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iROCS: Integrated accident management framework for coping with beyond-design-basis external events

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HIGHLIGHTS

- An integrated mitigating strategy to cope with extreme external events, iROCS, is proposed.
- The strategy aims to preserve the integrity of the reactor vessel as well as core cooling.
- A case study for an extreme damage state is performed to assess the effectiveness and feasibility of candidate mitigation strategies under an extreme event.

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ABSTRACT

The Fukushima Daiichi accident induced by the Great East Japan earthquake and tsunami on March 11, 2011, poses a new challenge to the nuclear society, especially from an accident management viewpoint. This paper presents a new accident management framework called an integrated, RObust Coping Strategy (iROCS) to cope with beyond-design-basis external events (BDBEEs). The iROCS approach is characterized by classification of various plant damage conditions (PDCs) that might be impacted by BDBEEs and corresponding integrated coping strategies for each of PDCs, aiming to maintain and restore core cooling (i.e., to prevent core damage) and to maintain the integrity of the reactor pressure vessel if it is judged that core damage may not be preventable in view of plant conditions. From a case study for an extreme damage condition, it showed that candidate accident management strategies should be evaluated from the viewpoint of effectiveness and feasibility against accident scenarios and extreme damage conditions of the site, especially when employing mobile or portable equipment under BDBEEs within the limited time available to achieve desired goals such as prevention of core damage as well as a reactor vessel failure.

1. Introduction

An extended loss of all electric power occurred at the Fukushima Dai-ichi nuclear power plant, on March 11, 2011, by a large earthquake and tsunami. This event led to a loss of reactor core cooling at several units of the site, and hydrogen was generated from the thermal oxidation reaction between the high-temperature fuel cladding and the steam of the reactor core. Consequently, the accumulated hydrogen was detonated inside the reactor building, and catastrophic failures have occurred at multiple reactors of the site, resulting in a large release of fission products into the environment (INPO, 2011; Investigation Committee, 2012; JANTI, 2011; ANS, 2012; NAS, 2014; KNS, 2013; Yang, 2014; Song and Kim, 2014).

Beyond-design-basis external events (BDBEEs) are natural extreme events that exceed the plant design basis. After the Fukushima Dai-ichi accident, the world nuclear society including operators and regulators have recognized that beyond-design-basis events can happen and must be prepared for in advance (Harter, 2014; Uhle, 2014). All EU nuclear power plants have conducted a comprehensive risk and safety assessment, so-called 'stress test', which is defined as targeted reassessments of the safety margins of nuclear power plants, against extreme natural events challenging the plant safety functions and leading to a severe accident (ENSREG, 2015). Through the stress test, each specific plant could identify its weak points and any cliff edge effects by the postulated extreme natural events, and could further find any provisions to prevent these cliff edge effects or increase its robustness through modification of hardware or procedures/guidelines, organizational preparedness, etc. (ENSREG, 2015).

In the U.S., even before the Fukushima Dai-ichi accident, they have already had the extensive damage mitigation guideline

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Nomenclature

ADV	atmospheric dump valve
AFST	auxiliary feedwater storage tank
AM	accident management
BDBEE	beyond-design-basis external events
CET	core exit temperature
CST	condensate storage tank
EDMG	extensive damage mitigation guidelines
EMEG	emergency mitigating equipment guidelines
EOP	emergency operating procedure
FLEX	diverse and flexible coping strategies
iROCS	integrated, RObust Coping Strategies
LLOCA	large loss of coolant accident
LOCA	loss of coolant accident
MCR	main control room
PDC	plant damage condition
PORV	power-operated relief valve
PSV	pressurizer safety valve
PWR	pressurized water reactor
RCP	reactor coolant pump
RCS	reactor coolant system
RVF	reactor vessel failure
SAG	severe accident guideline
SAM	severe accident management
SAMG	severe accident management guidelines
SBO	station blackout
SDS	safety depressurization system
SG	steam generator
SGTR	steam generator tube rupture
SHR	secondary heat removal
SIT	safety injection tank
SLOCA	small loss of coolant accident
SSC	structure, system, and component
TDAFW	turbine-driven auxiliary feedwater system

