INL/CON-20-60456-Revision-0

Bison Methods and Contact Algorithms

November 2020

Changing the World's Energy Future

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Idaho National Laboratory

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Bison Methods and Contact Algorithms

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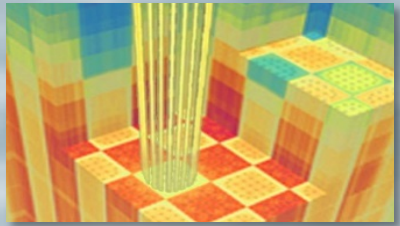
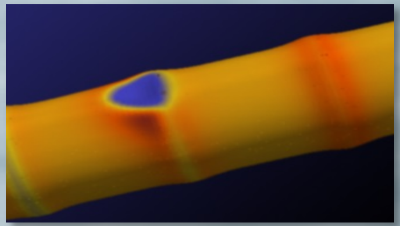
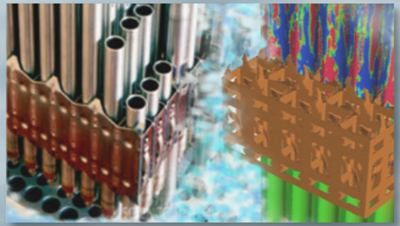




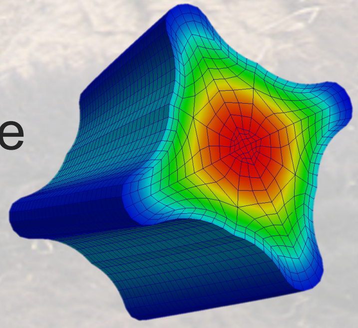
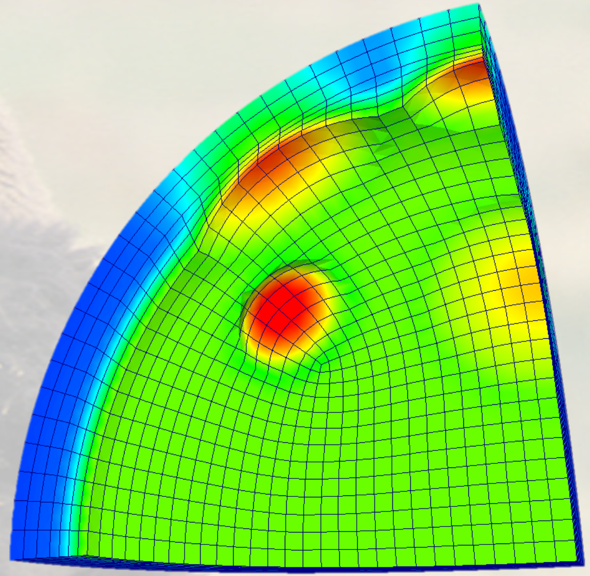
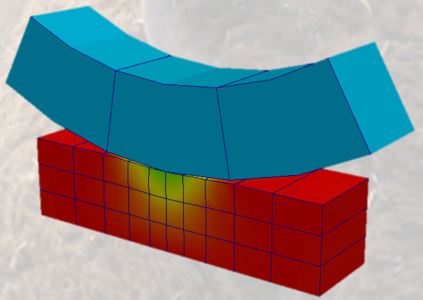
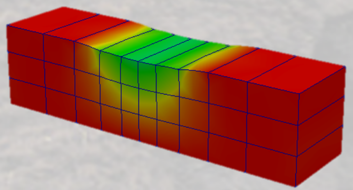
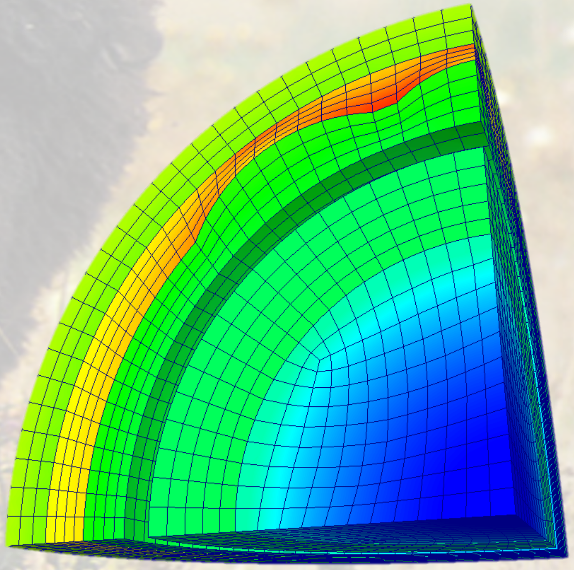
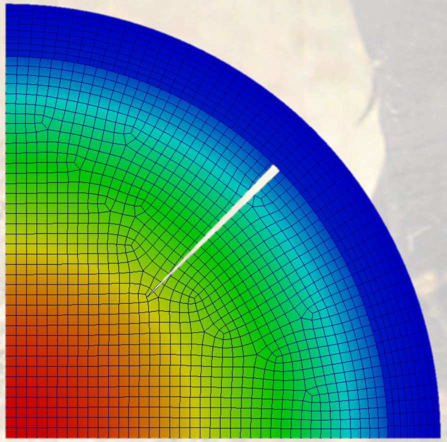
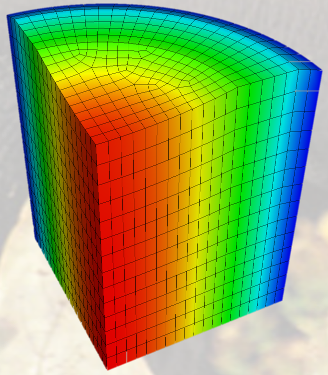
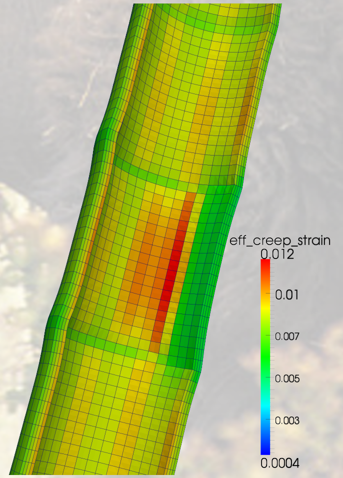


