# Storage & Transportation of Spent High-Burnup Fuel

## *(Implication of ISG-11 Rev 2)*

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# ------ Topics ------

## *Transportation-related Issues to be Resolved*

- **How to treat transportation Accidents?**
  - **As a case by case or on a generic basis?**
- **How to characterize transportation Accidents**
  - **Regulatory definition**
  - **Realistic definition**
- **Effects of storage temperature history on cladding behavior during a transportation accident**
- **How to analyze accidents for fuel reconfiguration**
- **Behavior models and data needed to comply with ISG requirements and respond to RAIs**
- **Conclusions**

# How to Treat Transportation Accidents
## *(A Case for Generic Treatment)*

- **Impact Loading is Generic**
  - **Governed by target hardness and drop height**
  - **Cask-specific design features cause small variations in g-loading**
  - **Impact-limiters are similar in designs to satisfy the regulatory g-force**
- **Response is Generic**
  - **Impact energy is the same for all casks**
    - **Small variations in overpack design induce small effects**
  - **Cladding response is governed by assembly design**
    - **Basket designs are similar, contribution is small anyway**
    - **PWR 17x17 assemblies bound the response of all fuel types**
- **Consequences are Generic**
  - **Governed by clad properties & storage conditions**
- **Conservative assumptions normally employed further reduce or eliminate case-specific effects**

# How to Characterize Transportation Accidents - I. Regulatory Definition

- **Objective: Satisfy 10 CFR 71.51 requirements**
- **Analysis of the effects of dry storage conditions on fuel-rods failure frequency and failure geometry is not explicitly considered**
- **Evaluation: 9- & .3-m drop Tests on unyielding surface**
- **Compliance with the regulations:**
  - **Impact-limiters limit g-loading on cask and fuel**
  - **1-foot limit on lifting height of bare casks/containers**
  - **Single-failure-proof cranes**
- **Definition eliminates reliance on subjective analysis**
  - **State of the art perceived to be inadequate for reliable risk assessment**

# How to Characterize Transportation Accidents - II. Realistic Definition

- **Objective: Quantify fuel failure frequencies and consequences**
- **The only way to evaluate what happens to the fuel**
  - **Fuel is modeled explicitly**
  - **Storage effects are directly used in quantifying consequences**
  - **Rod failure probabilities & failure frequencies are determined**
- **Requires definition of a bounding event in terms of actual impact loading and realistic targets**
- **Realistic conditions of the fuel assemblies and cladding**
- **Utilizes best estimate cladding properties and residual capacity, with appropriate bounds**

# Definition of a Realistic Bounding Transportation Accident

- **Definition of the drop event**
  - Side drop from a cg-over-corner equivalent height
  - Bare metal cask impacting a 3-ft. concrete pad on hard soil
  - Rod buckling under end-drop is judged to be non-governing
- **Justification**
  - Sand-90-2406-III - maximum failure probability = 2E-4/rod
  - NRC- and Industry-sponsored full-scale tests by BNFL
    - G-loading reaches maximum value asymptotically at a height equivalent to cg-over-corner (EPRI TR-108760) - *see next figures*
- **Definition of structural modeling and analysis**
  - Adaptation of Sand-90-2406-III methodology to realistic accidents, high-burnup cladding properties and residual effects of dry storage temperature history

