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Metal Fires and Their Implications for Advanced Reactors

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Overview

- SNL Programmatic Motivation
- Making a Safety Case for Metal Fires
- Metal Fires Project
  - Identify application requirements
  - Discovery experiments
  - Develop computational tools
  - Application Guidance and Pilot Safety Studies
- Summary

Programmatic Motivation: Metal Fires in Next Generation Nuclear Facilities

- Nuclear energy is undergoing revitalization in the U.S.
  - Significant commercial interest in building new capacity
  - New reactor designs being proposed and evaluated
  - GNEP - DOE Advanced Fuel Cycle Initiative - Proliferation resistant and transmutation technology
- Fast reactors:
  - Use of liquid sodium for neutronics and cooling
  - New fuel fabrication and fuel reprocessing facilities
- There are serious safety implications for these facilities
  - Accidents involving sodium leaks and metal fuels (UZr) resulting in fires

Making a Safety Case for Metal Fires

- Significance of the fire hazard:
  - Highly reactive and energetic materials
  - Critical components vulnerable to thermal damage
  - Nuclear materials can be dispersed through vaporization, boiling of other components and through particle entrainment
- Hazard mitigation required during regular operation, transportation, maintenance

Metal Fires Project: Technical Approach

- Identify application requirements:
  - The thermal environment/characteristics of metal fires
  - Means of mitigation
  - Study of past experience (lessons learned)
- Discovery Experiments:
  - Explore key physics issues
  - Data for code development and predictions
- Develop computation tools:
  - Understand the physics
  - Models for metal fire burning behavior (spray, pool)
- Application Guidance and Pilot Safety Studies:
  - Develop guidance for design and mitigation
  - Select two nuclear facilities (one reactor, one fuel cycle) as test bed for pilot safety studies

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Identify Application Requirements

Previous Sodium Fire Accidents

- MONJU, Japan 1995
  - Instrument port failure
  - Sodium leak and fire – ~0.05 kg/s (640 kg total)
  - Facility shut down for 12 years and counting
- 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

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Identify Application Requirements: Previous Sodium 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

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Identify Application Requirements: PIRT Results

- Oxides aerosol, crust, or 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

Discovery Experiments
Sodium Test Plans

- Initial tests to be conducted outdoors
  - Melt generator proof of operation
  - Spray into a pan
  - Pour into a pan, quenching phenomena
- Later tests will use Surtsey vessel
  - Sealed pressure vessel
    - Monitor pressure and temperature effects
  - Allows for range of test conditions
    - pool fire, spray into pool, spray only

Discovery Experiments Sodium Test Plans (2)

- Experimental focus:
  - Measure heat release rates and heat flux from sodium spray fires
    - Crucial but poorly understood parameters that will determine system response and consequence for hazard analyses for some scenarios
  - Aerosol measurements in vessel
    - Aerosol impactors will utilized to collect aerosol characteristics
  - Explore quenching behavior for pool fires
    - Pool fires have been explored but quenching behavior remains poorly understood
  - Spray and pool fire behaviors
    - A spray that is not fully consumed so it forms a pool fire as well
    - One of the more likely fire scenarios given relatively low system pressures (i.e., large droplet sprays)

Computational Tools: Sodium Spray Fire Design Simulations

- "Rough-cut" simulations to estimate effect of sodium droplet size in Surtsey-scale vessel.
- General parameters:
  - 25 kg of Na injected over 25 s at 1 kg/s
  - solid cone nozzle with spray angle of 20 degrees (uniform distribution over 0-20 degrees)
  - particles mean diameters are 0.5 mm, 1 mm and 3 mm, lognormal distribution with variance of log = 0.15.
  - initial particle temperature was 500 C (773 K).
  - SURTSEY-like chamber is rectangular prism and has dimensions 3.33 m x 3.33 m x 9 m high. The chamber volume is roughly correct.
  - Particles are injected 8 m above bottom.
  - Sodium oxidation leads to Na2O2 (over predicts heat release and oxygen consumption in low-oxygen situations).
  - Sodium particles radiate but Na2O2 aerosol does not participate in radiative heat transfer yet.
  - Walls are isothermal at 300 K. That is, walls cool the chamber by conduction / convection / radiation, but the walls to not heat up.

