SANDIA REPORT
SAND2025-10293
Printed August 2025

Sandia National Laboratories' Capabilities in Support of Space and Terrestrial Nuclear Applications

Nuclear Energy Safety and Security Group

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ABSTRACT

This SAND report showcases Sandia National Laboratories' extensive expertise in various areas, including advanced reactor technologies, artificial intelligence/machine-learning, atmospheric dispersion modeling, cyber-based vulnerability assessments, and more.

This report also highlights SNL's software development, modeling frameworks, and its specialized facilities and equipment.

The report aims to provide a comprehensive overview of SNL's capabilities and how these capabilities support the mission areas of nuclear operations for space and terrestrial nuclear applications. Emphasis here is on nuclear missions and facilities, but many of the tools, capabilities, and expertise described are not limited to nuclear applications.

This report is structured into four parts:

1. **Unique Capabilities**: An introductory table listing disciplines and sub-disciplines where SNL maintains capabilities and expertise.
2. **Sandia Capability Descriptions:** Detailed descriptions of SNL's capabilities, accrued knowledge, and subject matter experts.
3. **Sandia-Developed Software and Modeling Frameworks:** Descriptions of SNL-developed proprietary tools and information.
4. **Specialized Facilities or Equipment:** Descriptions of SNL's test facilities and equipment.

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EXECUTIVE SUMMARY

The report details the unique capabilities of Sandia National Laboratories (SNL) that are essential in supporting mission areas of space based and terrestrial nuclear and radiological applications, missions, and facilities. SNL's capabilities are not limited to nuclear or radiological applications, but are generally applicable to broader application spaces.

SNL's capabilities include the following:

- Advanced reactor technologies and fuel concepts
- Artificial intelligence/machine-learning (AI/ML)
- Atmospheric dispersion modeling
- Cyber-based vulnerability assessments
- Dose and risk assessments
- Economic impact analysis
- Emergency planning
- Environmental transport modeling
- Fire risk analysis research
- Food chain modeling
- Human reliability analysis research
- Hydrogen risk
- Integrated 3S (Safety, Security, Safeguards)
- International consultation
- Large-scale validation experiments
- MIDAS: Mobile Instrumentation Data Acquisition System
- Multi-scale, multi-process testing
- Non-proliferation
- Nuclear cyber security
- Physical security vulnerability assessments
- Probabilistic risk analysis research
- Radiation protection/health physics
- Regulatory gap analysis
- Severe accident modeling and analysis
- Socioeconomics
- Space nuclear
- Structural engineering and containment integrity research
- Structural phenomenological modeling and analysis of complex systems
- Thermal and thermomechanical phenomenology modeling of complex systems
- Uncertainty and sensitivity analysis
- Waste management

This report also highlights SNL's software and modeling frameworks, including the following:

- Advanced Reactor Cyber Security Analysis and Design Environment (ARCADE)
- Aerosol Physics and Chemistry of the Reactor Accident Source Term
- Coupled Fire-Thermal Analysis Codes
- Dynamic Event Tree Code
- Emergency Response Codes
- Environmental Fate and Atmospheric Transport Models
- Extremely Low Probability of Rupture (xLPR) Code
- Fire Science Research Codes
- Hydrogen Risk Assessment Models Toolkit
- MELCOR Accident Consequence Code System (MACCS) code suite
- Physical Security and Safeguards
- Sandia's High-Performance Computing (HPC) Codes
- Severe Accident and Consequence Research Modeling: MELCOR and MACCS
- Shock Physics
- ROCQUET – Radiological Off-Nominal Consequence Quantification and Evaluation Toolset

Additionally, the report describes SNL's specialized facilities or equipment, including:

- Access Delay Bunker (ADB)
- Aerosol Facility (AF)
- Center for Security Systems (CSS)
- Combustion Research Facility (CRF)
- Cylindrical Boiling Vessel (CYBL) Test Facility
- Design, Evaluation, and Test Technology Facility (DETTF)
- Energy-cyber lab complex
- Engineering Sciences Experimental Facilities (ESEF)
- Explosive Components Facility (ECF)
- Geomechanics Laboratory (GL)
- High-Performance Computing (HPC) Clusters
- Integrated Security Facility (ISF)
- Lurance Canyon Burnsite Facility
- Materials Science and Engineering Center (MSE)
- Mechanical Test and Evaluation Facility (MTEF)
- Microsystems and Engineering Sciences Applications (MESA) complex
- National Solar Thermal Test Facility (NSTTF)
- North Slope Research Facility
- Nuclear Control System Emulation Lab

- Nuclear Energy Safety Technologies (NEST)
- Nuclear Facilities Resource Center (NUFAC)
- Outdoor Test Facility (OTF)
- Packaging and container capabilities
- Sensor Test and Evaluation Center (STEC)
- Shock Thermodynamic Applied Research Facility (STAR)
- Surtsey Test Facility
- Thermal Test Complex (TTC)
- Superfuge/Vibrafuge
- Rocket Sled Track
- Water Impact Facility
- Aerial Cable Facility
- Blast Tube Facility
- Drop Tower
- Mechanical Shock Facility
- Mobile Gun Test Complex (MGTC)

ACRONYMS

Acronym	Definition
3S	Safety, Security, Safeguards
ACRR	Annular Core Research Reactor
ADAPT	A Dynamic Analysis and Prediction Tool
ADB	Access Delay Bunker
ADS	Accident Dynamic Simulation
AFRL	Air Force Research Laboratory
AHCF	Auxiliary Hot Cell Facility
AI/ML	Artificial Intelligence/Machine Learning
ARCADE	Advanced Reactor Cybersecurity Analysis and Design Environment
ARIA	SIERRA Multimechanics Module
ARTIST	Aerosol Trapping in the Steam Generator
ASME	American Society of Mechanical Engineers
BER	Biological and Environmental Research
CAFE	Container Analysis Fire Environment
CARS	Complementary Cumulative Distribution Function Analysis and Rollup Statistics
CEL	Critical Experiments Laboratory
CFD	Combustion Fluid Dynamics
CRF	Combustion Research Facility
CSOC	Cyber Security Operations Center
CTH	Code for Transient Hydrodynamics
CYBL	Cylindrical Boiling Vessel
DCFPAK	Dose Coefficient File Package
DCSA	Defensive Cyber Security Architectures
DETTF	Design, Evaluation, and Test Technology Facility
DOT	Department of Transportation
DPC	Dual-Purpose Canisters
ECF	Explosive Components Facility
EERE	Office of Energy Efficiency
ELK	Elasticsearch, Logstash, Kibana
EPHA	Environmental Primary Hazard Assessments
EPRI	Electric Power Research Institute
ESEF	Engineering Sciences Experimental Facilities
ETE	Emergency Transportation Exercise

Acronym	Definition
FNPP	Floating Nuclear Power Plant
FRMAC (TF)	Federal Radiological Monitoring and Assessment Center (Task Force)
GDSA	Geologic Disposal Safety Assessment
GIF	Gamma Irradiation Facility
GL	Geomechanics Laboratory
HAC	Hypothetical Accident Conditions
HE	high explosives
HFTO	Hydrogen and Fuel Cell Technologies Office
HLW	High-Level radioactive Waste
HPC	High Performance Computing
HRA	Human Reliability Analysis
HGTR	high-temperature gas reactor
HyRAM+	Hydrogen Plus Other Alternative Fuels Risk Assessment Models
HYSPLIT	Hybrid Single-Particle Lagrangian Integrated Trajectory
I&C	instrumentation and control
IBL	Ion Beam Laboratory
ICS	Industrial Control System
IDAC	Information, Decision, and Action in Crew
IDHEAS	Integrated Decision-Making for Hazardous Events Assessment and Safety
IND	Improvised Nuclear Device
ISF	Integrated Security Facility
LAPS	Loop Analysis Program Software
LASEP	Launch Accident Sequence Evaluation Program
LWR	Light Water Reactor
MACCS	MELCOR Accident Consequence Code System
MAPIT	Material Accountancy Performance Indicator Toolkit
MASCA	MAterial SCaling
MCNP	Monte Carlo N-Particle
MCR	Main Control Room
MELCOR	Modular Emergency Response Simulation Software
MESA	Microsystems and Engineering Sciences Applications
MGTC	Mobile Gun Test Complex
MIDAS	Mobile Instrumentation Data Acquisition System
MM	Mixture Manager
MS&E	Materials Science and Engineering Center

Acronym	Definition
MTEF	Mechanical Test and Evaluation Facility
NASA	National Aeronautics and Space Administration
NCT	Normal Conditions of Transport
NEPA	National Environmental Protection Agency
NEST	Nuclear Energy Safety Technologies
NNSA	National Nuclear Security Administration
NOAA	National Oceanic and Atmospheric Administration
NPP	nuclear power plant
NRA	Nuclear Risk Assessment
NRC	Nuclear Regulatory Commission
NSTTF	National Solar Thermal Test Facility
NUFAC	Nuclear Facilities Resource Center
OIP	Office of International Programs
OODA	Observe, Orient, Decide, Act
OTF	Outdoor Test Facility
PAR	Protective Action Recommendation
PETSc	Portable, Extensible Toolkit for Scientific Computation
PEVACI	Plutonium Entrainment and Vaporization After a Coincident Impact
PFLOTRAN	Parallel Flow and Transport
PHMSA	Pipeline and Hazardous Materials Safety Administration
PIDAS	Perimeter Intrusion Detection and Analysis System
PMT	Protective Measures Team
PRA	Probabilistic Risk Assessment
RADTRAN	Radiation Transportation
RASCAL	Radiological Assessment System for Consequence Analysis
RASPLAV	melt
RDD	Radiological Dispersal Device
RDEIM	Regional Disruption Economic Impact Model
REAcct	Regional Economic Accounting analysis tool
ROCQUET	Radiological Off-Nominal Consequence Qualification and Evaluation Tools
RTT	Response Technical Tools
SA	Security Assessment
SAMA	Severe Accident Mitigation Alternative
SAR	Safety Analysis Report
SCC	stress corrosion cracking

Acronym	Definition
SD	structural dynamics
SeBD	Secure-By-Design
SFM	Sandia Fireball Model
SFR	Sodium Fast Reactor
SHARC	Simulation for Hazardous Atmospheres with Radiological Consequences
SLDA	System Level Design Analysis
SM	solid mechanics
SME	subject matter expert
SNF	spent nuclear fuel
SNL	Sandia National Laboratories
SOARCA	State-of-the-Art Reactor Consequence Analyses
SQA	software quality assurance
STAR	Shock Thermodynamic Applied Research Facility
STEC	Sensor Test and Evaluation Center
STEM	Sulfur Transport and Deposition Model
STORM	Sandia-Developed Transport of Radioactive Material
STPA	Systems Theoretic Process Analysis
TF	Turbo FRMAC
THERP	Technique for Human Error Rate Prediction
TMI	Three-Mile Island
TTC	Thermal Test Complex
UAS	Unmanned Aerials Systems (UAS, aka “drones”)
V&V	Verification and Validation
VANESA	Vulnerability Assessment of Nuclear Energy Systems and Applications
VICTORIA	Vulnerability and Impact Assessment of Critical Infrastructure for Resilience and Adaptation
VTO	Vehicles Technologies Office
VVUQ	Verification, Validation, and Uncertainty Quantification
WIPP	Waste Isolation Pilot Plant
WKID	Wisdom, Knowledge, Information, Data
XLPR	eXtremely Low Probability of Rupture

CONTENTS

1. UNIQUE CAPABILITIES

This report details the unique capabilities of Sandia National Laboratories (SNL) that can support mission areas of space based and terrestrial nuclear and radiological applications, missions, and facilities.

This report highlights both capabilities that could be engaged both in support of surface power reactors at terrestrial locations to support the national security mission and need for reliable baseload power and lunar surface fission power needs or space-based nuclear or radiological applications.

These capabilities are not necessarily linked to nuclear or radiological applications and generally are applicable to broader application spaces.

This section detailing unique capabilities at SNL is structured in four parts:

1. Section 2 ("Unique Capabilities") provides an introductory table that contains all the disciplines and sub-disciplines in which SNL maintains capabilities and expertise.
2. Section 3 ("Sandia Capability Descriptions") contains descriptions of all capabilities, accrued knowledge of SNL, and its subject matter experts (SMEs).
3. Section 4 ("Sandia-Developed Software and Modeling Frameworks") contains descriptions of all SNL-developed proprietary tools and information (usually software) developed from SNL's legacy of expertise.
4. Section 5 ("Specialized Facilities or Equipment") contains descriptions of SNL test facilities and equipment leveraged as resources to support and expand SNL expertise.

2. UNIQUE TECHNICAL DISCIPLINES

Table 1 below details the disciplines and sub-disciplines in which Sandia maintains capabilities and expertise with respect to surface- and space-based nuclear assessments. These disciplines are not meant to be exhaustive of the work performed at Sandia, nor should they be constrained to only apply to nuclear and radiological applications and generally serve to support a broad range of mission and application domains.

These disciplines are identified as one or more of "Specialized Nuclear Engineering Technical Areas," "Specialized General Engineering and Scientific Areas," and "Environmental Technical Areas."