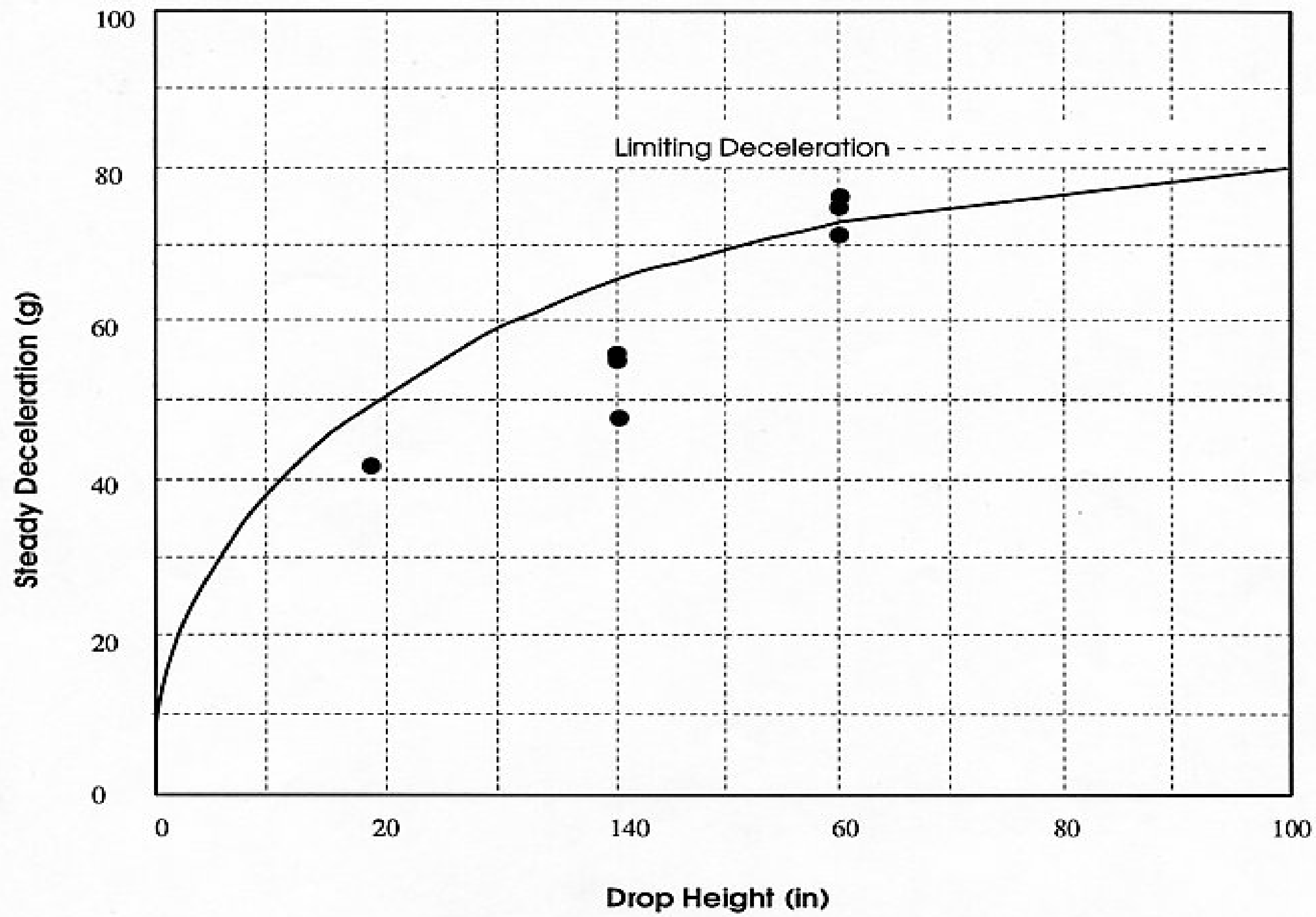



Figure 3-2. Steady Deceleration vs. Drop Height

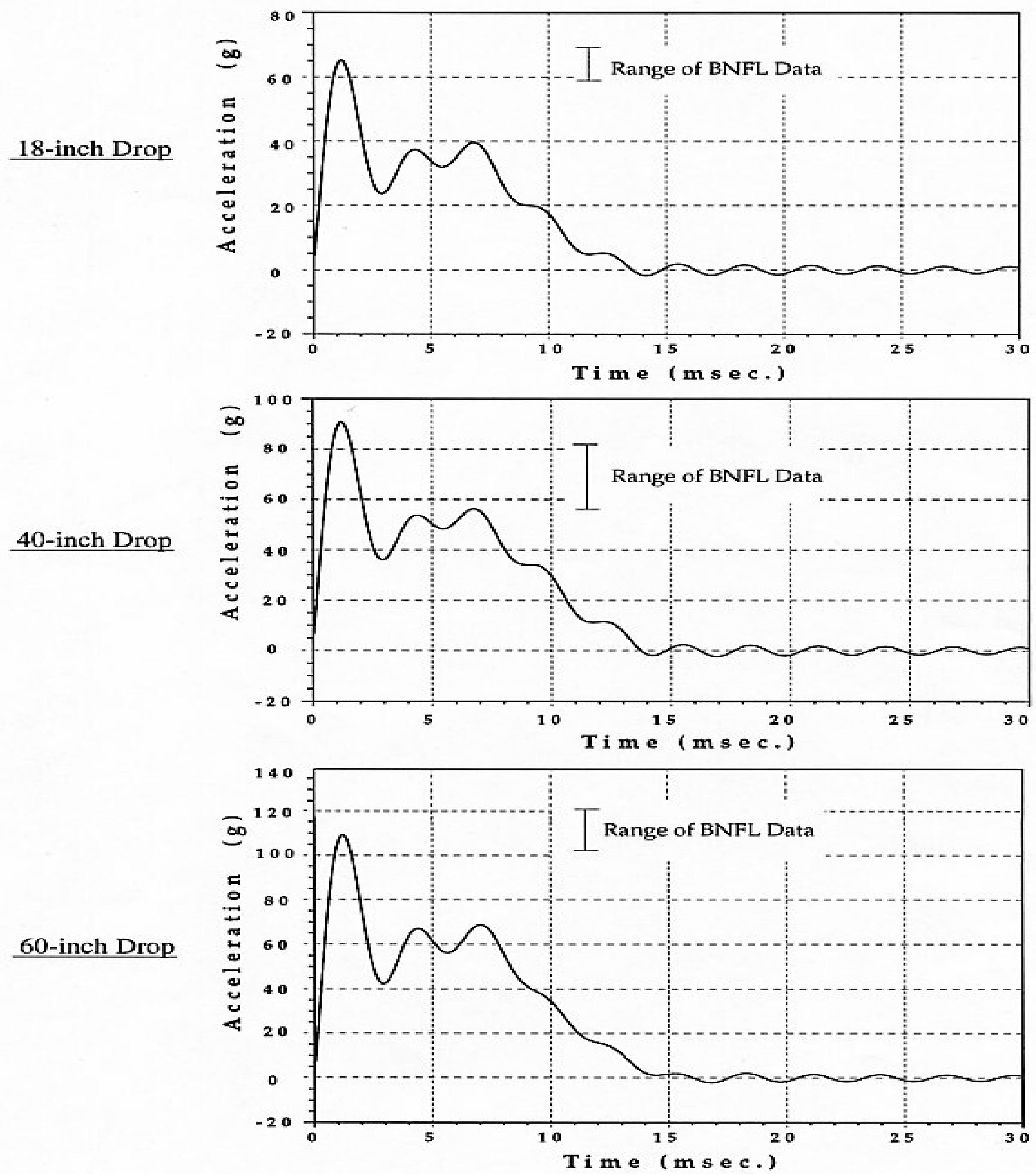





Figure 3-3 Computed Time Histories of Total G-Force for BNFL Cask Drop Tests

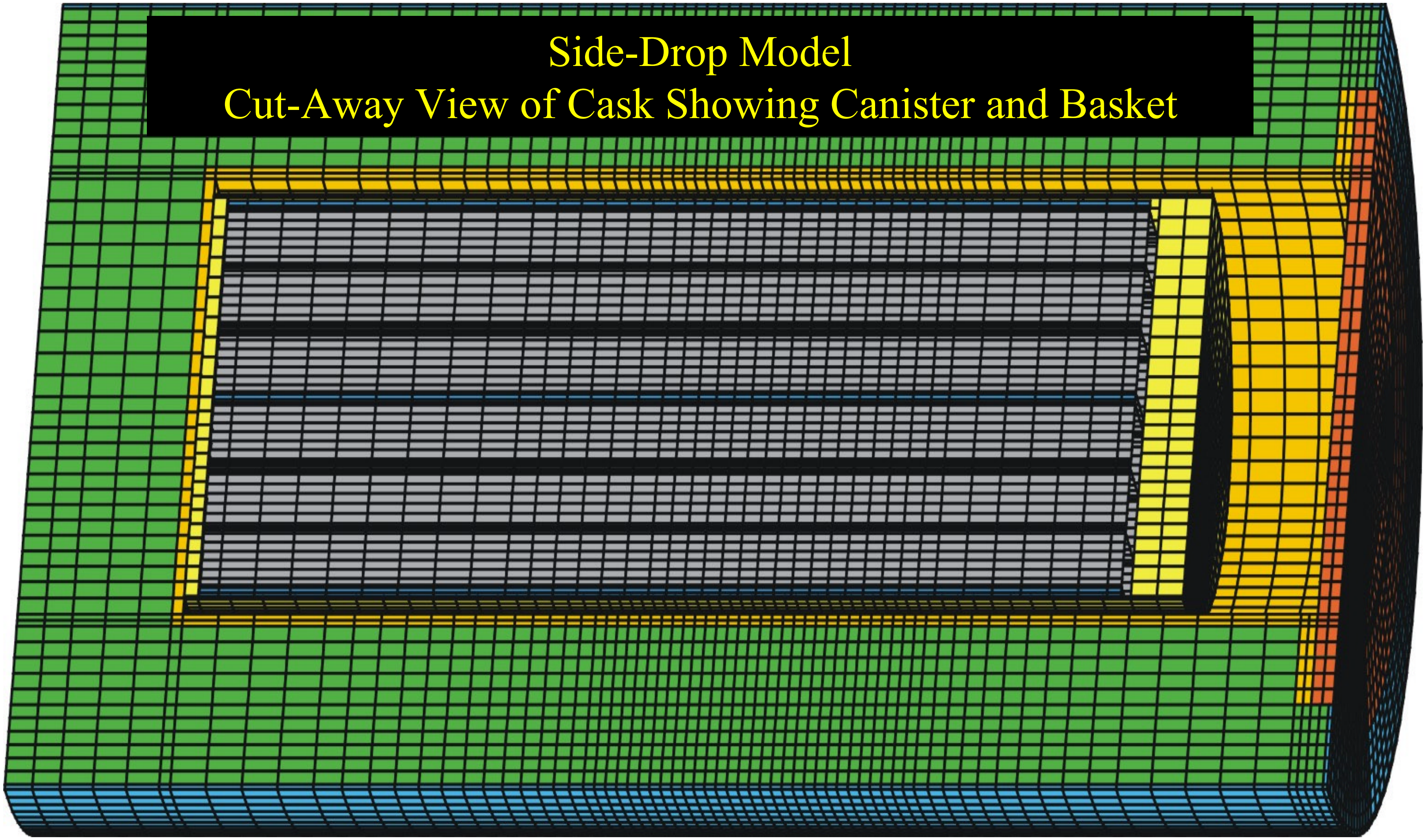
# Effects of Temperature-Stress History on Cladding Behavior During Accidents

- **Storage temperature-Stress history affect residual ductility and radial hydrides**
- **Higher drying temperature has benefits & detriments:**
  - **Benefits: Irradiation-damage annealing - ductility is regained**
    - **At 470°C irradiation-hardening is fully annealed within 24 hours**
  - **Detriments: Increase creep rate and r-hydride precipitation**
    - **Creep rate is also limited by hydrogen, which is non-recoverable**
      - **At high-burnup, creep-rate factor = 0.25-0.3 due to hydrogen alone**
    - **Radial hydrides would increase depending on stress level**
- **Benefits may outweigh detriments**
  - **Payoff in terms of reducing consequences can be significant**
  - **Therefore, better definition of stress-temperature is needed**
  - **Actual Internal pressures are lower than assumed**

