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Methods for Modeling Impact-Induced Reactivity Changes in Space Reactors

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National Nuclear Security Administration

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Overview

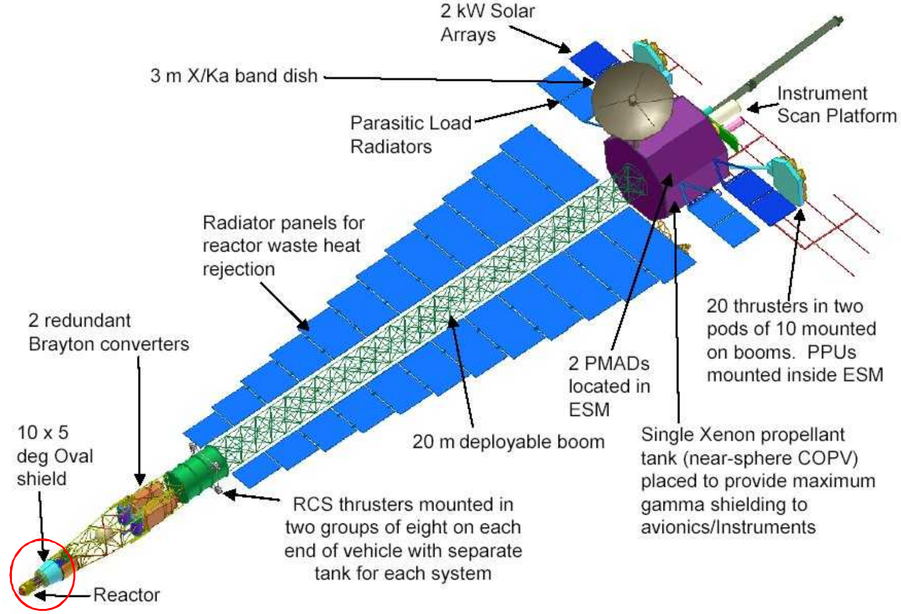
- NASA envisions use of small reactors for space (lunar surface power, spacecraft power, propulsion)
- Launch approval requires safety analysis on the effects of launch accidents
- Launch safety analysis codes for radioisotope power systems presently do not fully encompass reactor safety
- Reactor criticality from impact onto concrete is the primary unknown.
- Reactors are essentially non-radioactive until startup; impact might induce criticality.
- This project* is to develop the capability to model impact criticality using a detailed finite element continuum mechanics code coupled with MCNP

** Funded by Sandia National Laboratories through the Laboratory Directed Research and Development Program*

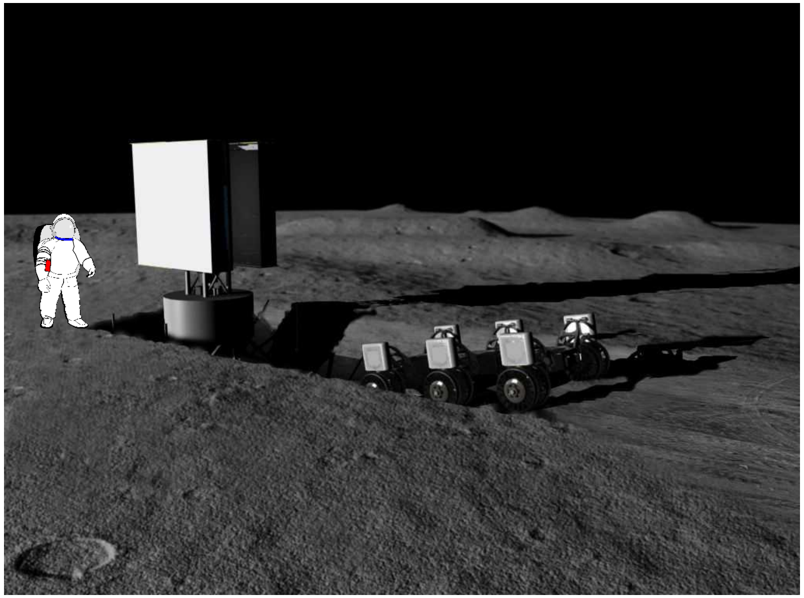
Prometheus (JIMO) Spaceship (2004)

Courtesy NASA

Figure 1: Flight System Configuration



Fission Surface Power System (2008)



Courtesy NASA

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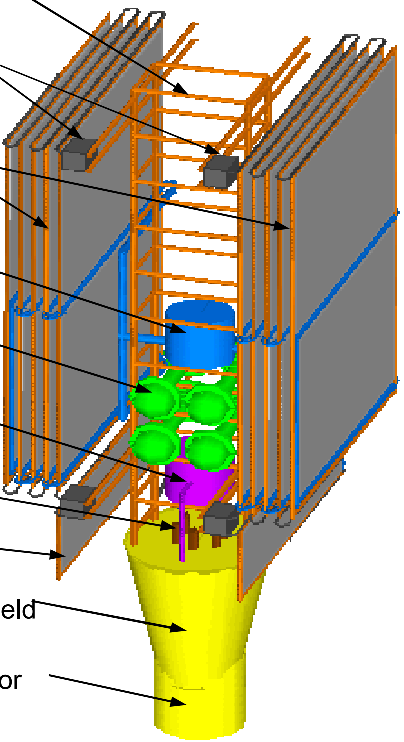
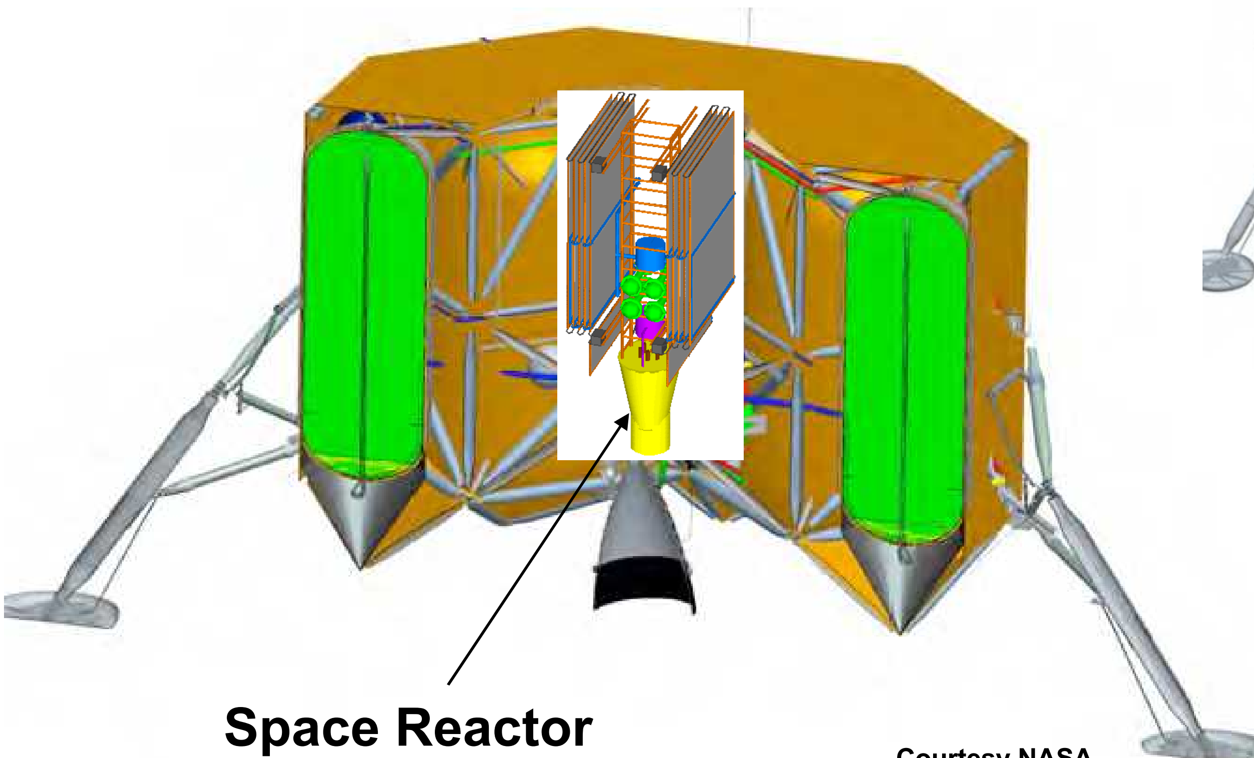
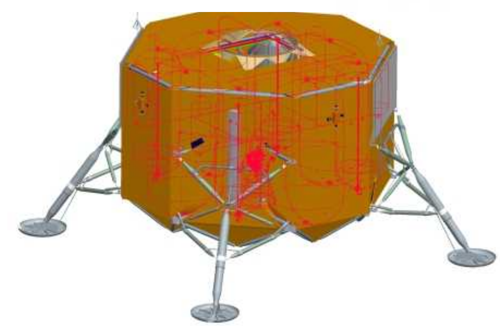