Table 1. Unique Technical Disciplines or Combination of Disciplines

Discipline	Specialized Nuclear Engineering Technical Areas	Specialized General Engineering and Scientific Areas	Environmental Technical Areas
Artificial Intelligence/Machine-Learning (AI/ML)		X	
Atmospheric Modeling / Atmospheric Transport Modeling		X	X
Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) Atmospheric Transport Model		X	X
Near-Field Transport Modeling		X	X
Atmospheric Dispersion		X	X
Dynamic Plume Rise		X	X
Tritium Dispersion Modeling	X	X	X
Modeling of Multiple Chemical Forms	X	X	X
Computer Science			
Code Development, Maintenance, Support, and Distribution		X	
Dakota Code		X	
High Fidelity Finite Element Analysis		X	
Numerical Methods		X	
Parallelized Processing		X	
Statistics		X	
Verification, Validation, and Uncertainty Quantification (VVUQ)		X	
Decommissioning, Nuclear Facility	X		X
Dose Assessment			
Microshield Analyses	X		

Discipline	Specialized Nuclear Engineering Technical Areas	Specialized General Engineering and Scientific Areas	Environmental Technical Areas
RADTRAD Analyses	X		
Dose Coefficient File Package (DCFPAK) and Radionuclide Viewer		X	
Economic Impact Analysis		X	X
Environmental Testing	X	X	X
Environmental Impact Analysis	X	X	X
Nuclear Risk Assessment (NRA) Analysis	X	X	X
National Environmental Policy Act (NEPA) Analysis	X	X	X
Nuclear Safety Analysis Reports (SARs)	X	X	X
Environmental Primary Hazard Assessments (EPHA)	X	X	X
Environmental Transport Modeling	X	X	X
Emergency Response and Planning	X		X
Evacuation Modeling			
Radiological Assessment System for Consequence Analysis (RASCAL) Code	X		
Response Technical Tools (RTT) Code	X		X
MACCS		X	X
Turbo Federal Radiological Monitoring and Assessment Center (Turbo FRMAC [TF]) Code	X	X	X
Simulation for Hazardous Atmospheres with Radiological Consequences (SHARC)	X		X
Sandia-Developed Transport of Radioactive Material (STORM)	X		X
Aerosol Analysis			
Food Chain Modeling	X	X	
Integrated 3S (Safety, Security, Safeguards)	X	X	
Licensing	X		
Non-Light Water Reactor (LWR) Technologies	X	X	X

Discipline	Specialized Nuclear Engineering Technical Areas	Specialized General Engineering and Scientific Areas	Environmental Technical Areas
Non-Proliferation		X	
Probabilistic Risk Analysis	X	X	X
Radiation Protection/Health Physics	X		X
Acute Health Effects	X	X	
Chronic (Long-Term) Health Effects	X	X	
Reactor Accidents			
Accident Analysis	X		
A Dynamic Analysis and Prediction Tool (ADAPT) Code	X		
Aerosol Sciences	X	X	X
Aircraft Impact Assessment		X	
Core Damage			
DCFPAK Database, Calculations, and Code	X	X	X
Dose Assessment		X	X
Emergency Planning and Response	X		X
Evacuation Time Estimates	X		X
Fuel Behavior			
HyRAM+ code		X	
MACCS Code / Suite	X	X	X
MelMACCS	X		
AniMACCS	X		
WinMACCS	X		
MACCS-UI	X		
Material Interactions			
MELCOR Code	X		
Meteorology and Air Quality		X	X
Methodology and Phenomenological Development	X		
Mitigation Alternatives		X	X
Radionuclide Viewer	X	X	X
RASCAL Code		X	X
Response Technical Tools (RTT) Code		X	X

Discipline	Specialized Nuclear Engineering Technical Areas	Specialized General Engineering and Scientific Areas	Environmental Technical Areas
Severe Accident Progression	X		
State-of-the-Art Reactor Consequence Analyses (SOARCA)			
Turbo FRMAC (TF) Code		X	X
Vulnerability Analysis		X	
Reactor Fuels and Fuel Cycle			
Fuel Handling Systems	X		
Reactor Phenomenology			
Fission Product Chemistry			
Fluid Dynamics	X	X	
Neutronics			
Radiological Engineering	X	X	
Thermal Hydraulics Analysis and Experiments	X	X	
Reactors			
Accident Source Terms			
Advanced Reactor Design and Analysis	X		
Advanced Reactor Fuel			
Containment Systems		X	
Aging, Degradation, and Integrity		X	
Electrical Systems		X	
Equipment Qualification		X	
Inspection Methods and Techniques		X	
Instrumentation and Controls		X	
LWR Design and Analysis	X	X	
Maritime and Naval Reactors	X	X	
Materials Science	X	X	
Material Behavior in Radioactive Environments	X	X	
Metallurgy	X	X	
Mechanical Systems		X	
Fracture Mechanics		X	

Discipline	Specialized Nuclear Engineering Technical Areas	Specialized General Engineering and Scientific Areas	Environmental Technical Areas
Piping, Welds, and Vessels		X	
Probabilistic Fracture Mechanics		X	
xLPR Code		X	
Nuclear Data Analysis	X	X	
Nuclear Systems	X	X	
Reactor Chemistry			
Reactor Core Analysis	X		
Systems, Structures, and Components	X	X	
Concrete, Metals, and Polymers (Cables)		X	
Corrosion and Electrochemistry		X	
Structural and System Materials	X	X	
Thermal and Fire		X	
Review			
Alternative	X	X	X
Historic	X	X	X
Land Use	X		X
Safety Basis			
Risk and Reliability			
Fire Protection (Engineering)		X	
Fire Sciences		X	
Hydrogen Risk		X	
Human Reliability Analysis		X	
Seismic Studies			
Site Hazards		X	X
Safeguards		X	
Security			
Cyber Security	X	X	
Physical Security	X	X	
Physical Protection	X	X	
Sensing and Motion Detection	X	X	
Socioeconomics	X	X	X

Discipline	Specialized Nuclear Engineering Technical Areas	Specialized General Engineering and Scientific Areas	Environmental Technical Areas
Benefits Assessment		X	X
Demography		X	X
Environmental Justice		X	X
Space Systems	X	X	X
Accident Progression		X	
Blast (Shock) and Impact		X	
Computational Fluid Dynamics (CFD) modeling		X	
Consequence / Environmental Impact Analysis		X	X
Fire and Thermal		X	
Integrated Monte Carlo N-Particle (MCNP) / Solid Mechanics modeling	X	X	
MCNP Modeling	X	X	
Risk and Uncertainty Qualification/Quantification		X	
Solid Mechanics		X	
Training and Consultation	X	X	X
Transportation			
Containers and Package Design and Analysis	X	X	
Large-Scale Testing		X	
Mobile Instrumentation and Data Acquisition System (MIDAS)		X	
RADTRAN	X	X	
Waste Management			
Disposal	X	X	X
Interim Storage	X	X	X
PFLOTRAN		X	X
Spent Nuclear Fuel	X	X	X
Thermal Hydraulics, Flow, and Drying	X	X	X

3. SANDIA CAPABILITY DESCRIPTIONS

3.1. Advanced Reactor Technologies and Advanced Fuel Concepts

Sandia possesses a broad range of capabilities to model for advanced designs and advanced fuel concepts, whether for a terrestrial or space based reactor concept. Capabilities include nuclear data management and analysis for the high-temperature gas reactor (HTGR) design/fuel development and qualification; graphite reactor research and development (R&D); heat pipe design, test, and failure; very high temperature reactor materials analysis; fast reactor technology-gas, lead, sodium cooled; super-critical water-cooled reactor technology; molten-salt reactor; and advanced fuel concepts as being developed through Department of Energy (DOE) programs.

3.2. Assuring Safe Transportation of Nuclear 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: (1) integrity of the transport package and (2) the route used. Sandia has expertise and sophisticated testing and analysis resources to analyze both 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.

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 Parallel Flow and Transport—subject packages to extreme environments allowing researchers to execute performance and risk analysis.

To ensure the safe transport of radiological materials, Sandia developed Radiation Transportation (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.

<u>Selected Reports and Studies for the Transportation of Nuclear and Hazardous Materials:</u>

1. NUREG-2125, *Spent Fuel Transportation Risk Assessment.*

2. Osborn, C. A., et al. *An Economic Model for RADTRAN*. SAND2007-7120. Albuquerque, NM, 2008.
3. Williams, B. J., et al. *System Theoretic Frameworks for Mitigating Risk Complexity in the Nuclear Fuel Cycle*. SANDA2017-10243. Albuquerque, NM, 2017.
4. Williams, B. J., et al. *System Theoretic Frameworks for Mitigating Risk Complexity in the Nuclear Fuel Cycle*. SANDA2017-10243. Albuquerque, NM, 2017.

3.3. Atmospheric Dispersion Modeling

An essential aspect of modeling the impact of a potential or actual reactor accident or an accident involving a nuclear spacecraft to the environment is knowledge of atmospheric dispersion modeling. Through its development and support of environmental assessments for the NRC via MACCS; through its development and support of emergency response for the NRC via Radiological Assessment System for Consequence Analysis (RASCAL); through its development of STORM and SHARC in support of space nuclear launch safety assessment; Sandia has built extensive expertise in atmospheric dispersion modeling. Much of this expertise is used in the assessment of the Fukushima accident and in follow-on impact studies. This expertise has also been used for Nuclear Risk Assessments (NRAs) and Safety Analysis Reports for various Nation Aeronautics and Space Administration (NASA) missions spanning from Pluto New Horizons to Mars 2020.

For advanced reactors and space-based reactor designs for which new and novel radionuclides are of concern, Sandia also investigates unique aspects of Tritium transport modeling and modeling of radionuclides that transform from one physical form to another during transportation. This transition of physical form can have significant impacts on radioactivity dose and risk to the public and the environment.

Selected Reports and Studies for Atmospheric Dispersion Modeling:

1. Clayton, D. J., N. E. Bixler, and K. L. Compton. *HYSPLIT/MACCS Atmospheric Dispersion Model Technical Documentation and Benchmark*, 2022.
2. Villa, D. L. *Initial Atmospheric Transport of Particles*. SAND2020-2209. Sandia National Laboratories, Albuquerque, NM, February 2020.
3. Clayton, D. J., N. E. Bixler, K. L. Compton. *HYSPLIT/MACCS Atmospheric Dispersion Model Technical Documentation and Benchmark Analysis*. SAND2022-5515. Sandia National Laboratories, Albuquerque, NM, April 2022.
4. SNL Meteorology Program. Accessed April 1, 2024. https://clean-air.sandia.gov/.
5. Miller, A. *2022 Annual Site Environmental Report for Sandia National Laboratories*. SAND2023-07908O. Sandia National Laboratories, Albuquerque, New Mexico; Sandia National Lab (SNL-CA), Livermore, CA; Sandia National Lab (SNL-NM), Albuquerque, NM, October 2023. doi:10.2172/2203066.
6. Wharton, S., et al. "Capturing Plume Behavior in Complex Terrain: An Overview of the Nevada National Security Site Meteorological Experiment (METEX21)." *Frontiers in Earth Science* 11 (2023). Accessed April 1, 2024. https://www.frontiersin.org/articles/10.3389/feart.2023.1251153.

7. Andrews, N., M. Higgins, A. Taconi, and J. Leute. *Preliminary Radioisotope Screening for Off-site Consequence Assessment of Advanced Non-LWR Systems*. SAND2021-11703. Sandia National Laboratories, Albuquerque, NM, USA, 2021.
8. Clavier, K., D. Clayton, and C. Faucett. *Quantitative Assessment for Advanced Reactor Radioisotope Screening Utilizing a Heat Pipe Reactor Inventory*. SAND2022-12018. Sandia National Laboratories, Albuquerque, NM, USA, 2022.
9. Clavier, K., and D. Clayton. *Reviewing MACCS Capabilities for Modeling Variable Physiochemical Forms*. SAND2022-12766. Sandia National Laboratories, Albuquerque, NM, USA, 2022.
10. Clavier, K., and D. Clayton. *Reviewing MACCS Capabilities for Assessing Tritium Releases to the Environment*. SAND2022-12016. Sandia National Laboratories, Albuquerque, NM, USA, 2022.
11. Clavier, K., and M. Smith. *Comparison of Tritium Dose Calculations from MACCS, UFOTRI, and ETMOD*. SAND2023-10896. Sandia National Laboratories, Albuquerque, NM, USA, 2023.

3.4. Cyber-Based Vulnerability Assessments

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.

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.

Sandia is currently leading a DOE Physical Security project that looks to develop and demonstrate a performance assessment method to characterize the physical security of a nuclear powerplant.

3.5. Dose and Risk Assessments

A critical aspect in assessing the significance of the impact of a reactor accident or spacecraft powered by a fission or radioisotope system is the ability to appropriately convert radioactivity released to the environment to dose and health impacts to the public (such as latent cancers) as well as environmental impacts.

Through its leadership of the Federal Interagency Assessment Working Group, development of Turbo FRMAC, DCFPAK, MACCS, RASCAL, and STORM; Sandia has a long track record in leading in the avenue of dose and risk assessment to the public and the environment regardless of the mechanism by which the activity is released.

<u>Selected Reports and Studies of Dose and Risk Assessments:</u>

1. Hunt, B., A. W. Morris IV, and J. Fleener. *FRMAC Assessment Manual Volume 1 - Assessment Division Operations*. Albuquerque, NM: Federal Radiological Monitoring and Assessment Center, May 2023. Contract No.: SAND2023-04456 R.
2. Hunt, B., A. W. Morris IV, and J. Fleener. *FRMAC Assessment Manual Volume 2 - Overview and Methods*. Albuquerque, NM: Federal Radiological Monitoring and Assessment Center, May 2023. Contract No.: SAND2023-04457 R.
3. Hunt, B., A. W. Morris IV, and J. Fleener. *FRMAC Assessment Manual Volume 3 - Pre-Assessed Default Scenarios*. Albuquerque, NM: Federal Radiological Monitoring and Assessment Center, May 2023. Contract No.: SAND2023-04459 R.
4. Mitchel, D., et al. *Dose Calculations from Source Models and Gamma-Ray Spectra*. SAND2020-2543. Albuquerque, NM, February 2020.

3.6. Economic Impact Analysis

Through its support of NRC Hazard Analysis Branch and MACCS code development, Sandia has developed and maintain an expertise in the economic impacts following a nuclear emergency. For the past half century, Sandia has developed the economic models inside the MACCS codes and used them to support the NRC in its evaluation of the potential economic impacts from nuclear power plant accidents.

During the 2020s, Sandia added the state of practice Gross Domestic Product (input/output) Regional Disruption Economic Impact Model (RDEIM) to MACCS to bring the evaluation of economic impacts up to current practices.

<u>Selected Reports and Studies of Economic Impact Analysis:</u>

1. Bixler, N. E., et al. *Economic Model for Estimation of GDP Losses in the MACCS Offsite Consequence Analysis Code*. SAND2020-5567. Albuquerque, NM, June 2020.
2. Outkin, A. V., et al. *Updated Economic Model for Estimation of GDP Losses in the MACCS Offsite Consequence Analysis Code RDEIM Model Report for MACCS v4.2*. SAND2022-10453. Albuquerque, NM, December 2022.
3. *Understanding Public Response to Nuclear Power Plant Protective Actions*. Risk, Hazards & Crisis in Public Policy 1, no. 3: 35-61.

3.7. Emergency Planning

Since the 1970s Sandia has supported the DOE and NRC in Emergency Planning and response and evaluation of licensee applications via development of the science and modeling in the MACCS code suite. Sandia has engaged to develop human health consequence models, environmental transport models, evacuation models, economic impacts and decontamination models. Sandia also has extensive expertise in supporting the DOE's Nuclear Emergency Support Teams (NEST) and the interagency FRMAC, as well as code used by these organizations, to plan for a response to emergencies.

Sandia also heavily supported the NRC Emergency Preparedness staff review of the planning basis for nuclear power plant emergency preparedness programs (SECY-03-0165). Sandia was at the forefront of this review. Sandia also supported the 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. This 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 provides technical expertise to assist the NRC staff in determining whether Combined License and Early Site Permit applications meet appropriate regulatory requirements, specifically related to radiological emergency plans and emergency transportation exercises (ETEs) associated with the application.

