High Burn-up Spent Nuclear Fuel Structural Response When Subjected to a Hypothetical Impact Accident

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Presentation Ou

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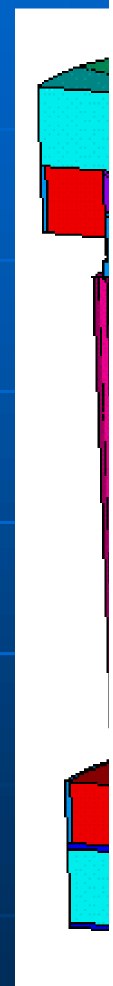
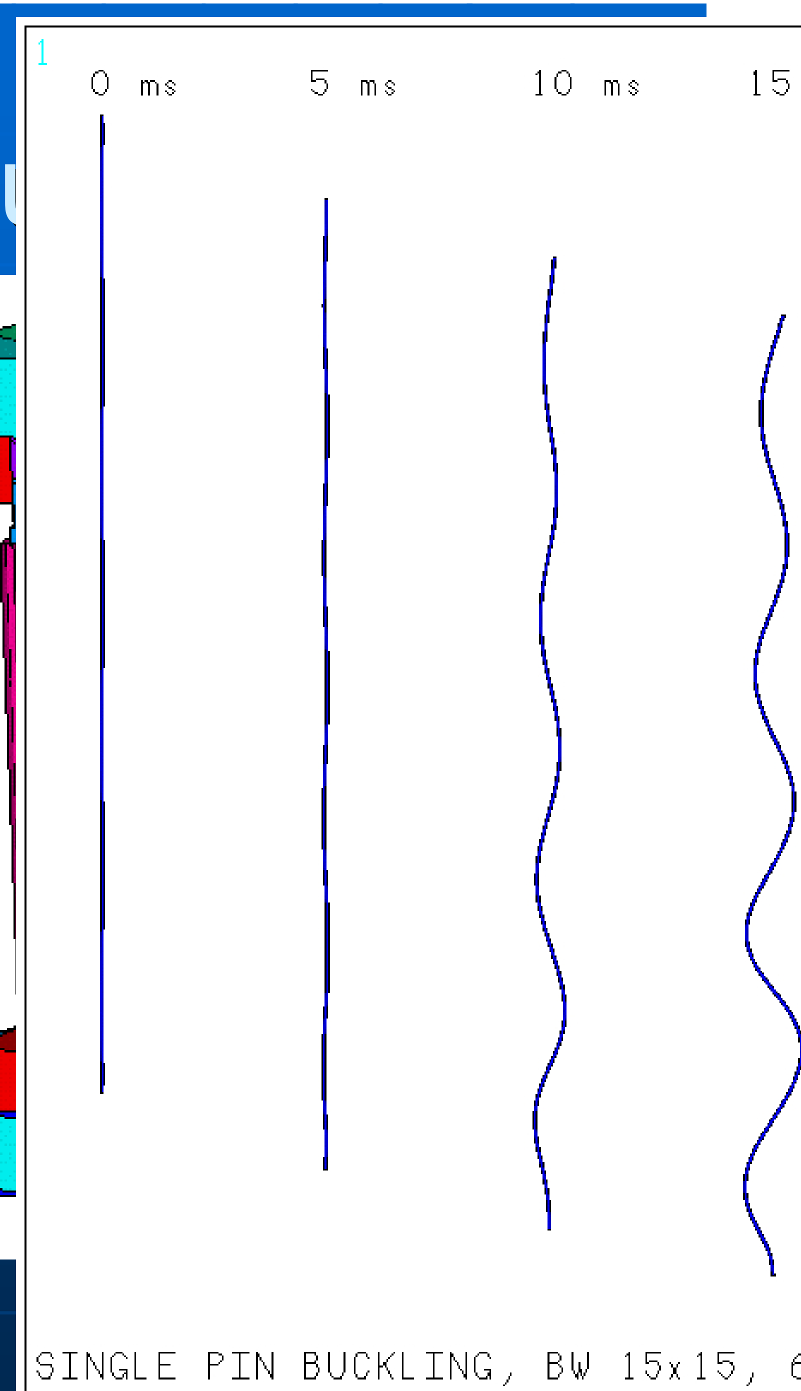
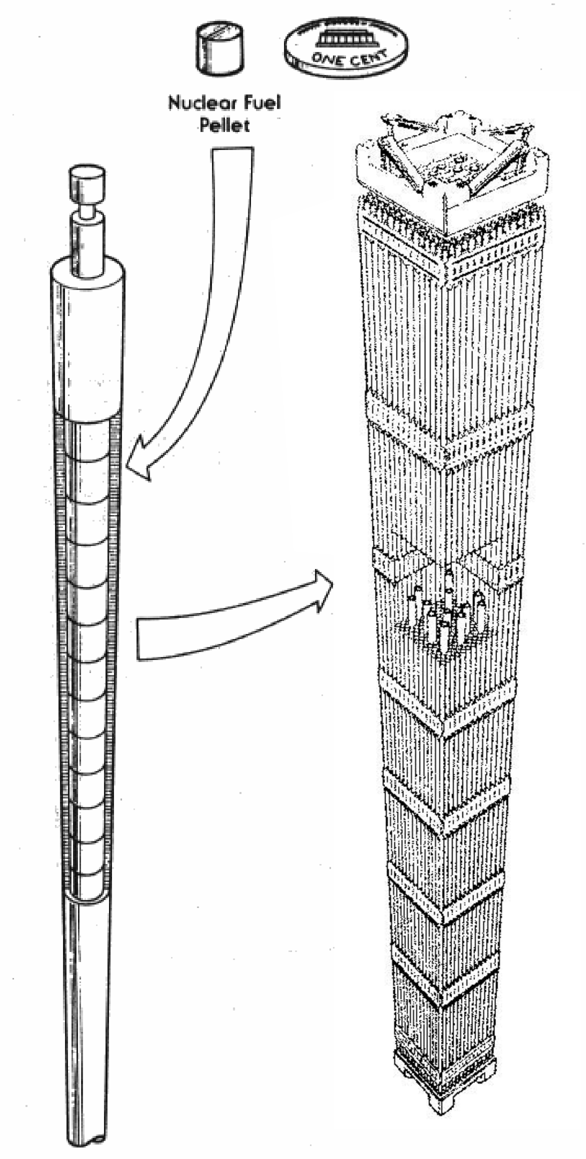
- Acknowledgements





