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Risk assessment of uranium hexafluoride release from a uranium conversion facility by using a fuzzy approach

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ABSTRACT

Amongst the Industrial hazards, the release of toxic materials is of great importance to risk assessment of chemical industries. Uranium Hexafluoride (UF_6) under some circumstances could be a very dangerous material to human health and the environment and in the case of release may have catastrophic consequences. In this study, the probability of UF_6 release from a uranium conversion facility was analyzed by utilization of fault tree analysis (FTA) method. FTA is a well-known established technique in risk analysis of potential hazards. However, some shortcomings such as lack of reliability data are always a matter of concern in FTA application. To overcome this issue, expert elicitation and fuzzy set theory was applied. Results of the study showed the probability of 5.378E-4 for UF_6 gas release from the uranium conversion systems. Importance and sensitivity analyses have also been conducted to evaluate the percentage contribution of each component to the top event occurrence and to identify the weak points of the whole facility. Through the study, it was determined that the operator failure and lack of a reliable automatic shut-down system are the two main important reasons for UF_6 release.

1. Introduction

The objective of risk assessment in an industrial system is to predict what might happen, beginning with an undesired initiating event and ending with an undesired consequence. In other words, risk involves the potential occurrence from such accidents. FTA has been known as a powerful approach to calculate and analyze the risk in many engineering systems. FTA is a logical and diagrammatic method to evaluate the probability of an accident resulting from sequences and combinations of faults and failure events. In the present paper, FTA has been applied to evaluate the probability of UF_6 release from a uranium conversion facility. Uranium is the basic raw material for nuclear power plants (NPPs). For most of the world's NPPs, enriched uranium is required as fuel. The best known uranium chemical compound for enrichment process is UF_6 gas. At a conversion facility, uranium in the form of U_3O_8 known as yellowcake undergoes some complicated chemical reactions to be converted to UF_6 (Tsoulfanidis, 2013). UF_6 is a volatile white crystalline which sublimes at room temperature. As an alpha-emitter, the existing uranium in UF_6 compound is not especially hazardous unless ingested by the body. In UF_6 release accident, chemical hazard greatly exceeds radiation hazard. The ready reaction of UF_6 with moisture makes it a potentially hazardous substance. When it comes in contact with water, even traces, it reacts vigorously to form uranyl fluoride (UO_2F_2) and the corrosive and toxic gas hydrofluoric acid (HF). The corresponding chemical equation is as follows:

$$UF_6 + 2H_2O \rightarrow UO_2F_2 + 4HF$$

Even at very small concentrations, these fluoride compounds can be highly corrosive and cause lung inflammation, vomiting, pulmonary edema and mucous membrane irritations (IAEA, 2010). Thus, a comprehensive risk analysis of UF_6 release and the identification of its root causes seems vital.

To this end, FTA method has been applied in this research. Despite FTA merits, some shortcomings associated with the basic events (BEs) failure probabilities (FPs) exist. FTA uses exact or precise values of BEs to estimate the top event probability. However, sometimes and in some particular engineering systems due to the rare events or lack of reliability data, it is hard to obtain the exact values of FPs. To overcome this issue, we have to generate the data artificially. Expert elicitation and fuzzy set theory have been extensively applied into various risk analysis researches and yielded valuable results. For the first time, Onisawa (1989) introduced fuzzy set theory as a useful method to complement conventional

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reliability theories. Since then, there have been numerous researches on the development and application of fuzzy set theory and expert elicitation (Senol et al., 2015; Wang et al., 2013; Lavasani et al., 2015a; Shi et al., 2014; Purba, 2014a; Lu et al., 2015). As an example, Purba (2014b) developed a new methodology to evaluate the FP of nuclear power plants components through a fuzzy set approach and qualitative data processing. In some studies, the researchers showed that expert judgment in the form of qualitative natural languages are more appropriate for system reliability assessment when quantitative data is scarce or unavailable (Celik et al., 2010; Coletti and Scozzafava, 2004; Gupta and Bhattacharya, 2007; Hryniewicz, 2007). In a research by Renjith et al. (2010) fuzzy fault tree analysis (FFTA) has been performed for chlorine gas release from a chlor-alkali industry. In this study, for balancing the hesitation factor involved in expert elicitation, two-dimensional linguistic terms were applied. Lavasani et al. (2015b) used FFTA as a solution to analyze the leakage through permanently abandoned oil and natural gas wells. All researches mentioned above, indicate the capability of expert elicitation with fuzzy set theory for tackling the lack of data problem and its usefulness to complement the reliability data.

