SAND2013-8811P

Demonstration of Safety in Nuclear Materials Transport

Presentation to UNM Engineering Class

October 14, 2031

Ken B. Sorenson

Sandia National Laboratories
Albuquerque, New Mexico

Sandia National Laboratories

- Sandia is a multi-program laboratory of the U.S. Department of Energy and is one of the three National Nuclear Security Administration (NNSA) Laboratories with research and development responsibilities in nuclear weapons and associated programs in nonproliferation and arms control. Sandia also supports programs in energy, critical infrastructures, and emerging threats.

Sandia National Laboratories is a multi program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

Today's Presentation

International regulations ensure safe transport of nuclear materials

(Focus will be on Type B Spent Nuclear Fuel Packages)

- Safety Functions of Transport Packages
- Regulations
- Regulatory Tests
- Extra-Regulatory Tests and Analyses
- Complex Technical Issues
- Conclusions

- Current Issues in the U.S. nuclear fuel cycle

Safety Functions of SNF Transport Packages

- **Transport packages are designed to address four principal safety functions:**
  - **Containment – package must contain contents during normal and accident conditions**
  - **Shielding - package must provide shielding from gamma and neutron radiation**
  - **Criticality Control - package must prevent a nuclear chain reaction**
  - **Heat Dissipation - package must dissipate heat from spent fuel assemblies**

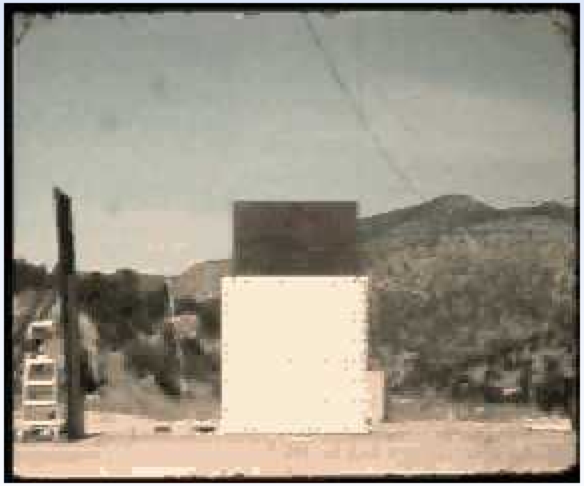
Regulatory Environment

- Transport in the public domain necessitates stringent requirements.
- The regulations are performance-based and define design requirements:
  - IAEA TS-R-1: Regulations for the Safe Transport of Radioactive Materials
    - Normal Conditions of Transport
    - Hypothetical Accident Conditions
      - Free drop
      - Puncture
      - Thermal
      - Immersion

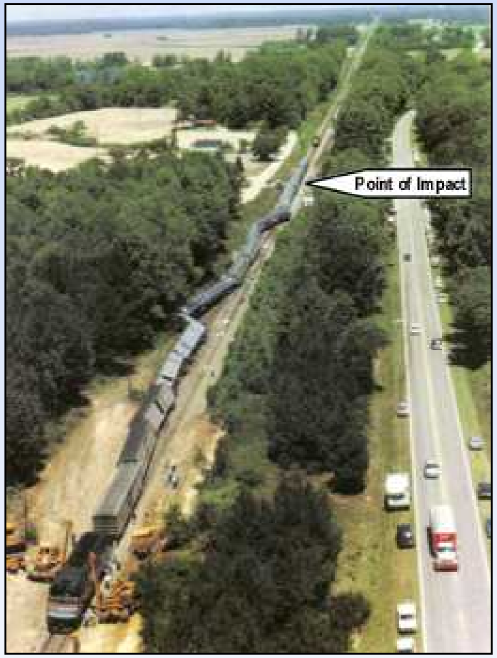
These test conditions envelope 99+% of all real accidents

Regulatory Testing Environments

- Drop Test
  - 9 meters = 48 kph (30 mph)
  - Unyielding target = 40 – 300 g's
  - Package oriented to cause maximum damage



1,300,000 kgs (2,860,000 lbs.) of force present in this full-scale drop test



Train-Tractor/Trailer Impact: South Carolina, May 2, 1995

Less than 450,000 kgs (990,000 lbs.) of force present in this real-life non-nuclear accident.