Background

- The pin consists of a hollow tube containing numerous fuel pellets
- The assembly consists of numerous pins held by spacer grids
- Multiple assemblies are then transported and stored in casks
- Per U.S. NRC regulations, the cask/pins must withstand (i.e. no loss of containment) a 30 ft drop for various orientations including axial



Background

- Axial loading can lead to buckling instability of the fuel pins
- A recent initiative will permit transport and storage of high burn-up fuels (45-75 GWd/MTU)
- High burn-up can cause cladding corrosion and embrittlement due to hydride alignment, reducing its strength and ductility
- Effects of degraded material properties on SNF pin response to hypothetical accident conditions such as end impact have not been analyzed

Project Objectives

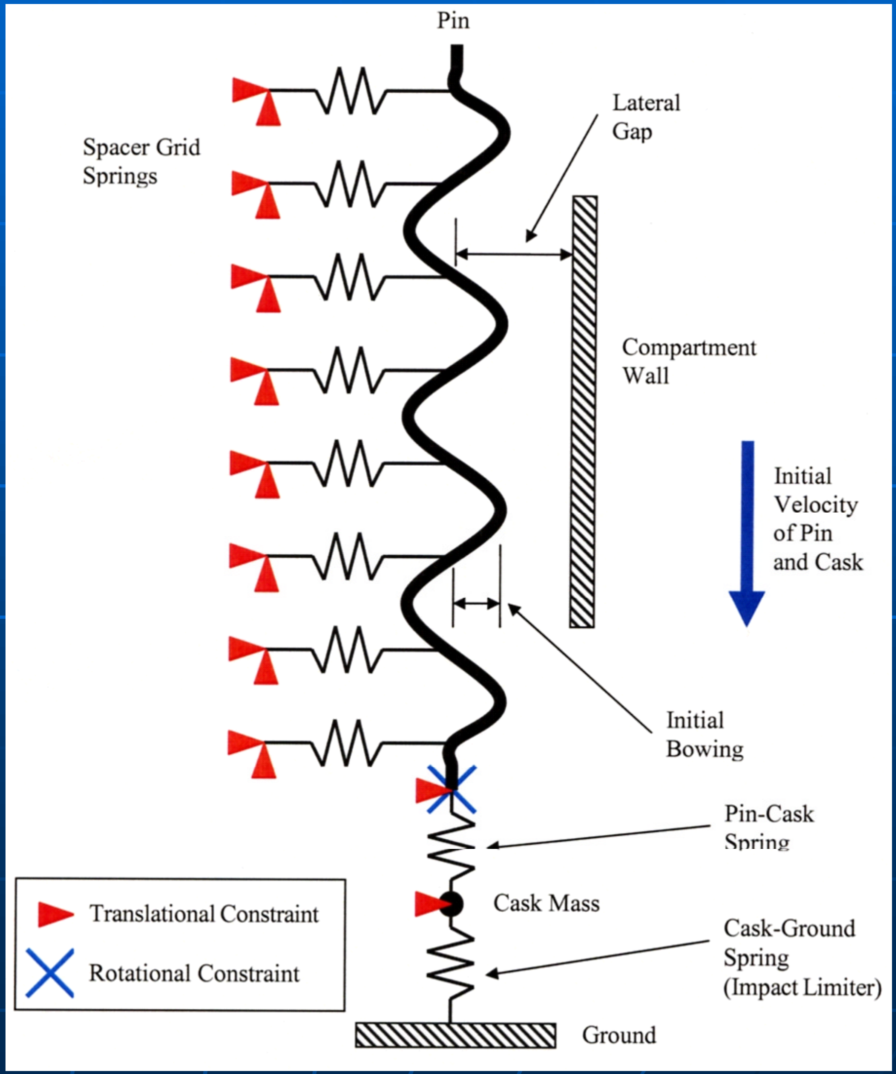
- Develop a conservative finite element (FE) model to study end impact of spent nuclear fuel pins
- Evaluate the buckling acceleration and post-buckling behavior of the fuel pin cladding
- Perform parametric analysis to evaluate effects of
  - Average acceleration
  - Internal pressurization
  - Pin lateral gap width
  - Cladding thickness reduction due to corrosion
  - Pin/basket geometry