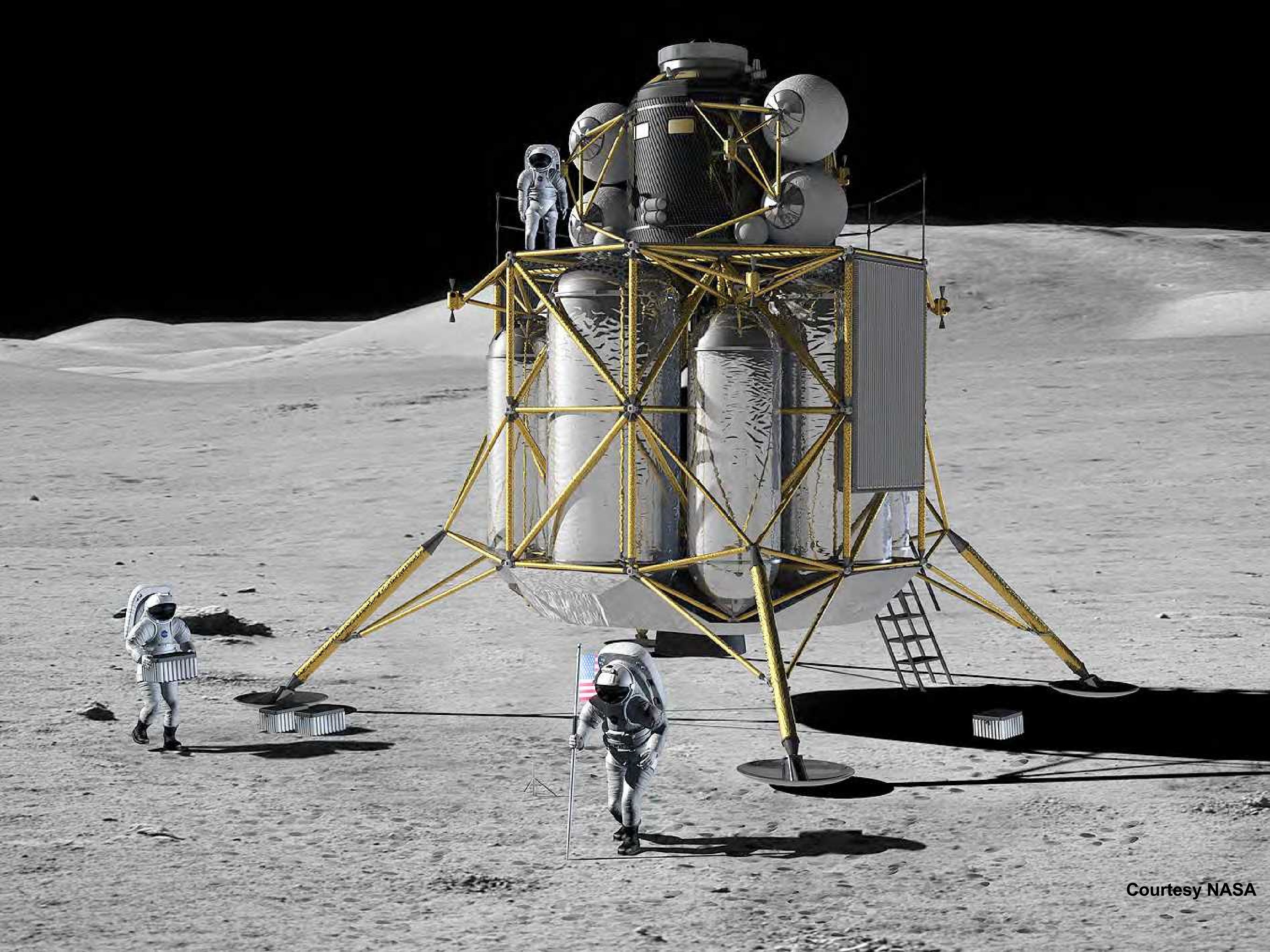
Lunar Descent Module

- Reactor is envisioned as being placed in the center of the module, surrounded by propellant tanks
- LV destruct might allow reactor to fall free





Courtesy NASA



Courtesy NASA

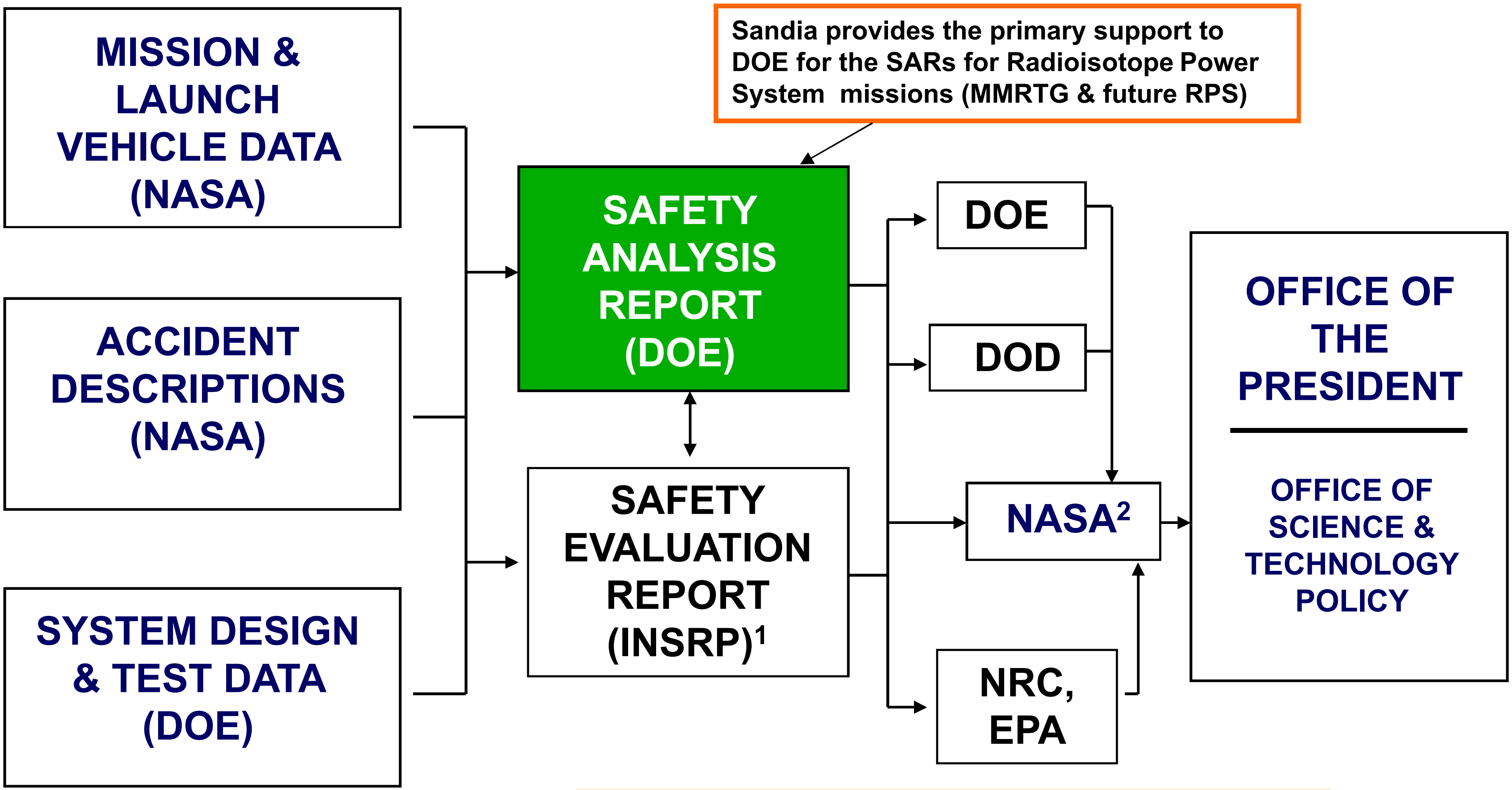
Launch Failures Can Occur

Atlas Fallback

Delta 241 Jan 27, 1997

Delta 241

A Process Exists for Launch Approval of Radiological Payloads



[1] Interagency Nuclear Safety Review Panel
[2] Responsible mission agency makes launch recommendation

