INL/CON-23-71313-Revision-1

Bison Verification and Validation Activities for TRISO

November 2023

Aysenur Toptan, Jason D Hales, Wen Jiang

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Idaho National Laboratory

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Idaho National Laboratory
Idaho Falls, Idaho 83415

http://www.inl.gov

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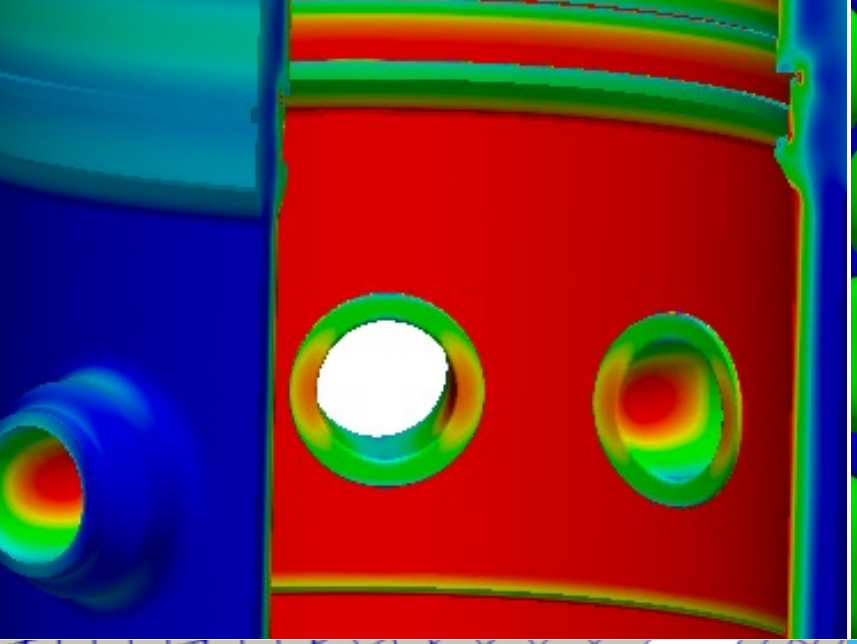

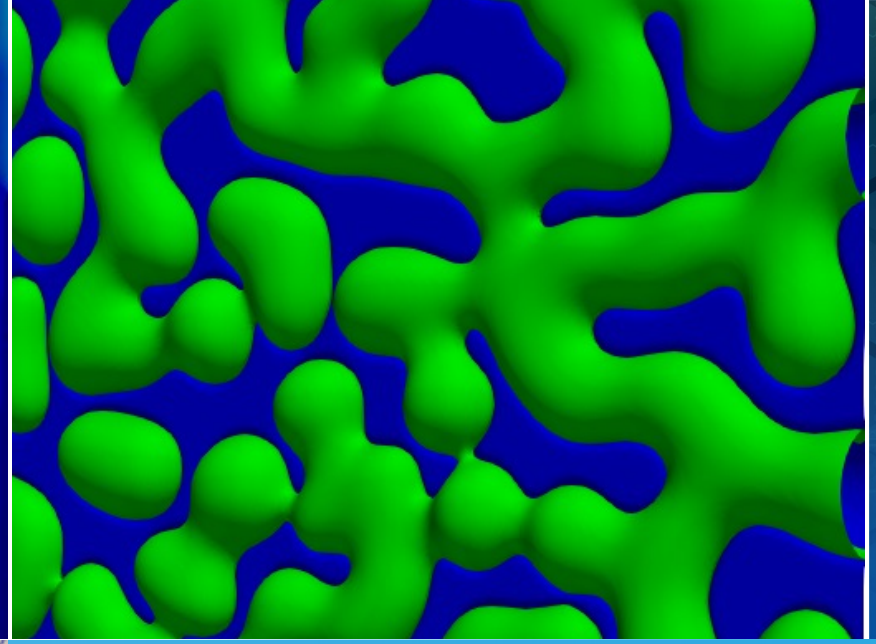

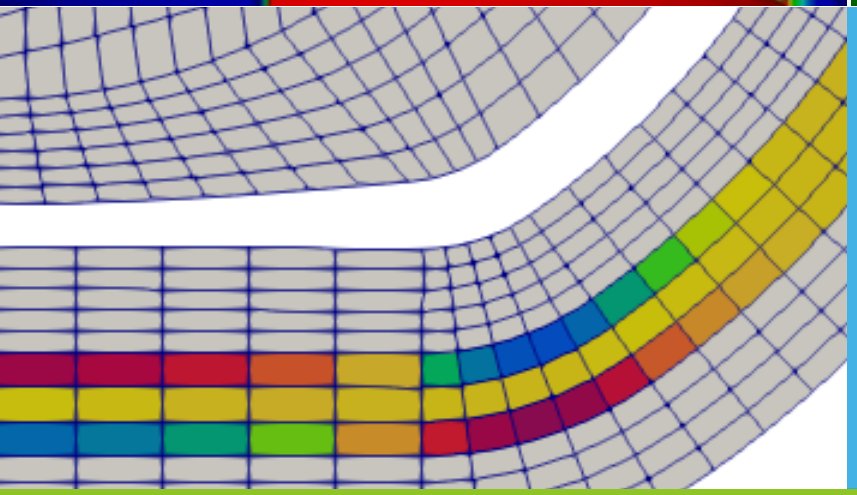

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November 2, 2023

Jason Hales
Idaho National Laboratory

Idaho National Laboratory

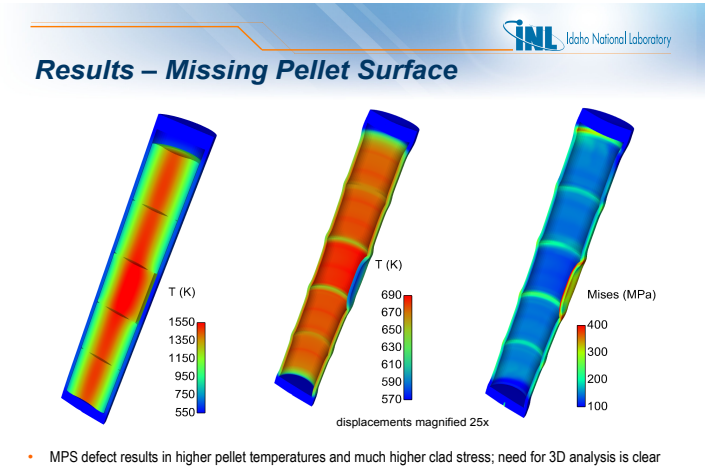
Acknowledgements

- Aysenur Toptan
  - Former INL employee
  - Now at Westinghouse
  - Primary author of this paper
  - Focused on verification and validation

