INL/CON-23-74461-Revision-1

Challenges and Solutions for Fast Neutron Irradiation of Bulk Material Specimens

March 2024

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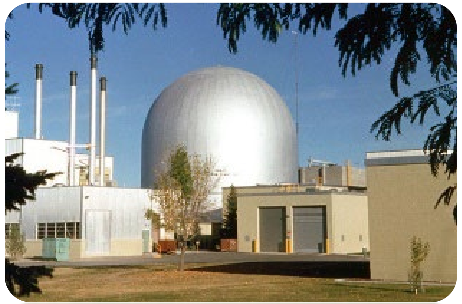
TMS Conference, 2024

Background

- The value of advanced fuels and materials for fast spectrum reactors has been and remains a crucial area for research and development
  - Most historic material test reactors were thermal spectrum, only a few were fast spectrum
  - Situation worse today, no operating fast spectrum test reactors available in or to United States
  - Proposed Versatile Test Reactor (VTR) not cancelled, but not yet funded, future uncertain
  - Joyo restart would alleviate the situation, but not likely meet all needs for US programs
- Spectral modification methods in water-cooled reactors can achieve some crucial fast reactor-like effects in test specimens
  - Even when historic reactors were operational thermal spectrum test reactors were occasionally used to test fast reactor fuels
  - Spectral modification methods, both old and new, can be used in Advanced Test Reactor (ATR) to accomplish several valuable aims, INL performing experiments and design studies currently



EBR-II, US
(decommissioned)

FFTF, US
(decommissioned)

Phenix, France
(decommissioned)

Joyo, Japan
(standby since 2007)

What the Big Deal with Fast Neutrons Anyway?

- The probability of all neutron interactions depend on two things
  1. The neutron energy
  2. The isotope identity (target nuclide)
- Fast neutrons penetrate further into material
  - Especially important to achieve desired power/burnup gradients in high-density fast reactor fuels
- Fast neutrons more likely to knock atoms around, thermal neutrons more likely to get absorbed and cause transmutation
  - Important to get the right material effects (properties changes from atom displacement vs. gas production)
  - Some materials very sensitive to transmutation damage (e.g., nickel turns into helium)
- Fast neutron cross sections differ for important reactions in fast reactor fuels (breeding, burning, minor actinide destruction)
  - Representative neutron energy spectrum crucial to achieve representative isotopic evolutions
- Differences in these effects remain true, and in some cases amplified, in fusion relevant neutron spectra
  - More on this later

Neutron irradiation damage

From Wikipedia, the free encyclopedia

Neutron irradiation damage refers to material changes caused by high neutron flux, typically in a nuclear reactor after many years.

Graphite may shrink and then swell.[1]

See also [edit]

- Neutron embrittlement
- Neutron radiation#Effects on materials

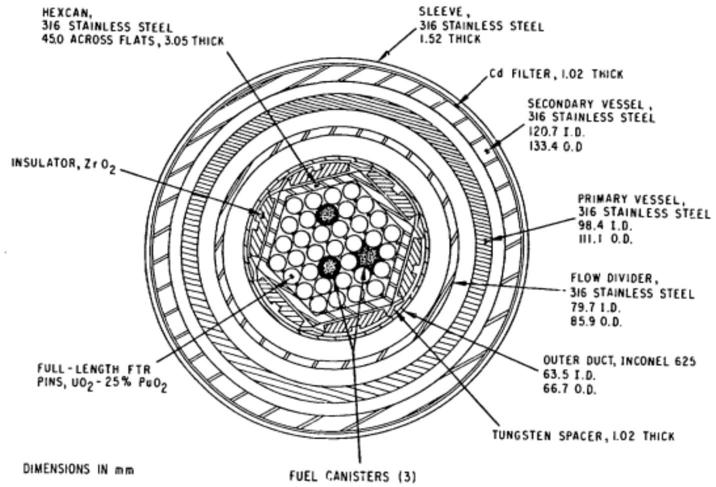
References [edit]

1. ^ *Neutron Irradiation Damage in Graphite and Its Effects on Properties* Burchell 2002

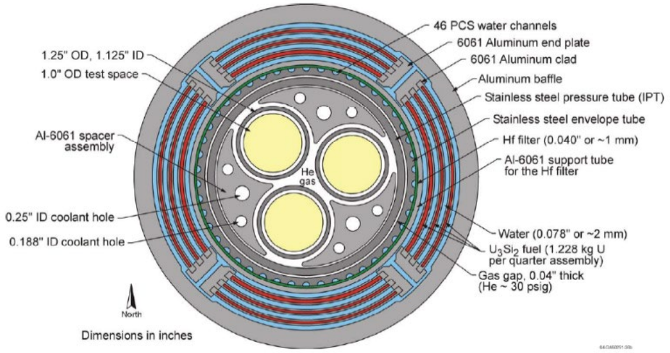
Sorry if this slide was insultingly simple, but its at least more helpful than this Wikipedia article

Tricks of the Trade

- How does one modify neutron spectra in a water-cooled reactor
- Proximity to driver fuel
  - Peak fast flux in a water-cooled material test reactor typically in or near the center of the core
- Displace as much moderator as possible (recognizing that some is needed for cooling)
  - Al-alloy, Zr-alloy, SST typical choices for displacing water
  - Beryllium is double edged sword, n-2n reaction multiplies neutrons, but also moderates them, can work in some situations
- Surround specimens with neutron absorbers
  - Several constraints to consider, more on next slide
- Booster fuel
  - Add more fuel around/by specimen to multiply incoming thermal neutrons into ~2 fission-fast neutrons
  - Fast flux improves with higher power density, requires favorable heat transfer configurations to minimize water content
- Fusion reactions
  - Some materials can convert incoming fission-born neutrons into fusion reactions, emitting “very fast” neutrons (14 MeV)



