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INTRODUCTION

On March 11, 2011, a magnitude 9.0 earthquake followed by a tsunami caused loss of offsite power and disabled the emergency diesel generators, leading to a prolonged station blackout at the Fukushima Daiichi site. After successful reactor trip for all operating reactors, the inability to remove decay heat over an extended period led to boil-off of the water inventory and fuel uncovery in Units 1-3. A significant amount of metal-water reaction occurred, as evidenced by the quantities of hydrogen generated that led to hydrogen explosions in the auxiliary buildings of the Units 1 & 3, and in the de-fuelled Unit 4. Although it was assumed that extensive fuel damage, including fuel melting, slumping, and relocation was likely to have occurred in the core of the affected reactors, the status of the fuel, vessel, and drywell was uncertain.

To understand the possible evolution of the accident conditions at Fukushima Daiichi, a Markov model [1] of the likely state of one of the reactors was constructed and executed under different assumptions regarding system performance and reliability. The Markov approach was selected for several reasons: It is a probabilistic model that provides flexibility in scenario construction and incorporates time dependence of different model states. It also readily allows for sensitivity and uncertainty analyses of different failure and repair rates of cooling systems. While the analysis was motivated by a need to gain insight on the course of events for the damaged units at Fukushima Daiichi, the work reported here provides a more general analytical basis for studying and evaluating severe accident evolution over extended periods of time. This work was performed at the request of the U.S. Department of Energy to explore “what-if” scenarios in the immediate aftermath of the accidents.

MARKOV MODEL DEVELOPMENT

The first step in developing a model is to provide a representation of the possible states of the core, vessel and containment and the transitions between these states. A generic model with damaged fuel inside the reactor vessel cooled by feed-and-bleed (F&B) was used as the initial state representing any of the damaged units. The core can be cooled by F&B, or preferably by a closed-loop recirculation system. Both cooling mechanisms are assigned approximate failure and repair rates based on engineering judgment, as shown in Table I. If cooling to the reactor vessel is lost for any reason, given the damaged core in-vessel and the then existing decay heat level (i.e. about 2 months after reactor scram), the core will melt and relocate to the bottom of the vessel, start to attack the bottom head and possibly penetrate the vessel to slump to the floor of the drywell. This will initiate the core-concrete interaction as the molten corium spreads on the drywell floor, leading possibly to drywell failure from a number of different mechanisms if no further injection occurs. The approximate timing of key events is based on analysis of a similar BWR reactor for which severe accident evaluations were performed several years ago [2], and is shown in Table I. Table I also shows worst and best cases, which were used for sensitivity studies, for the various parameters. These sensitivity calculations address the uncertainty of the then current status of the core and the water level in the timing of the key events in the accident progression, and the use of very approximate estimates for failure and repair rates of the cooling systems.

Table I. Key Transition Rates for In-Vessel Markov Model Development

	Reference case	Worst case	Best case
Recir. failure	500	100	900
Recirc. Recovery	45	60	30
F&B failure	60	30	150
F&B recovery	1	5	0.25
Fuel to bottom head	1.63	1	3
Fuel outside vessel	0.19	0.1	1

The basis for the in-vessel Markov model is shown in Figure 1. The transition rates [1] between events or states shown in this figure are derived from Table I.

The loss of F&B cooling triggers another node that can then progress on to other nodes representing more severe events in the accident progression, or not, depending on the competition between restoration of F&B and the timing of core degradation, melt and slump events. After recirculation cooling is established, F&B cooling with venting would become a backup cooling system to prevent core melt and vessel breach scenarios. This is shown in Figure 1 in the lines connecting the various nodes that depict transitions from one state to another. The failure and repair rates, as stated earlier, are approximate, to allow the model to be run and provide intuitively useful results that give confidence in the basic setup of the model.