Regulatory Testing Environments

- **Puncture Test**
  - 1 meter = 16 kph (10 mph)
  - 15 cm (6″) ø steel pin welded to unyielding surface
  - Package oriented to cause maximum damage

Regulatory Testing Environments

- **Thermal Test**
  - 30 minutes
  - Fully engulfing
  - 800°C (1475°F) minimum

- **Howard Street Tunnel Fire**

  Baltimore, Maryland July 18, 2001
  - Peak Temperature ~1000C (1800F)
  - Intense fire duration ~3 hours
  - NRC analyses indicate that a Type B package would have survived the fire environment without release of contents

Sandia National Laboratories

Extra-Regulatory Testing

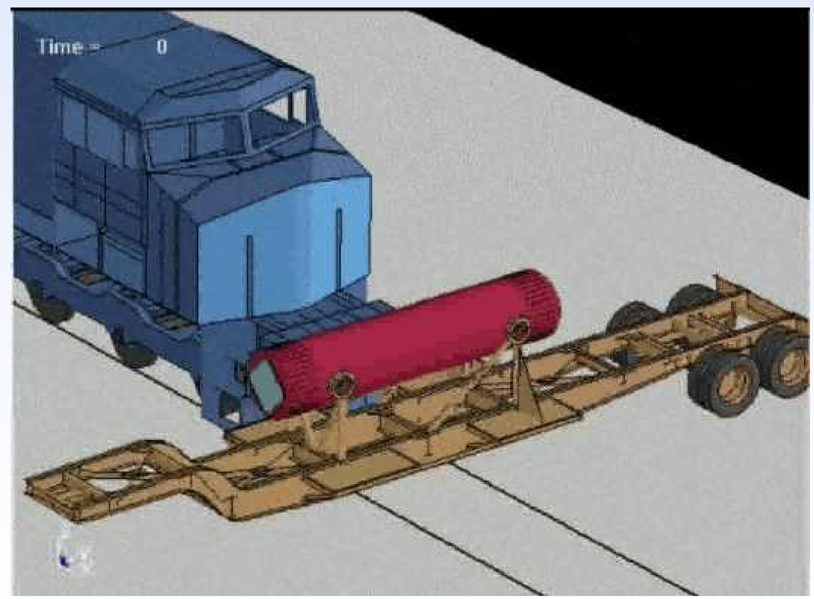
- **Full-Scale Rail Test at SNL**
  - **A 74-ton package on a railcar crashed into a 690-ton concrete block at 130 kph (81) mph**

Extra-Regulatory Testing

- Full-Scale Railroad Grade Crossing Test at SNL
  - A 25-ton packaging on a semi-trailer was struck by a 120-ton diesel locomotive traveling at 130 kph (81 mph)
  - ~30 g loading

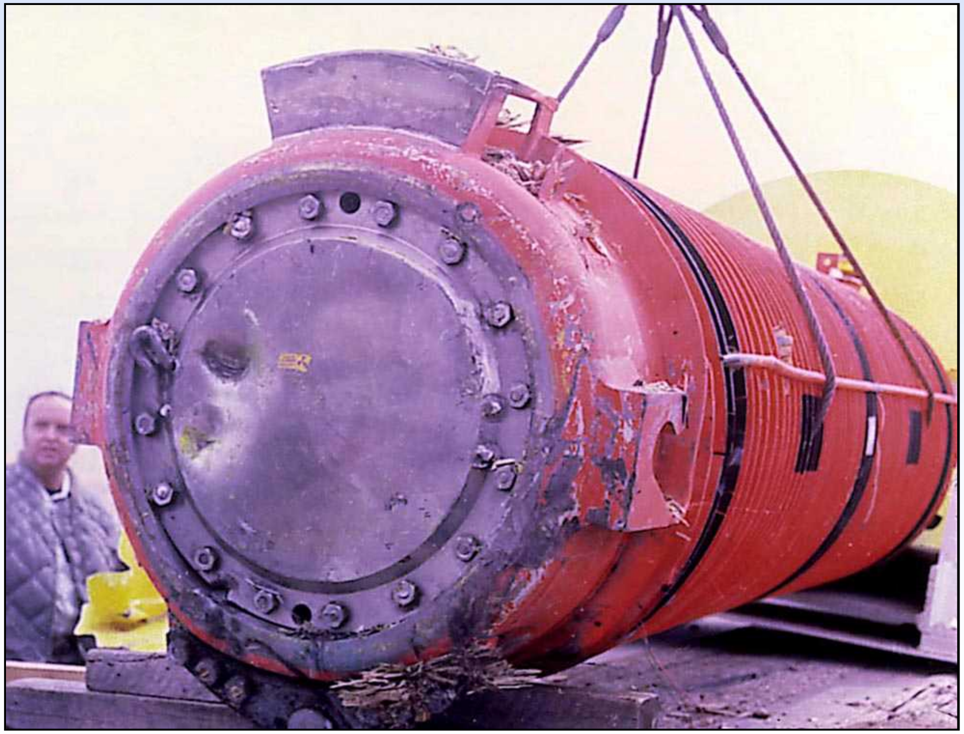
Extra-Regulatory Analysis

- **Locomotive impact into a truck package at a railroad grade crossing.**
  - **Analyses at 113 kph (70mph) and 130 kph (80mph)**
  - **Limited plastic strains in bolts and localized plastic strain in the containment boundary**
  - **No failure in seal region or packaging containment boundary**



Extra-Regulatory Testing

- **Full-Scale Truck Testing at SNL**
  - **A 22-ton package on a flatbed semi-trailer crashed into a 690-ton concrete block at 135 kph (84 mph)**
  - **~120 g loading**