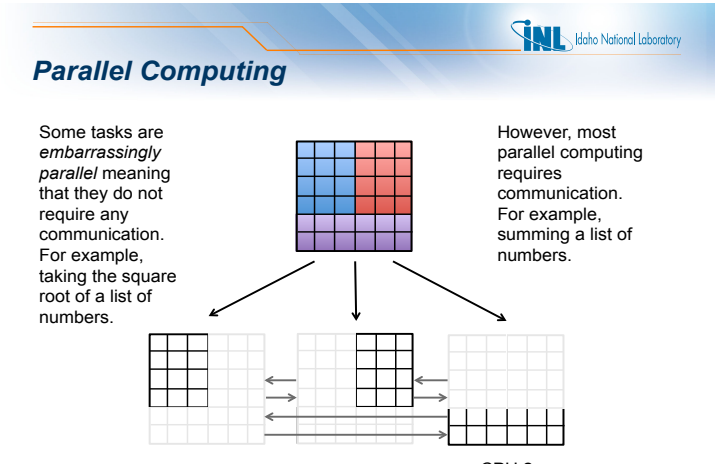
- Wen Jiang
  - Former INL employee
  - Now at North Carolina State University
  - Focused on tristructural isotropic (TRISO) capability development in Bison

And many others

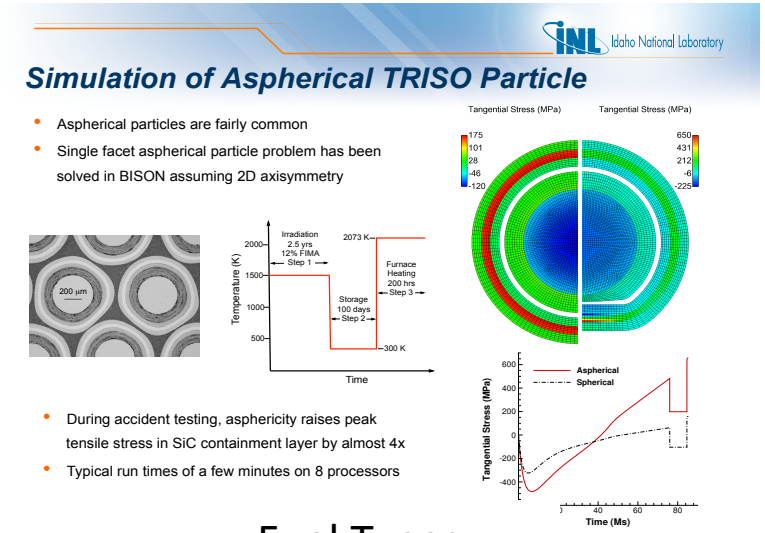
Bison



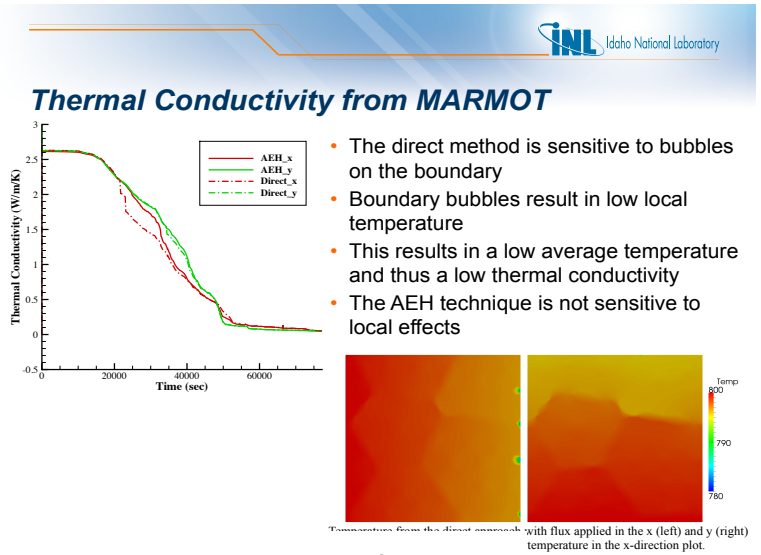
3D/Arbitrary Geometry



Parallel Computing



Fuel Types



Coupling

https://mooseframework.inl.gov/bison

Bison TRISO Fuel Capabilities

General Capabilities

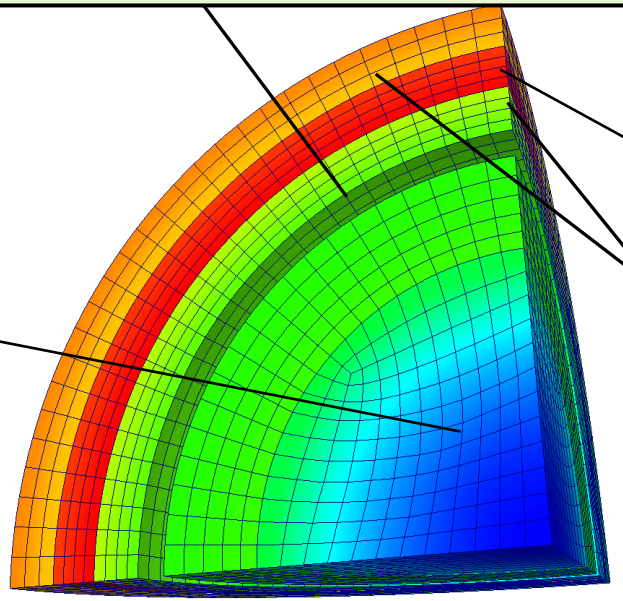
- Finite element based 1D-Spherical, 2D-RZ and 3D fully-coupled thermo-mechanics with species diffusion
- Linear or quadratic elements with large deformation mechanics
- Elasticity with thermal expansion
- Steady and transient behavior
- Massively parallel computation

Fuel Kernel

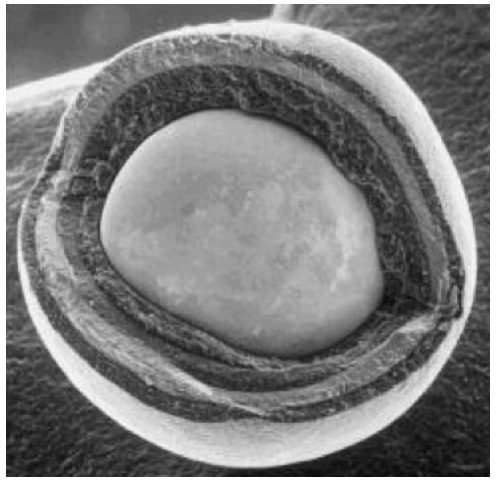
- Temperature/burnup/porosity dependent thermal conductivity
- Solid and gaseous fission product swelling
- Densification
- Thermal and irradiation creep
- Fission gas release (two stage)
- CO production
- Radioactive decay

Gap Behavior

- Gap heat transfer with k_g= f (T, n)
- Gap mass transfer
- Mechanical contact
- Particle pressure as a function of:
  - evolving gas volume (from mechanics)
  - gas mixture (from FGR and CO model)
  - gas temperature approximation



