SANDIA REPORT

SAND2014-1345
Unlimited Release
Printed: February 2014

Nuclear Energy Related Capabilities at Sandia National Laboratories

Susan Y. Pickering, Editor

Prepared by
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ABSTRACT

Sandia National Laboratories' technology solutions are depended on to solve national and global threats to peace and freedom. Through science and technology, people, infrastructure, and partnerships, part of Sandia's mission is to meet the national needs in the areas of energy, climate and infrastructure security. Within this mission to ensure clean, abundant, and affordable energy and water is the Nuclear Energy and Fuel Cycle Programs.

The Nuclear Energy and Fuel Cycle Programs have a broad range of capabilities, with both physical facilities and intellectual expertise. These resources are brought to bear upon the key scientific and engineering challenges facing the nation and can be made available to address the research needs of others. Sandia can support the safe, secure, reliable, and sustainable use of nuclear power worldwide by incorporating state-of-the-art technologies in safety, security, nonproliferation, transportation, modeling, repository science, and system demonstrations.

ACKNOWLEDGEMENT

The work presented in this report was mainly supported by the U.S. Government, specifically, the U.S. Department of Energy and the U.S. Nuclear Regulatory Commission. This report was completed with contributions from the following individuals at Sandia National Laboratories:

Douglas J. Ammerman,
Nathan E. Bixler,
Shawn P. Burns,
Felicia A. Duran,
Randall O. Gauntt,
Margaret A. Harvey,
Michael F. Hessheimer,
Joseph A. Jones,
Imane Khalil,
Patrick D. Mattie,
John T. Michalski,
David R. Miller,
Eleni Otto,
Douglas M. Osborn,
Dana A. Powers,
William G. Rhodes III,
Gary E. Rochau,
Ruth F. Weiner, and
Timothy A. Wheeler.

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LIST OF ACRONYMS

ACRR	Annular Core Research Reactor
ACRS	Advisory Committee on Reactor Safeguards
ASLB	Atomic Safety and Licensing Board
ATHEANA	A Technique for human error analysis
C	Classified
CAROL FIRE	cable response to live fire
CYBL	Cylindrical Boiling facility
DOE	U.S. Department of Energy
DUQI	DedUctive Quantification Index
ETE	evacuation time estimate
EPZ	emergency planning zone
GIF	Gamma Irradiation Facility
HPC	high performance computing
HRA	human reliability analysis
HSRT	Homeland Security Red Team
IDART	Information Design Assurance Red Team
IND	improvised nuclear device
ISFIS	independent spent fuel storage installation
ISL	Information Systems Laboratories
IT	information technology
LEU	low enriched uranium
LNG	liquefied natural gas
LWR	light water reactor
MACCS	MELCOR Accident Consequence Code System
MIDAS	Data Acquisition System
MOX	mixed oxide
MRS	monitored retrievable storage
NMSS	Office of Nuclear Material Safety and Safeguards
NRC	U.S. Nuclear Regulatory Commission
NRR	Office of Nuclear Reactor Regulation
NSIR	Nuclear Security and Incident Response
PCCV	pre-stressed concrete containment vessel
PIRT	A Phenomena Identification and Ranking Table
PPS	physical protection system
PRA	probabilistic risk assessment
RES	Office of Research
RDD	radiological dispersal device
RG	Regulatory Guides
RMIEP	Risk Methods Integration and Evaluation Program
RTM-96	Response Technical Manual
SA	security assessment
SAMA	Severe Accident Mitigation Alternative
Sandia	Sandia Corporation

SFP	spent fuel pool
SMR	small modular reactor
SNL	Sandia National Laboratories
SNSI	Secret National Security Information
SOARCA	State-of-the-Art Reactor Consequence Analyses
THERP	Technique for Human Error Rate Prediction
TMI-2	Three Mile Island Unit 2
TTC	Thermal Test Complex
U	Unclassified
VAI	vital area identification

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1. BACKGROUND

Sandia National Laboratories (SNL) has over a 60-year history in scientific research, technology development, and supporting programs in nuclear energy-relevant safety, security, and nonproliferation. These programs were mainly funded by the U.S. Government through the U.S. Department of Energy (DOE) and U.S. Nuclear Regulatory Commission. Specific to nuclear energy safety research, the NRC has been a major contributor. This has led to a combined suite of highly specialized and unique expertise and capabilities. This report focuses on SNL work related to capabilities from a regulatory perspective.

After the accidents at Browns Ferry in 1975 and again after the Three Mile Island accident in 1979, the NRC turned to Sandia Corporation (Sandia) because of its nuclear safety expertise in nuclear weapons and lack of organizational conflict of interest. Sandia led much of the foundational research in reactor accident phenomena.

The NRC-Sandia relationship has continued for decades. Sandia was a principal contributor to major NRC activities including the following:

<u>NUREG 1150</u> assesses severe accident risks at five US nuclear power plants using advanced methods and improved data. This brought defensible, probabilistic risk assessment to the nuclear energy world [1].

<u>MELCOR</u> is a fully integrated, engineering-level computer code and includes a broad spectrum of severe accident phenomena (e.g., core heat-up, degradation, relocation, core-concrete attack, hydrogen production and transport, fission product release). It models the progression of accidents in nuclear power plants. It estimates severe accident source terms and their sensitivities and uncertainties in a variety of regimes and scenarios. Sandia develops and maintains MELCOR for the NRC and has done so for decades.

<u>MACCS</u> calculates atmospheric transport, environmental deposition, radiation dose to humans, radiation health effects, and economic losses. Sandia develops and maintains MACCS for the NRC and has done so for decades.

<u>SOARCA</u>, the State-of-the-Art Reactor Consequence Analysis, incorporated over 25 years of research to analyze the realistic outcomes of postulated severe reactor accidents [2].

<u>Aircraft vulnerability assessment after 9/11;</u> Sandia analyzed reactor, balance of plant, spent fuel pools, and dry cask storage vulnerabilities.

<u>Fukushima Dai-ichi accident response;</u> Sandia advised the NRC, DOE, US Embassy in Japan, and the military on potential source terms, reactor and spent fuel pool accident progression, efficacy of potential responses, and potential impacts from seismic aftershocks. Currently for the NRC, Sandia is representing the US and leading an international benchmarking exercise.

1.1. Capabilities

Sandia's capabilities have many unique characteristics:

- Expertise reflects accumulation of knowledge gained by conducting over six decades of nuclear energy-relevant research funded by the US Federal Government, including the DOE and NRC;

- Multi-disciplinary breadth and depth of expertise rarely found in any other organization;

- State of the art experimental and analytical capabilities;

- Enduring capabilities and organizational continuity; and

- Technical quality to provide the basis for regulatory decision making including promulgating regulations.

Sandia's capabilities have multiple applications. The capabilities most relevant to nuclear energy safety and security are summarized below. Other capabilities exist at Sandia that could be utilized to address very specific issues in nuclear energy, e.g., materials science, but are not discussed.

The key capabilities discussed and their locations in this document are:

- *Multi-Scale, Multi-Process* Testing, Section 2.1;
- *Assuring Safe Transportation of Nuclear & Hazardous* Materials, Section 2.2;
- *Extreme Environment* Testing, Section 2.3;
- *Large-Scale Validation* Experiments, Section 2.4;
- *Aerosol Physics and Chemistry of the Reactor Accident Source Term*, Section 2.5;
- *Structural Engineering and Containment Integrity Research,* Section 2.6;
- *Structural Phenomenological Modeling & Analysis of Complex Systems,* Section 2.7;
- *Thermal & Thermal-Mechanical Phenomenological Modeling Complex Systems,* Section 2.8;
- *Severe Accident and Consequence Research Modeling: MELCOR and MACCS,* Section 2.9;
- *Probabilistic Risk Analysis Research,* Section 2.10;
- *Human Reliability Analysis Research*, Section 2.11;
- *Fire Risk Analysis Research,* Section 2.12;
- *Uncertainty & Sensitivity Analysis*, Section 2.13;
- *Cyber-Based Vulnerability Assessments,* Section 2.14;
- *Physical Security Vulnerability Assessments,* Section 2.15;
- *Nonproliferation*, Section 2.16;
- *Emergency Planning,* Section 2.17;
- *Urgent Response Capability,* Section 2.18; and
- *Regulatory Gap Analysis*, Section 2.19.

1.1.1. Facilities

Sandia has extensive, unique, and world-class specialized facilities and equipment. Multi-scale and multi-process testing facilities are used to explore and understand how individual components and subsystems will behave in different environments. Large-scale validation testing is used to understand natural phenomenon and validate in-house models and codes. The nuclear energy-relevant facilities include, but are not limited to:

- Annular Core Research Reactor (ACRR) – fuel testing facility;
- Gamma Irradiation Facility (GIF) – irradiation effects testing facility;
- Cylindrical Boiling facility (CYBL) – Spent Fuel Pool (SFP) fuel assembly testing;
- Surtsey – aerosol mechanics;
- Rocket Sled Tracks – aircraft impact experiments, transportation accidents;
- Aerial Cable Site – drop tests facility;
- Laurence Canyon Burn Facility – cable fire testing;
- Thermal Test Complex – highly flexible burn/fire testing facility;
- Outdoor Lake – drop tests and fire tests;
- 300g Centrifuge, and;
- Custom sites based on user needs (e.g., quarter-scale reactor containment vessel and cryogenic exposure).

Many of these facilities are described further within this document.

1.1.2. Supercomputing

Sandia's high performance computing platforms include some of the world's most powerful supercomputers, which are used for numerically intensive physics simulations. Sandia is capable of modeling the most difficult physics simulations using code developed commercially, and by Sandia, including the following:

- SIERRA
- Presto
- FUEGO
- ARIA
- Patran
- ABAQUS
- FLUENT

In addition, Sandia has access to hundreds of single core clusters for uncertainty quantification studies (Monte Carlo and Latin Hyper-cube Sampling).

2. KEY CAPABILITIES

This section provides further discussion of the capabilities listed in Section 1.1.

2.1. Multi-Scale, Multi-Process Testing

Designers and regulators must know whether a test unit (e.g., a package used for transport of radioactive or hazardous material) will be able to effectively contain the material and prevent material releases. They must be able to predict how specific parts of a test unit will behave under a variety of circumstances. Whether considering the seal of a package or wiring within a nuclear reactor, it is important to understand the behavior of individual components and subsystems, and how that behavior will affect the system as a whole. Sandia uses multi-scale and multi-process testing to explore and understand how components and subsystems will behave in different environments. The ability to test components and total systems serves as an important element to ensure system integrity and performance assurance.

Combining principles of both applied and pure science, Sandia's testing is designed to generate detailed, increasingly useful data for both designers and regulators. Sandia also leverages pure science in its testing to better-understand and more accurately characterize the physics of events. Sandia looks beyond the simple question of whether or not a component or subsystem performed successfully in order to understand the phenomenology of the environmental conditions. This results in a more complete, thorough examination of subject and phenomena of interest.

Systems evaluations are of particular importance in high consequence situations such as those in the area of nuclear energy involving radioactive and hazardous materials. Component manufacturers provide limited information about their products. They may provide performance assurances under general use, but when components are used in high consequence systems, general use assurances are not enough. Industry and regulatory agencies must know that the component can withstand a number of environments that may pose serious risks to the system.

2.1.1. A Legacy of Testing Leadership

Sandia serves as an intermediary between component manufacturers, industry, and regulatory agencies, using component and subsystem testing to help fill information gaps. By testing components at varied temperatures, strain rates, and damage states, users will have the behavior and performance information they need to know whether or not a component or subsystem is suitable for use in a high consequence system. Testing of this nature is used to inform risk and safety assessments leading to safer, more reliable complete systems.

Leveraging over six decades of extensive experience in weapons component testing, Sandia serves as a hub of testing expertise. Sandia can apply a multi-physics approach to testing achieved through its vast expertise base including important areas such as fire science, instrumentation, explosives, and mechanics. With a wide variety of fielded expertise, Sandia's testing experts are capable of performing all steps of the experimentation process. Sandia is also home to a number of notable testing facilities. With high profile facilities like the Thermal Test Complex, which is used to demonstrate the performance of components and assemblies under a variety of abnormal thermal environments; the Water Impact Facility, which provides a controlled environment for high-velocity water impact and underwater testing; and several Structural Test Facilities (component and full-scale) that are capable of simulating nearly any environmental testing requirements.

2.2. Assuring Safe Transportation of Nuclear & Hazardous Materials

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. 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 has expertise and sophisticated testing and analysis resources to analyze both of these elements.

In order to accurately characterize a package's behavior and response to a specific set of transportation-related conditions, Sandia leverages expertise and tools in a number of areas constructing a comprehensive full-spectrum approach to transportation risk analysis including: package design (development of design models), thermal testing and analysis, structural testing and analysis, extreme environment analysis, fabrication shops and laboratories, quality assurance, and regulation development and refinement.

Drawing on nearly 60 years of support provided to the NRC, Sandia applies its extensive knowledge of both regulation-based and extra-regulatory environments to model, test, and analyze nuclear transportation packages. Since most standard regulations are based on general, foreseeable operating conditions and likely complications, the extra-regulatory element is of increasing importance when working with nuclear materials. Natural disasters, terrorist attacks, and other situations requiring "above and beyond" safety and security assurance are essential factors that must also be considered in the implementation of a particular package design. Sandia determines the response of packages in regulation and extreme environments to ensure the integrity and reliability of hazardous and radioactive material packages.

