J4.3   NARAC MODELING DURING THE RESPONSE TO THE FUKUSHIMA DAI-ICHI NUCLEAR POWER PLANT EMERGENCY

G. Sugiyama*, J.S. Nasstrom, B. Pobanz, K. T. Foster, M. Simpson,
P. Vogt, F. Aluzzi, M. Dillon, and S. Homann

Lawrence Livermore National Laboratory, University of California
Livermore, California

1. INTRODUCTION

This paper summarizes the activities of the National Atmospheric Release Advisory Center (NARAC) during the Fukushima Dai-ichi nuclear power plant crisis. NARAC provided a wide range of products and analyses as part of its support including:

- Daily Japanese weather forecasts and hypothetical release (generic source term) dispersion predictions to provide situational awareness and inform planning for U.S. measurement data collection and field operations
- Estimates of potential dose in Japan for hypothetical scenarios developed by the Nuclear Regulatory Commission (NRC) to inform federal government considerations of possible actions that might be needed to protect U.S. citizens in Japan
- Estimates of possible plume arrival times and dose for U.S. locations
- Plume model refinement and source estimation based on meteorological analyses and available field data

The Department of Energy / National Nuclear Security Administration (DOE/NNSA) deployed personnel to Japan and stood up "home team" assets across the DOE complex to aid in assessing the consequences of the releases from the Fukushima Dai-ichi Nuclear Power Plant. The DOE Nuclear Incident Team (NIT) coordinated response activities, while DOE personnel provided predictive modeling, air and ground monitoring, sample collection, laboratory analysis, and data assessment and interpretation. DOE deployed the Aerial Measuring System (AMS), Radiological Assistance Program (RAP) personnel, and the Consequence Management Response Team (CMRT) to Japan. DOE/NNSA home team assets included the

- Consequence Management Home Team (CMHT)
- National Atmospheric Release Advisory Center (NARAC)

 * *Corresponding author address*: Gayle Sugiyama, L-103, LLNL, P.O. Box 808, Livermore, CA 94550, USA; e-mail: sugiyama1@llnl.gov

- Radiation Emergency Assistance Center / Training Site (REAC/TS)
- Radiological Triage

NARAC was activated by the DOE/NNSA on March 11, shortly after the Tohoku earthquake and tsunami occurred. The center remained on active operations through late May when DOE ended its deployment to Japan. Over 32 NARAC staff members, supplemented by other LLNL scientists, invested over 5000 person-hours of time and generated over 300 analyses and predictions.

2. NARAC Background

The National Atmospheric Release Advisory Center (NARAC) provides detailed assessments of the dispersion and potential downwind consequences of atmospheric releases of hazardous materials (Nasstrom et al. 2007; Sugiyama et al. 2010). NARAC experts at Lawrence Livermore National Laboratory (LLNL) are available 24/7 to provide quality-assured analyses, utilize observations and field measurement data to refine analyses, and assist decision makers in product interpretation. The center supports real-time emergency response, pre-planning and post-incident assessments, and research.

NARAC is the atmospheric dispersion modeling center for DOE/NNSA emergency operations and one of the components of the Consequence Management Home Team (CMHT). The center supports other sponsors and missions and serves as the operations hub for the Department of Homeland Security (DHS)-led Interagency Modeling and Atmospheric Assessment Center (IMAAC), whose role it is to coordinate plume modeling during events requiring federal coordination.

NARAC utilizes a distributed modeling system to predict the potential impacts of hazardous atmospheric releases. The system incorporates a suite of source term, meteorological, dispersion, and dose-response models, databases of hazardous material properties, and graphical and statistical analysis tools. The center maintains extensive global geographical databases and obtains real-time global meteorological data from the National Oceanic and Atmospheric Administration (NOAA), the Department

of Defense (DoD), regional networks, and other sources. Both a meteorological data assimilation model (ADAPT) and the Weather Research and Forecasting (WRF) model are used to develop analysis and forecast atmospheric fields. The center's dispersion model, LODI, solves the advection-diffusion equation using a Lagrangian stochastic Monte Carlo approach. Other specialized modeling capabilities are available to estimate nuclear prompt effects, blast damage, fallout, resuspension, urban impacts, and corrections to indoor exposures based on sheltering/shielding.

