INL/EXP-23-73736-Revision-0

The Study of Lightbridge Metallic Fuel Rods in MOOSE for Meshing Capabilities and Studying Lightbridge Metallic Fuel Rods with MOOSE

August 2023

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Changing the World's Energy Future

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The Study of Lightbridge Metallic Fuel Rods in MOOSE for Meshing Capabilities

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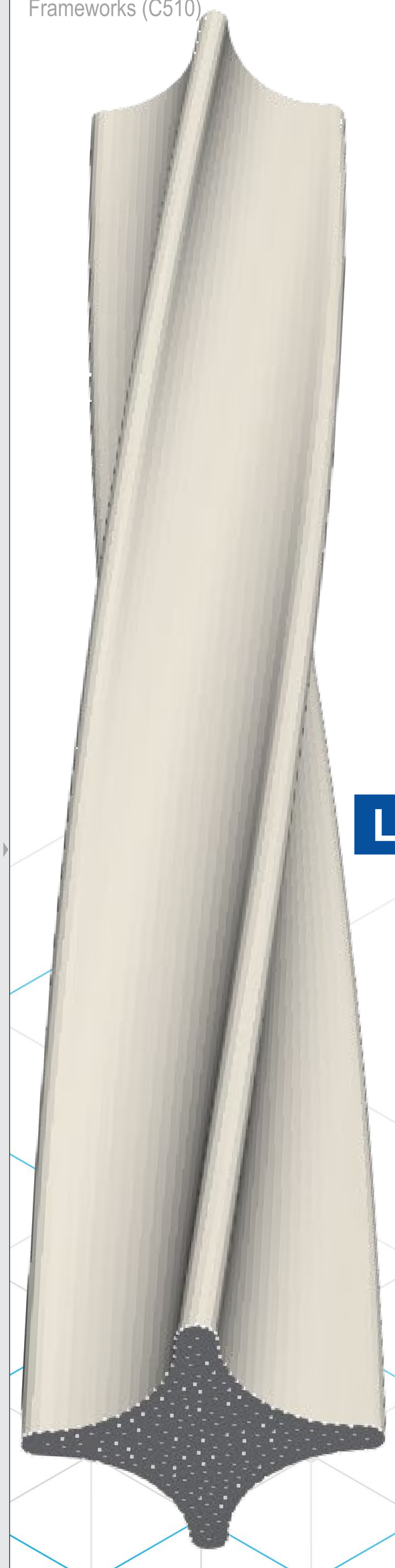
University of New Mexico, INL Computational Frameworks (C510)



Introduction

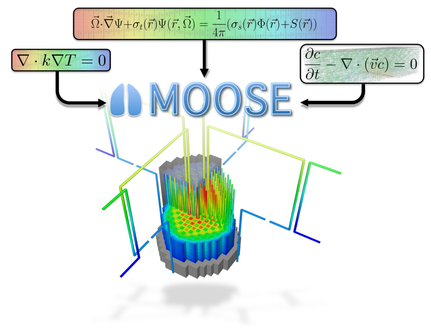
INL's mission is to lead by example in discovering and ensuring various methods of clean energy and critical infrastructure for the world.

- The MOOSE team, is participating in achieving this goal by introducing groundbreaking software to model several different energy systems that can better help us understand them for practical application.
- Through MOOSE it was possible to generate a next generation nuclear fuel rod application that allows nuclear reactors to operate at a higher power density while increasing the safety margins of a reactor.

MOOSE

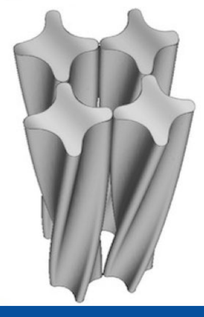
A **multi-physics object-oriented simulation environment** that allows state-of-the-art modeling and simulation techniques for several branches of science and engineering.

