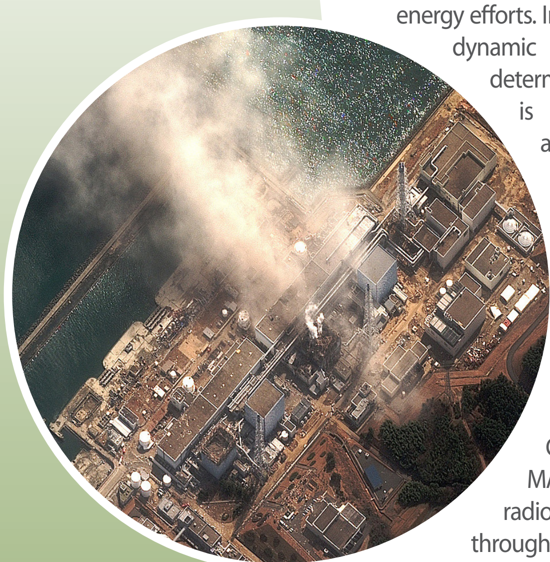
Sandia National Laboratories

Energy, Climate & Infrastructure Security

Severe Accident Modeling

SAND2012-0987P

Sandia leverages severe accident modeling to support its nuclear energy efforts by developing risk margins, creating risk assessments, sequencing nuclear reactor accident progression, and performing reactor consequence modeling.



Damaged reactor buildings from the Fukushima Daiichi Nuclear Power Plant

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Dynamically Modeling Severe Accidents

Sandia draws on capabilities developed through severe accident modeling to support its nuclear energy efforts. In addition to developing risk margins, dynamic probabilistic risk assessments, and deterministic risk assessments, Sandia is able to sequence nuclear reactor accident progression as well as reactor consequence modeling. Severe accident modeling phenomena include thermal-hydraulic response; core heat-up; degradation and relocation; hydrogen production, transportation, and combustion; and fission product release and transport behavior.

Computer codes such as MELCOR and MACCS dynamically model sequences of radioactive material release from inception through potential radiological release allowing estimations of atmospheric dispersion, as well as economic and health consequences.

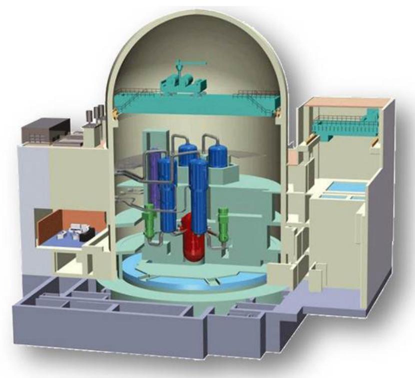
Systems-Based Capabilities

Supporting the modeling and analysis of accidental nuclear and hazardous material releases from nuclear power plants, Department of Energy facilities, and other hazardous facilities, Sandia draws on its legacy weapons-based mission work in support of the nation's evolving needs. Though capable of performing analysis on specific aspects of a severe accident situation, Sandia's strength lies in applying a comprehensive, systems-based approach to modeling and simulation analysis.

- Comprehensive Event Modeling and Analysis: Accident modeling from event inception through the potential radiological release is critical in creating useful, realistic simulations. These comprehensive simulations model multiple critical elements of the situation including variants such as atmospheric dispersion, economic consequences, and health consequences with enhanced detail. This ultimately creates an increasingly robust and reliable set of information for analysis.

- Uncertainty Analysis and Sensitivity Studies: As accidents represent a convergence of any number of situational variants, uncertainty analysis and senstivitiy studies prove instrumental in producing useful, representative models and simulations. Applying degrees of measurement and statistical models to uncertain elements and potential variation attribution enhance and refine the models and the resulting analysis.

- MELCOR: A fully integrated, engineering-level computer code designed to model accident progression in light water reactor (LWR) nuclear power plants, MELCOR models a broad spectrum of severe accident phenomena through a unified framework. MELCOR applications can estimate severe accident source terms and their associated sensitivities and uncertainties in a variety of regimes and scenarios.