As a second element to ensure safe transport of radiological materials Sandia developed RADTRAN as a unique environmental impact and risk assessment code. This code was initially developed for the NRC and has been in use around the globe for 35 years. As an internationally-validated code, RADTRAN is also accepted by the International Atomic Energy Agency. RADTRAN displays the transport vehicle as a sphere depicting the external radiation dose as a virtual source. RADTRAN also evaluates accident scenarios by 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 the loss of lead shielding in the absence of a loss of radioactive material.

2.3. Extreme Environment Testing

Sandia serves as a unique environment for the study of hazardous and radioactive material transportation because it combines a number of sophisticated, hard-to-find tools with distinct testing facilities into a single organization. These tools and testing facilities allow researchers to examine the risks to a 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. Facilities including the Rocket Sled Track, the Mechanical Shock Facility, and the Thermal Test Complex subject packages to extreme environments allowing researchers to execute performance and risk analysis.

2.3.1. Supporting Industry and Regulatory Agencies

With a long history of support to regulatory institutions, Sandia works closely with national standards and regulatory agencies to make the nuclear energy enterprise safer by providing essential scientific support to create and refine those standards as industry and environmental needs evolve with time. Using this sophisticated knowledge base comprised of existing regulations and extra-regulatory needs, Sandia's work plays an important role in making the nuclear energy enterprise a safer, increasingly assured industry.

2.4. Large-Scale Validation Experiments

The nuclear energy industry and its regulators must have confidence that the technologies used in all aspects of the enterprise will perform accurately and reliably. Performance is often tested through large-scale validation experiments. This allows researchers, designers, and regulators to observe and evaluate how a technology responds to an environment. The results of these experiments indicate whether regulatory requirements are satisfied, and can also be used as a benchmark for further analysis. Sandia leverages nearly six decades of extensive testing experience with a wide variety of high-profile testing facilities to serve as an institutional hub for the design, preparation, and execution of large-scale validation experiments. With a long history of support to regulatory agencies, Sandia researchers apply detailed knowledge of nuclear energy regulations and the regulatory environment to experiments, ensuring that experiments generate the best, most accurate data.

Drawing on its legacy mission work in nuclear weapons testing, Sandia performs classified and unclassified experiments, and high consequence testing involving hazardous and radioactive material. As the only institution in the world to have performed a containment certification test using radioactive material, Sandia maintains strong leadership in this area. Sandia researchers perform validation experiments on complete assemblies or high fidelity models. By testing what will actually be in use, researchers gather accurate, increasingly realistic performance data. This allows determination to be made on how the technology's performance measures up to regulatory requirements.

Sandia performs a number of large-scale validation experiments that cannot be done anywhere else in the country. It is the only institution in the US capable of testing air transportation packages. Air transportation package designs are tested and certified in extreme environments according to regulations and validation standards. Full-scale fire tests of large packages are also performed at Sandia, but nowhere else in the US. These large-scale validation experiments leverage Sandia's extensive collection of high profile, large-scale fire testing facilities including the Lurance Canyon Burn Facility and the Thermal Test Complex. Using a variety of data acquisition tools, researchers efficiently and effectively gather performance data needed to satisfy fire-based regulatory and validation requirements.

Depending on the needs of a specific experiment, Sandia customizes its facilities, adapting them to meet the unique needs of each situation. For example, Sandia maintains a large outdoor lake facility that was used for Liquefied Natural Gas (LNG) experiments. Researchers are able to adjust the pool's size, blocking off sections when needed, to accommodate the needs and parameters of individual tests. This customization helps researchers generate increasingly detailed, accurate performance data since the physical characteristics of the test environment closely resemble those of the actual environment of interest. Sandia also constructs custom facilities, when needed. In support of the NRC and Japan's Nuclear Power Engineering Corporation, Sandia's researchers built a quarter-scale nuclear reactor containment vessel designed to test the point at which over-pressurization would result in structural failure to validate predictive models.

In general, data generated through large-scale validation experiments is analyzed to determine whether or not a technology meets requirements. Documenting and characterizing how the technology performs in a particular environment, the resulting analysis indicates what industry and regulatory agencies can expect if the situation were to occur when the technology was deployed. This data is particularly valuable when used to inform risk and safety assessments.

Data derived from large-scale validation experiments benchmarks modeling and simulation tools. Without physically executing the experiment, these tools generate performance data for technology subjected to a variety of environments and situational scenarios. However, since the experiments are simulated, benchmarks are necessary to permit high confidence in data generated from non-tested scenarios.

Sponsored by the NRC and Japan's Nuclear Power Engineering Corporation, the quarter-scale reactor experiment was performed to validate NRC computer codes used to predict pre-stressed concrete containment vessel (PCCV) pressure tolerances in severe accidents, and to demonstrate that existing reactors at power plants in Japan and the US could perform safety functions reliably in an accident. Over the course of three years, Sandia constructed a 70-foot tall, 35-foot diameter PCCV as a small replica of one operating at a nuclear power plant in Japan. During the experiment, the vessel was "tested to failure" as Sandia researchers pumped nitrogen gas and water into the concrete model, gradually increasing the pressure until the structure failed. It is the largest nuclear reactor containment vessel model ever tested to failure. The PCCV model was built with nearly 1,500 sensors and fiber optic lines embedded into its materials enabling researchers to gather tens of thousands of lines of data about its performance before and during the test. Data from the test was used by an international team of experts to benchmark structural analysis codes and develop new state-of-the-art accident response models.

2.4.1. MIDAS: Mobile Instrumentation Data Acquisition System

Data collection must to accurately characterize what happens to a test unit under a variety of circumstances including events such as impact, puncture, fire, and immersion. Sandia created the Mobile Instrumentation Data Acquisition System (MIDAS) to provide on-site data acquisition and analysis capabilities for testing of radioactive and hazardous materials packages and other test units. MIDAS allows researchers, designers, and regulators to examine and understand how a test unit behaves in a variety of environments.

MIDAS is a controlled, verified, and well documented system dedicated to providing high-quality measurement data in support of system testing. Data acquisition equipment is contained in a 44-foot trailer and, with an auxiliary power generator, provides a self-contained mobile data acquisition and reduction facility. MIDAS is equipped with acquisition systems to gather both structural and thermal data. The structural data acquisition system is capable of acquiring 72 channels of time domain data from any combination of piezo-resistive or voltage-based measurement devices. Commonly used to measure package response to regulatory impact, puncture, and immersion tests, the overall structural data bandwidth extends to 100 kHz at -0.5 dB, by sampling at 500,000 samples per second or greater. The thermal data acquisition system can acquire up to 80 channels of Type K thermocouple data and 20 channels thermocouple data. Sandia is currently upgrading MIDAS' capabilities which among those are to provide an additional 90 channels of time domain data (162 total). These upgrades will be complete at the end of calendar year 2014.

MIDAS performs in compliance with the highest level of quality assurance, ASME NQA-1 Quality Assurance Program Requirements for Nuclear Facilities. Constantly checking itself for errors and monitoring its own accuracy, the MIDAS onboard diagnostic system verifies that data acquisition components are functioning correctly. This diagnostic system can verify equipment calibration and characterize component performance. MIDAS also features an incredible level of data retrieval capability, through the system's documentation package. This package allows a record of equipment parameters and performance to be produced both during the test and retroactively, providing a computer-generated audit trail of each piece of gear in the data path. Every piece of data from nearly 1,000 tests using MIDAS is stored, which enables data comparisons over time and facilitates self-calibration.

While MIDAS is used extensively to gather data in performance and component tests of transportation packages and other test units, it is also used in modeling and simulation. Because MIDAS is exceptionally consistent and widely trusted throughout the regulatory community, systems, subsystems, and component level data are used to benchmark results supporting package design and certification analyses, and other computational simulations.

2.5. Aerosol Physics and Chemistry of the Reactor Accident Source Term

Sandia brings over 30 years of experience to understanding reactor accident source terms and aerosol physics. This expertise includes experimental investigations of source term generation and the behavior of radionuclides under prototypic accident conditions, development of validated, mechanistic, source term models and application of these models to NRC's specialized issues of reactor safety.

Specifically, Sandia has done the following:

- Developed the sectional method for the solution of the aerosol dynamic model now universally used in accident analysis computer codes such as the NRC's MELCOR code.

- Developed models of aerosol and radionuclide removal by engineered safety systems such as suppression pools and containment sprays. These models are used in the NRC's RADTRAD computer model for the siting and licensing of reactors and nuclear facilities, 10 CFR Part 100 (e.g., the RADTRAD computer model has been applied for particularly complicated regulatory issues such as leakage of main steam isolation valves). Results of studies of the engineered safety features are being used by NRC to assess possible safety requirements in the aftermath of the accident at Fukushima Dai-ichi.

- Developed methods for the effective sampling and characterization of aerosols produced in energetic severe accident processes such as melt-concrete interactions, direct containment heating and fuel-coolant interactions.

- Developed the VANESA model of radionuclide release and aerosol formation during core interactions with concrete. This model was adopted whole by both the NRC's Source Term Code Package and the MELCOR computer code.

- Developed the VICTORIA model to predict chemical transformations of radionuclides during transport from degrading reactor fuel through the reactor coolant system.

- Developed experimental methods to demonstrate both the reversible and irreversible deposition of radionuclide vapors and particles in the reactor coolant system under accident conditions. Results of these experiments were used in the interpretation of findings from the damaged reactor at Three Mile Island (TMI) and used to validate models such as MELCOR and VICTORIA.

- Developed methods based on risk for defining representative source terms for licensing of reactors using high burn up and MOX fuel. These methods are being used by NRC to update the Alternative Source Term used in NRC Regulatory Guide 1.183.

- Developed descriptions of containment dose during design basis and beyond design basis accidents for use in the qualification of equipment needed for accident management. These techniques are being used to update NRC Regulatory Guide 1.89.

- Detailed familiarity with international experimental programs involving aerosol formation and behavior (e.g., Marviken, Phébus-FP, BIP, STEM, ARTIST, and RASPLAV/MASCA)..

- Developed steady state water and iodine radiolysis models used in NRC's contributions to international standard problems in the chemistry of iodine.

- Developed data and modeling base for aerosol penetration through containment leaks and cracks used in assessing adequacy of 10 CFR Part 50 Appendix J testing.

2.6. Structural Engineering and Containment Integrity Research

Sandia is a nationally and internationally recognized leader in nuclear reactor containment research, supporting operations, lifetime extensions, security and vulnerability assessments, over a broad range of phenomena. Sandia's expertise includes evaluation of containment when subjected to high velocity impacts, enormous pressures and stresses, and attacks by saboteurs. Sandia's resources enable the completion of a complex scientific investigation in its entirety. Its engineers are capable of performing a numerical analysis in totality from modeling a structure in software to validating the calculations with experiments and journal data.

Sandia's infrastructure and capabilities include the knowledge and broad technical expertise supporting the collection of experimental data, numerical simulation analyses tools and the knowledge bases needed to provide regulatory institutions with the ability to make reliable and technically sound regulatory decisions. Sandia uses the latest engineering software both from industry (e.g., ABACUS), and developed by Sandia (e.g., SIERRA and Presto). These codes provide the most sophisticated analyses that can be made for finite element analysis of structures. Sandia's high performance computing (HPC) platforms include some of the world's most powerful supercomputers, which are used for numerically intensive simulations. On-site experimental facilities include the rocket sled track for testing high-velocity impacts, the drop tower facility to observe damage to falling objects and a centrifuge, which can subject items to inertial forces as high as 300g. The coupling of analytical expertise with the deep knowledge of the regulatory environment produces a comprehensive package uniquely available at Sandia.

Sandia researchers reduce uncertainties in areas of potentially high safety or security risk or significance and develop the technical basis for risk-informed, performance-based regulations. Sandia maintains the breadth of technical capability and information needed for the resolution of nuclear safety and security issues, and provides technical support and consultation to regulatory institutions in the related specialized disciplines. Sandia provides independent assessments through the review, analysis, and evaluation of the safety performance of facilities licensed by the NRC. Capabilities support the development and application of methods, data, standards, and modeling tools to assess the structural performance of structures, systems and components; the technical bases and computational methods to resolve structural engineering issues associated with security assessments; collection and analysis of data related to performance of structures and provide guidance for structural design elements. Sandia technical capabilities address emerging issues by providing the expertise supporting the revision and development of NRC Regulatory Guides (RGs), NUREG reports and responses to inquiries from the Commission, Advisory Committee on Reactor Safeguards (ACRS), and Congress.