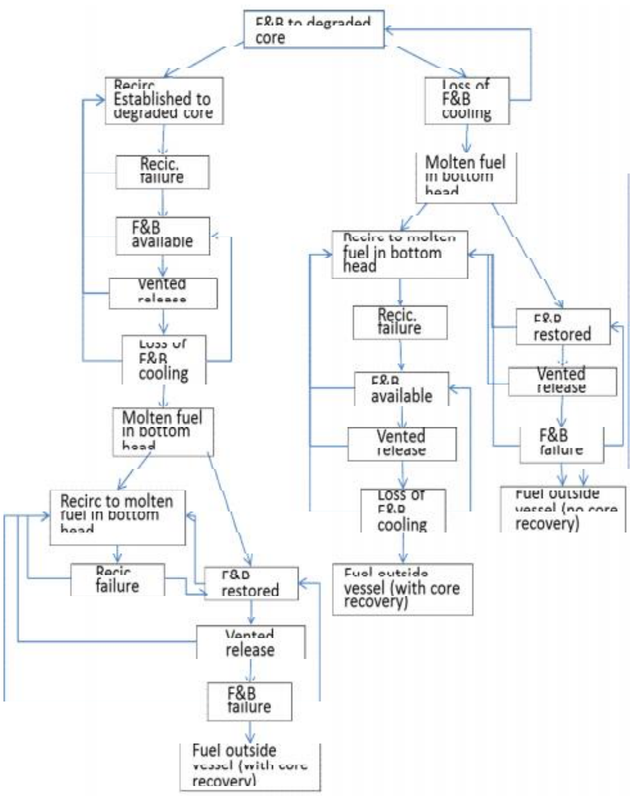

Fig. 1. Markov In-vessel Model.

RESULTS

A check of the Markov model logic was performed by calculating and comparing various cases using the parameters in Table I. For one case the reference values were used for all the parameters. The other two cases were a "worst" case and a "best" case. For the worst case the low values of the ranges in Table I were chosen for the mean times to equipment failure and core melt progression, while the high values of the range for equipment recovery were chosen. For the best case the opposite was true: the high range values were input for equipment failure and accident progression and the low times were input for equipment recovery.

The variation in the results between the three cases showed the expected trends. For example, as it can be seen in Figure 2, at 150 days the reference case showed about a 0.21 probability of fuel relocating ex-vessel, compared to a 0.85 probability for the worst case and essentially a zero probability for the best case. Similarly, the probability of being in a stable recirculation cooling mode at 150 days inferred from Figure 3 was about 0.75 for the reference case, 0.17 for the worst case and essentially 1.0 for the best case. From Figure 4, the probability of being in a feed and bleed mode by 150 days was only a few percent for the reference and worst case,

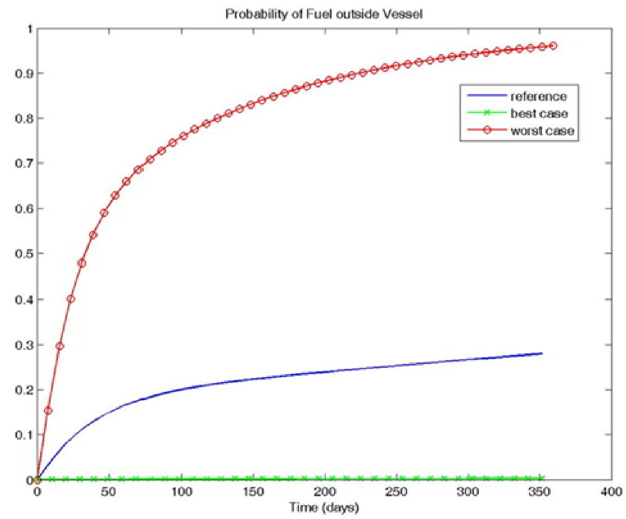

Fig. 2 Probability of fuel relocating ex-vessel.