NARAC predictions provide estimates of affected areas and populations, potential casualties, health effects, protective action guides, contaminated areas, and damage zones to assist decision makers and responders in taking actions to protect the public and the environment. Model outputs of air and ground contamination are processed to calculate radiological dose from inhalation, air immersion and ground-shine, chemical exposures, and/or lethal dose (chemical/biological) concentration levels. The concentrations of interest are related to available federal protective action guide levels for evacuation/sheltering, worker protection, relocation, and agricultural impacts as appropriate. During events, the center acquires chemical, biological, and/or radiological monitoring data for use in refining model predictions.

3. NARAC RESPONSE ACTIVITIES

NARAC provided a wide range of simulations and analyses at the request of DOE and other US government agencies during the Fukushima crisis. These included weather forecasts, dose calculations for hypothetical scenarios to inform emergency response planning, predictions of arrival times and dose levels reaching U.S. territories, and source estimates based on the incorporation of field measurement data. Each of these activities is described below (Sugiyama et al., 2012 provides further details).

3.1 Weather Forecasting for Mission Planning

NARAC provided weather forecasts to DOE and other US government agencies in Japan to support mission planning and situational awareness. Initially thrice-daily 24 hr or 48 hr forecasts were provided due to rapidly changing weather conditions and mission support requirements, although the frequency was later reduced to once per day. NARAC generated 5-km forecasts using the Weather Research and Forecast (WRF) model (Skamarock et al., 2008), driven by NOAA global GFS model output (Environmental Modeling Center, 2003). Regular consistency checks were made with available NOAA HYSPLIT forecasts and Japanese meteorological data. Animations of hypothetical generic plumes were produced from these forecasts to provide situational awareness to non-meteorologists, along with tabular

summaries of wind speed and direction, atmospheric stability, and precipitation for selected locations.

3.2 Hypothetical Scenarios

In the first weeks of the response, DOE/NARAC worked closely with the Nuclear Regulatory Commission (NRC) and the White House Office of Science and Technology Policy to develop and estimate impacts for a wide range of scenarios. These estimates were used as guidance to inform federal government considerations on possible actions that might be needed to protect U.S. citizens in Japan.

NARAC simulations were used to calculate plume arrival times and protective action guide areas for sheltering / evacuation, relocation, iodine administration, and worker protection from hypothetical source terms developed by the NRC. Simulations were made of both separate and combined impacts for potential releases from the reactor cores and spent fuel pools. The scenarios used a variety of meteorological conditions including both real-world weather and artificial conditions. Typical calculations modeled the top 20 radionuclide contributors to dose, although some calculations used extended lists of over 70 radionuclides. Figure 1 shows an example of the results of one such simulation.

Figure 1. Example of the 14-day Total Effective Dose for a hypothetical release scenario. The color contours show the 1 (yellow) and 5 (orange) rem dose levels.

3.3 Estimates of US Arrival Times and Dose

NARAC estimated plume arrival times for selected locations in the US and its territories, including the West Coast, Alaska, Hawaii and Guam, based on NOAA GFS 0.5 degree meteorological forecasts and/or analyses. Dispersion simulations were made of nominal unit release rates of radionuclide marker particles over sequential 12 or

24-hour periods (Figure 2). Dose estimates were developed by scaling the resulting air or surface concentrations with NRC-radionuclide source terms and DOE CMHT dose conversion factors and derived response levels (SNL, 2010).

NARAC predictions were later shown to be consistent with detected plume arrival times. NARAC/CMHT modeling also indicated that levels of concerns were not likely to be reached in the U.S. territories locations considered, a conclusion later verified by radiation measurements collected by the Environmental Protection Agency's RadNet monitoring network (EPA 2011).
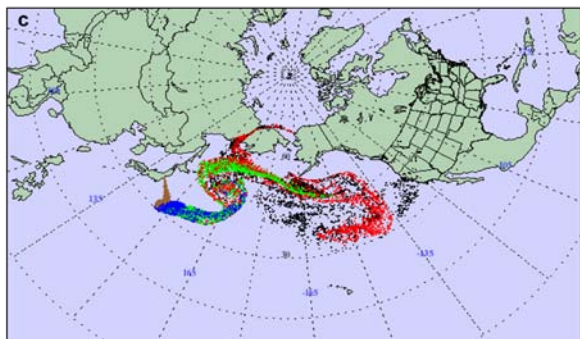

Figure 2. Example of a trans-Pacific simulation of radionuclide marker particles. Different colors are used to distinguish marker particles released during different 24-hour periods.

