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Atmospheric Transport and Consequence Analysis of the Fukushima Daiichi Accident

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Abstract – *The accident at Fukushima Daiichi Units 1, 2, and 3 began on March 11, 2011, and continued for approximately three weeks. The pattern of deposition resulting from the accident has been well characterized and is valuable for validating atmospheric transport modeling tools and for evaluating consequence analysis methods and tools. Sandia National Laboratories performed accident progression and source term analyses for each of the three units using MELCOR. These analyses account for the full three-week period of the accident. Furthermore, the results of the source terms were used to perform atmospheric transport and consequence analyses using HYSPLIT and MACCS. They agree remarkably well with the observed deposition patterns in the region surrounding the Fukushima Daiichi site. Several sources of uncertainty contribute to overall uncertainties in the deposition pattern, including the source term signatures for the three plants and the weather data used to perform the atmospheric transport analysis. These uncertainties are explored in this paper. A third source of uncertainty, wet deposition modeling, is outside the scope of this effort and is not assessed.*

I. INTRODUCTION

The accident at Fukushima Daiichi Units 1, 2, and 3 began on March 11, 2011, and continued for approximately three weeks. The pattern of deposition resulting from the accident has been well characterized. Thus, this accident, while highly unfortunate, is valuable for validation of atmospheric transport modeling and for evaluation of consequence analysis methods and tools. A significant portion of OECD's Benchmark of the Accident at the Fukushima Daiichi Nuclear Power Station (BSAF) Project, Phases I and II, and the follow-on Analysis of Information from Reactor Building and Containment Vessel and Water Sampling in Fukushima Daiichi Nuclear Power Station (ARC-F) Project, are focused on understanding the accident progressions, source terms, and consequences resulting from the three-unit accident.

As a participant in these projects, Sandia National Laboratories (SNL) performed accident progression and source term analyses for each of the three units using MELCOR. These analyses account for the full three-week period of the accident. Furthermore, the predicted source terms were used to perform atmospheric transport and consequence analyses using HYSPLIT and MACCS. They agree remarkably well with the deposition patterns observed in the region surrounding the Fukushima Daiichi site. However, there are several sources of uncertainty that contribute to differences between the observed and calculated deposition patterns; two of these are explored in this paper. The two uncertainties are those from source term and weather. A third contribution to uncertainty, deposition modeling, and especially the contribution of wet deposition, is beyond the scope of this effort.

II. Objectives

The atmospheric transport analysis of the Fukushima Daiichi accident has three main objectives: (1) to demonstrate the capability to perform a beginning-to-end analysis (source terms and consequences) of a complex, multi-unit accident like the one at Fukushima Daiichi; (2) to guide source term modelers by providing feedback on the timing and magnitude of releases during critical times when the on-land deposition pattern was established; and (3) to benchmark the tools that the NRC and Sandia are developing for source term (MELCOR) and radiological consequence analysis (MACCS). For the first objective, evaluation of the accident at Fukushima presented significant challenges. MELCOR had never been used to predict accident progression and source terms for periods as long as three weeks and code improvements were made to enable such long calculations. Performing a best-estimate calculation of the atmospheric transport and consequences required coupling results for the three units, each with a

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different release location, source term signature, aerosol size distribution, and buoyancy, into a single result. For the second objective, the predicted deposition pattern depends critically on the timing of significant releases from one or more of the three units involved in the accident. Aligning the source terms with the weather based on the resulting deposition pattern is an iterative process that provides feedback to the source term modelers. Finally, demonstrating that the source term and atmospheric transport tools can reasonably predict the observed ground deposition patterns provides a valuable validation of these tools.

To simplify and focus the atmospheric transport analysis, the authors evaluated Cs-137 rather than the full spectrum of isotopes that can be important for nuclear reactor consequence analysis. One of the reasons for this choice is that Cs-137 is one of the more studied isotopes and its deposition pattern was well quantified following the Fukushima accident. Furthermore, Cs-137 is the most important isotope for long-term consequences because of its 30-yr half-life and the significant groundshine doses that it produces. (In fact, it is the decay product of Cs-137, Ba-137m, which has a half-life of only 2.55 min, that contributes most of the groundshine dose that is associated with Cs-137.)