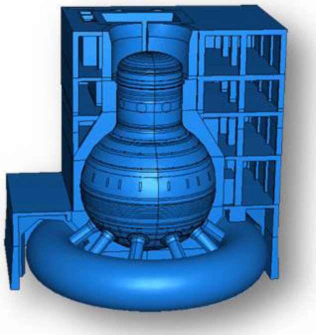


A MELCOR model of a pressurized water reactor, containment, and auxiliary building.

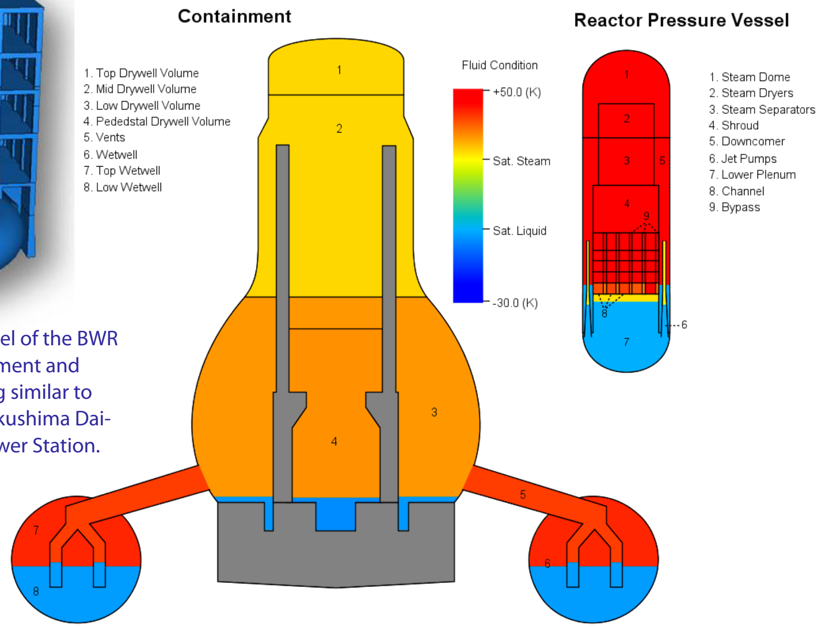
- MACCS2: Developed to analyze the offsite consequences of an accidental atmospheric release of radioactive material, MACCS2 is a fully integrated, engineering-level computer code. MACCS2 provides detailed analysis of an accident by calculating a radiological release's atmospheric transport and envrionmental dispersion. Designed primarily as a probabilistic risk assessment (PRA) tool, MACCS2 analysis results include land contamination levels and areas, doses to individuals and populations, health effects and risks, and economic losses resulting from an accident.

Accident Planning, Preparation, and Management

The analysis of severe accident models and simulations provides input that can be used for a variety of purposes. For example, Sandia uses this type of analysis as support for its nuclear power plant risk assessments. Accounting for complex systems-based variables including situational dimensions such as human reliability, emergency preparedness and response, physical security, and cyber security, accident modeling illuminates and identifies areas of potential vulnerability informing both probabilistic and deterministic risk analyses.



A detailed model of the BWR Mark I containment and reactor building similar to those at the Fukushima Dai-ichi Nuclear Power Station.



Once vulnerabilities are identified, comprehensive accident modeling also plays an important role in designing and carrying out accident management and mitigation measures. Although difficult, stressful, and at times dangerous, effective accident management requires strategic preparation based on many situational factors that can be simulated through accident models. Creating a variety of accident scenarios accounting for specific conditions, Sandia assesses the severity of the modeled accident and a number of potential recovery options are devised.

Sandia also assists regulatory agencies in decision processes and negotiation using its severe accident modeling capabilities. As a Federally Funded Research and Development Center (FFRDC), Sandia occupies a position of trust and independent technical judgement for the federal government. This allows it to leverage its expertise in accident modeling to inform and educate decisionmakers in addition to numerous tactical applications.

At 70-feet tall and 35-feet in diameter, this ¼ scale containment is the largest nuclear reactor containment vessel model ever tested to failure.