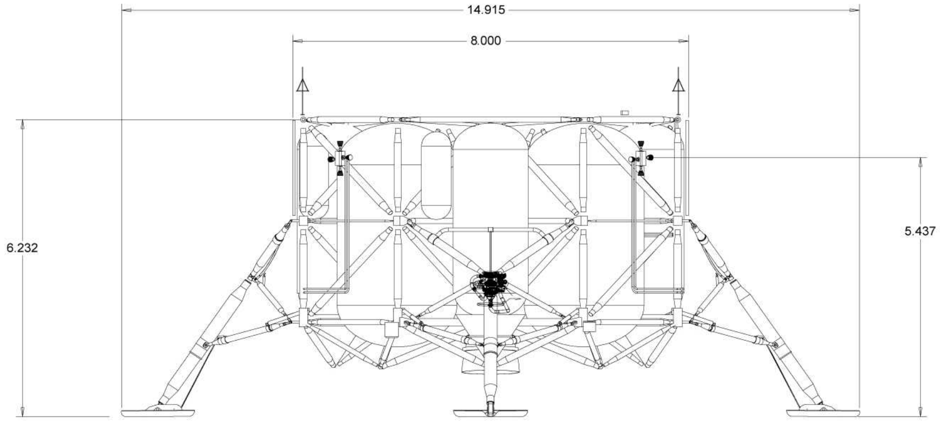
Close-up of Atlas en-route to Launch Pad

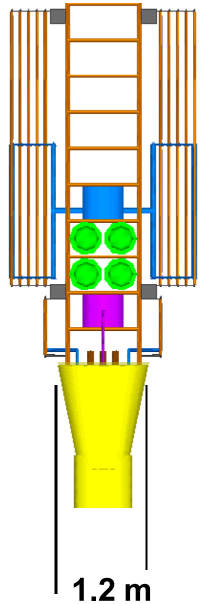
- **Space reactor would sit at the top of a 50 to 100 m tall launch vehicle**
- **A launch accident could threaten the reactor integrity**
- **Launch site has considerable area of concrete, asphalt and water**

Impact Velocity Estimates

- Atlas V payload is 47 m above the concrete launch pad; Ares V payload will be about 100 m
- Launch trajectory for the Atlas V remains over the concrete launch pad up to altitudes of about 540 m, and over concrete roads up to 1300 m and 1600 m
- Terminal velocity for Lunar power system is 220 m/s and for lunar lander is 120 m/s
- Impact velocities of 44 m/s to 200 m/s on concrete are possible
- Internals will have a reduced "impact" velocity
- 40 m/s (100 ft/s) used for initial calculations

Height (m)	Impact Velocity Neglecting Air (m/s)
100	44
200	63
400	89
1000	140
2000	198





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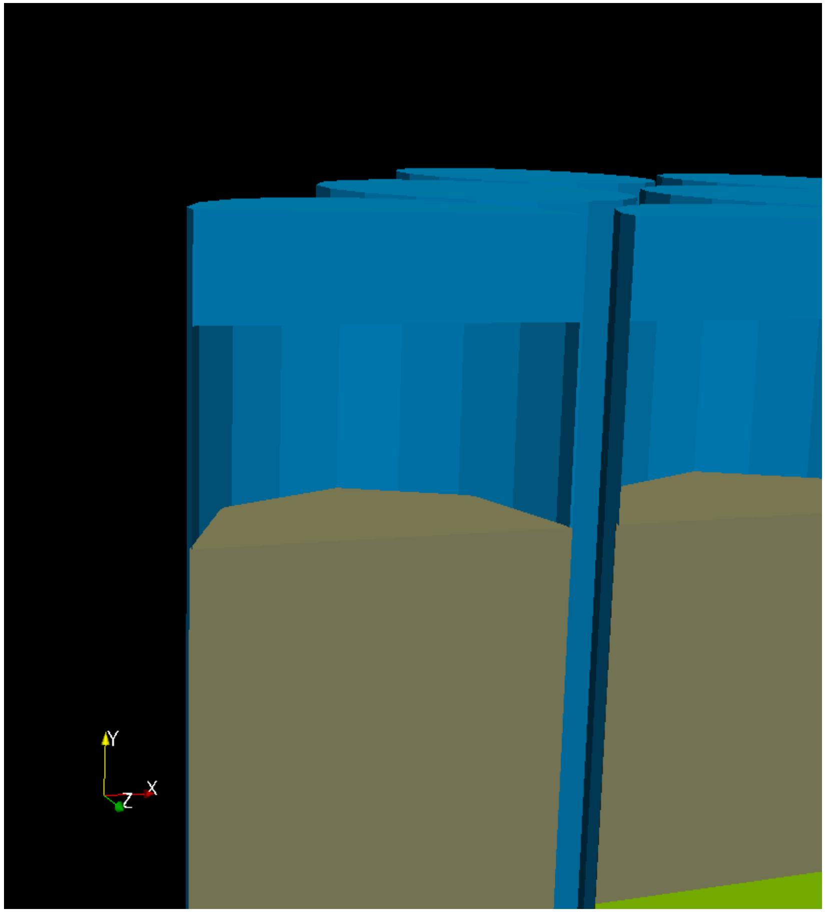
Analysis Workflow

- CUBIT used to generate mesh
- Continuum mechanics codes used to simulate impact and obtain deformed geometry (PRONTO3D/PRESTO)
- DAGMC reads pre-deformed geometry to define ray tracing geometry
- DAGMC then reads post-deformed geometry and updates the location of the nodes in the mesh
- DAG-MCNP5 performs Monte Carlo radiation transport/criticality calculation

Challenge: Complement Volumes

- Complement volumes are the non-solid portions that are not explicitly represented in the solid model representation
- DAGMC currently recognizes these all as one disjointed region with the same material properties
- Developments are underway at UW-Madison to add the capability of recognizing multiple regions, allowing the user to distinguish between the coolant, gas plenums, etc.



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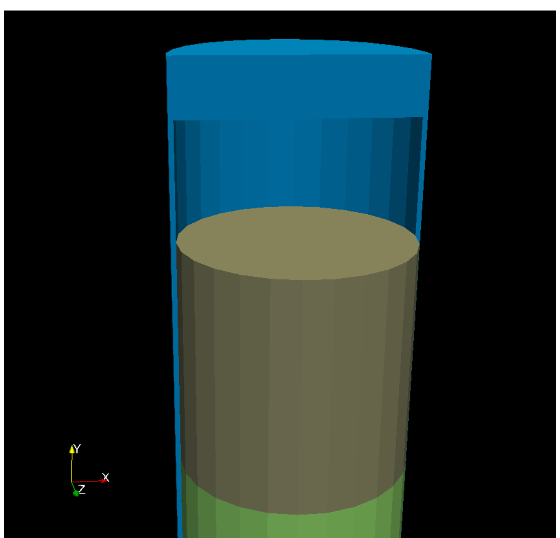
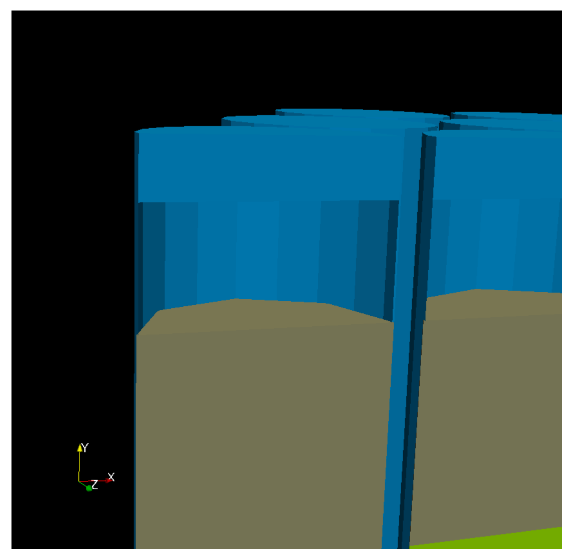
Challenge: Shell Elements

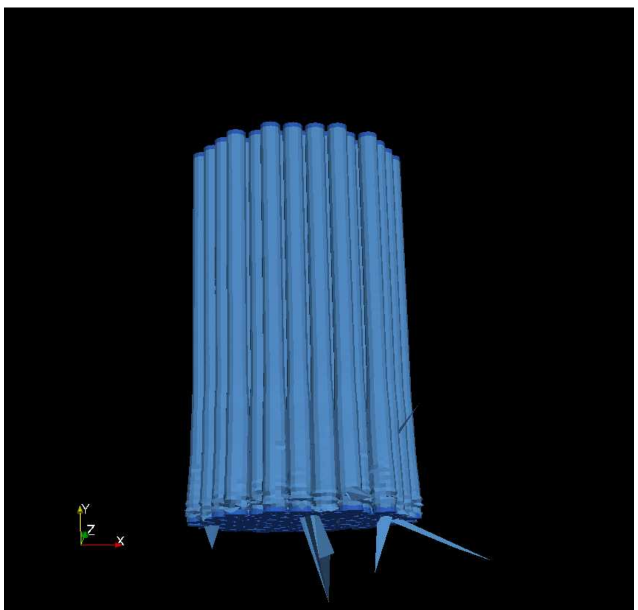
- Shell elements are used in the impact code to simulate very thin materials, such as the fuel clad
- They have no volume, but do have mass and stiffness
- DAGMC does not currently know how to treat these
- Shells can be manually removed prior to running DAG-MCNP5, but we are working on a way to deal with them automatically
- Would like to use the surface of the shell element to define complement volumes