III. Sources of Uncertainty

There are three major sources of uncertainty in the process of simulating an accident like the one at Fukushima as follows:

1. Uncertainty in the source term;
2. Uncertainty in the weather data, mainly in terms of wind velocities and precipitation rates; and
3. Uncertainty in deposition modeling, especially wet deposition that occurs during periods of precipitation.

On the third uncertainty, wet deposition can be different depending on whether the precipitation is rain or snow and whether the interactions with suspended aerosols occur within or below clouds. Most wet deposition models do not fully distinguish these possibilities and use simple empirical models rather than mechanistic ones. The first two of these uncertainties are qualitatively explored in terms of sensitivity analyses. Deposition modeling uncertainty is not explored.

Source term uncertainty is explored by evaluating deposition patterns for a set of source terms simulated for the Fukushima accident. Weather uncertainty is explored by evaluating deposition patterns corresponding to three sources of weather data. While this exploration is not a full uncertainty analysis and does not provide a quantitative indication of the relative importance of the sources of uncertainty, it provides a very good qualitative understanding of the contributions of these inputs to predicted ground deposition patterns.

Fig. 1 shows five source terms that were created by SNL during BSAF Phase II for the Fukushima accident. These source terms are combined, integral releases of Cs-137 for the three units that underwent severe accidents. The earliest of the source terms was evaluated mid-2016 and is the largest of the set, nearly 30 PBq, the early-2017 and mid-2017 source terms are intermediate in magnitude, between 20 and 25 PBq, the early-2018 source term is the smallest, less than 15 PBq, and the most recent source term, evaluated mid-2018, is the second largest, almost 25 PBq. During the BSAF Phase II project, the MELCOR model was significantly changed to reflect better understanding of operator actions and their success, pre-existing damage caused by the earthquake, and other failures that occurred during the accident. The improvements in understanding did not lead to a monotonic convergence to a best estimate, at least in terms of source-term magnitude. Also shown on the figure are several independent estimates of the Cs-137 release magnitude at various times during the accident. These estimates are largely based on monitoring and other observational data and span a range from less than 10 PBq to more than 35 PBq of Cs-137. Clearly, the MELCOR source terms generated at SNL fall within the range of other independent estimates, but most of them are at the upper half of the range. While the accident persisted for about 3 weeks (the MELCOR simulations end at 500 hr), most of the release had occurred by the end of the first week. The 1/2017 and 7/2017 MELCOR simulations are exceptions, with significant releases continuing for about two weeks; however, these results are no longer considered to be best estimates of the Fukushima accident and source term and the current understanding is that most of the releases had occurred by the end of the first week. Several of the source terms shown in Fig. 1 are evaluated in the following section.

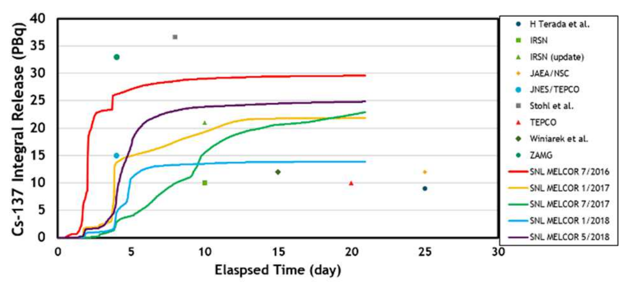


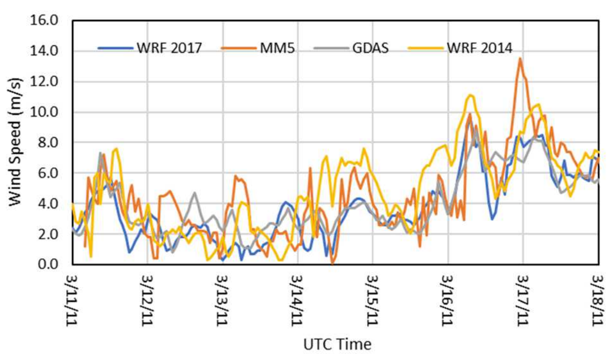
Fig. 1. Comparison of SNL Cs-137 source terms combined for the three Fukushima units with independent estimates of source term magnitude.

