DEVELOPMENT OF A SYSTEMATIC METHODOLOGY TO SELECT HAZARD ANALYSIS TECHNIQUES FOR NUCLEAR FACILITIES

Vanderley de Vasconcelos, vasconv@cdtn.br
Sérgio Carneiro dos Reis, reissc@cdtn.br
CDTN/CNEN – Caixa Postal 941, CEP 30161-970, Belo Horizonte, MG, Brazil

Antônio Carlos Lopes da Costa, aclc@cdtn.br
CDTN/CNEN – Caixa Postal 941, CEP 30161-970, Belo Horizonte, MG, Brazil

Elizabete Jordão, bete@feq.unicamp.br
FEQ/UNICAMP – Caixa Postal 6066, CEP 13083-970, Campinas, SP, Brazil

Abstract. *In order to comply with licensing requirements of regulatory bodies risk assessments of nuclear facilities should be carried out. In Brazil, such assessments are part of the Safety Analysis Reports, required by CNEN (Brazilian Nuclear Energy Commission), and of the Risk Analysis Studies, required by the competent environmental bodies. A risk assessment generally includes the identification of the hazards and accident sequences that can occur, as well as the estimation of the frequencies and effects of these unwanted events on the plant, people, and environment. The hazard identification and analysis are also particularly important when implementing an Integrated Safety, Health, and Environment Management System following ISO 14001, BS 8800 and OHSAS 18001 standards. Among the myriad of tools that help the process of hazard analysis can be highlighted: CCA (Cause-Consequence Analysis); CL (Checklist Analysis); ETA (Event Tree Analysis); FMEA (Failure Mode and Effects Analysis); FMECA (Failure Mode, Effects and Criticality Analysis); FTA (Fault Tree Analysis); HAZOP (Hazard and Operability Study); HRA (Human Reliability Analysis); Pareto Analysis; PHA (Preliminary Hazard Analysis); RR (Relative Ranking); SR (Safety Review); WI (What-If); and WI/CL (What-If/Checklist Analysis). The choice of a particular technique or a combination of techniques depends on many factors like motivation of the analysis, available data, complexity of the process being analyzed, expertise available on hazard analysis, and initial perception of the involved risks. This paper presents a systematic methodology to select the most suitable set of tools to conduct the hazard analysis, taking into account the mentioned involved factors. Considering that non-reactor nuclear facilities are, to a large extent, chemical processing plants, the developed approach can also be applied to analysis of chemical and petrochemical plants. The selected hazard analysis techniques can support cost-effective decisions about design alternatives to detect, control and mitigate risks, looking for ways of improving safety, reliability and environmental quality.*

Keywords: *hazard analysis, risk assessment, nuclear facilities, methodology*

1. INTRODUCTION

Risk assessment of an activity includes the identification of hazards that could result in unacceptable consequences to people, properties, and environment. Within the licensing process, in Brazil such assessment is required by both competent environmental bodies and CNEN (Brazilian Nuclear Energy Commission). The environmental bodies require a Risk Analysis Study of all facility or activity that has the potential of harming the environment (CETESB, 2003, and FEPAM, 2001, for instance). On the other hand, inside the Safety Analysis Reports required by CNEN an accident risk analysis shall be presented (CNEN, 2002, and USNRC, 1974).

In addition to licensing purposes, hazard identification and analysis play an important role in the implementation of Integrated Safety, Health, and Environment Management Systems following BS 8800, OHSAS 18001, and ISO 14001 standards. The main purpose of this analysis is to help decision makers on improving safety and reducing risks. Once a potential accident has been identified, corrective actions to prevent it are proposed and, if feasible, implemented (Chaib, 2005).

A systematic approach that identifies all accident scenarios for a particular facility does not exist because even after the application of the best efforts, there will be the likelihood of occurrence of unidentified accidents. There are a myriad of tools that can be employed to help this task. The choice of a particular technique or a combination of techniques depends on many factors, including motivation of analysis, available data, complexity of the processes, expertise of the involved team, and initial perception of the involved risks, among others (USNRC, 2001). This paper presents a systematic methodology proposed to facilitate the selection of a suitable set of hazard analysis techniques, structured into a single decision tree. Risk concepts and terminology, as well as a brief description of the mentioned hazard analysis techniques are also presented.