Modeling Approach

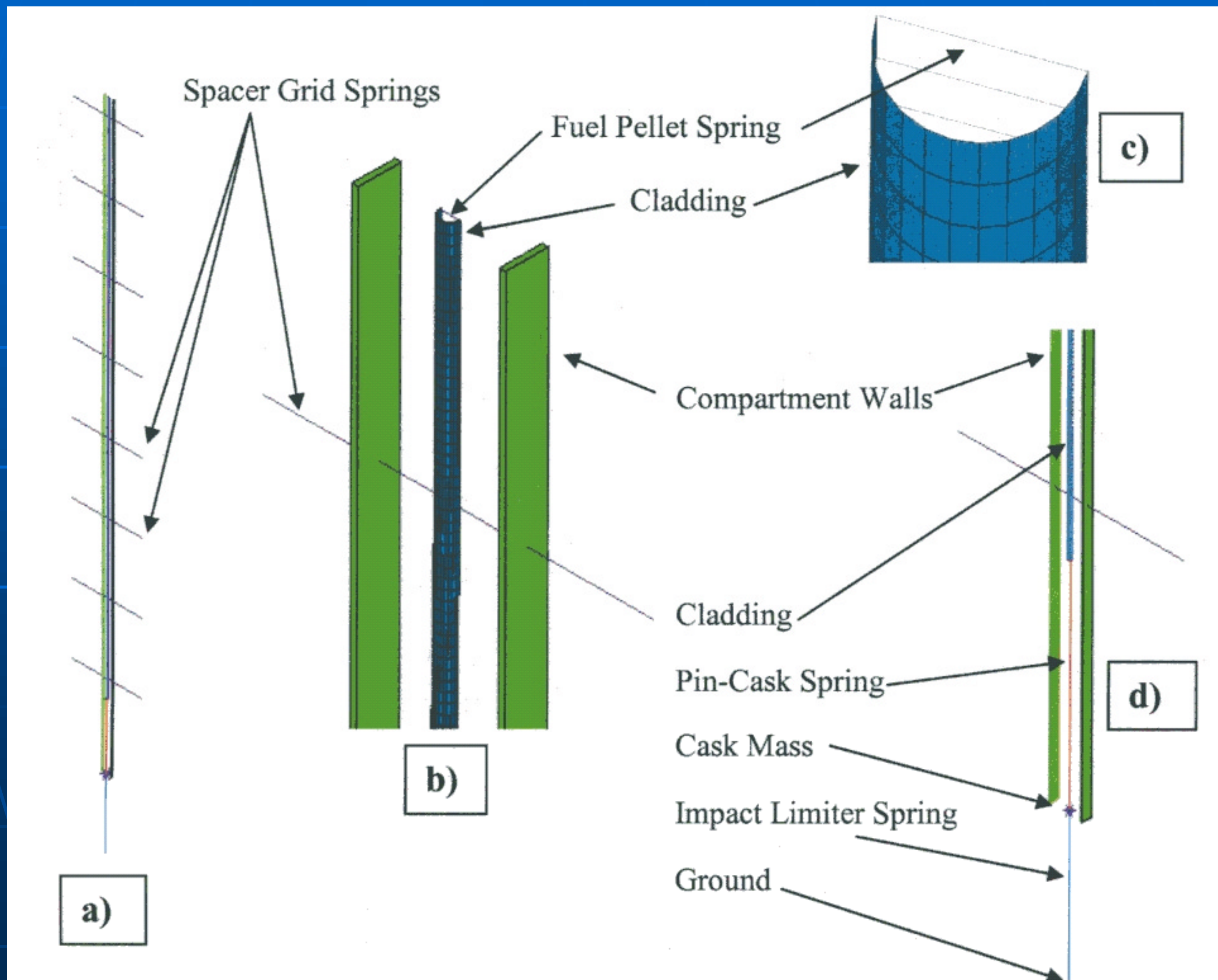
- Model full pin length
- Include transient dynamic effects: LS-DYNA
- Include cask/impact limiter effects
- Keep it simple: single pin assumption
- Include 100% of the fuel mass (U.S. NRC ISG 12)
- Ensure conservatism in approach
  - Fuel-fuel and fuel-pin interfaces bonded?
  - Fuel fractured?
  - Neglect effect of fuel on the bending rigidity of the pin

