Trends in Fast Reactor Development Strategy in US and Sodium Technology Development Progress

Tsuruga Summer Institute

Dr. John E. Kelly
Senior Manager
Sandia National Laboratories
Albuquerque, NM USA

Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company,
for the United States Department of Energy's National Nuclear Security Administration
under contract DE-AC04-94AL85000.

Outline

- **Fast Reactor Research Trends in the US**
- **Sodium Safety Technology Development**

Nuclear Waste Management in the United States

- United States is considering alternatives to the Yucca Mountain site
- This includes considering alternate repository sites as well as alternate fuel cycle systems
- No near-term deployment of recycling is being considered
- Fuel cycle research is directed at developing recycling technology for long-term deployment
  - Science-based approach
  - New concepts for fast reactors

Advanced Fuel Cycle Initiative Objectives

- Develop options for used nuclear fuel management that reduce the long-term environmental burden
  - Significantly reduce radiotoxicity
  - Reduce the time-scale for managing the waste from many hundred thousand years time-frame (geologic) to centuries (engineering)

- Reduce overall nuclear fuel cycle proliferation risk via improved technologies for used fuel management
  - Improve inherent barriers and safeguards

- Enhance energy security by extracting energy recoverable in used fuel, avoiding uranium resource limitations
  - Extend nuclear fuel supply

- Continue competitive fuel cycle economics and excellent safety performance of the entire nuclear fuel cycle system

Advanced Fuel Cycle Initiative Major Research Elements

- **<u>Separations</u> technologies to improve proliferation resistance with very low "near-zero" process losses and minimal undesirable waste streams**
- **<u>Nuclear fuels or targets</u> to achieve multi-fold increases in performance over previous generation fuels**
- **Advanced <u>fast neutron spectrum systems</u> to transmute actinides**
- **<u>Fissile material control and accountability instruments</u> to allow an order of magnitude improvement in the ability to detect fissile materials in fuel cycle systems**
- **Advanced <u>waste storage forms</u> that have predictable, long-term behavior and enhanced resistance to degradation for a variety of geologic repository environments**
- **<u>Alternate repository concept</u> studies to improve characterization of geologic environments**
- **Advanced <u>modeling and simulation</u> to support science-based research**

Sandia National Laboratories

Fast Reactor R&D Issues and Challenges

- **Today's Technology Challenges in U.S.**
  - Fast reactors have not been commercially deployed
    - Perception of higher system cost of electricity
  - Current licensing regime is based on light water reactor technology
- **Grand Challenge for new Fast Reactors**
  - Cost of fast spectrum systems less than current ALWR
  - Risk to public health and safety prevented by inherent safety

Sandia National Laboratories

Fast Reactor Research Objectives

- For the closed fuel cycle, must develop and demonstrate the advanced recycle reactor
  - Fast spectrum reactor needed for transmutation system
  - Sodium coolant technology would be chosen for near-term applications
- For future fast reactor technology deployment, a key research focus is capital cost reduction
  - Improved design approach (e.g., compact configuration)
  - Advanced technologies (e.g., materials, energy conversion)
  - Advanced simulation for optimized design
- A second research focus is assurance of safety by promoting design simplification
- A third research focus is high system reliability

Fast Reactor Research Program

Research is organized into several technical areas

- Fast Spectrum Systems
  - Research on innovative cost reduction and performance enhancing technologies
  - Analyze performance of transformational fast spectrum concepts
- Advanced Materials
  - Research on advanced alloys
- Nuclear Data
  - Nuclear data measurements to reduce important uncertainties
- Energy Conversion
  - Research on Supercritical CO2 Brayton Cycle
- Safety Research
  - Develop enhanced safety technologies for accident prevention and mitigation
  - Develop fast reactor licensing criteria and science-based approach for demonstration of regulatory compliance
- Reliability and Monitoring Technology
  - Under-sodium viewing

Summary of Fast Reactor R&D Strategy

- The primary unifying theme is to develop advanced, innovative technologies for cost reduction and improved safety
- Infrastructure re-establishment also remains a priority
- Given longer time frames, expand the list of options
  - Generation-IV includes limited R&D on lead-cooled fast reactor (LFR) and gas-cooled fast reactor (GFR) in addition to the SFR
  - Fusion hybrid, ADS, salt-cooled, liquid fueled, thorium fueled fast reactor options also have been proposed