2. RISK CONCEPTS AND TERMINOLOGY

As sciences analyzing and describing risks are relatively new and developing, there are ambiguities in the use of terms, both between different risk sciences and between different parties involved in risk debates. At the scope of the present paper, the following risk concepts and terminology are adopted. These concepts and terminology are based on Christensen et al. (2003) and WHO (2004), if not otherwise indicated.

- *Risk*: expresses the combination of the probability of an undesired event and its consequence.
- *Risk source*: activity, condition, energy or agent potentially causing unwanted consequences or effects.
- *Hazard*: inherent property (or properties) of a risk source potentially causing consequences or effects. Hazard does not include the probability of an adverse outcome, which is the main difference from the risk term.
- *Accident*: an unforeseen or unintentional happening that causes injury, damage, or loss.
- *Hazard identification:* systematic investigation of the possible hazards associated with a facility, particularly the identification of the hazards of chemicals, radioactive materials, or energy that can cause injury or death to people or damage to property or environment through the release of these agents in the event of an accident.
- *Hazard analysis (HA)*: systematic identification of potential hazards and critical accident scenarios associated with hazardous materials or activities. A comprehensive HA should be able to eliminate or control process hazards during the life cycle of the plant. Engineering and administrative measures that are in place to control process parameters, and how these controls are degraded by technical failures, human failures or external events to lead to undesired events should be considered in this type of analysis.
- *Risk estimation*: refers to the technical assessment of the nature and magnitude of a risk. It involves basically the answers to three questions: What can go wrong? How frequently does it happen? What are the consequences? Fig. 1 illustrates the entire process of risk estimation including the scenario identification, as well as the quantification of scenario frequency and consequences (Stamatelatos et al., 2002).

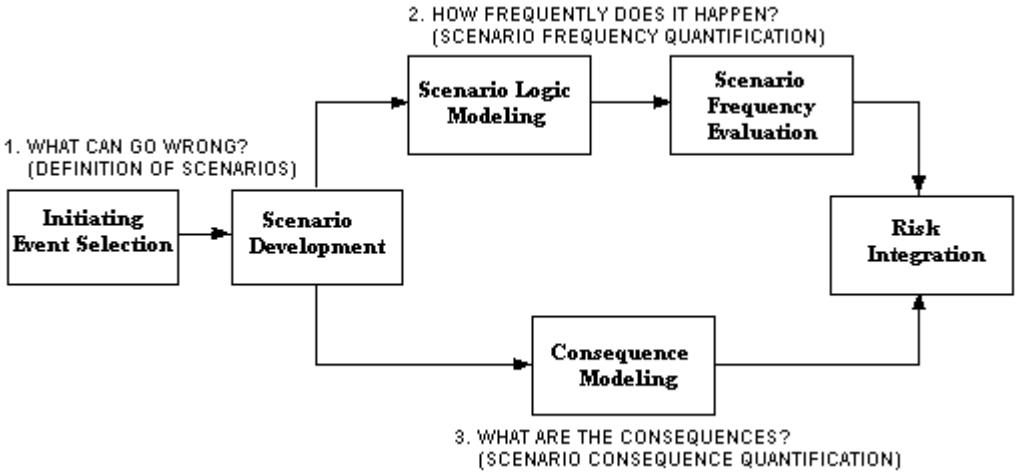


Figure 1. Process of risk estimation through the evaluation of scenario frequency and consequences (Stamatelatos et al., 2002)

- *Risk assessment*: includes those functions, as well as methods to best use the resulting information from risk estimation. In this paper it is used as synonym of risk analysis and includes methods for hazard identification, risk estimation, determining the significance of a risk, and communicating risk information.
- *Risk management*: systematic application of management policies, procedures and practices to the tasks of establishing the context, identifying, analyzing, planning and managing risks in a way that will enable organizations minimizing loss and maximizing opportunity in a cost-effective way. The risk management process includes the activities of identifying, analyzing, planning and managing the risk.
- *Quantitative Risk Assessment (QRA)*: quantitative evaluation of risk using probability theory. The probability of accidents and resultant risk levels should reflect the level of design, and the operational and organizational controls available at the plant. Uses intensively probabilistic tools, like fault trees and event trees, as well as accident modeling.
- *ALARP*: a principle ("As Low as Reasonably Practicable") usually applied to risks in some areas as radiation protection and chemical accident prevention, preparedness and response that fall below a defined level of "intolerable" risk. This principle recognizes that not all risk can be eliminated; there will be always a residual risk of an accident since it may not be practicable to take further actions to reduce the risk or to identify the potential accidents.