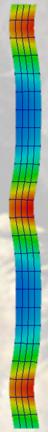
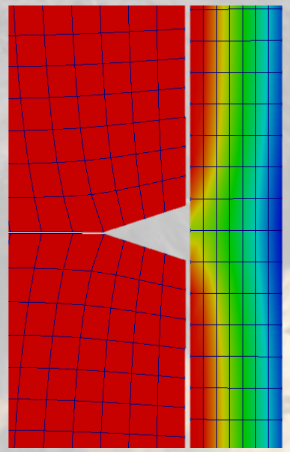
CASL
The Consortium for Advanced Simulation of LWRs
A DOE Energy Innovation Hub

U.S. DEPARTMENT OF ENERGY

Bison: What is it?

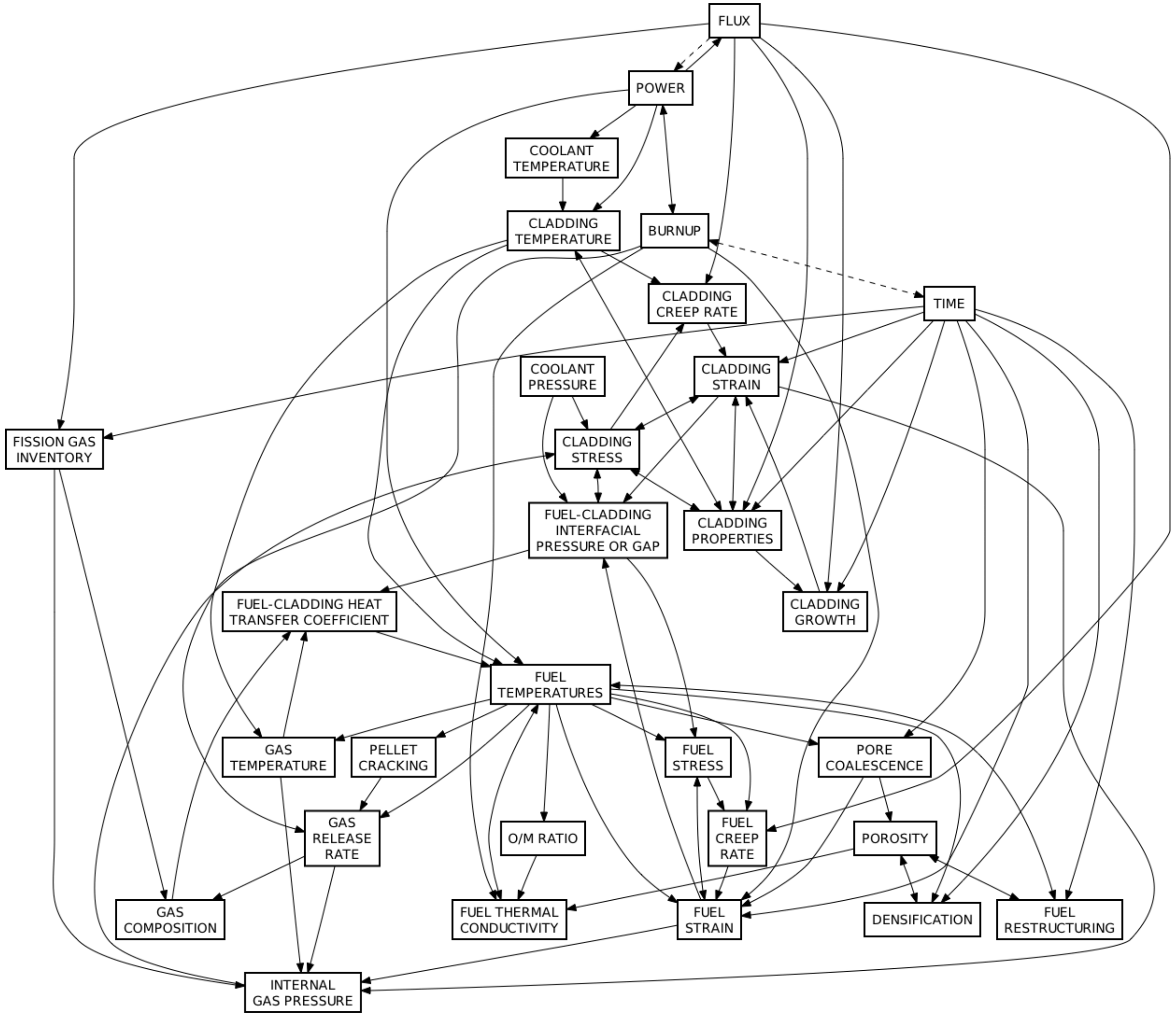
- A finite element, thermo-mechanics code with material models and other customizations to analyze nuclear fuel
  - Accepts user-defined meshes/geometries
    - 1D, 2D, or 3D
  - Runs on one processor or many
  - Analyzes a variety of fuel types
  - Couples to other analysis codes

Fuel Behavior Modeling - Coupled Multiphysics

- Multiphysics
  - Fully-coupled nonlinear thermomechanics
  - Mass transport
  - Chemistry
  - Neutronics
  - Thermal-hydraulics
- Multi-space scale
  - Important physics operate at level of microstructure
  - Need real predictions at engineering scale
- Multi-time scale
  - Long, steady operation
  - Short power ramps
  - Rapid transients



Reproduced from Beyer et al., BNWL-1898, PNNL (1975)

Burnup

- Burnup is a measure of how much fissionable material has been used
- Bison uses FIMA (fissions per initial metal atom) as the burnup unit

$$\beta = \frac{\dot{F} t M_w}{\rho N_{av}}$$

$$\dot{F} = f_a f \dot{\bar{F}}$$

- The fission rate, $\dot{F}$, is a function of power, axial power factor, and radial power factor
- Axial power factor, f_a, is supplied as input
- Radial power factor, f, is estimated by Bison