Tangential Stress

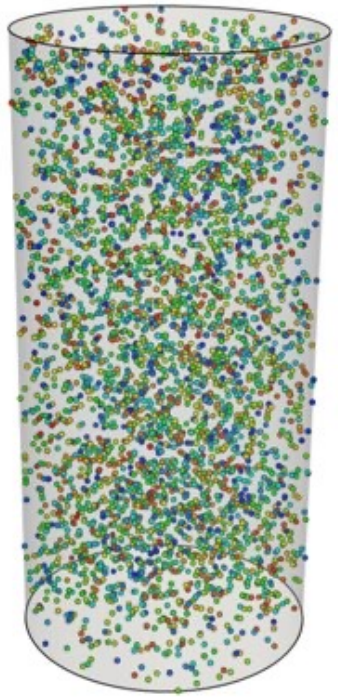


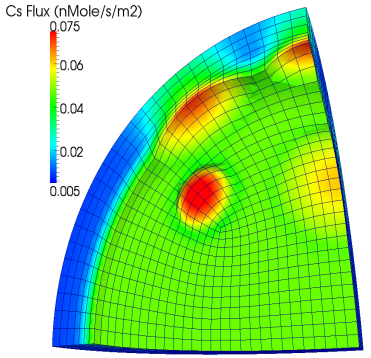
Silicon Carbide

- Irradiation creep

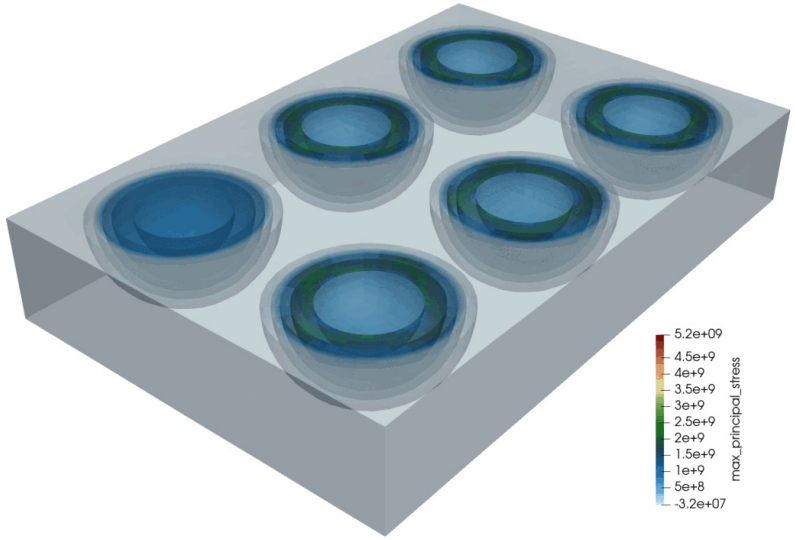
Pyrolytic Carbon

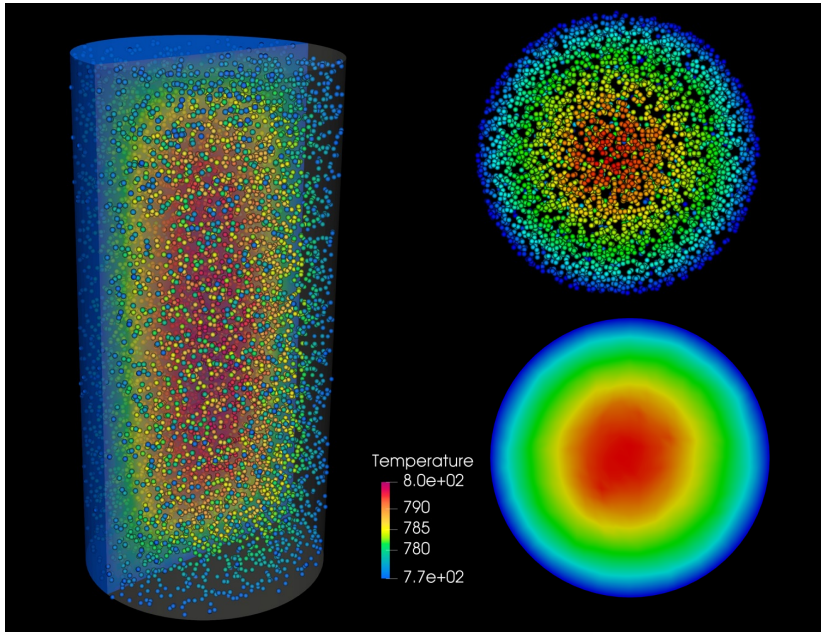
- Anisotropic irradiation-induced strain
- Irradiation creep