- *Failure mode*: a symptom, condition, or a way in which a component, equipment or system fails. A mode might be identified as a loss of function, premature function, out-of-tolerance condition, or an incipient failure mode observed during inspection.
- *Single failure events*: accidents that result from the failure of a single control or item.
- *Double contingency*: a principle of criticality control that states that process designs should incorporate sufficient safety factors to require at least two, unlikely, independent, and concurrent changes in process conditions before a criticality accident is possible (USDOE, 2007).

3. OVERVIEW OF HAZARD ANALYSIS TECHNIQUES

Hazard Analysis (HA) by itself does not identify hazards or failure mechanisms that cause accidents, but provides opportunities for the team conducting the study to use their knowledge and experience. Once the accident sequences have been identified, corrective actions to prevent them will be possible. Among the most common hazard evaluation tools that can support the team in analyzing process systems and identifying potential accidents can be highlighted (Borysiewicz et al., 2003, and Lees, 1996):

- *ETA (Event Tree Analysis)* - It is a technique that uses a graphical logic model that identifies and quantifies possible outcomes following an initiating event. It is a kind of decision tree that provides a logical framework for determining and quantifying the sequence of events that can cause potential accidents. Event trees use inductive logic (normally binary) and are widely used in risk analysis in combination with fault trees. There are two different applications which lead to the development of pre-accident and post-accident event trees, respectively. Event trees starting with an initiating event and proceeding until the releasing of hazardous materials or another undesired consequence are called pre-accident event trees. Event trees starting with the releasing of hazardous materials or another undesired consequence and examining the development of the physical phenomena following the accident or actuation of engineering safety features are called post-accident event trees. Pre-accident event trees are employed for both evaluating the effectiveness of plant protective systems and operator actions after the occurrence of the initiating event. Post-accident event trees are employed for evaluating the different types of accident outcomes that might arise, for instance, after a release of hazardous materials. Of course, post-accident event trees can be appended to corresponding branches of pre-accident trees, providing an overview of all unsafe plant states.
- *FTA (Fault Tree Analysis)* - It is a technique used for estimating the frequency of a hazardous incident (called the top event) through a logic model of the failure mechanisms of the system. The analysis is initialized with the selection of an undesired top event and then tracing back to the possible causes, which can be component failures, human errors or any other events that can lead to the top event. This procedure proceeds systematically, identifying the sub-events that are the immediate precursors to the top event, the immediate precursors to the sub-events, and so on, until the basic events that are the primary causes of the top event be reached. Then, it is possible to estimate the frequency or the probability of occurrence of the top event though the logical combination of the primary events, using concepts of Boolean algebra and probability theory. The fault trees can also be evaluated qualitatively through the determination of minimal the cut sets, that is, the minimal combination of primary events that can lead to the top event. The fault tree is not a model of all system failures or possible causes for system failure because it only includes events that will contribute to the top event. One of the most important by-products of the FTA is the gain of knowledge about the process, system, or facility. This can be very useful during the subsequent steps of hazard analysis.
- *CCA (Cause Consequence Analysis)* - It is a method that uses diagrams for seeking the possible outcomes arising from the logical combination of selected input events or states. This technique combines the ability of fault trees to show the way various factors may combine to cause a hazardous event with the ability of event trees to show the possible outcome. Sequence and time delays can be illustrated in the consequence part of the diagrams. Logical symbols similar to that used in fault trees are used in cause consequence diagrams. This technique has the power to analyze a system subject to sequential failures. CCA diagrams are not as widely used as fault trees or event trees, possibly because these later techniques are easier to follow and so tend to be preferred for performing analysis of separate parts of processes or facilities.
- *CL (Checklist Analysis)* - It is a technique used to identify hazards and examine compliances with applicable standard procedures or codes of practice. Checklists are applicable to management systems in general and to a design throughout all its stages. The checklist must be appropriate to the stage of the project, starting with checklists of basic materials properties and process features, continuing on to checklists for detailed design and ending with operations audit checklists. Checklists should be used for the purpose of checking that nothing had been neglected. They are, of course, limited to the experience base of their authors. Qualitative results from this analysis may vary with the specific situation, including the knowledge of the process, system or facility.
- *WI (What If Analysis)* - It is a method of hazard identification that reviews a process design by asking a series of questions beginning with What If? The method is a team exercise and typically makes use of checklists, but

otherwise tends not to be highly structured. When used together with Checklist Analysis the method it is called What If/Checklist Analysis *(WI/CL)*.