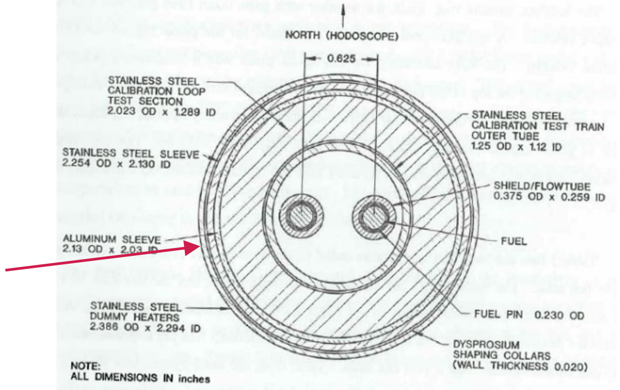
Cd-shrouded sodium loop irradiated in the water-cooled Engineering Test Reactor, CONF-820406-28, 1982



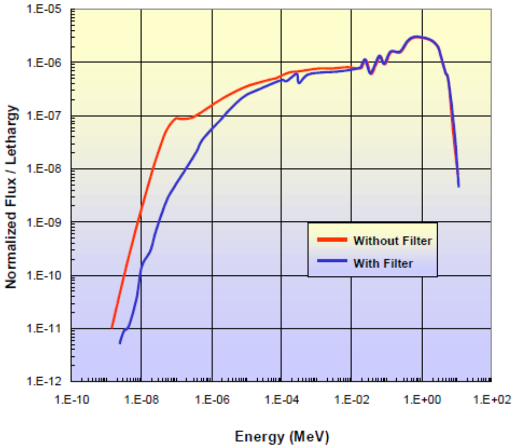
Fuel plate boosted, hafnium filtered, gas-cooled loop concept in ATR (never constructed)
INL/EXT-09-16413, 2009

Spectral Modification by Filtering

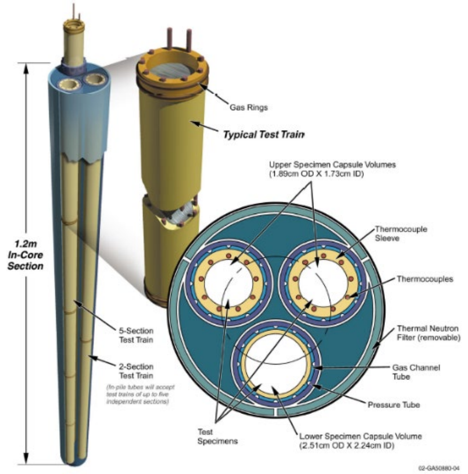
- Neutron absorbers surround specimens to preferentially filter thermal neutrons
- Things to consider
  - Does nothing to boost fast flux, in fact all options reduce it, just not as much they reduce thermal flux
  - The best options also burnout the fastest (B, Cd, Gd, Er), must be designed to last the life of the test or be replaceable
  - Some options are exotic, expensive, and become highly radioactive (Dy, Eu, Hf) or otherwise difficult to obtain in quantity (^{3}He)
  - Special consideration for low melting temperature (metallic Cd) or carcinogenic hazards (CdO particles)
  - Management of nuclear heating and gas production (B → He, Li → ^{3}H)
- No perfect option, but with care these approaches can be rather effective

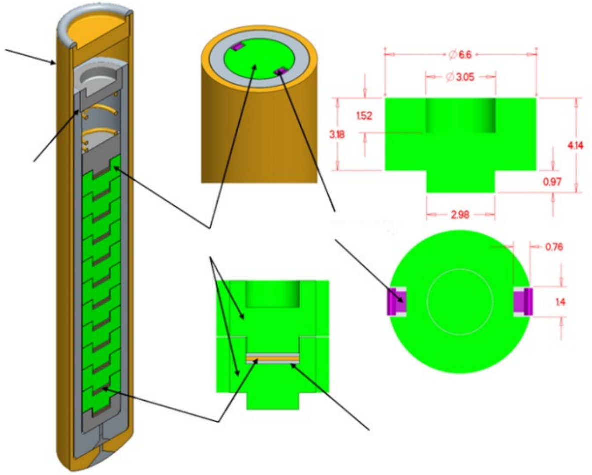


Dysprosium wrapped around historic Transient Reactor Test facility (TREAT) sodium loop test (ANL-IFR-232, 1994)



Historic ATR flux trap test rig spectrum with and without neutron filters (INEEL/EXT-02-01064)