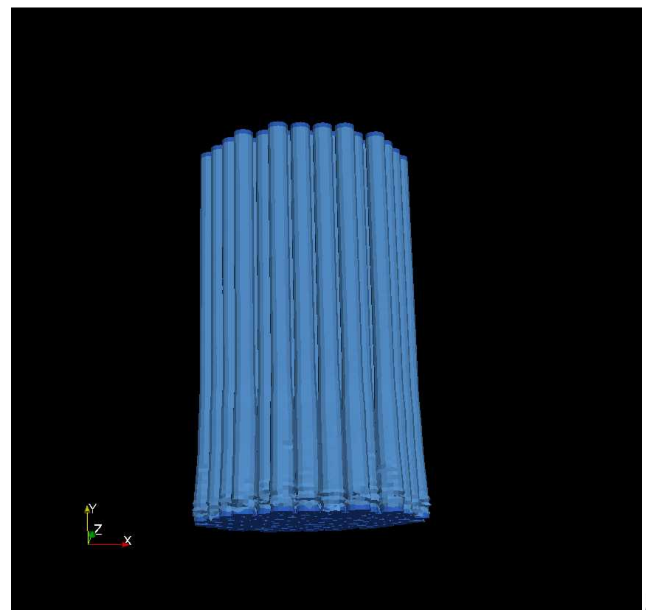




Challenge: Element Death

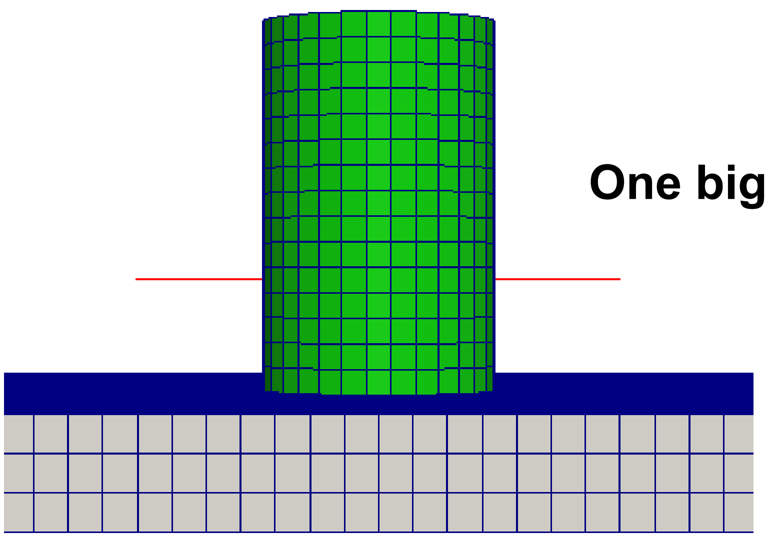
- Elements that have experienced an excessive amount of deformation in the impact calculation are sometimes “killed”, where the stiffness is set to 0
- Nodes of elements with 0 stiffness can simply move off to infinity, creating very large artificial volumes
- Portions of the material “disappearing” is non-physical and development is required for DAGMC to deal with this



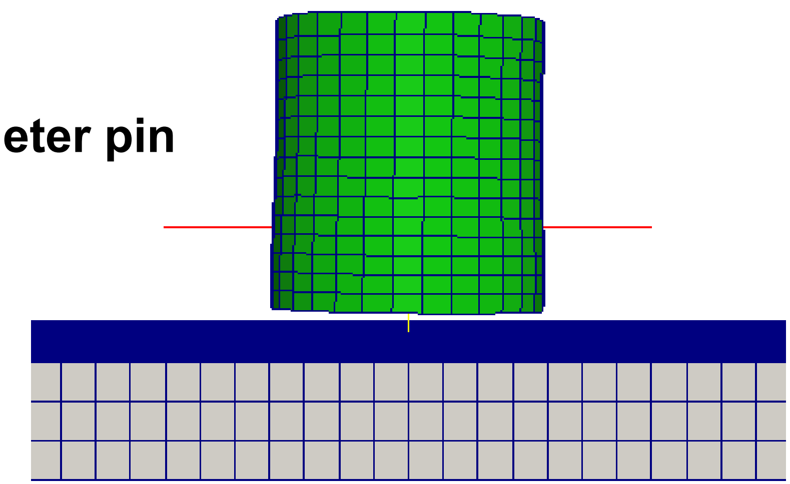


Simple test-geometry impact and reactivity

- One large-diameter fuel pin used for proof of concept
- Demonstrated entire process
  - Geometry → meshed → impacted → read with DAGMC → reactivity using DAG-MCNP5
- Discovered that the fuel model* resulted in a decrease in fuel density
- Needed to adjust density in criticality code to conserve fuel mass
- Results for k-eff: Undeformed = 0.988, Deformed = 1.030, Deformed (density adjusted): 1.007



One big diameter pin

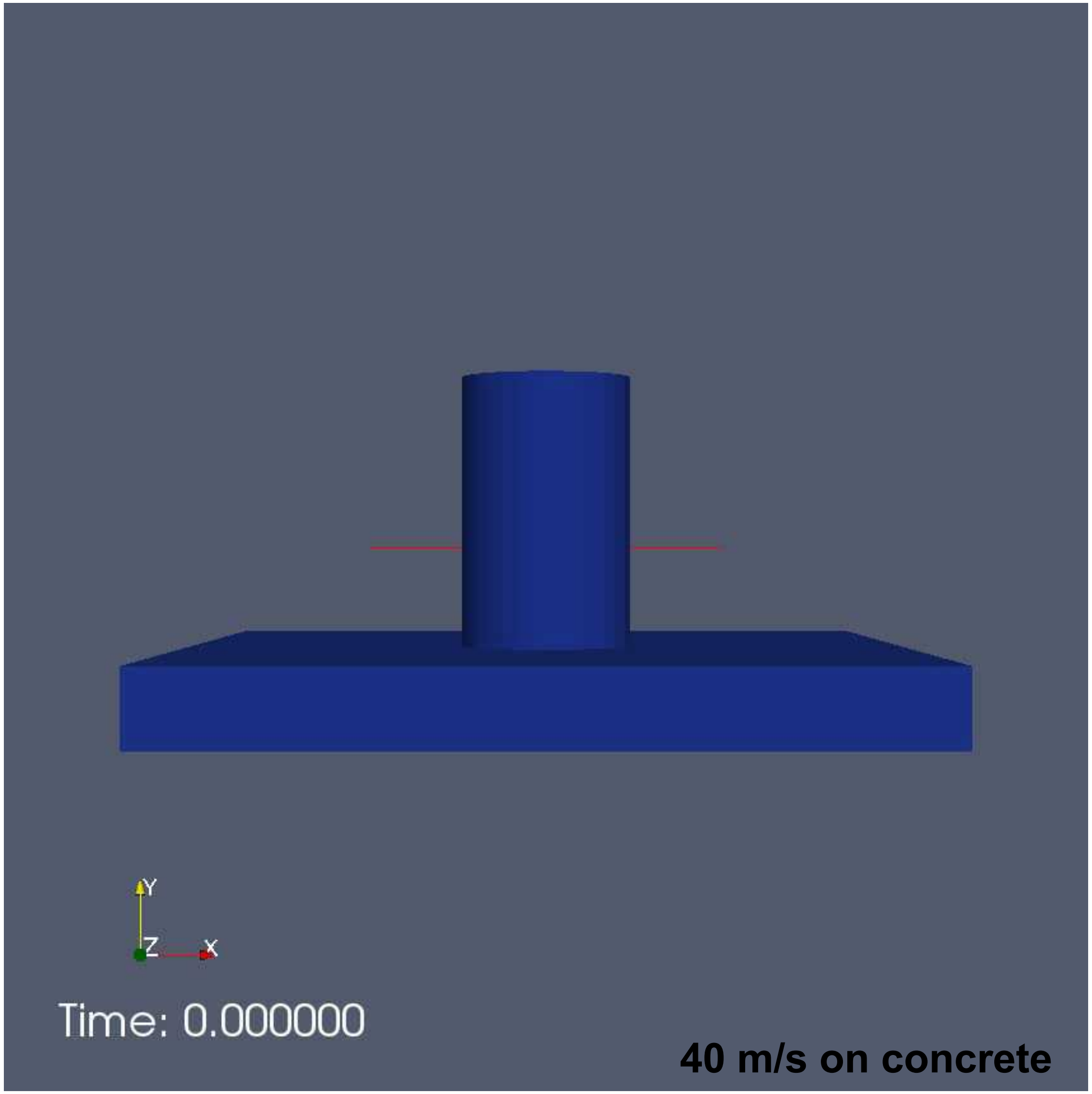


a) undeformed

b) deformed (40 m/s impact)

*Pronto3D "soil in foam" model validated in RTG impact tests for PuO_2 and UO_2

Impact of Large-Diameter Pin



- **Peak compression is for a few milliseconds**
- **Rebound configuration is similar to peak compression**