- *SR (Safety Review)* - It is a walk-through on-site inspection that can vary from an informal routine visual inspection, with emphasis on housekeeping, to a formal comprehensive examination by a team with the appropriate background, responsibility and authority. In addition to providing an overall assessment of the safety of the process, system or facility, these reviews intend to identify plant conditions or operational procedures that could lead to accidents. This type of analysis includes a systematic on-site inspection of equipments, process facilities and safety systems, as well as interviews with the staff associated with plant design and operation. Examination of available documents, as operational and maintenance procedures, accident reports, emergency plans and procedures, and quality manuals can be also carried out.
- *RR (Relative Ranking)* - It is a method that uses indices that assign penalties to process materials and conditions that can contribute to an accident, and credits according to plant features that can mitigate the effects of an accident. An index for a relative ranking of the plant risk is derived from the combination of penalties and credits. The method gives also qualitative information on equipments exposed to possible damage during accident propagation.
- *PHA (Preliminary Hazard Analysis)* - It is a method designed to recognize early hazards and focuses on hazardous materials and major plant systems during the early stages of life cycle of the plant, when only few details on the plant design and possibly no information about plant procedures may be available. The method consists of formulating a list of hazards related to the design details with recommendations to reduce or eliminate the hazards in the subsequent plant design phase. The results are qualitative with numerical estimation or prioritization.
- *HAZOP (Hazard and Operability Study)* - It is a systematic technique for identifying potential hazards and operability problems. It involves essentially a multi-disciplinary team which methodically brainstorms the plant design focusing on deviation from the design intention. The HAZOP procedure gives a full description of the process and systematically questions every part of it to discover how deviations from the design intent can occur. The consequences of these deviations are then determined and, if significant, remedial actions are recommended. The identification of potential hazards is carried out using a series of keywords to examine deviations in the process and their subsequent effects on the process as a whole. These keywords are used to ensure that the design is explored in every possible way.
- *FMEA (Failure Mode and Effects Analysis)* - It is a tool that aids in quantifying severity, occurrences and detection of failures, as well as guiding the creation of corrective action, process improvement and risk mitigation plans. It may be useful for: identifying design or process related failure modes before they happen; determining the effect and the severity of these failure modes; identifying the causes and the possibility of occurrence of the failure modes; quantifying and prioritizing the risks associated with the failure modes; and developing and registering action plans that will be implemented to reduce risk. Among the types of FMEA can be mentioned: *Design FMEA (DFMEA* - d*riven by part or component functions)* - a design part is a unit of physical hardware that is considered a single replaceable part with respect to repair. DFMEA is typically done later in the development process when specific hardware has been determined; *Process FMEA (PFMEA* - d*riven by process functions and part characteristics)* - a process is a sequence of tasks that is organized to produce a product or provide a service. A PFMEA can involve fabrication, assembly, transactions or services.
- *FMECA (Failure Mode Effects and Criticality Analysis)* - It is an extension of FMEA focusing on the quantitative parameters for the criticality assigned to each probable failure mode. The results highlight failure modes with relatively high probability and severity of consequences, allowing remedial effort to be directed where it will produce the greatest value. The typical goal, when FMECA is used as a design tool, is to eliminate failure modes with high severity and high probability, and to reduce as much as possible those with high severity or high probability. While FMEA is based on a qualitative approach, FMECA takes a quantitative approach assigning a criticality and a probability of occurrence for each given failure mode.
- *HRA (Human Reliability Analysis)* - Human reliability is the probability that a person will correctly perform some activity required by a system during a given time period without performing any extraneous activity that can degrade the system. A HRA produces the human action probabilities that are needed by a QRA. The accident sequence that is analyzed by a QRA is typically represented as an event tree. A node in the sequence of events that may lead to the accident represents a specific function, task, or activity that can have two different outcomes, usually denoted as success and failure. If the node represents the function of a mechanical or electronic component, the failure probability can, in principle, be calculated based on engineering knowledge alone. If the node represents the interaction between an operator and the process, engineering knowledge must be supplemented by a way of calculating the probability that the human, as a "component", will fail. The role of HRA is providing the foundations for calculating this probability.
- *PA (Pareto Analysis)* - It is a prioritization technique that identifies the most significant items among many. This technique uses the 80-20 rule, which considers that about 80 percent of the problems or effects are produced by about 20 percent of the causes. Then, the efforts should be prioritized in removing these causes. Although this