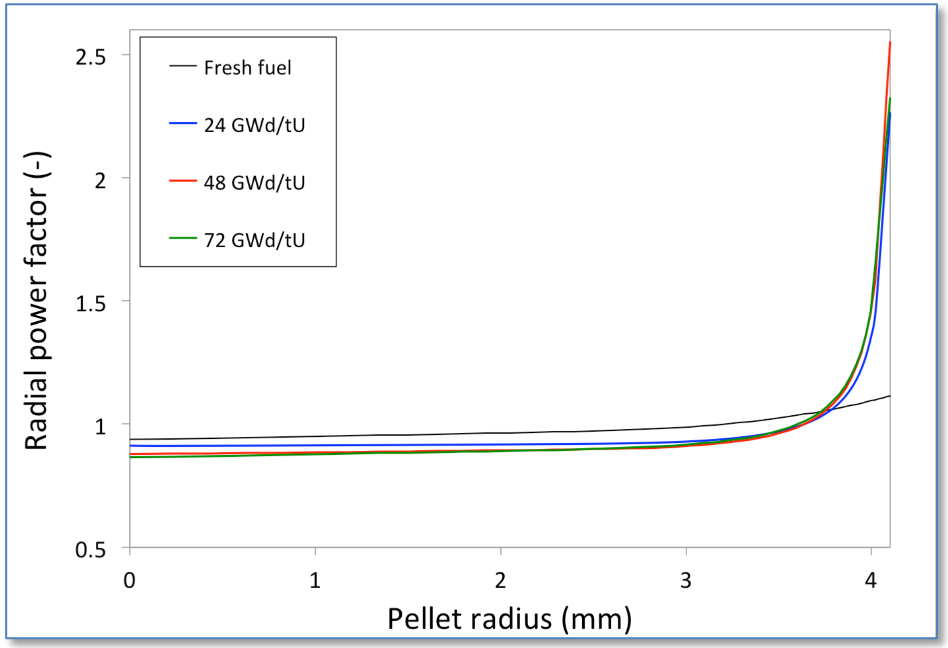
Radial Power Factor

$$q'''(r) \propto \sum_k \sigma_{f,k} N_k \phi$$

$$q'''_{av} = \frac{1}{r_{max}} \int_{r_{min}}^{r_{max}} q'''(r)\,\mathrm{d}r$$

$$f(r) = \frac{q'''(r)}{q'''_{av}}$$

$f(r)$



$$\frac{\mathrm{d}\,N_{235}}{\mathrm{d}\,t} = -\sigma_{a,235} N_{235} \phi$$

$$\frac{\mathrm{d}\,N_{236}}{\mathrm{d}\,t} = -\sigma_{a,236} N_{236} \phi + \sigma_{c,235} N_{235} \phi$$

$$\frac{\mathrm{d}\,N_{238}}{\mathrm{d}\,t} = -\sigma_{a,238} N_{238} \phi$$

$$\frac{\mathrm{d}\,N_{239}}{\mathrm{d}\,t} = -\sigma_{a,239} N_{239} \phi + \sigma_{c,238} N_{238} \phi$$

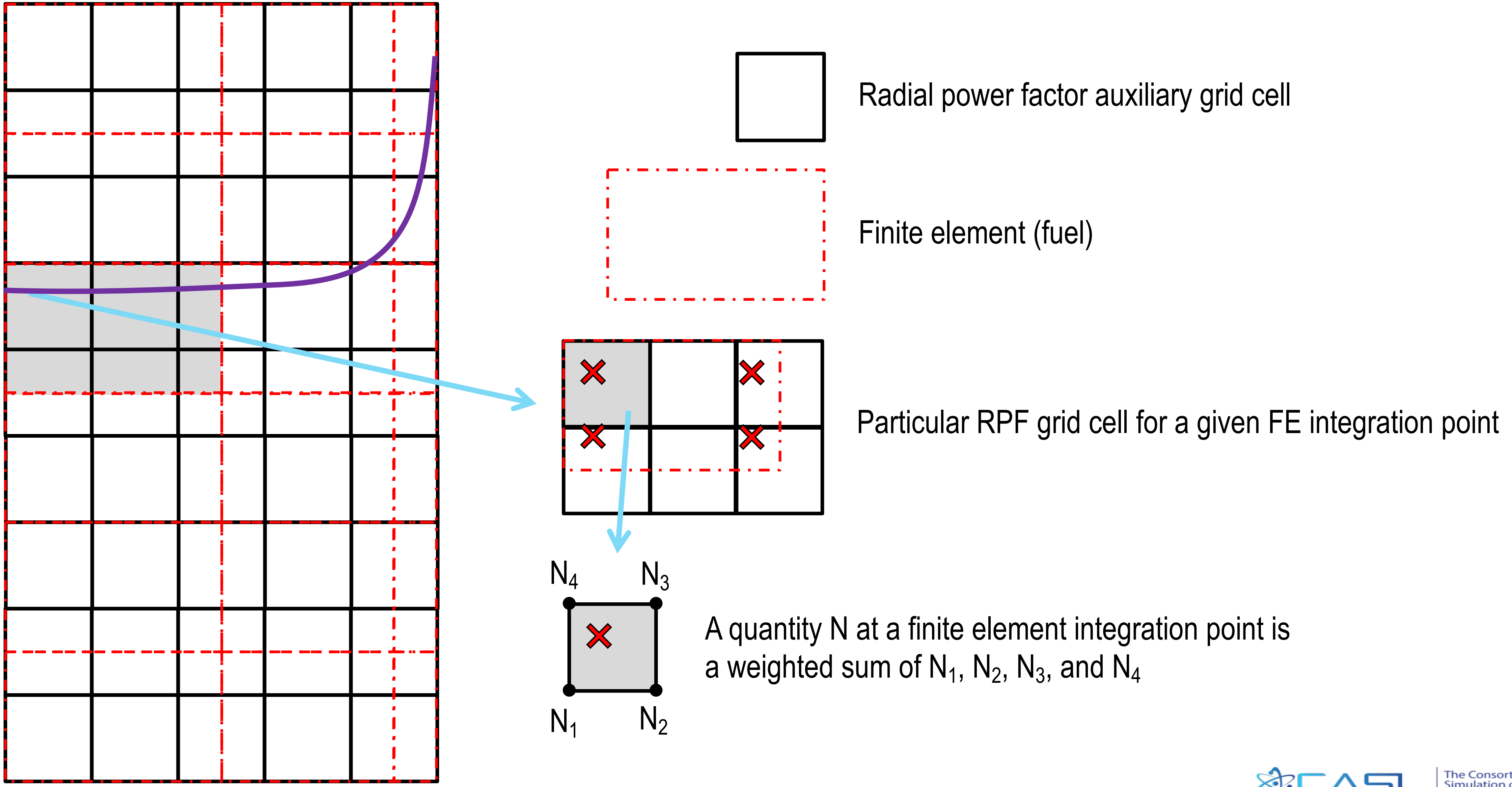
$$\frac{\mathrm{d}\,N_{240}}{\mathrm{d}\,t} = -\sigma_{a,240} N_{240} \phi + \sigma_{c,239} N_{239} \phi$$