Drawing on nearly 60 years of accrued knowledge and support provided to the U.S. Government, Sandia applies its extensive knowledge of both regulation-based and extra-regulatory environments to model, test, and analyze structures within the area of nuclear energy to address structural engineering and containment integrity issues. Selected works are listed below:

1950 – WASH-3: Exclusion vs. Containment
1957 – Shippingport Nuclear Power Plant (Defense in Depth)
1971 – 10 CFR 50, Appendix A: General Design Criteria
1973 – WASH-1250: Reactor Safety Study (definition of Severe Accidents)
1973 – ASME B&PV Code, Section III, Div. 2 (ACI-359) (concrete containment design)
1975 – WASH-1400: Rasmussen Report (estimates of containment capacity)
1979 – Three Mile Island, Unit 2 Accident
1981 – SNL Background Study on Containment Capacity
1982 – NRC-Sponsored Containment Integrity Program at SNL
    1982 – 1:32 Scale Steel Model Tests
    1984 – 1:8 Scale Steel Model Tests

1986 – NRC Qualitative Safety Goals
1986 – Individual Plant Examination Guidance
    1987 – 1:6 Scale Reinforced Concrete Model Test
    ~1988 - SNL and EPRI/CTL Separate Effects Tests
    ~1988 - Personnel Airlock Test
    1988 – F4 Phantom Jet Impact Test
    ~1989 - Electrical Penetration Tests

1989 – Sizewell-B 1:10 Scale Model Test
1990 – NUREG-1150: Risk Study (probabilistic risk assessment, PRA)
1991 – NUPEC-NRC Cooperative Containment Research Program at SNL
    1994 – Containment Bellows Test
    1996 – 1:10/1:4 Scale Steel Model Test

1996 – Watts Bar 1 (latest US commercial nuclear power plant)
    2000- 1:4 Scale Prestressed Concrete Model Limit State Test

2000 – NUPEC 1:10 Scale Seismic Capacity Tests
    2001 – 1:4 Scale Prestressed Concrete Model Structural Failure Test
    2005 – OECD/NEA/CSNI ISP#48 on Containment Capacity
    2006 – Containment Integrity at SNL Summary

2005 – Seismic Behavior of Spent Fuel Storage Cask Systems
2006 – Completed Aircraft Threat Assessment for Nuclear Power Plants
2009 - Began supporting OECD (IRIS) [*on-going*]
2012 – NUREG supporting NRC-AERB Collaboration on Grouted Tendons
2013 – IAEA Fukushima Dai-ichi International Peer Review Team Assessment
2013 – NRC degraded containment program support [*on-going*]

2.6.1. Integration of Capabilities

- Multi-scale, multi-process testing and experimental facilities;
- Large-scale validation experiments and experimental facilities;
- Materials science and characterization;
- Chemical phenomenological modeling;
- Structural phenomenological modeling;

- Thermal phenomenological modeling;
- Severe accident modeling;
- Aerosol chemistry, dispersion, transport;
- Computational simulation and High Performance Computing;
- Uncertainty and sensitivity analysis;
- Probabilistic risk assessment methods development and application;
- Regulatory analysis; and
- Nuclear-rigor quality assurance.

2.7. Structural Phenomenological Modeling & Analysis of Complex Systems

Sandia is a nationally and internationally recognized leader in complex systems analysis, structural/mechanical analysis and design in support of safety and security assessments of commercial nuclear power generation plants and fuel cycle facilities. Sandia focus on both probabilistic and deterministic risk analyses to support regulatory investigations and high consequence engineering analysis and testing. We have planned and conducted large-scale structural tests and complex structural analyses using both commercial and Sandia codes. Computational methods developed in structural mechanics, heat transfer, fluid mechanics, shock physics, and many other fields of engineering can be an enormous aid to understanding the complex physical systems.

Sandia supports the regulations and regulatory guidance with regard to risk significance, burden reduction potential, and engineering design margins associated with facility systems, structures and components supporting existing and new reactor designs. Capabilities include development of methods, data, standards, and metallurgical modeling tools for evaluating degradation mechanisms on reactor pressure vessel steels; fracture mechanics measurement and analysis technologies; tools to quantitatively assess changes in structural reliability of nuclear plant systems, structures and components as a result of operating environment effects or aging of materials.

Sandia infrastructure and capabilities include the multidisciplinary technical expertise and accrued knowledge needed to provide regulatory institutions with the ability to make reliable and technically sound regulatory decisions. For instance, Sandia's Corrosion and Electrochemical Sciences conducts research and development in the areas of materials aging and materials interactions. Sandia's ongoing investment in electrochemical and surface analytical techniques and expertise enables us to quantify material behavior under accelerated aging conditions and to develop empirical, phenomenological and fundamental models and understanding of materials aging. Sandia material scientists are supporting many science and engineering functions that include vulnerability assessments, failure analyses, measurement of unknown material properties, development of improved materials, the correlation of secondary evidence with aging processes (e.g., chemical signatures, the development and deployment of predictive, physical-based mathematical models, the characterization of specific material-aging processes, and age-related defects).

Sandia addresses emerging issues and supports the revision and development of NRC Regulatory Guides (RGs), NUREG reports and responses to inquiries from the Commission, Advisory

Committee on Reactor Safeguards (ACRS), and Congress. Sandia researchers reduce uncertainties in areas of potentially high safety or security risk or significance and develop the technical basis for risk-informed, performance-based regulations. Sandia maintains the breadth of technical capability and information needed for the resolution of nuclear safety and security issues, and provides technical support and consultation to regulatory institutions in the related specialized disciplines and supports independent assessments of the safety performance of facilities licensed by the NRC.

Sandia has performed structural and mechanical analyses supporting safety and risk analyses for many complex system accident scenarios. Built on a foundation of accrued knowledge involving multidisciplinary expertise these analyses have led to the development of technologies and design modifications to mitigate and prevent the consequences of a release of nuclear or radioactive material during severe accident scenarios. Selected NUREGs are listed below:

NUREG/CR-3234 – The Potential for Containment Leak Paths through Electrical Penetration Assemblies under Severe Accident Conditions (1983)

NUREG/CR-3222 – The Search for a High Elongation Strain Gage System (1983)

NUREG/CR-3724 – Ultimate Strength Analyses of the Watts Bar, Maine Yankee, and Bellefonte Containments (1984)

NUREG/CR-4944 – Containment Penetration Elastomer Seal Leak Rate Test (1987)

NUREG/CR-5096 – Evaluation of Seals for Mechanical Penetrations of Containment Buildings (1988)

NUREG/CR-5099 – Evaluation of Materials of Construction for the Reinforced Concrete Reactor Containment Model (1988)

NUREG/CR-5096 – Evaluation of Seals for Mechanical Penetrations of Containment Buildings (1988)

NUREG/CR-5334 – Severe Accident Testing of Electrical Penetration Assemblies (1989)

NUREG/CR-6154 – Experimental Results from Containment Piping Bellows Subjected to Severe Accident Conditions (1995)

NUREG/CR-6906 – Containment Integrity Research at Sandia National Laboratories (2006)

NUREG/CR-6920 – Risk-Informed Assessment of Degraded Containment Vessels (2006)

NUREG-2110 – xLPR Pilot Study Report (2012)

2.7.1. Integrated Capabilities

- Materials science and characterization;
- Structural phenomenological modeling;
- Thermal phenomenological modeling;
- Computational simulation (various systems);
- Uncertainty and sensitivity analysis;

- Probabilistic risk assessment methods development and application;
- Regulatory analysis; and
- Nuclear-rigor quality assurance.

2.8. Thermal & Thermal-Mechanical Phenomenological Modeling Complex Systems

Sandia leverages extensive multi-scale test facilities, accrued knowledge and over 30 years of validation testing to model the presence of fire and intense heat during an accident involving nuclear material. Using a comprehensive suite of resources including numerical modeling software and a number of on-site experimental and testing facilities, Sandia performs complete investigations of thermal phenomena. Sandia researchers have expertise in the development and application of a number of numerical thermal analysis codes. With high-performance computing capabilities and a broad knowledge of commercial and in-house-developed software, Sandia is capable of modeling the most complex multidisciplinary physics simulations related to fire and heat transfer.

FUEGO: Developed at Sandia, FUEGO is a low Mach number fluid mechanics code. Typically used for heat and mass transport modeling, FUEGO can also be coupled with Syrinx to simulate fire environments.

ARIA: This Sandia-developed Galerkin finite element-based program is capable of solving nonlinear, implicit, transient, and direct-to-steady state problems on massively parallel architectures. ARIA also solves coupled-physics problems.

Patran: Sandia successfully coupled Patran with an in-house computational fluid dynamics fire code for the heat transfer analysis of objects affected by fire. Patran is a commercial finite element code with a comprehensive selection of thermal loading possibilities.

Sandia runs these numerically intensive simulations on some of the world's most powerful supercomputers. Sandia has the nation's leading fire test facility. Sandia's Thermal Test Complex (TTC) was specially created for fire and thermal experiments. TTC provides a controlled environment in which to demonstrate the performance of components and assemblies under a variety of abnormal thermal environments. The importance of fire in nuclear accidents has brought Sandia's work to the forefront of the field of thermal phenomenology. Leveraging its researchers' unmatched expertise and experience along with the extensive resources, Sandia is able to conduct the most challenging experiments and numerical calculations. Sandia infrastructure and capabilities include the knowledge and broad technical expertise needed to provide regulatory institutions with the ability to make reliable and technically sound regulatory decisions.

Sandia addresses emerging issues and supports the revision and development of NRC Regulatory Guides (RGs), NUREG reports and responses to inquiries from the Commission, Advisory Committee on Reactor Safeguards (ACRS), and Congress. Sandia researchers reduce uncertainties in areas of potentially high safety or security risk or significance and develop the technical basis for risk-informed, performance-based regulations. Sandia maintains the breadth of technical capability and information needed for the resolution of nuclear safety and security issues, and provides technical support and consultation to regulatory institutions in the related specialized disciplines and supports independent assessments of the safety performance of facilities licensed by the NRC.

Sandia has performed safety and risk analyses for many fire-related accident scenarios including fire in a shipping container caused by a vehicle collision, an explosion near a nuclear reactor and its impact on the plant, and how burning rocket fuel affects the nuclear battery after an explosion on a launch vehicle. These analyses have led to the development of technologies to mitigate and prevent the consequences of a release of nuclear or radioactive material. Selected NUREGs and Sandia reports are listed below:

NUREG/CR-2142 – CORCON-MOD 1: An Improved Model for Molten-Core/Concrete Interactions (1981)

NUREG/CR-2385 – CSQ Calculations of H2 Detonations in the Zion and Sequoyah Nuclear Plants (1982)

NUREG/CR-3920 – CORCON-Mod2: A Computer Program for Analysis of Molten-Core Concrete Interactions (1984)

NUREG/CR-3638 – Hydrogen-Steam Jet-Flame Facility and Experiments (1985)

NUREG/CR-4558 – Interaction of Hot Solid Core Debris with Concrete (1986)

NUREG/CR-4803 – The Possibility of Local Detonations During Degraded-Core Accidents in the Bellefonte Nuclear Power Plant (1987)

NUREG/CR-5321 – A Thermodynamic Model of Fuel Disruption in the ST-1 (1991)

NUREG/CR-6025 – The Probability of Mark-I Containment Failure by Melt-Attack of the Liner (1993)

NUREG/CR-6109 – The Probability of Containment Failure by Direct Containment Heating in Surry (1995)

NUREG/CR-6338 – Resolution of the Direct Containment Heating Issue for All Westinghouse Plants with Large Dry Containments or Subatmospheric Containments (1996)

NUREG/CR-6527 – Final Results of the XR2-1 BWR Metallic Melt Relocation Experiment (1997)

NUREG/CR-6475 – Resolution of the Direct Containment Heating Issue for Combustion Engineering Plants and Babcock and Wilcox Plants (1998)

Alex Brown and Thomas Blanchat, A Fire Simulation with a RWCU Pipe Break Steam Source (U), Review Copy, Sandia National Laboratories, Albuquerque NM, April 2006. SNSI.

Eric Klamerus and Paul Demmie, Vulnerability of a Mark I Spent Fuel Pool Subjected to an Airplane Attack – letter Report (U), SAND2005-5181P, Sandia National Laboratories, Albuquerque NM, August 2005. SNSI.

Jeff Smith et al., An Analysis of the Potential for Secondary collapse of the Spent Fuel Pools of a BWR Mark I and Mark II Nuclear Power Plant (U), SAND2006-2450, Sandia National Laboratories, Albuquerque NM, April 2006. SNSI.

2.8.1. Integrated Capabilities

- Multi-scale, multi-process testing and experimental facilities;
- Large-scale validation experiments and experimental facilities;
- Materials science and characterization;
- Structural phenomenological modeling;
- Thermal phenomenological modeling;
- Computational simulation (various HPC systems);
- Uncertainty and sensitivity analysis;
- Probabilistic risk assessment methods development and application;
- Regulatory analysis; and
- Nuclear-rigor quality assurance.

2.9. Severe Accident and Consequence Research Modeling: MELCOR and MACCS

Sandia develops and maintains the MELCOR severe accident analysis code and the MELCOR Accident Consequence Code System (MACCS) atmospheric transport and radiological consequence assessment code for the NRC through an on-going contract with NRC for decades. Both codes are under ongoing development responding to emerging regulatory issues such as assessment of power plant vulnerabilities, development and modernization of regulatory tools such as Regulator Guides, assessment of licensee submittals including license amendments and new reactor design certifications, addressing user-need requests, application to State-of-the-Art Reactor Consequence Analyses of power plant risks (SOARCA) and application to full scope probabilistic risk assessment (PRA) activities at NRC. Both MELCOR and MACCS are widely used both domestically and internationally by regulatory agencies and industry alike to support safe reactor regulation. Sandia both develops these essential regulatory tools and provides integrated and expert application of the codes to often urgent safety issues, such as the Aircraft Vulnerability Assessments following the terrorist acts of 2001, and the evaluation of potential consequences and lessons learned from the recent severe accidents at Fukushima Dai-ichi.

