Case Studies to Quantify Safety Benefits of Disaster Robots

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1. Introduction

This paper discusses a new approach based on the probabilistic risk assessment (PRA) technique, which can be used to quantify safety benefits associated with disaster robots, along with a case study for seismic-induced station blackout condition (SBO) and loss of offsite power (LOOP). The results indicate that to avoid core damage in this special case a robot system with reliability > 0.65 is needed because otherwise core damage is inevitable. As a result, considerable efforts are needed to improve the reliability of disaster robots, because without assurance of high reliability, remote response techniques will not be practically used.

2. Methods and Results

This section discusses the case studies which demonstrate a significant risk reduction achieved by the robotic intervention.

2.1 Salient aspects and assumptions

Various types of accident mitigation actions might be performed by disaster robots in nuclear power plants in the case of extreme events causing hazardous environments. Example robotic actions include:

- Station blackout condition induced by a strong earthquake (e.g., a peak ground acceleration of about 0.2g to 0.3g) is used as the target scenario for which the robotic safety benefit will be evaluated.
- The conditional core damage probability (CCDP) for LOOP and SBO conditions is used as the risk metric in this analysis. If the spent fuel pool is considered along with the reactor core as a potential radiological source that may release radioactivity in the SBO condition, the conditional fuel damage probability could be used together with CCDP. However, the condition of the spent fuel pool is not considered in this simplified approach.
- An internal events PRA model for a pressurized water reactor (PWR) plant is used with an increase of all the human error probabilities (HEPs) and non-recovery probabilities in the target scenario by an order of magnitude to reflect the seismic condition. In performing a seismic PRA based on the internal events PRA model, a variety of different adjustments are typically made to the HEPs developed for analyzing the internal events [1, 2]. However, an increased factor of 10 is conservatively applied to the human error probabilities and non-recovery probabilities in this example.
- The earthquake might create harsh environments (e.g., high heat, humidity, contamination, radiation) and unforeseen situations beyond the scope of expectation and imagination. Hence, it is assumed that at least 5 to 6 hours will be needed for successful robotic interventions (i.e., deployment to the location where mitigating measures can be taken with subsequent execution of the mitigating actions).
- The risk associated with a loss of offsite power depends upon whether the plant is critical or shut down. It is assumed here that the plant was at power, as a LOOP presents a greater challenge to the plant in general if it occurs during at-power condition as opposed to shutdown state.
- In modeling the SBO condition, all the diesel generators dedicated to the unit (i.e., DG A and DG B in the case of the nuclear power plant used in this study) are conservatively assumed to fail due to the same failure mode, i.e., failure to start, and the potentials for not only double but also triple common cause failures (CCFs) to start among the three diesel generators (i.e., DG A, DG B and SBO DG) are accounted for in the risk quantification.

2.2 LOOP and SBO models

A typical event tree for loss of offsite power at a pressurized water reactor nuclear power plant is used, where the LOOP scenarios are modeled in terms of 13 top events representing safety functions and recovery of AC power [3, 4]. The first top event is 'Reactor Trip'. The upper branch under this top event represents a successful reactor trip (i.e., insertion of the control rods into the core), while the lower branch a failure of reactor trip, i.e., an anticipated transient without scram (ATWS). The ATWS scenarios are modeled in another subsequent event tree (i.e., transfer to ATWS event tree). The second top event in the event tree is 'Emergency Power', and the lower branch under it represents an SBO condition because of failures of all unit-dedicated diesel generators (i.e., diesel generators A and B in the PRA model used in this study) given a LOOP. The SBO scenarios are modeled in a separate event tree, where the use of the turbine-driven auxiliary feedwater pump with control power provided by the battery, the potential use of SBO diesel generator, etc. are modeled [3, 4].

2.3 Data modifications and important analysis

An earthquake of a presetting level is assumed to have occurred with the reactor tripped but the offsite power lost due to the seismic impact. Because an internal events PRA model will be used for quantification of the robotic interventions, the probabilities of human failure events and non-recovery events are increased by one order of magnitude or to the maximum probability of 1.0 to reflect the seismic condition in previous study of KAERI [4]. Table 1 also shows Importance analysis for human actions in seismic-induced SBO. The risk sensitivity analysis was performed for these two cases in SAPHIRE code [5]. The quantification of all LOOP sequences in the PRA model for these cases yield the following conditional core damage probabilities: 1) 7.06×10^{-1} in the case of no robotic intervention; and 2) 3.21×10^{-1} in the case of successful robotic intervention. Therefore, the risk of CCDP associated with the seismic-induced SBO condition is reduced by 55% if the robotic system succeeds to start and align SBO DG within 8 hours following the seismic-induced LOOP and subsequent failure of both dedicated diesel generators. The SBO condition exists at the plant until the SBO diesel generator is successfully connected to either of the safety buses. The underlying assumptions in this regard are that all these actions will be performed within 8 hours: 1) the robot system along with the SBO diesel generator can be brought to the connection point of the SBO DG to the plant electrical distribution system in order to provide emergency AC power; 2) if there are debris on the route, the debris will be removed by a debris-removal robot; 3) the robot for mitigation action will enter one of the electrical rooms and operate circuit breakers to strip unnecessary DC bus loads; and 4) fuel continues to be provided to the SBO DG until the emergency power from this equipment is not needed any longer.