<u>Selected Reports and Studies for Emergency Planning:</u>

1. Clayton, D. J., N. E. Bixler, and K. L. Compton. *HYSPLIT/MACCS Atmospheric Dispersion Model Technical Documentation and Benchmark Analysis*. SAND2022-5515. Sandia National Laboratories, Albuquerque, NM, 2022.
2. Clayton, D. J., and N. E. Bixler. *Assessment of the MACCS Code Applicability for Nearfield Consequence Analysis*. SAND2020-2609. Sandia National Laboratories, Albuquerque, NM, February 2020.
3. Clayton, D. J. *Implementation of Additional Models into the MACCS Code for Nearfield Consequence Analysis*. SAND2021-6924. Sandia National Laboratories, Albuquerque, NM, June 2021.
4. Sandia National Laboratories. *MACCS User Guide – Version 4.2*. SAND2023-01315. Sandia National Laboratories, Albuquerque, NM, March 2023.
5. Sandia National Laboratories. *MelMACCS User Guide – Version 4.0.0*. SAND2022-13278. Sandia National Laboratories, Albuquerque, NM, November 2023.
6. Clayton, J., J. Leute, N. Bixler, D. Whitener, and K. Clavier. *AniMACCS User Guide*. SAND2022-0403. Sandia National Laboratories, Albuquerque, NM, January 2022.
7. Nosek, A. J., and N. Bixler. *MACCS Theory Manual*. SAND2021-11535. Sandia National Laboratories, Albuquerque, NM, September 2021.
8. Bixler, N., K. Compton, M. Dennis, L. Eubanks, R. Haaker, J. Jones, M. Kimura, K. McFadden, A. Nosek, A. Outkin, and F. Walton. *Technical Bases for Consequence Analyses Using MACCS (MELCOR Accident Consequence Code System)*. NUREG/CR-7270, SAND2022-12166R. Sandia National Laboratories, Albuquerque, NM, October 2022.
9. *State-of-the-Art Reactor Consequence Analyses (SOARCA) Project: Sequoyah Integrated Deterministic and Uncertainty Analyses*. NUREG/CR-7245. U.S. Nuclear Regulatory Commission, Washington, DC, 2019. ADAMS Accession No. ML19296B786.
10. *State-of-the-Art Reactor Consequence Analyses (SOARCA) Project: Uncertainty Analysis of the Unmitigated Short-Term Station Blackout of the Surry Power Station*. NUREG/CR-7262. U.S. Nuclear Regulatory Commission, Washington, DC, forthcoming 2022.

11. *NUREG-2254, Summary of the Uncertainty Analyses for the State-of-the-Art Reactor Consequence Analyses Project.*
12. Nuclear Regulatory Commission (NRC). *Guidance on the Treatment of Uncertainties Associated with PRAs in Risk-Informed Decisionmaking.* NUREG-1855, Revision 1. U.S. Nuclear Regulatory Commission, Washington, DC, 2017a. ADAMS Accession No. ML17062A466.
13. Nuclear Regulatory Commission (NRC). NUREG/CR-6981, SAND2008-1776P*, Assessment of Emergency Response Planning and Implementation for Large Scale Evacuations.* October 2008. (NRC, 2008a).
14. Nuclear Regulatory Commission (NRC). *NUREG/CR-6953, Vol. II, SAND2007-5448P, Review of NUREG-0654, Supplement 3, Criteria for Protective Action Recommendations for Severe Accidents – Focus Groups and Telephone Survey.* October 2008. (NRC, 2008b).
15. Nuclear Regulatory Commission (NRC). NUREG/CR-6953, Vol. I, SAND2007-5448P*, Review of NUREG-0654, Supplement 3, Criteria for Protective Action Recommendations for Severe Accidents.* December 2007. (NRC, 2007).
16. Nuclear Regulatory Commission (NRC). NUREG/CR-6863, SAND2004-5900*, Development of Evacuation Time Estimate Studies for Nuclear Power Plants.* January 2005. (NRC, 2005a).
17. Nuclear Regulatory Commission (NRC). *NUREG/CR-6864, SAND2004-5901, Identification and Analysis of Factors Affecting Emergency Evacuations.* January 2005. (NRC, 2005b).
18. NUREG/CR 7002, SAND2010-0016P*, Criteria for Development of Evacuation Time Estimate Studies.*

3.8. Environmental Transportation Modeling

Environmental impacts and transport modeling is historically and generally modeled as and thought of as atmospheric transport modeling. However, other modes of environmental transport are also important, such as the modeling of radiological transport from deep geologic repositories or movement through ground media and aqueous transport through rivers, oceans, and water bodies. Sandia has a long history of expertise in these areas given its need to evaluate storage at the Waste Isolation Pilot Plant (WIPP) it has managed since the 1970s and its deep involvement in Yucca Mountain. To support WIPP, and to evaluate transport through geologic media Sandia has developed the Parallel Flow and Transport (PFLOTRAN) code to support environmental transport evaluation.

<u>Selected Reports and Studies for Environmental Transportation Modeling:</u>

1. Lichtner, P. C., and G. E. Hammond. Quick Reference Guide: PFLOTRAN 2.0 (LA-CC-09-047) *Multiphase-Multicomponent-Multiscale Massively Parallel Reactive Transport Code.* LA-UR-06-7048. Los Alamos National Laboratory, Los Alamos, New Mexico, 2012.
2. Lichtner, Peter C., Glenn E. Hammond, Chuan Lu, Satish Karra, Gautam Bisht, Benjamin Andre, Richard Mills, and Jitendra Kumar. *PFLOTRAN User Manual: A Massively Parallel Reactive Flow and Transport Model for Describing Surface and Subsurface Processes.* United States: N. p., 2015. Web. doi:10.2172/1168703.

3.9. 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. This research has also been vital for evaluating the response of spacecraft using nuclear systems to a fire environment and its impact on the release of nuclear material.

Sandia research also provides 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 and the consequences of a spacecraft experiencing a fire environment triggered by a liquid or solid rocket propellant burn.

Selected Reports and Studies for Fire Risk Analysis Research:

1. Donaldson, B. *Compendium of Sandia Solid Propellant Studies*. SAND2018-7631. Sandia National Laboratories, Albuquerque, NM, July 2018.
2. Gelbard, F., and G. J. Koenig. *Temperature Measurements Beneath Burning Solid Rocket Propellants Using Witness Materials*. SAND2018-5430. Sandia National Laboratories, Albuquerque, NM, May 2018.
3. Lindgren, E. R., F. Gelbard, and G. J. Koenig. *Documentation of the 2014 SNL/JPL Solid Propellant Fire Experiments: Experimental Setup Diagrams, Photographs, Thermocouple (TC) Data Plots, TC Construction Details and Select TC Data Tables*. SAND2016-7491. Sandia National Laboratories, Albuquerque, NM, August 2016.
4. NUREG/CR-5384*, A Summary of Nuclear Power Plant Fire Safety Research at Sandia National Laboratories*. 1989.
5. NUREG/CR-6776*, Cable Insulation Resistance Measurements Made During the EPRI-NEI Cable Fire Tests*. 2002.
6. NUREG/CR-6834*, Circuit Analysis: Failure Mode and Likelihood Analysis*. 2003.
7. NUREG/CR-6850*, EPRI/NRCRES Fire PRA Methodology for Nuclear Power Facilities*. 2005.
8. NUREG/CR-6931*, Cable Response to Live Fire (CAROL FIRE)*. 2008.
9. NUREG/CR-6978*, A Phenomena Identification and Ranking Table (PIRT) Exercise for Nuclear Power Plant Fire Modeling Applications*. 2008.
10. Glover, A. M., A. C. LaFleur, and J. Engerer. *HEAF Cable Fragility Testing at the Solar Furnace at the NSTTF*. United States: N. p., 2021. Web. doi:10.2172/1820248.
11. Cruz-Cabrera, A. A., A. M. Glover, Ryan M. Flanagan, and Jamal A. Mohmand. *High Energy Arcing Fault (HEAF) Photometrics 2022 Test Report*. United States, 2023.
12. NUREG-2262*, EPRI 3002025942, High Energy Arcing Fault Frequency and Consequence Modeling – Final Report*. Accessed [date]. https://www.nrc.gov/reading-rm/doc-collections/nuregs/staff/sr2262/index.html#pub-info.

3.10. Food Chain Modeling

Through its support of NRC licensing reviews and consequence planning and assessments, and engagement with the Hazard Analysis Branch, Sandia has developed and maintained expertise in food chain modeling, which also applies to Space Nuclear Launch licensing.

Principle expertise has been in using the COMIDA2 application to determine the impacts of radiological environmental release scenarios to determine the impact to farming and grazing lands with respect to condemnation, embargo, economic impact, and ability to deliver radiation dose to the human population.

Sandia also has multi-decadal experience in developing the science and methodologies for determining impacts to the food chain and human dose through its support and development of the FRMAC Assessment Manual.

Selected Reports and Studies for Food Chain Modeling:

1. Chanin, D., and M. L. Young. *Code Manual for MACCS2: Volume 2, Preprocessor Codes COMIDA2, FGRDCF, IDCF2*. SAND97-0594. Sandia National Laboratories and U.S. Nuclear Regulatory Commission, 1997. NUREG/CR-6614.
2. Hunt, B., A. W. Morris IV, and J. Fleener. *FRMAC Assessment Manual Volume 1 - Assessment Division Operations*. Albuquerque, NM: Federal Radiological Monitoring and Assessment Center, May 2023. Contract No.: SAND2023-04456 R.
3. Hunt, B., A. W. Morris IV, and J. Fleener. *FRMAC Assessment Manual Volume 2 - Overview and Methods*. Albuquerque, NM: Federal Radiological Monitoring and Assessment Center, May 2023. Contract No.: SAND2023-04457 R.
4. Hunt, B., A. W. Morris IV, and J. Fleener. *FRMAC Assessment Manual Volume 3 - Pre-Assessed Default Scenarios*. Albuquerque, NM: Federal Radiological Monitoring and Assessment Center, May 2023. Contract No.: SAND2023-04459 R.

3.11. Human Reliability Analysis Research

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 the 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.

Sandia staff have experience in human reliability analysis (HRA) for nuclear power plant (NPP) and non-NPP applications (including Level 2 PRA). Sandia has supported the development of HRA methods such as Integrated Decision-Making for Hazardous Events Assessment and Safety (IDHEAS) at-power method and helped organize expert elicitation workshops to determine human error probabilities for quantification through use of the IDHEAS method.

Sandia served as HRA lead for the NRC's Level 3 PRA project, directing the overall implementation and integration of HRA into the project. This work included HRA in support of Level 1 and Level 2 at-power, internal events PRAs; Level 1 and Level 2 low- power and shut down PRAs; fire PRA; dry cask storage PRA; spent fuel handling PRA; and site wide, multi-unit risk analysis.

Sandia staff have extensive knowledge and experience with psychological and behavioral models, and human factors engineering, especially as it relates to contexts where decision-making and action performance does not take place in the Main Control Room (MCR). In addition, Sandia staff have In-depth knowledge of the guidance, both qualitative and quantitative, of operator actions taken in response to fire events, including possible contexts and other performance influencing factors for actions during main control room abandonment.

Selected Reports and Studies for Human Reliability Analysis Research:

1. NUREG/CR-6350*, A Technique for Human Error Analysis (ATHEANA)*. 1996.
2. NUREG-1842*, Evaluation of Human Reliability Analysis Methods Against Good Practices: Final Report*. 2006.
3. NUREG/CR-1278*, Handbook of Human Reliability Analysis with Emphasis on Nuclear Power Plant Applications*. 2011.
4. NUREG/CR-7016*, Human Reliability Analysis: Informed Insights on Cask Drops*. 2012.
5. NUREG/CR-7017*, Preliminary, Qualitative Human Reliability Analysis for Spent Fuel Handling*. 2012.
6. Boring, R. L., S. M. L. Hendrickson, J. A. Forester, T. Q. Tran, and E. Lois. "Issues in Benchmarking Human Reliability Analysis Methods: A Literature Review." *Reliability Engineering and System Safety* 95 (2010): 591–605.
7. Parry, G. W., J. A. Forester, V. N. Dang, S. M. L. Hendrickson, M. Presley, E. Lois, and J. Xing. "IDHEAS – A New Approach for Human Reliability Analysis." In *Proceedings of the ANS PSA 2013 International Topical Meeting on Probabilistic Safety Assessment and Analysis*, Columbia, SC, September 2013.
8. Hendrickson, S., S. Adams, N. Murchison, and P. Turner. "A Framework for Understanding Operator Decision Making in Simulated NPP Cyber Attacks." Paper presented at the 8th International Conference on Applied Human Factors and Ergonomics, Los Angeles, California, USA, July 17–21, 2017. [SAND2017-7370C, Presentation].
9. Hendrickson, S. M. L., A. M. Whaley, R. L. Boring, and D. L. Kelly. "A Mid-Layer Model for Human Reliability Analysis: Understanding the Cognitive Causes of Human Failure Events." INL/CON-10-18093, PREPRINT, 2010.
10. Wreathall, J., S. M. Hendrickson, J. Julius, S. Cooper, M. Presley, E. Collins, and T. Rivera. *Investigating Command and Control Issues During Main Control Room Abandonment*. SAND2017-3263C. Sandia National Laboratories (SNL-NM), Albuquerque, NM, 2017.

3.12. Hydrogen Risk

Sandia is leading hydrogen safety analyses and risk assessment as hydrogen is emerging as an energy carrier. Hydrogen production is being demonstrated at several nuclear power plants and Sandia has developed the probabilistic hydrogen leak frequencies and rates that enable risk assessment and mitigation. Sandia has also developed the open-source Hydrogen Risk Assessment Models (HyRAM) toolkit that enables physics-based models to be used to evaluate consequences from hydrogen dispersion, jet flames, and unconfined explosions.

Selected Reports and Studies for Hydrogen Risk:

1. Glover, A.M., Brooks, D.M., and Baird, A.R., *Hydrogen Plant Hazards and Risk Analysis Supporting Hydrogen Plant Siting near Nuclear Power Plants (Final Report)*. United States: N. p., 2020. Web. doi:10.2172/1678837.
2. Glover, A.M., and Brooks, D.M. *Risk Analysis of a Hydrogen Generation Facility Near a Nuclear Power Plant*, United States: 2023.
3. Vedros, K. G., Christian, R., and Otani, Y.H., and Mariko, C., *Expansion of Hazards and Probabilistic Risk Assessments of a Light-Water Reactor Coupled with Electrolysis Hydrogen*

Production Plants, United States: N. p., 2023. Web. doi:10.2172/1998560. (Sandia performed the hydrogen consequence analyses and is credited in the acknowledgement section.)

4. Ehrhart, B. D., and Hecht, E. S., *Hydrogen Plus Other Alternative Fuels Risk Assessment Models (HyRAM+) Version 5.0 Technical Reference Manual*. United States: N. p., 2022. Web. doi:10.2172/1900089.
5. Brooks, D., Ehrhart, B., and LaFleur, C., *Development of Liquid Hydrogen Leak Frequencies Using a Bayesian Update Process,* United States: N. p., 2021. Web.

3.13. Integrated 3S (Safety, Security, Safeguards)

Although high-level policy considerations encourage convergence of safeguards, security, and safety (SSS) during design and operations and use of alternative approaches to meet regulatory requirements, there is limited activity from industry to develop appropriate methodologies and tools to address future challenges in the interdependencies between SSS for advanced and micro reactors.

Sandia has lead research in Nuclear Safety for more than 30 years and has a long tradition of leadership. Sandia is also a recognized leader in Nuclear Security (both Physical and Cyber Security) and Safeguards. Integrated 3S research is a relatively new focus. Sandia has made a formal effort to integrate these three disciplines in support of advanced reactors.

Sandia has recently explored a notional physical protection system for floating nuclear power plants. These details were reported in SAND2023-13957R, *Security Considerations for the Deployment of Floating Nuclear Power Plants*. The system considered the adequacy of the design basis threat characteristics for floating nuclear power plants (FNPPs) and waterborne attack vectors and assessed emergency preparedness considerations for stationary FNPP deployment.

