Modeling U. S. Emergency Response

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Abstract: The U.S. Nuclear Regulatory Commission (NRC) staff has improved the realism of consequence analyses by developing advanced models of emergency response. In carrying out its mission to protect public health and safety, the NRC performs research to determine the risk to the public from commercial nuclear power plant operation. Realistic modeling of emergency plan implementation and the resulting public response has improved estimates of health consequences due to severe reactor accidents. These results show that emergency response programs that are implemented as planned, approved and demonstrated during inspected exercises will greatly reduce the impact of radiological releases from reactor accidents.

Keywords: Consequence analysis, emergency response, emergency planning

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1. INTRODUCTION

In carrying out its mission to protect public health and safety, the U. S. Nuclear Regulatory Commission (NRC) performs research to determine the risk to the public from commercial nuclear power plant operation. The NRC recently completed the State of the Art Reactor Consequence Analysis (SOARCA) (NRC, 2012a&b). The SOARCA project developed best estimates of public health consequences from potential severe accidents using state-of-the-art understanding of accident phenomena, plant performance, radiation health effects, and modeling of emergency response for important scenarios.

The project staff modeled emergency plan activation, decisionmaking, and the expected population movement in response to evacuation orders. Previous NRC studies used rather simple models of emergency response (NRC, 1990 and NRC, 2001). In the SORACA study, the staff used actual emergency plans, procedures, and evacuation time estimates to enhance model fidelity.

As required by NRC regulations, offsite response organizations (OROs) develop emergency response plans to be used to protect the public health and safety in the unlikely event of an accident at a nuclear power plant. These response plans are developed for the area about 16 kilometers (10 miles) around the plant, referred to as the plume exposure pathway emergency planning zone (EPZ) Within the EPZ, plant operators have detailed emergency plans in place, and this planning provides a substantial basis for expansion of response efforts, if necessary.

Plant operators regularly exercise emergency plans through an inspected biennial exercise that includes ORO participation. In biennial exercises, ORO personnel demonstrate timely decision making and the ability to implement public protective actions. Emergency plans escalate response activities in accordance with a classification scheme based on emergency action levels. Responders implement preplanned actions at each classification level, including Unusual Event, Alert, Site Area Emergency (SAE), and General Emergency (GE). The GE level requires public protective actions, but ORO plans commonly include precautionary protective actions at the SAE level and sometimes at the Alert level. For example, some OROs close schools and sound sirens at the SAE level to inform the public that an incident has occurred and that they should watch for updated information.

Emergency plans provide a substantial basis for expansion beyond the EPZ should that be necessary. Accident scenarios can result in the need to take protective actions beyond the EPZ. The NRC staff has modeled the timing and extent of such protective actions, but these actions would be taken ad hoc. The NRC studied ad hoc evacuations in the United States (NRC, 2005) during a 13 year period. That study concluded that all the evacuations studied were successful in saving lives. While the study identified improvement areas, it is clear the OROs can and do protect the public through ad hoc implementation of protective actions.

The staff has modeled emergency plan implementation based on accident sequence, timing, radiological release, response activities, and emergency response technical support. In the SOARCA study, sensitivity analyses were conducted to determine the impact of untimely implementation of various emergency response elements. The emergency response modeling techniques developed in the SOARCA study are being advanced in consequence analyses under development at the NRC but not yet published.

The NRC has estimated consequence results predicated on emergency plans being implemented as planned, approved, and demonstrated during inspected exercises. All U.S. nuclear power plants have demonstrated compliance with emergency response regulations as a condition for continued operations. Many have demonstrated emergency plan implementation since 1981.

2. TECHNIQUES

The techniques discussed in this paper are useful in accident analyses that result in containment failure and radiological release. Analysis of accident progression is necessary to model emergency plan activation and timing of protective actions. This is accomplished by comparing the operator's approved emergency classification procedure with parameter output from whatever accident analysis code is being used. Parameters such as coolant level, pressure, core temperature, and status of alternating current (ac) and direct current (dc) power systems are used as emergency action levels (EALs) that require certain emergency classifications. Declaration of an emergency can be correlated with the timing of response actions. For example, immediate loss of offsite ac power is an Alert. Loss of all ac is an SAE and loss of all ac for a period longer than the coping time is a GE. Response actions are assumed to follow in accordance with procedure. The staff generally assumes that response is not as timely as indicated in procedures to affect realism in modeling.