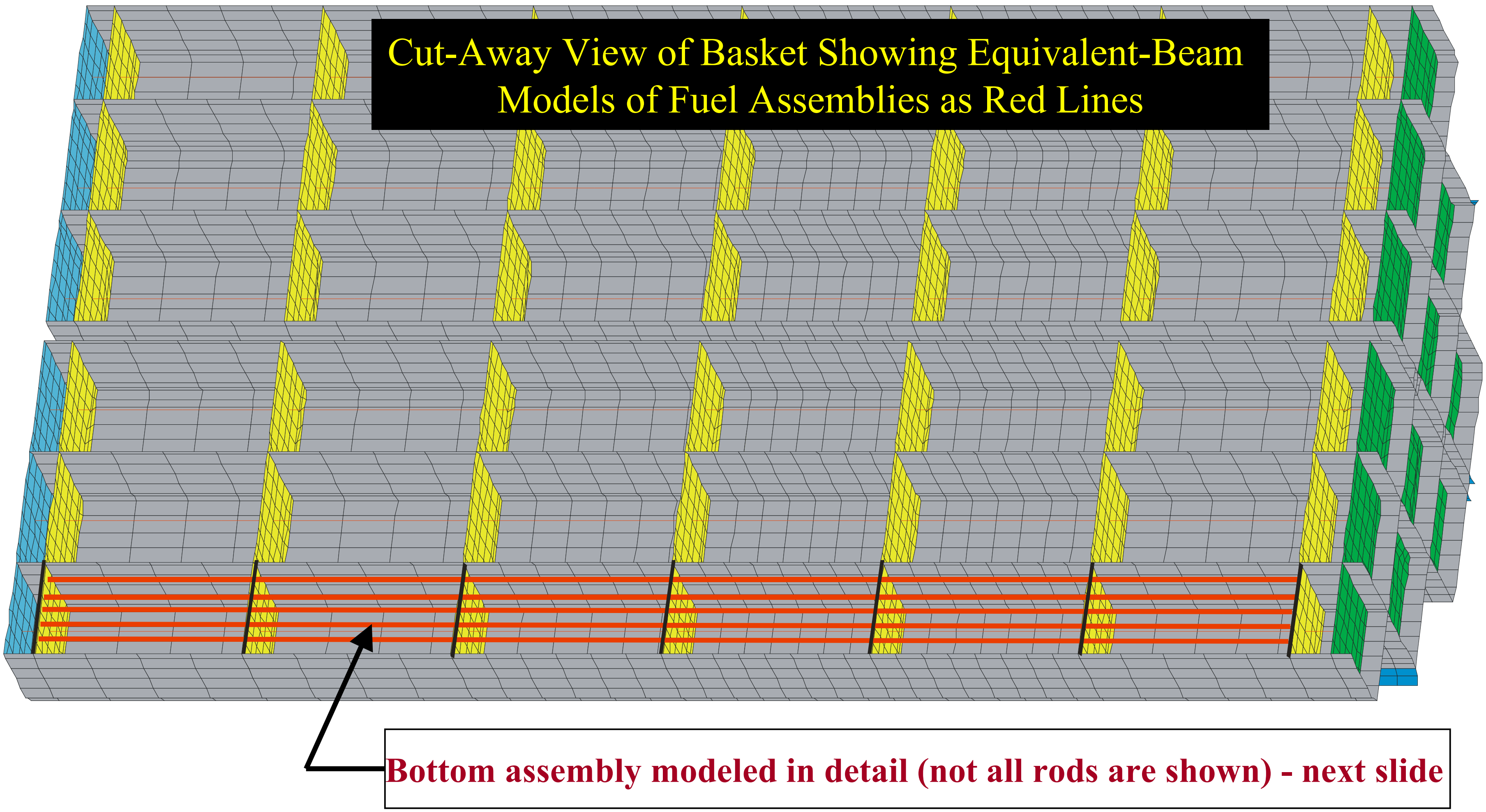
# Accident Analysis for Fuel Reconfiguration Adapt Sand-90-2406-III Methodology

- **Limit accident events to the following:**
  - **Side drop from an equivalent height of cg-over-corner is considered bounding**
  - **Impact target: Typical storage pad on soil**
- **Model transportation cask, including overpack, canister, basket & assemblies - *see figures***
  - **Bottom assembly modeled in detail, all others are modeled as beams with equivalent mass and stiffness**
  - **calculate local pinch/bending loads for single rod**
- **Develop detailed single-rod models and calculate each of the three potential failure failure modes - *see figure***
  - **Calculate failure frequency using distributions for material properties and failure criteria for potential failure modes**