Sandia and the Fukushima Reactor Crisis

In the face of a series of equipment failures, nuclear meltdowns, and releases of radioative materials at the Fukushima Nuclear Power Plant, Sandia was engaged to provide severe accident modeling support to the Nuclear Regulatory Commission (NRC)-led response effort. First, the Sandia-developed MELCOR computer code was used to develop baseline models. Reactor damage was estimated using these models to include fraction core damage and source term release. Additionally, forecasting was used to predict the outcome of future events.

Over a number of months, Sandia provided daily consults and assistance to the NRC as it managed the situation at Fukushima. Offering incident interpretation, results explanations, and exploration of mitigation options, Sandia played an active and imporatnt role in securing Fukushima.

Publications

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Ashbaugh, S. G., Wagner, K. C., & Gauntt, R. O. (2005). Simulation of mixed oxide (MOX) versus low enrichment uranium (LEU) fuel severe accident response using MELCOR (Sandia Report SAND2005-4361C). Albuquerque, NM: Sandia National Laboratories.

Cole, R. K. (2002, September). Coupling of MELCOR to other codes under an executive program using PVM message exchange. Paper presented at 2002 RELAPS

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Sandia National Laboratories

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RADTRAN

Developed at Sandia National Laboratories, RADTRAN is the national and international standard for transportation risk assessment for radioactive materials.

Transportation of Radioactive Materials: A Necessary Risk

Because the safe and secure transportation of radioactive and hazardous materials poses a number of prominent risks to employees within the nuclear energy enterprise, the environment, and the public at large, measures must be put into place to assess and manage risks. In order to better model and calculate transportation risk of this nature, Sandia National Laboratories developed RADTRAN, considered the national and international standard for transportation risk assessment for radioactive materials.

Risk assessment and consequence analysis for radioactive material transportation assures a safe TRUPCT shipment to WIPP.

RADTRAN: A Unique Code

Sandia developed RADTRAN as a unique environmental impact assessment code for analysis of transportation of radioactive and other hazardous materials. As an internationally validated code, RADTRAN is accepted by the International Atomic Energy Agency. RADTRAN combines user-determined demographic, routing, transportation, packaging, and materials data with meteorological data (partly user-determined) and health physics data to calculate expected radiological consequences of incident-free radioactive materials transportation and associated accident risks.

RADTRAN is a unique program that uses two models to analyze risk associated with the transportation of radioactive materials. First, it uses a routine model. This model displays the vehicle as a sphere depicting the external radiation dose as a virtual source at the center of the sphere. The second model is an accident scenario developed by Sandia using parts of other risk assessment codes. This model can be used to look at risk and uncertainty associated with events such as standard air pollution, economic modeling and loss of lead shielding in the absence of a loss of radioactive material.

A rail shipment modeled by RADTRAN

Using RADTRAN

Originally developed for the U.S. Nuclear Regulatory Commission, RADTRAN has been in use around the globe for 35 years. Publically available at no cost, RADTRAN has over 600 registered users spanning a variety of occupational sectors including federal employees and contractors, members of state and local governments, and individuals from educational institutions. Approximately 25 percent of registered users are international.

However, although RADTRAN and complimentary programs such as RADCAT are publically available, Sandia maintains a degree of RADTRAN expertise unlike that developed in other institutions involved in risk assessments and environmental impact studies. As the developing institution, Sandia researchers best-understand RADTRAN analytics, as well as the most appropriate code applications and limitations. With several follow-on code enhancements and adaptations released, Sandia continues to serve as the source of RADTRAN specialization and expertise.

