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Review

Accident management support tools in nuclear power plants: A post-Fukushima review

Mahdi Saghafi, Mohammad B. Ghofrani*

Department of Energy Engineering, Sharif University of Technology, Azadi Street, Tehran, Iran

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ABSTRACT

In stressful situations such as severe accidents in nuclear power plants, operators need support tools to ease decision making in the selection of accident management measures. Following the Three Mile Island (TMI) accident in 1979, the first severe accident in a nuclear power plant, Accident Management Support Tools (AMSTs) were extensively developed and installed in a number of nuclear power plants. Lessons learned from the Fukushima accident highlighted the importance of accident management in mitigation severe accidents and suggested the reconsideration of accident management programs, which in turn created the need for AMSTs adaption and modernization.

This paper provides the first post-Fukushima comprehensive review of AMSTs, covering the particularities of all their elements, unlike other previous review papers which are limited to the study of individual fields, such as fault detection or decision-making support. Applications, advantages, and disadvantages of various methods which can be used in the design of AMSTs are investigated, categorized and compared in general well-known categories (Artificial neural networks, fuzzy logic, etc.). Moreover, human factor related issues in implementation of AMSTs are introduced and discussed. It was concluded that a modern AMST can provide vital information about the plant states, e.g. timing of critical events and a quantitative estimation of important parameters, which cannot be provided by typical Severe Accident Management Guidelines (SAMG). Nonetheless, it is emphasized that AMSTs should only have a supporting role in accident management, not replace SAMG.

1. Introduction

Accident management is defined as a set of actions during the evolution of a Beyond Design Basis Accident (BDBA[1]) in Nuclear Power Plants (NPPs): (1) to prevent escalation of the event into a severe accident, (2) to mitigate the consequences of a severe accident, and (3) to achieve a long term safe stable state (IAEA, 2004). A severe accident is more severe than Design Basis Accidents (DBA) and can lead to significant core degradation (IAEA, 2007). BDBAs are usually caused by one of the following reasons (Andreeva et al., 2008):

1. Unfavorable development of a DBA as a result of additional system failures, or human error,
2. Beyond design basis combination of failures or/and human error,
3. A low frequency initiating event for which corresponding safety systems have not been foreseen in the design.

Acronyms: AMST, Accident Management Support Tool; ANN, Artificial Neural Network; BDBA, Beyond Design Basis Accident; CHLA, Candidate High Level Action; DBA, Design Basis Accident; EOP, Emergency Operation Procedure; EU, European Union; FDD, Fault Detection and Diagnosis; HSI, Human-System Interface; LOCA, Loss Of Coolant Accident; MCR, Main Control Room; NPP, Nuclear Power Plant; PDS, Plant Damage State; PRA, Probabilistic Risk Assessment; RBF, Radial Basis Function; SAM, Severe Accident Management; SAMG, Severe Accident Management Guideline; TMI, Three Mile Island; TSC, Technical Support Center; USNRC, United States Nuclear Regulatory Commission.

* Corresponding author.
E-mail address: ghofrani@sharif.edu (M.B. Ghofrani).

[1] Postulated incidents and accidents in NPPs are divided into three categories according to their frequency of occurrence and severity: Anticipated Operational Occurrences (AOO), Design Basis Accidents (DBA) and Beyond Design Basis Accidents (BDBA) including severe accidents. By changing design requirements and allocation of safety systems for the beyond design basis accidents, IAEA replaced "beyond design basis accident" by "design extension condition" recently (IAEA (2012), Safety of nuclear power plants: design. Specific safety requirements. International Atomic Energy Agency, Vienna.). But "beyond design basis" phrase widely has been used in the safety related literature, therefore it is used here too.

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The BDBA category (including severe accidents) is related to the fourth level of defense in depth concept in NPPs safety. Safety requirement for this level is to control severe plant conditions, including prevention of accident progression and mitigation of the consequences (INSAG, 1999). The objective of the fourth level is to ensure that both the probability of severe accidents and the magnitude of radioactive releases are kept as low as reasonably achievable (IAEA, 2003). Three Mile Island (TMI), Chernobyl, and Fukushima accidents belong to the severe accidents category.

Similarly, Severe Accident Management (SAM) is a subset of accident management measures and is designed to: (1) terminate core damage once it has started, (2) maintain capability of the containment as long as possible, (3) minimize on-site and off-site releases, and (4) to return the plant to a controlled safe state (IAEA, 2003).

