INL/CON-23-75761-Revision-0

Evaluation of Irradiation Creep Effects in HT9 Cladding for FAST Experiments

December 2023

Changing the World's Energy Future

Alexander Lee Swearingen, Boone Beausoleil, Kyle Mitchell Paaren, Sobhan Patnaik, Luca Capriotti

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MiNES Conference 2023

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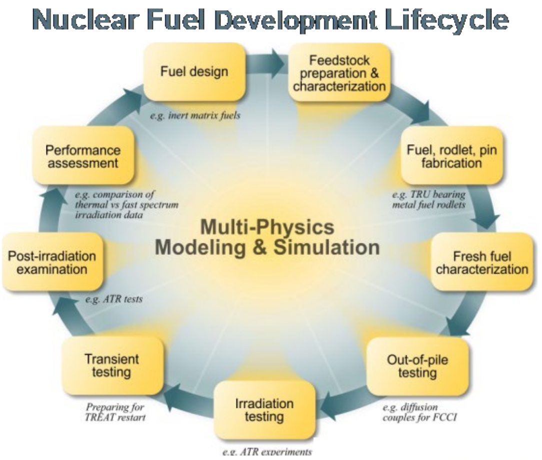
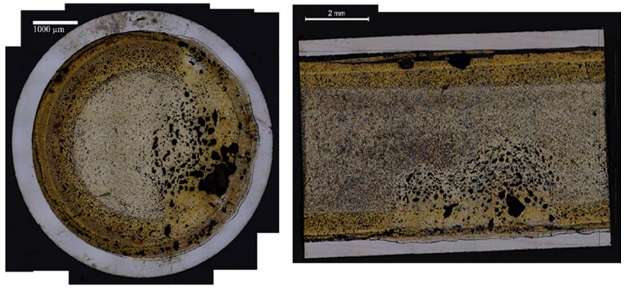
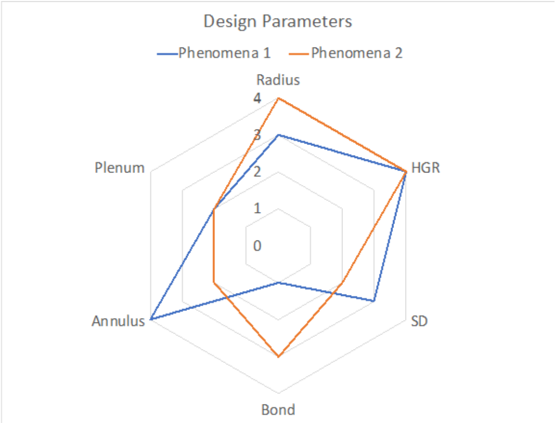
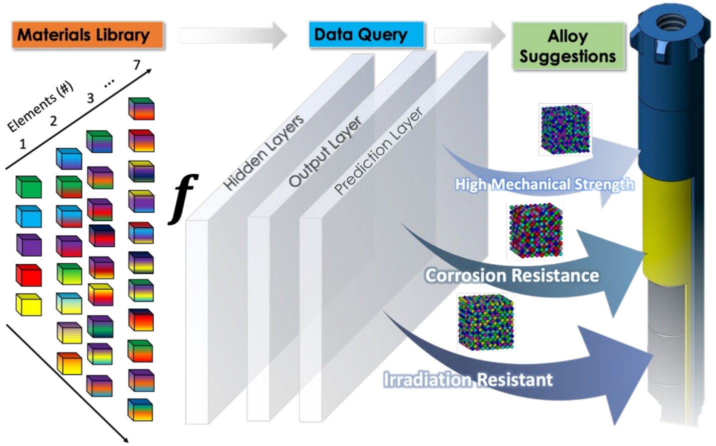
FAST Motivation

- Fuel testing takes too long
  - Slow iteration around the wheel
- Conventional fuel tests within ATR is high risk
  - Highly sensitive to fabrication tolerances
  - Execution failures are unknown for extended periods of time
- Model based design and true multi-physics performance codes require deeper, more diverse data sets
  - 13,000 data points of one design is not useful
  - Increased variation in experimental designs allows for more robust assessment and V&V









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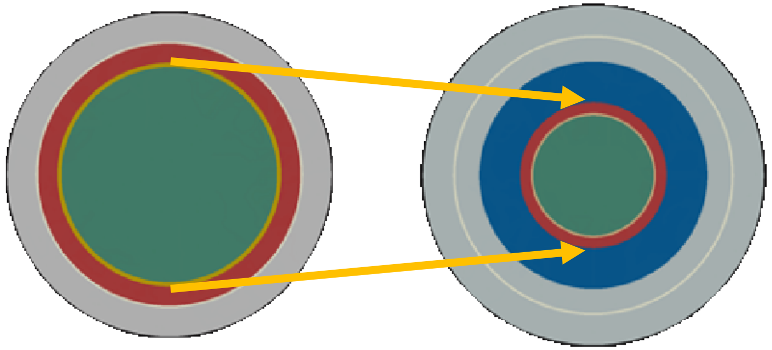
A Revised Capsule Design

