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The role of situation awareness in accidents of large-scale technological systems

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ABSTRACT

In the last two decades, several serious accidents at large-scale technological systems that have had grave consequences, such as that at Bhopal, have primarily been attributed to human error. However, further investigations have revealed that humans are not the primary cause of these accidents, but have inherited the problems and difficulties of working with complex systems created by engineers. The operators have to comprehend malfunctions in real time, respond quickly, and make rapid decisions to return operational units to normal conditions, but under these circumstances, the mental workload of operators rises sharply, and a mental workload that is too high increases the rate of error. Therefore, cognitive human features such as situation awareness (SA)—one of the most important prerequisite for decision-making—should be considered and analyzed appropriately. This paper applys the SA Error Taxonomy methodology to analyze the role of SA in three different accidents: (1) A runaway chemical reaction at Institute, West Virginia killing two employees, injuring eight people, and requiring the evacuation of more than 40,000 residents adjacent to the facility, (2) The ignition of a vapor cloud at Bellwood, Illinois that killed one person, injured two employees, and caused significant business interruption, and (3) An explosion at Ontario, California injuring four workers and caused extensive damage to the facility. In addition, the paper presents certain requirements for cognitive operator support system development and operator training under abnormal situations to promote operators' SA in the process industry.

1. Introduction

In the early morning hours of December 3rd of 1984, more than 40 metric tons of methyl isocyanate (MIC) gas leaked into the air from a pesticide plant located in the region of Bhopal, central India and caused one of the worst industrial disasters in history. Several hundred thousand people in towns nearby were exposed to the chemicals, and approximately 3800 were killed immediately, at least 600,000 were injured, and at least 6000 have died since (Broughton, 2005). Three decades after the disaster, still high levels of contamination of toxic organic chemicals are found in the soil and water samples. The investigation of the disaster showed that on account of a series of mechanical and human errors in the production plant, water entered a tank containing a large amount of MIC, reacted exothermically and increased the temperature and pressure inside the tank, resulting in the release of MIC into the atmosphere. Although multiple factors including poor maintenance, the failure of safety systems and the substandard operating procedure have been identified as the

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underlying causes of the accident, the accident was officially blamed on human error as workers did not close the critical isolation valves before pipes were flushed with water and did not shut down the flare (Shrivastava, 1992).

The tragic event at Bhopal provides an extreme example of accidents in large-scale technological systems that have been attributed to human error. There are also several other accidents that show the difficulties of operators in working with complex systems or facing data overload. In fact, the majority of these accidents are caused by a combination of many factors which can be found in the lack of human factor considerations. Further investigation has revealed that of the human factors, operators' situation awareness (SA) is one of the most important prerequisite for decision-making (Endsley, 1995; Kaber and Endsley, 1998; Niu et al., 2009; Niu et al., 2013). Situation awareness describes how operators in dynamic complex systems develop and maintain a sufficient awareness of 'what is going on' in order to perform tasks successfully. Therefore, SA is likely to be at the root of many accidents in the process industry, where multiple goals must be pursued simultaneously, multiple tasks require the operator's attention, operator performance is under high time stress, and negative consequences associated with poor performance are anticipated (Naderpour et al., 2014b). In the case of the Texas City, TX BP Amoco Refinery explosion on 23 March 2005, where 15 workers were killed and 170 injured, several failures in control instrumentation and alarms caused an overfilled and over-pressurized tower to discharge a large quantity of flammable liquid into the atmosphere. The control room operator could not maintain good SA when monitoring this complex, dynamic environment, and an ignition created one of the worst industrial disasters in recent US history (Pridmore, 2007).

Today in many large-scale technological systems, operators are moved to a control room far away from the physical process, where automated systems pass more and more information to them. In fact, the automated systems and their over-deployment have changed the nature of operators work. In the past, the systems were analogue and a casual visit at the plant site was sufficient to monitor the progress and production of plants (Nazir et al., 2014c). Operators now must be alert in order to monitor, assess, and understand the incoming information from various sources and act/react accordingly. The decisions made by operators define the outcomes of possible abnormal situations, near misses, or even accidents. A recent report shows that the loss of abnormal situations cost 20 billion USD for US process plants every year. Among the attributes triggering these abnormal situations the contribution of human errors has been found to be 50% (Walker et al., 2011).

This paper highlights the role of SA in three process accidents in recent US history taken from Chemical Safety Board (CSB) investigation reports (www.csb.gov), and presents certain requirements for improving operators' SA. The accidents include a runaway chemical reaction which occurred at a methomyl production facility, an explosion at an open top tank located in a chemical mixing area, and an explosion at an ethylene oxide sterilization facility. The accidents were formally investigated by CSB and directly blamed on human error; however, the role of SA remained unexplained which was intriguing for authors to investigate in this paper. The investigation reports provide sufficient real data, information, and other material from these safety-critical environments than can help human factor analysts to conduct proper analyses. All of these are done in the following sections by (a) an introduction to SA and distributed SA in the process industry, (b) an accident analysis methodology, (c) three process accident analyses, (d) an overview of the requirements to maintain and promote SA in large-scale technological systems, and (e) concluding remarks.

2. Situation awareness and process industry

To date, several SA models have been developed; however, Endsley's three-level model has undoubtedly received the most attention. This model describes SA as "the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning and the projection of their status in the near future" (Endsley, 1995). The three-level model describes SA as an internally held product, comprising three hierarchical levels that is perception, comprehension, and projection, that is separate from the processes called situation assessment, used to achieve it. Operators actively try to construct a coherent, logical explanation to account for their observations. This cognitive activity involves two related concepts: the mental model and the situation model. Mental models refer to mechanisms whereby humans are able to generate descriptions of system purpose and explanations of system functioning. Mental models embody stored long-term knowledge about the systems that can be called upon during interaction with the relevant system when needed. A situation model is described as a schema depicting the current state of the mental model of the system. Endsley believes that the situation model provides a useful window on the broader mental model (Endsley, 2000a,b).

Kaber and Endsley (1998) believe that many of the performance and safety problems that currently occur in the process control arena are the result of difficulties with operators' SA. The analysis of offshore drilling accidents has revealed that more than 40% of such accidents are related to SA, and that the majority of those SA errors (67%) occurred at the perceptual level, 20% concerned comprehension, and 13% arose during projection (Sneddon et al., 2013). Nazir et al. (2012) highlight the importance and significance of SA for Field Operators and Control-Room Operators in the process sector and identify the major factors that influence their SA. Naderpour et al. (2014c) highlight the role of SA in performance of process operators when they confront abnormal situations and propose a method to model the operators' mental models about such situations using Bayesian networks (Naderpour et al., 2015). They then developed a cognition-driven SA support system to assist operators in safety critical environments (Naderpour et al., 2014b).

Today, in the process industry, the overall performance of systems depends on coordinated work among individuals that have responsibility for different subsets of goals, different access to data, and different situation perspectives. Therefore, there is a growing interest in understanding the cognitive and collaborative factors that enable such teams to work effectively (Roth et al., 2006). Thus, the concepts of team SA and shared SA are equally important in this regard. The degree to which every team member possesses SA on these elements for task performance is team SA (Kaber and Endsley, 1998). Thus, the success or failure of a team depends on the success or failure of each of its team members. In contrast, shared SA is defined as the degree to which team members possess the