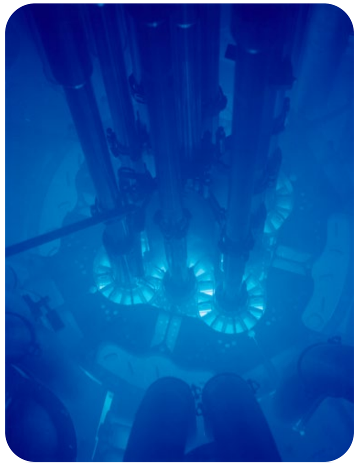




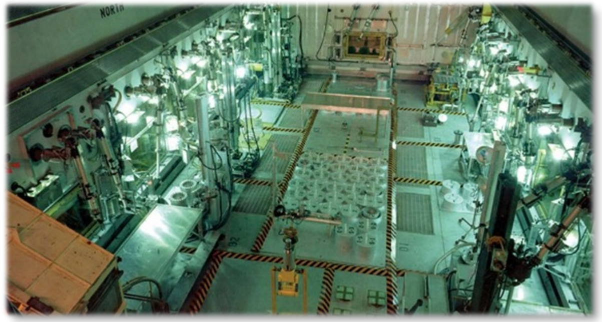
Gd-filtered capsules for High Flux Isotope Reactor (HFIR) hydraulic rabbits (PLN-3832)

ATR Overview

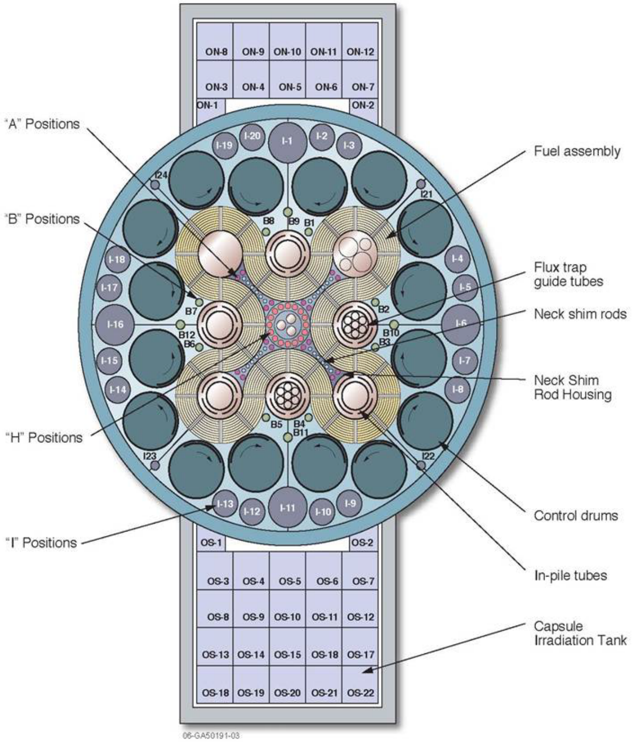
- Water-cooled plate-type material test reactor started 1967, still one of the newest and most advanced in the world
- Serpentine driver core creates nine flux traps and numerous other test positions
- High flux, large useable test geometries (1.2 m long core, test positions up to 13 cm dia)
- Rich history of capsule, water loop, and instrumented lead out irradiation tests
- Collocated with world class suite of properties testing and characterization equipment in shielded hot cells
- Fluxes range from as high as ~1E15 n/cm^{2}s (inner core) to as low as ~1E13 n/cm^{2}s (outer reflector)
- Fast-to-thermal neutron ratios ranging from 1:1 (inner core) to 10:1 (inner reflector) and 100:1 (outer reflector)
- Inner core positions naturally most interesting for fast spectrum testing



ATR Core



Hot Fuel Exam Facility



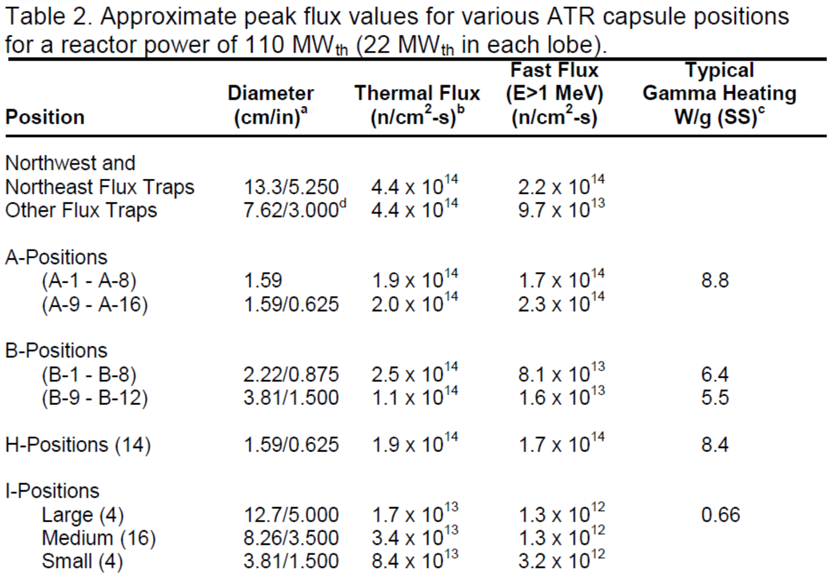
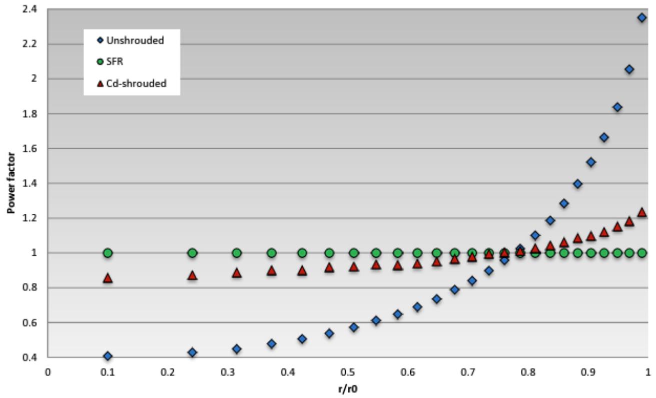