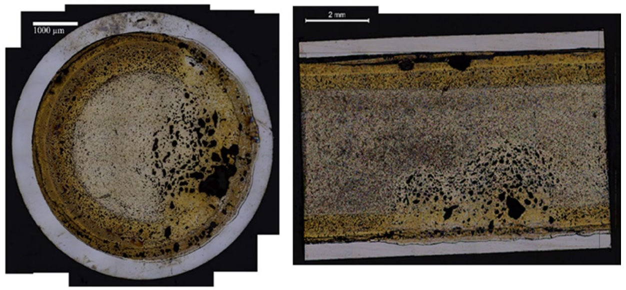
- Rekindling a small test performed in the 1960's, a FASTer approach to testing was developed
- The Fission Accelerated Steady-state Test (FAST) utilizes a reduced diameter fuel pin to achieve two objectives:

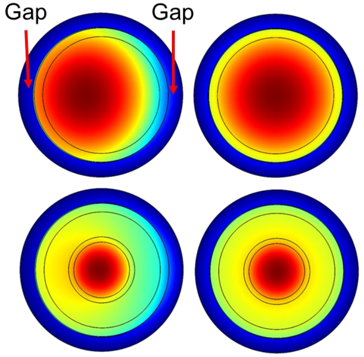


Standard capsule design
Prototypic rodlet diameter

Double-encapsulated design
~1/2 standard rodlet diameter

1. Improve experiment reliability: reduced sensitivity to fabrication tolerances and capsule/pin eccentricity





2. Increase burnup rate for fuel experiments: reduce time to achieve high burnup

Given

$$Q_0 = \frac{LHGR_0}{\pi r_0^2}$$

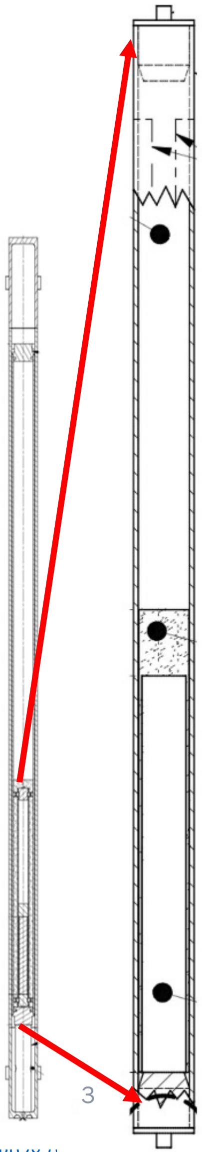
if $r = \alpha r_0$ and $LHGR = LHGR_0$, then

$$Q = \frac{Q_0}{\alpha^2}$$

For $\alpha = ½$,

$$Q = 4Q_0$$

$$t \sim Q^{-1} \quad \therefore \; t \sim \frac{t_0}{4}$$



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https://doi.org/10.1016/B978-0

FAST Metal Fuel Test Matrix

- Each capsule contains a novel experiment and control experiment
  - Controls are solid, 75% SD U-10Zr in HT9
- Experiments include
  - He-bonded annular fuel
  - Additives: Pd, Sb, & Sn
  - Zr liners
- PIE underway for all low burnup pins (green)
- Recently transported to HFEF and awaiting PIE (yellow)

Capsule	Rodlet ID	Fuel Comp	Geometry	Bond	Liner	Target BU
AFC-FAST-016	FAST-035	U-10Zr	Solid	Na	-	2.0%
	FAST-036	U-10Zr	Solid	Na	-	2.0%
AFC-FAST-005	FAST-007	U-10Zr	Annular	He	-	4%
	FAST-008	U-10Zr	Solid	Na	-	4%
AFC-FAST-009	FAST-025	U-10Zr	Solid	Na	Zr	8%
	FAST-051	U-10Zr	Solid	Na	-	8%
AFC-FAST-006	FAST-015	U-10Zr	Annular	He	-	8%
	FAST-016	U-10Zr	Solid	Na	-	8%
AFC-FAST-014	FAST-039	U-10Zr	Solid	Na	-	10%
	FAST-040	U-3Pd-10Zr	Solid	Na	-	10%
AFC-FAST-013	FAST-031	U-10Zr	Solid	Na	-	10%
	FAST-032	U-3Sn-10Zr	Solid	Na	-	10%
AFC-FAST-015	FAST-045	U-10Zr	Solid	Na	-	10%
	FAST-046	U-3Sb-10Zr	Solid	Na	-	10%
AFC-FAST-003	FAST-003 (OA)	U-10Zr	Solid	Na	-	12%
AFC-FAST-010	FAST-026	U-10Zr	Solid	Na	Zr	12%
	FAST-052	U-10Zr	Solid	Na	-	12%
AFC-FAST-007	FAST-047	U-10Zr	Annular	He	-	12%
	FAST-048	U-10Zr	Solid	Na	-	12%
AFC-FAST-011	FAST-027	U-10Zr	Solid	Na	Zr	16%
	FAST-053	U-10Zr	Solid	Na	-	16%
AFC-FAST-008	FAST-049	U-10Zr	Annular	He	-	16%
	FAST-050	U-10Zr	Solid	Na	-	16%
AFC-FAST-012	FAST-028	U-10Zr	Solid	Na	Zr	20%
	FAST-054	U-10Zr	Solid	Na	-	20%