Modeling Approach

- Model features
  - Full pin length
  - Initial bowing assumed
  - Spacer grid supports
  - Distributed fuel mass
  - Cask mass
  - Impact limiter
  - Rigid wall with lateral gap
- Model loading
  - Initial velocity
  - Internal pressure
- Model boundary conditions
  - Rigid ground surface



Model Description: FE Model Mesh

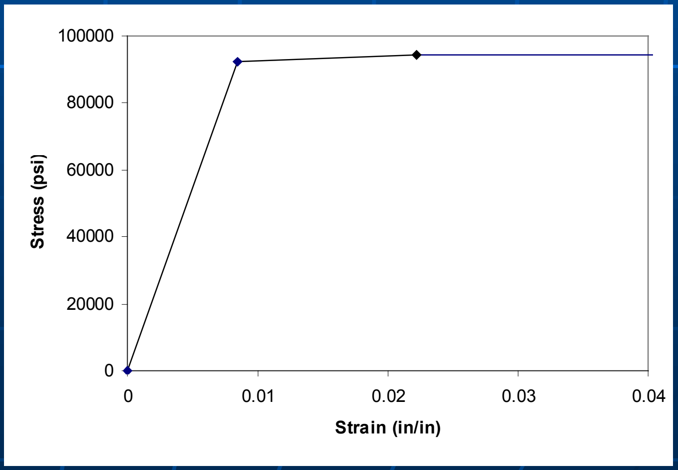


Model Description: Fuel Pin (Baseline Case)

- Pressurized water reactor (PWR) fuel cladding generally more vulnerable to impact events than boiling water reactor (BWR) clads
- Baseline geometry: Babcock & Wilcox (B&W) 15x15 PWR fuel cladding
  - Pin length: 153.7 in (390.4 cm)
  - Pin outer diameter: 0.429 in (1.09 cm)
  - Pin wall thickness: 0.0265 in (0.0673 cm)
  - Pin weight: 7.011 lb (3.183 kg)
  - Fuel weight: 5.578 lb (2.535 kg)

Model Description: Clad Material Properties

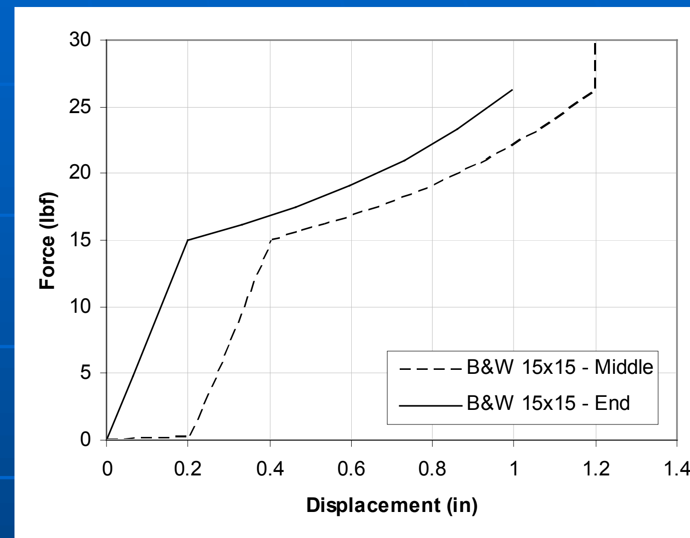
- Evaluation of high burn-up fuel material properties is ongoing at PNNL and ANL (to be published in NUREG/CR's)
- Yield strength, tensile strengths, and elongations established from axial tube, burst, and ring tests
- Assumed properties are
  - Elastic modulus 11E6 psi
  - Yield Strength 92E3 psi
  - Ultimate Strength 94E3 psi
  - Total Strain ~2.5%



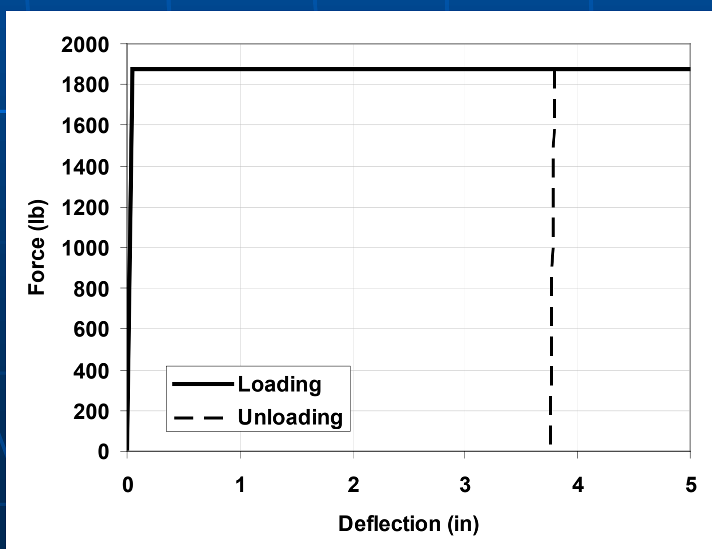
Model Description: Spring Element Properties