Uncertainty in weather data is also evaluated in the following section for three data sources as follows:

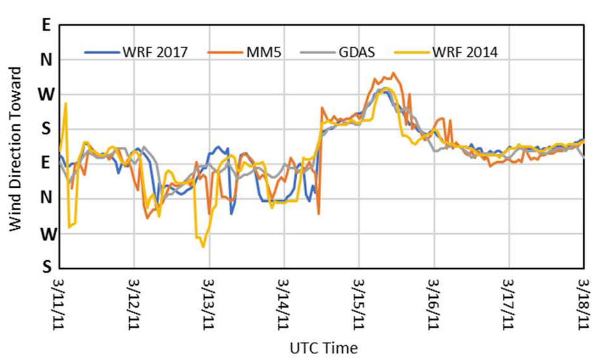
1. Data generated by Weather Research and Forecasting (WRF) code in 2014. The calculation is on a 4-km grid spacing with a 20-min time interval.

2. Data generated using the Global Data Assimilation System (GDAS). The data are on a 0.5-degree latitude and longitude spacing (roughly 40 km at the Fukushima latitude) with a 3-hr time interval.
3. Data generated by WRF in 2017. The data are on a 4-km grid spacing with a 5-min time interval. Unlike the 2014 WRF data, these are nudged using observational data, which forces the simulation to track weather tower and rawinsonde measurements.

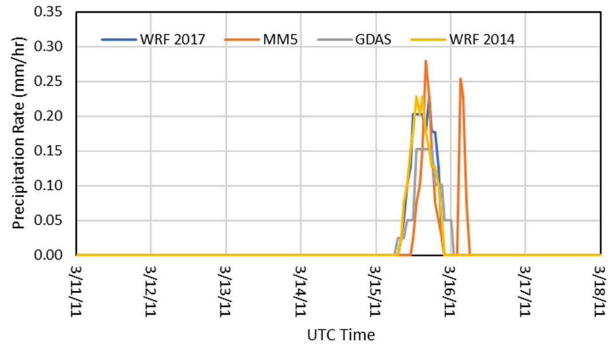
Fig. 2 shows wind speeds, directions, and precipitation rates at the Fukushima site for the three data sets described above plus a Japanese weather data set labeled MM5. While the trends are similar, the details are clearly different, and these details make a difference in the results shown below. Notice that the wind direction in the MM5 data set is shifted more to the north mid-day on March 15; whereas, the wind directions in the other data sets are toward the west during the same time interval. This difference affects the direction of the predicted deposition peak, which was observed to go toward the northwest. Also, notice that the MM5 data contain a secondary precipitation peak early on March 16, which may have affected the deposition pattern. Unfortunately, SNL was unable to use the Japanese weather data because of a formatting issue, so the following section does not show a comparison for the MM5 data.



(a)



(b)



(c)

Fig. 2. Comparison of four weather data sets at the Fukushima site during the first week of the Fukushima accident. (a) shows wind speed, (b) shows wind direction, and (c) shows precipitation rate.

III. Results

Fig. 3 shows the observational data from Fukushima for Cs-137 deposition. Most of the on-land deposition is to the NW of the Fukushima site and maximum ground concentrations (the orange-shaded isopleth) are between 3.5 MBq/m^2 and 14.7 MBq/m^2.