Table 1: Importance analysis for human actions in seismic-induced SBO

Basic event	Description	FV	RAW	RRW
OEP-XHE-XL-NR08H	Operator fails to recover offsite power in 8 hr	9.92E−01	1.07E+00	8.96E+00
EPS-XHE-XL-NR08H	Operator fails to recover emergency diesel in 8 hr	9.92E−01	1.00E+00	8.96E+00
ACP-XHE-XM-ALT	Operator fails to start and align SBO DG	2.92E−01	1.06E+00	1.03E+00
OEP-XHE-XL-NR02H	Operator fails to recover offsite power in 2 hr	1.07E−01	1.01E+00	1.01E+00
EPS-XHE-XL-NR02H	Operator fails to recover emergency diesel in 2 hr	1.07E−01	1.00E+00	1.01E+00
AFW-XHE-XM-TDP	Operator fails to locally start TDP	4.61E−02	1.05E+00	1.00E+00
EPS-XHE-XL-SBORMC	Operator fails to recover room cooling to SBO DG	4.30E−03	1.00E+00	1.00E+00

DG, diesel generator; EPS, emergency power system; FV, Fussell-Vesely importance measure; RAW, risk achievement worth; RRW, risk reduction worth; SBO, station blackout; TDP, turbine-driven pump.

2.4 Quantification result of potential robotic interventions

A risk sensitivity analysis was carried out using SAPHIRE code [5] for the robotic intervention (i.e., the robotic system starts and aligns SBO DG) by evaluating the effects of varying the failure probability of the ACP-XHE-XM-ALT basic event on the CCDP risk metric. The conditional core damage probability is plotted as a function of the robotic mission failure probability in Fig. 1. As can be seen in this figure, the CCDP almost linearly increases as the robotic mission failure probability increases because the survivability of the SBO DG in the station blackout condition (i.e., failure of both dedicated DGs) predominantly drives the conditional risk.

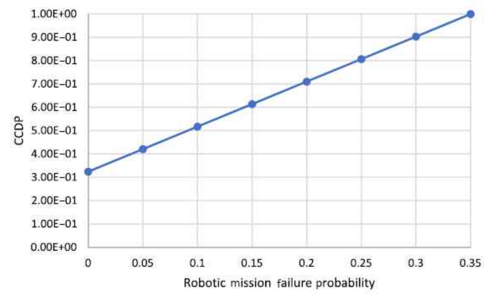

Fig. 1 Sensitivity analysis of robot intervention

From Fig. 1 one can observe the following, among others: (1) the failure probability of robotic intervention in the seismic SBO condition should be < 0.35; in other words, a robotic reliability of at least 0.65 is needed, because otherwise core damage is inevitable (namely, CCDP of 1.0) according to the PRA model. This is based on the presumption that a decision has been made to deploy a disaster robotic systemto perform themitigating action (e.g., due to harmful environments in the location where the mitigating measure needs to be taken); (2) in the case where a human operator tries to execute the mitigating action in the harsh environment, the CCDP is estimated to be 9.36×10^{-1}, because the human error probability in the seismic SBO condition is estimated to be as high as 0.2 due to the limited time available and high stress; (3) if the robotic system successfully performs the mitigating action (i.e., starting and aligning the SBO DG) in time, then the CCDP is reduced to 3.24×10^{-1} which is the CCDP value corresponding to the zero failure probability of robotic intervention, shown in Fig. 1; (4) note that failure of support systems (e.g., service water, DC power, DG room cooling) to the SBO DG, and all other potential failure mechanisms, are accounted for in the CCDP evaluation by the seismic PRAmodel; and (5) given that the accident situation is so serious that the human operator cannot access the area to execute themitigating action (i.e., a human error probability of ACP-XHE-XM-ALT is 1.0), then the PRA model yields a CCDP of 1.0, implying that core damage is certain to occur under such circumstances. One can see the benefit of remote response techniques in this case, because the possibility of core damage can be reduced to some extent if a robotic system is available to carry out the mitigating action.

The underlying assumptions in the risk sensitivity analysis are that all these actions will be performed within 8 hours: (1) the robotic system along with the SBO DG can be brought to the connection point of the SBO DG to the plant electrical distribution system in order to provide emergency AC power; (2) if there is debris on the route, the debris will be removed by a debris-removal robot; (3) the robot for mitigation action will enter one of the electrical rooms and operate circuit breakers to strip unnecessary DC bus loads; and (4) fuel continues to be provided to the SBO DG until the emergency power from this equipment is not needed any longer.

3. Conclusions

As part of the fundamental research in the robotics development program of KAERI [6], a risk sensitivity analysis was carried out. The result of the case study performed indicates that a robot systemwith reliability > 0.65 is needed in this special case to avoid core damage because otherwise core damage is inevitable. Therefore, considerable efforts are needed to improve the reliability of disaster robots because, without the assurance of high reliability, the remote response technique cannot be practically used [7].

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