Currently these tools are being used to assess the recommendations from the Fukushima Dai-ichi Task Force with respect to potential back-fit design changes and Rule Making activities coming from the NRC Japan Lessons Learned Directorate and Commission orders to consider the utility and effectiveness of hardened filtered vents on certain US reactor designs as well as enhanced hydrogen control. Both MELCOR and MACCS have been under development and improvement for several decades as new issues continue to emerge and new information concerning the complex physics and phenomena surrounding severe accidents becomes available, and thereby serve as an essential "repository of severe accident knowledge" for generations to come. Following is a brief review of the development and evolution of these tools in the context of decades of exploratory phenomenological research that followed after the Three Mile Island Unit 2 (TMI-2) accident in 1979.

2.9.1. Core Melt Progression Research

Some of the pioneering investigations into core melt progression behavior were conducted at Sandia in the 1980's and 1990's through experiments using reactor fuels subjected to severe accident conditions, many of the nuclear-heated test fuel assemblies done in the Sandia Annular Core Research Reactor (ACRR) are illustrated in Figure 1. These experiments served as the basis for developing physics models for the heat up, oxidation, and hydrogen generation models used in MELCOR and in other severe accident codes in order to model full reactor response to accidents involving fuel damage. The experimental programs must be tightly coordinated with the model development activities to ensure effective transfer of knowledge gained through experiments to the analytical and code models is achieved. Without this coordinated approach, often critical insights are lost and fail to be integrated into the model development process.

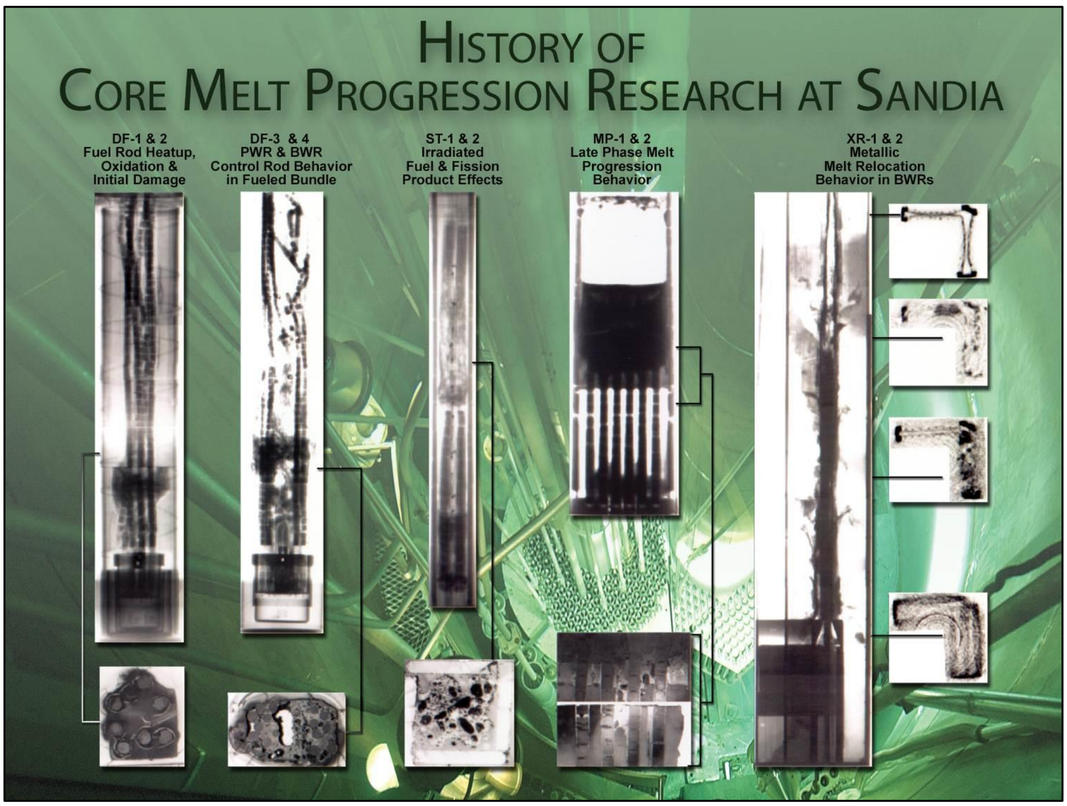

Figure 1: Reactor Fuel Melt Progression Tests Conducted at Sandia for the NRC

2.9.2. Sandia Lower Head Failure Tests Core Melt Progression Research

Following the accident at TMI-2, it was known that molten core materials had come to rest upon the lower head of the reactor vessel, producing significant heating of the head structure. While it is known that the lower head remained intact under the combined thermal and pressure load of the relocated core materials, analyses performed at the time predicted that head failure should have been expected. It is now known that enhanced water cooling made possible by the formation of gaps between the vessel inner wall and the refrozen core mass was likely responsible for the vessel wall remaining intact. However, without the operator injecting water (accident management actions) during the course of the accident evolution, the lower head may well have been dry instead, in which case lower head failure would have been expected. In recognition of this possibility, the Lower Head Failure experiments were commission at Sandia for the NRC to research various lower head failure modes as a function of potential thermal loading conditions. Visual end state results of the Sandia Lower Head Failure Experiments showing failure modes under different thermal loading conditions are shown in Figure 2. The findings from these experiments are embodied in the phenomenological models included in the MELCOR code and thereby part of the repository of knowledge invested in the code.

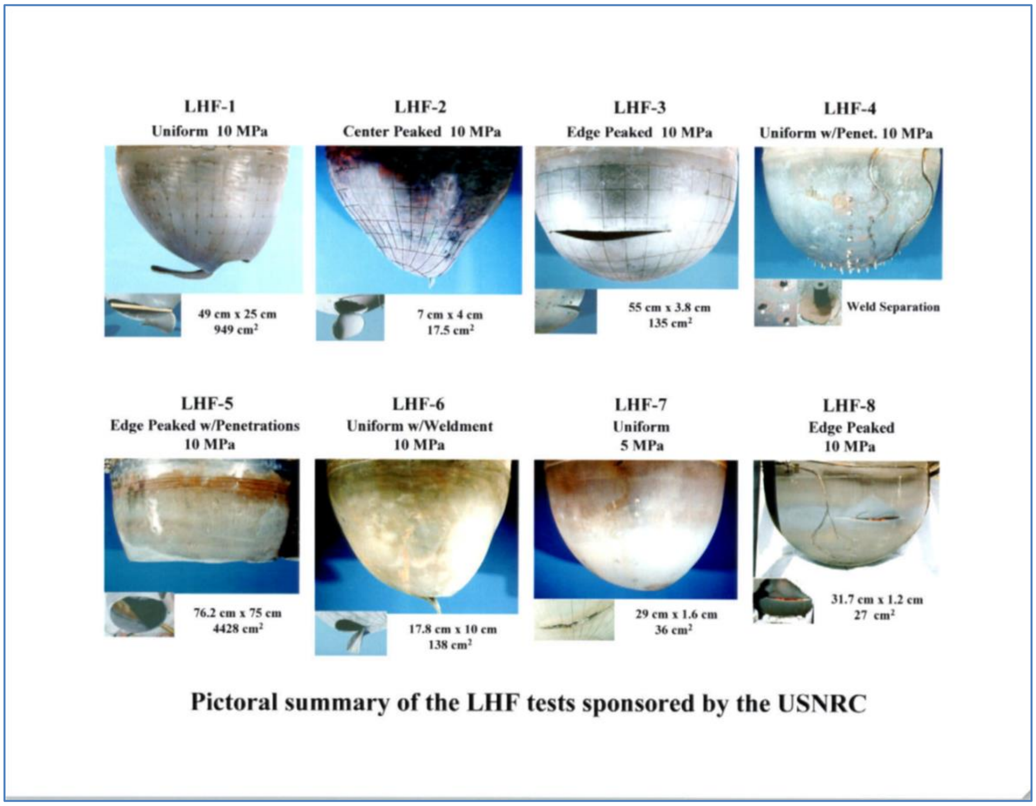

Figure 2: Visual Results from the Sandia Lower Head Failure Experiments

2.9.3. Other Experiments Performed at Sandia in the Area of Severe Accidents

Many other phenomenological experiments have been performed over the years at Sandia by specialists in a range of science and engineering backgrounds. In a severe accident, if the core melts and slumps into pools of water such as in the lower reactor vessel or reactor cavity regions, violent interactions or so-called steam explosions can result. An example of a steam explosion test performed at Sandia to explore the potential energy release from such events is illustrated in Figure 3. Such energetic events, although now considered to be extremely rare events, can potentially threaten the reactor containment integrity and lead to release of radioactivity to the environment. Two other potentially important threats to the reactor containment from core melt-down accidents were explored experimentally at Sandia, pressurized melt ejection from a rupture of the reactor pressure vessel producing direct heating of the containment environment, illustrated by the experiment shown in Figure 4, and energetic erosion of the containment floor (basemat) by molten core materials that have failed to lower reactor pressure vessel and fallen to the floor of the reactor building, Figure 5.

It should be noted that while many of these phenomena clearly appear to have the capability of significantly challenging containment integrity, subsequent research has determined that many are of extremely low likelihood. Evidence is strong from the recent accident at Fukushima Dai-ichi that lower head failure did take place in pressure vessels in these accidents (Figure 2) and that core-concrete interactions ensued following core melt relocation to the reactor cavity (Figure 5).

Figure 3 shows a steam explosion test performed at SNL exploring potential energy release from melt-coolant interactions.

Figure 3: Sandia Steam Explosion Tests

Figure 4 shows a Sandia experiment characterizing containment thermal loads resulting from a pressurized ejection of molten core materials into a simulated containment reactor cavity.

Figure 4: Sandia Experiment Characterizing Containment of Thermal Loads

Figure 5 shows a Sandia experiment investigating the thermal attack and erosion of containment concrete by overlying molten core materials.

Figure 5: Sandia Experiment Investigating Thermal Attack and Erosion

2.9.4. MELCOR Severe Accident Analysis Code

The development of the MELCOR code began at Sandia in 1982, shortly after and in response to the core-melt accident at TMI-2. Prior to this, severe accidents were considered hypothetical and little was known about the complexity of coupled in interacting phenomena participating in a severe accident. Estimations of consequences of hypothetical severe accidents were made using the Source Term Code Package, a loose and explicitly (by hand) coupled collection of separate estimation tools that were crude and approximate in comparison to the present-day MELCOR code. MELCOR unified the complex phenomena under a common data base with semi-implicitly coupled physics packages. Figure 6 below illustrates the diversity of coupled physics and phenomena that are modeled in a self-consistent manner in MELCOR. The phenomena treated in MELCOR are based on experimental data developed since TMI-2 on such topics as fuel melt-down behavior, fission product release physics, interactions between molten core materials and concrete, interactions between molten core materials and pools of water, pressurized melt ejection from the reactor vessel to the containment (direct containment heating), and containment failure modes under sever accident loads, much of which has been developed over the past several decades at Sandia as well as a wide source of internationally generated data.

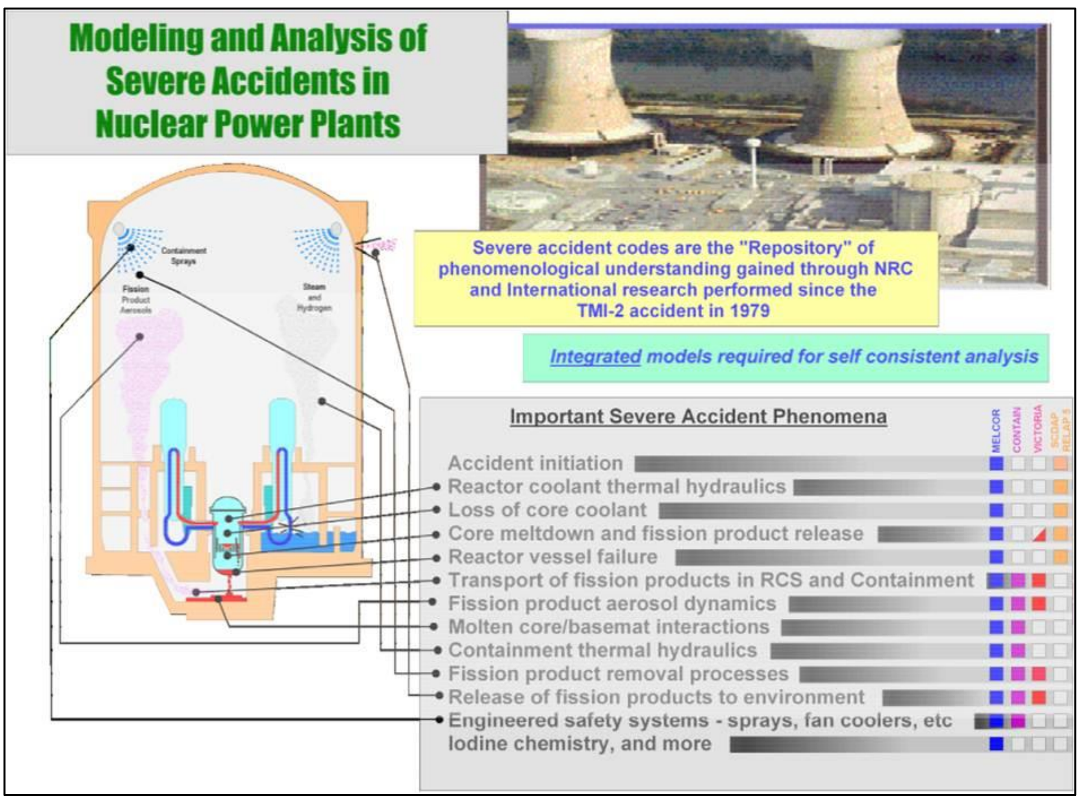

Figure 6: Coupled Phenomena and Physics Modelled in MELCOR

2.9.5. Atmospheric Transport of Radiological Releases: MACCS Code

While the MELCOR code predicts the progression of a severe accident in terms of core damage and radiological release, the MACCS code propagates the MELCOR-predicted radiological release to the environment where atmospheric transport processes disperse and deposit the radioactivity offsite. MACCS then estimates the health and economic impacts of radiological releases. Figure 7 illustrates graphically the phenomena modeled in the MACCS code. Sandia has developed and maintained the MACCS code for the NRC since its inception in 1979, originally titled CRAC and developed to support the WASH-1400 Reactor Safety Study. CRAC2 was released in 1982 to support the Sandia Siting Study (NUREG/CR-2239). The code was renamed MACCS (MELCOR Accident Consequence Code System) and subsequently used to support the NUREG-1150 study, for which Sandia was a principal contributor, and most recently, the improved MACCS Versoin 2 (MACCS2) code has been used to support the SOARCA study (NUREG-1935 and NUREG/CR-7110, Volumes 1 and 2); a major study completed for the NRC by Sandia to update the earlier Sandia Siting Study, and provide state of the art estimates of radiological consequences of severe accidents in current generation power plants.