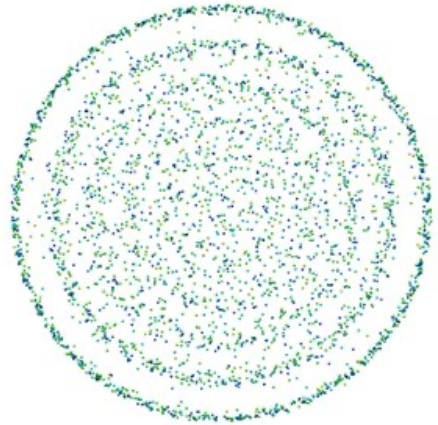


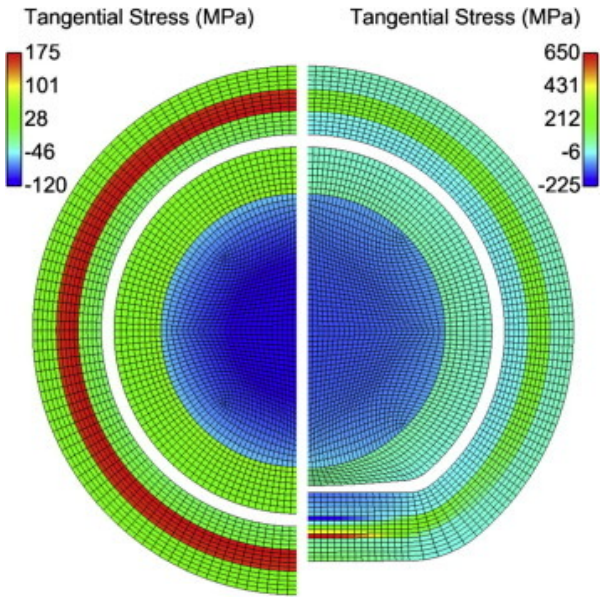


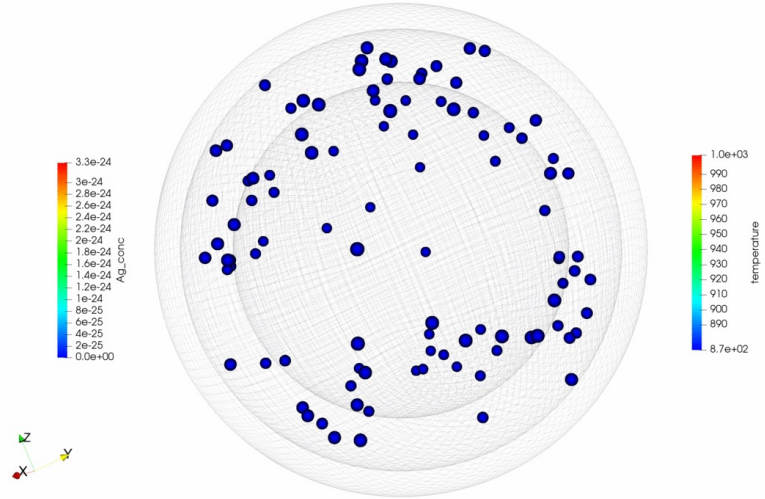
Bison for TRISO Fuel Analysis

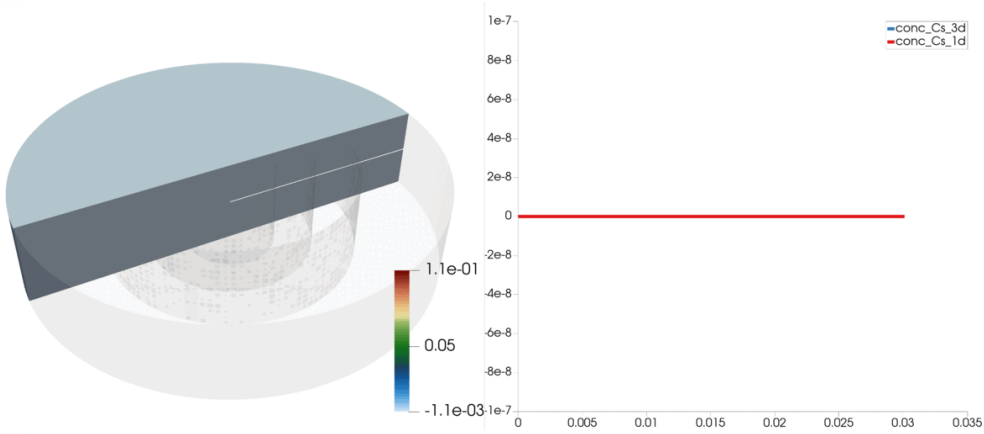












Software Quality Assurance

- Software engineering procedures such as revision control, issue tracking, peer review, defect analysis, automated testing (see https://github.com/idaholab/civet), and creation of online documentation help ensure the development of a high-quality code.
- Bison uses a GitHub server internal to INL for revision control, issue tracking, and peer review.
- Automated testing occurs with every pull request.
- Online documentation is at https://mooseframework.inl.gov/bison/

LCOV - code coverage report

			Hit	Total	Coverage
Current view:	top level	**Lines:**	41803	45438	92.0 %
Test:	idaholab/bison: #5644 (f54bdd) with base 6ba5c9	**Functions:**	3879	4410	88.0 %
Date:	2023-10-18 13:52:54				
Legend:	Rating: low: < 75 % medium: >= 75 % high: >= 90 %				

Directory	Line Coverage			Functions	
include/actions		94.1 %	48 / 51	22.5 %	27 / 120
include/auxkernels		100.0 %	19 / 19	50.0 %	21 / 42
include/bcs		100.0 %	6 / 6	50.0 %	7 / 14
include/functions		82.8 %	48 / 58	5.0 %	1 / 20
include/interfaces		25.0 %	4 / 16	40.0 %	2 / 5
include/materials		72.4 %	21 / 29	38.7 %	12 / 31
include/materials/tensor_mechanics		70.8 %	46 / 65	78.8 %	26 / 33
include/meshgenerators		93.3 %	28 / 30	80.0 %	4 / 5
include/postprocessors		100.0 %	22 / 22	85.2 %	23 / 27
include/userobject		61.3 %	19 / 31	61.5 %	16 / 26
include/utils		93.3 %	28 / 30	57.1 %	8 / 14
include/vectorpostprocessors		100.0 %	7 / 7	75.0 %	6 / 8
src		100.0 %	5 / 5	100.0 %	1 / 1
src/actions		91.3 %	7522 / 8236	99.7 %	297 / 298
src/auxkernels		92.5 %	1153 / 1246	100.0 %	120 / 120
src/base		76.1 %	35 / 46	54.5 %	6 / 11
src/bcs		93.7 %	667 / 712	96.3 %	79 / 82
src/constraints		87.1 %	182 / 209	100.0 %	24 / 24
src/cxxmatpro		93.6 %	132 / 141	90.6 %	29 / 32
src/dirackernels		100.0 %	20 / 20	100.0 %	4 / 4
src/functions		91.2 %	1405 / 1540	96.4 %	81 / 84
src/interfacekernels		91.0 %	71 / 78	87.5 %	7 / 8
src/interfaces		100.0 %	13 / 13	100.0 %	2 / 2
src/kernels		90.8 %	687 / 757	87.9 %	102 / 116
src/materials		92.8 %	11517 / 12404	90.1 %	1050 / 1165
src/materials/tensor_mechanics		93.2 %	7567 / 8117	89.6 %	1123 / 1254
src/meshgenerators		95.7 %	4488 / 4692	96.6 %	143 / 148
src/parser		100.0 %	78 / 78	100.0 %	1 / 1
src/postprocessors		92.3 %	1624 / 1759	97.7 %	254 / 260
src/timesteppers		75.0 %	21 / 28	100.0 %	3 / 3
src/userobject		86.3 %	2408 / 2791	93.8 %	255 / 272
src/utils		89.2 %	1210 / 1356	77.4 %	103 / 133
src/vectorpostprocessors		83.0 %	702 / 846	89.4 %	42 / 47