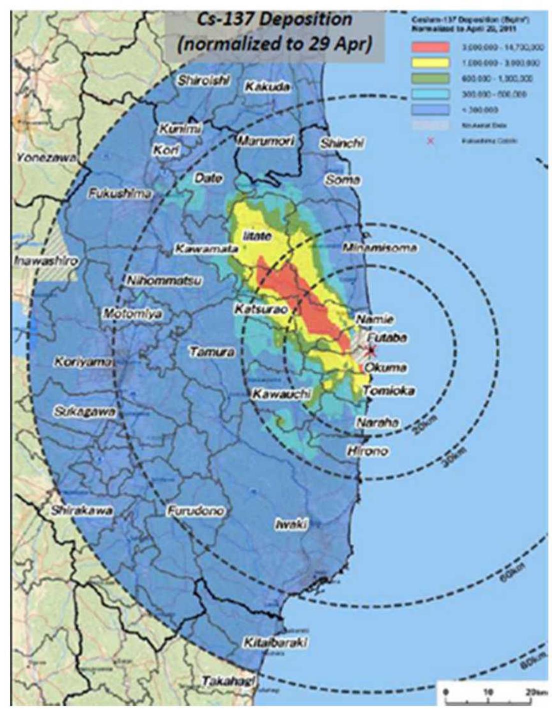


Fig. 3. Deposition isopleths for Cs-137, normalized to 29 April 2011, measured in the area around the Fukushima site.

Figs. 4, 5, and 6 show deposition patterns using the final (mid-2018) SNL-predicted source terms for Fukushima Units 1, 2, and 3 for the three weather data sets described above (excluding the MM5 data set). These patterns were evaluated by SNL using the HYSPLIT code[1,2,3] and show deposition over the ocean as well as over the land. Unlike deposition over land, deposition over water cannot be observed because of rapid dispersion by ocean currents. The color scales used for the isopleths in these figures match those used in Fig. 3 to facilitate comparison. Notice that the choice of weather data set makes a significant difference in the predicted pattern. All three predicted isopleths have a deposition peak toward the NW like the observed deposition pattern, although shifted slightly toward the west compared with the observational data, possibly indicating that the wind directions in the MM5 data set better reflect the actual weather during the Fukushima accident. The WRF 2017 and the GDAS deposition patterns both have strong secondary deposition patterns along the coastline to the SSW, which seems to explain the significant contamination of the seashore by tidal pumping that has been observed[4].

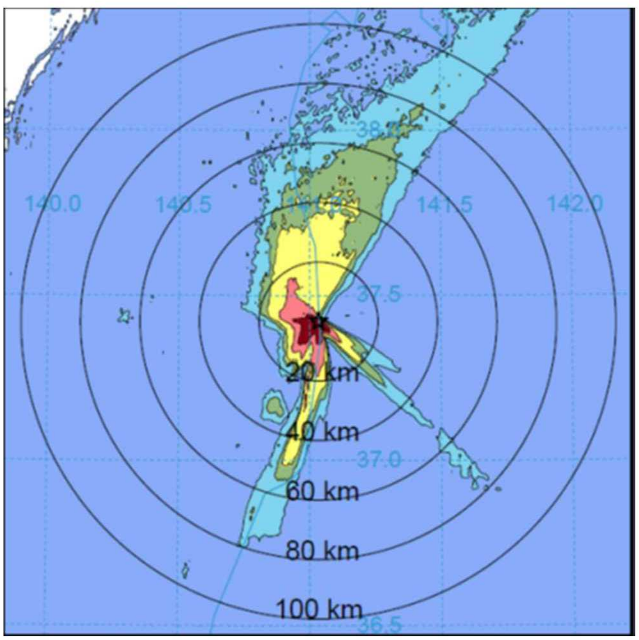


Fig. 4. Predicted deposition isopleths using HYSPLIT with WRF 2017 data and the SNL mid-2018 source term.

