

METHODS FOR ESTIMATING THE ATMOSPHERIC RADIATION RELEASE FROM THE FUKUSHIMA DAI-ICHI NUCLEAR POWER PLANT

BY PAUL E. BIERINGER, STEVEN HANNA, GEORGE YOUNG, BRANKO KOSOVIC, JOHN HANNAN, AND RYOHI OHBA

On 11 March 2011, a 9.0-magnitude earthquake off the east coast of Japan and subsequent tsunami caused widespread damage in northeastern Japan and resulted in a cooling system failure, partial reactor core meltdown, and radiation release from the Fukushima Dai-ichi nuclear power plant (FD-NPP). Following the devastating earthquake and tsunami that severely damaged the nuclear power plant in Fukushima, Japan, an unknown quantity of radioactive material was released into the air and water surrounding the crippled nuclear power plant. Assessments of the remaining nuclear fuel following the incident have allowed the scientific community to approach a consensus on the total amount of radioactive material released from the FD-NPP. What is still unclear, however, is the timing of the releases and how much of the radioactive material was released into the atmosphere versus directly into the nearby ocean. The complexity of this disaster—which included disabled observation systems; multiple intermittent explosive releases of radioactive materials combined with a long-duration continuous release of radiation at an unknown rate; and changes in boundary layer depth, wind speed/direction, and precipitation in the region surrounding the FD-NPP—complicates these estimates.

An accurate estimate of the radiation released into the atmosphere from the FD-NPP is necessary for scientists and government officials to make informed decisions that impact the estimation of long-term

SOURCE TERM ESTIMATION METHODS FOR ESTIMATING RADIATION RELEASE FROM THE FUKUSHIMA DAI-ICHI NUCLEAR PLANT

WHAT: A multidisciplinary group of scientists and engineers from academia/private industry/government/national laboratories in the United States, Japan, and Europe convened to discuss the Fukushima Dai-ichi nuclear power plant incident, observations of the radiation deposition patterns, and methods to use these measurements to better estimate the total radioactive material released into the atmosphere.

WHEN: 22–23 February 2012

WHERE: National Center for Atmospheric Research, Boulder, Colorado

doses and the safety of people living and working near Fukushima. While extensive observational surveys of the radiation fallout pattern have been made, using these measurements to estimate the magnitude and timing of radiation released into the atmosphere versus the ocean remains a challenging undertaking. Despite the large number of observations available, they cover only a small fraction of the area and time period. Consequently, current estimates include a large degree of uncertainty, resulting in correspondingly large uncertainties regarding the total amount of radiation fallout and associated environmental impacts, which significantly hamper the Japanese

government's ability to estimate doses and preserve the public's safety.

To address these ongoing challenges, the National Science Foundation (NSF) recently sponsored a workshop held at the National Center for Atmospheric Research (NCAR) that brought together an international group of researchers, pictured in Fig. 1, from academia, government labs, government agencies, and private industry and included representatives from the Japan Atomic Energy Agency (JAEA), the Japan Nuclear Safety Research Association (NSRA), and the Kansai Electric Power Company. The names and affiliations of the participants, plus all of the other conference materials that could be publically released (agenda, presentations, and working group summaries), are currently available online (see www.ral.ucar.edu/nsap/events/fukushima/).

Together, the participants' wide diversity of skill sets included expertise on the Fukushima Dai-ichi incident, nuclear power plant operations and safety, issues associated with measuring radiation during and following the incident, atmospheric boundary layer, transport and dispersion, source term estimation (STE) methods for hazardous airborne materials, and numerical weather prediction and data assimilation. The goal of the workshop was to present current STE approaches, available data, and discuss how the current state of the science can be extended to address these challenging unanswered questions related to the FD-NPP incident. Information from the workshop is being compiled and documented for use by the scientific community to develop and enhance technologies that could be used in the future should a similar release of radiation of unknown quantity happen again. A day and a half of technical presentations set the stage for a subsequent day of open discussions both among the workshop steering



FIG. 1. Meeting participants take a break from the workshop in Boulder, Colorado, to pose in the falling snow.

committee and within separate breakout sessions during which everyone at the meeting participated. Five breakout sessions were organized around the following topics: 1) observations, 2) uncertainty and physical process modeling, 3) back-trajectory STE methods, 4) nongradient descent STE methods, and 5) gradient descent and miscellaneous STE methods. The results and findings from both the formal presentations and the follow-on discussions resulted in recommendations for scientific options that can be used to quantify the amount of radiation released from the Fukushima power plant and inform the broader scientific community on how to better address this type of problem. These results are being provided to our Japanese colleagues to help address their immediate needs and will also be published in a peer-reviewed journal to inform the broader scientific community.