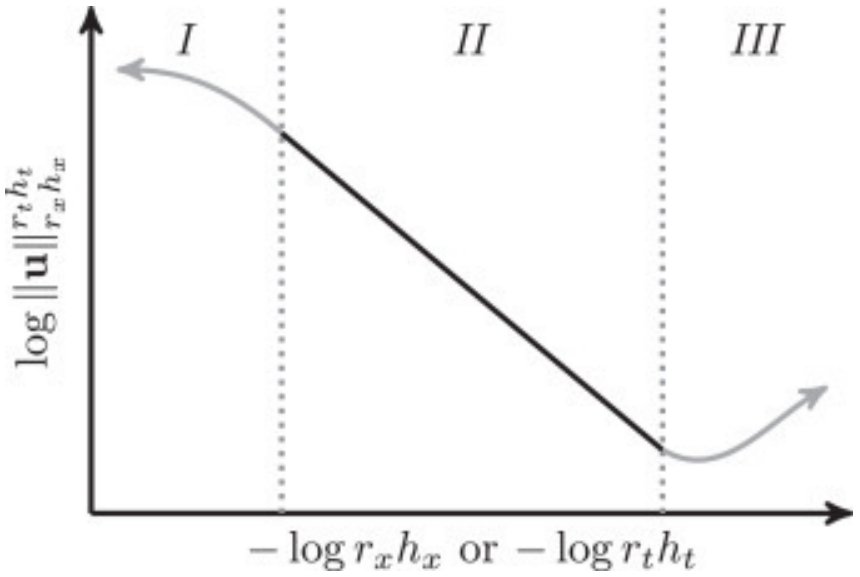
Generated by: LCOV version 1.14

Verification

- Verification comes in two parts:
  - Code verification: ensures the code represents the underlying mathematical model. Does it match analytical solutions?
  - Solution verification: assesses sources of numerical errors like round-off, tolerances, and truncation error for a specific application problem, which likely does not have an analytical solution. Does the code reduce error at the expected rate with mesh refinement?

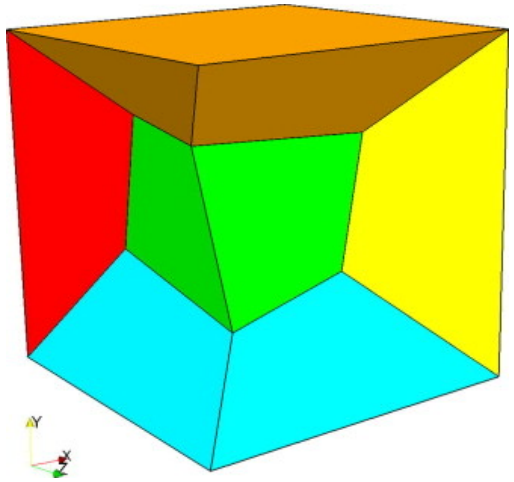
$$||u - \tilde{u}|| = \left[\int_\Omega (u - \tilde{u})^2 \mathrm{d}\Omega\right]^{1/2}$$

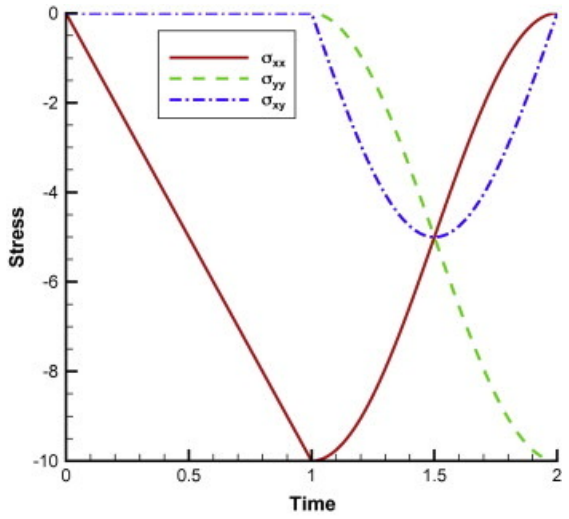
$$||u_{\text{refined}} - \tilde{u}_{\text{coarse}}|| = \left[\int_\Omega (u_{\text{refined}} - \tilde{u}_{\text{coarse}})^2 \mathrm{d}\Omega\right]^{1/2}$$

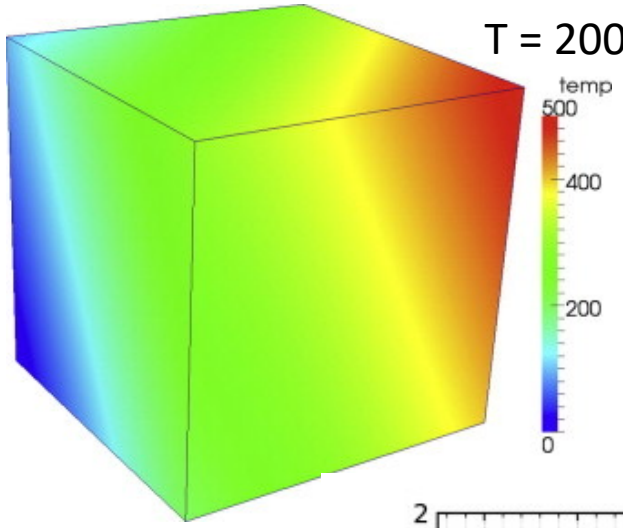


Bison Verification of TRISO Capabilities

Foundational code verification:

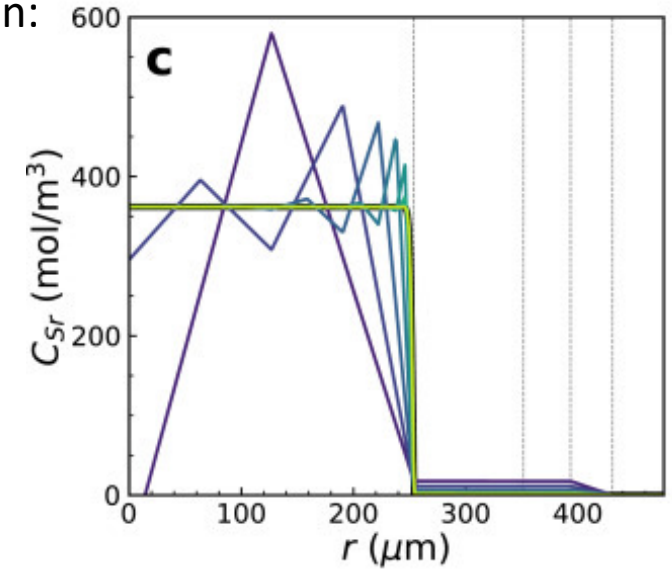


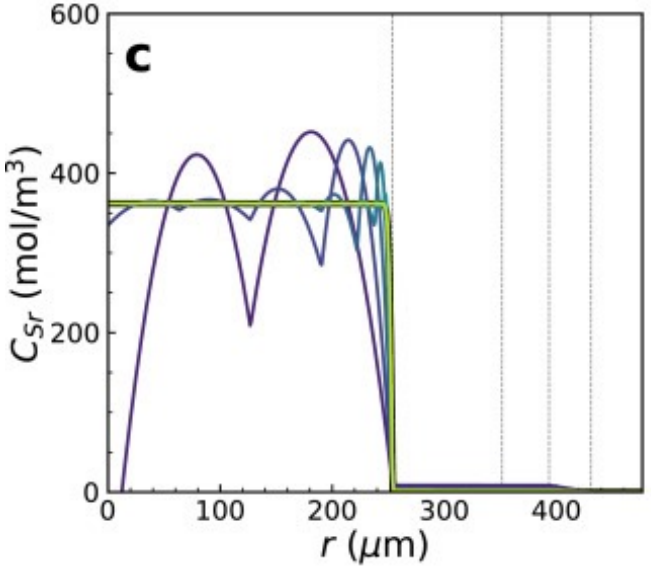


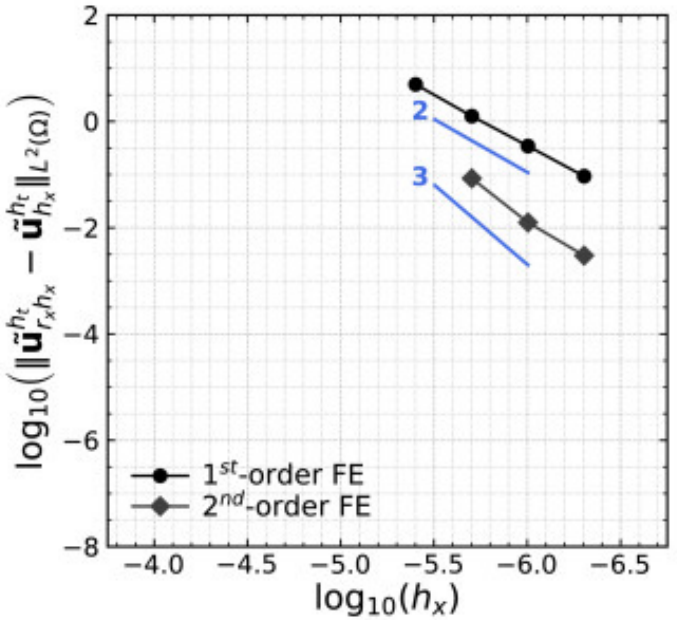


T = 200x + 100 y + 200z

Solution verification:

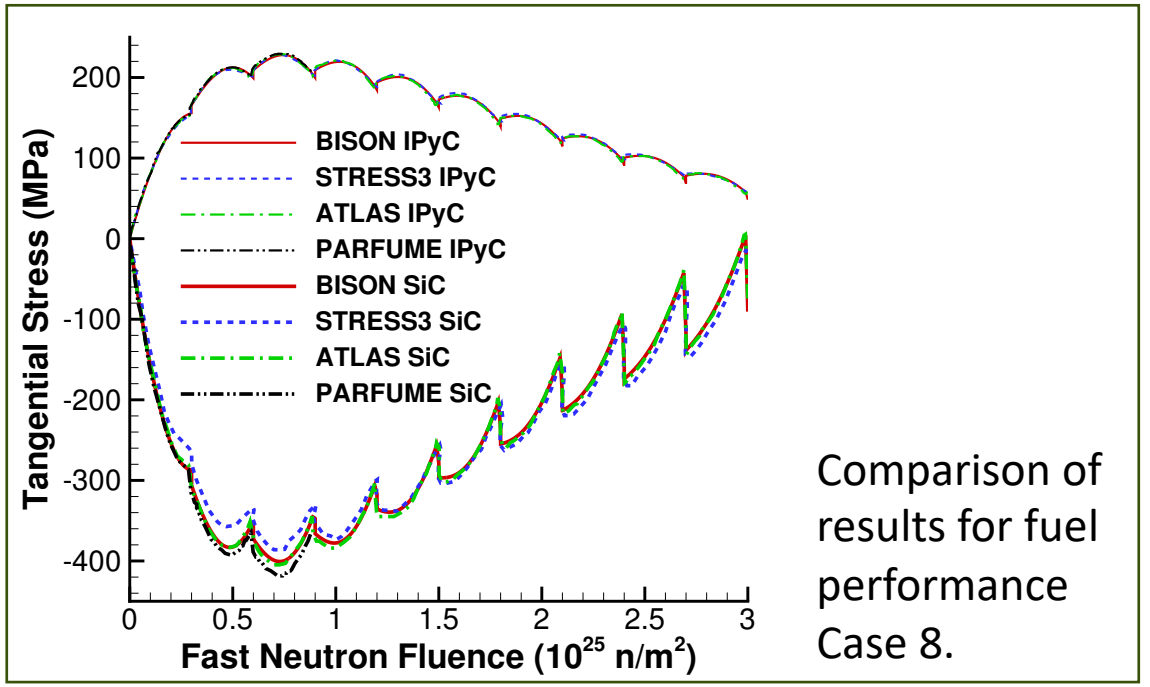




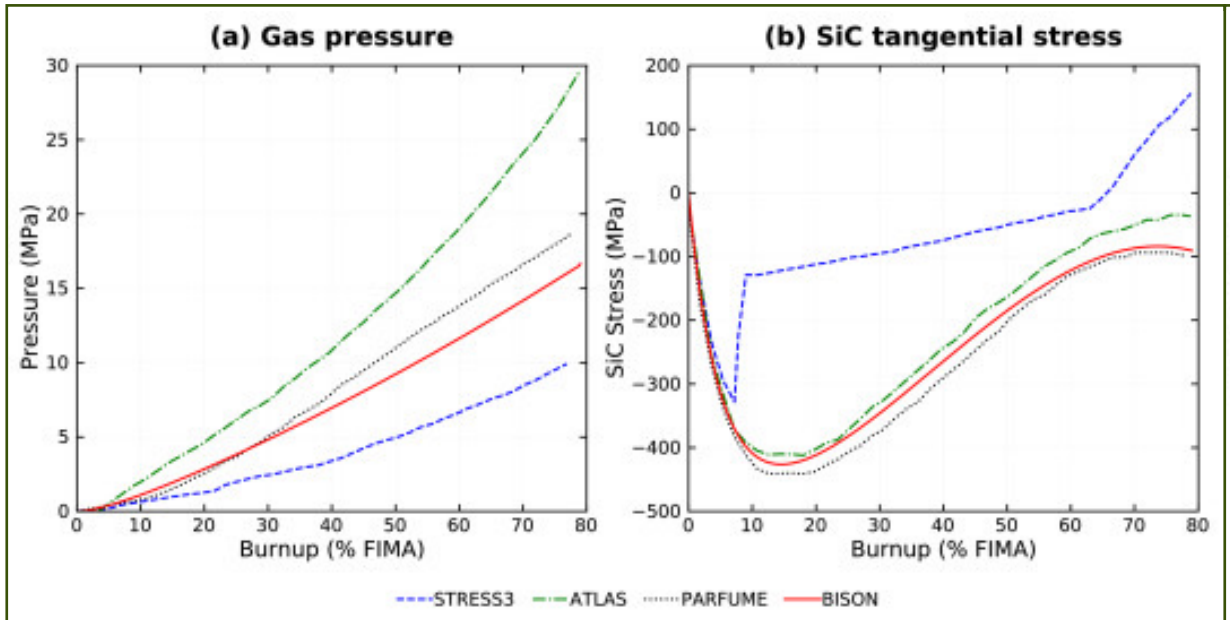


Benchmarks

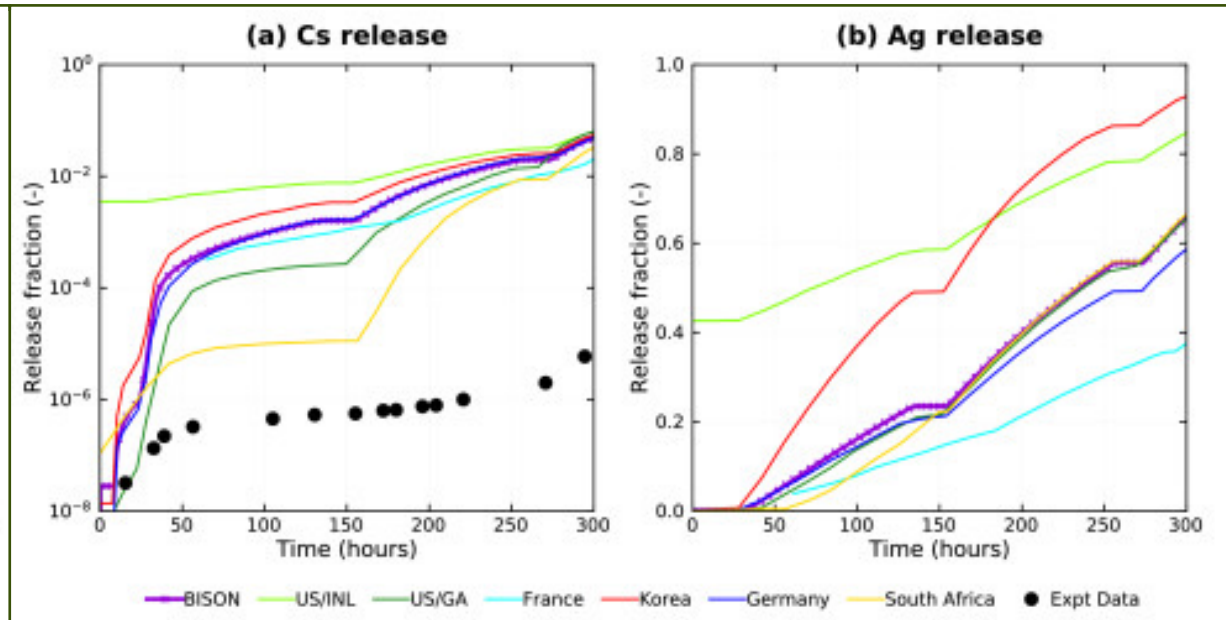
- Benchmarks or code-to-code comparisons can be helpful in providing confidence in a code's capabilities, but they lack the rigor of verification and validation activities.
- The International Atomic Energy Agency sponsored CRP-6, including two benchmark exercises: fuel performance (stress, 13 cases) and fission product release (diffusion, 11 cases)



Comparison of results for fuel performance Case 8.



Comparison of results for fuel performance Case 12.