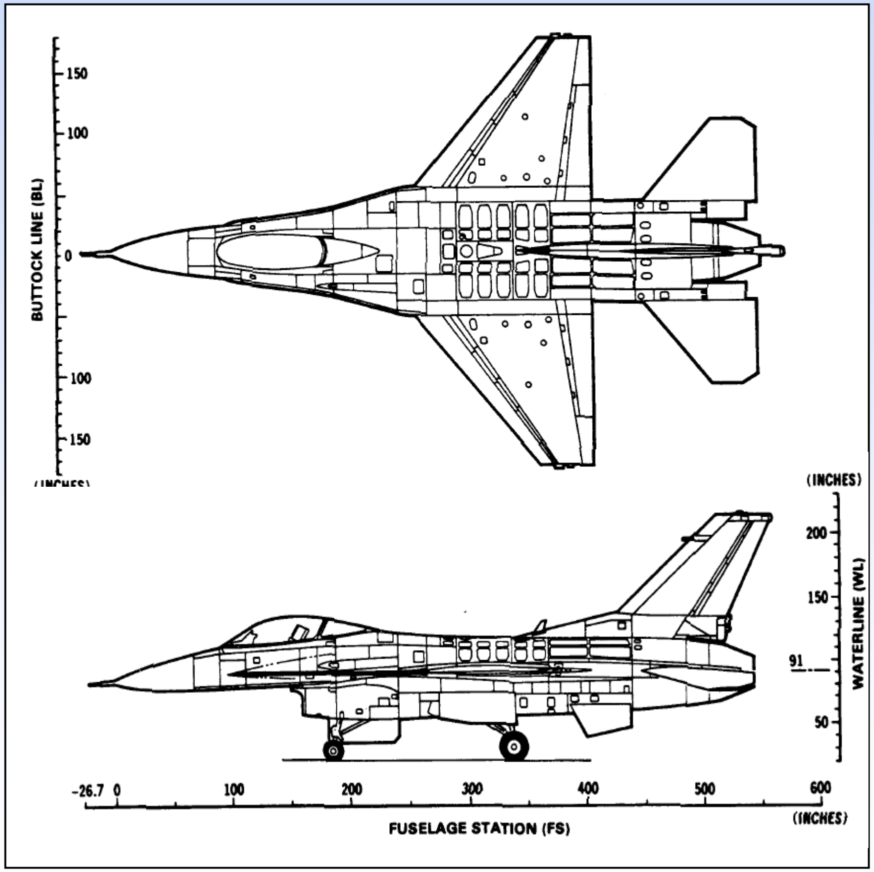
Sandia National Laboratories

Aircraft Crash Test and Analysis
F-4 Crash Test

Velocity – 780 kph (485 mph)
Weight – 18,750 kgs (41,250 lbs)