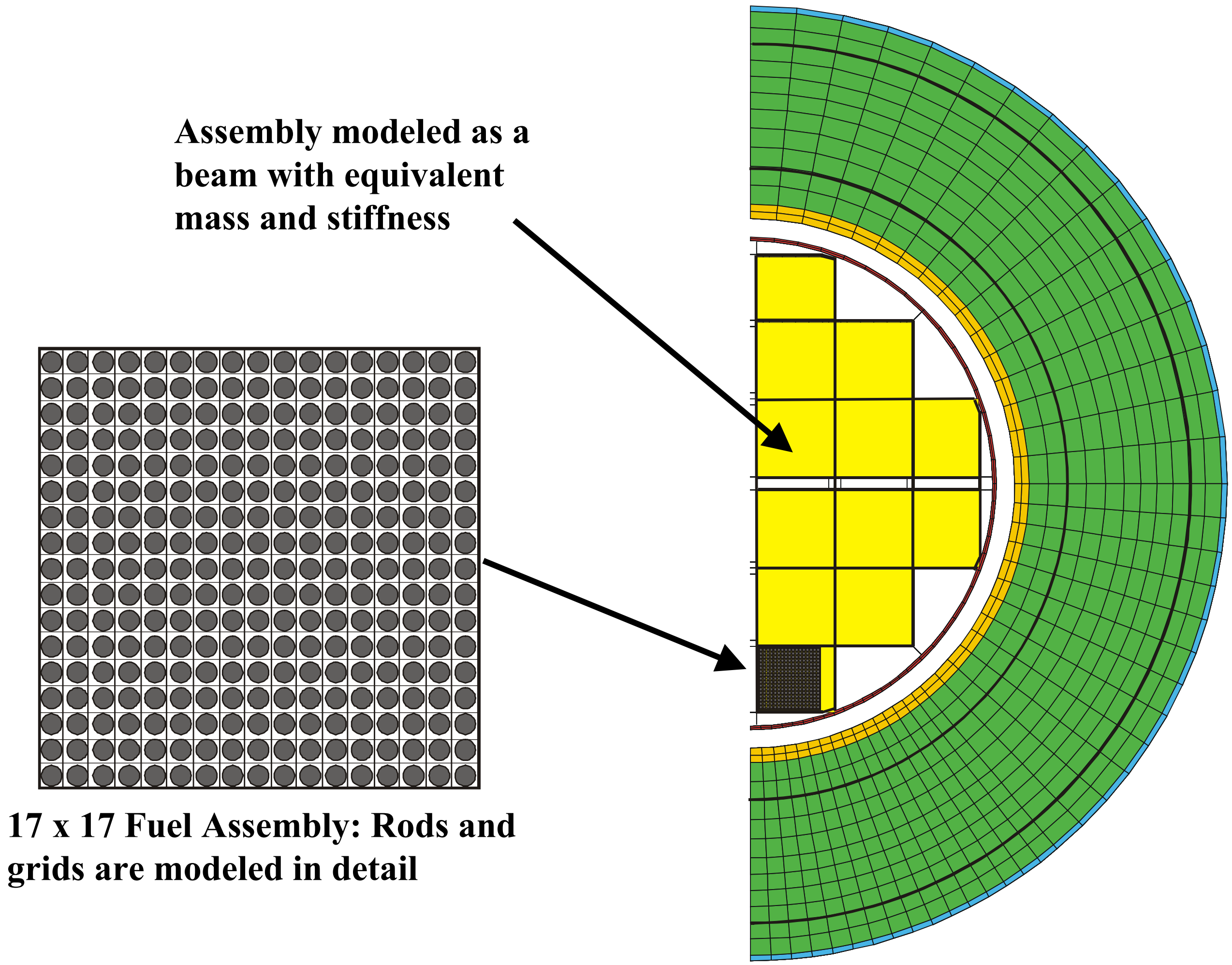
# Accident Analysis for Fuel Reconfiguration Cask & Canister Details