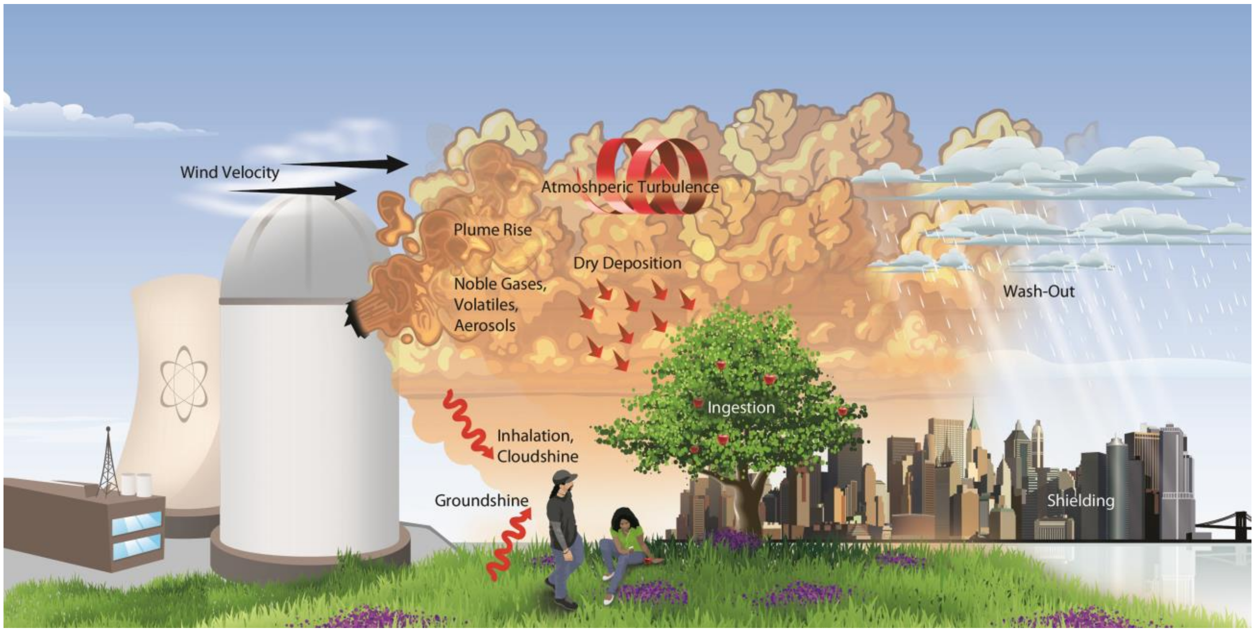

Figure 7: Illustration of the Phenomena Modeled in the MACCS Code

2.9.6. Recent MELCOR Applications

The preceding sections illustrate the multi-discipline nature of the reactor safety research performed by the scientists and engineers at Sandia and the close integration of large scale experimental endeavors with phenomenological model development and implementation in the MELCOR code. The following sections highlights a number of the significant research campaigns performed over the years at Sandia, drawing upon the specialized scientific workforce at the laboratories and the significant collective of knowledge and testing capabilities at Sandia.

2.9.6.1. Aircraft Vulnerability Assessments

Following the attacks on the World Trade Center and the Pentagon in 2001, Sandia was tasked to assess the vulnerability of US nuclear power plants to aircraft attack by terrorists. The study was urgently needed to take any appropriate measures that might be deemed necessary and drew upon the broad capabilities of Sandia ranging from structural response, fire assessment, severe accident progression analysis and source term consequence assessment, and requirement to perform these assessments in a classified environment. Extensive MELCOR and MACCS2 analyses were performed on a variety of plant damage states that were determined through the structural and fire response analyses. Mitigation and accident management measures were explored using MELCOR to prevent or delay core damage for plant damage states that led to core damage. As a result of these studies, the NRC developed requirements for having additional on-site equipment such as portable pumps and generators, referred to a “B5b Measures.” This urgent effort mobilized a wide range of laboratory expertise to produce effective recommendations that have increased power plant safety in the post-9/11 environment.

2.9.6.2. Spent Fuel Pool Accident Studies – Analytical and Experimental

Also motivated by post-911 concerns, Sandia was tasked to perform MELCOR analyses of spent fuel pool configurations employed in the increasingly full spent fuel pools in power plants across the US. This involved evaluating a range of fuel loading patterns of older and more freshly offloaded fuel assemblies using MELCOR to assess the potential for initiation of a zirconium fire as pool water levels drain down under various drain-down scenarios. The analyses were aimed at determining optimum loading patterns that would minimize the time period of vulnerability to fire between successive fuel offloads from the reactor (i.e., there are periods of time following offload of irradiated fuel where a zirconium fire cannot be avoided if the pool water is lost by a drain-down accident and not replaced). So-called “salt and pepper” loading arrangements were found to significantly reduce the period of vulnerability. This work was reviewed by the National Academy of Science in a public report titled, “Safety and Security of Commercial Spent Nuclear Fuel Storage” (2006).

Closely integrated with the analytical studies was a large scale experimental investigation of pool drain-down accidents using prototypic electrically heated fuel assemblies performed in the CYBL facility at Sandia. These experiments provided experimental verification of the analytical studies performed by MELCOR and led to improvement in the phenomenological models in MELCOR for zirconium fire initiation in fully drained pool configurations. As a result of this combined state of art analytical investigations and large scale experimental capabilities, Sandia was able to provide quick response to the urgent NRC concerns over spent fuel pool accidents. The findings from this study resulted in NRC issuing orders to the reactor fleet to adopt optimal offload patterns and significantly reducing the risk of a zirconium fire in a pool drain-down accident. Since the potential release of radioactivity in a pool fire accident can be very large, these orders also result in significant reduction in potential risks to the public.

2.9.6.3. State-of-the-Art Reactor Consequence Analysis (SOARCA)

In performing the aircraft vulnerability assessments with MELCOR, a great emphasis was placed on realism in the analyses. Best estimate principals were applied to the analyses and unwarranted conservatisms in the phenomenological models were avoided. Previous accident consequence studies, notably the Reactor Safety Study (WASH-1400) and the 1982 Sandia Siting Study (NUREG/CR-2239), included conservatisms that resulted in unrealistically large potential health effects due to very large predicted radiological releases. The MELCOR and

MACCS2 codes had been significantly improved and made increasingly best estimate through improvements made in phenomenological models made possible by decades of research since the TMI-2 accident. The SOARCA study was initiated to assess the impact of these phenomenological improvements and to "update" the findings of the 1982 Siting Study with more realistic analytical methods. The SOARCA study was a joint effort between Sandia and the NRC, with the MELCOR and MACCS2 analyses performed at Sandia, drawing upon the extensive depth of knowledge in severe accidents accumulated over the past 30 years. The analyses performed in SOARCA for the Surry and Peach Bottom nuclear power stations concluded that unmitigated severe accidents typically develop over a longer period of time and subsequent radiological releases are significantly less than predicted by the 1982 Siting Study. The SOARCA study also confirmed the effectiveness of the "B5b measures" for mitigated accident sequences in either preventing core damage or mitigating radiological releases.

2.9.6.4. Fukushima Dai-ichi Response

Sandia expertise developed over the past 30 years in severe accident phenomenology and analysis was called upon immediately following the accidents at the Fukushima Dai-ichi Nuclear Power Station and under DOE support, Sandia experts were deployed to support the US government interests in Japan, including the US military and Department of State. Immediate concerns were for the safety and well-being of US citizens in Japan as the accidents were being brought under control. Sandia experts also supported the NRC team that was deployed to Japan following the accidents. The cumulative experience at Sandia in severe accident analysis was extremely useful in evaluating what had transpired in the Fukushima Dai-ichi core-melt accidents, and estimating what potential future risk might be posed by the crippled reactors. Sandia provided radiological source term estimates to the NRC Emergency Operations Center to address concerns about releases from the reactors as well as potential releases from the spent fuel pools, which lost cooling and suffered significant boil-down of the cooling water. The analyses previously performed in the SOARCA study for the Peach Bottom reactors, which are of the same type as the Fukushima Dai-ichi reactors, proved strikingly similar in overall signature to the accidents in Japan, and the SOARCA study results were extremely valuable in understanding the accidents at Fukushima Dai-ichi.

Following the accidents, the DOE in collaboration with NRC, funded a detailed forensics evaluation of the three Fukushima Dai-ichi reactor accidents, which has both provided significant understanding of what happened as well as provided validation of the phenomenological models in the MELCOR code. Evaluation of the Fukushima Dai-ichi accidents will continue for many years, but presently the MELCOR code is being used to evaluate recommendations made by the NRC Fukushima Dai-ichi Task force and instructions from the Commission to consider use of "hardened filtered vents" for US boiling water reactors. Sandia is uniquely capable of providing this support owing to the decades of accumulated knowledge in severe accident progression and consequence assessment.

2.9.6.5. Development of Regulatory Source Term for MOX and High Burnup Fuels

The regulatory source term is a stylized radiological release presumed to accompany a design basis accident in order to evaluate the effectiveness of the reactor containment barrier in meeting control room and site boundary dose limits as defined in 10CFR100 licensing requirements. This presumed source term has evolved significantly over the years and is currently defined in NUREG-1465. This source term however was developed for lower fuel burnup and for low enrichment uranium fuels. Sandia is currently developing revised source terms for high-burnup fuel and for mixed oxide (MOX) fuel, and in the process revising the existing NUREG-1465 source term for low enriched uranium (LEU) fuels also. These revisions are being based on state-of-the-art MELCOR analyses for high burnup LEU and MOX fuels. The phenomenological models for fission product release in MELCOR are extended based on data recently available from the French VERCORS and VERDON experiments, and Sandia's expertise in the development of these models is essential in revision of the regulatory source term.

2.10. Probabilistic Risk Analysis Research

Sandia has established a best-in-class reputation in several specific technology areas relevant to Probabilistic Risk Analysis (PRA) of civilian nuclear power. Sandia researchers use an array of analysis techniques including event and fault trees, influence diagrams, decision trees, and network diagrams, combined with deep systems knowledge and substantial professional expertise to produce realistic risk estimates for complex systems. The resulting analyses explore the often subtle and non-intuitive interactions among initiating events, hardware failures, human errors, and operational and organizational factors that influence the risk profile for a system. Insights obtained from PRA play valuable roles throughout the system life cycle varying from design and licensing, to construction, operation, decommissioning, and regulation. Sandia combines this analytical and systems expertise with experimental facilities and experience needed to develop empirical reliability and performance data needed to support specific PRA applications.

There are many compelling challenges in the area of civilian nuclear power risk analysis which will need to be addressed in the coming decades. Some of the challenges are associated with emerging nuclear reactor designs including small modular reactors, as well as next generation light water reactors and advanced gas and metal cooled reactors. Sandia researchers are exploring solutions to the risk analysis challenges presented by new technology incorporated into these designs including digital instrumentation and control and passive safety features. For example, Bayesian belief networks allow analysis of systems with limited operational data, and dynamic risk analysis techniques are valuable where system performance depends on event progression. Sandia continues to extend current PRA methods and conduct empirical studies providing system and component performance data upon which future risk analyses will depend.

The challenges posed by analysis of the current aging US and international fleet of third generation reactor designs are no less important than those posed by new designs. The impact of aging on the performance of existing reactor systems and components is of particular importance, and will require new empirical and analytical studies. In support of these needs, Sandia researchers are developing new data and methods to improve current understanding of the risk profile for existing designs and extending PRA analysis into operating states that are currently poorly characterized.