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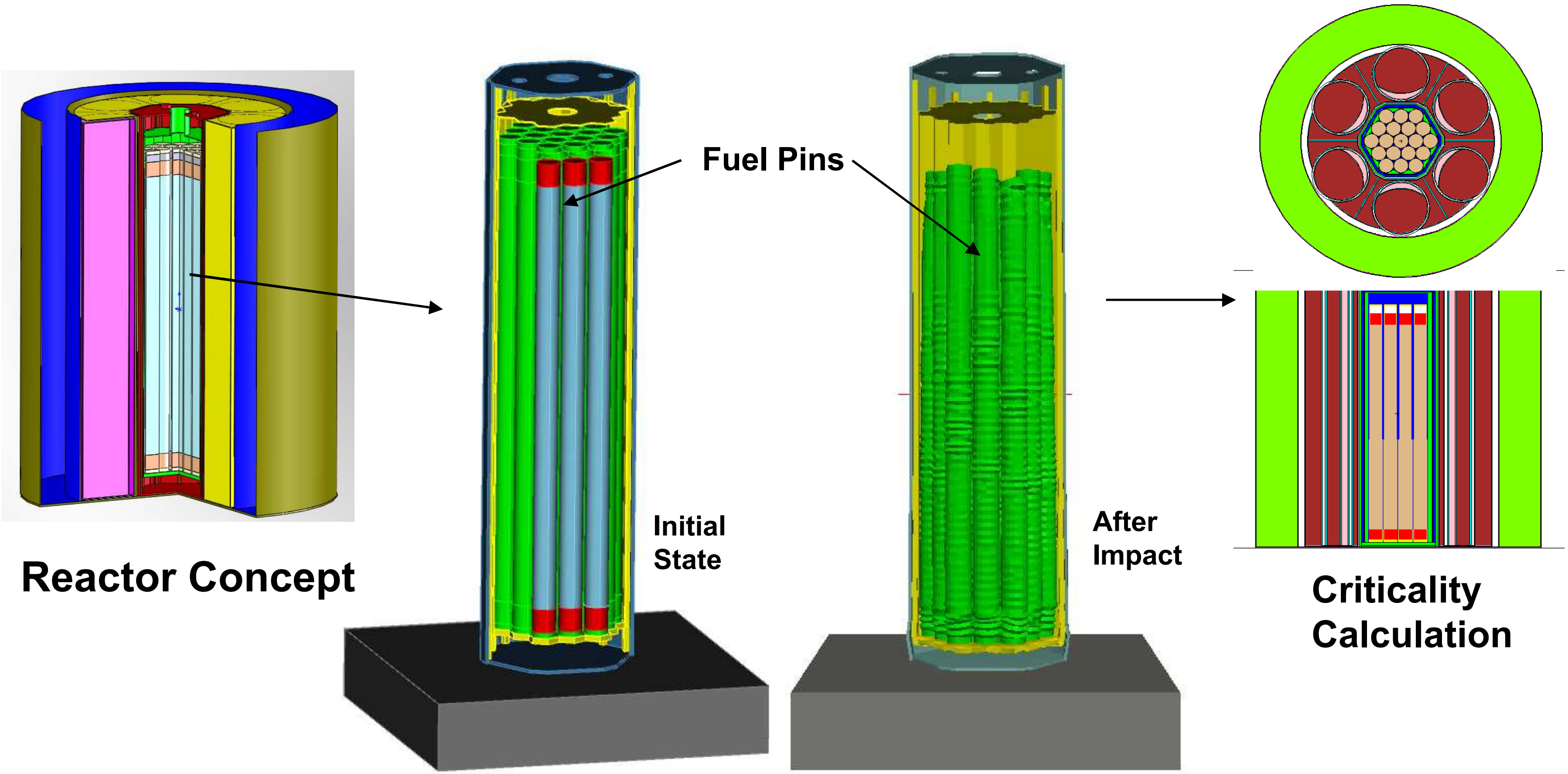
Challenge: Non-uniform Density Changes

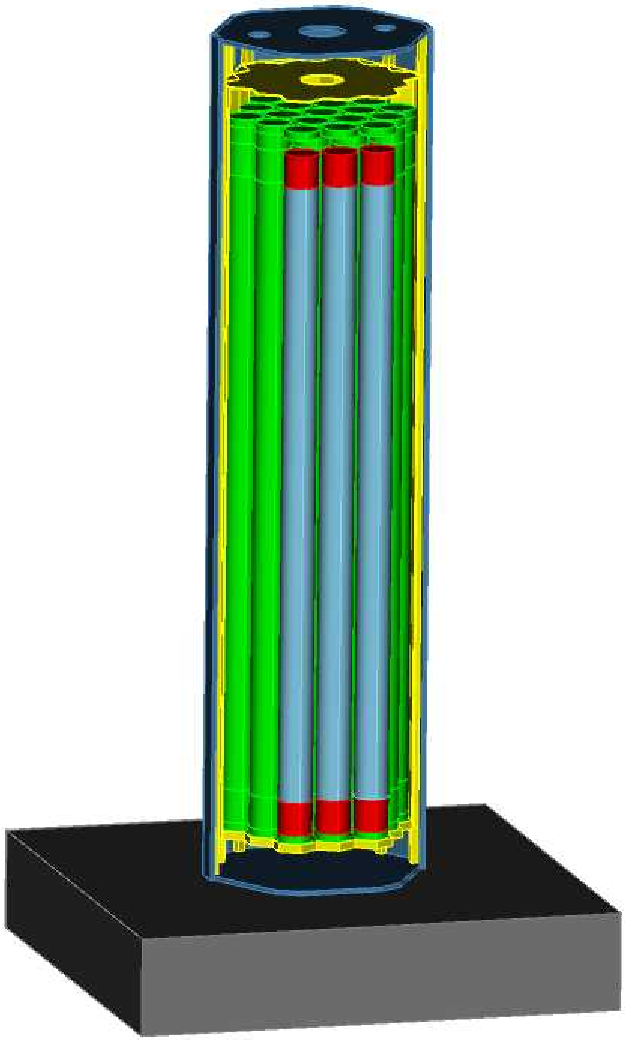
- Deformation causes non-uniform changes in material density
- In single large-diameter pin test
  - 9% increase in volume/decrease in density
    - ~0% in top mesh elements
    - >9% in bottom mesh elements
- Need to characterize variation in density change in realistic reactor geometries
  - Narrow distribution of volume change permits uniform density adjustment
  - Wide distribution of volume change requires high-fidelity ray-tracing