3.4 Meteorological Forecasting and Analysis

Complex, rapidly-changing meteorological conditions during the on-going releases presented a significant modeling challenge. NARAC meteorological forecasts and analyses showed that winds remained primarily off-shore during the first two days of the release period (except for one brief period on March 12), followed by a rapid clockwise directional rotation over the period of March 14-16 which drove the plume first to the south, then the west, northwest and back off-shore. Wind directions remained primarily off-shore again until approximately March 21, when wind directions veered toward the south taking potential plumes in the general direction of Tokyo.

Precipitation occurred episodically throughout the release period (Japan Weather Association, 2011) and was found to be a significant factor affecting radionuclide transport and deposition during both the March 14-16 and March 21-22 periods of on-shore flow. In particular, precipitation appears to be a primary contributor to the high deposition footprint later measured to the northwest of the Fukushima nuclear power plant (Figure 3).

Real-time NARAC weather forecasting using the WRF model captured the overall wind shifts and occurrence of precipitation. Initial meteorological forecasts were refined by conducting WRF four dimensional data assimilation (FDDA) simulations that used Japanese meteorological observations as these data became available. The FDDA simulations used analysis nudging (Stauffer and Seaman 1994) for the outer model domains (27, 9, and 3 km grid spacing) and observational nudging (Liu et al. 2005) for the innermost domain (1 km grid spacing). The higher resolution WRF FDDA simulations provided increased accuracy in modeling the timing and location of wind shifts, precipitation, and deposition. For example, comparisons of time series of measured and WRF-modeled precipitation rates showed good agreement with data from meteorological stations located near Tokyo and Fukushima City
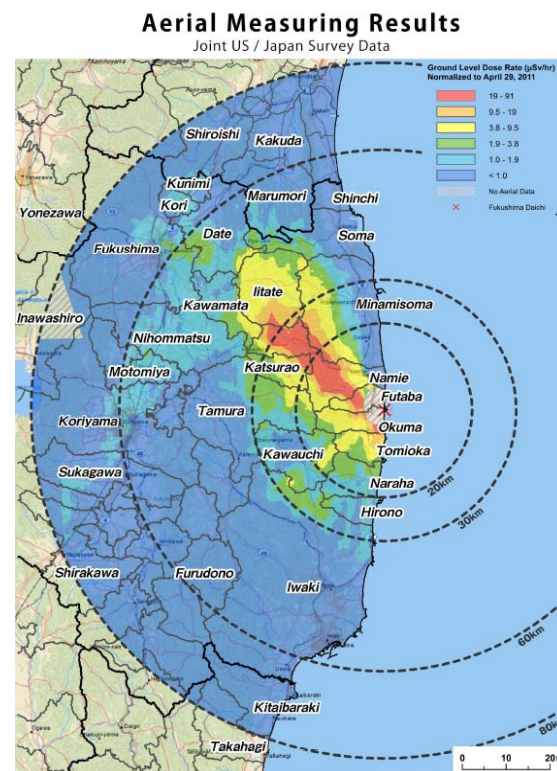

Figure 3. Example of DOE/NNSA Aerial Measuring Survey (AMS) dose rate data (US DOE/NNSA 2011).
.

3.5 Model Refinement Based on Data

NARAC conducted an initial set of source reconstruction and model refinement analyses during the response. A preliminary review of meteorological conditions and the limited environmental radiological measurement available at that time led the center to focus most of its source reconstruction efforts during the response on the period from March 14-16.

NARAC was only able to quality assure and incorporate into its analyses a small portion of the voluminous data collected. The center primarily utilized dose-rate measurements from Japanese locations, since this was the focus of DOE data collection. Initially radiological (and meteorological) data were very sparse with increasing volumes of data collected after the first week. Data used by NARAC included:

- On-site plant radiological measurements (however, time gaps occurred during key periods when the monitors were off-line due to the earthquake and tsunami and when the plant was evacuated on March 15)
- Dose rate time series from Japanese radiological monitoring stations (MEXT), although most data was only available post March 15 0900 UTC (GOJ 2011d)
- DOE Aerial Measuring Survey (AMS) data that was collected starting on March 17-18 (US DOE/NNSA 2011)
- DOE / DoD ground monitoring data
- DOE laboratory sample analyses
- Limited information regarding reactor and spent fuel pool conditions.