Sandia has over 30 years of experience developing and applying PRA methods to civilian nuclear power applications, dating from the Three Mile Island event in 1979. This history coincides with the development of the modern risk-informed, performance-based regulatory framework employed by the NRC today. Sandia played a central role in many of the seminal works which form the basis of the NRC's regulatory structure, and continues serving as an active contributor in the development of industry standards which provide guidance for the correct application of these techniques in an industrial setting. Sandia's staff includes many original developers of current PRA methods as well as a new generation of researchers capable of continuing the development of this important methodology into the future. Selected NUREGs are listed below:

1980 – NUREG/CR-1338: Allocation of NRC inspection effort to risk-related activities in nuclear power plants

1983 – NUREG/CR-3233: The effect of resolution of the Millstone Point Unit 1 systematic evaluation program issues on probabilistic calculations of risk

1986 – NUREG/CR-4514: Controlling principles for prior probability assignments in nuclear risk assessment.

1987 – NUREG/CR-4551: Evaluation of severe accident risks and the potential for risk reduction

1987 – NUREG/CR-4825: A Preliminary evaluation of the economic risk for cleanup of nuclear material licensee contamination incidents.

1987 – NUREG/CR-4834: Recovery actions in PRA for the Risk Methods Integration and Evaluation Program (RMIEP).

1988 – NUREG/CR-4836: Approaches to uncertainty analysis in probabilistic risk assessment.

1990 – NUREG-1150: Severe Accident Risks

1992 – NUREG/CR-4839: Methods for external event screening quantification : Risk Methods Integration and Evaluation Program (RMIEP) methods development.

1993 – NUREG/CR-4832: Analysis of the LaSalle unit 2 nuclear power plant: risk methods integration and evaluation program (RMIEP).

1993 – NUREG/CR-5863: Risk assessment of isolation devices in safety systems.

1993 – NUREG/CR-4551: Evaluation of severe accident risks: methodology for the containment, source term, consequence, and risk integration analyses

1994 – NUREG/CR-6166: Risk impact of BWR technical specifications requirements during shutdown.

1999 – NUREG/CR-5593: Risk comparisons of scheduling preventive maintenance for boiling water reactors during shutdown and power operations

2.10.1. Capabilities

- Event tree analysis
- Fault tree analysis
- Influence diagrams
- Decision trees
- Bayesian network modeling and analysis
- System dynamics
- Boiling water reactor system analysis
- Pressurized water reactor system analysis
- PRA industry standards

2.11. Human Reliability Analysis Research

Human reliability is comprised of two primary components: knowledge of the system and human behavior. The interplay between these two disciplines requires a balanced interdisciplinary approach leveraging elements of industrial ergonomics and cognitive psychology with knowledge-based analysis of the engineered system. Investigating various phases of human information processing includes: detection, assessment, response planning, and response execution. Sandia researchers identify and quantify the ways that human actions selectively initiate, propagate, or terminate fault and accident sequences.

Human reliability analyses (HRAs) represent a difficult task since researchers need to understand all elements of the situational context ranging from hardware functions to operator responses during accident progression. Due to this complex nature, successful HRAs use inputs from many technical disciplines to generate a systems-based assessment of total risk. Inputs from probabilistic risk assessments, systems engineering, plant design, human factors engineering, cognitive and behavioral science, and ergonomics are only a few of the diverse areas that are drawn upon as input for HRA analysis. While other institutions may specialize within a contributing discipline, Sandia maintains an exceptionally balanced multidisciplinary team with experts spanning all relevant disciplines. This balanced team of psychologists, engineers, and mathematicians provide a sensible and synergistic blend of disciplines.

Sandia researchers are extending the state of the art in HRA through method development and empirical data collection and analysis. The resulting body of work not only enhances the understanding of the risks associated with the operation of current civilian nuclear power reactors, but supports the licensing and regulation of new reactor designs. In addition, Sandia researchers are developing new methods and techniques applicable to the analysis of current and future designs. For example, Bayesian analysis methods are of particular interest in this area given the often limited data available for human performance in operational and accident contexts. Sandia researchers also develop and study models of human cognition to provide insights into situational awareness and learning. These efforts represent a portion of a broader Sandia program in advanced probabilistic risk assessment which has supported civilian nuclear energy regulatory rule making since the late 1970s.

The origins of HRA trace back to Sandia's development of the first-ever HRA methodology for the NRC. Sandia developed the Technique for Human Error Rate Prediction (THERP) to evaluate the probability of human failure events occurring at a nuclear power plant. Serving as foundation of HRA methodology and practice, THERP is capable of modeling dependent relations between actions and errors in a way unlike any other technique. It is an extensively documented and widely used HRA technique throughout the U.S. and the international community. Since the development of THERP Sandia has been a key contributor and developer of other NRC HRA methodologies including ATHENA and most recently the ATHENA methodologies. Selected NUREGs are listed below:

1996 – NUREG/CR-6350: A Technique for human error analysis (ATHEANA)

2006 – NUREG-1842: Evaluation of Human Reliability Analysis Methods Against Good Practices: Final Report

2011 - NUREG/CR-1278: Handbook of human reliability analysis with emphasis on nuclear power plant applications

2012 - NUREG/CR-7016: Human reliability analysis: informed insights on cask drops.

2012 - NUREG/CR-7017: Preliminary, qualitative human reliability analysis for spent fuel handling.

2.11.1. Capabilities

- Human reliability analysis
- Human factors
- Industrial ergonomics
- Cognitive psychology

2.12. Fire Risk Analysis Research

Sandia's fire science research plays a significant role in ensuring the safe, secure, and responsible operation of nuclear power plants worldwide. Sandia research provides the scientific basis for cable and circuit testing and evaluation, transportation vulnerabilities, metal fire phenomenology, and spent nuclear fuel pool ignition phenomena. Through research and experimentation in areas including basic fire behavior, fire modeling, fire protection engineering, and structure fire protection regulation compliance practices, Sandia's nuclear fire protection work leads the field in characterizing and evaluating fire risks and protection strategies necessary for the safe operation of nuclear energy infrastructure.

Recent research by Sandia's scientists and researchers includes work in further characterizing fire behavior in nuclear-specific applications. The experimental data is also used to validate complex models of fire incident progression and dynamics. Sandia's Energized Cable Fire Program investigates elements of cable performance when exposed to a thermal environment. Cable performance research is applied to circuit reliability studies to investigate failure modes such as hot shorting behavior and spurious operation of components. Researchers use custom built equipment to test circuits and study electrical insulation degradation during thermal exposure. Sandia researchers have worked on characterizing spent fuel assembly fires utilizing a phased experimental approach to study Zircaloy fires in prototypic spent fuel assemblies. Two test series were conducted to examine the behavior of prototypic boiling water reactor and pressurized water reactor fuel assemblies during a complete Loss-of-Coolant accident in a spent fuel pool. This work advanced the state-of-the-art in thermal hydraulics modeling during heat-up and the phenomenology of Zircaloy combustion which supported computational simulation validation.

Fire testing facilities available at Sandia include a large variety and range of capabilities.

Thermal Test Complex (TTC): The TTC provides a controlled environment in which to evaluate the performance of components and assemblies under controlled temperatures (up to 2,200°C) or programmed heat fluxes (up to 200 W/cm2), and includes facilities such as the FLAME Test Cell, the Cross Flow Fire Test Facility, and the Radiant Heat Test Cell. These facilities provide capabilities in both quiescent (calm) wind and wind speeds up to 20 mph.

Surtsey Test Facility: The Surtsey test facility features a sealed pressure vessel used to conduct accident phenomenology testing including steam explosions, hydrogen detonations, core melt progression, core concrete interactions, high pressure melt ejections, and liquid metal fire testing.

CYBL Test Facility: The CYBL facility features a scaled reactor pressure vessel system originally designed for severe accident cooling studies. It also provides an outstanding controlled environment for Sandia's recent spent nuclear fuel combustion experiments.

Lurance Canyon Burnsite Facility: The facilities within Lurance Canyon are used to study both indoor and outdoor fires associated with nuclear material transportation and handling accidents for safety studies and for evaluating and certifying hazardous material shipping containers. Tests at Lurance Canyon also include rocket propellant fires and test units containing explosives. The facility includes an enclosed pool fire test facility, three open pools used to simulate liquid fuel fires, an igloo structure used to simulate building fires and hot spots in weapons storage bunkers, and a 1.8 m round pool enclosure for smoke reduction tests.

The cable spreading room fire at Browns Ferry Nuclear Power Plant in 1975 illustrated the need for increased research into safety system reliability during abnormal events such as fire. Months prior to the incident, the NRC contracted with Sandia to begin analyzing nuclear fire safety. For over 35 years, Sandia has conducted experimental nuclear fire research to address increasingly important and complex risk and reliabilities studies. Current nuclear-specific fire research investigates fire phenomenology and the effects of fire on various nuclear energy applications and components, including circuit reliability. Whether it's investigating fire induced small component failure or a large-scale configuration, this capability is used to quantify the overall fire risk of a nuclear power plant. Selected NUREGs are listed below:

1989 - NUREG/CR-5384: A summary of nuclear power plant fire safety research at Sandia National Laboratories

2002 - NUREG/CR-6776: Cable insulation resistance measurements made during the EPRI-NEI cable fire tests

2003 - NUREG/CR-6834: Circuit analysis: failure mode and likelihood analysis

2005 - NUREG/CR-6850: EPRI/NRCRES fire PRA methodology for nuclear power facilities

2008 - NUREG/CR-6931: Cable response to live fire (CAROL FIRE)

2008 - NUREG/CR-6978: A phenomena identification and ranking table (PIRT) exercise for nuclear power plant fire modeling applications

2.12.1. Capabilities

- Fire risk analysis;
- Electrical fire phenomenology and testing;
- Cable and electrical component performance;
- Metal fire phenomenology and testing;
- Hydrocarbon pool fire phenomenology and testing; and
- Fire modeling and simulation.

2.13. Uncertainty & Sensitivity Analysis

Beginning over 30 years ago Sandia has been pioneering and conducting research to quantify margins, reduce unnecessary burden, and reduce uncertainties for areas of potentially high risk supporting nuclear safety. Sandia plans, develops, and manages research programs supporting risk-informed regulatory decision-making. Sandia uses probabilistic modeling to understand how well simulations model reality, and thus recognize when we can have confidence in a computational answer. Sandia manages the development of computation tools within a robust quality assurance environment.

Sandia’s fundamental scientific strengths in optimization and uncertainty estimation include developing software that quantifies the uncertainty and variability in predictions of a complex system. This prediction uncertainty can arise from physical uncertainties, for example uncertain material properties, which appear as parameters in the computational model. Uncertainty in computed system response can also result from the omission of pertinent physics or from an under-resolved deterministic model. Sandia has a suite of design tools that couple optimization and uncertainty software and has extensive experience in assessing the sensitivity of model outputs with respect to model inputs. Sandia's programs have helped establish computation as a third pillar of science (along with theory and physical experiments).

Sandia addresses emerging issues and supports the revision and development of NRC Regulatory Guides (RGs), NUREG reports and responses to inquiries from the Commission, Advisory Committee on Reactor Safeguards (ACRS), and Congress. Sandia researchers reduce uncertainties in areas of potentially high safety or security risk or significance and develop the technical basis for risk-informed, performance-based regulations needed for the resolution of nuclear safety and security issues.

Nationally and internationally recognized, Sandia has been leading the state-of-the-art in uncertainty and sensitivity analysis for over 30 years. Selected NUREGs are listed below:

NUREG/CR-3440 – Identification of Severe Accident Uncertainties (1979)

NUREG/CR-2350 – Sensitivity Analysis Techniques: Self-Teaching Curriculum (1982)

NUREG/CR-3226 – Station Blackout Accident Analysis (1983)

NUREG/CR-3624 – A FORTRAN 77 Program and User's Guide for the Generation of Latin Hypercube and Random Samples for Use with Computer Models (1984)

NUREG/CR-4350 – Probabilistic Risk Assessment Course Documentation (1985)

NUREG/CR-3904 – A Comparison of Uncertainty and Sensitivity Analysis Techniques for Computer Models (1985)

NUREG-1150 – Severe Accident Risks: An Assessment for Five US Nuclear Power Plants (1990)

NUREG/CR-5305 – Integrated Risk Assessment for the LaSalle Unit 2 Nuclear Power Plant: Phenomenology and Risk Uncertainty Evaluation Program (PRUEP) (1992)

NUREG/CR-6134 – Uncertainty and Sensitivity Analysis of Chronic Exposure Results with the MACCS Reactor Accident Consequence Model (1995)

NUREG/CR-6135 – Uncertainty and Sensitivity Analysis of Early Exposure Results with the MACCS Reactor Accident Consequence Model (1995)

NUREG/CR-6136 – Uncertainty and Sensitivity Analysis of Food Exposure Results with the MACCS Reactor Accident Consequence Model (1995)

NUREG/CR-5593 – Risk Comparisons of Scheduling Preventative Maintenance for Boiling Water Reactors During Shutdown and Power Operation (1999)

NUREG/CR-6823 – Handbook of Parameter Estimation for Probabilistic Risk Assessment (2003)

NUREG-2110 – xLPR Pilot Study Report (2012)

NUREG/CR-7155 – State-of-the-Art Reactor Consequence Analysis Project: Uncertainty Analysis of the Unmitigated Long-Term Station Blackout of the Peach Bottom Atomic Power Station (2013)

2.13.1. Integrated Capabilities

Sandia has extensive programs in Computer Science and Applied Mathematics, and multidisciplinary programs linking activities to theory and physical experiments including:

- The development of the first Latin Hyper-cube Sampling code in the late 70's, Sandia has continuously maintains and develops expertise in the domain of sensitivity and uncertainty analysis.