$$\frac{\mathrm{d}\,N_{241}}{\mathrm{d}\,t} = -\sigma_{a,241} N_{241} \phi + \sigma_{c,240} N_{240} \phi$$

$$\frac{\mathrm{d}\,N_{242}}{\mathrm{d}\,t} = -\sigma_{a,242} N_{242} \phi + \sigma_{c,241} N_{241} \phi$$

See Soba, et al., JNM, 433.

Auxiliary Radial Power Factor Grid to FE Mesh



Thermalhydraulic Boundary Condition

- The thermal boundary condition used by Bison at the outside of the cladding may be specified in a variety of ways, including setting the temperature directly.
- If desired, a simple one-dimensional enthalpy balance may be used to determine the thermal boundary condition

$$H(z) = H_{in} + \frac{\int_0^Z q''(z)\pi D_h \mathrm{d}z + \int_0^Z f_c q' \mathrm{d}z}{GA}$$

$$T(z) = \mathrm{IAPWS}(H(z), P)$$

IAPWS -> International Association for the Properties of Water and Steam
P -> assumed constant in z

Heat Transfer Coefficient Correlations

- A set of correlations is available for single phase liquid forced convection, transition boiling, film boiling, saturated boiling, and other conditions.
- For single phase forced convection, the Dittus-Boelter correlation is used, giving:

$$h = \frac{0.023 Re^{0.8} Pr^{0.4} k}{D_h}$$

h -> heat transfer coefficient
Re -> Reynolds number
Pr -> Prandtl number
k -> thermal conductivity

- Then,

$$\phi = h(Tc(z) - T(z))$$

Tc -> temperature of cladding
ϕ -> heat flux

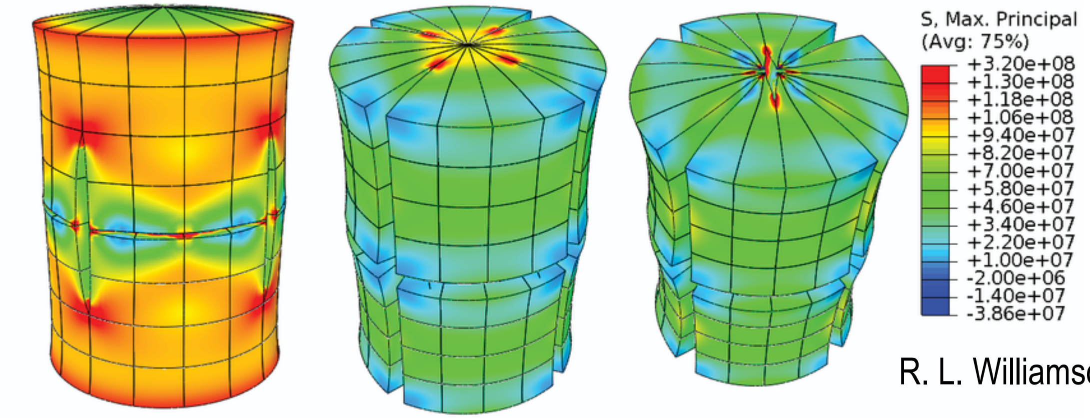
Fuel Cracking

- During the initial rise to full power, the ceramic UO_2 fuel pellets crack.
- This is due to the center of the pellet being hotter than the radial edge, which creates tensile hoop stresses at the radial edge.
- This cracking releases stress and allows the pellet to displace slightly in the outward radial direction.
- The result is a smaller gap between fuel and cladding, which affects the temperature of the fuel.
- Options for modeling include:
  - Relocation model
  - Smeared cracking
  - Isotropic softening
  - XFEM

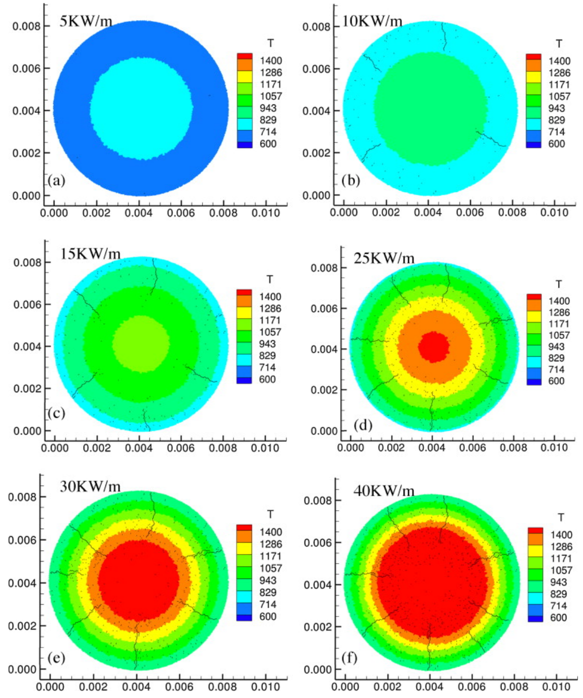
$$E_i = \left[\frac{2}{3}\frac{2-\nu}{2+\nu}\frac{1}{1-\nu}\right]^n E$$