Sandia National Laboratories

Sodium Safety Technology Development Team

Steven P. Nowlen
Risk and Reliability Analysis
Principal Investigator

Tara J. Olivier
Risk and Reliability Analysis
Technical Lead

Thomas Blanchat
Fire and Aerosol Science
Test Director

John Hewson
Fire and Aerosol Science
Modeling Lead

Sandia National Laboratories

Background and Motivation

- Nuclear energy is undergoing revitalization in the U.S.
  - Commercial interest in new capacity
- Advanced Fuel Cycle Initiative
  - proliferation resistant fuel cycle
  - transmutation technology
- Fast reactors are one option:
  - Advantages: efficiency, ability to burn Pu and actinides.
- Use of sodium coolant is common for fast reactors

Sandia National Laboratories

Potential Safety Issues

Use of Sodium has unique safety implications not faced by the current LWR fleet

- Accidents involving sodium leaks can result in fires
- Highly reactive and energetic materials
  - Adverse interactions with water and concrete
  - Self-ignites in air at typical reactor operating temperatures
- Critical electrical/mechanical components vulnerable to thermal damage
  - An issue even for today's plants
- Radioactive material can be dispersed through vaporization, boiling of other components, or through particle entrainment

Sandia National Laboratories

Hazards associated with sodium leaks

- **Molten sodium reacts rapidly with air (O_2, H_2O, CO_2) and concrete.**
- **Consequences:**
  - **Heat transfer**
    - **Structural damage, plume dispersion**
  - **Aerosols**
    - **Corrosion, electrical damage**
  - **Public relations**
    - **Economic damage**

Overview of Sandia Research Program

Research involves three coordinated areas of study:

- **Reactor safety assessments**
  - **General literature review**
  - **Review proposed reactor designs**
  - **Identify credible risk scenarios involving sodium**
- **Discovery experiments**
  - **Identify key but poorly understood phenomena**
  - **Design and execute experiments to explore important phenomena and to support model development and validation**
- **Development of simulation tools**
  - **Build on existing SNL analysis tools and incorporate sodium fire analysis and modeling capability**
  - **Verify/validate analysis tools through discovery experiments**

Current Program Status

- Program began in 2007
- Background reviews completed in 2008
- Phenomena Identification and Ranking Table (PIRT) completed in 2008
- Test plan for discovery experiments complete in 2008
- Discovery experiments currently underway (2009-2010)
- Development and assessment of fire modeling tools in progress (2008-2010)