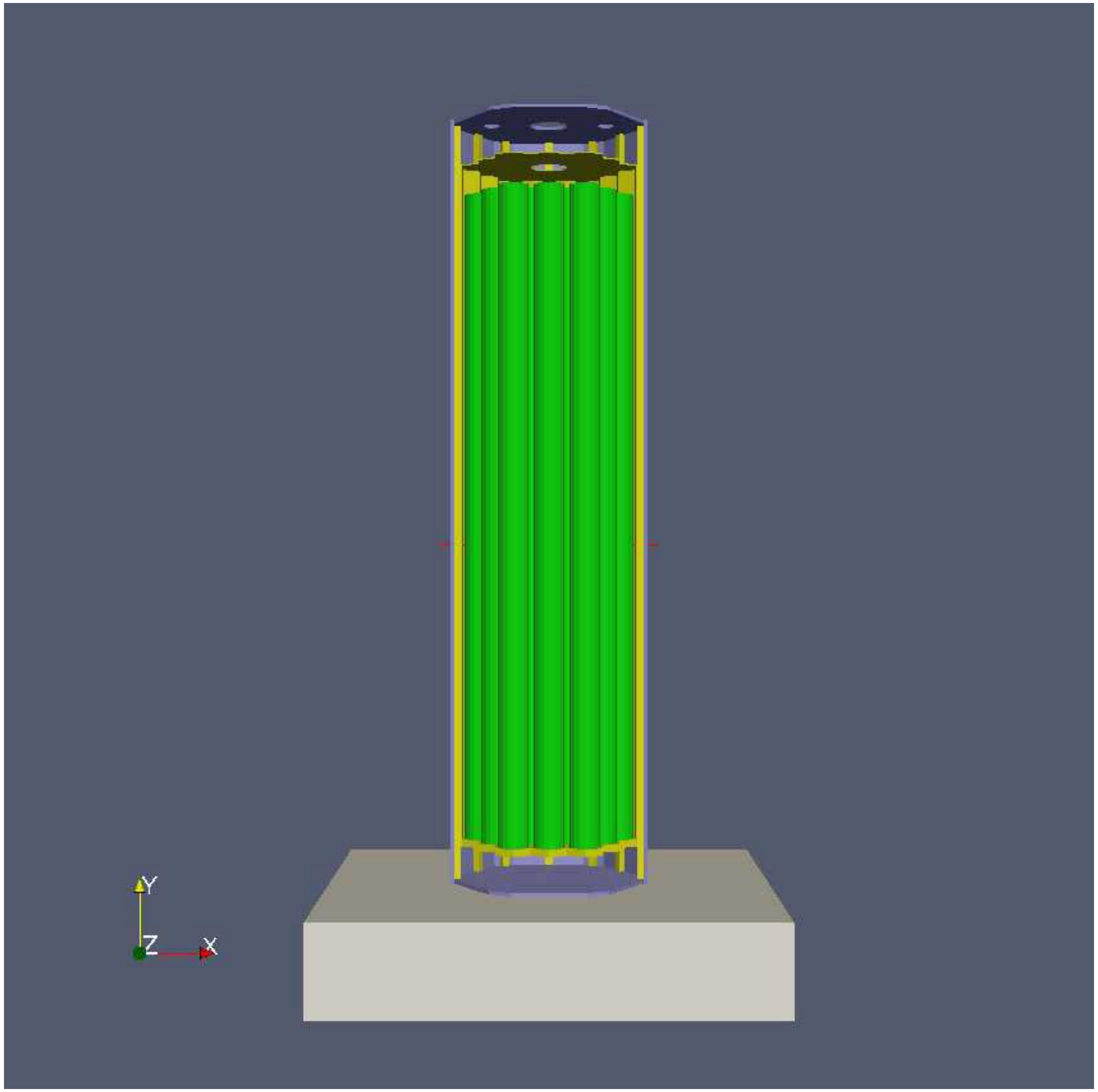
19-Pin Sample Reactor Impact



40 m/s (90 mph) impact on concrete

19-Pin Core, 40 m/s (90 mph)





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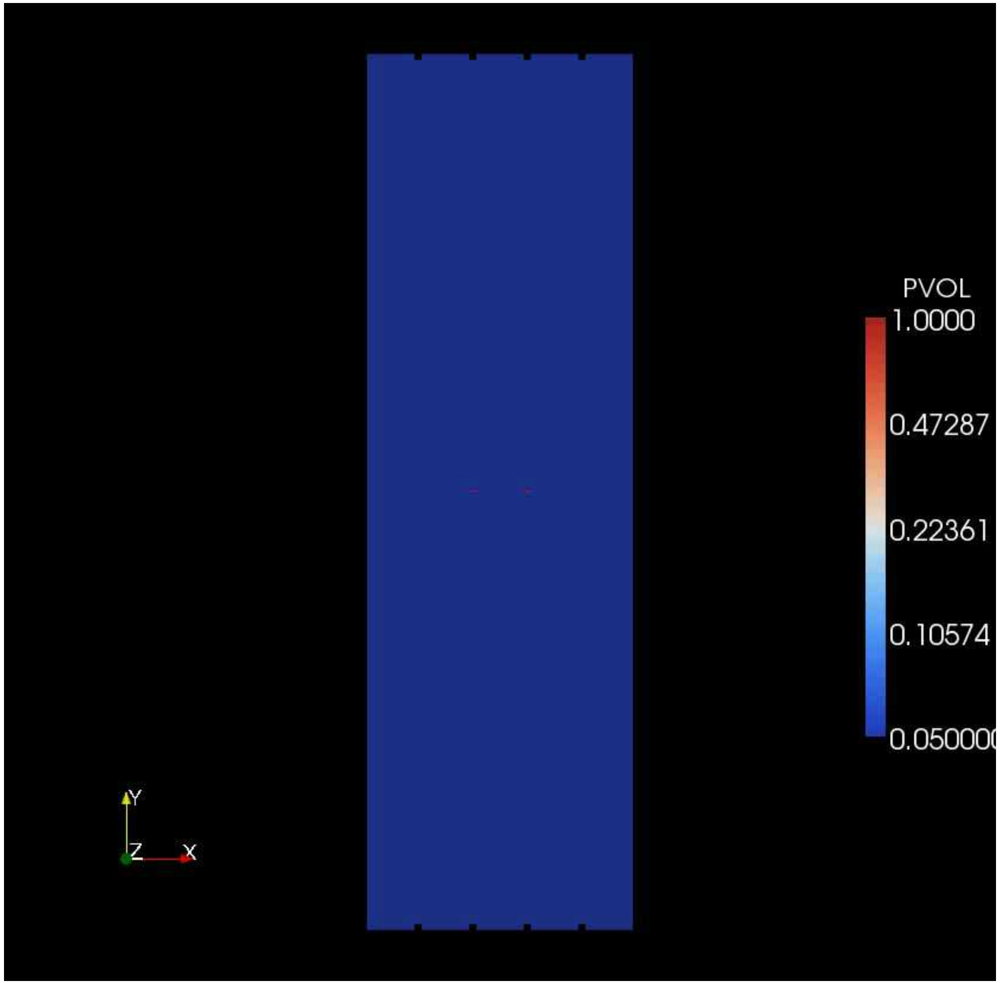
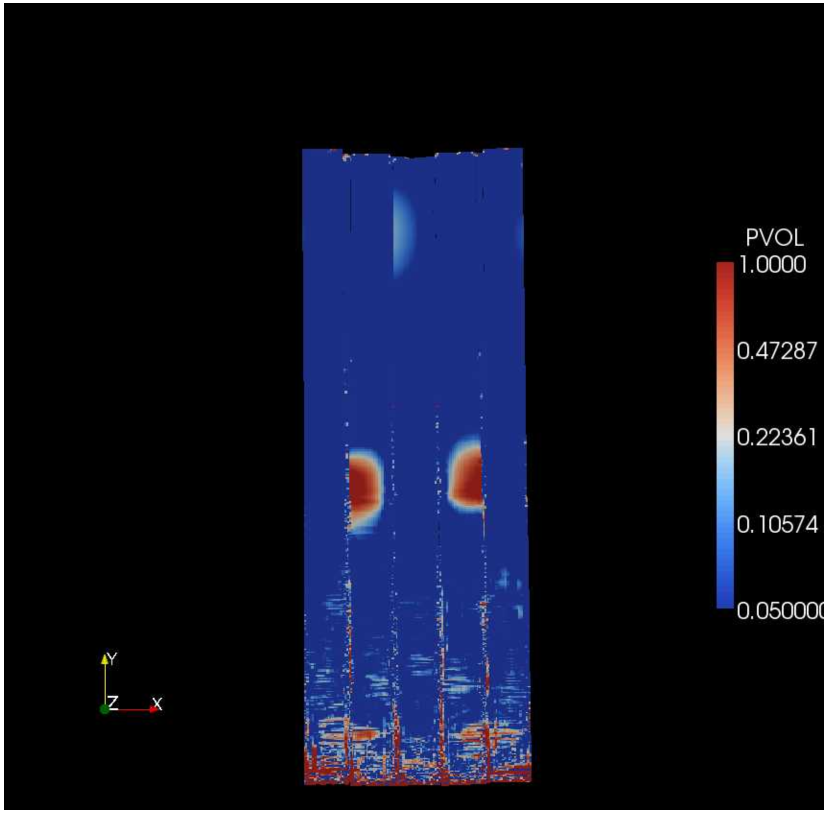
Non-uniform Density Change in 19-Pin Core