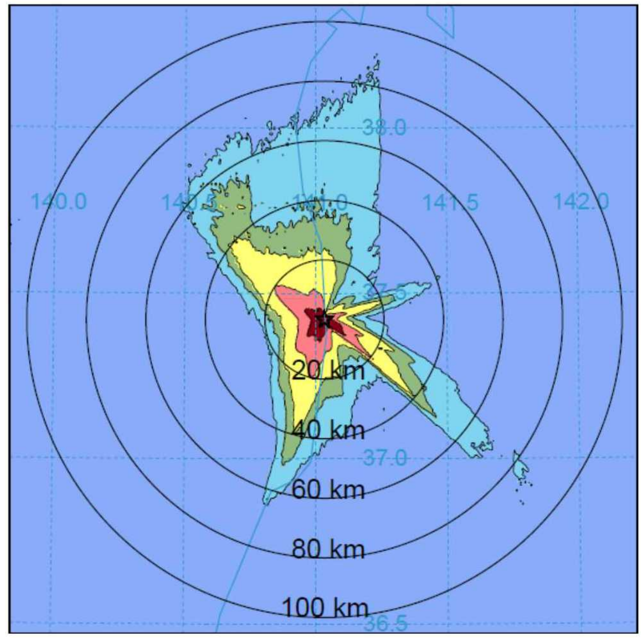


Fig. 5. Predicted deposition isopleths using HYSPLIT with GDAS data and the SNL mid-2018 source term.

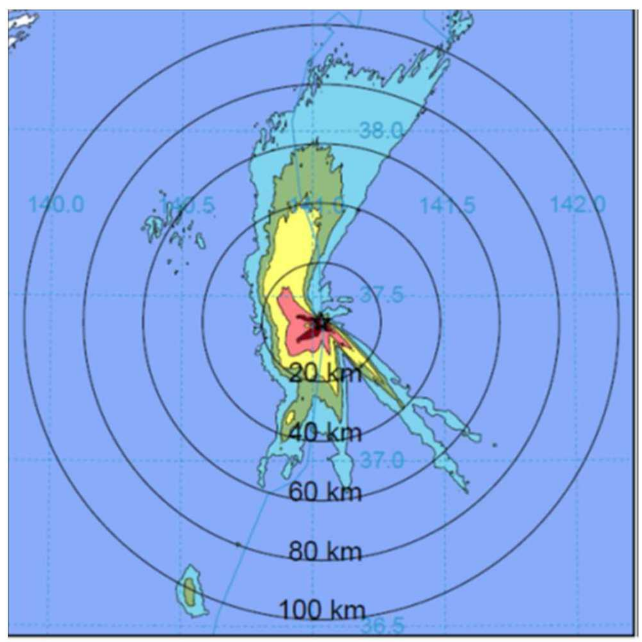


Fig. 6. Predicted deposition isopleths using HYSPLIT with WRF 2014 data and the SNL mid-2018 source term.

Figs. 7, 8, and 9 show deposition patterns individually for each of the three units based on the SNL mid-2018 source term. According to these source terms, Unit 1 does not contribute much to the on-land deposition while Units 2 and 3 both contribute significantly. Notice that the deposition pattern from Unit 3 more closely resembles the observed pattern. From this we can speculate that the source term for Unit 3 may have been larger than the SNL prediction for that unit and the one for Unit 2 may have been smaller than the SNL prediction for that unit, although there are certainly other possibilities.

Figs. 10 and 11 show results for SNL source terms that were calculated at early and intermediate points during the BSAF Phase II Project, which were calculated mid-2016 and early-2018, respectively. The mid-2016 source term did not accurately capture many of the accident progression features that were observed by TEPCO during the accident and did not produce the observed ground deposition pattern. By early 2018, the SNL source term calculations had become much more realistic and captured many of the accident progression features observed by TEPCO and reasonably matched the deposition pattern shown in Fig. 3. The deposition pattern shown in Fig. 4 is the final result calculated by SNL for the BSAF Phase II Project. Over the course of the project, the SNL-predicted source terms improved considerably, and the atmospheric transport modeling provided valuable information that helped improve its fidelity. The integrated approach used in the BSAF Phase II Project demonstrated that it is possible to combine detailed source-term modeling with atmospheric transport and consequence analysis to perform a beginning to end analysis of a complex accident. In addition, this effort is valuable as a benchmarking tool for both MELCOR and MACCS.