NARAC source reconstruction and model refinement (Figure 4) was conducted by simulating a small number of primary contributors to radiological dose: ^{137}Cs, ^{134}Cs, ^{131}I and ^{133}Xe, with the later addition of ^{132}I and ^{132}Te. Relative activity ratios of these radionuclides were determined *a priori* from available radionuclide analyses. Releases from all reactor units and spent fuel pools were treated as one combined source. Meteorological fields were developed from both local meteorological data provided by Japanese stations and numerical weather prediction forecasts using WRF (FDDA) simulations at 1, 3, 5, and 15-km resolution. NARAC optimized the overall fit to dose-rate data using comparisons of model predicted values paired in space and time to the available measurement data.
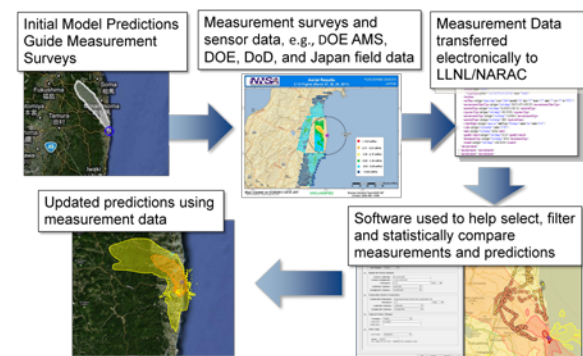

Figure 4. Schematic diagram of the process by which monitoring and sampling data are incorporated into NARAC model predictions.

A range of emission rates were found to be consistent with the available dose-rate data, within model and measurement uncertainties. Source term estimates were sensitive to source term input assumptions (e.g., time-varying vs. constant emission rates, assumed radionuclide mix and activity ratios, release characteristics, reactor conditions), the choice of meteorology (e.g., observational data vs. WRF FDDA fields), and the selection of the radiological data (e.g., AMS, MEXT) to preferentially match in the model refinement process. Predicted ground-shine deposition patterns were found to be heavily influenced by precipitation scavenging, especially the northwest deposition "footprint" measured by the Aerial Measuring Survey (see Figure 3 and US DOE/NNSA 2011).

NARAC source estimates for the March 14-16 period are consistent with a number of published estimates (e.g., Chino et al. 2011; GOJ 2011a, 2011b, and 2011c; Stohl et al. 2011), within expected uncertainties inherent in physics models, source reconstruction methodologies, and data. Source estimates for off-shore-wind times are significantly more speculative as Japanese radiological measurement data are generally unavailable for these periods, requiring the use of sparser and longer-range measurements and model calculations.

4. FUTURE WORK

During the DOE After Action Review process a number of scientific challenges were identified and a set of recommendations were made to make improvements. These included the need to:

- Improve modeling to more accurately simulate complex meteorological conditions and dispersion, including precipitation scavenging
- Incorporate nuclear reactor expert analyses and laboratory analysis data more quickly to improve source term estimates and refine modeled isotopic mix
- Investigate the use of ensemble forecasts to develop probabilistic arrival times and impact estimates for both regional (e.g. Japan) and long-range (e.g., trans-Pacific) cases
- Determine to what degree multiple release events from different reactor sources can be distinguished via time-varying radionuclide signatures and/or reactor analyses
- Develop better understanding of the interplay between, and sensitivity of, source estimates, meteorological conditions and other release characteristics (e.g., release height, radionuclide mix, particle size distribution)
- Determine to what degree available data constrains release rates during off-shore flow periods
- Utilize the complete set of Japanese and global radiological data sets (e.g., sample and spectral analyses, Comprehensive Test Ban Treaty

Organization, EPA RadNET (2011), and U.S. nuclear power plant data) to develop more comprehensive source estimates

5. CONCLUSION

The releases from the Fukushima Dai-ichi nuclear power plant are still incompletely characterized due to the long-term duration of the event, the rapidly changing and still unknown reactor and spent fuel conditions at multiple units, the complicated geography of the region, the highly-variable meteorological conditions, and the relatively limited data available during the early stages of the event when the most significant releases are likely to have occurred. The Fukushima data set needs to be further analyzed and used to improve and evaluate meteorological and dispersion modeling, data assimilation, dose assessment, and source reconstruction methodologies in order to improve capabilities for responding to future events of a similar scale and complexity.

REFERENCES

Chino M, Nakayama H, Nagai H, Terada H, Katata G, Yamazawa H., 2011: Preliminary Estimation of Release Amounts of I-131 and Cs-137 Accidentally Discharged from the Fukushima Dai-ichi Nuclear Power Plant into the Atmosphere. J. Nuc. Sci and Tech. 48: 1129-1134.