Once a source term is available, the staff uses the MELCOR Accident Consequence Code System Version 2 (MACCS2) and the MACCS2 graphical user interface called WinMACCS (NRC, 1998). WinMACCS allows fairly detailed modeling of the road network. It allows simulation of traffic flow through congested areas by slowing down evacuation speed and free-flowing traffic by speeding up the speed. The MACCS2 code calculates population exposure. It uses census data to determine population in a fine grid structure and calculates doses as the population evacuates or shelters and the radiological plume disperses. MACCS2 integrates exposure through four modules: ATMOS, EARLY, CHRONC, and COMIDA. ATMOS estimates exposure during atmospheric transport and deposition of the plume. EARLY integrates exposures during the emergency phase (7 days). CHRONC is used for intermediate and long-term phase calculations, and COMIDA is the ingestion pathway model. In recent consequence analyses, COMIDA is not because few, if any, members of the public will eat contaminated food after an accident in the United States.

MACCS2 consequence results are provided through several metrics: population dose, early fatalities, latent cancer fatalities (with and without dose truncation values), land contamination, land condemnation, early fatality risk, latent cancer fatality risk, etc. Recent analyses have used these latter two metrics as an effective way to communicate risk to individual members of the public.

MACCS2 is probabilistic based on weather trials. The model analyzes dozens of weather scenarios using actual site meteorological data and it outputs ranked consequences. In general, the 95th percentile is used for regulatory purposes and the mean is used as a best estimate for the purposes of consequence studies.

WinMACCS allows for discrete analysis of individual segments of the population by establishing cohorts. The user is able to identify multiple cohorts, each of which represent a segment of the population that has different response characteristics than other population segments. The number of cohorts is not limited, but there is diminishing value in establishing a large number of cohorts because the response characteristics begin to overlap within the evacuation period, and the effects on different cohorts become indistinguishable.

Evacuation time estimates (ETE) are required for every U.S. nuclear power plant. Regulations require that operators update these ETEs with each decennial census and that they use the results in the development of protective actions (NRC 2011). Generally, the ETE identifies cohorts. However, a critical feature of ETEs is the rate at which the public enters the road network. This is analyzed and reported as "road loading curves." MACCS2 currently cannot directly accept road loading curve data. This data is most important for the general public cohort as it is the largest. An innovative solution to this issue is to separate the general public cohort into multiple discrete cohorts to allow a dispersed loading onto the roadway network. This allows improved simulation of evacuation road network loading.

Cohorts also can be established for large transient facilities, such as amusement parks and school populations.

3. POPULATION COHORTS

An example of modeling follows for a site with a relatively high population. This site has a large summertime transient population that includes high attendance attractions. There is a large transient employee population that commutes into the EPZ during the day to work. Analysts established 12 cohorts for this site.

Cohort 1 represents a shadow evacuation of 20 percent of the general public residing in the area 8 kilometers (5 miles) beyond the EPZ. A shadow evacuation occurs when members of the public evacuate from areas that are not under official evacuation orders. These generally begin when a large-scale evacuation is ordered. The 20 percent estimate was derived from a national telephone survey of residents of EPZs who were asked questions about evacuation and protective actions (NRC, 2008).

In an evacuation, the general public will mobilize and evacuate over a period of time (Wolshon and Walton, 2010). Before the alert and notification of the emergency, researchers assume the general public is performing normal activities (e.g., working, running errands, at home, etc.). The evacuation time period, therefore, depends on when they receive the warning, where they are when they receive the warning, and what actions they need to take to evacuate once they understand the protective action order. To represent the movement of the general public over a period of time, analysts established cohorts 2 through 6, as described below.

Cohort 2 represents members of the general public who evacuate promptly upon receiving notification. These include people at home and those within the EPZ who do not return home before evacuating. Analysts assume approximately 10 percent of the general public mobilizes and begins to evacuate within 30 minutes of notification.