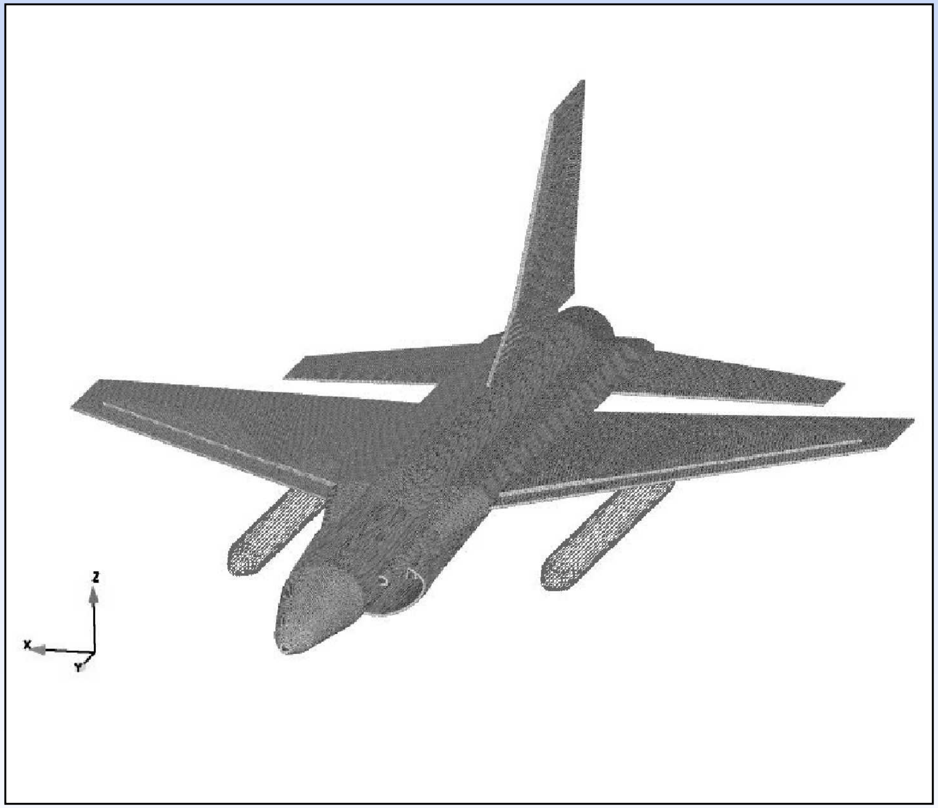
Sandia National Laboratories

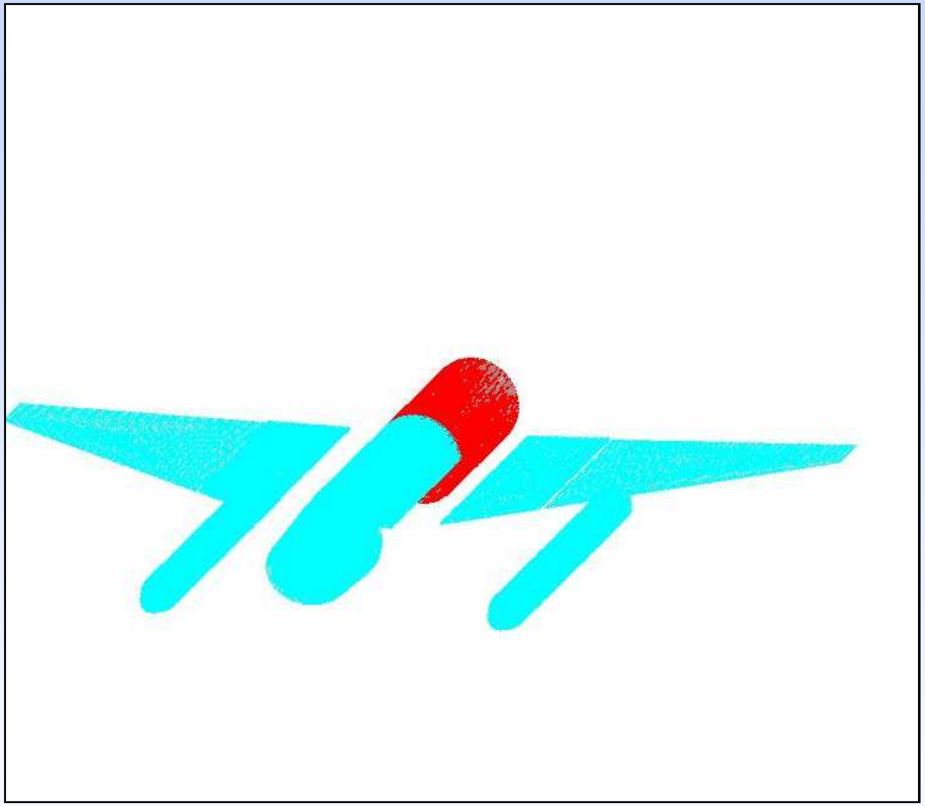
Aircraft Crash Test and Analysis
F-16 Aircraft Analysis



Estimated Weight 16,100 kgs (36,000lbs)