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Sandia National Laboratories

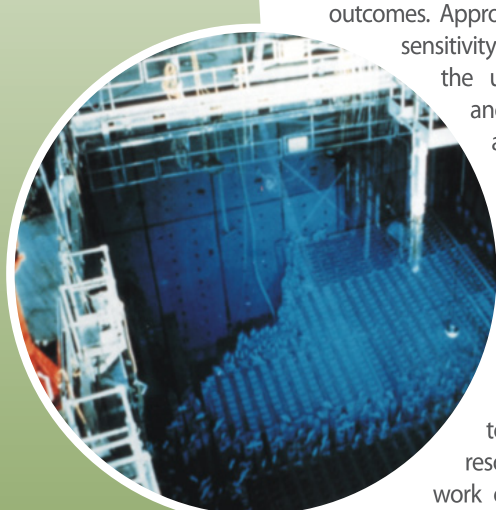
Energy, Climate & Infrastructure Security

Uncertainty and Sensitivity Analysis

Assessing the uncertainty present in any complex problem is an essential part of its analysis and is many times required by major US and international regulatory agencies.

Uncertainty in Complex Systems

Important questions must be answered about the nature, quality, and significance of calculated results. Uncertainty and sensitivity analysis are central to answering such questions. The objective of an uncertainty analysis is to determine the uncertainty in analysis outcomes that results from uncertainty in analysis inputs. The objective of a sensitivity analysis is to determine the effects of the uncertainty in individual analysis inputs on the uncertainty in analysis outcomes. Appropriately designed uncertainty and sensitivity analyses are essential to enhance the usefulness and credibility of risk and safety analyses by providing an unbiased representation and assessment of the relationships between the uncertainty in individual analysis inputs and the uncertainty in analysis outcomes. Such analyses support verification and validation of the model under consideration and provide guidance on how to appropriately invest additional resources to carry out experimental work or detailed studies to reduce the uncertainty in important inputs and thus reduce the uncertainty in analysis outcomes.



Spent fuel is stored in large pools of water to shield its radioactive properties.

Analyzing the Effects in a Systematic Way

When viewed at a high level, most uncertainty and sensitivity analyses involve five components:

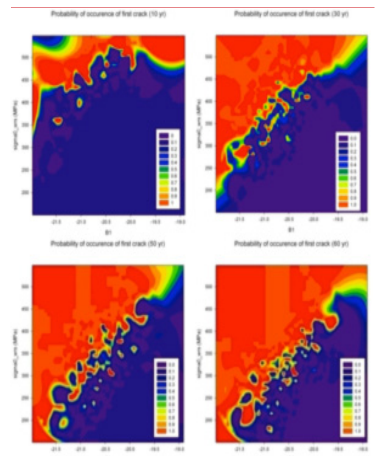
(i) definition of probability distributions to characterize the uncertainty in analysis inputs,

(ii) generation of a sample from the probability distributions for the uncertain analysis inputs,

(iii) propagation of the generated sample through the model under consideration to produce a mapping between values for uncertain analysis inputs and corresponding analysis outcomes,

(iv) organization and display of the probabilistically-based uncertainty in the generated analysis outcomes, and

(v) exploration of the generated mapping between analysis inputs and analysis outcomes with a variety of procedures to obtain sensitivity analysis results.



Contour plots for the parameter sensitivity in the probability of occurrence of the first crack in pressurizer surge nozzles in the primary water piping for Commercial boiling water nuclear reactor.

Sandia has pioneered the development and implementation of techniques for use in the five preceding areas. Sandia's expertise in the design and implementation of uncertainty and analyses for complex systems has successfully played a central role in many applications supporting nuclear reactor safety analysis, severe consequence analyses, and nuclear fuel cycle programs including storage, transportation, and disposal. Sandia maintains world class computing facilities and supporting software for uncertainty and sensitivity analysis utilizing advanced approaches, such as evidence theory and probability theory. Sandia personnel are experts in effectively using these resources.

Building Confidence in High Fidelity Analyses

In a time where great value and trust is placed in computational analyses, future computational analysis that supports an important societal decision may not be accepted as being complete without an adequate assessment of the uncertainties present in its results. This importance is now recognized in many regulatory requirements including assessment of the risk from commercial nuclear power and throughout the nuclear fuel cycle. Uncertainty analyses are used as critical input to probabilistic risk assessments, which use a systematic process to identify possible points of vulnerability within the complex system (such as a nuclear power plant) before an incident or emergency

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situation occurs (i.e., the NUREG-1150 and NUREG/CR-7110 analyses).