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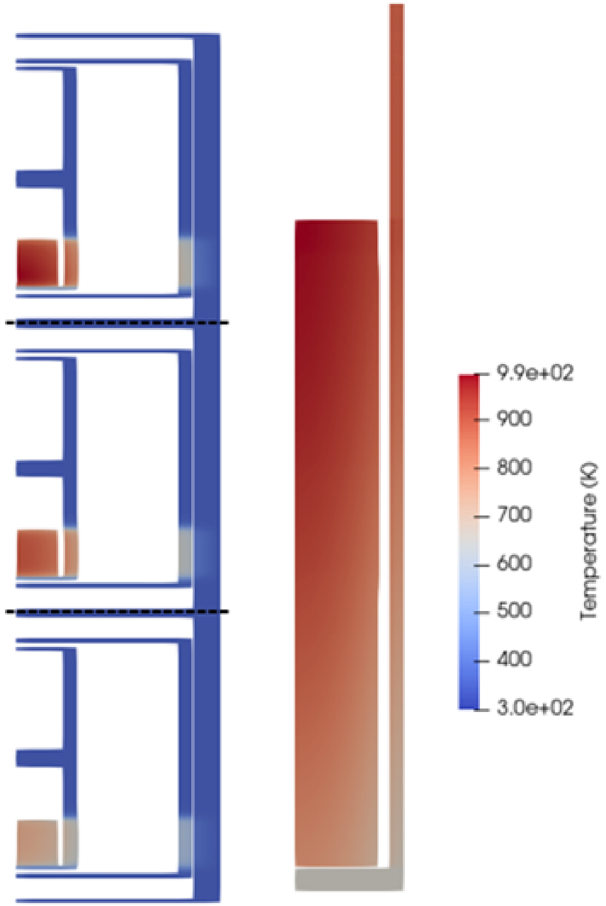
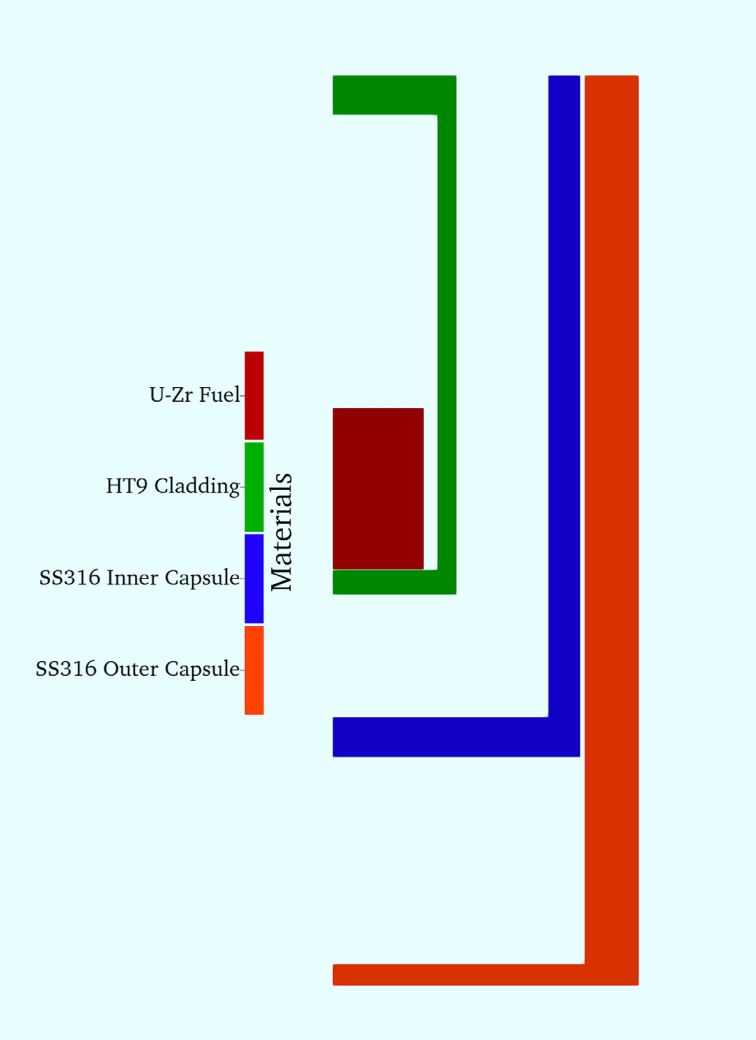
FAST to EBR-II

- FIPD provides extensive datasets of burnup history and PIE data from EBR-II data as well as supporting Bison input file setup
- X425 and sub-assemblies have a burnup range that matches well with all control pins of the FAST tests
  - Pin T423
  - Pin T424
- Assessments of X425 are being used to compare cladding irradiation behavior with burnup levels
- Concern over applicability of HT9 behavior in FAST to comparison
  - Scaling fuel burnup, NOT neutron fluence