Aircraft Crash Test and Analysis



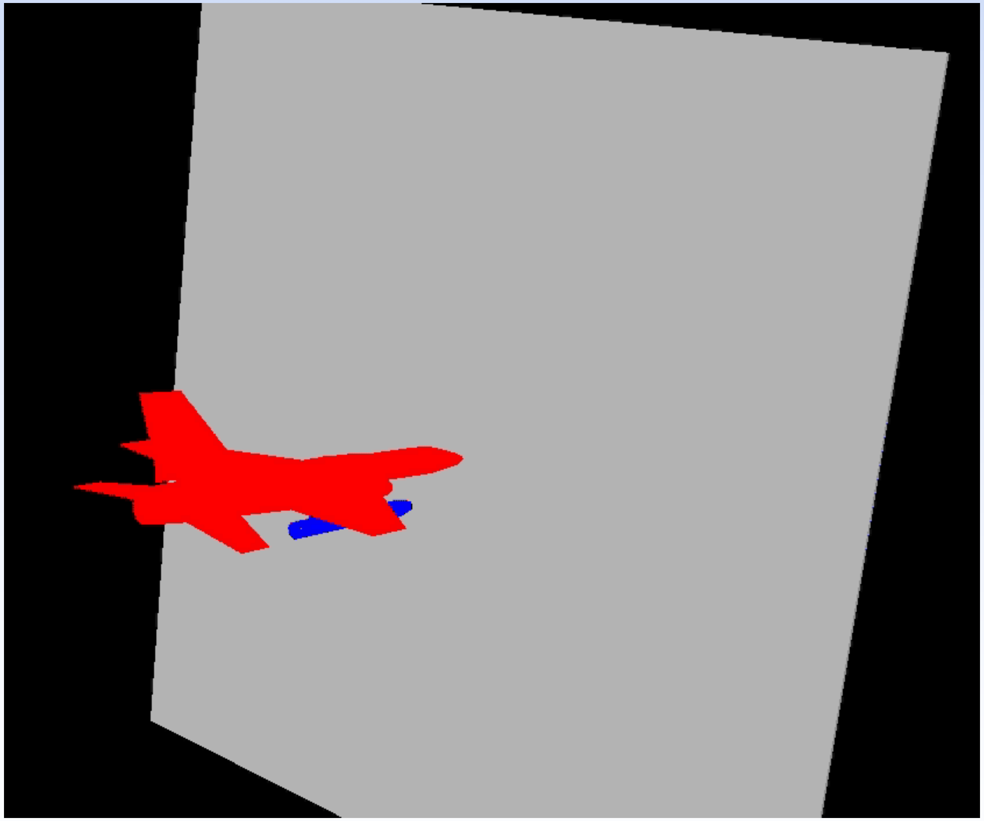


Smooth Particle Hydrodynamics (SPH) F-16 Model

(Mirrored for visualization purposes)
300,000 SPH elements in half-symmetry model

SPH F-16 Model Internals
Fuel Tanks and Engine

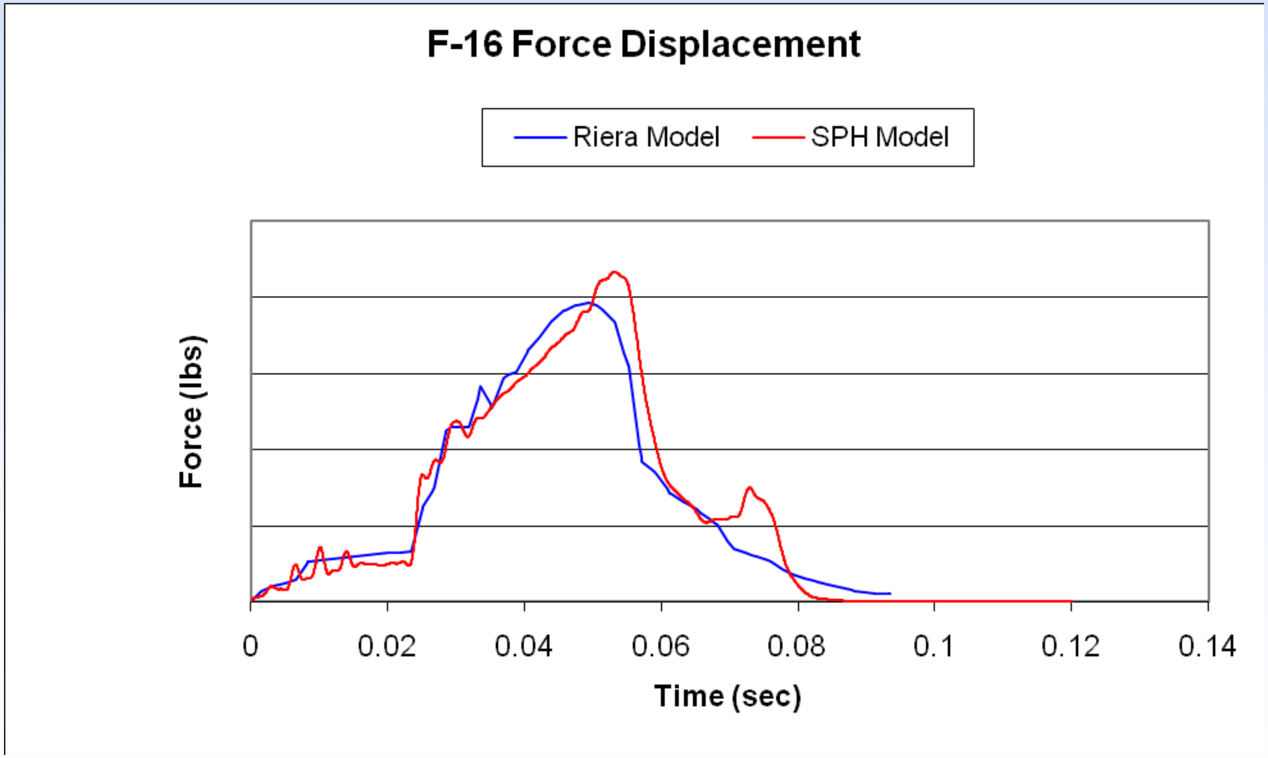
Aircraft Crash Test and Analysis
Model Verification