Cohorts 3, 4, and 5 each represent 26.6 percent of the general public. Analysts model these cohorts as evacuating sequentially, beginning immediately following the prompt evacuees. The cohorts were established to allow segmented roadway loading simulating the time for residents to prepare to evacuate and enter the roadway network.

Cohort 6 represents the last 10 percent of the general public to evacuate. This last 10 percent is referred to as the evacuation tail (Wolshon and Walton, 2010). The evacuation tail takes longer to evacuate for valid reasons, such as shutting down farming or manufacturing operations, performing other time-consuming actions before evacuating, and those who may have missed the initial notification.

Figure 1 illustrates an evacuation curve that represents evacuation of the general public. This illustration is consistent with research (Wolshon and Walton, 2010) that shows a small portion of the public evacuates early.

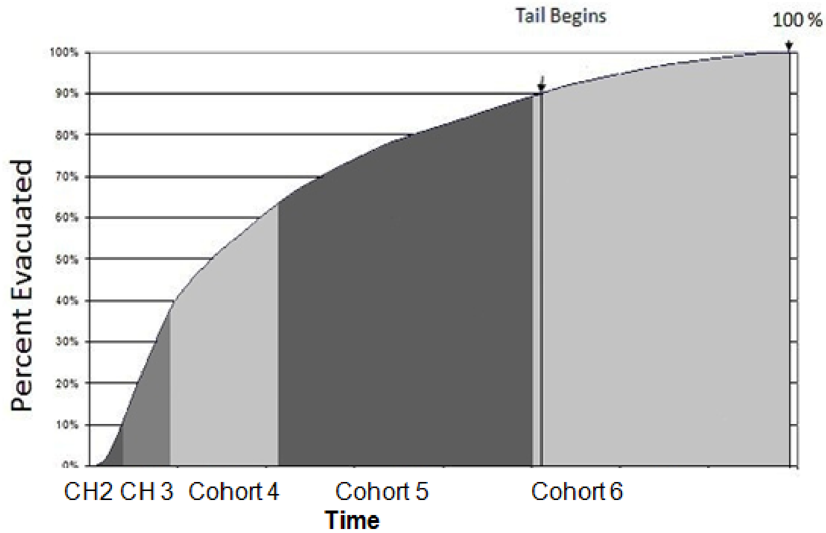

Figure 1. General Public Loading Curve

Cohort 7 represents the special facilities population within the EPZ, which includes residents of hospitals, nursing homes, assisted living communities, and prisons. These facilities are typically large and robust, providing better shielding than typical residential housing. In an emergency, special facilities would be evacuated individually over a period of time based upon available transportation and the number of return trips needed to evacuate a facility. As described earlier, the consequence model does not accept such input spread over a period of time. Because the percent of population of this cohort is very small compared to the total population and the other cohorts, this population is not separated into multiple cohorts as was done with the general public. Analysts determined that an appropriate representation of this cohort in the modeling would be to start the evacuation of this cohort later in the event and apply shielding factors consistent with the types of structures within which these residents reside.

Cohort 8 represents special needs residents within the EPZ who do not reside in special facilities. Results of a national telephone survey of EPZ residents show that 6 percent (± 3.5 percent at the 95 percent confidence level) of the EPZ population may be special needs residents who do not reside in special facilities and who would need additional assistance from outside the home to evacuate (NRC, 2008). Actual survey results showed 8 percent; however, a quarter of these people believed that, if necessary, they might be able to evacuate on their own.

Cohort 12 represents the nonevacuating public from within the EPZ. This cohort represents a portion of the public who may refuse to evacuate and is assumed to be 0.5 percent. Research of large-scale evacuations has shown that a small percent of the public refuses to evacuate, and this cohort accounts for this group (NRC, 2005). This cohort, having decided not to evacuate, is assumed to be performing normal activities.

Analysts divided the transient population within the EPZ into three groups. There are two facilities that attract large numbers of transients (Cohorts 9 and 10), and the remaining transients are distributed throughout the EPZ (Cohort 11). Analysts assumed that some of these transients will return to their hotels to pack before evacuating the EPZ.