- Grants the ability to intelligently predict a wide range of simulations which allows the user to focus on the problem at hand.
- MOOSE enables to have a quicker, more adaptable, and accessible environment for scientists/engineers to utilize.



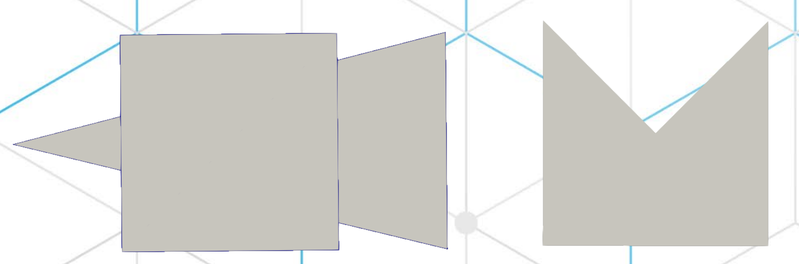
Lightbridge Metallic Fuel Rod

- Next generation nuclear fuel technology
- Improves the safety, economic, and proliferation resistance of existing and new reactors
- The LBFR consists of a cruciform, multi-lobed, helically twisted design



Diagnosing Mesh Defects

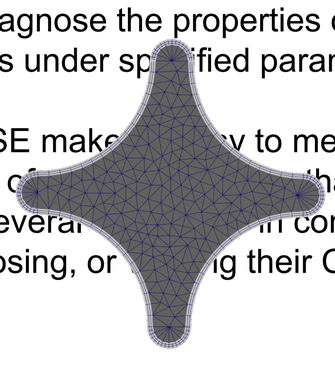
- Ability to read external mesh files (e.g. .e, .dat, .fro, .nem, etc.) in MOOSE is a huge attribute in being able to refine already existing meshes.
- It is crucial for meshes to be stitched correctly before examining because it can affect results.
- Meshes can have multiple errors like:
  - Non-conformality
  - Element/Node overlap
  - Non-planar element sides
  - Volume discrepancies



Middle : Overlapping elements
Right : May cause a negative volume discrepancy
Left: Poor 3-D helical extrusion

Meshing in MOOSE

- Meshing is the automated process of computer aided designs (CAD) to analyze and diagnose the properties of geometric shapes under sp[illegible]fied parameters.
- MOOSE make[illegible]y to mesh with their library o[illegible]hat helps users with several [illegible]n connecting, diagnosing, or [illegible]g their CAD's.

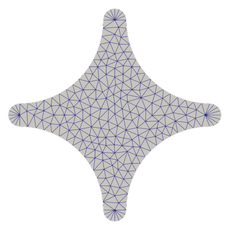


Extruding with a twist!

- Advanced Extruder Generator : Modified generator to allow 2D mesh to be helically twisted
- Parsed Curve Generator : Allows for several curves to be connected and made to a mesh
- Stitched Mesh Generator: Allows for multiple meshes to be stitched together.

Repairing Meshes

- As discussed previously, meshes may have impurities restricting good results.
- MOOSE includes a repair generator that can identify where in the mesh it is faulty through user specification.



Top: Mesh not stitched due to overlapping nodes
Bottom: Repair generator fixing the overlapping nodes

MSIPP Minority Serving Institutions Partnership Program — Department of Energy Office of Environmental Management

MOOSE

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Studying Lightbridge Metallic Fuel Rods with MOOSE

Daniel Levario | University of New Mexico | Computational Frameworks Intern (C510) with Dr. Guillaume Giudicelli

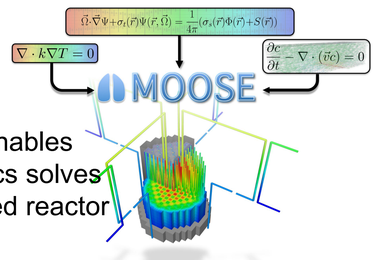
Introduction

Supporting INL's mission to transform our nation's energy future, notably through innovative nuclear energy solutions, this project focuses on modeling accidental tolerant fuel. In collaboration with MIT, we modeled with MOOSE-based tools the Lightbridge metallic fuel design. Lightbridge fuel is envisioned to enable higher power output and larger safety margins for both current and advanced nuclear reactors.
We present here the advanced meshing capabilities developed and preliminary physics results.