Aircraft Crash Test and Analysis

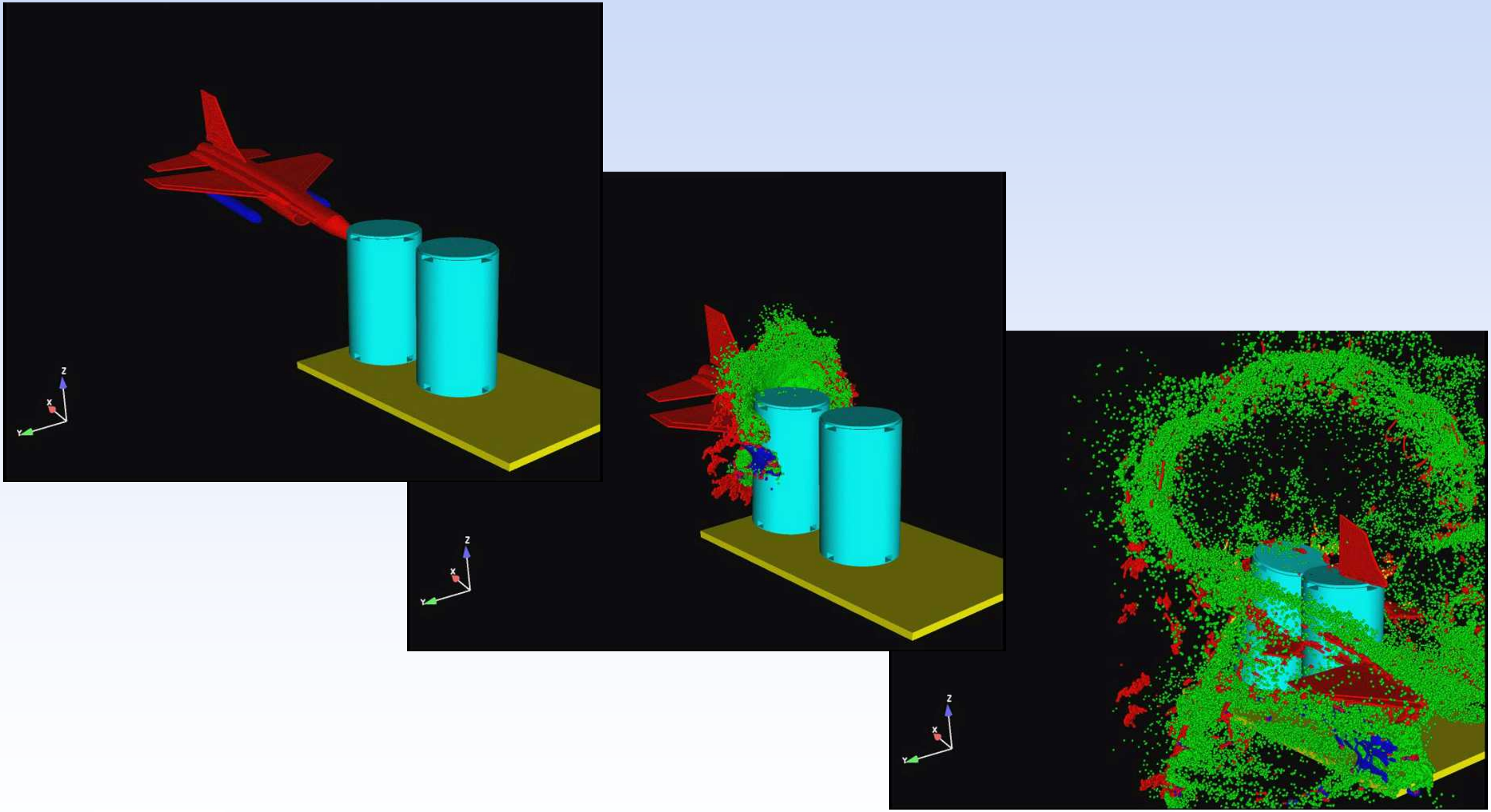
Model Verification
Force-Time-History Functions

Comparison of F-16 SPH Model and Riera Force-Time Functions



Aircraft Crash Test and Analysis

Model Analysis



Sandia National Laboratories

Benefits of Testing and Analysis

- The unyielding target produces very rigorous impact loading criteria relative to real-life accidents.
- The fully-engulfing fire produces very rigorous thermal loading criteria relative to real-life accidents.
- A significant amount of testing has been conducted that provides benchmark data for analytic verification.
- Benchmarked codes and analyses can then be used to evaluate many different scenarios without expensive testing.
- Testing provides insights into component response that may be missed in modeling and analysis.