Cohort 9 represents a large area tourist attraction that covers a few hundred acres represented as Transient 1 in the timelines. The transients from this facility would hear sirens and would receive a notification from the facility. They then would complete their activities, walk to their vehicles, and evacuate. Although this attraction covers a large area, there is no preplanned traffic control for exit from this attraction. Analysts assumed that after hearing the siren, this cohort would wait for a site notification and then walk to their vehicles, drive to their hotels, pack their belongings, and evacuate the EPZ.

Cohort 10 represents a second large tourist attraction, but this attraction is more concentrated (e.g., a stadium, amusement park, etc.) and is represented as Transient 2 in the timelines. The parking facility is onsite, and upon receiving an evacuation order from park management, members of this group should be able to readily access their vehicles and evacuate the area. Visitors would walk to their nearby vehicles, drive to their hotels, pack their belongings, and evacuate the EPZ. There is no preplanned traffic control for exit from this attraction.

Cohort 11 represents the remaining transients in the area, including employees who work within the EPZ but do not live within the EPZ, including visitors, shoppers, etc. This group is dispersed throughout the EPZ and receives the warning generally at the same time as the general public. These transients are defined as daily visitors and employees who, upon hearing the sirens and receiving the evacuation message, promptly evacuate the EPZ.

Figure 2 shows emergency classification and evacuation timing for an immediate loss of ac and dc power at a pressurized-water reactor site in the United States. The population is modeled in accordance with the recent protective action strategy guidance issued by the NRC (NRC 2011). Large facilities are notified by telephone at the SAE level. The model assumes it is summertime so the transient populations are large and schools are not in session. This models the emergency plan, as approved.

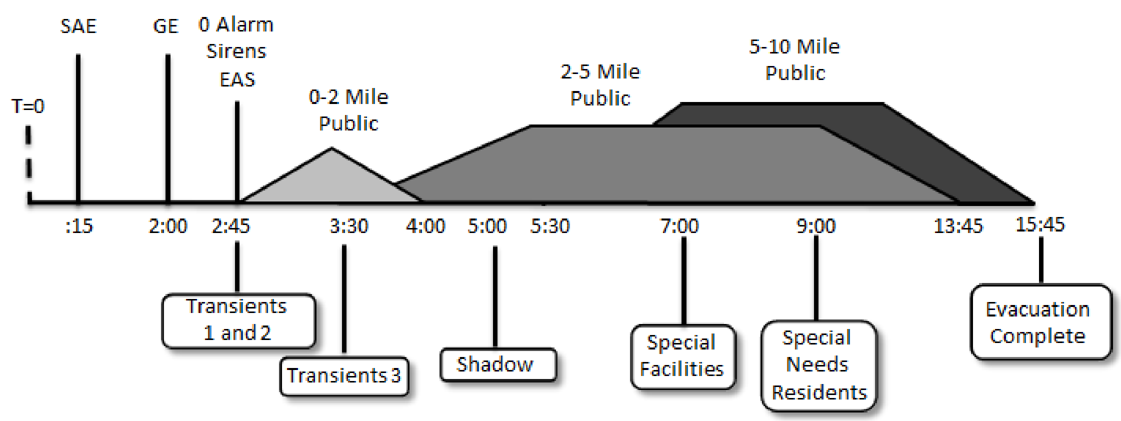

Figure 2. Model of Response Timing

The staff also has pursued research to determine the value of nuclear power plant emergency response programs as required by regulation. To do that, analysts modeled an ad hoc response and then compared it to the response required by regulation for a suite of accident scenarios. The example that follows in Figure 3 is for the same site and accident as above. The results show that the evacuation takes much longer to accomplish than might be expected.