In this research, to provide the FPs of BEs, a combination of fuzzy set theory and traditional method is applied. For those components and subsystems such as valves, pumps, indicators, etc. in which their reliability data are available, mathematical formulation of FP functions are developed. By substituting the data in the functions, the FP of each corresponding BE is obtained. For the rest of the components and subsystems which their reliability data are unknown or for the undesired events which have never been occurred, their probability of failure or occurrence is obtained through the expert elicitation and fuzzy set theory. The purpose of this research is not only to calculate the release probability of UF_6, but also to identify the weak points of the whole system, evaluate the reliability of operators, classify the critical components through the importance measures and propose possible upgrades, improvements and useful recommendations.

2. Materials and methods

2.1. Fault tree construction

As mentioned before, in the present paper, FTA has been applied to assess the risk of UF_6 release from a uranium conversion facility. To construct a fault tree, the process starts from identification of a top event or higher faults to the more BEs. This part of process is so critical because every following event must be considered in terms of its effect upon that top event. So that, at the beginning, a hazard and operability analysis (HAZOP) was applied to identify the different types of failures affecting the systems and components. In next step, the fault trees are constructed according to the logical rules and the appropriate use of logic gates to show the relationship between the top event and the BEs. To solve the fault tree and to obtain the top event FP, there are numbers of methods including minimal cut sets, gate by gate technique and monte-Carlo simulation (U. S. Nuclear Regulatory Commission, 2012). Among these methods, the minimal cut sets (MCS) strategy, gives the analyst the capability to analyze the fault tree both qualitatively and quantitatively. The MCS are the specific and smallest combinations of BEs in which the simultaneous failure of all combinations cause the undesired top failure event to occur. In this paper, the MCS method is applied. In order to evaluate the FP of top event quantitatively, it is necessary to assign numerical values to all BEs. Normally, the values are obtained through the historical data collected during the lifetime of corresponding components. In some new design systems which their components have never failed before, there will not be sufficient historical data. Therefore, to deal with the lack or incompleteness of the reliability data, there is a necessity to use expert elicitation and fuzzy logic. The FPs of BEs are classified into two different groups. The first group is obtained through the generic data books or the technical-historical records existing in the facility and the second group is calculated through the expert judgment based on a fuzzy approach. Fig. 1 shows the frame work of the process.

2.2. Obtaining FPs through the data sources

In the case where quantitative reliability data is readily available, FPs of BEs could be calculated through the definition of unreliability functions. Unreliability is the probability that a system or component is not performing its required function at a given point in time or over a stated period of time when operated and maintained in a prescribed manner. There are different types of unreliability functions which are defined according to the operational role of components, their failure rates, types of maintenance and repairs and other reliability parameters (Modarres et al., 2009). The simplest model of unreliability is the constant FP which is independent of time (failure per-demand) and applied directly in reliability calculations. This model is usually employed for components with simple structure and design.

For systems and components that do not undergo repair and their failure rates are available, the unreliability function follow an exponential behavior and could be obtained by employing Eq. (1).

$$U(x) = 1 - e^{-\lambda t} \tag{1}$$

In the case where the value for λt is very small ($\lambda t < 0.1$), the Eq. (1) could be diminished to

$$U(x) = \lambda t \tag{2}$$

Where

$U(x)$ = Unreliability of the components
λ = The failure rate
t = The time interval for operation

The third model is defined for those components and systems that undergo repair and maintenance. The FP is obtained as follows:

$$U(x) = \frac{\lambda}{\lambda + \mu}\left(1 - e^{-(\lambda+\mu)t}\right) \tag{3}$$

Where μ is the corrective maintenance rate.

By some mathematical simplifications, Eq. (3) could be converted to Eq. (4).

$$U(x) = \frac{\lambda}{\lambda + \mu} \tag{4}$$

In most of complex industries, there are some systems which are reserved in standby mode. It means that they are not working at the time but would be in alert for emergency operations. The components of these systems are of the kind that must be inspected periodically due to the existence of hidden failures. In standby components, the unreliability term is replaced with unavailability. Unavailability contributions can be normally divided into two main categories as (Martorell et al., 2000):

1) Unavailability due to hidden failures.
2) Unavailability due to maintenance and repair downtimes.