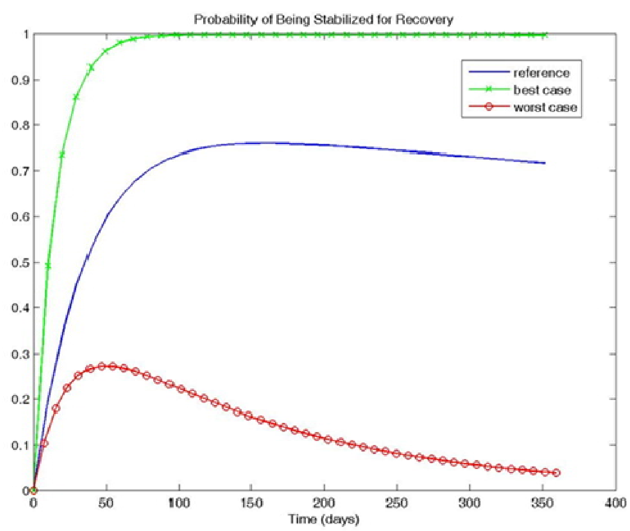

Fig. 3 Probability of being in recirculation mode.

and negligible for the best case. These results appear reasonable given the parameters chosen.

Sensitivity runs were performed to establish the importance for the results of the various parameters. These parametric studies shed light on what parameters play a vital role in minimizing vessel failure and migration of fuel ex-vessel, and indicated that the assumed mean time to failure of the recirculation system was a key parameter. For instance, Figure 5 shows that at 150 days the probability of fuel relocating ex-vessel increased from 0.21 to 0.33 when the mean time to failure was decreased from 500 days to 100 days, while it did not change much (from 0.21 to 0.20) when the mean failure time was increased to 900 days. Similarly, the probability of being in a stable recirculation cooling mode at 150 days decreased to 0.64 when the mean failure time was decreased to 100 days (Figure 6), while the probability of being in a feed and bleed mode by 150 days (Figure 7) was basically unaffected.

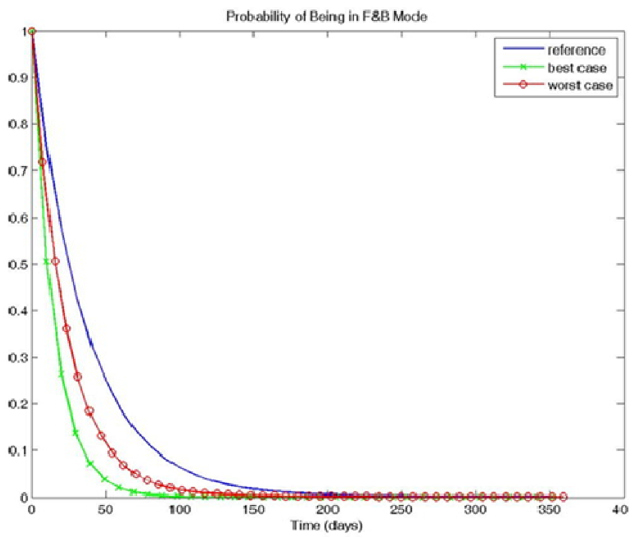

Fig. 4 Probability of being in Feed & Bleed mode.

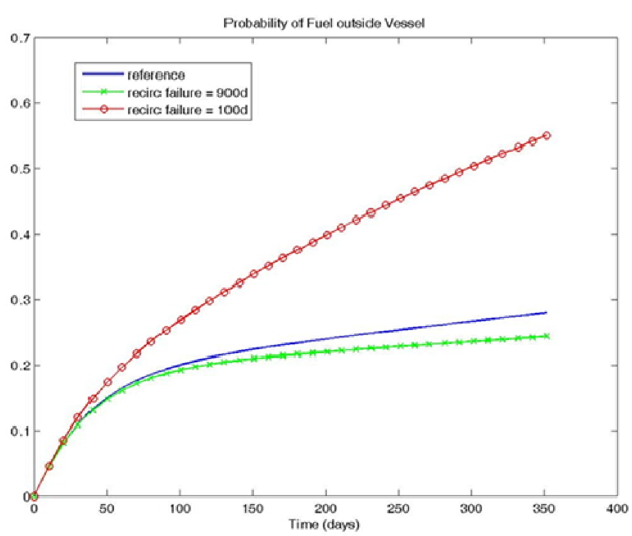

Fig. 5 Sensitivity of recirculation cooling failure time – Probability of fuel relocating ex-vessel.

