management to evident new priorities and implementing continuously a safety philosophy, training and other actions. The risk management is fundamental to ensure a safe environment for all users. The methodology used perform a satisfactory structuring of the steps to identify, analyze and reduce risk in the laboratory. We believe that safety instruction is so important that it should be included in all chemistry laboratory courses.

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