- Define load-deflection curves
  - Spacer grids
  - Impact limiter
  - Fuel pellet

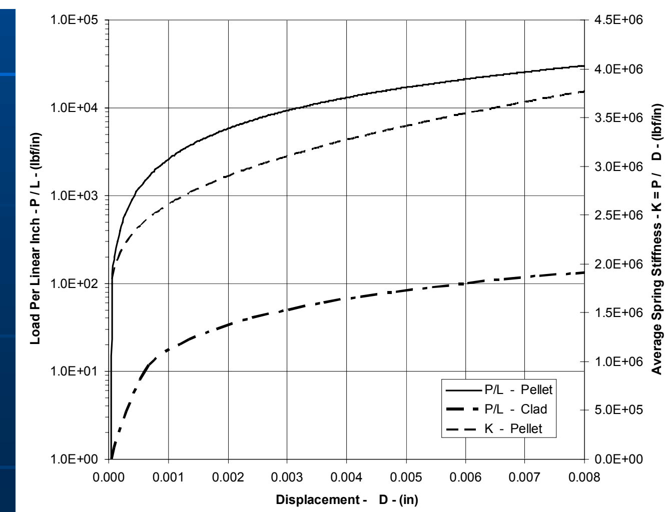
Spacer Grids



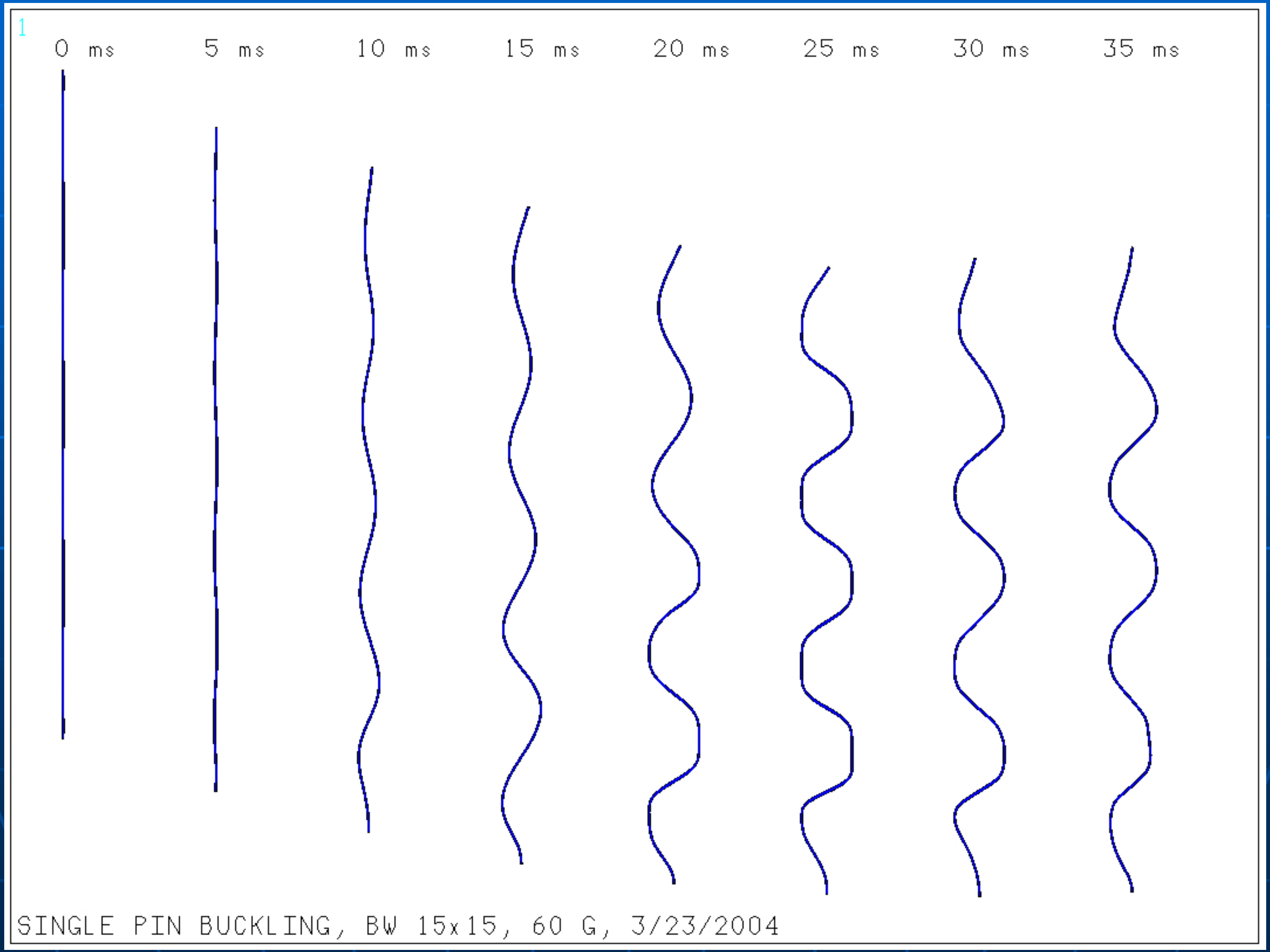
Impact Limiter



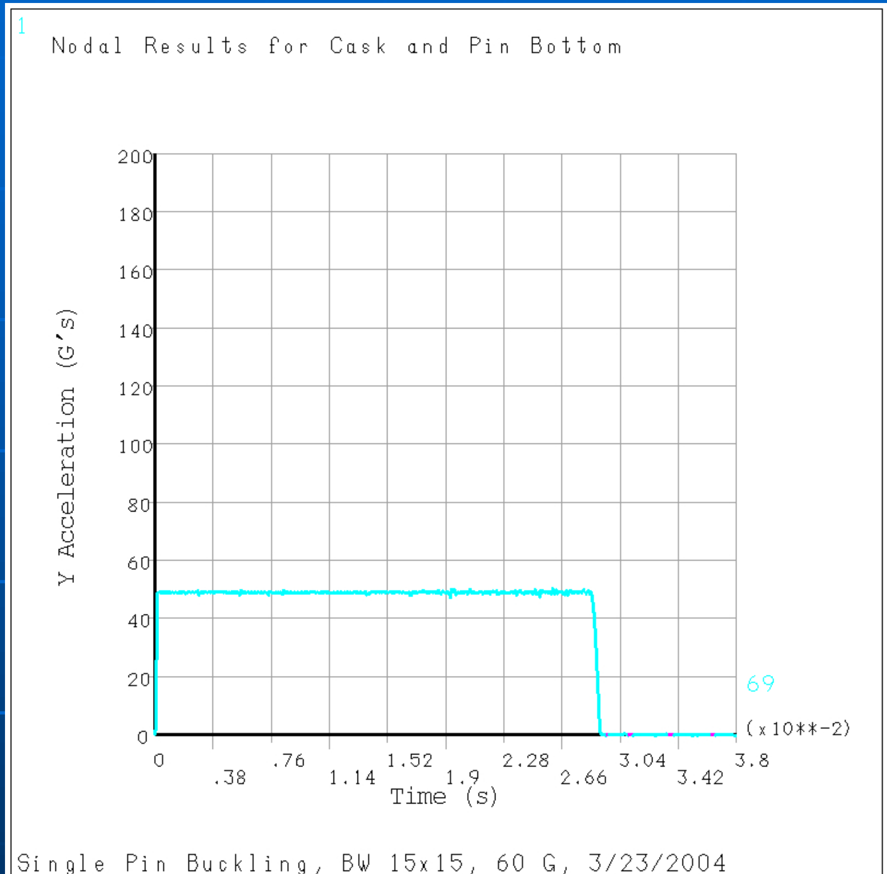
Fuel Pellet