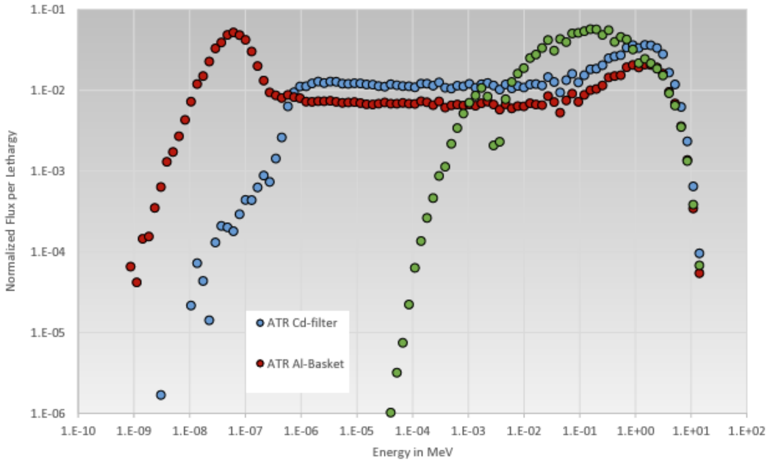
Table 2. Approximate peak flux values for various ATR capsule positions for a reactor power of 110 MW$_{th}$ (22 MW$_{th}$ in each lobe).

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 x 10^{14}	2.2 x 10^{14}	
Other Flux Traps	7.62/3.000^d	4.4 x 10^{14}	9.7 x 10^{13}	
A-Positions				
(A-1 - A-8)	1.59	1.9 x 10^{14}	1.7 x 10^{14}	8.8
(A-9 - A-16)	1.59/0.625	2.0 x 10^{14}	2.3 x 10^{14}	
B-Positions				
(B-1 - B-8)	2.22/0.875	2.5 x 10^{14}	8.1 x 10^{13}	6.4
(B-9 - B-12)	3.81/1.500	1.1 x 10^{14}	1.6 x 10^{13}	5.5
H-Positions (14)	1.59/0.625	1.9 x 10^{14}	1.7 x 10^{14}	8.4
I-Positions				
Large (4)	12.7/5.000	1.7 x 10^{13}	1.3 x 10^{12}	0.66
Medium (16)	8.26/3.500	3.4 x 10^{13}	1.3 x 10^{12}	
Small (4)	3.81/1.500	8.4 x 10^{13}	3.2 x 10^{12}	

Current Spectrum Modification Capabilities at ATR

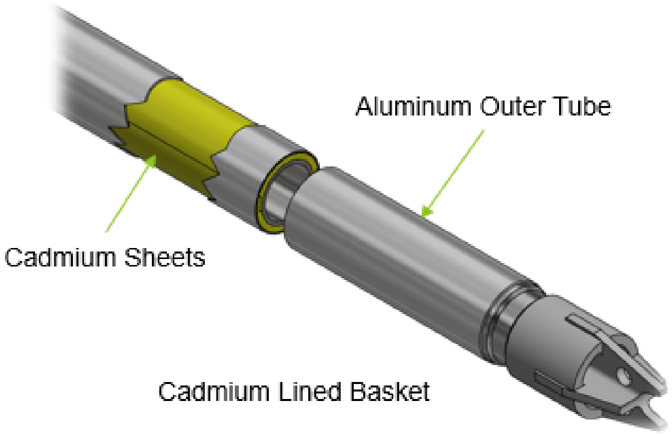
- **Workhorse Cd-basket and Advanced Fuel Campaign (AFC) capsule design**
  - Years of successful use for nuclear fuels
  - Prototypic SFR diameter, short fuel length rodlet (3.8 cm)
  - Capsule gas gap between specimen and water-cooled wall for elevated specimen temperature
  - Cd-lined basket filters thermal neutrons for harder flux, mimics fuel radial power profile in true fast spectrum reactor (INL/EXT-17-41677)
  - Prototypic heating rates, ~3 at% burnup per year in fuel, ~3-5 dpa per year in cladding

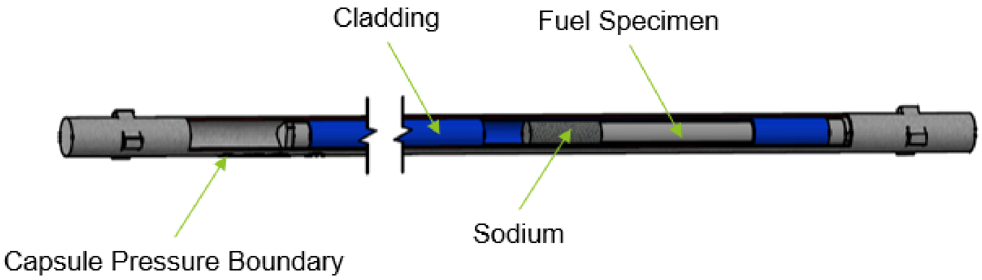




Radial power gradients and neutron spectra comparing:

- **Unfiltered basket**
- **Cd-basket**
- **True SFR**





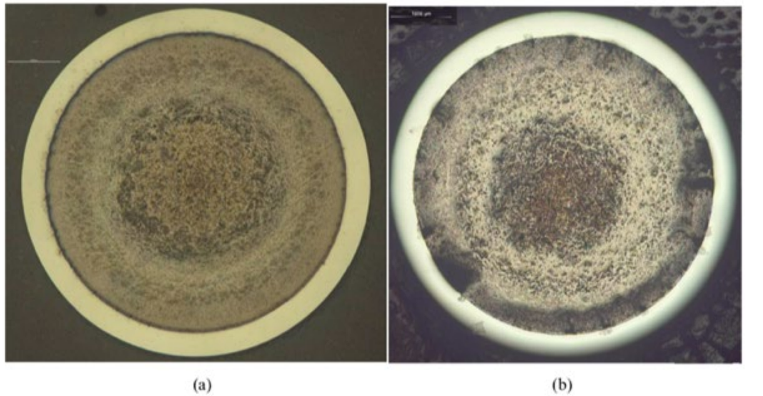
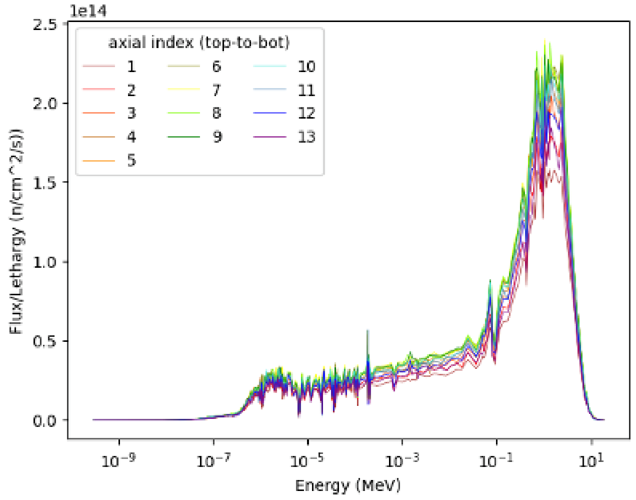


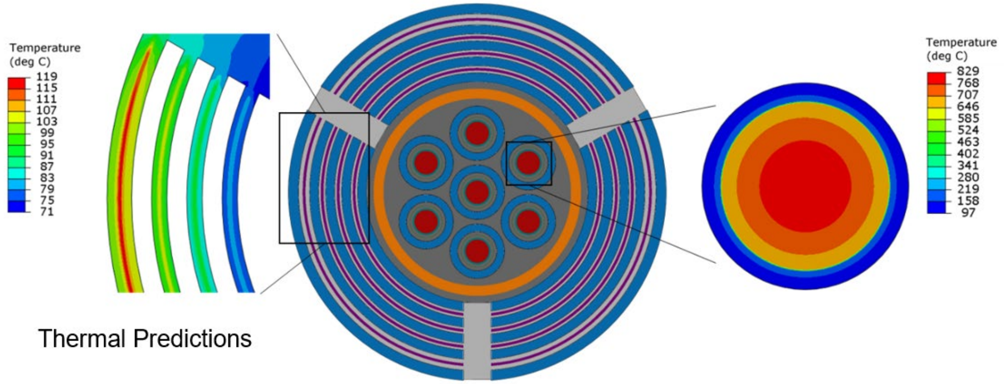
Figure 69. Metallography of Pu-12Am-40Zr irradiated to approximately 20% burnup in: a) Phénix fast reactor (FUTURIX-FTA DOE2), and b) cadmium-filtered position in ATR (AFC-1D R4).

Boosted Energy Advanced Spectrum Test (BEAST)

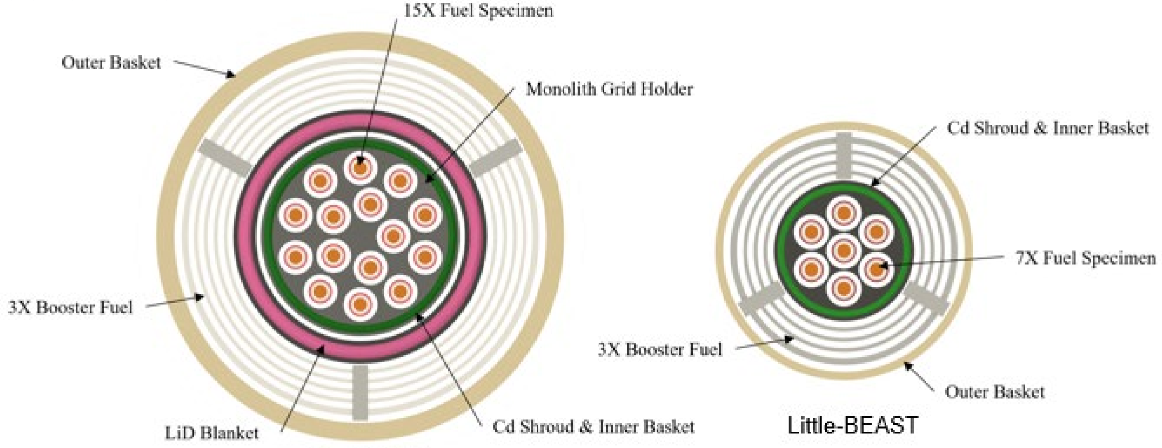
- AFC supporting development of next gen device "BEAST" based on historic concepts (INL/EXT-05-00263) and recently published work (https://doi.org/10.1016/j.nucengdes.2021.111623)
  - $1E15\ n/cm^2s$ fast flux (>0.1 MeV), 10 dpa/yr in SST, should be achievable with HEU booster based on historic designs
  - Recent calcs show $\sim 7E14\ n/cm^2s$ fast flux with LEU booster design
    - Broadens booster fuel supplier options, preferred option to reduce cost
  - Prototypic SFR heating rates in test pins, gas gap capsules for prototypic temperatures
- Large and small flux trap options assessed
  - Conflicting needs with other programs under evaluation, decision not yet made
- Cd and Eu filtered baskets give fast-to-thermal ratios of ~50:1 and ~100:1, respectively
  - Cadmium option preferred based on higher fast flux peak and years of economical/successful use in ATR
- Booster fuel plates $250\ W/cm^2$ surface heat flux, well within ATR thermal hydraulic limits