technique is very effective on identifying the most significant contributors to an activity or a problem, there are some limitations: it focuses only on the past, not considering potential problems; it is very influenced by the time required to perform the analysis and the way the data are grouped; and the quality of the analysis is completely dependent on availability of relevant and reliable data.

4. METHODOLOGY POR SELECTING HAZARD ANALYSIS TECHNIQUES

The selection of a HA technique depends on many factors including available data, motivation of analysis and results needed.

First of all, if quantitative information about hazards associated with the activity, process or facility is available, the Pareto Analysis is a tool that can be used to prioritize the most important hazards and guide the remainder of the analysis. After that, the motivation of the analysis and the results needed are the issues to be addressed. Fig. 2 shows the proposed decision tree that intends to help the task of choice of the suitable techniques for each combination of factors.

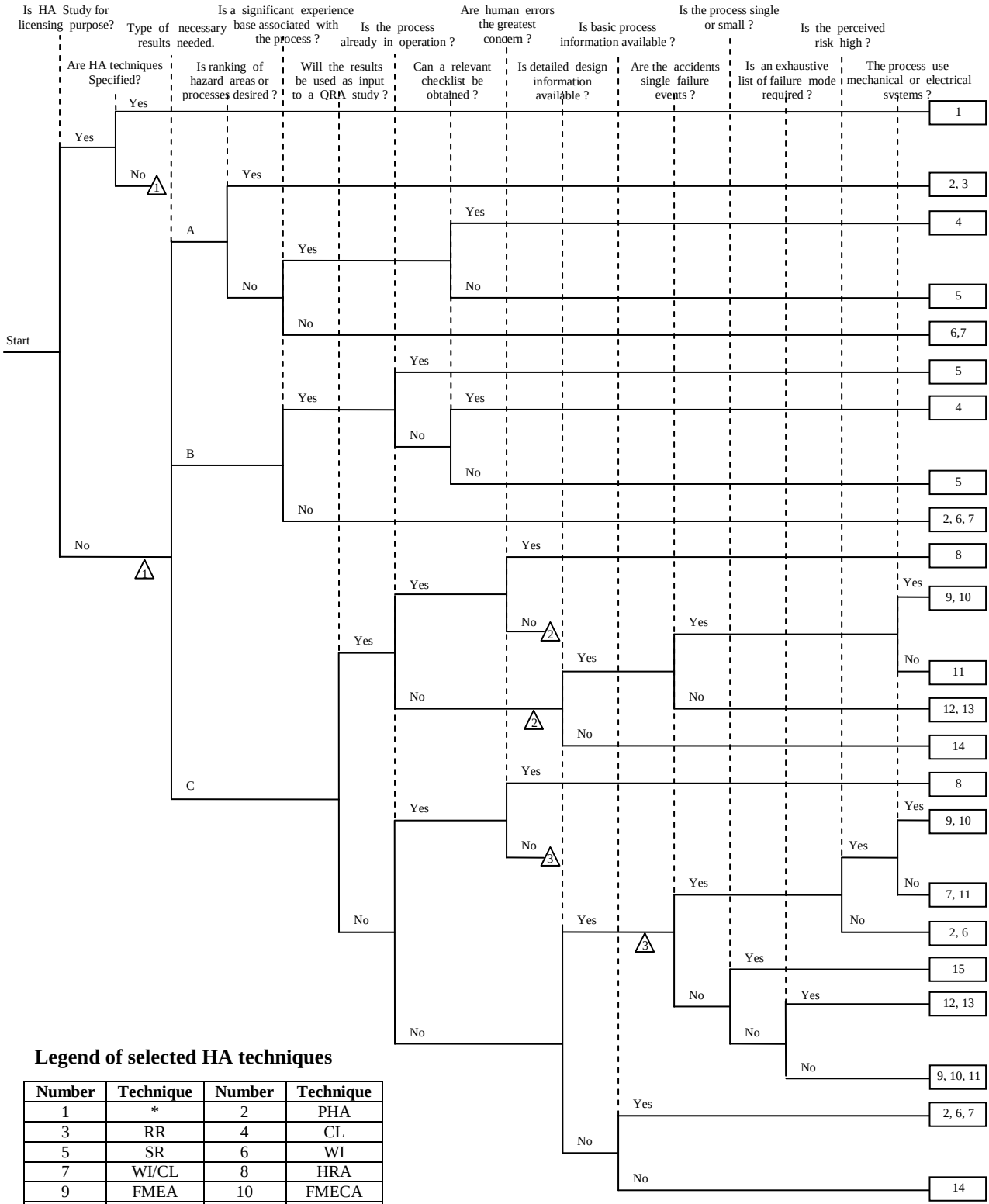
If the HA study will be carried out to meet licensing requirements, it will be needed to verify whether the use of specific HA techniques are prescribed by the regulatory bodies. Some environmental regulatory bodies, for instance, the State Environmental Sanitation Agencies of São Paulo and Rio Grande do Sul recommend through their Reference Terms to Risk Analysis Studies (CETESB, 2003, and FEPAM, 2001, respectively) the use of techniques like PHA, HAZOP, ETA and FTA, depending on involved risks. On the other hand, the nuclear licensing process conducted by CNEN is less prescriptive. In this case, the licensing process is nearly always carried out in a deterministic basis and the HA techniques are only used to support the process, for instance, in looking for the accident scenarios in a somewhat qualitative way (CNEN, 2002, and USNRC, 1974). Sometimes, specific Probabilistic Safety Assessments for certain systems or facilities are required and then the use of quantitative HA techniques like ETA, FTA or HRA are necessary.