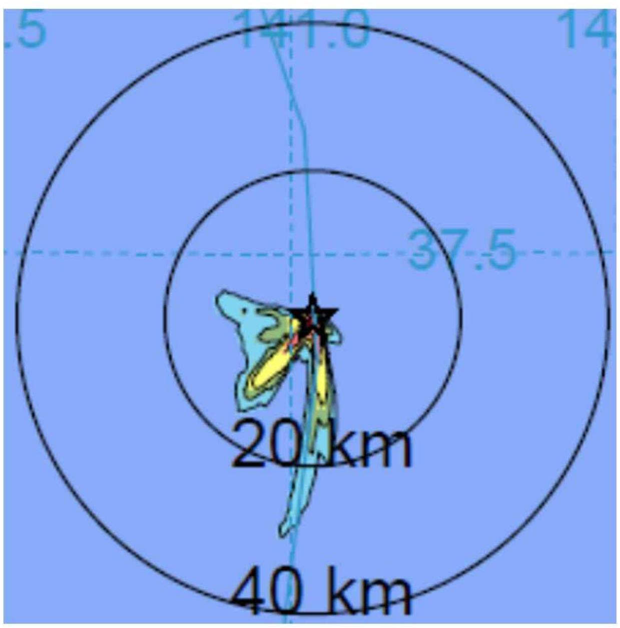


Fig. 7. Predicted deposition isopleths using HYSPLIT with WRF 2017 data and the SNL mid-2018 source term for Unit 1.

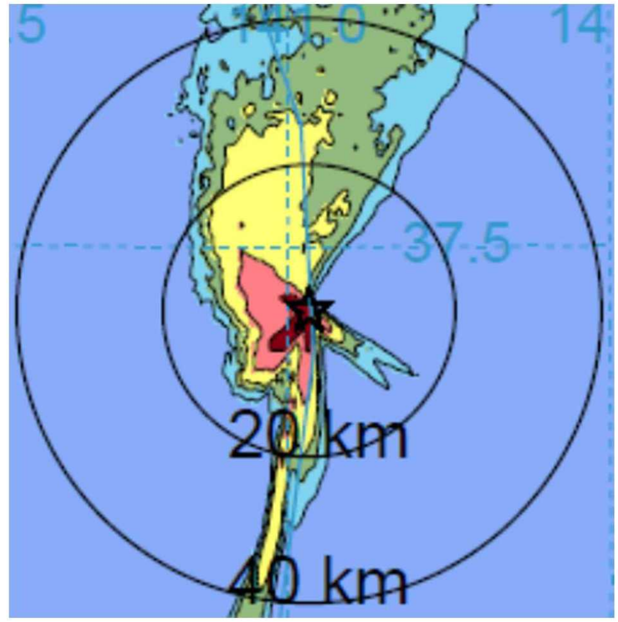


Fig. 8. Predicted deposition isopleths using HYSPLIT with WRF 2017 data and the SNL mid-2018 source term for Unit 2.

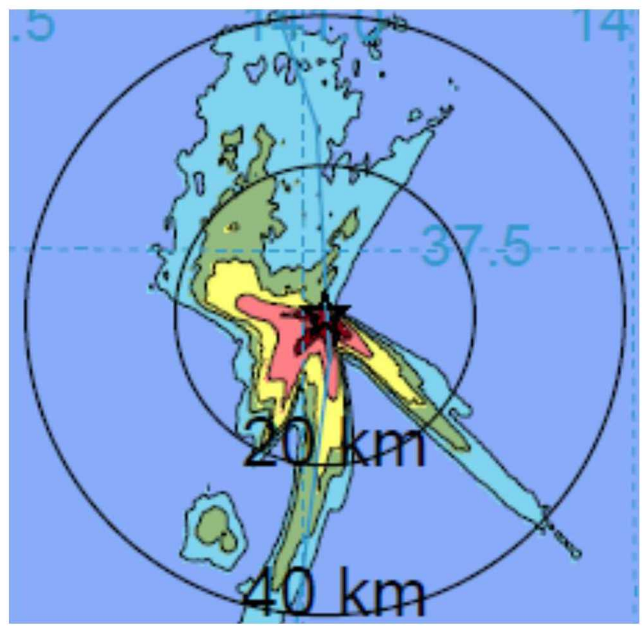


Fig. 9. Predicted deposition isopleths using HYSPLIT with WRF 2017 data and the SNL mid-2018 source term for Unit 3.