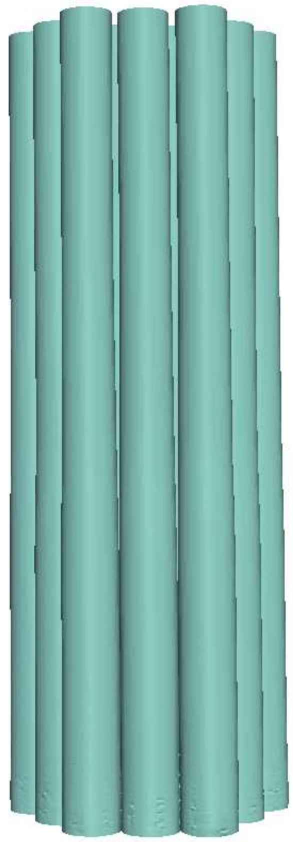


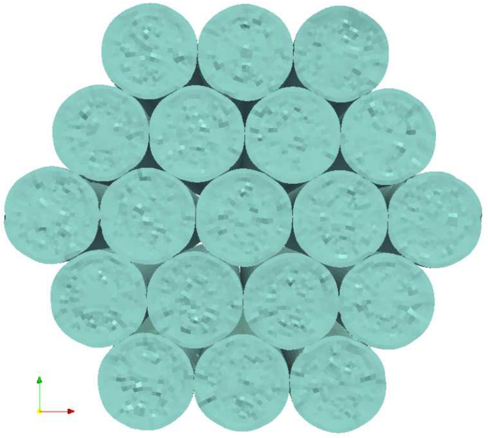


Scale represents percent change in volume for that mesh element

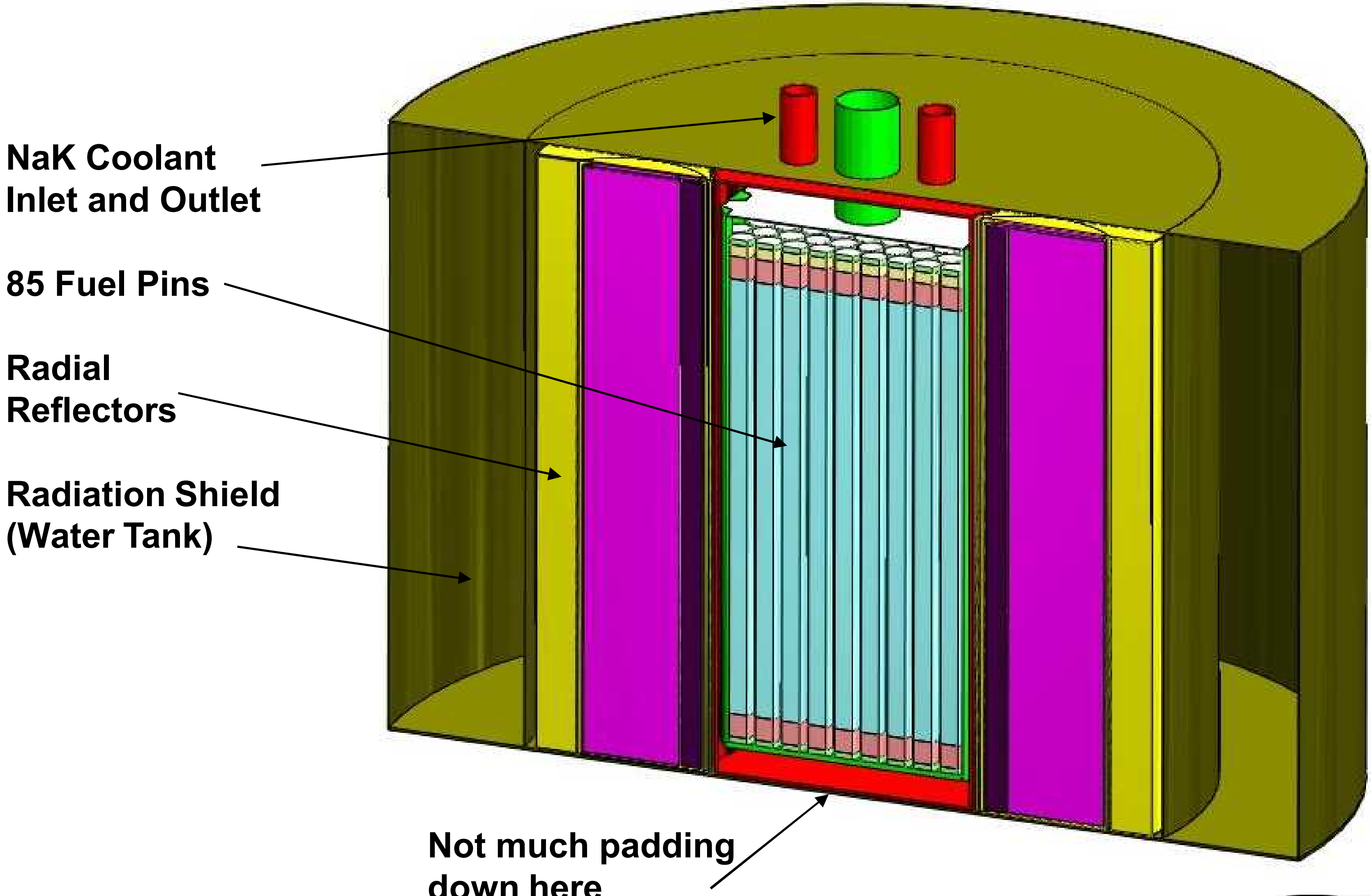
19-Pin Sub-Scale Reactor Results

- All the pins bulge and touch in the lower half of the core

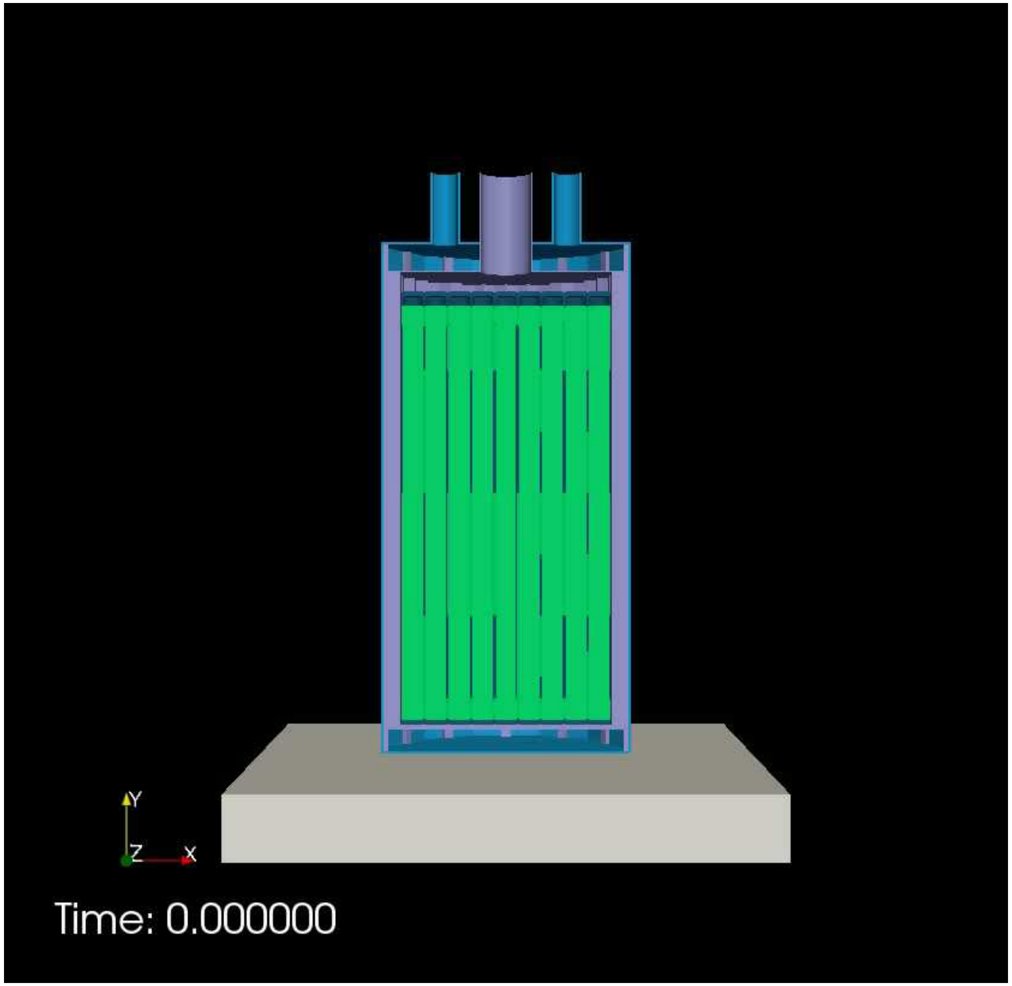


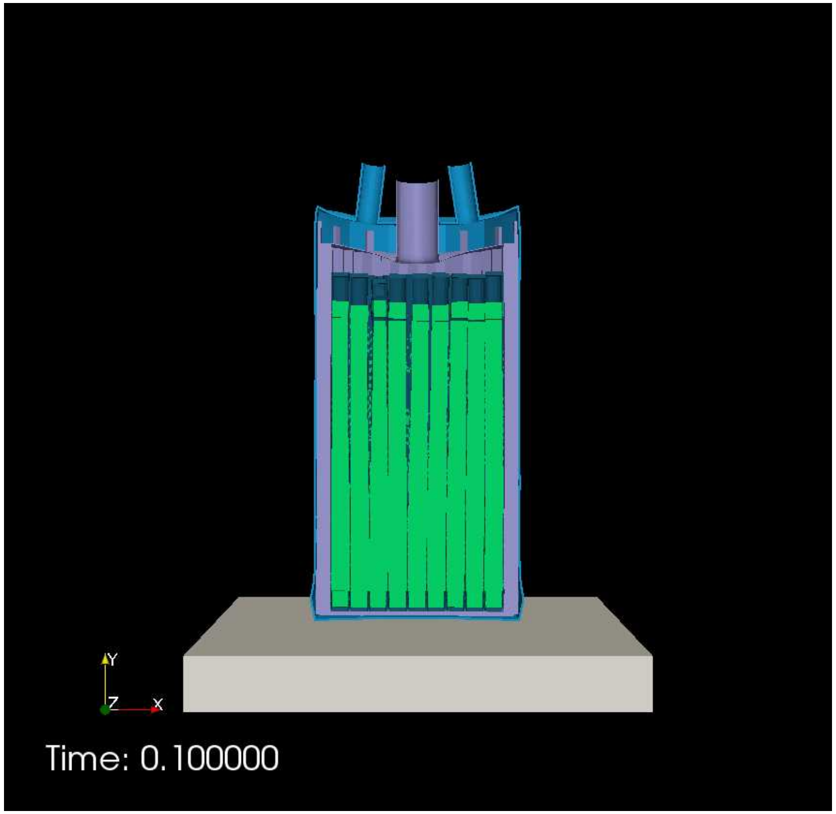


85-Pin Full-Scale Space Reactor



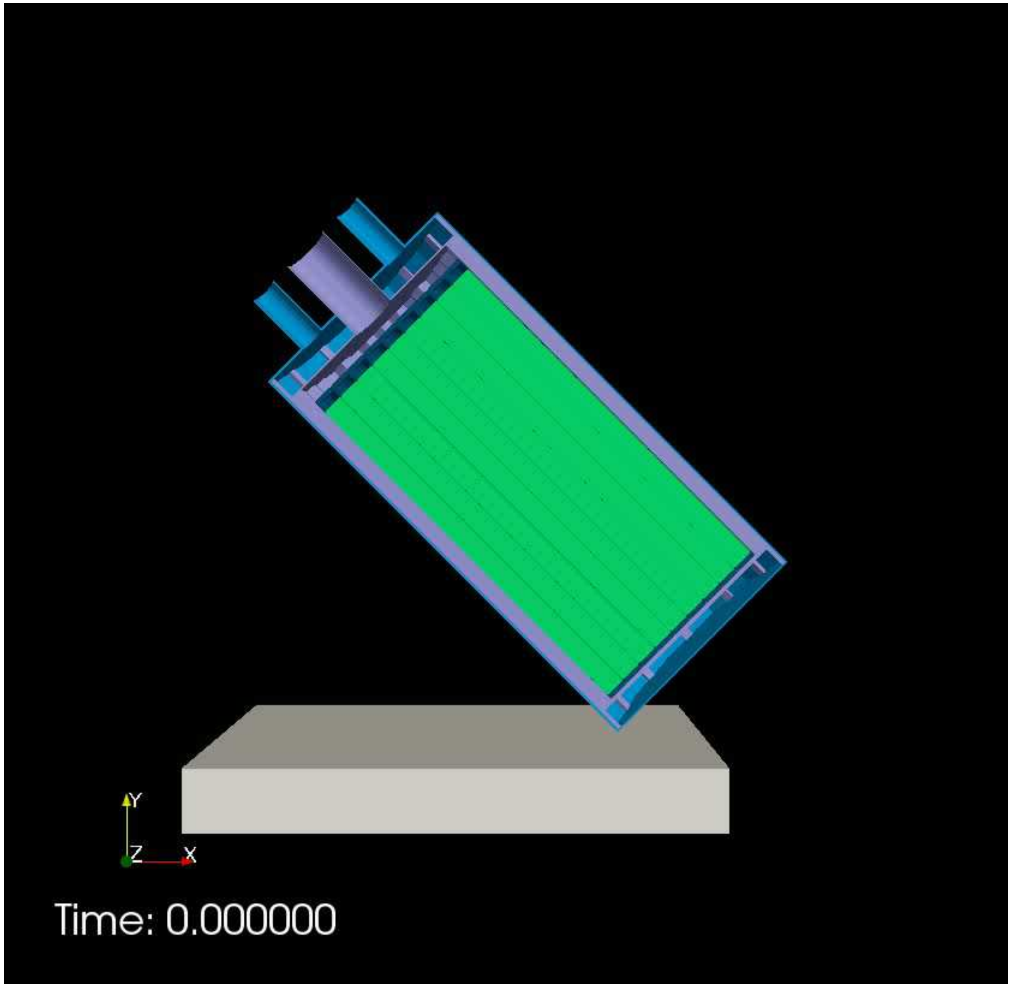
85-Pin Full-Scale Space Reactor Impact

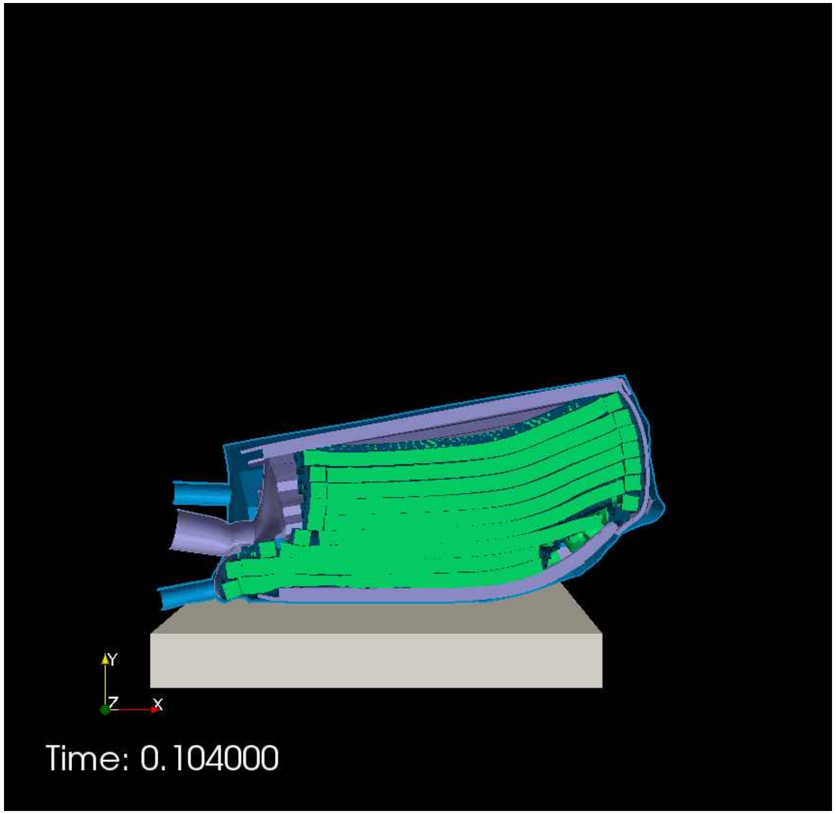




40 m/s on concrete

85-Pin Full-Scale Space Reactor Impact, 45°

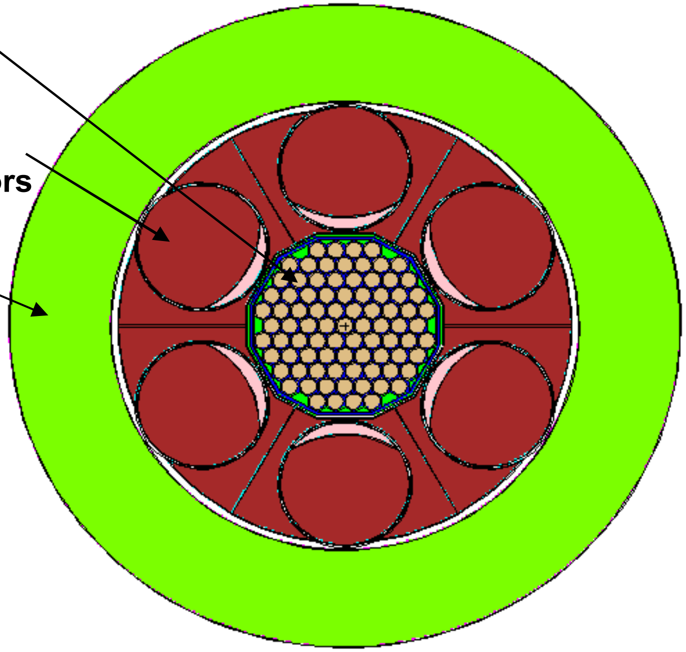




40 m/s on concrete

Reactivity Changes for Assumed Deformation

- Scoping studies were made of reactivity changes from assumed deformation
- Bottom half of all pins were expanded until they touched
- Pin lengths were reduced to keep the same total fuel mass
- Neutron Multiplication (k-eff) increased by 5% ($7)
- Reactor stayed subcritical



85 pin reactor cross section

MCNP Results for 85-pin Reactor Model

Status	Geometry (CD* position)	Surrounding Material	Keff (std dev)
Pre-Impact	Water Shield (0)	Void	1.02072 (0.00096)
Pre-Impact	Water Shield (180)	Void	0.86142 (0.00101)
Post-Impact	Water Shield (180)	Void	0.90915 (0.00076)
Post-Impact	Pressure Vessel (NA)	Water	0.88644 (0.00105)
Post-Impact	Pressure Vessel (NA)	Wet Sand	0.95541 (0.00098)
Post-Impact	Pressure Vessel (NA)	Liquid H_2	0.81910 (0.00092)

* Control Drum, 0 degrees is full out, 180 is full in

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Summary

- Simple geometry impact run performed
- Simple geometry post-impact criticality determined with DAG-MCNP5
- 19-pin sub-scale reactor geometry impact run performed at 0^o and 45^o impact angles
- 85-pin full-scale reactor geometry impact run performed for core and core basket
- Overcoming issues identified in the transfer of deformed geometry into DAG-MCNP5