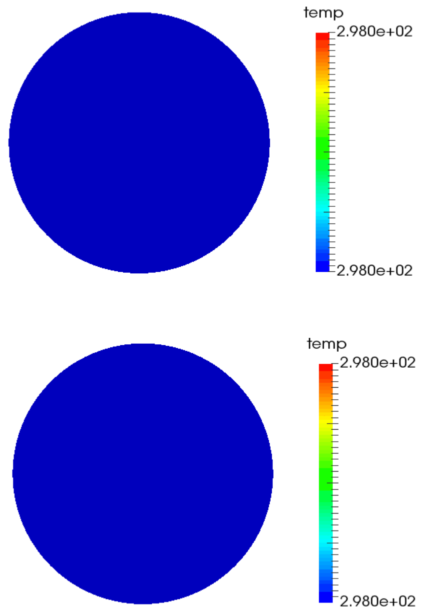
$$\nu_i = \frac{\nu}{2^n + (2^n - 1)\,\nu}$$

n is number of cracks



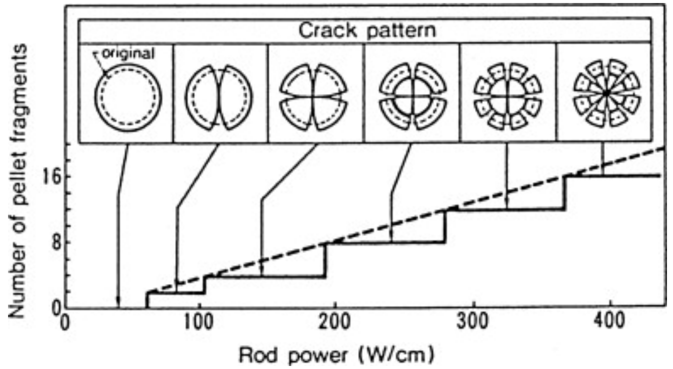
R. L. Williamson



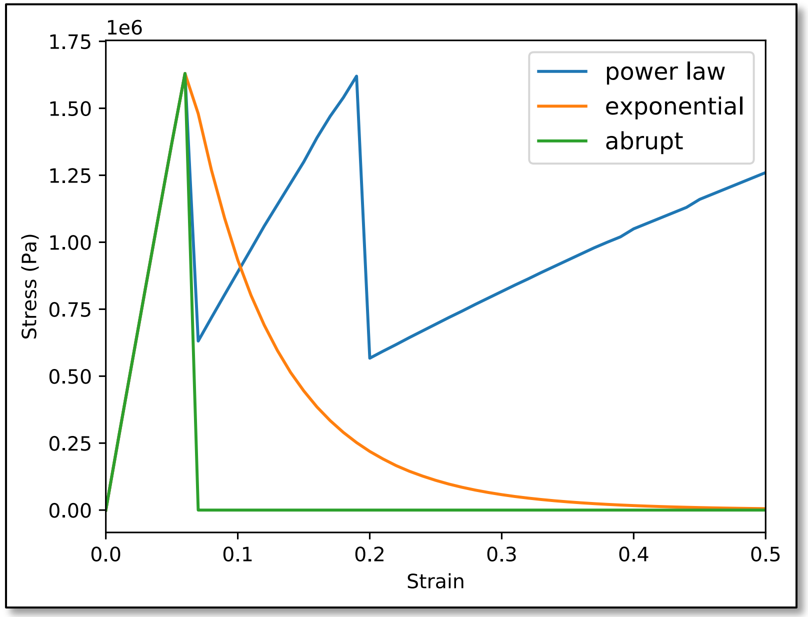


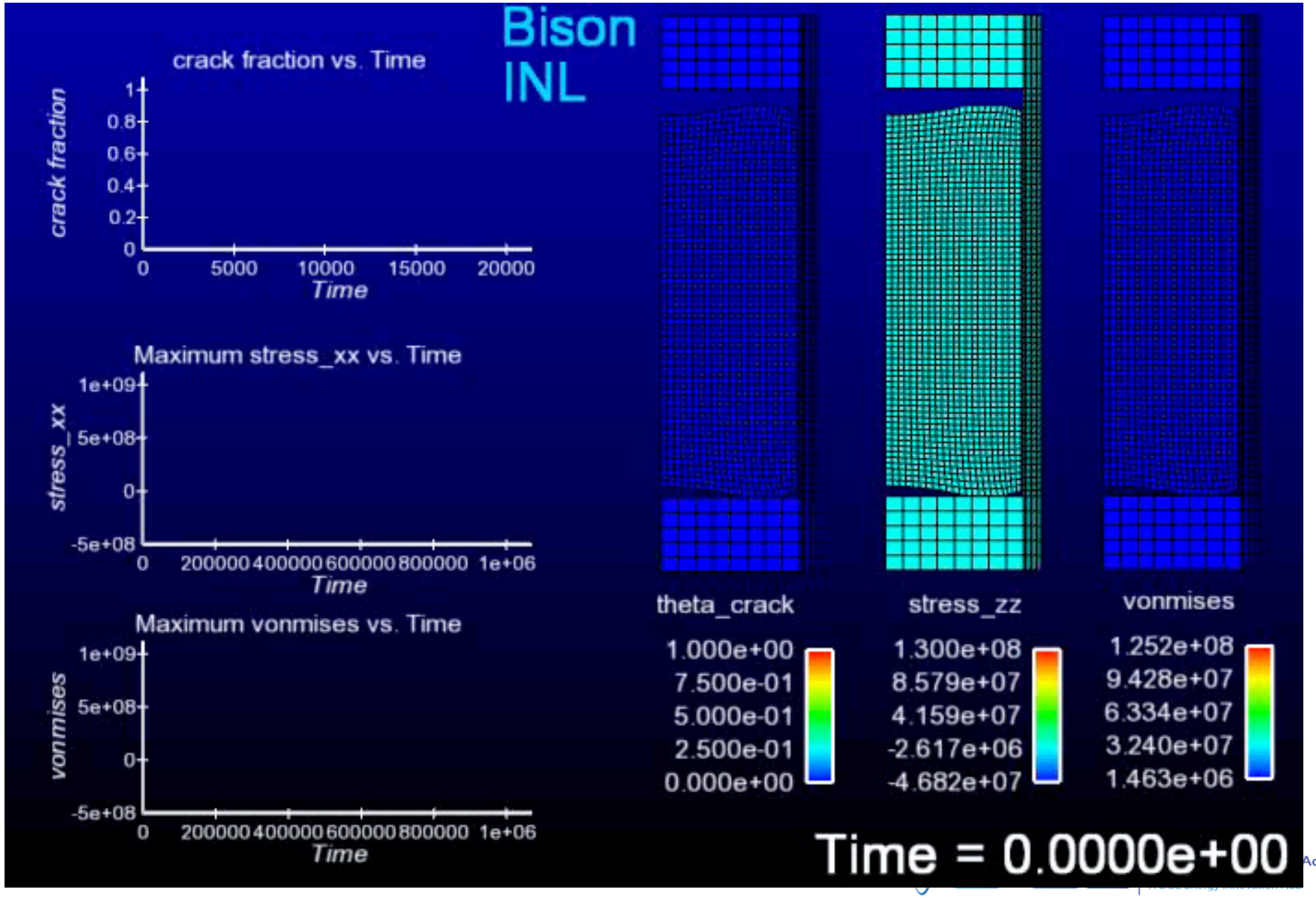
Smeared Cracking

- Smeared cracking adjusts the material stiffness at individual integration points