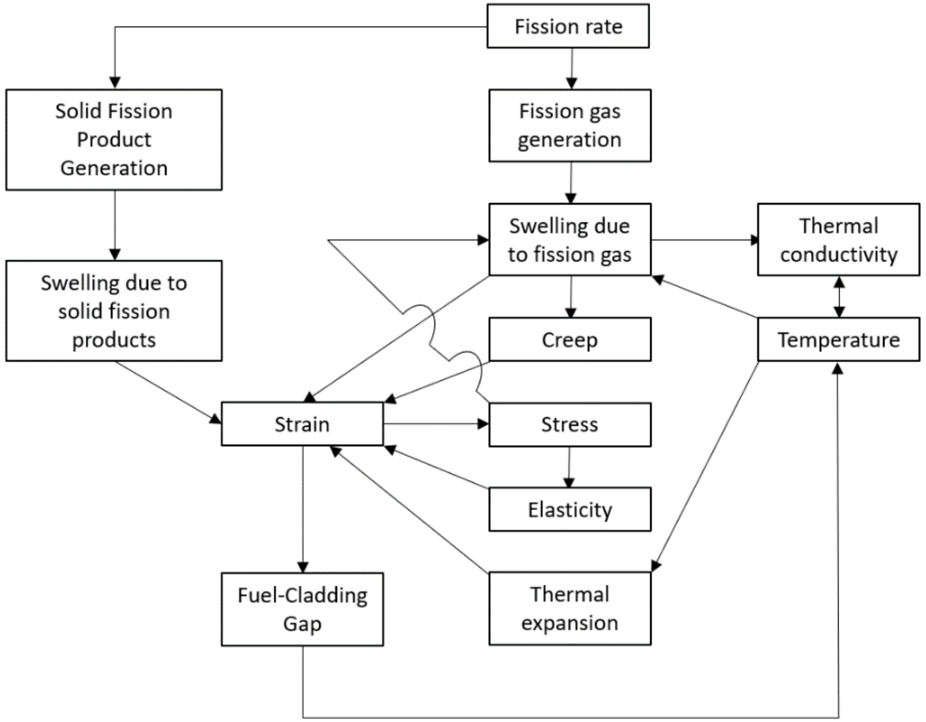
Experiment	Burnup (%FIMA)	Cladding Fluence ($\frac{n}{cm^2}$)	PICT (°C)	Cladding DPA
FAST-008	3.9%	4.44×10^{20}	410	1.61
FAST-016	8.5%	7.98×10^{20}	470	2.89
FAST-031	9.54%	7.36×10^{20}	510	2.66
FAST-048*	14.6%	1.14×10^{21}	543	4.16
FAST-052*	13.2%	1.20×10^{21}	475	4.33
FAST-050*	18.9%	1.49×10^{21}	500	5.40
FAST-053*	17.8%	1.60×10^{21}	476	5.78
X425A-T423 (142B-0.15)	3.9%	1.77×10^{23}	411	16.43
X425A-T423 (146A-0.583)	8.03%	4.53×10^{23}	468	39.82
X425A-T423 (146B-0.55)	9.55%	5.51×10^{23}	512	47.96
X425A-T424 (144A-0.117)	3.83%	6.84×10^{22}	435	17.3
X425A-T424 (150A-0.717)	8.57%	4.55×10^{23}	477	42.2
X425B-T424 (149A-0.517)	9.48%	4.24×10^{23}	504	47.85
X425C-T424 (158A-0.783)	14.6%	1.78×10^{24}	526	73.52
X425B-T424 (153A-0.417)	13.78%	1.25×10^{24}	477	71.65
X425C-T424 (158A-0.517)	17%	2.17×10^{24}	489	90.49
X425C-T424 (158A-0.517)	17%	2.17×10^{24}	489	90.49



BISON Simulated Conditions



- 2D-RZ simulation
- Thermal BC
  - ATR coolant on outside of outer capsule
  - Helium between inner and outer capsule
  - Sodium between cladding and inner capsule
  - Thermal bond between fuel and cladding
  - Top of fuel set to Peak Inner Cladding Temperature (PICT)