Similarly, uncertainty and sensitivity analysis informs performance assessments, which are used to support radioactive waste repository licensing applications. Critical analyses support the National Nuclear Security Administration's mandate for the quantification of margins and uncertainties (QMU) in assessments of the safety and reliability of the United States' nuclear stockpile. Serving as a cornerstone of risk-informed regulation and decision making, these analyses play an ever-increasing role in shaping the future of nuclear and non-nuclear risk analyses.

Publications

Example Sandia references related to uncertainty analysis, sensitivity analysis, and the analysis of complex systems:

(2012). State-of-the-art reactor consequence analyses project (NUREG/CR-7110). Albuquerque, NM: Sandia National Laboratories.

Bonano, E. J. et. al. (2011). Performance assessment at Sandia National Laboratories (SAND2011- Unknown). Albuquerque, NM: Sandia National Laboratories.

Mattie, P. D., Sallaberry, C. J., Helton, J. C., & Kalinich, D. A. (2010). Development, analysis, and evaluation of a commercial software framework for the study of extremely low probability of rupture (xLPR) events at nuclear power plants (SAND2010-8480). Albuquerque, NM: Sandia National Laboratories.

Helton, J. C. (2009). Conceptual and computational basis for the quantification of margins and uncertainty (SAND2009-3055). Albuquerque, NM: Sandia National Laboratories.

(2008). Total system performance assessment model/ analysis for the license application (MDL-WIS-PA -000005 Rev. 00, AD 01). Las Vegas, NV: U.S. Department of Energy Office of Civilian Radioactive Waste Management.

Helton, J. C., Johnson, J. D., Sallaberry, C. J., & Storlie, C. B. (2006). Survey of samplingbased methods for uncertainty and sensitivity analysis (SAND2006-2901). Albuquerque, NM: Sandia National Laboratories.

Helton, J. C. & Davis, F. J. (2002). Latin hypercube sampling and the propagation of uncertainty in analyses of complex systems (SAND2002-0417). Albuquerque, NM: Sandia National Laboratories.

Sandia's uncertainty and sensitivity analysis were critical to permitting the U.S. Department of Energy Waste Isolation Pilot Plant repository shown above.

Special journal issues guest edited by Sandians containing results from analyses performed at Sandia and other institutions related to uncertainty analysis, sensitivity analysis and the analysis of complex systems:

Helton JC, Pilch M, eds. Special Issue: Quantification of Margins and Uncertainty. Reliability Engineering and System Safety 2011;96(9):959-1256.

Helton JC, Cooke RM, McKay MD, Saltelli A, eds. Special Issue: The Fourth International Conference on Sensitivity Analysis of Model Output (SAMO 2004). Reliability Engineering and System Safety 2006;91(10-11):1105-1472.

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Helton JC, Marietta MG, eds. Special Issue: The 1996 Performance Assessment for the Waste Isolation Pilot Plant. Reliability Engineering and System Safety 2000;69(1-3):1-451.

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Helton JC, Burmaster DE, eds. Special Issue: Treatment of Aleatory and Epistemic Uncertainty. Reliability Engineering and System Safety 1996;54(2-3):91-257.

Helton JC, Breeding RJ, eds. Special Issue: The NUREG-1150 Probabilistic Risk Assessments. Nuclear Engineering and Design 1992;135(1):1-137.

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Sandia National Laboratories

Energy, Climate & Infrastructure Security

Transportation of Nuclear and Radioactive Materials

Sandia National Laboratories develops and applies technology to assure the the safe transportation of hazardous materials.

Transporting Materials: A Source of Risk

Because of potential risk to the public, the safe transportation of radioactive and hazardous materials is a matter of significant concern. When evaluating the risks of hazardous and radioactive material transportation, two primary elements must be considered: integrity of the transport package and the route used. Sandia National Laboratories has expertise and sophisticated testing and analysis resources to analyze the risk component of package design. In order to provide accurate, reliable data for informing regulations, environmental management, and the nuclear energy industry, this element serves as an extricable component of the safe and secure transport of radioactive and hazardous materials.