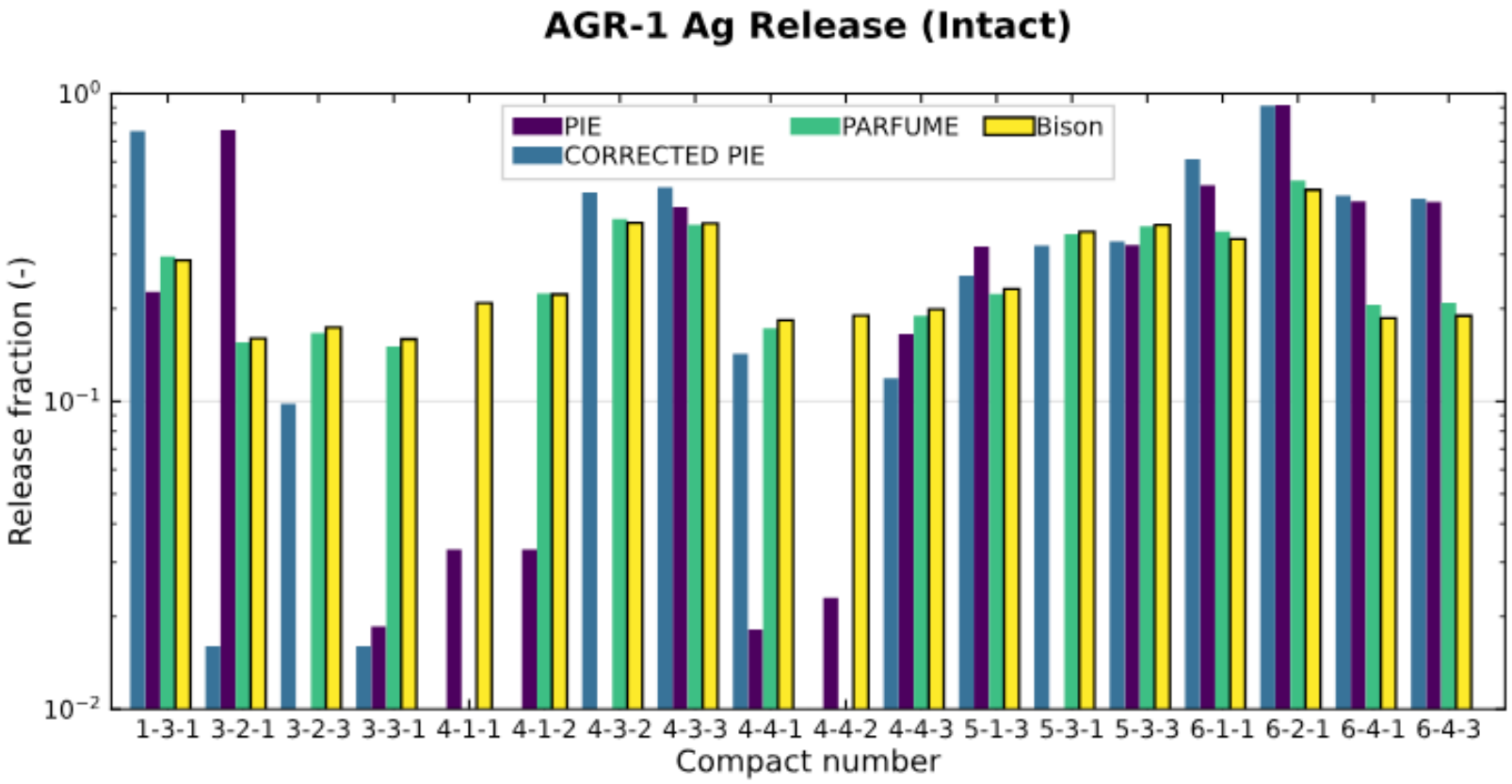


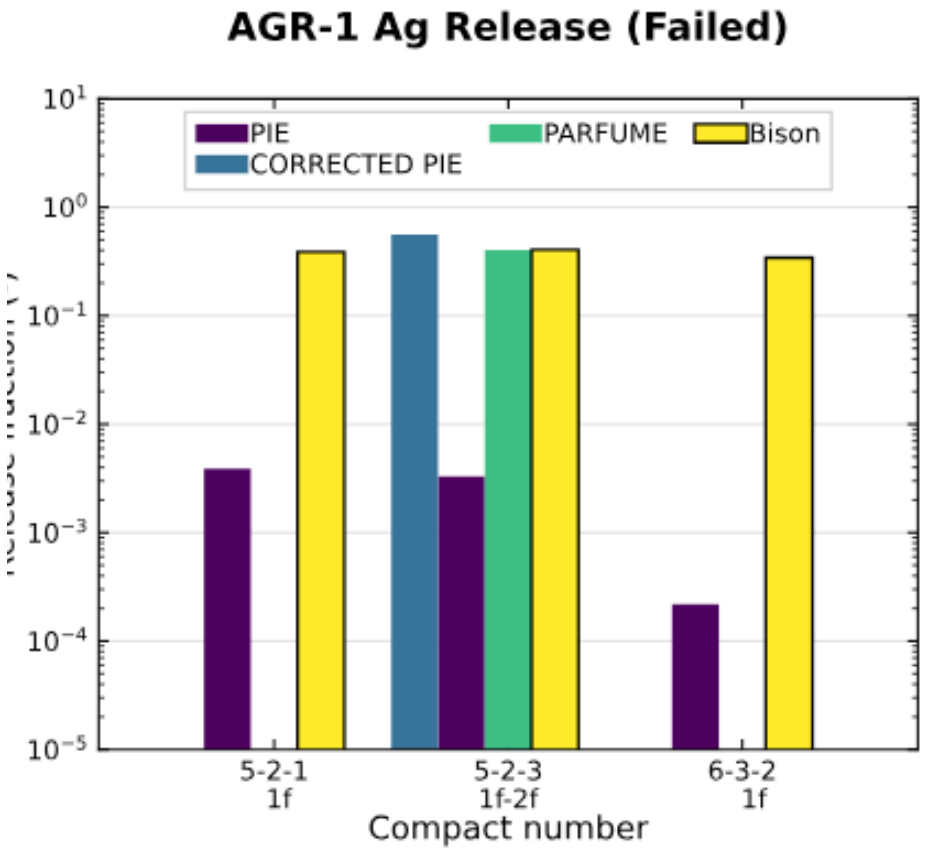
Comparison of results for fission product release Case 9.

Validation

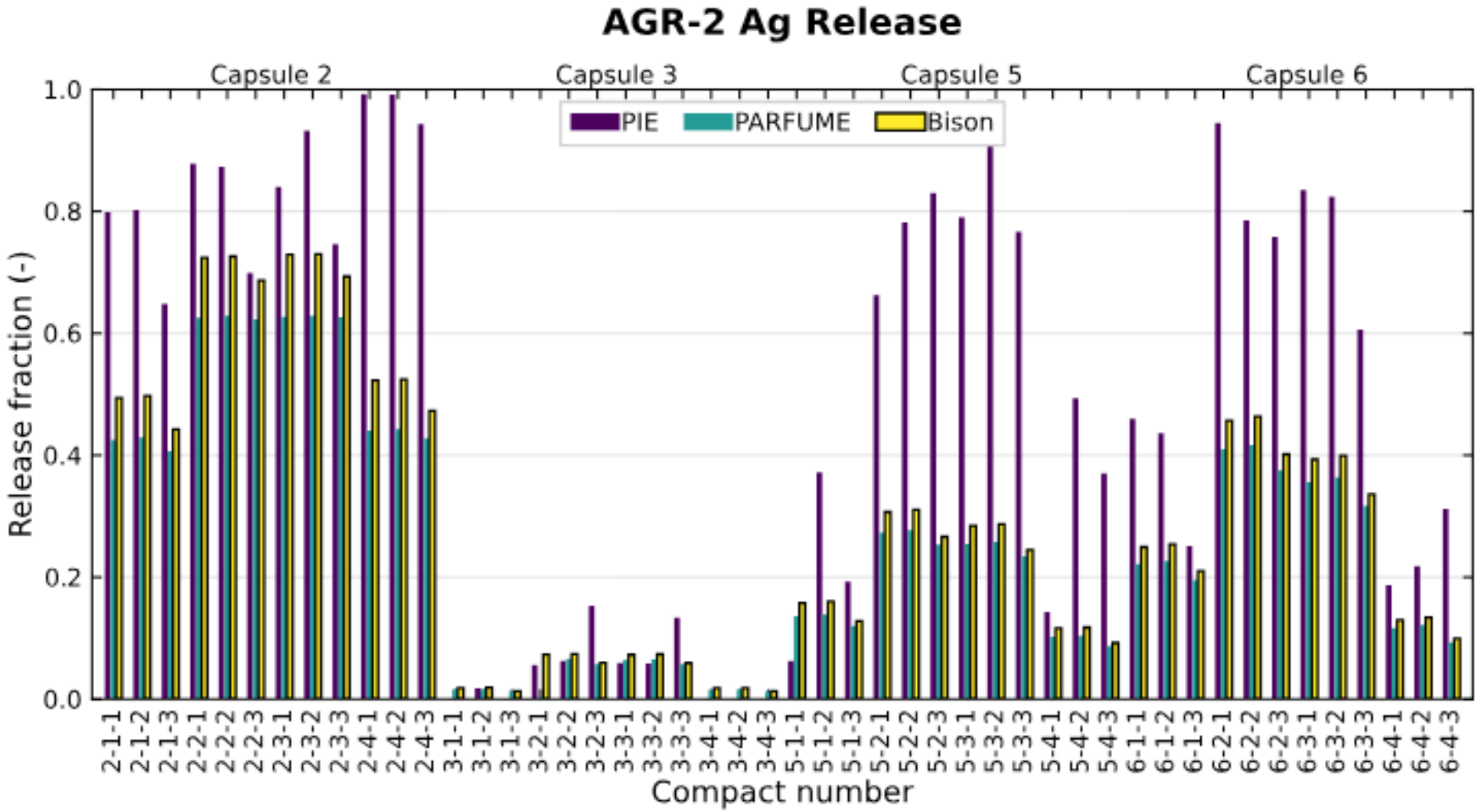
- Validation is the process of comparing simulation results to experimental data. How well does the code model reality?

DOE's Advanced Gas Reactor program irradiated TRISO fuel in a total of 72 cylindrical compacts as part of AGR-1. Post-irradiation examination determined the release fractions of fission products such as silver, cesium, and strontium.





Bison Validation of TRISO Capabilities



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