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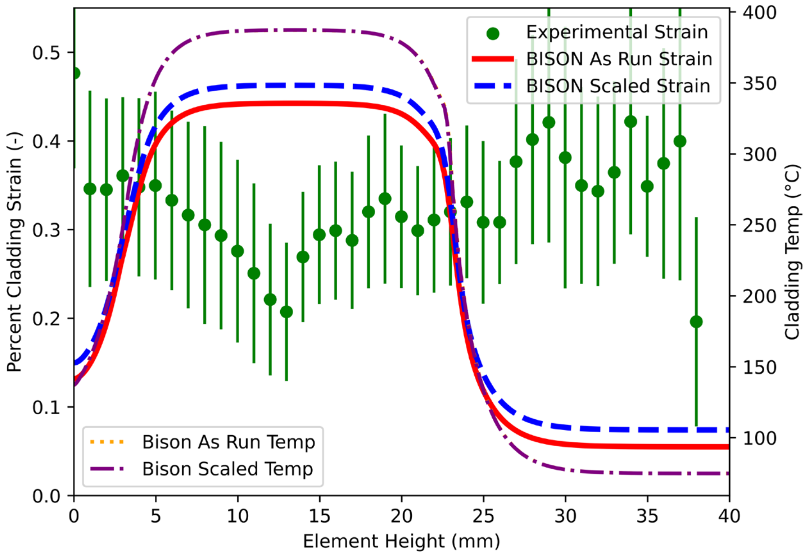
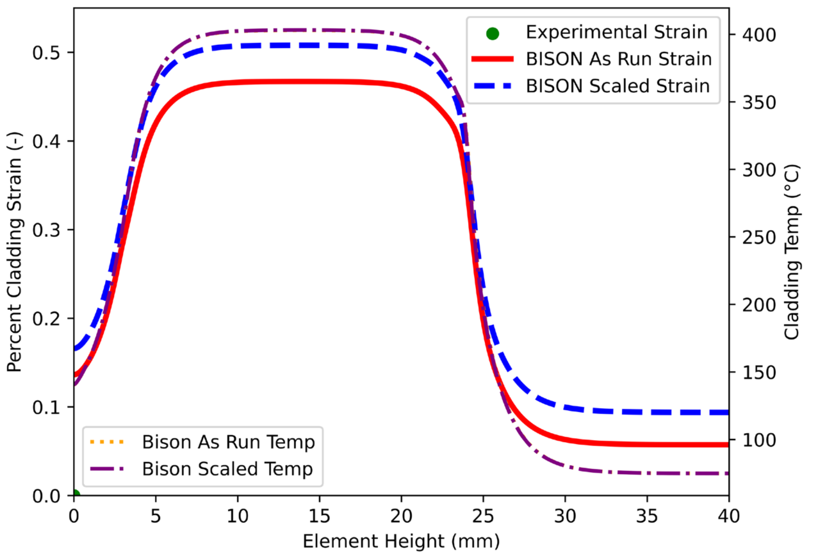
BISON Comparison of HT9 Clad Strain

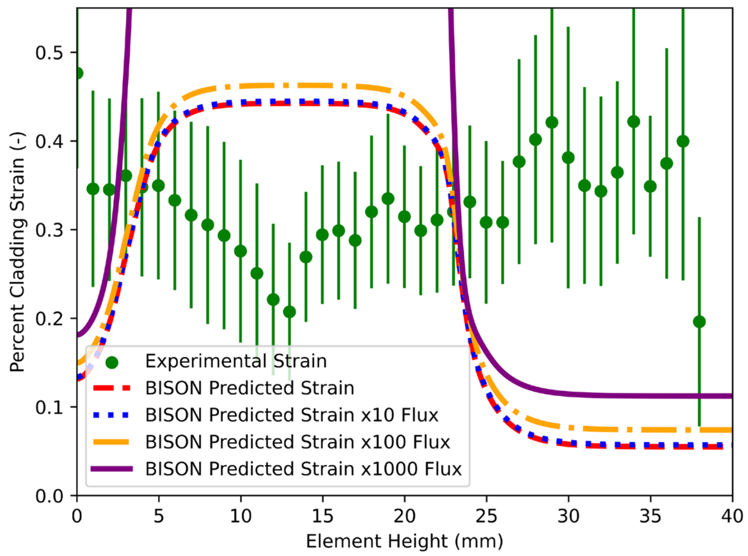
- Two approaches for comparing irradiation creep effects
  - EBR-II Fluence Comparison
    - Applied average fluence of X-425 experiment to FAST HT9 cladding
    - $\phi_{scaled} = \frac{BU_{FAST}}{BU_{X425}} \frac{F_{X425}}{t_{FAST}}$
    - Compares diametral cladding strains from FAST to nominal EBR-II radiation environment
  - Flux Scaling Comparison
    - Multiplying the flux by factors of 1, 10, 100, and 1000
    - Shows how models are affected by irradiation creep scaling