- The user has options for how the stiffness is reduced



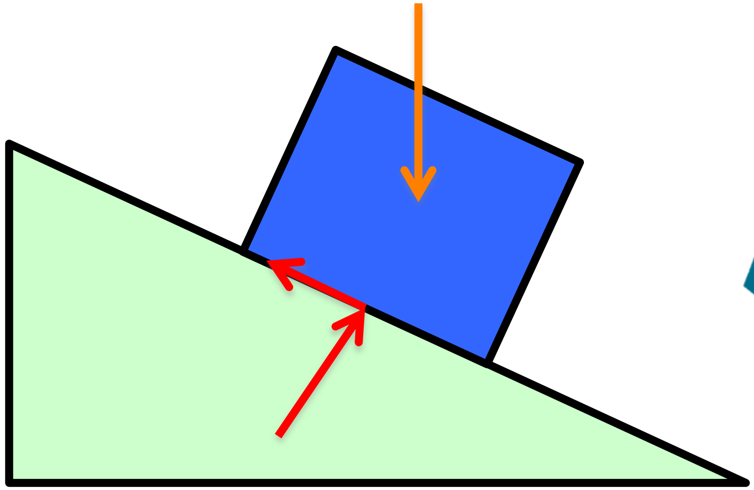
Oguma, 1983

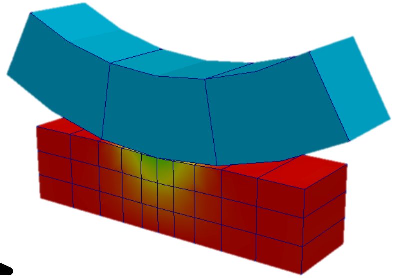


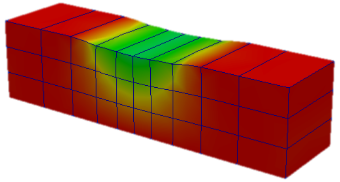


Mechanical Contact

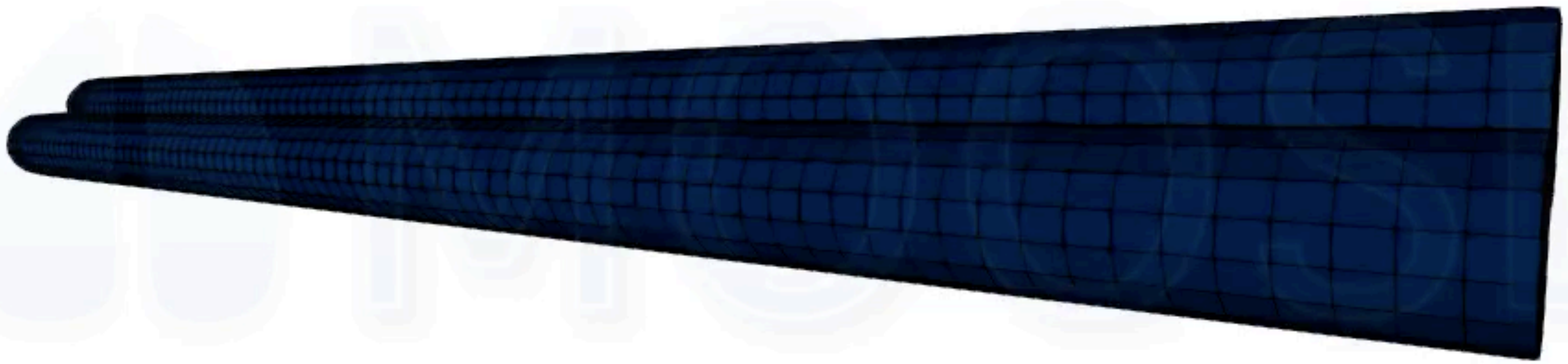
$$F^{\text{int}}(d(t)) + F^{\text{c}}(d(t)) = F^{\text{ext}}(d(t))$$