HIGHLIGHTS. Situations like the FD-NPP incident have the potential to be high-consequence events, which result in large numbers of injuries, casualties, and radiological doses that may have long-term health consequences and have long-lived and severe economic impacts. The information needs of the first responders and local and national decision makers span a broad time range extending from hours to months, even years, from the initiation of the incident. This incident highlights many of the challenges that must be overcome for decisions to be made in an event that has significant temporal variation; occurs over a long time frame; and follows a catastrophic natural disaster where much of the local

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infrastructure, including observational networks, are inoperable. The STE methods employed must be capable of contributing actionable knowledge of the incident and flexible enough to meet the varied information fidelity and needs across this same time range.

The workshop presentations covered a broad range of topics that are elements of the airborne contaminant source inversion problem. These include prior knowledge of the source term (e.g., location, limits on rates/amounts of material released, timing of release), atmospheric physics (e.g., transport and dispersion and physical effects such as deposition, decay, and dilution), and observations of contaminant material and the atmosphere required to reconstruct the source term. There are several research communities currently developing this type of technology for various applications (Fig. 2) including air quality monitoring, volcanic ash plume hazard estimates for aviation, and chemical/biological/radiological/nuclear/high explosives (CBRNE) defense applications. While the specific needs of the CBRNE, volcanic ash, and air quality monitoring applications can differ significantly from what is required for a nuclear power plant radiation

release incident, the core set of technical approaches commonly used is similar. The range of methods for STE presented at the workshop included examples and descriptions of back-trajectory methods, gradient descent and adjoint-based methods, Bayesian methods, evolutionary algorithm methods, and polynomial chaos methods. While not exhaustive, the workshop attendees believe that the methods presented cover the most commonly used approaches for this class of problem.

Following the formal presentations, the workshop participants discussed the challenges faced by the scientific and engineering communities who are attempting to better understand the implications of this disaster. The challenges fell into three primary categories. The first challenge discussed was the limitations associated with the fidelity of the models used in the STE process. This includes the atmospheric transport and dispersion models as well as the models representing physical processes associated with interpreting the radiation measurements and diagnosing the contributions of sky shine, cloud shine, and ground shine to the total radiation measurements observed from airborne measurement