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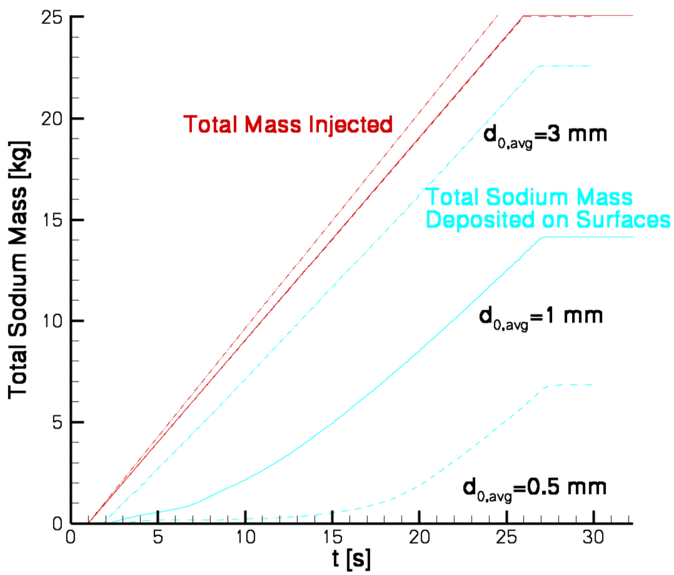
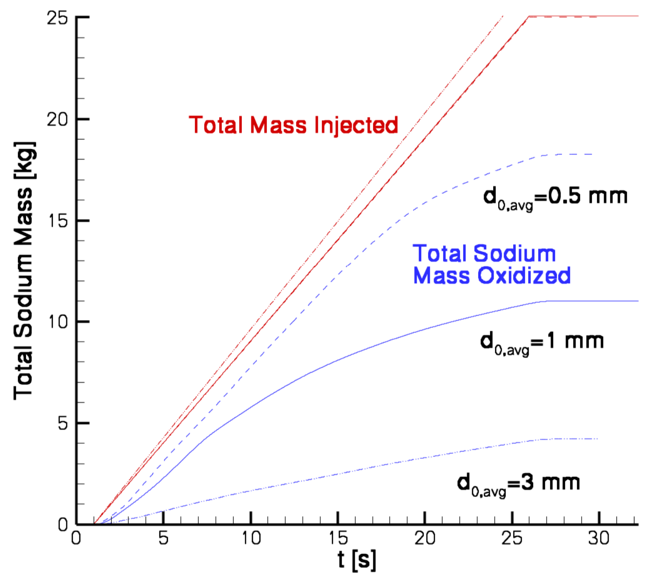
Computational Tools: Initial Sodium Spray Fire Results

- "Rough-cut" simulations to estimate effect of sodium droplet size in Surtsey-scale vessel.
  - For 3 mm (typical initial diameter) particles, the majority of the sodium sticks to the walls.
  - For 0.5 mm particles, the majority is oxidized and oxygen limitation is an issue.
  - For 1 mm particles, the split is close to 50-50.





Summary

Bringing modern analysis methods (experimental and computational) to bear on metal fire problem.

- Interface combustion models: liquid-gas (sodium-air/steam),
  - Develop and incorporate metal surface-reaction models
    - Significant in heating sodium for both pool and spray fires.
    - Models for oxide crust effect on surface oxidation are particularly challenging.
  - Extend single droplet models to include aerosol formation.
    - Couple aerosol with radiation heat transfer.
    - Study radiation/spray interactions as function of scale.
- Sodium flux data for code development and validation
- Future opportunities
  - Guidance on hazard mitigation strategies for new reactor designs.
  - Safety case assessments for future facilities.

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