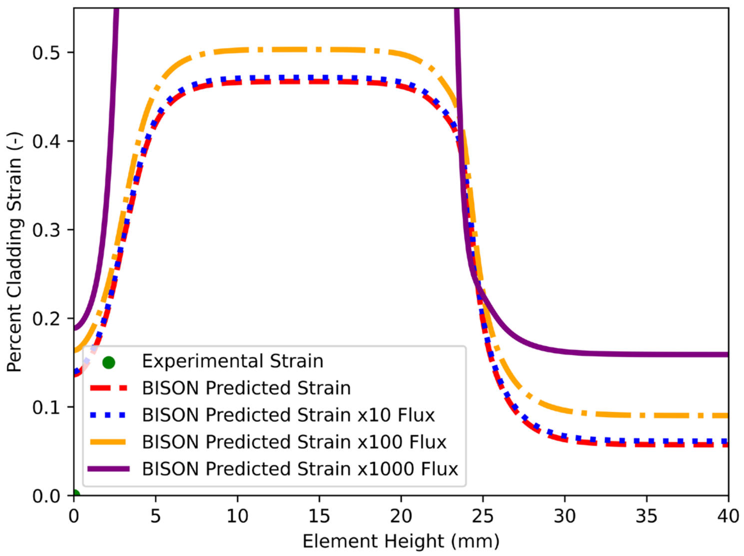


FAST-008



FAST-016





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Conclusions and Future Work

- Conclusions
  - Difference between FAST experiment and EBR-II flux conditions have minor effect on simulated diametral cladding strain.
    - Changes caused by irradiation creep increase remain below the experimental and modeling error.
  - Affect of scaling flux multiplicatively shows expected increase in cladding strain.
    - Demonstrates importance of understanding model limitations
      - Irradiation creep models used in BISON for HT9 only valid up to $11 \times 10^{22}\ \frac{n}{cm^2}$
  - FAST Experiments can confidently inform the maximum irradiation induced strain of HT9 cladding at accelerated rates.
- Future Work
  - Compare FAST simulation results to EBR-II simulations
  - Evaluate the FAST simulations for novel experiments with experimental data
  - Apply FAST methodology to other fuel forms

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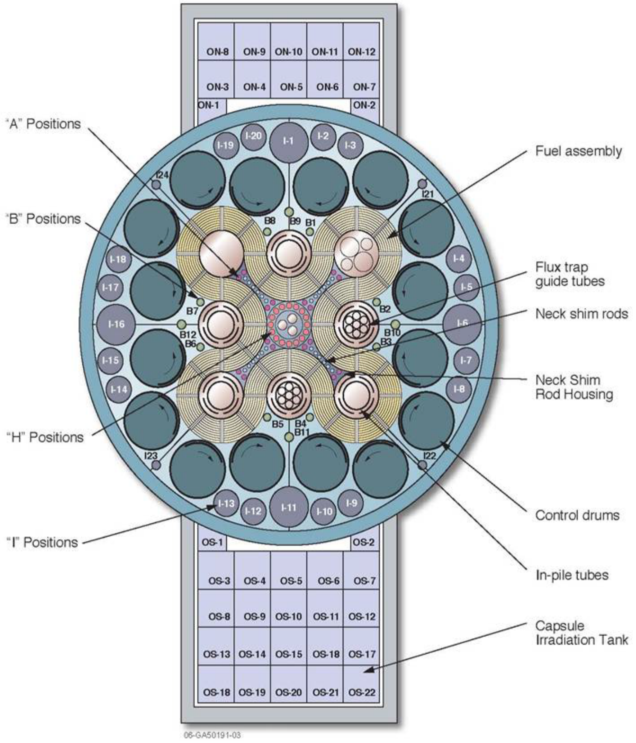
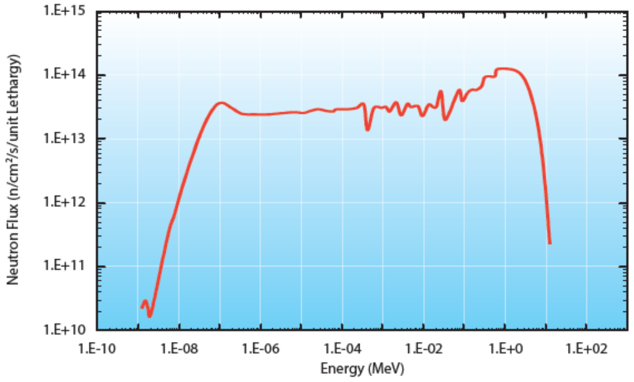
AFC Advanced Fuels Campaign

Advanced Test Reactor (ATR)

- Serpentine driver core creates nine flux traps and numerous other test positions
- 77 test volumes – up to 48 inches long and <5.25 inches in diameter
- 60-day cycles with ~3 cycles per year
- High neutron flux enables accelerated testing for fuel and materials development
  - Fast/thermal flux ratios ranging from 0.1 – 1.0
  - Thermal flux in the range of 1E13-1E14 n/cm2/s
  - Fast flux in the range of 1E12-1E14 n/cm2/s
- Collocated with world class suite of properties testing and characterization equipment in shielded hot cells





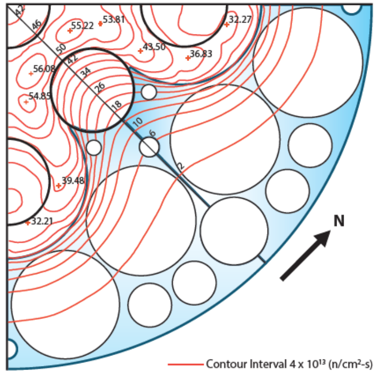


Table 2. Approximate peak flux values for various ATR capsule positions for a reactor power of 110 MW_{th} (22 MW_{th} in each lobe).