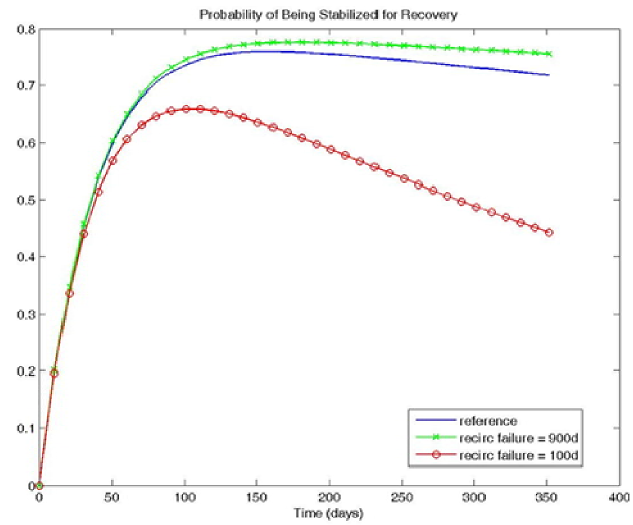

Fig. 6 Sensitivity of recirculation cooling failure time – Probability of being in recirculation mode.

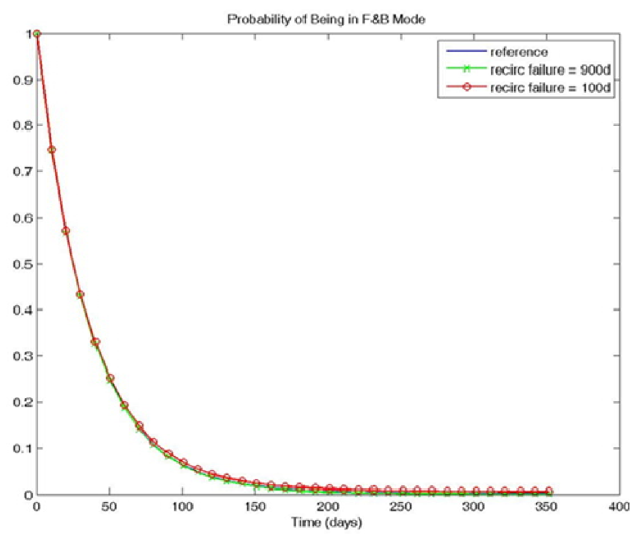

Fig. 7 Sensitivity of recirculation cooling failure time – Probability of being in Feed & Bleed mode.

CONCLUSIONS

This work illustrates how a Markov model approach can be used to describe and predict outcomes of a severe accident for which much uncertainty exists. Further it enables the study of the time-dependent dynamic events associated with failure and restoration of cooling modes to be evaluated in comparison to heat-up times for damaged fuel

The results obtained from the Markov model provide reasonably consistent physical descriptions of the challenge and expected plant responses. There was no severe and unexpected downturn of events at Fukushima

Daiichi after this work ended in late spring of 2011. Since then, Units 1-3 have been brought to cold shutdown with a mode of recirculation cooling established [3].

ACKNOWLEDGEMENTS

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2. U.S. NUCLEAR REGULATORY COMMISSION, “Severe Accident Risks: An Assessment for Five U.S. Nuclear Power Plants,” NUREG-1150, U.S Nuclear Regulatory Commission, December 1990.
3. The website of the International Atomic Energy Agency provides monthly updates (and links) to the status of the Fukushima plants and their impact: http://www.iaea.org/newscenter/news/tsunamiupdate01.html.