- Early application and continuous development of uncertainty and sensitivity analysis techniques.

- Continuous leadership in the fields of large-scale optimization and uncertainty estimation.

- Advanced scientific computing research programs at Sandia supporting world-class, high-performance computing and networking infrastructures supporting fundamental research in mathematical and computational sciences to enable researchers to analyze and predict complex phenomena for scientific discovery.

- R&D activities spanning the spectrum of stand-alone design optimization and assessment tools, to intrusive capabilities that tightly couple with simulations and frameworks for computing sensitivities and derivatives (e.g., DAKOTA, FUEGO, and SIERRA).

- Software development supporting large-scale optimization and uncertainty estimation (e.g., DAKOTA).

- Sandia optimization and uncertainty estimation software development key strengths including effective collaboration with experts from other parts of Sandia, DOE labs, universities, and industry.

- Discrete mathematics applications including scientific computing, parallel algorithms, logistics, and scheduling.

- Expertise in developing advanced capabilities for exploration of data. Enabling the examination of very large and/or very complex data with the goal to provide enabling capabilities, which allow applications to significantly improve productivity and/or create entirely new technologies in their own respective fields.

- Advanced numerical algorithms: Krylov Subspace methods, preconditioning methods, finite element discretization, time integration methods, and iterative solvers.

- Supercomputing facilities and advanced software architectures, algorithm scalability, network technologies, and systems reliability.

- Computational mechanics R&D and development resources for the development of modeling and simulation software that includes a thorough understanding of the underlying physics along with a careful design of the numerical implementation. Computational methods developed in structural mechanics, heat transfer, fluid mechanics, shock physics, and many other fields of engineering can be an enormous aid to understanding the complex physical systems.

2.14. Cyber-Based Vulnerability Assessments

Based upon over 60 years of security assessment activities and strengthened by multi-disciplinary technical programs across the laboratory, Sandia applies a wide variety of assessment and cyber-based Red Teaming techniques, tools, and facilities to optimize the security assessment process for a wide range of information systems throughout their life cycle. Red Teaming is the practice of viewing a product under evaluation from an adversary's perspective. The goal of most Red Teams is to identify approaches, techniques or procedures that can be used to undermine the product under evaluation. This "product" can take many forms depending on the desired evaluation. The result of the Red Team is normally used to enhance some aspect of security by understanding the strategy of the adversary. Sandia teams have developed and applied a set of consistent and transparent methodologies to ensure that an effective and efficient approach is applied to each assessment.

2.14.1. Cyber-Based Red Teams

Sandia maintains advanced system security assessment and Red Teaming capability in multiple programs, including the Homeland Security Red Team (HSRT) and the Information Design Assurance Red Team (IDART). HSRT was created to focus on Red Team assessment activities for our national infrastructure systems. IDART is a methodology developed by Sandia that is performed from the adversary's point of view and is consequence based and system oriented. This methodology provides the most comprehensive approach to vulnerability assessment. Both programs are managed at Sandia. Sandia Red Teams provide multi-disciplinary groups of subject matter experts; each customer project is evaluated for objectives, requirements, and technology in order to provide a customized plan and team for adversarial-based assessment. Using engineering-based assessment methods, Sandia Red Teams provide actionable information and work with our sponsors to develop prioritized mitigations to harden systems against malevolent threats.

The IDART program has been providing adversarial-focused vulnerability analysis (Red Teaming) since 1996 for the Department of Defense, the DOE, and other federal agencies such as the Department of Interior and Department of State. IDART has also performed these assessments for critical infrastructure system customers, including electric power generation, transmission and distribution management, banking and finance, manufacturing, e-business, gas and oil systems, and transportation.

2.14.2. Physical and Cyber-Based Industrial Control System Modeling

Sandia has developed a modeling and simulation environment that provides an analysis capability that supports assessing and improving the cyber security of control systems used in the energy sector. The modeling environment called "Sceptre" bridges the gap between control system models and process simulation. Tools and techniques exist for simulating and emulating control system field devices, but results from the security analysis these tools currently support are limited because the physical processes being controlled are not included. Leveraging Sandia's proven Umbra modeling environment, the Sceptre intertwines the device and process simulations to provide an integrated system capable of representing realistic responses in the physical process as events occur in the control system and vice versa. The Sceptre provides a means for creating large-scale control system test environments suitable for cyber security experiments. Leveraging modeling and simulation, the test environments can be scripted to suite each experiment as necessary, are repeatable, and are much cheaper to construct than real or even lab-scale test environments. The use of standards-based SCADA protocols in the simulated field devices also means 3rd party ICS and cyber security testing applications can still be used, and supports the use of simulated and emulated network environments as well.

2.14.3. Supply Chain Risk Management

Supply chain security is emerging as one of the top security threats facing critical systems. It is no longer just sufficient to identify all cyber based vulnerabilities associated with the actual assessment of an installed base of cyber based assets but to also assess the supply chain in which the assets are acquired. Industry's reliance on commercial off-the-shelf products is apparent, as is the threat of the systems almost exclusively being designed, manufactured and developed overseas. It is extremely challenging to establish transparency and trustworthiness of supply chain for a product/system in today's globalized climate, especially given the complexity and variability of the hardware/software and the geographical areas where they are made. These attacks can be inserted at any point during the product or system life cycle and can have detrimental effects to mission success. Sandia has developed a decision support methodology built around the supply chain life cycle that can be used to identify processes that help identify integrity risk to any life cycle phase. Risk can then be reduced by identifying the appropriate security controls and applying it to the supply chain life cycle phases.

2.14.4. Previous NRC Cyber-Based Security Work

Starting in 2003, Sandia led a series of risk informed security assessments (SAs) of NRC materials licensees. This work was performed for the Office of Nuclear Material Safety and Safeguards. The SAs addressed both sabotage events leading to a release of material and events involving theft by outsiders or diversion by insiders of material for potential use in an improvised nuclear device or in a radiological dispersal device. Vulnerabilities of structures, process and protective systems, security operations and physical protection systems (PPSs), information technology (IT) systems, material control and accountability systems, and access control systems were assessed, as applicable. Vulnerabilities were identified through a review of site-specific documentation as well as on-site interviews of knowledgeable staff. This effort did not include hands-on testing of actual equipment. A prioritized ranking of consequences, vulnerable systems and structures, threats, and countermeasures was developed. The cyber assessments performed for this effort included the (1) characterization of critical IT system architectures, features and capabilities, (2) delineation and characterization of IT system controls, and (3) identification of potential IT system vulnerabilities and consequences. The cyber assessments were performed by the Sandia IDART. These teams ranked the identified cyber vulnerabilities in terms of adversarial resources required and the potential consequences of exploitation. Mitigations were recommended.

From 2006 thru 2012 Sandia has been working with the NRC's Office of Nuclear Regulatory Research on multiple projects to assess and improve the design and implementation of digital instrumentation & control systems. These systems are responsible for the safe and secure operations of electricity generation. Their assessment is necessary to determine the risk associated with their design, configuration and operation. Additionally the NRC needs to validate the adequacy of cyber protection within nuclear digital safety networks when subjected to deliberate attempts to modify their configuration and/or disrupt their safety function.

The goal of this work was to raise awareness of the importance of adequate cyber security of nuclear safety systems, identify potential vulnerabilities, and propose effective mitigation measures.

Sandia has also been involved with the Office of Nuclear Security and Incident Response (NSIR) in the cyber based training of regional NRC inspectors. Sandia has developed training modules to help increase the cyber knowledge set for regional inspectors who must validate on-site cyber protection mechanisms.

2.15. Physical Security Vulnerability Assessments

As a National Security Laboratory for the National Nuclear Security Administration (NNSA), Sandia has almost four decades of experience providing technical expertise for designing and developing physical security systems, technology, testing, and assessment methods. Our physical security activities have supported the DOE, the NNSA, the NRC, the Department of Defense, other Federal, State, and Local agencies, and private industry. Sandia security facilities and capabilities are summarized below.

Sandia has been a premier physical security laboratory for several decades and has developed several physical security-related facilities that can be used for security testing, demonstration and training activities. These include:

- Integrated Security Facility – Training, Demonstration, and Testing (former DOE Category 1 Facility);
- Sensor Test and Evaluation Center – Intrusion detection lab and test field;
- Access control and contraband detection lab;
- Active response and denial test area;
- Fixed barrier designs and activated dispensable materials for access delay applications test area;
- Physical protection test area;
- Force-on-force simulation laboratory;
- Development and conduct of system vulnerability and risk assessments;
- Nuclear facilities;
- Infrastructure, cyber; and
- Water utilities, dams, communities, prisons, chemical facilities.

2.15.1. Technical Assistance for Advanced Reactors

Sandia has supported review of the Standard Review Plan for the Review of Safety Analysis Reports for Nuclear Power Plants, and development of Design Specific Review Standards for new advanced reactors, specifically small modular reactor (SMR) designs. Related efforts have addressed Emergency Response and Planning, as well. In addition, Sandia has provided an initial identification of vital equipment and target sets for SMR designs.

2.15.2. Vital Area Identification and Loss of Large Area Analyses

Sandia developed the methods for vital area identification (VAI) analyses, provides VAI training to international customers, and has capabilities to perform VAI analyses for new reactor designs. Sandia staff supported the VAI analyses performed for the US nuclear plants in the 1980s. In 2008, Sandia documented a structured process for identifying vital areas in nuclear power plants. In addition, Sandia is developing methods for loss of large area analyses to address beyond design basis events that might impact large areas of a power plant. Sandia is currently performing VAI analyses and security planning for the Korea Hydro Nuclear Power APR1400 reactor design, which includes consideration of random failures, maintenance unavailability, and operator errors in the selection of areas to protect.

2.15.3. Security Requirements for Spent Nuclear Fuel and High-Level Waste Storage

Sandia performed a security assessment for spent fuel storage systems to address post September 11, 2001, concerns for these commercial facilities (i.e., the Spent Fuel Vulnerability Assessment Reports). Building on this previous work, Sandia is currently supporting the NRC in its development of the technical basis for the rulemaking to update the security requirements for facilities storing spent fuel and high-level waste. The proposed security rule is using a risk-informed and performance-based approach under which licensees would calculate potential releases from an independent spent fuel storage installation (ISFIS) or monitored retrievable storage (MRS) facility to certain NRC-specified security scenarios.

2.15.4. Vulnerability Assessments for Non-Power Reactor Facilities

As part of the NRC's efforts to address post-September 11, 2001, security issues, Sandia performed security assessments for NRC-licensed non-power reactor facilities, including research and test reactors and radioactive material facilities. The results of these assessments were used by the NRC and the DOE to establish new security requirements and make changes to improve security at these facilities.

Research and test reactors: These studies were performed for the Office of Nuclear Reactor Regulation (NRR). The facilities reviewed included NRC-licensed research and test reactors at universities and other DOE and commercial institutions. A key focus of these studies were on the radiation dose levels of the fuel in the pools where the fuel was stored and what levels might prevent an adversary from completing theft of an assembly. In addition, Sandia made site visits to the test reactors, evaluated their effectiveness of their protection measures against several different levels of adversary threats, and made recommendations for security changes. The NRC and DOE implemented many of these recommendations to improve security at these facilities.

Radioactive Material Facilities: The studies were performed for Office of Nuclear Material Safety and Safeguards (NMSS). The facilities reviewed included common applications of radioactive sources including radiography, medical applications (e.g., blood irradiation and cancer treatment, large facilities for irradiating food stuffs or sterilizing medical equipment, well-logging, and radiological equipment manufacturing). The vulnerability assessments also include facilities related to the nuclear fuel cycle including uranium conversion and enrichment, and nuclear fuel fabrication. The purpose of the study was to identify vulnerabilities of these facilities to theft of material or sabotage. Both physical (including material control and accountability) and cyber security were included in the evaluations. Sensitivity studies were performed for evaluating potential improvements in the physical protection systems at each type of facility. Twelve reports were developed documenting the individual facility evaluations and a summary report was prepared comparing the relative risk at each facility.

2.15.5. New Power Reactor Security Requirements

On March 27, 2009, the Final Rule for the Power Reactor Security Requirements was published in the Federal Register [FR 13926, Vol. 74, No. 58], which amended security regulations and added new security requirements for nuclear power reactors in 10 CFR Parts 50, 52, 72, and 73.

Sandia provided technical support to security assessment guidance. The guidance documents included:

- The *Nuclear Power Plant Security Assessment Technical Manual*, which was published as a SANDIA technical report [Whitehead et al., SAND2007-5591, September 2007], and

- The *Nuclear Power Plant Security Assessment Format and Content Guide*, which was published by Information Systems Laboratories (ISL) [ISL, September 2007]

The *Technical Manual* includes a discussion of best practices for incorporating security systems design as early as possible in the overall facility design. This is highly recommended for new reactor technology designs.