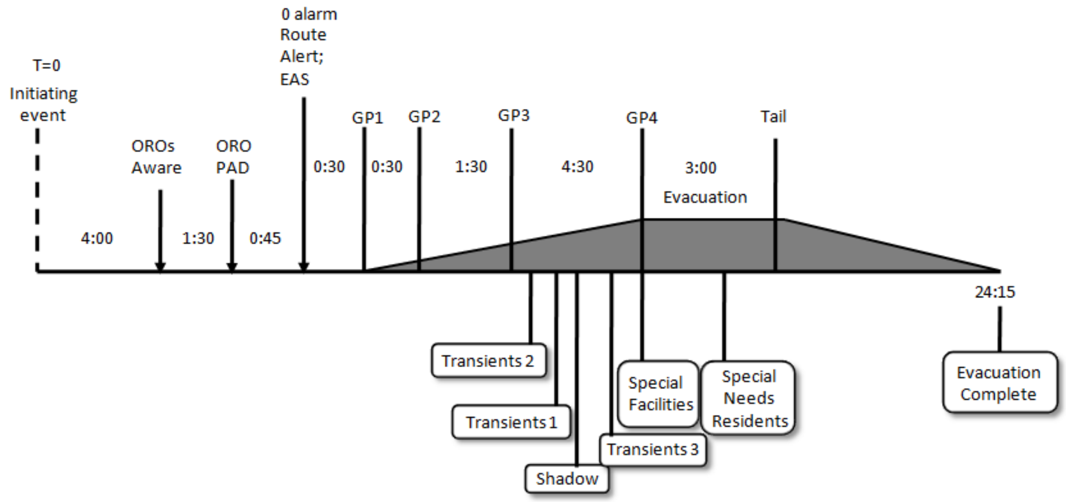

Figure 3. Ad Hoc Response Timeline

The population in this model is split into groups to simulate road loading. The timing of cohort departure and the speed at which they move is loaded into the WinMACCS program. Once the model is created, it can be used for multiple accident scenarios.

4. CONCLUSION

Modeling of emergency response plans as written, approved, and demonstrated can enhance the efficacy of consequence analyses. Modeling of emergency response has been advanced to show the benefit of emergency planning. Sensitivity analyses can be conducted using these models to identify the most risk-significant elements of protective action strategies, and identify the impact of road closures, procedural changes, equipment malfunctions, and the like. The NRC staff is pursuing this applied research to risk inform regulatory oversight.

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References

U.S. Nuclear Regulatory Commission (NRC, 1998). "Code Manual for MACCS2." NUREG/CR-6613, SAND97-0594. Volumes 1 and 2. Washington, DC. May 1998.

U.S. Nuclear Regulatory Commission (NRC, 1990), "Severe Accident Risks: An Assessment for Five U.S. Nuclear Power Plants." NUREG-1150. U.S. Nuclear Regulatory Agency: Washington, DC. December 1990.

U.S. Nuclear Regulatory Commission (NRC, 2001) "Technical Study of Spent Fuel Pool Accident Risk at Decommissioning Nuclear Power Plants." NUREG-1738. U.S. Nuclear Regulatory Agency: Washington, DC. February 2001.

U.S. Nuclear Regulatory Commission (NRC, 2005). "Identification and Analysis of Factors Affecting Emergency Evacuations." NUREG/CR-6864, SAND2004-5901. Washington, DC. January 2005.

U.S. Nuclear Regulatory Commission (NRC, 2007). "Review of NUREG-0654, Supplement 3, 'Criteria for Protective Action Recommendations for Severe Accidents.'" NUREG/CR-6953, Volume I. SAND2007-5448P. Washington, DC. December 2007.

U.S. Nuclear Regulatory Commission (NRC, 2008). "Review of NUREG-0654, Supplement 3, 'Criteria for Protective Action Recommendations for Severe Accidents,'—Focus Groups and Telephone Survey." NUREG/CR-6953, Volume. 2. SAND2007-5448P. Washington, DC. October 2008.

U.S. Nuclear Regulatory Commission (NRC, 2011). "Criteria for Protective Action Recommendations for Severe Accidents." Update to Supplement 3 to NUREG-0654/FEMA-REP-1, Revision 1, "Washington, DC. 2011.

U.S. Nuclear Regulatory Commission (NRC, 2012a). "State-of-the-Art Reactor Consequence Analyses Project: Peach Bottom Integrated Analysis." NUREG/CR-7110, Volume 1. Washington, DC. January 2012.

U.S. Nuclear Regulatory Commission (NRC, 2012b). "State of the Art Reactor Consequence Analyses Project: Surry Integrated Analysis." NUREG/CR-7110, Volume 2. Washington, DC. January 2012.

Wolshon, Brian, J. Jones, and F. Walton (2012). The evacuation tail and its effect on evacuation decision making." *Journal of Emergency Management.* Volume 8, Number 1.20. January/February 2010,