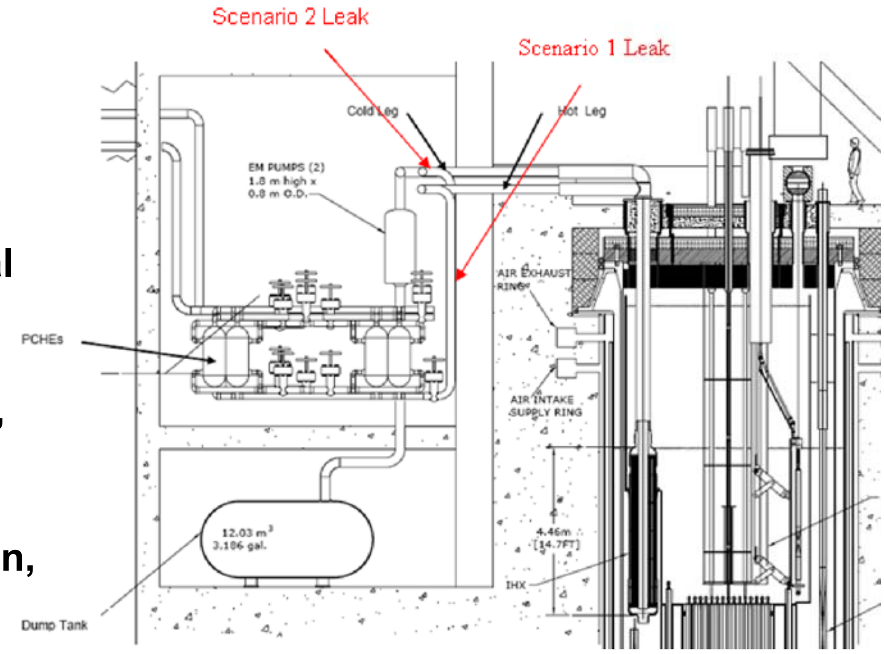
Insights from Literature Survey

Previous Sodium Fire Accidents

- MONJU, Japan 1995
  - Instrument port failure
  - Sodium leak and fire – ~0.05 kg/s (640 kg total)
  - Facility shut down since then
- Alermia Solar Power Plant, Spain 1986
  - Valve maintenance failure – 14 kg/s leak (14 tons total)
  - Spray and pool fire (12 m^2 hole burned in roof)
- ILONA Sodium Test Loop, Germany 1992
  - Pressure relief valve failure – 0.2 kg/s leak (4 tons total)
  - Sodium pool fire burns for 14 hours
- Russian study – categorizes 46 sodium leaks at two reactor facilities (1980's and 1990's)
  - Dominated by equipment problems/failures
  - Procedural errors also significant cause

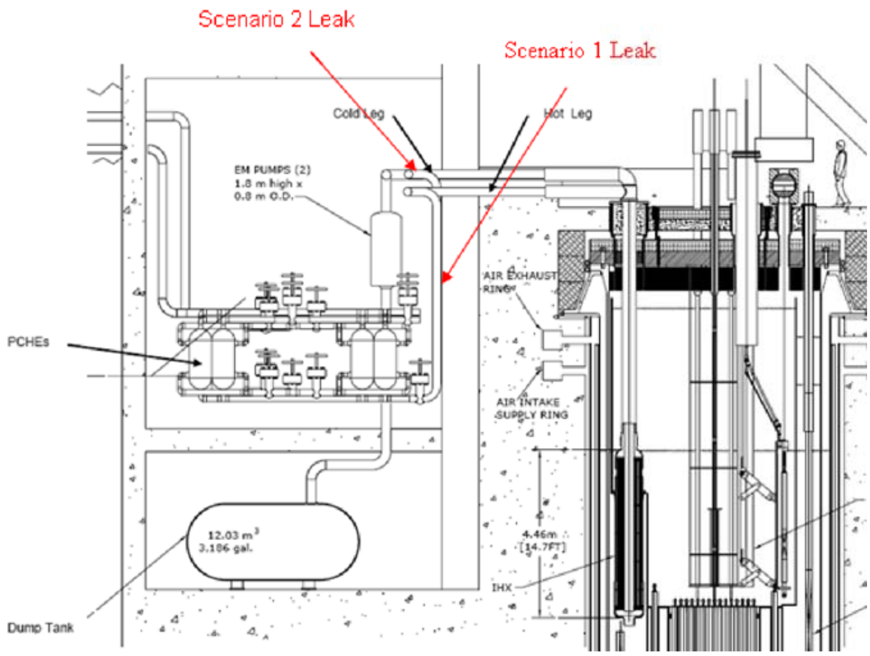
Pool Fire Research Needs

- **Pool fire:**
  - **Pool spreading.**
  - **Burning rate, thermal balance.**
  - **Aerosolized fraction, size distribution.**
  - **Oxide crust formation, oxidizer transport.**
  - **Surface reactions**
    - **concrete-sodium.**



Spray Fire Research Needs

- **Spray fire:**
  - **Liquid jet breakup**
  - **Sodium droplet size distribution.**
  - **Droplet burning rate.**
  - **Heat transfer.**
  - **Aerosolized fraction, size distribution.**



Prior Sodium Fire Research

- Heat release rates and flux from sodium fires are crucial to determine system response and consequence for hazard analyses

- Previous experiments cannot be used to advance analytical capabilities:
  - Experimental initial and boundary conditions are poorly defined
  - Historic experiments focused only on individual droplet and quiescent pool fire behavior
  - Focus was integral behavior and containment response due to sodium release
  - Lack of data on local heat flux and potential damage to safety equipment