The Foreword of the ISL report also refers to the following sections of the Standard Review Plan:

- Section 13.6.4 Physical Security – High Assurance Evaluation
- Section 13.6.5 Physical Security – Mitigative Measures Evaluation
- Section 13.6.6 Physical Security – Security Assessment – Cyber Assurance Evaluation

These sections are associated with new requirements in the March 2009 Final Rule for Power Reactor Security Requirements. Sandia supported the development of the NRC High Assurance Evaluation for reactor security assessments. In addition, Sandia has the capabilities to evaluate the applicability of the requirements for these security areas to new reactor technologies and to develop new guidance, if needed.

2.15.6. Physical Security Requirements

10 CFR 73 provides the NRC's requirements for Physical Protection of Plants and Materials against theft and radiological sabotage. Section 73.55 provides Requirements for Physical Protection of Licensed Activities in Nuclear Power Reactors Against Radiological Sabotage. These requirements provide performance objectives and requirements for security plans, the physical protection system (PPS), and security operations. Sandia has significant experience in the design and evaluation of a PPS to meet specific customer requirements and to identify security vulnerabilities. In addition, Sandia has the expertise to determine the applicability of the current security requirements to new reactor technologies, and to identify possible regulatory gaps and issues. As previously discussed, Sandia has also developed design and evaluation guidance for reactor security assessments to support implementation of the NRC's high assurance evaluation.

2.15.7. Aircraft Attacks

With regard to aircraft impacts, the March 2009 Final Rule for Power Reactor Security Requirements included the new 10 CFR 50.54 (hh) – Mitigative Strategies and Response Procedures for Potential or Actual Aircraft Attacks. Sandia has physical security and intelligence capabilities to support the determination of the applicability of these requirements to new reactor designs and the consideration of features that can be incorporated in new plant designs as mitigative and response measures.

Also, the Final Aircraft Impact Rule was published on June 12, 2009, adding the new 10 CFR 50.150 – Aircraft Impact Assessment [74 FR 28146, Jun. 12, 2009]. Sandia has the expertise to determine the applicability of these requirements to new reactor technologies, and to identify possible regulatory gaps and issues.

The Aircraft Impact Assessment requirements focus on avoiding or mitigating the effects of aircraft on the following key safety functions:

- core cooling capability;
- containment integrity;
- spent fuel cooling capability; and
- spent fuel pool integrity.

This type of assessment could be viewed as a safety analysis with the aircraft impact as the initiating event. It is important to maintain the perspective that safety events initiated by malevolent attacks are security events and consider what physical protection measures can be incorporated in a new plant design to prevent or mitigate these events. Sandia has significant safety analysis and probabilistic risk assessment expertise to analyze the integrated security and safety of new reactor designs.

2.15.8. Other NRC Security Support Programs

Sandia has provided technical support for other NRC security projects, including performing vulnerability assessments for research and test reactors for NRR and for fuel cycle and materials facilities for NMSS. In addition, Sandia conducts security training courses for the NRC, including:

The Advanced Intrusion Detection: Sandia teaches this class once a year to about 40 NRC nuclear power plant inspectors. This class was developed in 2008.

The Security Fundamentals class: Sandia's two-day portion of this two-week class is taught once a year in Chattanooga to about 30 NRC security specialists. This class was developed in 2008.

The Increased Controls class: Sandia teaches this class about three times a year to about 35 NRC and state inspectors of Radioactive Materials in Quantities of Concern. In the advent of Part 37 (new regulations developed by the NRC), Sandia is currently supporting the NRC in developing new course material geared toward the new regulations. This class was developed in 2006.

2.15.9. Security for Advanced Fuel Cycle Facilities

As part of the DOE Office of Nuclear Energy Fuel Cycle Technologies Program, Sandia has provided technical support for security research and development of future commercial fuel cycle facilities, including used fuel storage, recycling facilities, and advanced reactor designs. The context of this work is identifying and addressing issues, developing strategies, new analysis methodologies and technologies to support meeting NRC security requirements for licensing of these future fuel cycle facilities.

2.15.10. Reactor Licensing Reviews

For current commercial light water reactors, Sandia has supported the NRC's license reviews.

2.16. Nonproliferation

Sandia's has decades of experience in reducing proliferation and terrorism threats to US national security and includes developing and applying technical controls and analytical tools to properly manage nuclear, biological, and chemical technologies and materials; and ensure their safe, secure, and responsible use. Sandia develops the technologies and approaches for the use in safeguards, monitoring, and security systems that provide transparency essential to arms control and nonproliferation efforts.

Sandia develops the technology to protect potentially vulnerable nuclear and radiological material from malevolent use (e.g., in civilian locations that could be used in either a

Radiological Dispersal Device (RDD) or an Improvised Nuclear Device (IND)). Sandia conducts work both domestically and internationally, including over 25 countries on five continents. We take a systematic life-cycle approach including analysis, design, implementation, training, operation and sustainment, and disposal/disposition. Additionally, we provide expert training in how to effectively search for and secure orphan or lost sources. This methodical approach ensures that the materials that could threaten our homeland security are protected throughout the world.

Our capabilities detect and deter illicit trafficking of nuclear material international borders, at points of entry/exit, and through the global maritime shipping network. Specific capabilities include:

- Threat definition and analysis, physical security, site survey, Megaport prioritization, and related system integration;
- Information assurance and analysis, intrusion detection sensors, video, and communication technologies, containment/surveillance technologies, systems integration, assessment, training, and development;
- Nuclear fuel cycle and nuclear weapons and delivery system technologies;
- Regional security policy related to the Middle East, South Asia, and East Asia;
- Nonproliferation, physical security, export controls, and nuclear safeguards monitoring and verification technology;
- Systems analysis and decision support tools for understanding nuclear threats;
- Assessment across a number of testing facilities ranging from materials effects testing to equipment operability, functionality and vulnerability assessment;
- Chemical laboratory safety and security management;
- Chemical process safety and chemicals management;
- Chemical site physical security assessment; and
- Structured decision analysis tools for understanding chemical threats.

Sandia brings decades of experience to reduce these threats as evidenced by these selected reports:

“Defense Science Board Task Force on Unconventional Nuclear Warfare Defense” 2001 (Sandia contributor)

“A Risk-Based Approach to RDD Analysis” SAND2003-1331

Description and Validation of ERAD: An Atmospheric Dispersion Model for High Explosive Detonations” SAND92-2069

“Economic Impacts of Detonating RDDs” 2008 (Sandia contributor)

“Explosive Dispersal of Materials Relevant to Radiological Dispersal Devices – Experimental Results and Ramification” SAND2008-0733

“Self-Contained Irradiator in the US: Risks of Terrorist Acquisition & Use for RDDs” SAND2006-3703

“A Red Team Effort to Obtain Radioactive Material from a Self-Contained Irradiator” SAND2006-2352

Radioactive Sources Relative Risk Reduction Study” 2009 (Sandia contributor)

“Assessment of the Chemical Security Posture at Facilities Subject to NRC Regulation” 2010

“2010 Radiation Source Protection and Security Task Force Report” submitted by Chairman of the US NRC (Sandia contributor)

2.17. Emergency Planning

In the aftermath of the attacks of September 11, 2001, the NRC Emergency Preparedness staff began a review of the planning basis for nuclear power plant emergency preparedness programs (SECY-03-0165), and Sandia was at the forefront of this review. In 2003, Sandia supported NRC in the research and assessment of large scale emergency evacuations publishing NUREG/CR-6864, "Identification and Analysis of Factors Affecting Emergency Evacuations," which presented a comprehensive investigation of public evacuations and quantitatively demonstrated that evacuations reduce risk to the public. The data collected has proven valuable in identifying emergency planning activities, public behavior, and other trends observed during evacuations and supported the 2004 project to analyze the efficacy of alternative protective action strategies in reducing consequences to the public from a spectrum of core melt accidents. The study, documented in NUREG/CR-6953, “Review of NUREG 0654, Supplement 3, ‘Criteria for Protective Action Recommendations for Severe Accidents,’ Volumes 1, 2, and 3” (referred to as the PAR [protective action recommendation] study) provided a technical basis for enhancing protective action guidance and was used as the technical basis to update NUREG-0654/FEMA-REP-1, Supplement 3, “Criteria for Protective Action Recommendations for Severe Accidents.” Supplement 3 also defines the staged evacuation as the preferred evacuation approach and suggests wind persistence information be used in the PAR determination.

Sandia applied the results of the evacuation and PAR project research across multiple program areas for the NRC including updating guidance for development of evacuation time estimates (fs) in NUREG/CR-6863, “Development of Evacuation Time Estimate Studies for Nuclear Power Plants.” Sandia implemented upgrades for MACCS to allow more realistic modeling of emergency response. Upgrades included improving the Network Evacuation model, a capability to model a keyhole evacuation, and adding predictive weather capabilities to represent actions authorities may include when making protective action decisions.

Sandia applied the practical emergency response knowledge base and advanced MACCS model in the SOARCA project around 2008, which at the time represented the most advanced approach to modeling emergency response. As part of the SOARCA emergency preparedness modeling, Sandia developed ETEs using commercial models for areas beyond the emergency planning zone (EPZ). Subsequently, Sandia was asked by NRC to integrate the modeling methods, applications, and measures of effectiveness into the ETE guidance, which was published in 2011 as NUREG/CR-7002, "Criteria for Development of Evacuation Time Estimate Studies." As part of Appendix E to 10 CFR 50 rulemaking efforts, promulgated in 2011, NRC added requirements, based largely on Sandia research, that licensees use NRC approved ETEs in the formulation of protective action recommendations (PARs), and update the ETEs following a prescribed schedule.

In 2012, Sandia completed the most advanced application of MACCS ever performed developing a prototype tool, the DedUctive Quantification Index (DUQI), in a proof of concept application to provide a means to risk inform regulatory oversight of nuclear power plant emergency preparedness programs. The methods are published in NUREG/CR-7160, "Emergency Preparedness Significance Quantification Process: Proof of Concept."

Sandia is intimately familiar with the NRC Headquarters Operations Center procedures and conduct of operation. Beginning in 2005, Sandia updated NRC Incident Response Manual and all of the Headquarters, regional and site team position procedures, to ensure consistency with the National Response Plan and to integrate updated response protocols. Sandia has a unique understanding of the responsibilities and interface among response teams and response positions and is currently automating the Response Technical Manual (RTM-96), which is the NRC operations center response team document that defines the analytical methods, algorithms, and processes used for event assessment during an emergency. Sandia has developed a draft version analysis tool that replicates the reactor core damage assessment evaluation methods.

Sandia has also provided technical expertise to assist the NRC staff in determining whether Combined License and Early Site Permit applications met appropriate regulatory requirements, specifically related to radiological emergency plans and ETEs associated with the applications.

2.17.1. Severe Accident Mitigation Alternatives (SAMAs)

NRC has leveraged the depth of expertise of Sandia in the areas of emergency preparedness, MELCOR and MACCS modeling. Sandia has supported NRC developing technical positions and testifying in SAMA analysis hearings related to license renewal applications for Pilgrim, Indian Point, Davis-Besse, and Seabrook nuclear power plants. Sandia reviewed and provided technical expert Affidavits related to ETEs, MACCS consequence modeling, and MELCOR modeling. Also, Sandia provided expert witnesses testifying in front of the Atomic Safety and Licensing Board (ASLB) at the Pilgrim hearing and at the Indian Point hearings.

Sandia provided technical support to a related, but terminated Rulemaking for 10 CFR 73.62, Security Assessment Rule.

2.18. Urgent Response Capability

Sandia's breadth and depth in multiple technical fields enabled significant contributions to the understanding of risks to the US nuclear power plant fleet after the Three Mile Island accident, World Trade Center bombings, and Fukushima Dai-ichi accidents.

- After the Three Mile Island accident in 1979, the NRC turned to Sandia because of its nuclear safety expertise in nuclear weapons. Sandia led much of the foundational research in reactor accident phenomena including direct containment heating, molten core concrete interaction, core melt progression, and lower head failure.

- After 9/11, Sandia assessed aircraft impact vulnerabilities to a nuclear power plant's reactor, balance of plant, spent fuel pools, and dry cask storage.

- After the Fukushima Dai-ichi accident, Sandia advised the NRC, DOE, US Embassy, and military on potential source terms, reactor and spent fuel pool accident progression, efficacy of potential responses, and potential impacts from seismic aftershocks.

When needed, Sandia's specialized expertise and capabilities are available to support the most urgent of needs.

2.19. Regulatory Gap Analysis

The NRC developed an advanced non-light water reactor (LWR) probabilistic risk assessment (PRA) research program to ensure that the NRC staff has the proper knowledge and tools to support risk informed licensing activities for advanced non-LWRs. The objective of this program, supported by Sandia, was to identify where guidance, methods, and data are needed to support the technical review of an advanced non-LWR PRA. This work had as its scope the performance of a "gap analysis" to identify where there might be gaps in the guidance, methods, and data needed for an adequate review of an advanced non-LWR PRA. Many insights gathered while reviewing existing PRA methods, tools and standards were found to be technology neutral and potentially applicable to nuclear power concepts in the design phase.

3. REFERENCES

[1] NRC, "Severe Accident Risks: An Assessment for Five U.S. Nuclear Power Plants," NUREG-1150, NRC, Washington D.C., 1990.

[2] NRC, "State-of-the-Art Reactor Consequence Analysis (SOARCA) Report," NUREG-1935, NRC, Washington D.C., 2013.

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