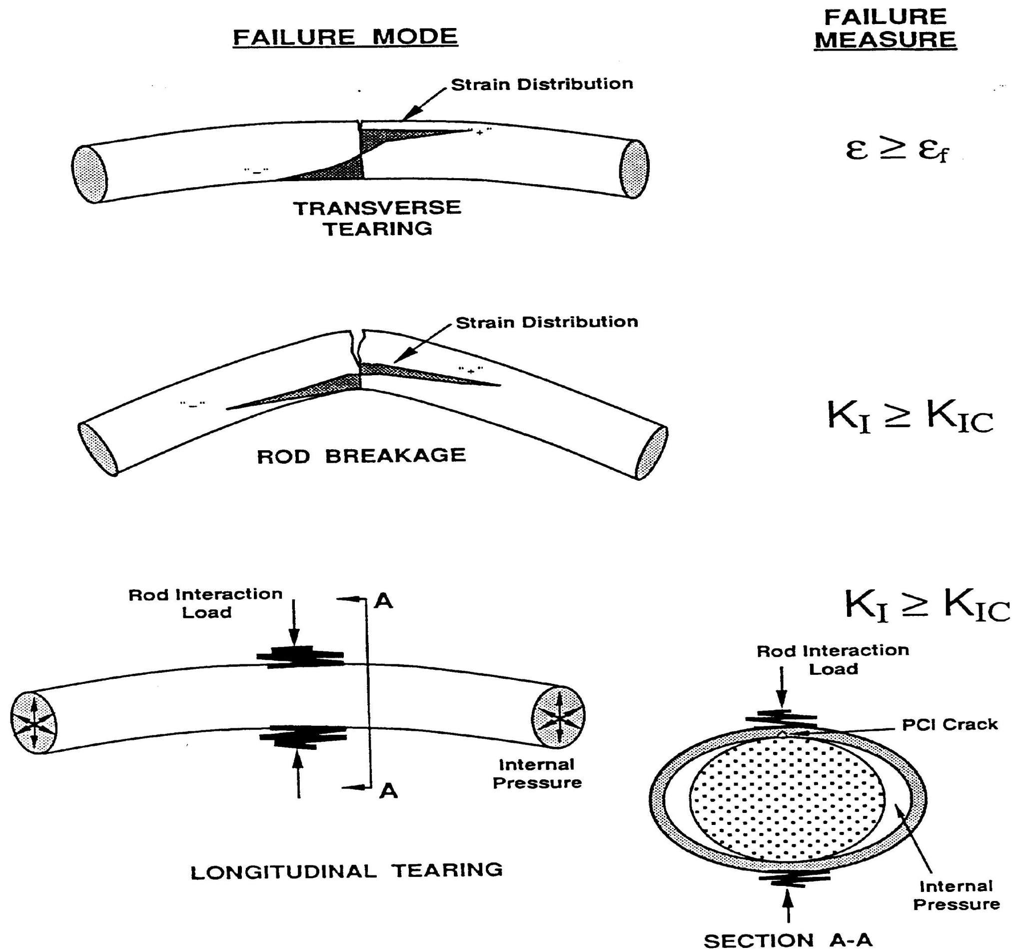
# Accident Analysis for Fuel Reconfiguration Basket & Fuel Assemblies Details



# Symmetry Section of Cask Modeled for Side Drop from CG-Over-Corner Height



# Potential Failure Modes for Side Drop




**Mode I Extending to Mode II, does not engage r-hydrides**

**Mode II, does not engage r-hydrides**

**Mode III, can engage r-hydrides**

Figure III-29. Fuel Rod Failure Modes

# What is Needed to Adapt SAND-2406 Methodology

- **Update (Due to High-Burnup & Hydrides Effects) Probability Distributions for:**
    - **Flaw Size**
    - **Fracture Toughness**
    - **Ductility (Strain Limit) / Critical Strain Energy Density**
- **Develop New Information and Material Data for:**
    - **Radial Hydrides**
        - **Concentration / Fraction $F_N$**
        - **Size and Distribution**
        - **Failure Criterion as Function of $F_N$**
    - **Oxide / Hydride-Rim: Thicknesses & Properties**
    - **Spacer Grids High-Burnup Properties**

# Conclusions

- **Transportation can and should be treated generically**
- **Hypothetical accident consequences are intimately related to ISG-11 Rev 2**
- **Possible to derive relief from temperature limitations through consequence analysis**