Sandia National Laboratories

Phenomena Important to Study

- Oxide behavior as aerosol, crust, or in solution
  - The amount of oxides that is removed from the crust
  - Consequences of the aerosolized oxides on electrical equipment
- Oxygen transport through oxide crusts
  - Important for predicting thermal damage to surfaces on which sodium pools form
- Radiative heat transfer
  - Consequence of thermal load on nearby equipment
- Thermal coupling of sodium pools to surfaces
  - Thermal insult to surfaces below sodium pools
  - Useful for characterizing pool oxidation rate

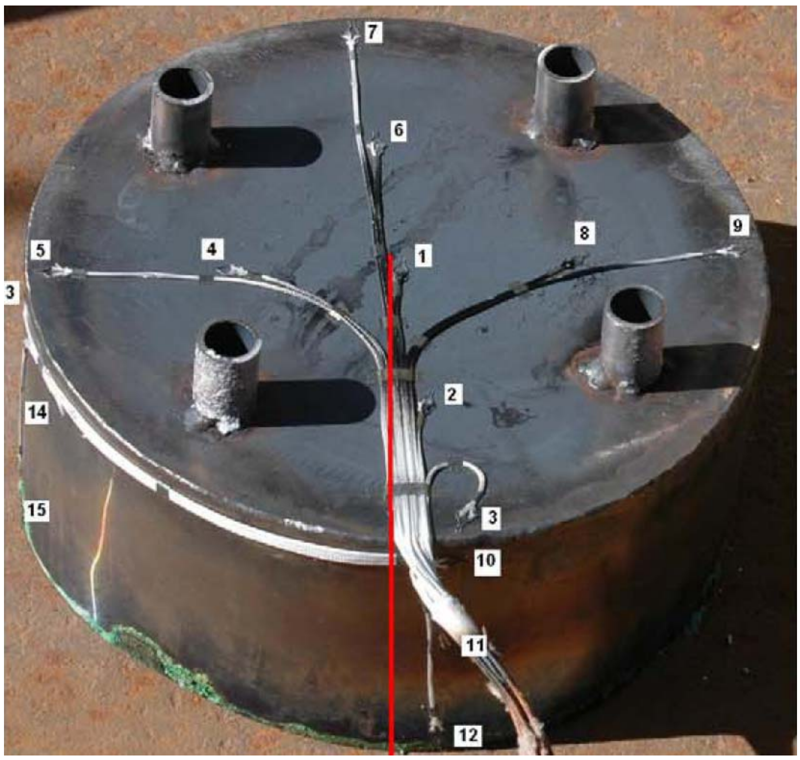
Sandia National Laboratories

Sandia Discovery Experiments

- Initial tests were completed and were conducted outdoors
  - Melt generator proof of operation
  - Spray into a pan
  - Pour into a pan, quenching phenomena

Sandia National Laboratories

Thermocouples on pan bottom



Sandia National Laboratories

Initial Pool Fire Scoping Experiments

- **Sodium Pool Fires: varied the ratio of the sodium liquid level to pan thickness**
  - **Ratio < 1 (pan thicker than Na):**
    - **Cooler and slower burn**
    - **Pool temperatures > 400C**
    - **Residue was a powdery oxide mixture**
  - **Ratio > 1 (Na thicker than pan):**
    - **Hotter and faster burn**
    - **Pool temperatures > 800C**
    - **Residue was a solid rock-like oxide mixture (pool temps were above melting point, different phase transformation)**

Sandia National Laboratories

Initial Scoping Experiments
Video: Pool Burn, Ratio <1 (thin Na layer)