Result: There will always be a need for some amount of testing, regardless of the sophistication of modeling and analyses

Complex Technical Issues

- **Full-scale testing is becoming important. Issues associated with these tests include:**
  - **Large unyielding target (target mass is 10x test article mass)**
  - **Lifting test article**
  - **Temperature conditioning of the test article**
  - **Demonstration of scaling laws**

- **Fuel performance in an accident environment is not well understood.**
  - **Little data on high burnup fuel cladding properties.**
  - **Little data or analyses on fuel response.**
  - **Canistered systems impact on package performance.**

- **Energy transfer from external accident force to loading on fuel is design dependent.**
  - **Compliance of package systems in reducing energy inputs to fuel.**

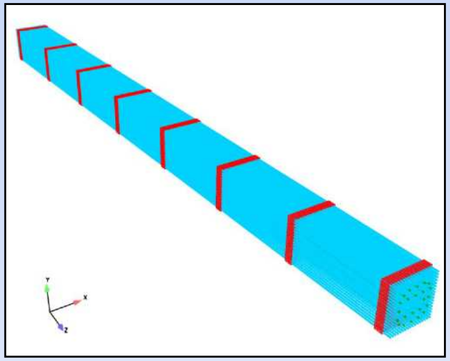
Complex Technical Issues

- **Full-scale Testing**
  - **Scale model testing may not provide complete full-scale response characteristics (e.g. seals and welds).**
  - **Public comments in U.S. consistently ask for full-scale tests.**

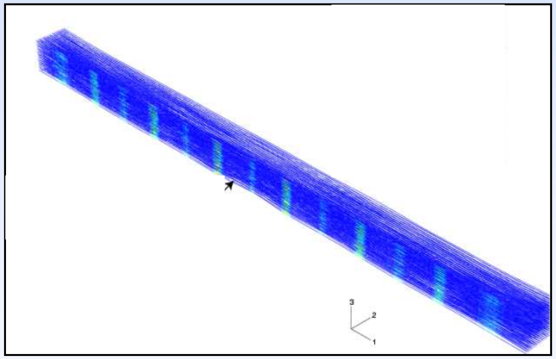
Sandia National Laboratories

Complex Technical Issues

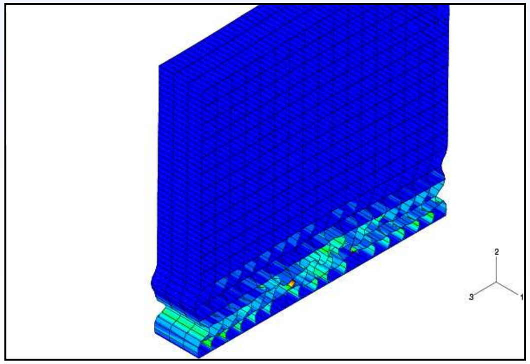
- **Fuel Performance**
  - Fuel performance is an important safety and operational issue.
  - Correct energy inputs, mechanical properties, and analyses provide quantifiable estimates of fuel behavior.



Finite element model of a PWR fuel assembly with spacer grids



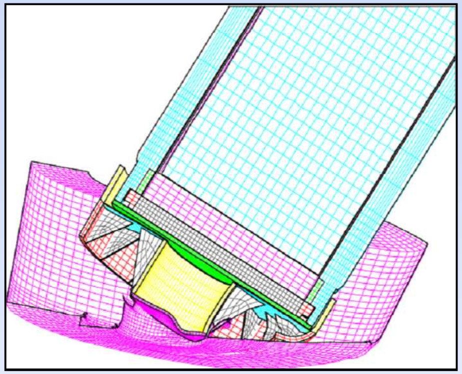
Side drop analysis of the PWR fuel rod



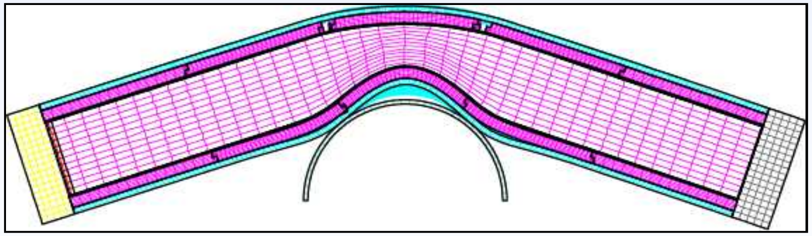
Side drop analysis of the spacer grid

Complex Technical Issues

- **Energy Transfer**
  - test data usually tracks rigid-body package decelerations
  - analyses usually homogenizes fuel cavity only to simulate mass
  - certification testing and analyses provide little information on fuel response
  - energy transfer is dependent on:
    - packaging design
    - impact orientation



Center-of-gravity over corner
9 meter drop test analysis



"Backbreaker" Analysis

Conclusions

- **Testing has demonstrated that current regulations bound historical accident severities.**
- **Benchmarked analyses are very useful in comprehensively assessing package response to a wide range of loading events.**
- **Resolution of identified technical issues will provide enhanced operational safety, increase understanding of how package systems respond to accident environments, and increase public confidence.**

Current Issues in the U.S. Nuclear Fuel Cycle

1. Storage and Transportation

Policy

The decision to cancel Yucca Mountain means that the nation will need to store used fuel for the foreseeable future (>120 yrs).

Issues

Licenses for long term dry storage of used fuel are issued for 20 years, with possible renewals up to 60 yrs. A new rule-making will allow the initial license for 40 years with one possible 40-year extension.