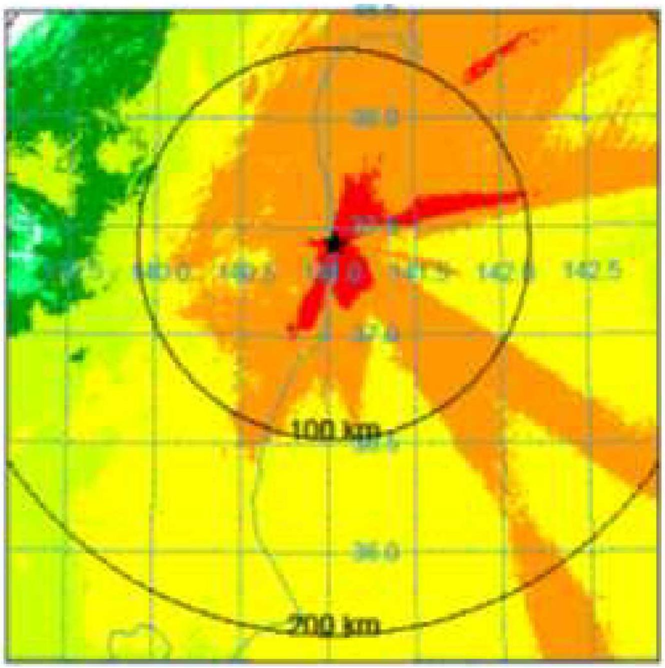


Fig. 10. Predicted deposition isopleths using HYSPLIT with WRF 2014 data and the SNL mid-2016 source term for the three Fukushima units.

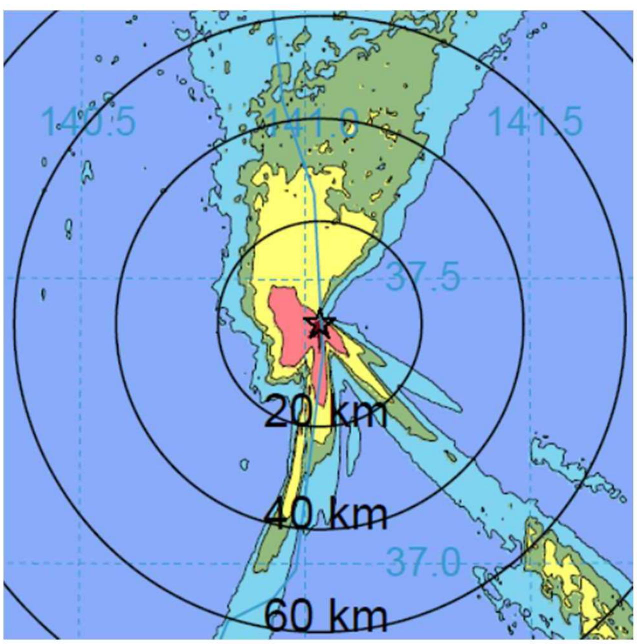


Fig. 11. Predicted deposition isopleths using HYSPLIT with WRF 2017 data and the SNL early-2018 source term for the three Fukushima units.

IV. CONCLUSIONS

As part of their participation in OECD's BSAF Phase II Project, SNL performed MELCOR analyses of all three Fukushima Daiichi units that underwent severe accidents to create best-estimate source terms that evaluated the entire three-week duration of the accident. In addition, SNL performed atmospheric transport and deposition modeling using HYSLIT and MACCS using the SNL source terms to estimate the resulting ground deposition patterns that would have resulted from the predicted source terms. The MELCOR modelers were guided by TEPCO data, including dry well and wet well pressure histories. In addition, the predicted deposition patterns provided feedback to judge the adequacy of the source term results during periods of on-shore winds. The overall results of this effort demonstrated that a complex accident, like the one at Fukushima Daiichi, can be modeled from beginning to end in a realistic fashion. It also provided an important benchmark for tools that are being used to evaluate consequences and risks for hypothetical accidents, as required to perform a Level 3 Probabilistic Safety Assessment (PSA).

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