MOOSE

MOOSE is a **multi-physics object-oriented simulation environment** that allows state-of-the-art modeling and simulation to support science and engineering, notably in the nuclear field.

Several NEAMS reactor modeling tools are built on MOOSE: Bison, Griffin, Pronghorn, enabling this study



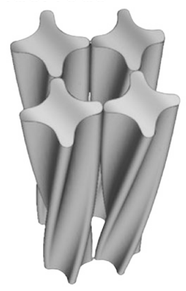
MOOSE enables Multiphysics solves of advanced reactor systems

Lightbridge© Fuel

Accident Tolerant Fuel (ATF) is a program created after the Fukushima accident to provide additional resistance to potential accidents in nuclear power plants.

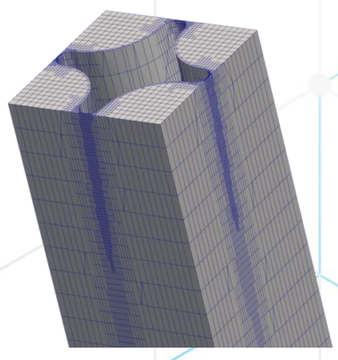
- The Lightbridge metallic fuel is designed to improve the **safety**, economics, and proliferation resistance of existing and new reactors.
- Due to the increase in surface area & metallic fuel, the fuel rod has a **decreased** operational **temperature**, allowing for an increase in power, improving the economic performance.
- The design consists of a cruciform, multi-lobed, helically twisted Zirconium-alloy cladded rod.

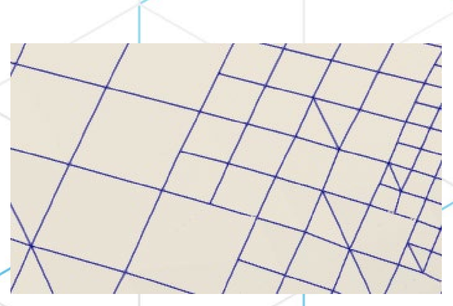
Small lattice of Lightbridge fuel rods



Simulating the fuel starts with a mesh

- Partial differential equations can be solved with the finite element method. Physical quantities, like temperature are represented on a mesh.
- MOOSE can read numerous external mesh file types, such as Exodus, Abaqus' .inp, or gmsh's .msh
- The Lightbridge fuel was meshed in StarCCM©, but some features are not supported in MOOSE
- Unsupported features, in general, include:
  - Non-conformality
  - Element/Node overlap
  - Adaptivity creating non-conformal meshes
  - Mixed element types in a subdomain
- Analysts need a way to distinguish which of these features may be present in their mesh and if possible, have MOOSE automatically fix it.
- In my internship we created, the MOOSE **repair** and **diagnostic** generators in order to be able to read the external Lightbridge fuel mesh.





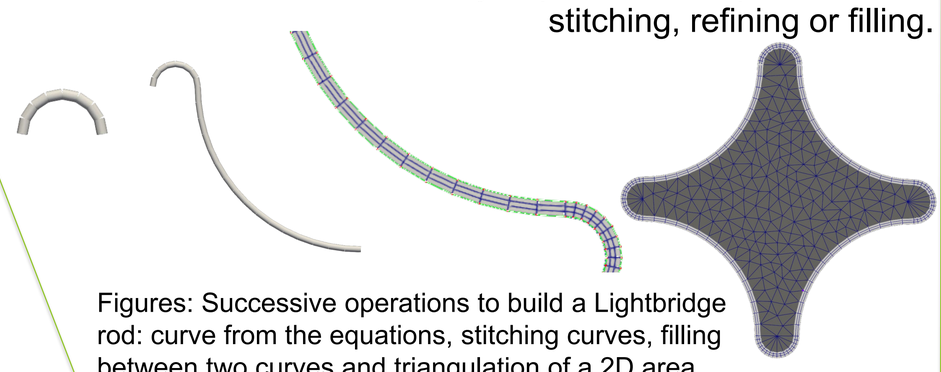
Top: Initial mesh (left) and its unsupported features (beneath). We can see non-conformality born out of adaptive refinement, mixed element types (hexahedra and prisms)