Questions regarding:

- **retrieval and transport of used fuel after long term storage**
- **storage and transportation of high burnup fuel (>45 GWD/MTU)**

Consequences

Technical bases need to be developed to justify licensing:

- **used fuel storage beyond 60 to 80 years**
- **retrievability and transportation of used fuel after long-term storage**
- **transportation of high burnup fuel**

Current Issues in the U.S. Nuclear Fuel Cycle

2. Blue Ribbon Commission (BRC) on the America's Nuclear Future

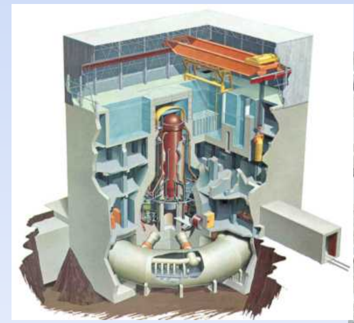
- Charter: conduct a comprehensive review of policies for managing the back end of the nuclear fuel cycle and recommend a new plan.
- Members: former high-ranking public officials, academia, and industry representatives who have significant background (not necessarily technical) in this area.
- Three sub-committees:
  - Reactor and Fuel Cycle Technology
  - Transportation and Storage
  - Disposal
- Schedule:
  - Draft report out for public comment, July 2011
  - Final report due January 2012

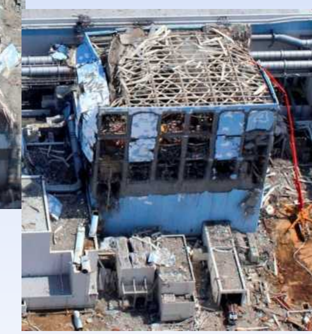
Sandia National Laboratories

Current Issues in the U.S. Nuclear Fuel Cycle

3. Recent events related to safety

- **Fukushima: March 2011**
  - **Unit 4 was down for maintenance and all fuel was off-loaded into the pool.**
  - **Status of the Unit 4 pool was questionable for several weeks.**
  - **Safety implications of pool storage is being considered in the U.S.**
  - **NRC assessment is that leaving the fuel in the pools adds minimal risk**





- **Virginia Earthquake: August 2011**
  - **Dominion North Anna Plant**
  - **5.8 magnitude earthquake**
  - **Safety implications of dry storage resulting from natural events**

Current Issues in the U.S. Nuclear Fuel Cycle

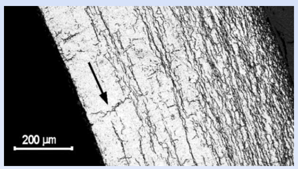
4. Making a Case for Transport of High Burnup Fuel

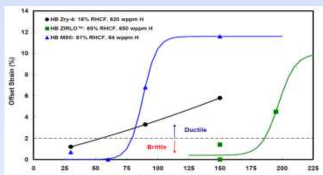
Experimental +
- Material properties
- Benchmark data

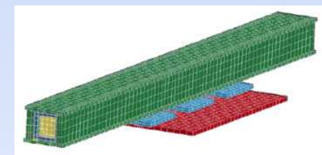
Transportation +
- Realistic configurations
- Realistic loads
- Regulatory alignment

Analysis ⟹ $\sigma < \sigma_{ys}$?

$K_I < K_{Ic}$?





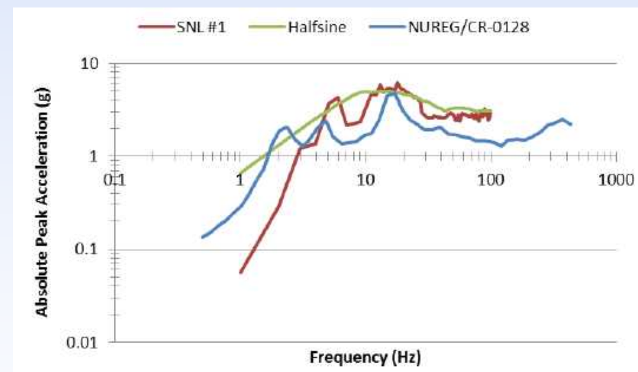


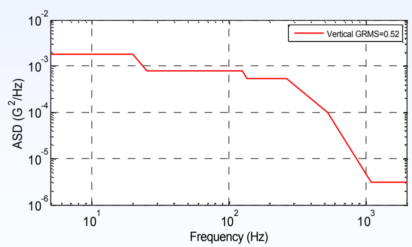
Clad morphology ⟷ **Clad properties**:

- Hydrogen
  - Concentration
  - Distribution
  - Orientation
- Oxidation
- Pellet/clad interaction

σ_{ys} = yield stress
σ_{ult} = ultimate stress
K_{Ic} = fracture toughness
E = elastic modulus
ϵ_{ult} = ultimate strain

Loads:
- Shock/vibrations loads representing normal conditions of transport
- g = accelerations





Response:
- g and ϵ on individual rods

Instron 8511 used for Ring Compression Tests