Environmental Modeling Center, 2011: The GFS Atmospheric Model. NCEP Office Note 442, Global Climate and Weather Modeling Branch, EMC, Camp Springs, Maryland, 2003.
http://nws.noaa.gov/ost/climate/STIP/AGFS_DOC_1103.pdf

Environmental Protection Agency (EPA) 2011: Japanese Nuclear Emergency: Radiation Monitoring. http://www.epa.gov/japan011/rert/radnet-data.html

Government of Japan, 2011a: Ministry of Economy Trade and Industry News Release,: INES (the International Nuclear and Radiological Event Scale) Rating on the Events in the Fukushima Dai-ichi Nuclear Power Station by the Tohoku District – off the Pacific Ocean Earthquake, 12 April, 2011.

http://www.nisa.meti.go.jp/english/files/en20110412-4.pdf

Government of Japan, 2011b: Report of Japanese Government to IAEA Ministerial Conference on Nuclear Safety – The Accident at TEPCO's Fukushima Nuclear Power Stations. Transmitted by Permanent Mission of Japan to IAEA, 7 June 2011. http://www.iaea.org/newscenter/focus/fukushima/japan-report/

Government of Japan, 2011c: Additional Report of the Japanese Government to the IAEA – Accident at TEPCO's Fukushima Nuclear Power Stations. Transmitted by Nuclear Emergency Response Headquarters, Government of Japan, 15 September 2011.
http://www.iaea.org/newscenter/focus/fukushima/japan-report2/

Government of Japan, 2011d. Ministry of Education, Culture, Sports, Science & Technology in Japan (MEXT). Reading of environmental radioactivity level (English version);
http://www.mext.go.jp/english/incident/1303962.htm

Japan Weather Association, 2011: Meteorology Data Service. http://tenki.jp

Liu Y, Bourgeois A, Warner T, Swerdlin S, Hacker J. An implementation of obs-nudging-based FDDA into WRF for supporting ATEC test operations. 2005 WRF user workshop paper 10.7; 2005.
http://www.rap.ucar.edu/projects/armyrange/references/publications/Liu_WRF-WK.2005.pdf

Nasstrom JS, Sugiyama G, Baskett RL, Larsen SC, Bradley MM, 2007: The NARAC modeling and decision support system for radiological and nuclear emergency preparedness and response. *Int. J. Emergency Management* **4:**524-550

Sandia National Laboratories, 2010: *FRMAC Assessment Manual Volume 1, Overview of Methods.* SAND2010-1405P, Sandia National Laboratories, Albuquerque, NM.

Skamarock WC, Klemp JB, Dudhia J, Gill DO, Barker DM, Duda MG, Huang X-Y., Wang W, Powers JG. A Description of the Advanced Research WRF Version 3. NCAR Technical Note, NCAR/TN–475+STR; 2008.
http://www.mmm.ucar.edu/wrf/users/docs/arw_v3.pdf

Stauffer DR, Seaman NL., 1994: On Multi-Scale Four-Dimensional Data Assimilation, *J. Appl. Meteor.* **33**:416-434.

Stohl A., Seibert P, Wotawa G, Arnold D, Burkhardt JF, Eckhardt S, Tapia C, Vargas A, Yasunari T., 2011: Xenon-133 and caesium-137 releases into the atmospheric from the Fukushima Dai-ichi nuclear

power plant: determination of the source term, atmospheric dispersion, and deposition, Atmos. Chem. Phys. Discuss. 11:28319–28394; www.atmos-chem-phys- discuss.net/11/28319/2011/doi:10.5194/ /acpd-11-28319-2011

Sugiyama G, Nasstrom JS, Baskett R, Simpson M. National Atmospheric Release Advisory Center (NARAC) Capabilities for Homeland Security. 2010: Proceedings of the *5th International Symposium on Computational Wind Engineering,* Chapel Hill, NC May 23-27, 2010; 2010.

Sugiyama, G., J. Nasstrom, B. Pobanz, K. Foster, M. Simpson, P. Vogt, F. Aluzzi, and S. Homann, 2011: Atmospheric Dispersion Modeling: Challenges of the Fukushima Dai-ichi Response, accepted for publication in the *Health Physics* (LLNL-JRNL-521757)

US DOE/NNSA, 2011 Response to 2011 Fukushima Incident- Raw Aerial Data and Extracted Ground Exposure Rates and Cesium Deposition; 2011. Available at http://explore.data.gov