Assessments of hazards and accident sequences associated with the marine environment (e.g., sinking, capsizing, collision, shipboard fires) can be coupled to Sandia's existing reactor safety expertise. Some unique capabilities are under development within MELCOR, including introduction of fire scenarios, buoyant jets, and stratification models. When combined with Sandia's extended hazardous material transport modeling—including refinements relevant to treatment of fission products release from liquid pools—SNL provides a unique capability for assessing waterborne initiating events.

3.14. Computational Tools

The use of modeling and simulation (M&S) for physical security analysis is an ongoing area of research and has been pursued by the existing reactor fleet to support decision making. A variety of M&S tools were developed for this purpose and the different tools address different elements of physical security considerations. Among these tools are Dante, PathTrace, and Scribe3D, all developed by Sandia, and each of which is intended to address different aspects within physical security.

<u>Selected Reports and Studies of Computation Tools:</u>

- Sandia is currently executing an NRC project entitled *Enabling Technologies for Physical Security and Integration of SSS During Design and Operations* (number OFA06823053-0), scheduled to run through FY25. Recently, this project completed the draft report *Integration of Safety, Security, and Safeguards During Design and Operations – A Technical*

Assessment and Regulatory Considerations for Advanced Reactor and Advanced Fuel Fabrication Facilities.

- *Security Considerations for the Deployment and Transport of Floating Nuclear Power Plants (Volume II)*, SAND2023-13957R, Office of International Nuclear Security, October 2023.

3.15. International Consultation

The Office of International Programs (OIP) assists the Chairman, the Commission, and the NRC staff on international issues. The OIP plans and implements programs to carry out policies in the international arena; including regulatory assistance and support to international regulatory counterparts to improve the safe and secure use of nuclear and radioactive materials. Sandia provides support in a wide range of technical and scientific disciplines, in supporting the work of the Office of Nuclear Material Safety and Safeguards and the Office of International Programs.

3.16. Experimental Facilities: Small Modular / Advanced Reactor Training and Test (SMARTT) Facility

Sandia's facilities include an existing reactor facility, which is currently in operation. Historically, the reactor site included a reactor with weapon's grade fuel. Such fuel must be protected at the highest level and the site includes a state-of-the-art Perimeter Intrusion Detection and Analysis System (PIDAS). The PIDAS is actively maintained even though the fuel is no longer present at the facility. The areas' capabilities provide a valuable opportunity for training and development and it has been actively used for many international courses and demonstrations.

In 2023, the SMARTT facility hosted an international delegation—the Canada-US Blended Cyber-Physical Exercise was a successful, first of its kind, multi-organization and multi-laboratory exercise that culminated years of complex system development, planning and partnership. The project organizations were national laboratories from both Canada and the United States, the Canadian regulator (CNSC), and a Canadian nuclear power plant (NPP) operator (Bruce Power) aimed to answer three driving research questions:

1. How do cyberattacks support malicious acts leading to theft or sabotage [at a nuclear site]?
2. What are aspects of an effective combined cyber-physical response?
3. How to evaluate effectiveness of that response?

The final exercise presented: (1) a cyber-attack scenario that supports malicious acts leading to theft or sabotage, (2) define aspects of an effective combined cyber-physical response, and (3) analysis to evaluate the effectiveness of the incident response against pre-established exercise evaluation criteria, in a real-life environment.

To support the observer experience and anticipate player actions during the exercise, a time-based application of the Wisdom, Knowledge, Information, Data (WKID): Observe, Orient, Decide, Act (OODA) decision making processes was successfully used.

3.17. Large-Scale Validation Experiments

Performance is often tested through large-scale validation experiments. 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. Of note, is that Sandia is the only institution in the United States 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 and nowhere else. 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 (TTC). Using a variety of data acquisition tools, researchers efficiently and effectively gather performance data needed to satisfy fire-based regulatory and validation requirements.

3.18. MIDAS: Mobile Instrumentation Data Acquisition System

Data collection must accurately characterize behavior of 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), a fully NQA-1 compliant system, to provide on-site or off-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.

3.19. Multi-Scale, Multi-Process Testing

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.

Sandia leverages 60 years of weapons component testing experience in generating detailed, increasingly useful data for both designers and regulators.

3.20. Non-Proliferation

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 in over 25 countries on five continents. Sandia takes a systematic life-cycle approach including analysis, design, implementation, training, operation and sustainment, and disposal/disposition.

Additionally, Sandia provides 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.

Sandia's capabilities to detect and deter illicit trafficking of nuclear material international borders, at points of entry/exit, and through the global maritime shipping network.

Selected Reports and Studies for Non-Proliferation:

1. Defense Science Board Task Force on Unconventional Nuclear Warfare Defense. 2001. (Sandia contributor).
2. A Risk-Based Approach to RDD Analysis. SAND2003-1331.
3. Description and Validation of ERAD: An Atmospheric Dispersion Model for High Explosive Detonations. SAND92-2069.
4. Economic Impacts of Detonating RDDs. 2008. (Sandia contributor).

5. Explosive Dispersal of Materials Relevant to Radiological Dispersal Devices – Experimental Results and Ramification. SAND2008-0733.
6. Self-Contained Irradiator in the US: Risks of Terrorist Acquisition & Use for RDDs. SAND2006-3703.
7. A Red Team Effort to Obtain Radioactive Material from a Self-Contained Irradiator. SAND2006-2352.
8. Radioactive Sources Relative Risk Reduction Study. 2009. (Sandia contributor).
9. Assessment of the Chemical Security Posture at Facilities Subject to NRC Regulation. 2010.
10. 2010 Radiation Source Protection and Security Task Force Report. Submitted by the Chairman of the US NRC. (Sandia contributor).

3.21. Nuclear Cyber Security

Sandia's Nuclear Cybersecurity Research program serves both the current nuclear fleet and designers of advanced reactors and related technologies under development. Sandia aims to adapt the best cybersecurity discoveries and practices from other sectors to the rigorous needs of nuclear power applications and to address any unique challenges not being addressed elsewhere, especially where these can enable innovative nuclear power use cases under consideration for advanced reactors.

Key activities include the following:

- Developing models and methods to prioritize cybersecurity risks in nuclear plant control systems, for more effective and economically efficient risk management;
- Supporting advanced reactor designers with tools and techniques for considering cybersecurity by design;
- Removing any barriers to implementing modern cybersecurity best practices (such as ongoing implementations supporting Zero Trust principles) in nuclear power applications; and
- Investigating and addressing any cybersecurity challenges in future technologies and use cases (e.g. machine learning, autonomous control, wireless controls).
    - Sandia has also had a long pedigree of nuclear physical and security experience, which have been leveraged in two recent NRC licensing-related efforts.

<u>Selected Reports and Studies for Nuclear Cyber Security:</u>

1. Sandia helped support the development of the NRC design guide DG 5075 (https://www.nrc.gov/docs/ML2328/ML23286A278.pdf) - "ESTABLISHING CYBERSECURITY PROGRAMS FOR COMMERCIAL NUCLEAR PLANTS LICENSED UNDER 10 CFR PART 53".
2. Clark, A. and Williams, A., *Addressing Cyber Hazards in Nuclear Power Plants with STPA-Informed Fault Trees*, Proceedings of the INMM Annual Meeting, July 14-18, 2019, Palm Desert, CA.
3. Cyber-Informed Engineering for Nuclear Reactor Digital Instrumentation and Control
4. Risk Analysis Methods

5. Survey of cyber Risk Analysis Techniques for Use in the Nuclear industry
6. Cyber-Physical Risks for Advanced Reactors
7. Architectures and Technologies
8. Security Evaluation of Smart Cards and Secure Tokens: Benefits and Drawbacks for Reducing Supply Chain Risks of Nuclear Power Plants

3.22. 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. Sandia's 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 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 the following:

- Integrated Security Facility (ISF): 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;

3.23. Probabilistic Risk Analysis (PRA) Research

Sandia has over 40 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, such as the Joint Committee of Nuclear Risk Management, which provide guidance for the correct application of these techniques in an industrial setting.

Sandia has also applied the PRA techniques to evaluating the consequences of a launch involving nuclear material and applied this to the Safety Analysis Reports for Mars Science Lab, Mars 2020, and several other missions. The Radiological Off-Nominal Consequence Quantification and Evaluation Toolset (ROCQET) is used to develop the probability versus consequence curves needed to evaluate the mission risk against metrics in National Security Presidential Memorandum – 20 (NSPM-20) to evaluate the mission tier and receive approval for launch.

Sandia has established a best-in-class reputation in several specific technology areas relevant to PRA of civilian nuclear power. Sandia researchers use an array of analysis techniques, including event and fault trees, dynamic event trees, influence diagrams, decision trees, systems theoretic process analysis (STPA), and network diagrams, combined with deep systems knowledge and substantial professional expertise to produce realistic risk estimates for complex systems.

Sandia has supported the NRC in scoping a dynamic human reliability analysis using a combination of the University of Maryland's / University of California Los Angeles's code ADS-IDAC and Sandia's codes A Dynamic Analysis and Prediction Tool (ADAPT) and MELCOR. Sandia supported the spent fuel pool analysis portion of the NRC's Vogtle Level 3 probabilistic risk assessment. Sandia's primary roles on developing and analyzing the level 1 to level 2 transition binning and the level 2 accident progression tress for the coupled multi-unit spent fuel pool. Sandia is also innovating new digital hazard informed fault trees using STPA insights.

<u>Selected Reports and Studies for Probabilistic Risk Analysis (PRA) research:</u>

1. NUREG/CR-1338*, Allocation of NRC Inspection Effort to Risk-Related Activities in Nuclear Power Plants*. 1980.
2. NUREG/CR-3233*, The Effect of Resolution of the Millstone Point Unit 1 Systematic Evaluation Program Issues on Probabilistic Calculations of Risk*. 1983.
3. NUREG/CR-4514*, Controlling Principles for Prior Probability Assignments in Nuclear Risk Assessment*. 1986.
4. NUREG/CR-4551*, Evaluation of Severe Accident Risks and the Potential for Risk Reduction*. 1987.
5. NUREG/CR-4825*, A Preliminary Evaluation of the Economic Risk for Cleanup of Nuclear Material Licensee Contamination Incidents*. 1987.
6. NUREG/CR-4834*, Recovery Actions in PRA for the Risk Methods Integration and Evaluation Program (RMIEP)*. 1987.
7. NUREG/CR-4836*, Approaches to Uncertainty Analysis in Probabilistic Risk Assessment*. 1988.
8. NUREG-1150*, Severe Accident Risks*. 1990.
9. NUREG/CR-4839*, Methods for External Event Screening Quantification: Risk Methods Integration and Evaluation Program (RMIEP) Methods Development*. 1992.
10. NUREG/CR-4832*, Analysis of the LaSalle Unit 2 Nuclear Power Plant: Risk Methods Integration and Evaluation Program (RMIEP)*. 1993.
11. NUREG/CR-5863*, Risk Assessment of Isolation Devices in Safety Systems*. 1993.
12. NUREG/CR-4551*, Evaluation of Severe Accident Risks: Methodology for the Containment, Source Term, Consequence, and Risk Integration Analyses*. 1993.
13. NUREG/CR-6166*, Risk Impact of BWR Technical Specifications Requirements during Shutdown*. 1994.
14. NUREG/CR-5593*, Risk Comparisons of Scheduling Preventive Maintenance for Boiling Water Reactors During Shutdown and Power Operations*. 1994.
15. Jankovsky, Zachary Kyle, Troy Christopher Haskin, and Matthew R. Denman. *How to ADAPT*. United States: N. p., 2018. Web. doi:10.2172/1457610.

16. Sandia National Laboratories. *Mars 2020 Final Safety Analysis Report – For Launch Approval.* SAND2019-8180. Sandia National Laboratories, Albuquerque, NM, July 2019.

3.24. Radiation Protection / Health Physics

Due to its long history with the Nuclear Weapons programs, Sandia has a high degree of expertise in radiation protection techniques and science. Sandia's radiation protection programs and internal dosimetry programs have led to the establishment of a robust capability to determine both acute (near-term) and chronic (long-term) radiation consequences to the human body and the environment. This capability has also established a long history for developing Environmental Impact Statement, National Environmental Policy Act (NEPA) Assessments, Environmental Primary Hazard Analyses (EPHA), Nuclear Safety Analysis Reports, and Safety Analysis Reports.

Selected Reports and Studies for Radiation Protection/Health Physics:

1. Hunt, B., Morris IV, A. W., and Fleener, J. *FRMAC Assessment Manual Volume 1 - Assessment Division Operations*. Albuquerque, NM: Federal Radiological Monitoring and Assessment Center, May 2023. Contract No.: SAND2023-04456 R.
2. Hunt, B., Morris IV, A. W., and Fleener, J. *FRMAC Assessment Manual Volume 2 - Overview and Methods*. Albuquerque, NM: Federal Radiological Monitoring and Assessment Center, May 2023. Contract No.: SAND2023-04457 R.
3. Hunt, B., Morris IV, A. W., and Fleener, J. *FRMAC Assessment Manual Volume 3 - Pre-Assessed Default Scenarios*. Albuquerque, NM: Federal Radiological Monitoring and Assessment Center, May 2023. Contract No.: SAND2023-04459 R.
4. Nosek, A. J., and Bixler, N. E. *MACCS Theory Manual.* Albuquerque, NM: Sandia National Laboratories, 2021. Contract No.: SAND2021-11535.
5. Chanin, D., and Young, M. L. *Code Manual for MACCS2: Volume 2, Preprocessor Codes COMIDA2, FGRDCF, IDCF2*. Sandia National Laboratories and U.S. Nuclear Regulatory Commission, 1997. Report No.: SAND97-0594. NUREG/CR-6614.
6. Haaker, R. F., and Bixler, N. *MACCS Threshold and Acute Health Effects Models*. Conference paper presented at the IMUG 2016, September 15-16, 2016, Bethesda, Maryland. United States: Medium: ED; Size: 34 p.
7. Nosek, A. J., and Bixler, N. E. *MACCS Theory Manual.* Albuquerque, NM: Sandia National Laboratories, 2021. Contract No.: SAND2021-11535.
8. Sandia National Laboratories. *MACCS User Guide – Version 4.2*. Albuquerque, NM: Sandia National Laboratories, March 2023. Report No.: SAND2023-01315.
9. Clayton, D. J., Bignell, J., Jones, C. A., Rohe, D. P., Flores, G. J., Bartel, T. J., Gelbard, F., Le, S., Morrow, C. W., Potter, D. L., Young, L. W., Bixler, N. E., and Lipinski, R. J. *Nuclear Risk Assessment for the Mars 2020 Mission Environmental Impact Statement.* SAND2013-10589. Sandia National Laboratories, Albuquerque, NM, January 2014.
10. Clayton, D. J., Wilkes, J., Starr, M. J., Ehrhart, B. D., Mendoza, H., Ricks, A. J., Villa, D. L., Potter, D. L., Dinzl, D. J., Fulton, J. D., Clayton, J. M., Cochran, L. D., Eckert-Gallup, A. C., and Brooks, D. M. *Nuclear Risk Assessment 2019 Update for the Mars 2020 Mission Environmental Impact Statement.* SAND2019-11148. Sandia National Laboratories, Albuquerque, NM, September 2019.