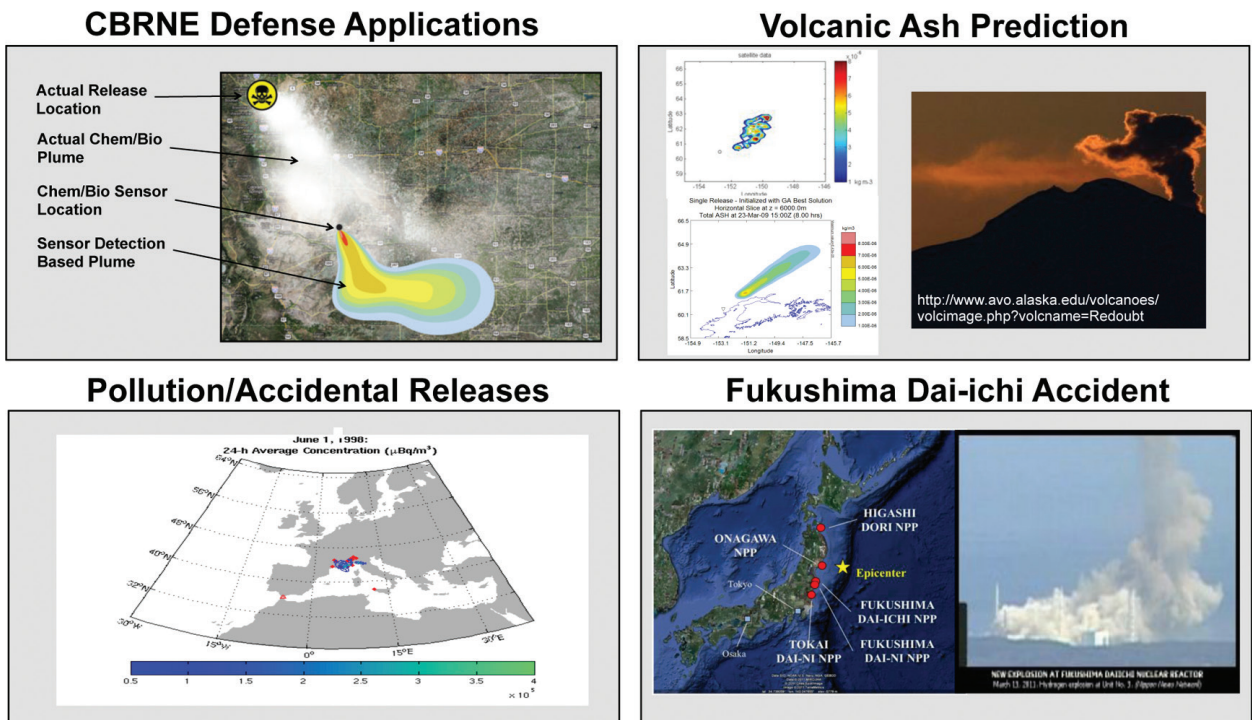


FIG. 2. Applications where STE methods are commonly used. (top left) Image depicts the source location and downwind hazard challenge faced by the CBRNE defense community (Bieringer et al. 2011). (top right) Image depicts the results from a STE study by Schmehl et al. (2012) investigating ash releases from Mount Redoubt. (bottom left) Image depicts downwind concentration simulations based on an STE estimate of the release of radioactive materials from Algeciras, Spain (Delle Monache et al. 2008). (bottom right) The location of the Tohoku earthquake, locations of impacted nuclear power plants, and an image of the FD-NPP during the incident.

platforms. The second challenge is associated with the constant evolution of the incident. Not only is the radiation release event constantly evolving, but so too are the weather conditions impacting the dispersion and fallout of radiation. Throughout an event of this type, the background radiation is also continually evolving as the various radioactive materials both decay and interact with the environment. This complicates the use of radiation measurements collected at different times to estimate the radiation release rates in STE approaches. Finally, the Tohoku earthquake and subsequent tsunami destroyed not only the critical infrastructure required to operate the nuclear power plant but also the observation network and general power and communications infrastructure that are necessary to monitor the radiation releases and environmental conditions during the reactor meltdown. This resulted in a lack of useful observations and corresponding knowledge gap during the initial days of the incident when critical crisis mitigation and emergency response decisions were being made.

CONCLUSIONS AND RECOMMENDATIONS. During the breakout sessions, the five teams also identified a set of recommendations aimed to enhance our ability to address the challenges identified above and meet the need for improved information on radiation releases during nuclear power plant accidents. The first recommendation was to take better advantage of the knowledge gained and lessons learned from the FD-NPP incident. This includes creating a central database of observations and information from this incident that could be used in future investigations and algorithm development efforts by the research community. The second recommendation from the workshop participants stressed the need to further invest in the fundamental science associated with using radiation dosage in atmospheric STE. This topic has yet to be extensively studied and could be enhanced at a modest level of support by university and graduate student researchers. Furthermore, the establishment of a glossary of common terminology that would be used among the various research communities working on STE problems would enhance the information sharing between groups that traditionally have worked on STE methodologies in

isolation. Nominal environmental impacts for similar incidents could be precomputed for nuclear power plants in high-value/high-consequence locations and the results made part of the emergency response procedures. The information gap immediately following the FD-NPP incident could be addressed by hardening the existing observational platforms near nuclear power plants and by establishing an on-call, rapidly deployable set of instrumentation to replace or augment existing equipment. Finally, radiation STE methods and information on the associated uncertainties could also better be incorporated into the consequence management process by including STE information in the responding organizations, training exercises.

Overall, the FD-NPP disaster suggests a pressing need for nuclear power safety organizations and the scientific community to revisit this topic. These needs and corresponding priorities can be identified through panels such as the National Academy of Science in collaboration with government agencies (e.g., Department of Energy, Department of Homeland Security, Department of Defense) that have relevant expertise. Finally, in addition to the scientific aspects of providing better estimates of the radiation releases and subsequent downwind hazard, the connection to the decision-making process could benefit from a more detailed examination and refinement of the connections back to science.

REFERENCES

- Bieringer, P. E., and Coauthors, 2011: Fusion of chemical, biological, and meteorological observations for agent source term estimation and hazard refinement. *Multisensor, Multisource Information Fusion: Architectures, Algorithms, and Applications 2011*, J. J. Braun, Ed., International Society for Optical Engineering (SPIE Proceedings, Vol. 8064).
- Delle Monache, L., and Coauthors, 2008: Bayesian inference and Markov chain Monte Carlo sampling to reconstruct a contaminant source on a continental scale. *J. Appl. Meteor. Climatol.*, **47**, 2600–2613.
- Schmehl, K. J., S. E. Haupt, and M. J. Pavolonis, 2012: A genetic algorithm variational approach to data assimilation and application to volcanic emissions. *Pure Appl. Geophys.*, **169**, 519–537.