Position	Diameter (cm/in)[a]	Thermal Flux (n/cm^2-s)[b]	Fast Flux (E>1 MeV) (n/cm^2-s)	Typical Gamma Heating W/g (SS)[c]
Northwest and Northeast Flux Traps	13.3/5.250	4.4×10^{14}	2.2×10^{14}	
Other Flux Traps	7.62/3.000[d]	4.4×10^{14}	9.7×10^{13}	
A-Positions				
(A-1 - A-8)	1.59	1.9×10^{14}	1.7×10^{14}	8.8
(A-9 - A-16)	1.59/0.625	2.0×10^{14}	2.3×10^{14}	
B-Positions				
(B-1 - B-8)	2.22/0.875	2.5×10^{14}	8.1×10^{13}	6.4
(B-9 - B-12)	3.81/1.500	1.1×10^{14}	1.6×10^{13}	5.5
H-Positions (14)	1.59/0.625	1.9×10^{14}	1.7×10^{14}	8.4
I-Positions				
Large (4)	12.7/5.000	1.7×10^{13}	1.3×10^{12}	0.66
Medium (16)	8.26/3.500	3.4×10^{13}	1.3×10^{12}	
Small (4)	3.81/1.500	8.4×10^{13}	3.2×10^{12}	

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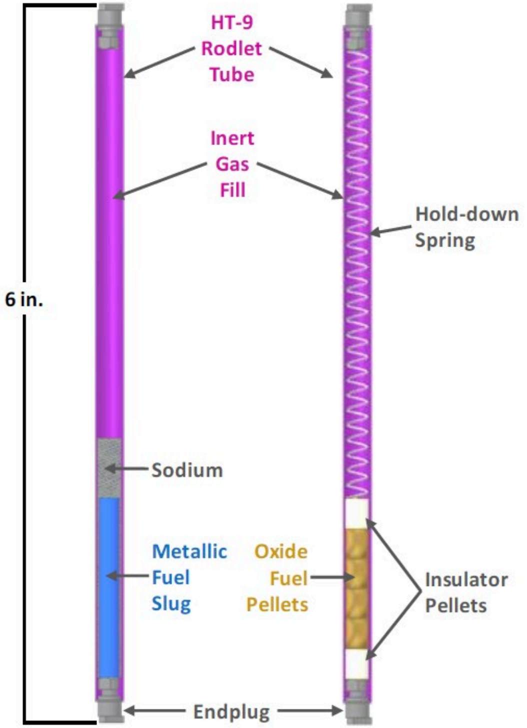
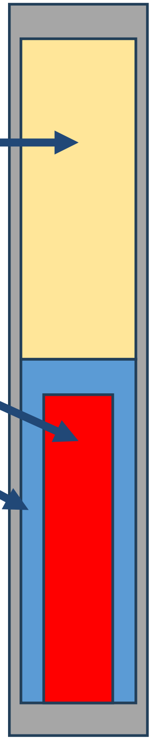
Fuel Testing Capsule Basics

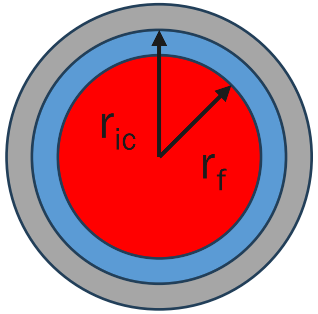
- Irradiation Experiment
  - Basket
  - Capsule
  - Rodlet