Crash test of a spent fuel truck cask

A Way to Ensure Safe Transport

Sandia plays a significant role in developing and applying technology to assure and demonstrate the safe transportation of radioactive and hazardous materials. While industry performs the majority of package design, Sandia conducts testing and analysis required to determine the response of packages to various situations. These demonstrations provide assurance that transportation of radioactive and hazardous materials is performed safely, and to the degree possible, economically.

Convergence of Disciplines

In order to accurately characterize a package's behavior and response to a specific set of transportation-related conditions (i.e. prolonged exposure to hot or cold weather, vehicle collision, system malfunction during transit, etc.), Sandia leverages expertise and tools in a number of areas constructing a comprehensive, full-spectrum approach to transportation risk analysis. These disciplines include:

Full scale fire test of a spent fuel transportation container

- Package design (development of design models)
- Testing and analysis
- Quality assurance
- Thermal testing and analysis
- Structural testing and analysis
- Fabrication shops/ labs
- Unique extreme analysis
- Regulation development and refinement

Drawing on nearly 60 years of support provided to the Nuclear Regulatory Commission (NRC) and other prominent regulatory agencies through regulation development and refinement, Sandia other situations requiring "above and beyond" safety and security assurance are essential factors that must be considered in the implementation of a particular radioactive package design. Determining the response of packages in regulation and extreme environments plays a key role in assuring the integrity and reliability of radioactive material packages.

RADTRAN

Sandia developed RADTRAN as a unique environmental impact assessment code for analysis of transportation of radioactive and hazardous materials. Although this code was initially developed for the NRC,

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it has been in use around the globe for 35 years. As an internationally validated code, RADTRAN is accepted by the International Atomic Energy Agency (IAEA).

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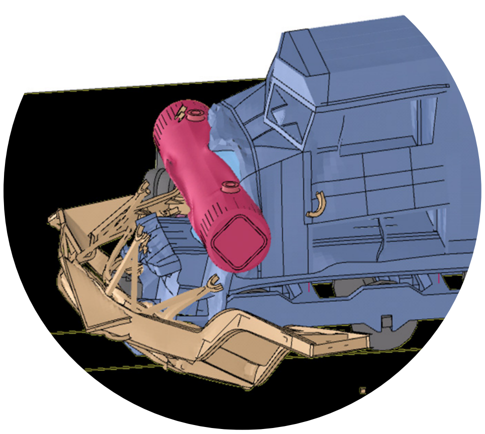
Extreme Environment Testing

Sandia serves as a unique environment for the study of radioactive material transportation because it combines a number of sophisticated, hard-to-find tools and distinct testing facilities into a single organization. These tools and testing facilities allow researchers to examine the risks to a radioactive



Simulation of a train striking a spent fuel truck cask

package in both regulation-based and extreme environments. With the ability to perform classified testing and analysis, Sandia is the only institution in the world that has tested a radioactive package containing radioactive materials.

Unlike other institutions, Sandia performs failure tests in extreme environments through physical testing. Using facilities such as the Rocket Sled Track (a controlled environment for high-velocity impact, aerodynamic, acceleration and related testing of both small and large items) and the Mechanical Shock Facility (where acceleration, strain, force and other data is captured through mechanical shock simulations representing environments produced by transportation, flight, impact, explosive and other dynamic events), packages are subjected to extreme environments allowing researchers to execute performance and risk analysis.

Supporting Industry and Regulatory Agencies

With a long history of support to the NRC and other regulatory institutions, Sandia works closely with national standards and regulatory agencies to make the nuclear energy enterprise safer. Sandia's radioactive transportation packaging analysis helps industrial designers understand and comply with national standards, while providing essential scientific support to create and refine those standards as industry and environmental needs evolve with time. Using this keen developed knowledge base of existing regulations and extra-regulatory needs, Sandia's radioactive transportation work plays an important role in making the nuclear energy enterprise a safer, increasingly assured industry.

Puncture test of the Trupact-III transuranic waste transportation container

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