11. Sandia National Laboratories. *Mars 2020 Final Safety Analysis Report – For Launch Approval.* SAND2019-8180. Sandia National Laboratories, Albuquerque, NM, July 2019.
12. National Aeronautics and Space Administration. *Final Environmental Impact Statement for the Mars 2020 Mission.* Science Mission Directorate, NASA, Washington, DC, November 2014.
13. *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.

Sandia also led a DOE-sponsored sodium fast reactor safety and licensing gap analysis from 2007 to 2012. This gap analysis surveyed the licensing readiness of sodium fire experiments and modeling, understanding of important phenomena in accident sequences, fuels and materials understanding, source term issues, and the current state of codes and methods. These gap analyses resulted in a DOE research plan to improve the listenability of the sodium fast reactor (SFR).

Selected Reports and Studies for Radiation Protection/Health Physics:

1. Sofu, Tanju, Jeffrey L. LaChance, R. Bari, Roald Wigeland, Matthew R. Denman, and George F. Flanagan. *Sodium Fast Reactor Safety and Licensing Research Plan. Volume I.* United States: N. p., 2012. Web. doi:10.2172/1044972.
2. Andrews, N., M. Higgins, A. Taconi, and J. Leute. *Preliminary Radioisotope Screening for Off-site Consequence Assessment of Advanced Non-LWR Systems.* SAND2021-11703. Sandia National Laboratories, Albuquerque, NM, USA, 2021.
3. Smith, M., J. Leute, K. Wagner, and K. Clavier. *Demonstration of MELCOR and MACCS Capabilities for Molten Salt Reactor Decay Heat Removal During Both Normal Operations and Salt Spill Scenarios.* SAND2021-12956. Sandia National Laboratories, Albuquerque, NM, USA, 2021.

3.25. Severe Accident Modeling and Analysis

Some of the pioneering investigations into core melt progression behavior were conducted at Sandia in the 1980s and 1990s through experiments using reactor fuels subjected to severe accident conditions. Many of the tests using nuclear-heated fuel assemblies were performed in the Sandia Annular Core Research Reactor (ACRR). These experiments served as the early basis for developing physics models for the heat up, oxidation, hydrogen generation, and core structural degradation models incorporated in MELCOR and in other severe accident codes to model full reactor response to accidents involving fuel damage.

MELCOR has become a vital capability used by the NRC as well as a range of domestic and international safety organizations. MELCOR has evolved beyond its original focus on core melt accidents to provide a broad characterization of all safety-significant processes and phenomena relevant to accident evaluation at nuclear facilities. MELCOR can characterize all nuclear reactor technologies—from traditional Light Water Reactors (LWRs) to water-moderated advanced reactors to the spectrum of developing non-LWR technologies.

MELCOR is currently under active evolution to extend its modeling capabilities to characterize safety-significant processes and phenomena being identified through study of advanced nuclear energy technologies across all aspects of the fuel cycle. It is being applied to develop radiological source terms that can be used in Alternative Source Term Regulatory Guidance (RG 1.183) to support the deployment of Accident Tolerant Fuel (ATF), including high burnup with increased enrichment (HBU/LEU+) fuels. Expanding on its heritage evaluating all stages of an accident scenario for PRAs (i.e., success criteria and source term evaluations), it is actively being applied to assess safety margin for non-LWR technologies currently being submitted to the NRC for certification.

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 Severe Accident Mitigation Alternative (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. Sandia also provided expert witnesses testifying in front of the Atomic Safety and Licensing Board (ASLB) at the Pilgrim hearing and at the Indian Point hearings.

Selected Reports and Studies for Severe Accident Modeling and Analysis:

1. Albright, L. I., L. Gilkey, D. Keesling, C. Faucett, D. M. Brooks, K. C. Wagner, L. L. Humphries, J. Phillips, and D. L. Luxat. *High Burnup Fuel Source Term Accident Sequence Analysis*. SAND2023-01313. Sandia National Laboratories, Albuquerque, NM, April 2023.
2. Wagner, K., C. Faucett, R. Schmidt, and D. Luxat. *MELCOR Accident Progression and Source Term Demonstration Calculations for a Heat Pipe Reactor*. SAND2022-2745. Sandia National Laboratories, Albuquerque, NM, March 2022.
3. Wagner, K., C. Faucett, and D. Luxat. *MELCOR Accident Progression and Source Term Demonstration Calculations for HTGR*. SAND2022-2750. Sandia National Laboratories, Albuquerque, NM, April 2022.
4. Wagner, K., T. Haskin, B. Beeny, F. Gelbard, and D. Luxat. *MELCOR Accident Progression and Source Term Demonstration Calculations for a FHR*. SAND2022-2751. Sandia National Laboratories, Albuquerque, NM, March 2022.
5. Wagner, K., B. Beeny, T. Haskin, D. Luxat, and R. Schmidt. *MELCOR Accident Progression and Source Term Demonstration Calculations for a Molten Salt Reactor*. SAND2023-01803. Sandia National Laboratories, Albuquerque, NM, April 2023.

3.26. Socioeconomics

Through its support of NRC Hazard Analysis Branch and MACCS code development, Sandia has developed and maintained an expertise in the socioeconomic impacts of a nuclear power plant accident. The importance and impact of considering non-radiological consequences to the response to a nuclear power plant accident and how to value demographic factors is integral in Sandia's evaluation of emergency response planning. Sandia has worked to highlight the non-monetary, non-radiological impacts that should be considered when defining emergency response policy and planning.

Selected Reports and Studies for Socioeconomics:

1. Understanding Public Response to Nuclear Power Plant Protective Actions. Risk, Hazards & Crisis in Public Policy 1, no. 3 (Year): 35-36.Nuclear Regulatory Commission (NRC). NUREG/CR-6864, SAND2004-5901, Identification and Analysis of Factors Affecting Emergency Evacuations. January 2005. (NRC, 2005b).
2. Nuclear Regulatory Commission (NRC). NUREG/CR-6981, SAND2008-1776P, Assessment of Emergency Response Planning and Implementation for Large Scale Evacuations. October 2008. (NRC, 2008a).
3. Nuclear Regulatory Commission (NRC). NUREG/CR-6953, Vol. II, SAND2007-5448P, Review of NUREG-0654, Supplement 3, 'Criteria for Protective Action Recommendations for Severe Accidents – Focus Groups and Telephone Survey'. October 2008. (NRC, 2008b).
4. Understanding Public Response to Nuclear Power Plant Protective Actions. Risk, Hazards & Crisis in Public Policy 1, no. 3 (Year): 35-36.

3.27. Space Nuclear

Sandia has over thirty years of experience in supporting the development of space nuclear missions. This experience includes development of Nuclear Safety Assessments, Environmental Impact Statements, NEPA documentation, and other safety analysis reports. Sandia has developed the ROCQET code suite to assess the impact of fire and thermal, blast and impact, and other off normal environments to assess the broad range of accident states a radiological or nuclear powered or propulsed space craft may encounter. A separate suite of tools enables PRA analysis and inclusion of atmospheric and environmental transport effects to assess consequences to human health, environment, and economy. Sandia is the world leader in understanding and assessing the consequences to launching and operating spacecraft with nuclear and radiological power sources.

Selected Reports and Studies for Nuclear Power Plant Protective Actions:

1. Clayton, D. J., J. Bignell, C. A. Jones, D. P. Rohe, G. J. Flores, T. J. Bartel, F. Gelbard, S. Le, C. W. Morrow, D. L. Potter, L. W. Young, N. E. Bixler, and R. J. Lipinski. *Nuclear Risk Assessment for the Mars 2020 Mission Environmental Impact Statement*. SAND2013-10589. Sandia National Laboratories, Albuquerque, NM, January 2014. (2013 NRA).
2. Clayton, D. J., J. Wilkes, M. J. Starr, B. D. Ehrhart, H. Mendoza, A. J. Ricks, D. L. Villa, D. L. Potter, D. J. Dinzl, J. D. Fulton, J. M. Clayton, L. D. Cochran, A. C. Eckert-Gallup, and D. M. Brooks. *Nuclear Risk Assessment 2019 Update for the Mars 2020 Mission Environmental Impact Statement*. SAND2019-11148. Sandia National Laboratories, Albuquerque, NM, September 2019. (2019 NRA).
3. Sandia National Laboratories. *Mars 2020 Final Safety Analysis Report – For Launch Approval*. SAND2019-8180. Sandia National Laboratories, Albuquerque, NM, July 2019. (FSAR)
4. National Aeronautics and Space Administration. *Final Environmental Impact Statement for the Mars 2020 Mission*. Science Mission Directorate, NASA, Washington, DC, November 2014. (Not a Sandia document; references the NRA).

3.28. 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. Sandia's engineers can perform a numerical analysis in totality—from modeling a structure in software to validating the calculations with experiments and journal data.

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 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.

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.

Selected Reports and Studies for Structural Engineering and Containment Integrity Research:

1. NUREG-1150, *Severe Accident Risks: An Assessment for Five U.S. Nuclear Power Plants*. 2021
2. NUREG/CR-6906, *Containment Integrity Research at Sandia National Laboratories*. 2006.
3. NUREG/CR-6920, *Risk-Informed Assessment of Degraded Containment Vessels*. 2006.
4. In 2019, Sandia completed a classified analysis regarding how Unmanned Aerial Systems (UAS, a.k.a., 'drones') might be leveraged in an attack on nuclear facilities. This study combined three Sandia strengths: (1) nuclear vital area analysis, (2) UAS, and (3) explosives in a technology evaluation and a prediction on how such technology might be leveraged. This work is currently being updated in a 2024 study, which is still in development.

3.29. Structural Phenomenological Modeling and Analysis of Complex Systems

Sandia has capabilities in computational methods developed in structural mechanics, heat transfer, fluid mechanics, shock physics, and many other fields of engineering that are an enormous aid to understanding complex physical systems.

Sandia supports the regulations and regulatory guidance regarding risk significance, burden reduction potential, and engineering design margins associated with facility systems, structures and components that support existing and new reactor designs. These 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 for piping, welds, and vessels; probabilistic fracture mechanics-based license submittals; tools to quantitatively assess changes in structural reliability of nuclear systems, structures, and components as a result of operating environment effects or aging of materials.

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 the quantification of material behavior under accelerated aging conditions and the development of empirical, phenomenological, and fundamental models and understanding of materials aging.

Selected Reports and Studies Structural Phenomenological Modeling and Analysis of Complex Systems:

1. NUREG/CR-3234, *The Potential for Containment Leak Paths through Electrical Penetration Assemblies under Severe Accident Conditions*. 1983.
2. NUREG/CR-3222, *The Search for a High Elongation Strain Gage System*. 1983.
3. NUREG/CR-3724, *Ultimate Strength Analyses of the Watts Bar, Maine Yankee, and Bellefonte Containments*. 1984.
4. NUREG/CR-4944, *Containment Penetration Elastomer Seal Leak Rate Test*. 1987.
5. NUREG/CR-5096, *Evaluation of Seals for Mechanical Penetrations of Containment Buildings*. 1988.
6. NUREG/CR-5099, *Evaluation of Materials of Construction for the Reinforced Concrete Reactor Containment Model*. 1988.
7. NUREG/CR-5334, *Severe Accident Testing of Electrical Penetration Assemblies*. 1989.
8. NUREG/CR-6154, *Experimental Results from Containment Piping Bellows Subjected to Severe Accident Conditions*. 1995.
9. NUREG/CR-6906, *Containment Integrity Research at Sandia National Laboratories*. 2006.
10. NUREG/CR-6920, *Risk-Informed Assessment of Degraded Containment Vessels*. 2006.
11. NUREG-2110, *xLPR Pilot Study Report*. 2012.
12. NUREG/CR–7278*, Technical Basis for the Use of Probabilistic Fracture Mechanics in Regulatory Applications*. 2022.

3.30. Thermal and Thermomechanical Phenomenology Modeling of Complex Systems

Sandia has multi-scale test facilities, accrued knowledge, and over 40 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 on-site experimental and testing facilities, Sandia performs complete investigations of thermal phenomena.

Sandia researchers have expertise in the development and application of numerical thermal analysis codes. With high-performance computing capabilities and a broad knowledge of commercial and in-house-developed software, Sandia can model the most complex multidisciplinary physics simulations related to fire and heat transfer.

Selected Reports and Studies for Thermal and Thermomechanical Phenomenology Modeling of Complex Systems:

1. NUREG/CR-2142, *CORCON-MOD 1: An Improved Model for Molten-Core/Concrete Interactions*. 1981.
2. NUREG/CR-2385*, CSQ Calculations of H2 Detonations in the Zion and Sequoyah Nuclear Plants*. 1982.

3. NUREG/CR-3920, *CORCON-Mod2: A Computer Program for Analysis of Molten-Core Concrete Interactions*. 1984.
4. NUREG/CR-3638, *Hydrogen-Steam Jet-Flame Facility and Experiments*. 1985.
5. NUREG/CR-4558, *Interaction of Hot Solid Core Debris with Concrete*. 1986.
6. NUREG/CR-4803, *The Possibility of Local Detonations During Degraded-Core Accidents in the Bellefonte Nuclear Power Plant*. 1987.
7. NUREG/CR-5321, *A Thermodynamic Model of Fuel Disruption in the ST-1*. 1991.
8. NUREG/CR-6025, *The Probability of Mark-I Containment Failure by Melt-Attack of the Liner*. 1993.
9. NUREG/CR-6109, *The Probability of Containment Failure by Direct Containment Heating in Surry*. 1995.
10. NUREG/CR-6338, *Resolution of the Direct Containment Heating Issue for All Westinghouse Plants with Large Dry Containments or Subatmospheric Containments*. 1996.
11. *NUREG/CR-6527 – Final Results of the XR2-1 BWR Metallic Melt Relocation Experiment*. 1997.
12. *NUREG/CR-6475 – Resolution of the Direct Containment Heating Issue for Combustion Engineering Plants and Babcock and Wilcox Plants*. 1998.
13. Brown, Alex, and Thomas Blanchat. *A Fire Simulation with a RWCU Pipe Break Steam Source (U)*. Review Copy. Sandia National Laboratories, Albuquerque, NM, April 2006. SNSI.
14. Klamerus, Eric, 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.
15. Smith, Jeff, 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.

3.31. Uncertainty and Sensitivity Analysis

For the past 30 years, Sandia has developed and conducted 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 can recognize the level of confidence in a computational answer. Sandia manages the development of computation tools within a robust, quality assurance environment.

<u>Selected Reports and Studies for Uncertainty and Sensitivity Analysis:</u>

1. NUREG/CR-3440, *Identification of Severe Accident Uncertainties*. 1979.
2. NUREG/CR-2350, *Sensitivity Analysis Techniques: Self-Teaching Curriculum*. 1982.
3. NUREG/CR-3226, *Station Blackout Accident Analysis*. 1983.
4. 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.

