PEGASUS™: A Versatile Nuclear Fuel Code for Used Fuel Modeling

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Introduction

PEGASUS™ is a fuel performance code that is built upon a robust finite element computational framework, has high-fidelity 3-D structural and thermo-mechanical capabilities which enable the modeling of fuel responses in the entire fuel cycle from in-core fuel performance analysis mode to ex-core structural analysis mode

"High Fidelity" 3D FEM-based Fuel Performance Code

Thermo-Mechanics + Structural Analysis

Total Fuel-Cycle Analysis:

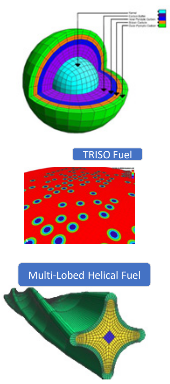
In-reactor Fuel Performance to Backend fuel storage & transportation

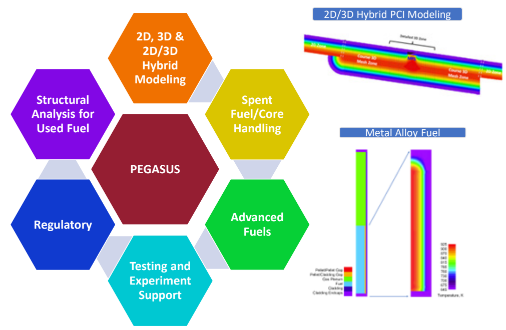
Built-in 2D & 3D mesh generation

2D/3D hybrid modeling for PCI

Applications

PEGASUS™ code application includes LWR fuel operation diagnostic, structural analysis for used fuel, modeling irradiation tests and various fuel forms for advanced reactors





New Approach for Used Fuel Modeling

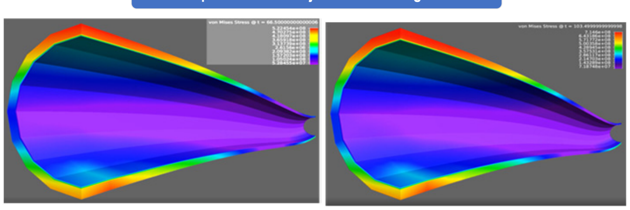
The current practice of used fuel safety evaluation have limitations which have contributed partly to the uncertainty in used fuel management.

A new approach using the PEGASUS™ code for the analysis of used fuel, treats used fuel modeling as a continuation of in-reactor fuel performance modeling, and it preserves the material property evolutions during base irradiation as the initial conditions for used fuel storage and transportation analyses.

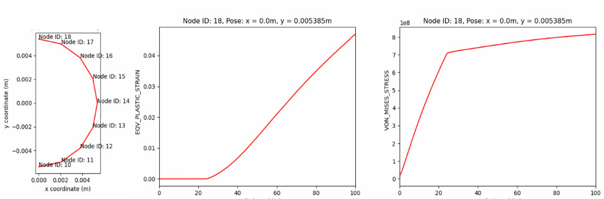
Modeling Results

This example models a hypothetical accident of a 9-m horizontal drop of a loaded dry storage cask. A 0.5 m segment of the irradiated fuel rod (with 2-year operating history) is modeled using a 3-D smeared fuel column. Structural analysis is performed under various load conditions.

Response When Subjected to Bending Load



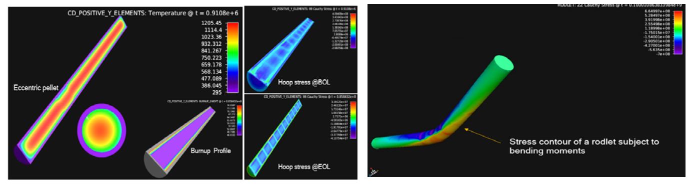
Cladding Deformed under: Left) the Moment of 62.2 N-m, and Right) the Moment of 87.5 N-m. The fuel is removed for clarity



Cladding Plastic Deformation Up to 4.7% Subjected to Bending Moment

Methodology

Fuel performance analysis is performed for in-reactor operation, and results are saved in a database that includes the material states at the end of life. The database is subsequently loaded into a restart input for the analysis of structural response under dry storage or transportation conditions.



3-D Rodlet Response in Reactor Irradiation (59 GWd/tU)   3-D Rodlet Stress Contour under Bending

Features to Facilitate Used Fuel Modeling

General finite element modeling capability

PEGASUS™ has the capability of modeling large deformations and implements non-linear elastic and plastic constitutive models and contact models, which enable the structural analysis of used fuel response without resorting to a separate structural analysis code.

Database to support restart analysis

Simulation results on all the field and state variables can be selectively saved in a database for a subsequent re-start analysis. The database can also be used for postprocessing. This technique eliminates repetitive calculations and saves engineering costs for performing different structural analyses of used fuel using the same as-irradiated initial condition.

Locking and unlocking simulation

In each simulation, the thermal and mechanical loads and boundary conditions can be altered by locking the simulation to terminate the current loads and boundary conditions and unlocking the simulation to re-assign new loads and boundary conditions. In this way, the loads and boundary conditions from the in-reactor irradiation are automatically transferred to the dry storage environment for continuation of the analysis.

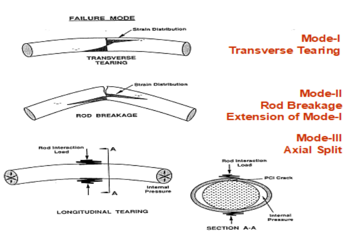
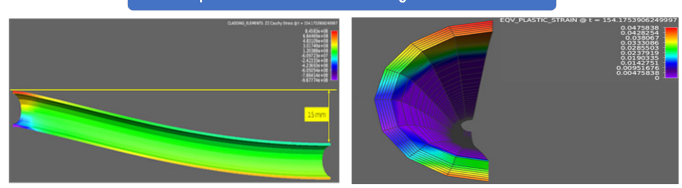


Fig. 1 Possible Failure Modes under Cask Drop in Horizontal Orientation [1]

Under the hypothetical accident and normal conditions of transport, fuel rods, with significantly degraded material states after base irradiation and dry storage, can experience various loads that could compromise the integrity of the cladding. The possible failure modes that can potentially exist under cask drop accidents are depicted in Figure 1. All three modes are coupled and can occur at the same point in time.

Response Under Combined Bending and Pinch Load



Cladding Stress and Plastic Strain Contours under a Pinch Loading of 7.4 kN Combined with a Bending Moment of 24 N-m: Left (Longitudinal Section Stress) and Right (Cross Section Plastic Strain)

The response under combined loading makes the principle of superposition inapplicable due to the non-linear behavior of both loading types separately and combined. Therefore, it is of interest to evaluate the integrity of used fuel cladding in a realistic scenario, which requires combined loading conditions.

Results with Pinch-load or Bending Moment Applied

Load	von Mises stress (MPa)	Plastic strain (%)
Pinch-load (9.32 kN)	816.0	2.2
Pinch-load (7.40 kN)	647.9	0.0
Bending (87.5 N-m)	715.0	0.0
Bending (62.2 N-m)	522.0	0.0

Conclusions

This new methodology has been demonstrated to be an efficient, and cost-effective solution for the safety evaluation of used fuel. It provides a more realistic modeling regime that can reduce conservatism by removing unnecessary assumptions, present in the current practice of used fuel analysis, and thus, achieve a more robust and accurate assessment of the integrity of used fuel cladding under accident conditions.

1. T. L. Sanders, et. al., "A Method for Determining the Spent-Fuel Contribution to Transport Cask Containment Requirements," SAND90-2406 *TTC-1019 * UC-820, November 1992.