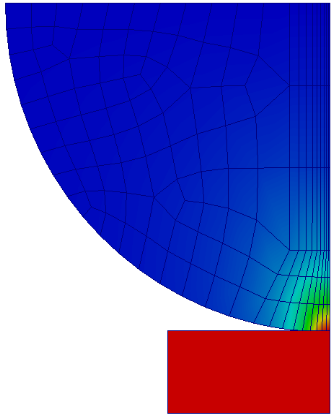






- Search
  - Exterior identification
  - Nearby nodes
  - Contact existence
    - More geometric work
    - Penetration point
- Enforcement
  - Formulation of contact force (many options)
  - Formulation of Jacobian
  - Interaction with other capabilities (e.g., kinematic boundary conditions)



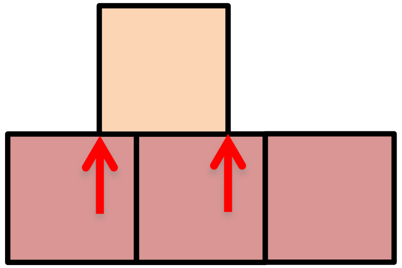


Mechanical Contact

$$g \leq 0$$ Distance of node through opposite surface

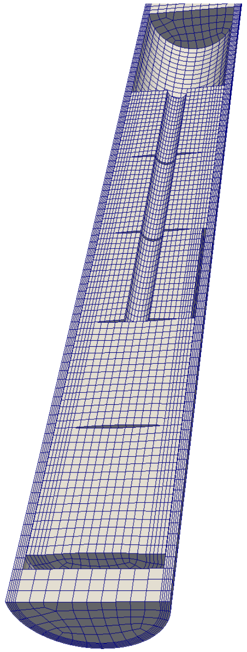
$$t_N \geq 0$$ Contact force in the normal direction

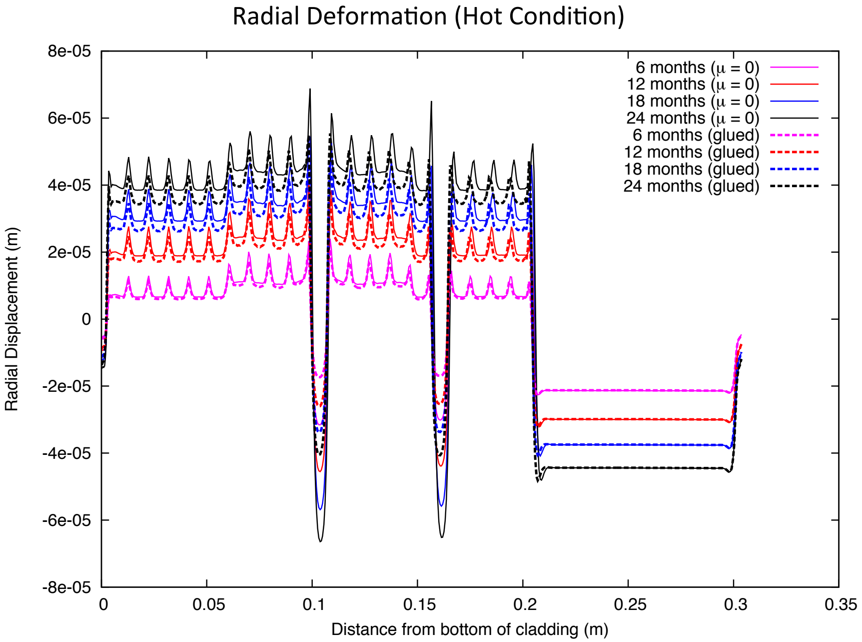
$$t_N g = 0$$

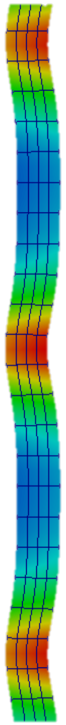


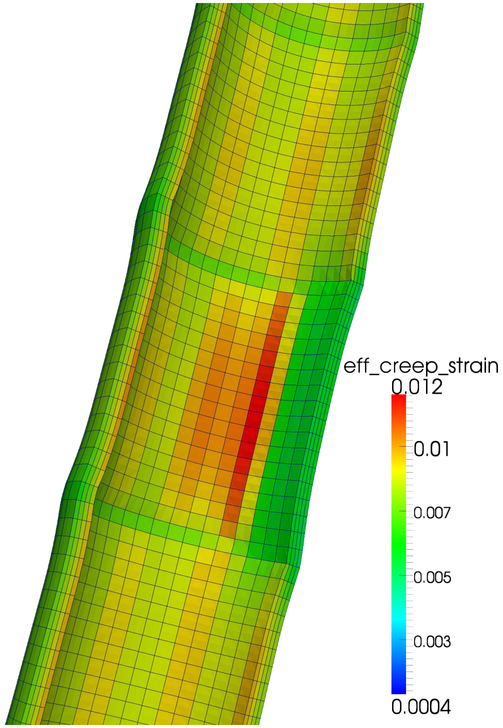
$$t_N = kg$$

Contact force is a penalty stiffness times the distance (e.g.)