5. NUREG/CR-4350, *Probabilistic Risk Assessment Course Documentation*. 1985.
6. NUREG/CR-3904, *A Comparison of Uncertainty and Sensitivity Analysis Techniques for Computer Models*. 1985.
7. NUREG-1150, *Severe Accident Risks: An Assessment for Five U.S. Nuclear Power Plants*. 1990.
8. NUREG/CR-5305, *Integrated Risk Assessment for the LaSalle Unit 2 Nuclear Power Plant: Phenomenology and Risk Uncertainty Evaluation Program (PRUEP)*. 1992.
9. NUREG/CR-6134, *Uncertainty and Sensitivity Analysis of Chronic Exposure Results with the MACCS Reactor Accident Consequence Model*. 1995.
10. NUREG/CR-6135, *Uncertainty and Sensitivity Analysis of Early Exposure Results with the MACCS Reactor Accident Consequence Model*. 1995.
11. NUREG/CR-6136, *Uncertainty and Sensitivity Analysis of Food Exposure Results with the MACCS Reactor Accident Consequence Model*. 1995.
12. NUREG/CR-5593, *Risk Comparisons of Scheduling Preventative Maintenance for Boiling Water Reactors During Shutdown and Power Operation*. 1999.
13. NUREG/CR-6823, *Handbook of Parameter Estimation for Probabilistic Risk Assessment*. 2003.
14. NUREG-2110, *xLPR Pilot Study Report*. 2012.
15. 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.
16. *State-of-the-Art Reactor Consequence Analyses (SOARCA) Project: Sequoyah Integrated Deterministic and Uncertainty Analyses*. NUREG/CR-7245. U.S. Nuclear Regulatory Commission, Washington, DC, 2019. ADAMS Accession No. ML19296B786.
17. *State-of-the-Art Reactor Consequence Analyses (SOARCA) Project: Uncertainty Analysis of the Unmitigated Short-Term Station Blackout of the Surry Power Station*. NUREG/CR-7262. U.S. Nuclear Regulatory Commission, Washington, DC, forthcoming 2022.
18. *NUREG-2254, Summary of the Uncertainty Analyses for the State-of-the-Art Reactor Consequence Analyses Project*.
19. *Complex Systems and Their Applications: Towards a New Science of Verification, Validation, and Uncertainty Quantification*. SAND2016-8409.
20. *Modeling the Potential Effects of New Tobacco Products and Policies: A Dynamic Population Model of Multiple Product Use and Harm*. This work was later used to develop FDA policy and published in the NE Journal of Medicine.

3.32. Waste Management

Sandia began work in the nuclear waste research area in the early 1970s and published its first report on nuclear waste in 1973. Since then, Sandia has developed long-lasting, collaborative teams of outstanding scientists and engineers, including geoscientists, material scientists, nuclear engineers, mechanical engineers, computer scientists, and mathematicians. These integrated teams generate the foundational science and engineering data and analyses for developing their recommendations and solutions to the nation’s challenges in spent nuclear fuel storage, transportation, security, and disposal.

Sandia performs research on systems engineering processes and postclosure safety assessment methods to plan, develop, implement, and evaluate deep geologic disposal facilities for spent nuclear fuel (SNF) and high-level radioactive waste (HLW). Geologic disposal options for nuclear waste include mined repository concepts in salt, argillite, and crystalline rock and borehole disposal. Sandia conducts experimental studies, develops process models, and performs quantitative and qualitative analyses to further the scientific basis to safely dispose of nuclear waste.

Sandia leads the DOE research efforts to evaluate the technical feasibility of disposing dual-purpose canisters (DPCs) containing commercial SNF in a geologic repository. Sandia-led studies initially concluded that direct disposal is technically feasible for most DPCs, depending on the repository host geology. Ongoing research is investigating:

- Thermal management
- Handling and emplacement operations for the large, heavy packages
- As-loaded DPC criticality modeling (reactivity margin)
- Postclosure criticality consequence analysis
- DPC fillers for criticality control
- Potential future DPC modifications (fuel/basket modification)

Sandia, the U.S. Department of Energy (DOE), and the Electric Power Research Institute (EPRI) have a decades-long collaboration to obtain data on how SNF ages while in long-term storage. Data obtained from this collaboration is being used to develop aging management plans to mitigate potential changes to the spent fuel over time to better ensure that the fuel maintains its integrity for as long as needed. An element of this work involves thermal hydraulic experiments and analysis of dry cask systems. Sandia performs R&D on:

- stress corrosion cracking (SCC) of canisters
- spent fuel dry storage systems drying cycles
- crack flow testing
- thermal hydraulic testing and code validation

3.33. Computational Tools

The Sandia-developed Geologic Disposal Safety Assessment (GDSA) Framework is an open-source software toolkit for probabilistic safety assessment of deep geologic disposal options, including mined repositories and borehole disposal. The simulation engine for this modeling and analysis framework is PFLOTRAN, a massively parallel, multiphase flow and reactive transport simulator. Sandia's PFLOTRAN software development team maintains and enhances the modeling capabilities necessary to simulate radionuclide transport in the subsurface and the thermal, hydrologic, mechanical, and chemical evolution of deep geologic disposal facilities. The open-source development environment has promoted worldwide use. GDSA Framework's state-of-the-art simulation and analysis capabilities for post-closure safety assessment were demonstrated on generic deep geologic repository concepts in crystalline, argillite, and salt host rocks, as well as on generic deep borehole disposal concepts.

4. SANDIA DEVELOPED SOFTWARE AND MODELING FRAMEWORKS

4.1. Advanced Reactor Cyber Security Analysis and Design Environment (ARCADE)

Sandia has a long history supporting the federal government with severe consequence analysis and probabilistic risk analysis. We also have strong experience in modeling, simulation, emulation, and analysis of control systems. These capabilities are integrated in our cybersecurity for nuclear control systems capability. We seek to deliver cybersecurity for nuclear applications that is both economical and provable. Thus, meeting industry goals for affordability while at the same time reducing regulatory uncertainty associated with obtaining licensing approval.

Sandia wrote the Design Guide (DG) 5075 for Advanced Reactor Control Systems (https://www.nrc.gov/docs/ML2328/ML23286A278.pdf), which describes a method that the U.S. Nuclear Regulatory Commission (NRC) staff deem acceptable for complying with the Commission's regulations for establishing, implementing, and maintaining a cybersecurity program at commercial nuclear plants that would be licensed under Title 10 of the Code of Federal Regulations (10 CFR) Part 53, "Risk-Informed, Technology-Inclusive Regulatory Framework for Commercial Nuclear Plants" (Ref. 6F1), subject to the requirements in 10 CFR 73.110, "Technology inclusive requirements for protection of digital computer and communication systems and networks". This guidance delivers a tiered approach for designing nuclear reactor control systems.

A key enabler of DG-5075 is cyber security testing using Sandia control system emulations to design and prove the security benefit of defensive cyber security architectures (DCSAs) using Sandia's Advanced Reactor Cyber Security Analysis and Design Environment (ARCADE) test bed. ARCADE combines control system emulation with nuclear plant simulation modeling to deliver a high-fidelity platform to enable rigorous, repeatable, and evidence-based cybersecurity analysis and evaluations. ARCADE is a suite of publicly available tools that can be used to develop emulations of industrial control system devices and networks and integrate those emulations with physics simulators. This integration of cyber emulations and physics models enables rigorous cyber-physical analysis of cyber-attacks on NPP systems. ARCADE supports:

- System Level Design Analysis (SLDA)
- Secure-by-design (SeBD) analysis
- Defensive Computer Security Architecture (DCSA) implementations
- Cyber security analysis of defensive measures and cyber-attack impacts

The test bed is ever growing as Sandia adds additional advanced reactor physics models and new capabilities for emulation and analysis.

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

Sandia brings over 30 years of experience in 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:

- 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 Vulnerability Assessment of Nuclear Energy Systems and Applications (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 Vulnerability and Impact Assessment of Critical Infrastructure for Resilience and Adaptation (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 mixed oxide (MOX) fuel. These methods are being used by the NRC to update the Alternative Source Term used in NRC Regulatory Guide 1.183, *Alternative Radiological Source Terms for Evaluating Design Basis Accidents at Nuclear Power Reactors*.
- 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, Phebus-FP, Sulfur Transport and Deposition Model (STEM), Aerosol Trapping in the Steam Generator (ARTIST), and RASPLAV/MAterial SCaling (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.

4.2.1. Coupled Fire-Thermal Analysis Codes

CAFÉ. The Container Analysis Fire Environment (CAFE) computer code was developed to model all relevant fire physics for predicting the thermal response of massive objects engulfed in large fires. The CAFE code can be coupled to commercial finite element codes such as MSC Patran/Thermal and ANSYS Mechanical. This coupled system of codes can be used to determine the internal thermal response of finite element models of packages to a range of fire environments.

4.3. Dynamic Event Tree Code

ADAPT. The ADAPT software works alongside a simulator (e.g., MELCOR) to generate event trees in response to state changes in both active and passive systems. For these systems, the time at which a branch is formed is controlled by the simulator in response to predetermined rules supplied by the user. This allows for event trees to be generated by the simulator instead of solely relying on expert judgement. ADAPT has been used to support NRC's dynamic assessments of human reliability projects by creating the structure to couple the human reliability models within the Accident Dynamic Simulation (ADS) / Information, Decision, and Action in Crew (IDAC) with the dynamic event tree capabilities in ADAPT.

4.4. Emergency Response Codes

- **Radiological Assessment System for Consequence Analysis (RASCAL)**. The Radiological Assessment System for Consequence Analysis is a tool used by the NRC's Protective Measures Team (PMT) in the Headquarters Operations Center and Regional Incident Response Centers for making independent dose and consequence projections during radiological incidents and emergencies.
- **Dose Coefficient File Package (DCFPAK).** The Dose Coefficient File Package is the software application developed to provide electronic access to the dose coefficient data files summarized in Federal Guidance Reports 11, 12, and 13. DCFPAK also provides access to standard information regarding decay chains and assembles dose coefficients for all dosimetrically significant radioactive progeny of a specified radionuclide and is used for dose assessment by various dose calculating tools including RASCAL, and Turbo FRMAC.
- **Nuclear Incident Response Program (NIRP).** The NIRP program provides research and technical solutions, expert analysis, and highly trained emergency response professionals to support the federal government's response to an accident or act of terrorism involving radiological, chemical, or biological material. This site provides access to software developed by NIRP's Software Development Team which is used in emergency response.
- **Response Technical Tool (RTT).** The RTT software was developed to make the NRC's Response Technical Manual (RTM), which is intended for use during a reactor severe accident, into a software application. The RTM is based on previous experiments and experience with severe accident phenomena. This work used section A of the RTM devoted to an assessment of core damage. The goal of the RTT is to automate the simple, yet very time consuming, calculations that are necessary to evaluate the status of a reactor during accident. This allows an analyst to spend more time making an evaluation as to the status of the plant and not performing simple calculations.
- **Turbo FRMAC (TF).** The TF software program is the software implementation of the science and methodologies utilized by the Federal Radiological Monitoring and Assessment Center (FRMAC). These methods are documented in the FRMAC Assessment Manual and are employed in the event of the intentional or accidental

release of radioactive material to guide. These methods also govern the response of the federal, state, local, and tribal governments.

- **Mixture Manager (MM).** The MM software tool provides the ability to view default mixtures of radionuclides, create custom mixtures, import mixtures from other radiological tools, and create mixtures from limited information. The primary purpose of MM is the management of mixtures for use in other radiological tools such as TF and RASCAL.
- **Radionuclide Viewer (RV).** RV is a tool for viewing the DCFPAK radiological data. RV allows a user to select a radionuclide and visualize its full decay chain and basic data (half-life, decay modes, etc.). In addition to this, RV allows for the viewing of all the various dose coefficients for the selected radionuclide or its daughters.

4.5. Environmental Fate and Atmospheric Transport Models

Sandia has a broad range of expertise and history in the development of environmental fate and atmospheric transport models. For the NRC, Sandia has developed the MACCS code for half a century, continually advancing the codes capability to perform atmospheric and environmental transport. Sandia developed the SHARC code for weapons of mass destruction response and worked with the National Oceanic and Atmospheric Administration (NOAA) to advance the capabilities of the HYSPLIT atmospheric transport model. Sandia has also worked to develop the PFLOTRAN code used to evaluate ground transport of radiological material through geologic media.

- **Atmospheric Transport Code (ATMOS).** The atmospheric transport code used in MACCS to evaluate the atmospheric transport of radiological material in the atmosphere is referred to as ATMOS. Sandia has developed and continually expanded the capabilities of ATMOS to support NRC operations since the 1970s. More recent additions include improvement to support near field atmospheric transport and additional modeling options to improve capabilities for advanced reactor licensing.
- **Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT)**. A code jointly developed by NOAA and the Australian Weather Bureau to simulate the atmospheric transport of material. HYSPLIT was recently added as an option inside the NRC MACCS code suite to perform more realistic 3D Lagrangian particle tracking simulations of radiological releases in the atmosphere. HYSPLIT is also the model used within the ROCQET code suite to evaluate the atmospheric transport of material after a launch anomaly of a spacecraft that is powered by nuclear material. Sandia, working with NOAA, has developed MACCS, and ROCQET specific improvements such as a radial grid, and incorporated HYSPLIT into several studies meant to enhance NRC preparedness for Advanced Reactor Licensing or the federal government's ability to assess the impact of a launch anomaly.
- **Initial Atmospheric Transport (IAT)**. Initial Atmospheric Transport calculates the dynamic plume rise and ensuing particulate transport for plumes driven by thermal events either from long duration fires or from instantaneous explosive events or other means for long duration thermal loads or instantaneous thermal releases. Results of the IAT code are traditionally handed off to long duration and range transport codes. IAT is heavily used in launch safety to understand the impacts of fire environments following launch anomalies involving rockets and their payloads.

- **Parallel Flow and TRANsport (PFLOTRAN)**. Simulates single phase water and multiphase (air, CO_2, water) flow, energy transport, geochemical reaction and biological reaction in the earth's subsurface environment. The problem may be discretized on structured and unstructured grids. The code is designed to run in parallel on supercomputers and leverages the open source Portable, Extensible Toolkit for Scientific Computation (PETSc) library for solvers and data structures and open source HDF5 for binary file I/O. See www.pflotran.org and/or doc-dev.pflotran.org for further information.
- **Specialized Hazard Accident Response Capabilities (SHARC)**. Specialized Hazard Accident Response Capabilities is a code developed by Sandia on behalf of the DOE that has atmospheric transport capabilities for Nuclear Fallout and explosively driven radiological dispersal events. SHARC uses a puff-gaussian model to perform its atmospheric transport and contains capabilities for using HYSPLIT for high resolution atmospheric transport as well as capabilities to compute land contamination and human health consequences.
- **Sandia Transport Of Radiological Material (STORM)**. Sandia Transport of Radiological Material was developed to support the assessment of radiological transport for the National Aeronautics and Space Administration (NASA) and the Department of Energy (DOE) caused by accidents involving radiologically powered space craft. In addition to atmospheric transport, STORM calculates radiological human health consequences and land contamination as well as impacts to the food chain.