Spectra Predicted for Fuel Pins in BEAST



Thermal Predictions

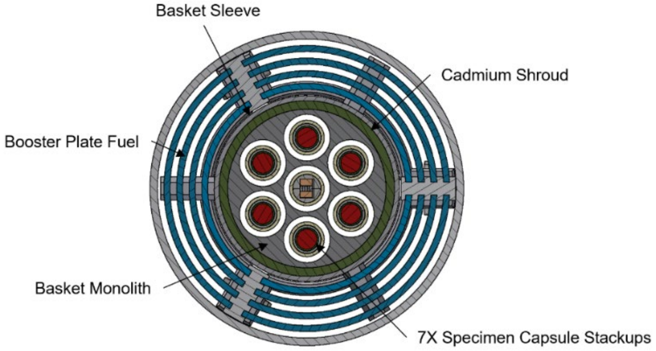


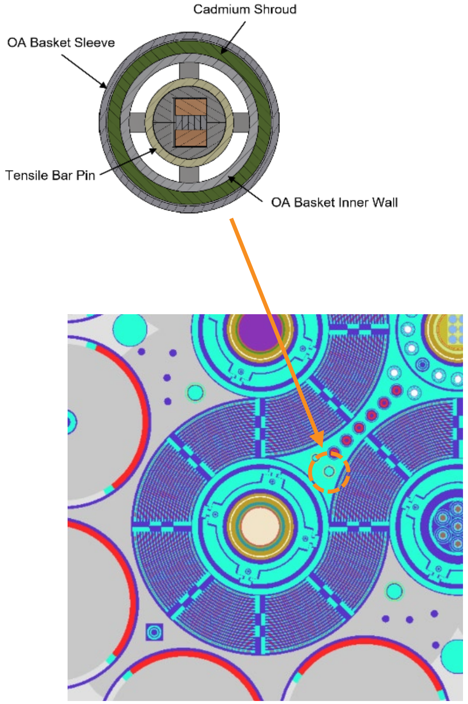
Big-BEAST

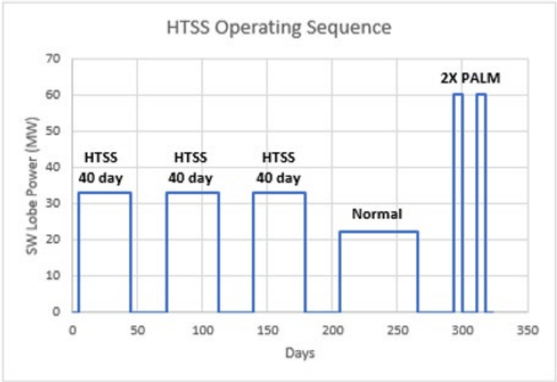
Little-BEAST

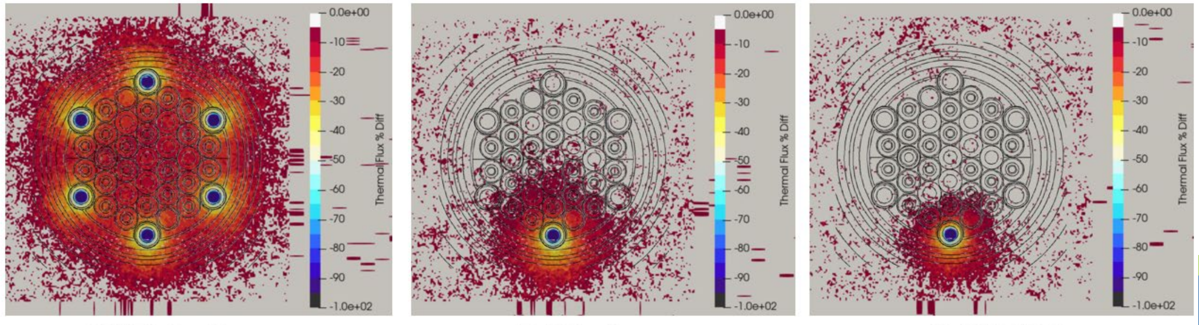
Options for Fast Reactor Materials Only Specimens