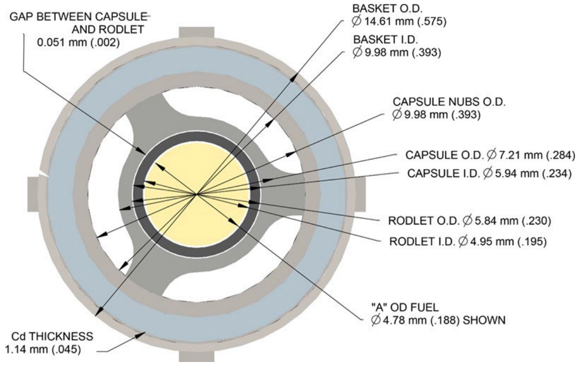


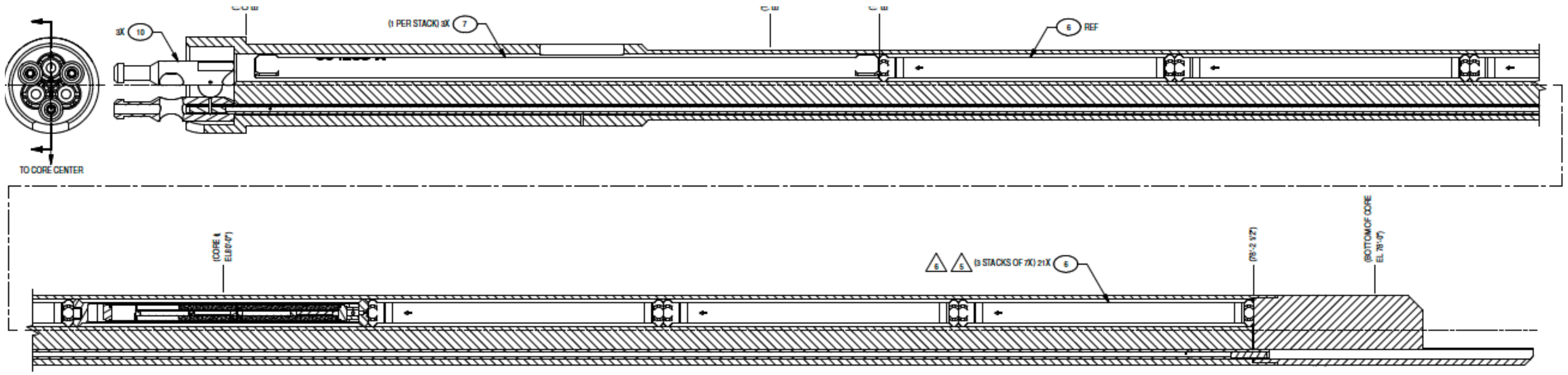
- Rodlet
  - Gas plenum
  - Fuel pin
  - Thermal bond
  - Smear density

    r_f^2/r_{ic}^2





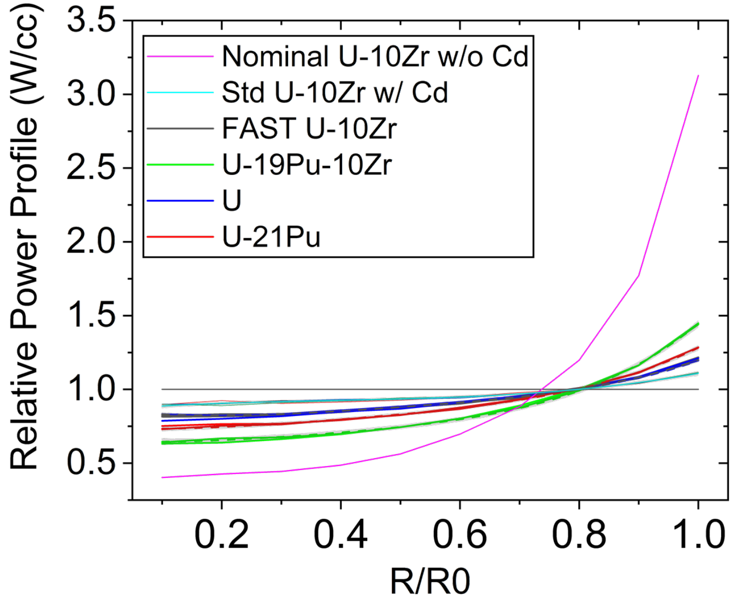


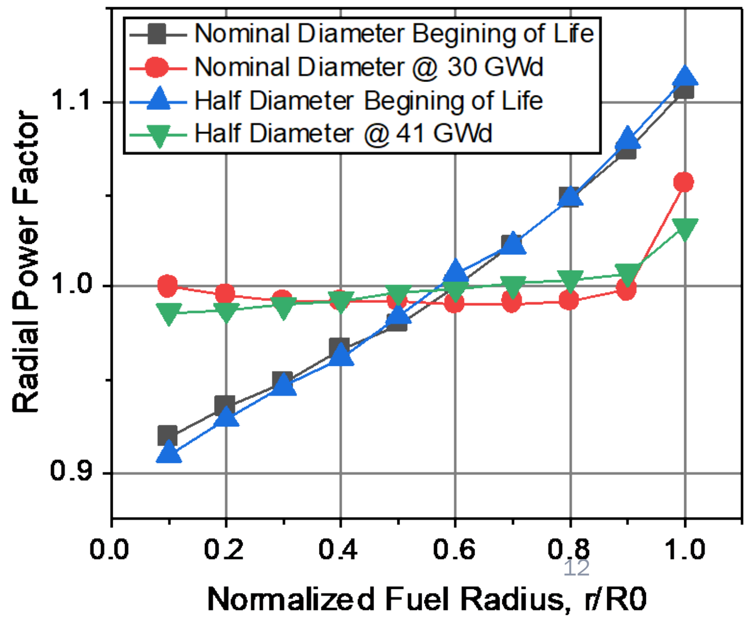


Burnup Acceleration

Case	Burnup (at%) per 55 day ATR cycle	Time to Achieve 30 at.% Burnup (years)
Full Diameter Small B, 365 W/cm	0.7	11.7
One-Half Diameter Small I, 300 W/cm	3.6	2.3
One-Third Diameter Small I, 180 W/cm	5.1	1.6

Initial Condition	Burnup Condition	Burnup (GWd/t_U) per 55 day ATR cycle	Time to Achieve 60 GWd/t_U
Full Diameter UO_2 595.4 W/cm, 4.95% Enrichment	28.6 GWd/t_U 321 W/cm 300 EFPD	~5 GWd/t_U	12 cycles (3 years)
One-Half Diameter UO_2 336.4 W/cm, 9.9% Enrichment	41.4 GWd/t_U 212 W/cm 180 EFPD	~12 GWd/t_U	5 cycles (1.25 years)





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