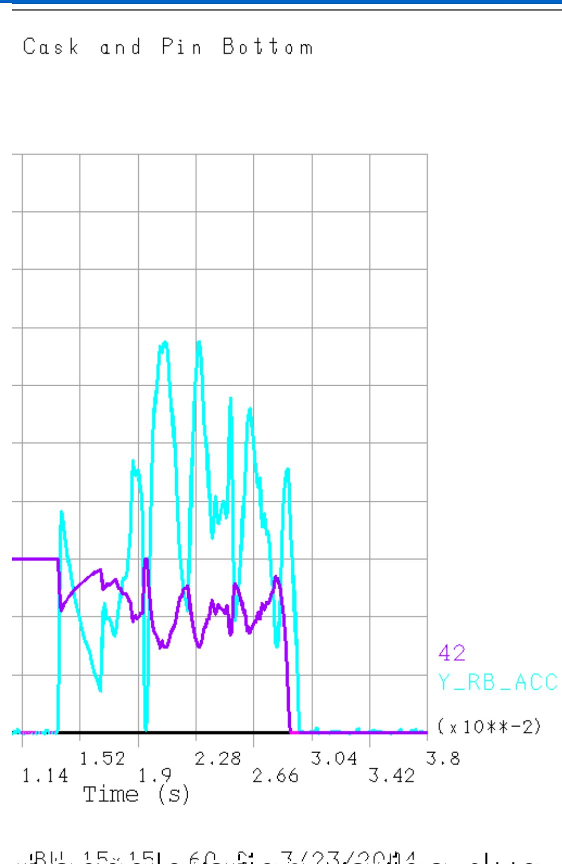


Results: Pin Deformation History



Results: Accelerations





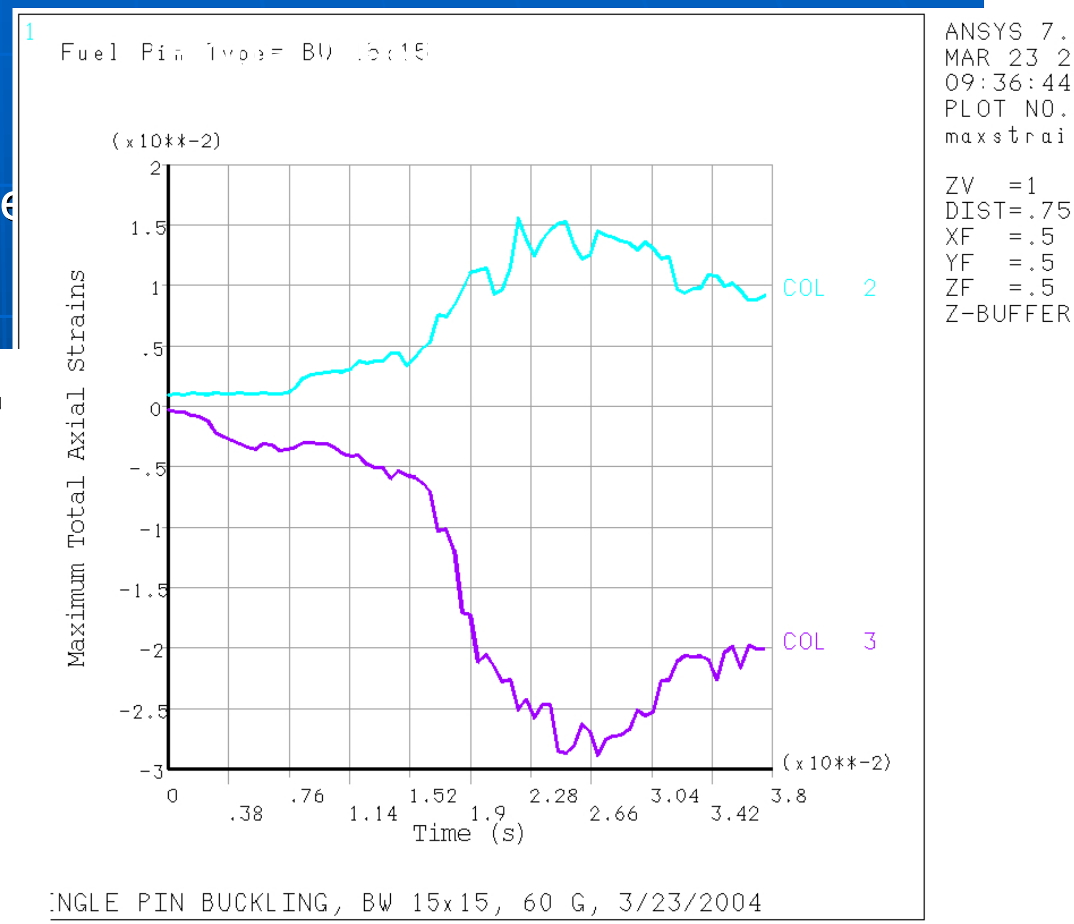
- Average system (i.e. cask+pin) acceleration is constant per the defined load-deflection curve for the impact limiter