- Innovative Nuclear Materials (INM) program supporting study for fast flux testing on “material-only” specimens in existing reactors
  - Objective: Best fast flux possible, minimize non-prototypic thermal neutron capture transmutation effects
- Option 1 ATR: Replacing some fuel pins in ATR-BEAST with materials-only specimens
  - 7E14 n/cm^2 fast flux (>0.1 MeV), 50:1 fast to thermal ratio
  - Replacing fuel specimens with unfueled specimens reduces fast flux to the primary specimens (e.g., neighboring fuel pins)
- ATR: Cd-filtered baskets in south-west lobe during future ~33 MW lobe power “HTSS” cycles
  - 5.5E14 n/cm^2 fast flux (>0.1 MeV), 45:1 fast to thermal ratio
  - Variable power history makes positions less desirable for fuels testing, gamma-heated materials less sensitive
  - Affordable approach based on standard designs, the most well round opportunity for materials-only irradiations
- HFIR: Gd-filtered peripheral target positions in flux trap
  - 1.1E15 n/cm^2 fast flux (>0.1 MeV), 40:1 fast to thermal ratio
  - Perhaps only one ~50 mm capsule tenable, due to effect on neighboring positions
  - A good fit for un-filtered capsules with specimen materials where the high thermal flux is not detrimental









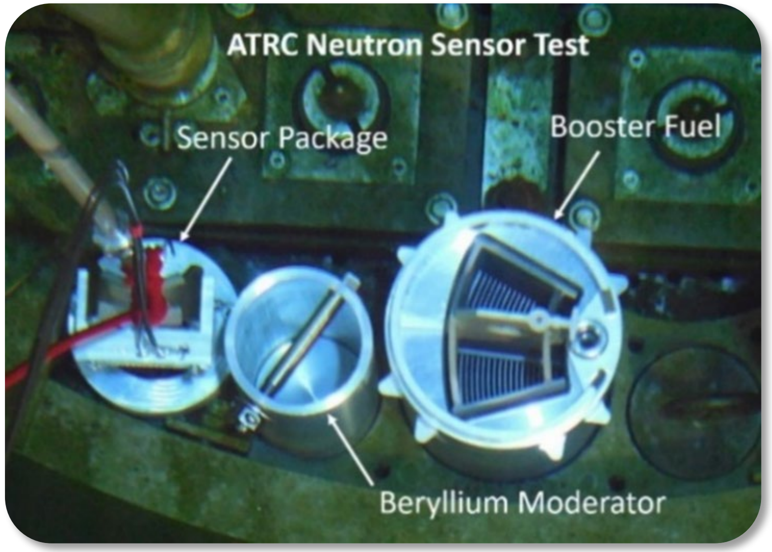
All PTP Positions
1 capsule each

D-1 Position
7 capsule stack

D-1 Position
1 capsule

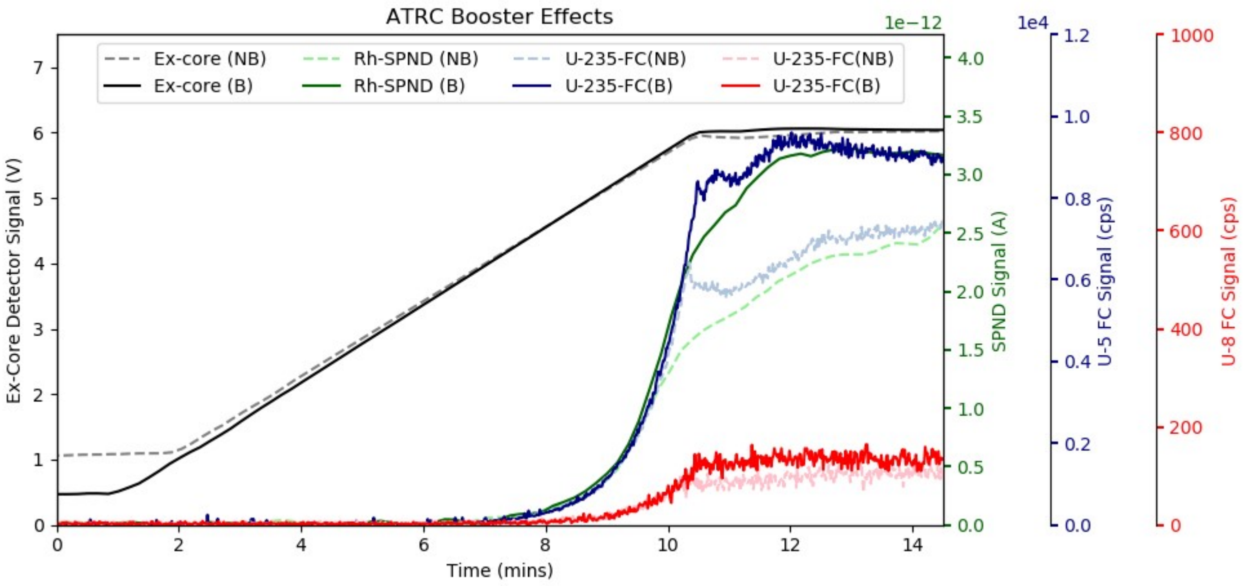
Spectral Characterization

- Advanced Sensors and Instrumentation (ASI) program developing methods to measure neutron spectra
  - To augment classical dosimeter-based methods
- Neutron flux sensors were used for I-Loop booster fuel testing at ATR-C
  - U-235 fission chamber (U-5-FC)
  - U-238 fission chamber (U-8-FC)
  - Rhodium self-powered neutron detector (Rh-SPND)
- FY24 activity to development SPNDs for real-time neutron spectrum measurement
  - First demonstration tantalum SPND → better performance in fast flux environment
  - Research objective to identify emitters that mirror dosimetry for neutron spectrum unfolding techniques