4.6. Extremely Low Probability of Rupture (xLPR) Code

Sandia developed key portions of the Extremely Low Probability of Rupture (xLPR) code. This is the NRC's state-of-the-art probabilistic fracture mechanics code for piping applications. This code provides the NRC and the public with new quantitative capabilities to analyze the risks associated with nuclear power plant piping systems subject to active degradation mechanisms, such as stress-corrosion cracking and fatigue.

4.6.1. Fire Science Research Codes

Sandia has the nation's leading fire test facility. Sandia's Thermal Test Complex (TTC) was specifically created for fire and thermal experiments. Sandia developed the following fire- related codes:

- **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 can solve 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.

4.7. Hydrogen Risk Assessment Models Toolkit

Hydrogen Plus Other Alternative Fuels Risk Assessment Models (HyRAM+) is a software toolkit that integrates publicly available data and models relevant to assessing the safety in the use, delivery, and storage infrastructure of hydrogen and other alternative fuels (i.e., methane and propane).

The HyRAM+ risk assessment calculations incorporate probabilities of equipment failures for different components for both compressed gaseous and liquefied fuels, and probabilistic models for the effect of heat flux and overpressure on people. HyRAM+ also incorporates experimentally validated models of various aspects of release behavior and flame physics. The HyRAM+ toolkit can be used to support multiple types of analysis, including code and standards development, safety basis development, facility safety planning, and stakeholder engagement.

HyRAM+ is supported by the U.S. Department of Energy (DOE) Office of Energy Efficiency (EERE) Hydrogen and Fuel Cell Technologies Office (HFTO), the DOE EERE Vehicles Technologies Office (VTO), and the U.S. Department of Transportation (DOT) Pipeline and Hazardous Materials Safety Administration (PHMSA).

4.8. MACCS Code Suite

- **MACCS.** MACCS is a fully integrated, engineering-level computer code developed at Sandia for the NRC. MACCS simulates the impact of severe accidents at NPPs and other nuclear facilities on the surrounding environment. As the only code used by the NRC to support Level-3 PRAs, MACCS can use a site's weather data to determine hypothetical land contamination levels, doses to individuals, health effects and risks on populations based on protective action recommendations, and economic losses resulting from a NPP accident.
    - MACCS is also used to assess the environmental transport of radioactive material from other sources. MACCS is heavily used in space nuclear launch safety to perform bounding studies. A version of the code, CHEM-MACCS is designed for chemical transport.
- **WinMACCS / MACCS-UI.** WinMACCS is a graphical user interface used to set up MACCS simulations. WinMACCS enables validation of input values, visualization of results, and establishment of uncertainty analysis by enabling multiple runs to be executed using uncertainty sampled input values.
- AniMACCS is a utility code in the MACCS software suite that allows for certain MACCS output information to be visually displayed and animated onto a geospatial map background.
- **MelMACCS.** MelMACCS is used to create a MACCS source term input file from the MELCOR plot file. The MELMACCS software was created to provide an interface utility between MELCOR and MACCS to extract and evaluate the required source term data for a consequence analysis.
- **COMIDA2.** COMIDA models transport through the human food chain and calculates the respective nuclide concentration in nine foodstuffs (grains, leafy vegetables, roots, fruits, legumes, milk, beef, poultry, and "other animal"), based on an initial unit deposition. All COMIDA calculations are performed for one user-specified accident day in the year, or "fallout" date, and foodstuff concentration data can be calculated for up

to 50 years following the accident, reported as both 1-year or cumulative (0 to *N* yrs) values.

- **SecPop.** SecPop calculates estimated population and economic data around any point specified by latitude and longitude. The NRC adopted SecPop to perform siting reviews for nuclear power-plant construction and license applications within the continental United States. SecPop Version 4.4.0 represents the current version, utilizing 2020 census data and 2017 economic data, which is the most recent available. In tandem, SecPop was created to be compatible with 2000 census and 2002 economic data. SecPop supports site analysis, which evaluates population, land use, and economic data on a polar grid centered on a prescribed site. Population estimates are made using block level census data and economic estimates are made using county level data.
- **RDEIM.** RDEIM has its roots in a code developed by Sandia for the Department of Homeland Security (DHS) to estimate short-term losses from natural and manmade accidents, called the Regional Economic Accounting analysis tool (REAcct). This model was adapted and modified for MACCS. This model is based on I-O theory, which is widely used in economic modeling. This model accounts for direct losses to a disrupted region affected by an accident, indirect losses to the national economy due to disruption of the supply chain, and induced losses from reduced spending by displaced workers. RDEIM differs from REAcct in in its treatment and estimation of indirect loss multipliers, elimination of double counting associated with inter-industry trade in the affected area, and that it is intended to be used for extended periods that can occur from a major nuclear reactor accident, such as the one that occurred at the Fukushima Daiichi site in Japan. Most input-output models do not account for economic adaptation and recovery, and in this regard RDEIM differs from its parent, REAcct, because it allows for a user-definable national recovery period. Implementation of a recovery period was one of several recommendations made by an independent peer review panel to ensure that RDEIM is state-of-practice.

4.9. Physical Security and Safeguards

- **Dante.** Dante simulates adversary attacks on sites of concern in an automated force-on-force simulation. These Monte Carlo, batch simulations produce large amounts of data allowing analysts to explore the statistical results of attacks against the site's physical security system.
- **Material Accountancy Performance Indicator Toolkit (MAPIT).** MAPIT is a Python package designed to aid in safeguards analysis of bulk materials. The inherent flexibility is designed to allow safeguards practitioners ask the "what if?" questions while providing transparency into commonly employed statistical tests. MAPIT provides both a graphical user interface (GUI) and an application program interface (API). The API can be used with other popular Python libraries to extend functionality and integrate with other analytical workflows.
- **PathTrace.** PathTrace is a quantitative analysis modeling and simulation tool that uses established algorithms to identify system vulnerabilities. PathTrace calculates probability of interruption, probably of detection, and critical detection point for multiple pathways. PathTrace also generates an adversary sequence diagram for each path, providing science-based, actionable data to help improve security at any facility.

4.10. Sandia's High-Performance Computing (HPC) Codes

Sierra is an engineering mechanics simulation code suite. Distinguishing strengths include: "application aware" development, scalability, software quality assurance (SQA), and verification and validation (V&V), multiple scales, and multi-physics coupling. Codes part of the Sierra suite include the following:

- **Multiphysics Coupling (ARIA).** ARIA is a general framework for thermal/ mechanical, thermal/fluid, and fluid/structure interactions. The framework permits a range of uni- and multi-directional coupling strategies from segregated in time and or space to fully coupled (in a matrix sense) in time and/or space.
- **Fluid Dynamics (FUEGO).** FUEGO has capability for low-Mach, laminar and turbulent reacting flow. Typically used for heat and mass transport modeling. It can also be coupled with Syrinx to simulate fire environments.
- **Solid Mechanics (SM).** SM is massively parallel capable and contains a full suite of features that span explicit and implicit transient dynamics, and implicit quasi-statics. These capabilities include a wide variety of element types including, bars, beams, tetrahedral, hexahedral, and particles (mass, SPH, and Peridynamics). Typically used to simulate container and package impact analyses and response of steel and concrete nuclear structures.
- **Structural Dynamics (SD) and Acoustics** is massively parallel capable and performs most traditional structural dynamics simulations in the time and frequency domains. This includes stress, fatigue calculations that could include energy dissipation at discrete joints.
- **Thermal Mechanics** is a general three-dimensional, transient capability for heat conduction and surface/surface radiation in and between solid materials as well as support for thermoelectric problems. Typically, thermal mechanics is used to simulate response of spent nuclear fuel containers under different environments.

The Dakota software's advanced parametric analyses enable design exploration, model calibration, risk analysis, and quantification of margins and uncertainty with computational models. These capabilities may be used on their own or as components within advanced strategies such as hybrid optimization, surrogate-based optimization, mixed integer nonlinear programming, or optimization under uncertainty. The Dakota toolkit provides a flexible, extensible interface between such simulation codes and its iterative systems analysis methods, which include the following:

- Optimization with gradient and nongradient-based methods;
- Uncertainty quantification with sampling, reliability, stochastic expansion, and epistemic methods;
- Parameter estimation using nonlinear least squares (deterministic) or Bayesian inference (stochastic); and
- Sensitivity/variance analysis with design of experiments and parameter study methods.

4.11. 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. 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 PRA activities at the 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 Daiichi.

4.12. Shock Physics

Code for Transient Hydrodynamics (CTH) is a multi-material, large deformation, strong shock wave, solid mechanics code. It has models for multi-phase, elastic, viscoplastic, porous and explosive materials. Three-dimensional rectangular meshes, two-dimensional rectangular and cylindrical meshes, and one-dimensional rectilinear, cylindrical, and spherical meshes are available.

CTH has adaptive mesh refinement and uses second-order accurate numerical methods to reduce dispersion and dissipation to produce accurate and efficient results. CTH provides an end-to-end simulation solution including visualization support and runs on Linux, Windows, Macintosh and UNIX workstations, and massively parallel supercomputers.

4.13. ROCQET – Radiological Off-Nominal Consequence Quantification and Evaluation Toolset

ROCQET uses a suite of codes to analyze the risk of a nuclear system launch into space. The code suite is partitioned into three groups of codes. The first group involves detailed phenomenological codes that determine the response of the space nuclear system to various threatening environments. The second group of codes determine the amount of radioactive material released from a particular accident sequence and the characteristics of that release. Many possible sequences are simulated, and the associated probability is tracked, so that the net output is a combination of released amount of radioactive material, its characteristics, and associated probabilities. The third code group determines the atmospheric transport of released material and the consequences of this release on human health and the environment. This third code also calculates a probability distribution for these consequences. A list of the major codes in ROCQET, with descriptions for each is given below:

- **Sierra/SM (Sierra Solid Mechanics)** is a Lagrangian, three-dimensional finite element code developed for modeling transient solid mechanics problems involving large deformations and contact. This model provides capabilities for explicit and implicit analyses. The explicit dynamics capabilities allow for the solution of models subjected to large, suddenly applied loads, which are characteristic of impact analyses.
- **Monte Carlo N-Particle (MCNP)** is a general-purpose, continuous-energy, generalized-geometry, time-dependent, Monte Carlo radiation-transport code designed to track many particle types over broad ranges of energies.
- **Sandia Fireball Model (SFM)** is a code used to determine the particle size distribution of the released material after it has been exposed to a liquid propellant fire environment.

- **Plutonium Entrainment and Vaporization After a Coincident Impact (PEVACI**) is a code used to determine the particle size distribution of the released material after it has been exposed to a solid propellant fire environment.
- **Loop Analysis Program Software (LAPS)** is overarching code compiling the aerodynamic, thermodynamic, heating, and thermal response analyses use to evaluate the space nuclear system performance during reentry accident scenarios. LAPS uses a combination of analytical/empirical techniques and one-dimensional thermal response analyses to provide rapid solutions for a wide range of scenarios.
- **Launch Accident Sequence Evaluation Program (LASEP)** is a Monte Carlo analysis codes used to evaluate the potential for release of material from the space nuclear system during a launch accident scenario. Inherently, there is a large degree of variability associated with each of the launch accident scenarios. The accident environments are dependent on many factors. Consequently, a stochastic model, which accommodates inherent variability by performing many simulations and represents results in a probabilistic fashion, is best suited for this analysis. LASEP samples from random distributions to Capture the full range of possible outcomes for each scenario.
- **Sandia-Developed Transport of Radioactive Material (STORM)** is an overarching code that collates the results from the initial atmospheric transport due to the fire environment, the transport through the environment due to the local weather conditions, and the resulting consequences to humans and the surrounding environment as a result of the release material.
- **Complementary Cumulative Distribution Function Analysis and Rollup Statistics (CARS)** is a code that compiles the accident, source term, and consequence probabilities into risk, and determines the uncertainty intervals about those risks.

5. SPECIALIZED FACILITIES OR EQUIPMENT

5.1. Access Delay Bunker (ADB)

The Access Delay Bunker (ADB) demonstration area offers a realistic environment for delay component and system research, development, and testing. Participants can also train on the effective use of many delay components.

- Barriers
- Passive and activated dispensable materials
- Delay methodologies

5.2. Aerosol Facility (AF)

The Aerosol Facility (AF) is one of several specialized, re-useable test facilities operated by Sandia National Laboratories Explosives Research & Development Organization 6648. The facility conducts explosive aerosol experiments using up to ¼-KG of high explosives. The facility consists of an air-supported hemispherical dome with an approximate contained volume of 1,000 m^3. To date, over 600 explosive tests were conducted at the facility using various materials and device configurations. Experimental results are used to inform predictive modeling efforts.

A wide array of active and passive diagnostic techniques has been successfully developed and deployed to characterize particle size, distribution, and total mass behaviors. A network of wire rope cables, data acquisition cabling conduits, and a fully integrated command-and-control fire-set allows for maximum data acquisition and cost-effective test conduct when multiple materials and/or configurations need to be investigated.

5.3. Center for Security Systems (CSS)

The CSS contains state-of-the-art equipment to measure attributes of security equipment, and includes exterior sensors test bed, video technology laboratory, robotic vehicle range, and access delay technologies.

5.4. Combustion Research Facility (CRF)

The CRF provides a controlled and well instrumented facility focused on understanding combustion and combustion-related processes. This includes specialization in instrument development.

5.5. Cylindrical Boiling Vessel (CYBL) Test Facility

The CYBL facility is a stainless-steel reactor-scale facility designed for testing the flooded-cavity design for reactor accident termination. The reactor vessel cavity configuration is replicated by a tank within a tank design, the outer vessel measuring 5.1 m inner diameter and 8.4 m high, 316L. There are 51 viewing windows, ranging in size from 0.3 m to 0.6 m in diameter, on the side and bottom of the outer vessel.

CYBL is used for thermal hydraulic investigations and fire ignition associated with safety cases for the evaluation of spent fuel in an air environment resulting from loss of water in a spent fuel pool. Additionally, the vessel can provide a location for observing thermal-hydraulic behavior of above and underground dry cask storage systems for spent nuclear fuel, using full length, highly prototypic fuel assemblies and a flexible data acquisition system.

5.6. Design, Evaluation, and Test Technology Facility (DETTF)

The DETTF is a controlled and well instrumented facility designed to test components and systems in normal and extreme accident conditions. The DETTF's capabilities include non-destructive testing, photometric and optics, and data acquisition devices.

5.7. Energy-Cyber Lab Complex

Sandia's Energy-Cyber Lab Complex is a series of digital instrumentation and control (I&C) and cyber security labs interconnected to provide integrated design, test, and evaluation of digital control systems.

5.8. Engineering Sciences Experimental Facilities (ESEF)

The ESEF is a series of controlled and well instrumented laboratories available for experiments in thermodynamics, heat transfer, fluid mechanics, multiphase flow, adhesion, surface rheology, material characterization, X-ray computed tomography (CT), and material decomposition.

5.9. Explosive Components Facility (ECF)

The ECF is a state-of-the-art well instrumented experimental facility that covers chemical, material, and performance analysis capabilities for energetic materials.