- Component acceleration varies due to pin-cask interaction and loss of contact

- Pin acceleration peak at 135 G's

Results: Cladding Strains
(Baseline Case)

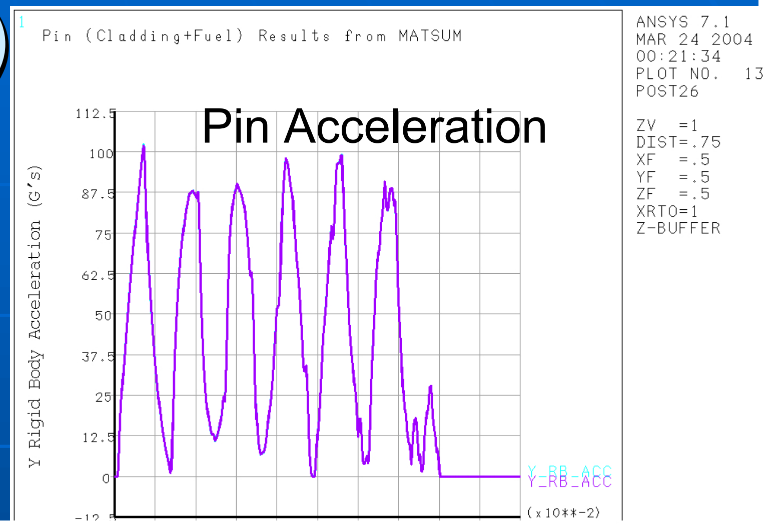
- 1.5% tensile strain
- 2.8% compressive strain
- 1.0%-2.8% estimate for allowable tensile strain