Thermal Contact

Contact constraint: heat transfer between separate surfaces →

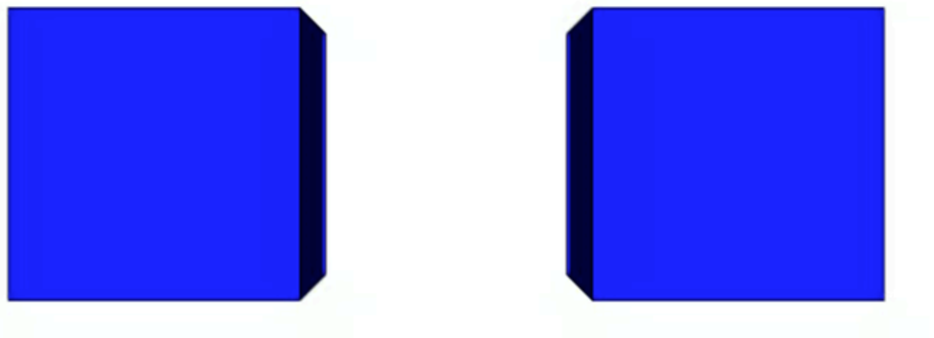
$$\int_{\Gamma_1} h_{g1}(T_2 - T_1) = \int_{\Gamma_2} h_{g2}(T_2 - T_1)$$

Gap conductance for axisymmetric system →

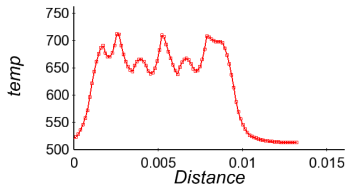
$$h_{g1} = \frac{k_g}{r_1 \left(\ln\left(\frac{r_2}{r_1}\right) + \frac{g_1}{r_1} + \frac{g_2}{r_2} \right)}$$

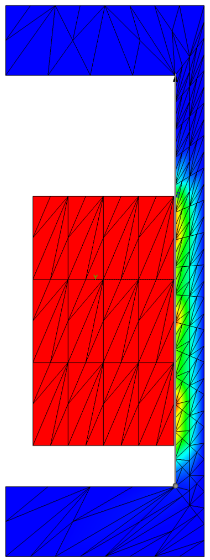
Jump distance →

$$g_1 + g_2 = 5756 \left(\frac{2 - a_{mix}}{a_{mix}}\right) \left(\frac{k_g \sqrt{T}}{P}\right) \left(\sum_{i=1}^{n} \frac{f_i}{M_i}\right)^{-1/2}$$

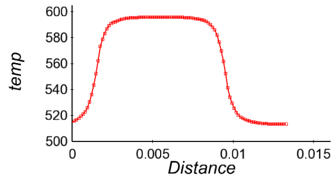


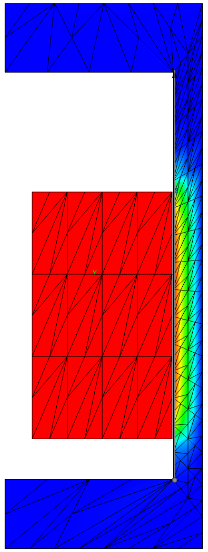
Node on Face



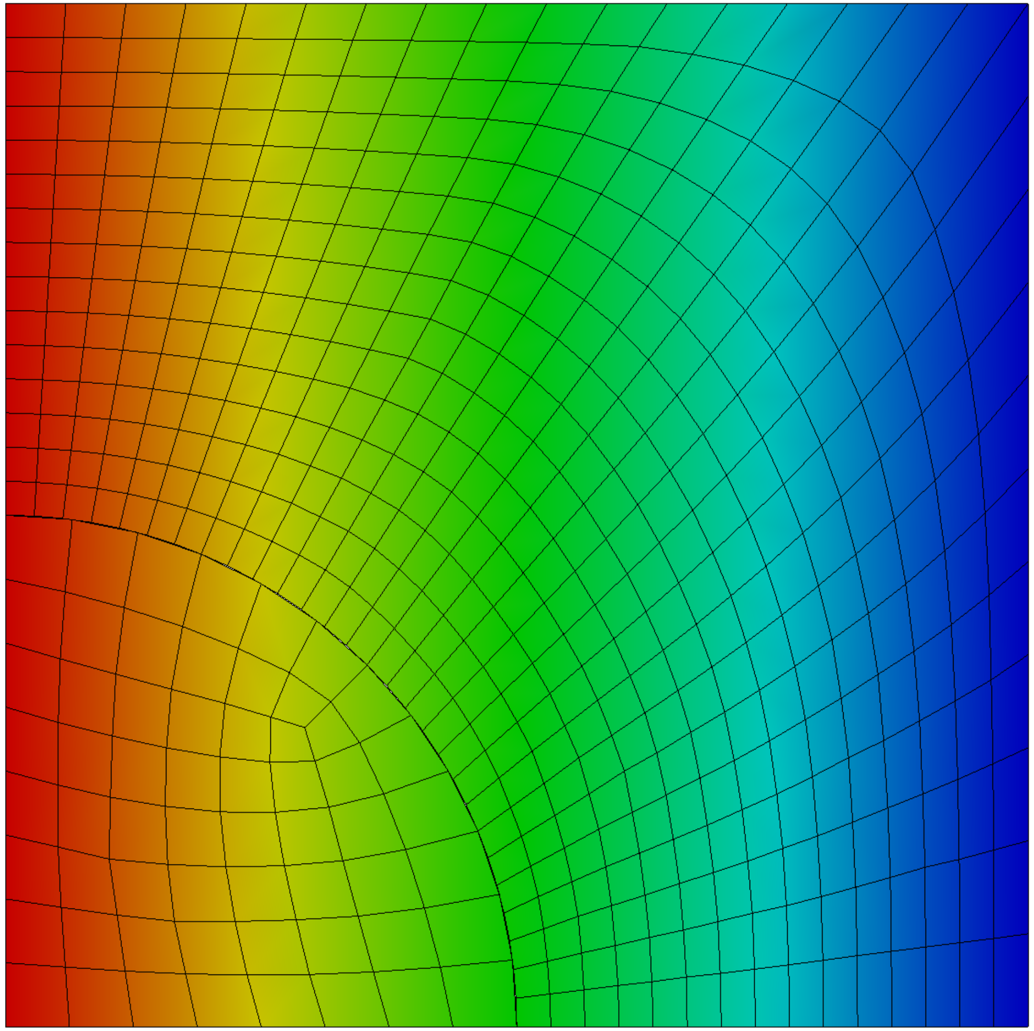


Quadrature/ symmetric





Advanced Contact



See
mooseframework.org/bison
for details about the
capabilities of Bison

More advanced methods (e.g., mortar) are in development

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