In-MOOSE mesh of the Lightbridge rod

Meshing directly in MOOSE

In parallel to adding capability to work with external meshes, we built the **in-MOOSE** mesh generation of the Lightbridge fuel.

- MOOSE mesh generation is a hierarchical process: mesh "generators" each perform one operation on the output of their predecessors.
- MOOSE has a wide variety of pre-defined operations like stitching, refining or filling.



Figures: Successive operations to build a Lightbridge rod: curve from the equations, stitching curves, filling between two curves and triangulation of a 2D area

Extruding with a Twist!

Extrusion is used to obtain 3D meshes from 2D meshes. Numerous nuclear reactor systems can be represented with axial extrusion.

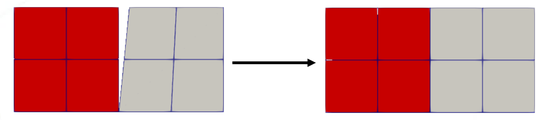
- Lightbridge is not axially symmetric, but we were able to modify the extrusion generator to perform the **helical twist**
  - *Current works*: symmetry-preservation and volume conservation!

$$\overrightarrow{M_i M_{i+1}} = \left(\cos\left(\frac{\pi * layer\ index * step\ size}{2 * twist\ pitch}\right) + ..\right)\vec{t} + \left(sin\left(\frac{\pi * layer\ index * step\ size}{2 * twist\ pitch}\right) + ..\right)\vec{r} + \delta\vec{z}$$

The step between to extruded layers can be expressed as a combination of the radial tangent axial vectors

Repairing Meshes

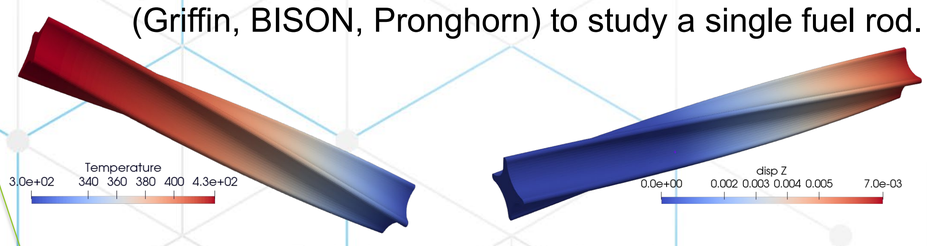
- Both for building a new mesh and for loading external meshes, we should be able to "fix" mesh features unsupported by MOOSE/libMesh.
- The MeshRepairGenerator was developed to remove **overlapping** nodes and **non-conformality** issues.
- *Current works*: element size control, splitting blocks by element types, fixing sideset orientation



Overlapping nodes (separated for clarity) can be merged using the new capability

Solving Physics

- The performance of nuclear fuel can be evaluated by modeling the core nuclear reactor physics: **neutronics**, **fuel performance** and **thermal hydraulics**.
- Using the mesh generated, we will use the NEAMS codes (Griffin, BISON, Pronghorn) to study a single fuel rod.



Preliminary physics studies using open-source MOOSE physics modules: heat conduction (left), tensile stress test (right)

References:
- Lindsay, Alexander D., et al. "2.0 - {MOOSE}: Enabling massively parallel multiphysics simulation.", 2022
- Hartmann, C., et al. "Measurement station for interim inspections of Lightbridge metallic fuel rods at the HBWR". EPJ , 2018

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