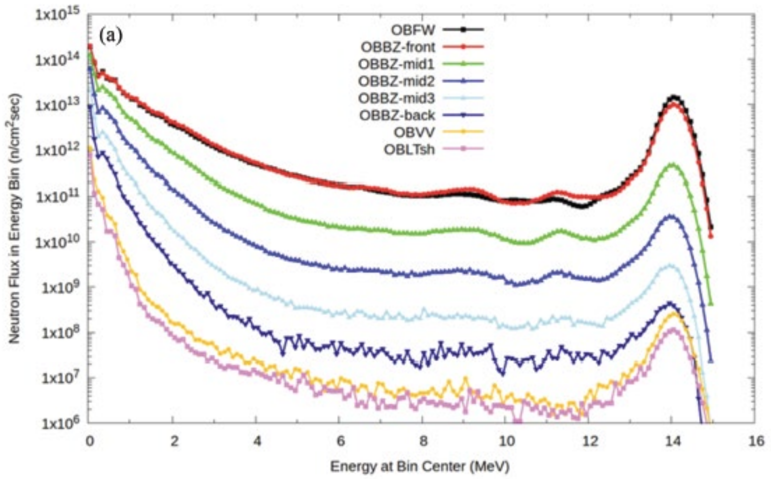
ATRC I-loop testing with booster fuel and beryllium moderator inserted

Neutron flux sensor data on booster fuel performance. NB = no booster fuel, B = with booster fuel.

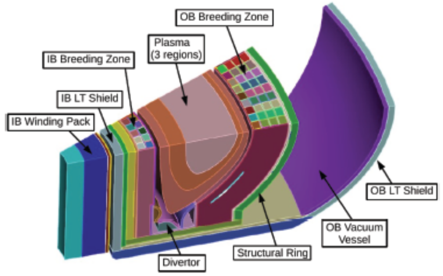


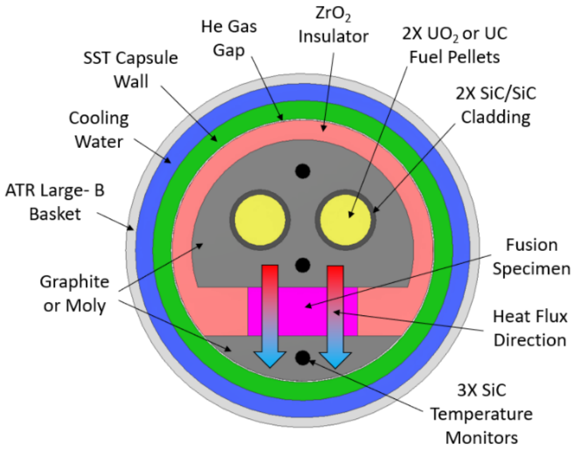
Fusion Potentials, LDRD

- Recently began internally-funded research project to study new spectral modification concepts
  - Focused towards potential fast-fission and fusion applications
- Spectral filters to permit custom-tuned amount of thermal neutron reactions to simulate targeted effects
  - Specimen ^{10}B doping for He production in select materials
  - ^{6}Li for ^{3}H permeation studies
  - ^{235}U fission to drive high heat flux testing
- Conversion of thermal neutrons into 14 MeV neutrons (historic LiD converter concept)
  - Unlikely to achieve first wall 14 MeV flux levels and obviate the need for new facility Fusion Prototypic Neutron Source (FPNS)
  - But perhaps useful for materials "behind the first wall"
- Fission isn't fusion, but certainly some useful concepts will be discovered, stay tuned



Neutron energy spectra in various "behind the first wall" layers of a tokamak
https://doi.org/10.1080/15361055.2022.2156205

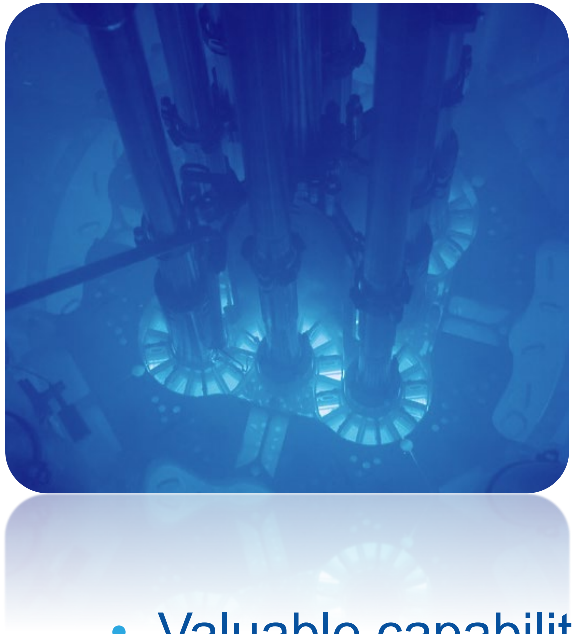




Capsule concept using fission fuel to drive high heat flux (~500 W/cm^2) with neutron irradiation through fusion specimens

Conclusions

- The need for fast neutron irradiation capabilities remains crucial
  - Historic facilities unavailable
  - New facilities yet to be built
- Spectral modification in ATR can't do everything, but it can do many things



- Valuable capabilities to:
  - Screen fuel/material technology candidates
  - Understand behaviors and answer questions
  - Build momentum and sharpen research focus for future facilities