From a core damage perspective, accident management measures are divided into two categories: Emergency Operation Procedure (EOP) and Severe Accident Management Guideline (SAMG). Accident management measures belong to the EOP category before significant core damage and to the SAMG afterward (Fig. 1). The main priority of EOP is to prevent fuel damage, while, the main purposes of SAMG are protection of the containment and mitigation of severe radiological consequences (Andreeva et al., 2008). In the preventive domain, operators have to follow EOPs line by line; while in the migratory domain, actions in SAMGs are selected based on observed symptoms of NPPs with no predetermined order.

SAM measures have both positive and negative impacts on either the progression or consequences of the accidents. The impacts depend on the Plant Damage State (PDS) when the measure is implemented, and the magnitude of the impacts changes as the accident progresses (Huh et al., 2012). Therefore, a decision-making process is required for weighing the pros and cons of implementing SAM measures.

Management of abnormal situations in a safety-critical environment such as severe accidents in NPPs needs to be supported by a cognitive perspective to reduce operators' workload, stress, and consequent error rate (Naderpour et al., 2014). A correct understanding of the situation, as one of the important cognitive activities, is a vital factor in improving performance and reducing errors. Accident Management Support Tools (AMSTs) aid Main Control Room (MCR) operators or Technical Support Center (TSC) staff in selection of suitable accident management measures to prevent or mitigate severe consequences of postulated accidents.

This paper presents a review of methods for AMSTs design and their applications in NPPs. It is predicted that design and application of AMSTs are going to be reaccelerated with the lessons learned from the Fukushima accident.

The rest of this paper is arranged as follows. In Section 2, the lessons learned from the Fukushima accident related to accident management are briefly reviewed. In Section 3, after an introduction to the general structure of AMSTs, principles of methods and techniques for designing different parts of AMSTs are presented. Then characteristics of each method for AMSTs design are compared and summarized. Finally, Section 4 includes a brief summary and conclusion.

2. Lessons learned from Fukushima accident in severe accident management

The great Japan earthquake on March 11, 2011 caused a series of large tsunami waves that led to the Fukushima accident (IAEA, 2011). In that accident, in operation units of Fukushima Dai-ichi NPP were successfully shut down by the earthquake scram signal, but then tsunami waves hit the NPP and caused a complete loss of electrical power supply to the NPP, both onsite and offsite (station blackout), resulting in severe core damage. Similar to the lessons learned from Chernobyl (NRC, 1987) and TMI (NRC, 1979), the lessons learned from the Fukushima accident were investigated and published (AESJ, 2011; Dautray and Brézin, 2012; Headquarters, 2011; Hirano et al., 2012; IAEA, 2011; Kurokawa et al., 2012; Miller et al., 2011; Repussard and Schwarz, 2012; Saghafi and Ghofrani, 2015; Urabe et al., 2014), in which the lessons relating to accident management compromised a considerable share. Modification in accident management programs and related safety systems, which can generally affect the design and applications of AMSTs, are summarized as follows:

- An active tsunami warning system should be established with the provision for immediate operator action (IAEA, 2011). With early notification of external natural hazards, accident management measures can be planned using the predictions of AMSTs.
- For severe situations, such as total loss of off-site power, loss of all heat sinks, or engineering safety systems, simple alternative sources for these functions including any necessary equipment (such as mobile power, compressed air and water supplies) should be provided for SAM (IAEA, 2011). These alternatives should be considered in the design of AMSTs with sufficient flexibility to support decision making.
- Emergency response centers should have access, as far as practicable, to essential safety related parameters such as coolant levels, containment status, pressure, etc. (IAEA, 2011). AMST placed in emergency response centers can benefit from a

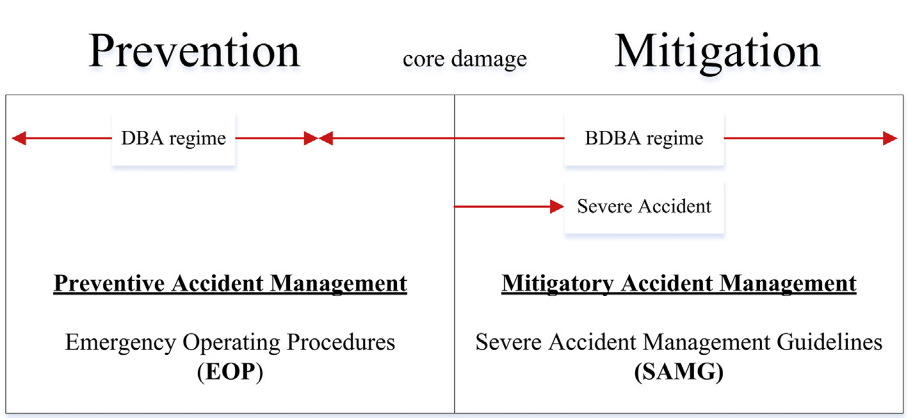

Fig. 1. EOPs and SAMGs application domain in accident management.