The type of results needed in the analysis can be classified into three groups (USNRC, 2001):

- *Group A - Rough screening or general hazard list.* In this group are included process or facilities in the design phase and enterprises during the initial steps of licensing;
- *Group B - List of safety improvement alternatives.* In this group are included activities or facilities under safety review processes and implementation of Integrated Safety, Health, and Environment Management Systems;
- *Group C - List of specific accident situations plus safety improvement alternatives.* In this group are included accident investigation processes, development of Quantitative Risk Assessments, enterprises during the final steps of licensing, and processes that require human reliability studies.

At each group of results needed the following questions, if applicable, are answered, guiding the choice of the suitable HA techniques:

- ***Is ranking of hazards areas or process desired?***
  In general, when comparing design alternatives of safety systems it is necessary to make relative comparisons between areas or process considering their importance to the global risk of the facility. This can be carried out using PHA or RR techniques, based mostly on interviews, documentation reviews, and field inspections.
- ***Is there a significant experience base associated with the process?***
  The availability of relevant experience associated with the existing or similar processes, including length of experience, and operating and accident histories is a factor that influences the choice of the HA technique. If this experience does not exist, tools of general uses like WI, WI/CL or PHA should be chosen.
- ***Will the results be used as input to QRA study?***
  If the results will be used in QRA studies the applicable techniques are ETA, FTA, HAZOP, HRA, FMEA and FMECA. At nuclear fuel fabrication plants, because the potential of UF_6 release accidents with serious consequences, detailed quantitative analysis using ETA and FTA are recommended, especially to identify the need of redundant protection systems.
- ***Is the process already in operation?***
  If the facility is already in operation the operational experience should be taken into account mainly using SR and HRA techniques. In particular, engineering, maintenance, process operations, and quality audit experiences are data sources for the application of these tools. Depending on other factors, tools of more general uses like WI, PHA, or CCA can be employed, as can be seen in Figure 2.
- ***Can a relevant checklist be obtained?***
  If a relevant checklist is available or can be developed CL is a recommended tool. Depending on the features of materials, processes, systems, operations, or hazards, there are checklists of general use that can be applied. For instance, there are specific checklists for different types of processes or systems (chemical, physical, mechanical, biological, electrical, electronic, computer, etc.), different types of operations (transport, temporary, continuous, batch, etc.), or different types of hazards (toxicity, flammability, explosivity, reactivity, radioactivity, criticality, etc.).