Sandia National Laboratories

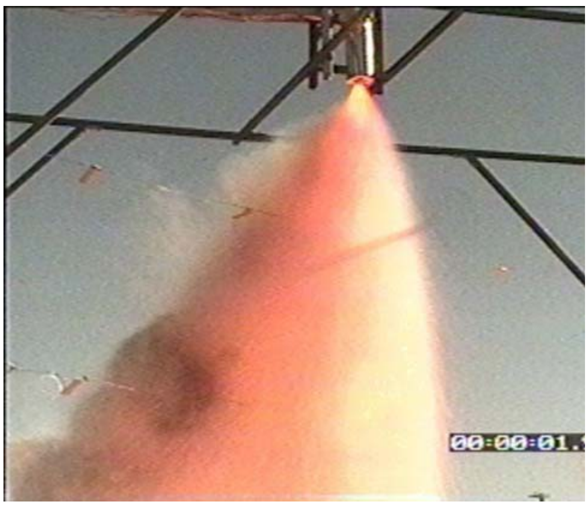
Future Research Questions

- As hot sodium pours from leak onto cold surfaces, does it quench?
  - Use of louvered floors to inhibit oxidation.
- Does it at least cool to be less hazardous?
  - Reduced heat release rates, aerosol release rates.
- What happens if we keep pool temperature below oxide melting temperature?
  - Oxygen transport through oxide crusts

Sandia National Laboratories

Initial Pool Fire Scoping Experiments

- Sodium Spray Fires
  - Two spray tests were performed where the droplet sizes were varied
  - The smaller droplet spray:
    - Burned hotter and faster
    - Mostly burned as spray (no pool)
    - Heat fluxes >250 kW/m^2
    - Temperatures ~1300 C
  - The larger droplet spray:
    - Pooled at the bottom of the pan
    - Temperatures >800 C
    - Heat fluxes > 40 kW/m^2

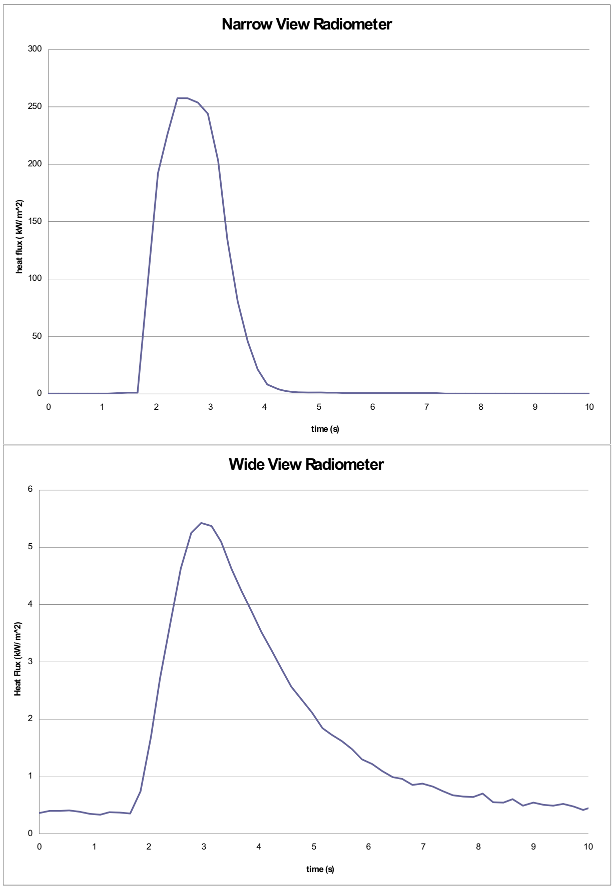


Sandia National Laboratories

Initial Scoping Experiments
Video: Small Droplet Spray

Initial Scoping Experiments
Video: Small Droplet Spray High Speed

Spray flame heat flux



High pressure spray

- 25 kg Na at 2.1 MPa
- 4.6 m spray height
- Narrow angle heat flux 250 kW/m2

Current Experiments

- Second stage of testing will use Surtsey vessel
  - Sealed pressure vessel
    - Monitor pressure and temperature effects
    - Measure heat transfer, pressure, temperature, O_2 consumption
  - Allows for range of tests under more controlled conditions
    - Pool fire
    - Spray into pool or spray only
    - Sodium flow rate
    - Droplet size

Summary

Goal of this research:

- Use modern analysis methods (experimental and computational) on metal fire problems for advanced fast reactor applications
- Develop the expertise and capability needed to identify, investigate, and assess key metal fires issues

Future applications of this work:

- Guidance on hazard mitigation strategies for advanced fast reactor designs
- Simulation tools needed to assess the risk of future fast reactors and supporting facilities