5.10. Geomechanics Laboratory (GL)

The GL focuses on the measurement of rock properties in a wide range of conditions, including very high pressures and complex load paths. The laboratories' capabilities make it useful for research and development in underground construction, mining, oil and gas production/reservoir management, hydrocarbon, and compressed air storage and much more.

5.11. High-Performance Computing (HPC) Clusters

Sandia National Laboratories is known around the world for its expertise and leadership in High Performance Computing (HPC), a capability critical to its multiple missions. Key focus areas include the following:

- Resources available for scientific computing, modeling, and simulation.
- Large-scale systems for data analytics, cloud computing, and emulytics.
- New computer architectures in our advanced systems test beds to guide future platform designs.
- Designing and developing innovative system management and operational methodologies to ensure the performance and efficiency of current and future systems.
- Advancing the Field of Computing through R&D and collaborative partnerships.

5.12. Integrated Security Facility (ISF)

The ISF is a decommissioned nuclear reactor facility that includes legacy capabilities and a realistic venue to demonstrate and evaluate security elements: perimeter intrusion detection and assessment system; central alarm station; entry control portal; mock nuclear material receiving and storage area; mock nuclear material processing facility; access delay and response survivability elements.

Recently the ISF was enhanced to include a Cyber Security Operations Center (CSOC). In May 2023, the integrated facility hosted the first ever combined Cyber / Physical (Hybrid) attack exercise against a nuclear facility. The exercise not only demonstrated the hybrid attack, but it also developed realistic control systems that were attacked and allowed the analysis of how cyber security functions (detect, delay, respond, etc.) could be integrated into the Central Alarm Station operations.

5.13. 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.

5.14. Materials Science and Engineering Center (MSE)

The MSE is focused on structure, properties, and performance of materials and has the capabilities in developing processes to produce materials.

Mechanical Test and Evaluation Facility (MTEF)
The MTEF is focused on micromechanics and materials mechanics experiments that study the mechanical behavior of materials. The laboratory also has experience in developing diagnostics tools.

5.15. Microsystems and Engineering Sciences Applications (MESA) Complex

MESA is a series of facilities that designs and fabricates radiation hardened microelectronics and microsystems for use in harsh environments. Additionally, capability in this area extends to advanced sensors, micromechanical fabrication, and advance electronics.

5.16. National Solar Thermal Test Facility (NSTTF)

Operated by Sandia National Laboratories for the U.S. Department of Energy (DOE), the National Solar Thermal Test Facility (NSTTF) is the only test facility of this type in the United States. The NSTTF's primary goal is to provide experimental engineering data for the design, construction, and operation of unique components and systems in proposed solar thermal electrical plants planned for large-scale power generation. In addition, the site was built and instrumented to provide test facilities for a variety of solar and non-solar applications. The facility can provide:

- The NSTTF is a venue which offers multiple molten salt loops for thermal hydraulic testing at >1 MWth.
- high heat flux and temperatures for materials testing or aerodynamic heating simulation;
- large fields of optics for astronomical observations or satellite calibrations;
- a solar furnace; and
- a rotating platform for parabolic trough evaluation.

5.17. North Slope Research Facility

Sandia National Laboratories has experience with the maintenance and operations of the Alaskan North Slope of Alaska DOE Office of Science Biological and Environmental Research (BER)

Atmospheric Radiation Measurement site. This site, in Utqiagvik (Barrow), Alaska, has been providing continuous, publicly available atmospheric environmental data since July 1997. More details on instrumentation are available through the DOE ARM website.

5.18. Nuclear Control System Emulation Lab

Sandia's Industrial Control System (ICS) Emulation capabilities include a distinct capability for Nuclear Control System Emulation. We continually develop and demonstrate capabilities that allow security experiments in support of defensive design and licensing security evidence. The nuclear-specific environment is called the Advanced Reactor Cyber Security Analysis and Design Environment (ARCADE).

Related Features:

- **Minimega:** A high fidelity virtual networking suite, capable of passing real ethernet traffic with JSON configurations.
- **Sceptre:** A Minimega-based networking suite with an Elasticsearch, Logstash, Kibana (ELK) stack diagnostic suite.
- **Phenix:** The glue that holds Sceptre to Minimega.
- **Kali Linux :** A very powerful cyber security operating system. Capable of launching most attacks for cyber defense purposes.

5.19. Nuclear Energy Safety Technologies (NEST)

NEST is focused on the development of nuclear energy and fuel cycle technologies, including repository sciences, safety and security, transportation, modelling, and systems demonstrations.

5.20. Nuclear Facilities Resource Center (NUFAC)

NUFAC is a combination of controlled and well-instrumented facilities together focused on designing, operating, and experimenting with nuclear reactors. This includes in core testing of reactor fuel and criticality experiments, radiation processing of semiconductors, performing activation analyses, characterizing radioactive materials, and producing radioisotopes. Facilities included in NUFAC are the Annular Core Research Reactor, Gamma Irradiation Facilities, and the Sandia Pulse Reactor Facility/Critical Experiments (SPR); its capabilities include dosimetry, diagnostic, data acquisition, modelling, and analysis.

- **Annular Core Research Reactor (ACRR):** The ACRR is an advanced swimming pool type reactor with steady-state, pulse, and transient shaping modes. It has two dry experiment cavities (9" and 20") that extend through the reactor core. Additionally, it has neutron radiograph capability.
- **Gamma Irradiation Facility (GIF):** GIF provides a single structure for performing a wide diversity of gamma irradiation experiments with various test configurations and at different dose and dose rate levels. It is divided into two types of irradiation facilities, in-cell dry and in-pool wet, based on the type of test to be performed.
- **Critical Experiments Laboratory (CEL):** The CEL is housed in the retired Sandia Pulse Reactor facility which is a critical experiment facility capable of performing criticality experiments for multiple purposes.

- **Auxiliary Hot Cell Facility (AHCF):** Materials are characterized and sorted in the AHCF to determine which materials are suitable for reapplication to DOE and other federal agencies and which materials—if any—have no practical or economic value and may be disposed of as waste at DOE designated facilities.
- **Ion Beam Laboratory (IBL):** Sandia has multiple facilities that contain ion beam capabilities and high-energy accelerators located throughout the laboratories. The ion beam facility is a centrally located facility that has the highest concentration of ion beams used in a broad arrange of configurations for multiple families of experiments.

5.21. Outdoor Test Facility (OTF)

The 200-acre Outdoor Test Facility (OTF) includes buildings, towers, paved and gravel areas, dirt paths, and a fenced perimeter, making it an ideal physical security test site and field training venue:

- Robotic vehicle systems
- Unattended ground sensors
- Radar detection
- Unmanned aerial systems (UAS or drones)

5.22. Packaging and Container Capabilities

Sandia has a full spectrum set of capabilities centered around nuclear waste storage and transportation containers. These include a fully NQA-1 compliant data collection system MIDAS, analysis across multiple physical domains (solid mechanics, thermal analysis, CFD) and expertise in experiments at Sandia facilities, including experiments on high burnup fuel, fire ignition testing, and full-scale impact (at Sandia's Sled Tracks, Aerial Cable Facilities, and Drop Towers) and thermal testing (at Sandia's Thermal Test Complex, the Lurance Canyon Burnsite) of packages under Normal Conditions of Transport (NCT) and Hypothetical Accident Conditions (HAC) scenarios.

5.23. Sensor Test and Evaluation Center (STEC)

The Sensor Test & Evaluation Center (STEC) is a 72-acre facility dedicated to the design, development, and real-world testing of current, new, and emerging sensor technologies.

- Electro-field
- Microwave
- Ported coax
- Fence disturbance
- Taut wire
- Object detection
- Radar

5.24. Shock Thermodynamic Applied Research Facility (STAR)

STAR is a unique facility that performs shock-physics type testing. It is the only facility in the world that can perform up to multi-Mbar pressures for material property study utilizing gas/propellant launchers, ramp-loading pulsers, and ballistic applications.

5.25. Surtsey Test Facility

Surtsey is a scaled containment structure (1/10th linear scale model of the Zion cavity). It is a 100 m^3 American Society of Mechanical Engineers (ASME) steel pressure vessel with 1 MPa (150psi) working pressure at 260°C (500°F), removable upper/lower heads, instrumentation ports at six levels, and flexible data acquisition and control. It is used for Studying Containment Atmosphere Processes. The location further offers large open areas for outdoor testing and smaller buildings for staging and indoor testing.

5.26. Thermal Test Complex (TTC)

The TTC provides a controlled environment to evaluate the performance of components and assemblies under controlled temperatures (up to 2,200°C) or programmed heat fluxes (up to 200 W/cm^2) 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.

5.27. Superfuge/Vibrafuge

To more closely simulate real flight environments, an innovative approach was developed at Sandia's Centrifuge complex to add controlled vibration to test units under inertial loading. This "Vibrafuge" capability has been proven to deliver combined environment testing over 100 g with up to 30 G_{rms} controlled vibration up to 4,000 Hz for payloads up to 500 lbs. This new test capability has consistently demonstrated important synergistic effects from the more realistic combined environments and provides the ability to determine margin assessment of system performance. Further advancement of flight simulation has been made through the development of a "Superfuge" system, capable of combining controlled acceleration, vibration and secondary axis spin for payloads up to 500 lbs.

During experiments in the super/vibrafuge additional thermal loading can be applied to assess the impacts of thermal loads on the test article. This further enables the assessment of impacts from harsh environment such as a spacecraft launch where rotational, vibrational, g-loads, and thermal loads can impact the vehicle simultaneously.

5.28. Rocket Sled Track

The Rocket Sled Track provides a controlled environment for high-velocity impact, aerodynamic, acceleration, and other related testing for both small and large test items. Tests can be designed to simulate unique scenarios and to provide the maximum data from each test. The facility provides a 10,000-foot track for testing items at very high speeds, and a 2,000-foot railroad gauge track for testing very large, heavy items at moderate speeds. The combination of ingenuity, experience, and instrumentation available at this facility makes it unique for research, test, and evaluation purposes.

The 10,000-ft Rocket Sled Track is also certified to handle the following:

- Weights up to 100,000 lbs. (~100 feet per second)
- Velocities up to 6,000 ft/s (up to ~500 lbs.)
- 500 lbs. net explosive weight (NEW) detonation maximum
- Test unit unique contents
- Extensive diagnostics, including instrumentation (recorded on-board and off-board), photometrics, and flash X-ray
- Brake sleds and split sleds (can release test units and eject test articles)

- Detonation of up to 250 pounds of high explosives (HE)

5.29. Water Impact Facility

The Water Impact Facility at Sandia provides a controlled environment for high-velocity water impact testing, gravity-assisted drop testing and underwater testing.

A 300-foot drop tower stands next to a 120-foot-wide by 188-foot-long by 50-foot-deep lake. A total depth of 80 feet for underwater testing can be obtained via a 6-foot-diameter, 30-foot-long steel pipe at the bottom of the lake.

Objects weighing up to 3,000 pounds can be subjected to free-fall drops or rocket-assisted pulldowns from angles of 30º to 90 degrees.

5.30. Aerial Cable Facility

Sandia National Laboratories' Aerial Cable Facility in Albuquerque, New Mexico, provides a unique capability to precisely simulate a wide variety of environments in a highly instrumented test arena. Primary among these environments are drop and high-velocity impact testing, suspension of large items hundreds of feet above the ground, and simulated free flight along an aerial cable. The facility has four primary cable systems that span two ridges over a mountain canyon. Each cable is approximately 5,000 feet long and has endpoint anchors about 1,000 feet above the valley floor. At the center of each cable span is a flat test arena about 300 feet in diameter. The ACF includes secluded, secure, open spaces in which to conduct a variety of tests.

5.31. Blast Tube Facility

The SNL Blast Tube Facility consists of trained, experienced personnel with the ability to design and execute tests using different blast tube configurations with varying lengths and diameters to meet a wide array of customer requirements. The explosively-driven blast tube facility consists of hundreds of feet of tube sections, ranging from 3 feet to 12 feet, that can be arranged to tailor the blast wave for each specific customer.

The facility is secure and routinely used to perform tests with energetic and hazardous materials, including detonation of explosive charges up to 2,600 lbs. The moderate-hazard facility can support test unit hazards that include some or all of the following:

- Explosives (including test unit main charges)
- Radioactive materials
- Beryllium
- Fires
- Rocket motors

SNL's shock physics codes allow analysts to design the test based on peak pressure, duration, and shape. Based on the simulations, the explosively-driven blast tube is then configured, to meet customer requirements. These modeling techniques reduce the amount of calibration shots needed to acquire the correct pressure pulse.

5.32. Drop Tower

The 185-foot Drop Tower Facility at Sandia National Laboratories in Albuquerque, New Mexico provides a controlled environment for testing a wide variety of small and large test items. This facility can test items which

- Contain radioactive materials
- Contain high explosives

Routine tests include shipping container certification, simulated transportation accidents, and moderate velocity impact. Tests units can be temperature-conditioned from temperatures of -65°C to 100°C. Test impact targets include dirt, reinforced concrete (5 1/2 x 12 x 5 1/2 feet thick), steel plate (5 1/2 x 12 x 4 inches thick), or other customer-specified targets. Crush tests are also routinely conducted by dropping a steel mass onto a test item positioned on the target. In a similar manner, puncture tests are conducted by dropping a test item onto a spike in the target.

The drop tower provide high-speed (5MHz s/s) digital data acquisition on up to 64 channels of hardwired instrumentation. A higher number of instrumentation data channels can be arranged. Transducers to measure acceleration, pressure, temperature, and strain are most often used.

5.33. Mechanical Shock Facility

At Sandia National Laboratories' Mechanical Shock Complex, we specialize in providing tailored impact environments, such as shock and crush. The facility has simulated many dynamic environments, including weapon delivery, severe accident, and pyroshock. The primary tools are a pneumatic actuator-and-sled system and a 6-inch bore gas gun. The Mechanical Shock Facility can test articles up to 10,000 lbs. Depending on the size and weight of the test article, velocity changes up to 1,140 ft/s, and attain acceleration levels on the order of 50,000 g can be applied. The Mechanical Shock Facility is an indoor facility that is temperature-controlled and shielded from weather. Instrumentation can measure unit function, test article kinematics, and material deformation. Our measurement tools range from accelerometers and strain gages to advanced photometrics and high-speed radiography.

5.34. Mobile Gun Test Complex (MGTC)

The Mobile Gun Test Complex (MGTC) is a set of mobile projectile launch systems (Guns) used to test a variety of projectiles and/or targets for civilian and military customers. The MGTC enables investigation of terminal ballistic events into in-situ geologies or engineered targets. There are two types of Mobile Guns:

- Davis Guns - Recoilless, propellant-driven guns.
  - Ø16 in x 40 ft smooth-bore barrel
  - Ø12 in x 35 ft smooth-bore barrel
  - Ø8 in x 36 ft smooth-bore barrel
- Gas Guns - These use compressed air, nitrogen, or helium for propulsion.
  - Ø16 in x 30 ft smooth-bore barrel (this is a conversion kit used on the 16" Davis Gun)
  - Ø6 in x 18 ft smooth-bore barrel

DISTRIBUTION

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