Legend of selected HA techniques

Number	Technique	Number	Technique
1	*	2	PHA
3	RR	4	CL
5	SR	6	WI
7	WI/CL	8	HRA
9	FMEA	10	FMECA
11	HAZOP	12	FTA
13	ETA	14	**

* Use required HA technique

** Obtain adequate information before performing HA Study

Figure 2. Developed decision tree for selecting the suited Hazard Analysis (HA) techniques

- ***Are human errors the greatest concern?***
  If the processes include human actions and the human errors are the greatest concern, the recommended tool is HRA. Wherever exist administrative controls of manual operations of functions of crucial importance for safety, the human errors should be analyzed an evaluated since, in general, the human actions are not considered to be as reliable as the engineered safeguards.
- ***Is detailed design information available?***
  If a facility is at the detailed design or construction stage, specific information about the processes or equipments may be available. At this stage, often there is enough information for performing a detailed analysis of a wide range of hazards in order to identify the potential accident sequences. Then, FMEA, FMECA, HAZOP, FTA, ETA, or CCA can be used, depending on the required depth of analysis or complexity of the processes.
- ***Is basic process information available?***
  If the enterprise is at the early stages of its life cycle, for instance, at research and development, or conceptual design stages, only basic chemical or physical data from raw material or products may be available. At these stages, only tools like WI, WI/CL, or PHA, which give a broad identification and an overview of hazards, can be applied.
- ***Are the accidents single failure events?***
  For identifying single failure events, the recommended tools are WI, WI/CL, PHA, HAZOP, FMEA, or FMECA. For HA of a fuel fabrication plant, for instance, criticality accidents can be analyzed using WI. As criticality events are frequently perceived to be high risks, there are redundant controls to prevent them. Although WI technique is not an appropriate technique for analyzing redundant systems, it can be applied by considering separately the failures of the moderation and geometry control systems. In order to demonstrate the compliance with the double contingency principle, WI can be supplemented by FTA that is more suited to redundant systems.
- ***Is the process simple or small?***
  If a system or process is nor complex neither large, CCA is a suitable technique. An overall analysis of a complex system can be carried out through its division into several sub-systems to reduce complexity. In this case, care must me taken in order to avoid omission of domino effects or any kind of system interactions that could occur when analyzing the whole system.
- ***Is an exhaustive list of failure modes required?***
  Particularly in new designs at which safety alternatives are being analyzed and detailed information of basic items is available, the concurrent use of FTA and ETA is appropriated to generate an exhaustive list of failure modes of the process or facility. The minimal cut sets of the fault trees can be used as input data for detailed accident sequence analysis using the event trees.
- ***Is the perceived risk high?***
  If the process is not yet in operation but the perceived risk of the potential accident sequences is high, FMEA, FMECA, HAZOP or WI/CL are the recommended techniques that give an initial evaluation of the perceived risks. Because the presence of UF_6 and HF in nuclear fuel fabrication plants in many processes, the use of HAZOP technique is particularly suited for analyses involving potential hazardous chemical or criticality reactions in these facilities.
- ***Does the process use mechanical or electrical systems?***
  FMEA and FMECA are the suited techniques wherever extensive analyses of mechanical or electrical systems are required.

Overall, if at the end point of each branch of the decision tree it is noted that the adequate information for choosing the suited techniques are not available, it is recommended to stop the process of hazard analysis and look for the information necessary to take decisions along the tree before proceeding the process.

5. CONCLUSIONS

A single decision tree for helping the process of selecting hazard analysis techniques to be applied on nuclear facilities was developed. This tree is intended to be a systematic guiding that can be used directly by a team with experience and knowledge on hazard analysis techniques. It is also an algorithm that can be used as an input for implementing a computer system to facilitate this process. Moreover, considering that non-reactor nuclear facilities are, to a large extent, chemical processing plants, the developed approach can also be applied to the analysis of chemical and petrochemical plants. Finally, the selected hazard analysis techniques can support cost-effective decisions about design alternatives to detect, control and mitigate risks, looking for ways of improving safety, reliability and environmental quality.

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