(EDMG) to maintain or restore core cooling, containment, and spent fuel pool cooling capabilities to cope with the loss of large areas of the nuclear facility due to large fires and explosions from any cause including beyond-design-basis aircraft impacts (USNRC, 2002; NEI, 2006). After the Fukushima accident, another set of mitigation strategies to cope with beyond design basis external events, diverse and flexible coping strategies (FLEX), were requested by the USNRC and are currently being implemented with developing FLEX Supporting Guidelines (FSGs) in most U.S. nuclear power plants (USNRC, 2012a; NEI, 2012). The USNRC near-term task force (NTTF) recommended strengthening and integrating the onsite emergency response capabilities such as emergency operating procedures (EOPs), severe accident management guidelines (SAMGs), and EDMGs. NEI 14-01 was issued to provide guidance for ensuring that EOPs, EDMGs, FSGs and SAMGs are integrated in a cohesive, effective and usable manner, and it also addresses recommendations for the development of accident or event mitigation and management guidelines, and command and control structures for responding to severe accidents and extreme events (NEI, 2014). In Canada, emergency mitigating equipment guidelines (EMEG), similar to FLEX, are being prepared in parallel with enhancements of SAMGs by reflecting the lessons learned from the Fukushima accident (Gilbert, 2014; Dermarkar, 2014).

In this way, the nuclear power plants nowadays require more strengthened accident management (AM) capability extending existing AM measures, in order to cope with BDBEEs such as the Fukushima Dai-ichi accident (Vayssier, 2012; Vayssier, 2014). The objective of this paper is to provide an integrated accident management framework to prevent core damage and maintain the reactor vessel integrity under BDBEEs. The strategy is called an integrated, RObust Coping Strategy (iROCS). The iROCS approach is characterized by the various plant damage conditions that might be impacted by BDBEEs, and corresponding integrated coping strategies aiming, firstly, to maintain and restore core cooling (i.e., to prevent core damage) and secondly, to maintain the integrity of the reactor pressure vessel if it is judged that prevention of core damage cannot be achievable considering the plant conditions. The iROCS approach will be extended to severe accident management (SAM) measures to preserve the containment integrity, but the present study will focus on achieving a long-term core cooling and maintaining the integrity of the reactor pressure vessel.

This paper is structured as follows. Section 2 introduces the overall framework of the iROCS approach including categorized plant damage conditions that might be impacted by BDBEEs. In Section 3, coping strategies for each categorized plant damage condition are delineated with an aim to maintain or restore core cooling, and to preserve the integrity of the reactor pressure vessel if the prevention of core damage is deemed not to be achievable within the time available, when considering plausible accident progressions. In Section 4, evaluations of candidate accident management strategies from the viewpoint of effectiveness and feasibility under an extreme damage condition are introduced with several insights for making accident management provisions more feasible and effective under an extreme event. Finally, discussion and conclusion from this study are made in Section 5.

2. Overall framework of the iROCS approach

This section provides an overall framework of the iROCS approach for maintaining and/or restoring core cooling and for preserving the integrity of the reactor pressure vessel under BDBEEs, and compares the concept of the iROCS approach with the other similar approaches such as EDMG and FLEX.

EDMG is developed to provide strategies and guidelines to maintain or restore core cooling, containment, and spent fuel pool cooling capabilities under the loss of large areas of the nuclear facility due to large fires and explosions from any cause including beyond-design-basis aircraft impacts (USNRC, 2002; NEI, 2006). Due to the nature of the security threat, prediction or predefinition of precise damage states is not possible and of little value in assessing and enhancing plant capabilities (NEI, 2006). Nevertheless, the guidelines for responding to the security threats are generally developed on the basic assumptions that include disruption of normal command and control structure, loss of access to the control room, loss of all personnel in the control room, loss of all AC and DC power required for the operation of plant systems, minimum site staffing levels, and so on. Therefore, most of the plant-specific EDMG start from establishment of initial command and control structure, and then local activation and control of the turbine-driven auxiliary feedwater system (TDAFW) and monitoring of plant status via local instrumentation measurements, by any available personnel at the plant or site, in addition to the reactor scram and turbine trip.

FLEX aims to provide indefinite coping capability to prevent damage to the fuel in the reactor and spent fuel pools and to maintain the containment function under both an extended loss of AC power (ELAP) and a loss of normal access to the ultimate heat sink (LUHS) which could arise following external events (NEI, 2012). In order to achieve the indefinite coping capability, FLEX provides a phased approach that utilizes installed equipment, on-site portable equipment, and pre-staged off-site resources. Similar to the EDMG, the baseline coping strategy of the FLEX starts with normal cooling and depressurization of the RCS by operation of the TDAFW