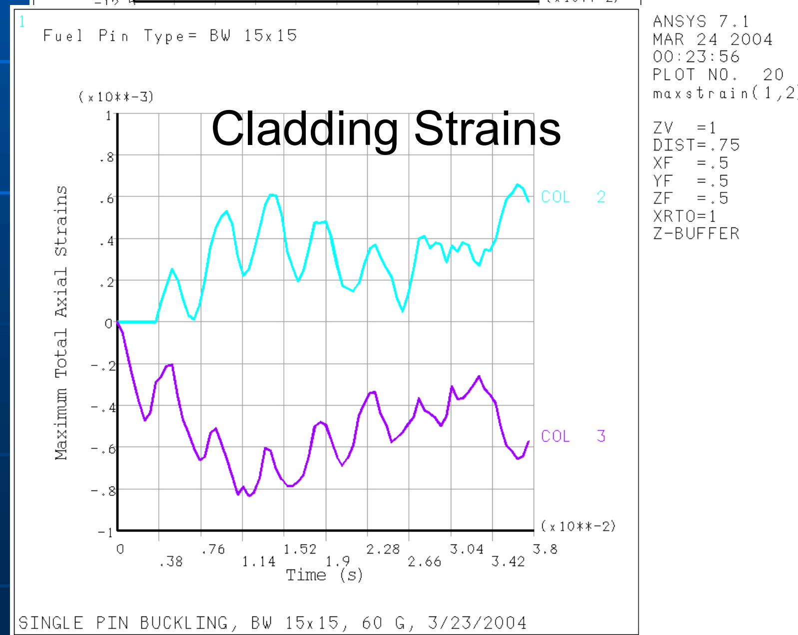


Results: Effects of Fuel Rigidity

(Case #12)

- A bounding case that accounts for fuel rigidity effects also evaluated
- Perfect bonding assumed at pellet-pellet and pellet-cladding interfaces
- Elastic material properties assumed for the fuel pellets
- No buckling response
- Small elastic strains in the cladding





Additional Parametric Study Cases

Case #	Fuel Type	Cask Deceleration (G)	Lateral Gap Width (in)	Internal Pressure (psi)	Cladding Thickness Reduction	Comments
1	**B&W 15x15**	**60**	**1.2**	**1400**	**0%**	**Baseline Case**
2	B&W 15x15	60	1.2	0	0%	
3	B&W 15x15	50	1.2	1400	0%	
4	B&W 15x15	70	1.2	1400	0%	
5	B&W 15x15	60	1.1	1400	0%	
6	B&W 15x15	60	1.3	1400	0%	
7	B&W 15x15	60	1.2	1400	10%	
8	B&W 15x15	60	1.2	1400	20%	
9	WE 17x17 OFA	50	1.2	1400	0%	
10	WE 17x17 OFA	60	1.2	1400	0%	
11	WE 17x17 OFA	70	1.2	1400	0%	
12	**B&W 15x15 + Fuel**	**60**	**1.2**	**N/A**	**0%**	**Effect of Fuel**
13	B&W 15x15	60	1.2	1400	0%	24 vs. 32 assembly basket
14	B&W 15x15	60	1.2	1400	0%	Ramped loading

Parametric Study Results

Case #	System[1] Average Deceleration (G)	Cask Maximum Deceleration (G)	Pin Maximum Deceleration (G)	Peak Tensile Strain (%)	Peak Compressive Strain (%)	Comments
1	**49**	**60**	**135**	**1.5**	**2.8**	**Baseline Case**
2	49	60	100	0.8	1.2	
3	41	50	118	1.2	2.2	
4	57	70	163	1.9	4.8	
5	49	60	148	1.1	2.2	
6	49	60	124	1.6	3.5	
7	49	60	120	2.0	5.5	
8	49	60	116	2.3	6.3	
9	42	50	111	1.9	3.6	
10	50	60	129	2.4	5.6	
11	59	70	138	2.7	6.5	
12	**49**	**60**	**104**	**0.07**	**0.09**	**No Buckling Initiated**
13	49	60	151	1.5	3.3	
14	49	60	126	1.3	2.6	

[1] Defined as cask and all contents.

Concluding Remarks

- Conclusions
  - An efficient analytical model was generated to capture transient dynamic response of a single fuel pin
  - Neglecting 100% of the fuel pellet influence on bending rigidity was overly conservative for a strain-based assessment of high burn-up fuel pins
- Future work
  - Improved handling of fuel pellet influence (fuel fracture, interface properties) required for realistic model
  - Assess cladding failure potential through probabilistic fracture analysis of the fuel pins, based on transient stress states