The Impact of the HEU to LEU Fuel Conversion on the Lifetime and Efficacy of Beryllium:

The primary neutron reflector at high-performance research and test reactors

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Facility Overview

Location: University of Missouri main campus in Columbia, Missouri, USA [200 km West of St Louis]

Purpose: Multi-disciplinary research and education facility also providing a broad range of analytical and irradiation services to the research community and the commercial sector.

History:

- First achieved criticality on October 13, 1966
- Initially licensed at 5 MW
- Uprated in power to 10 MW in 1974
- Started ≥150 hours/week operation in September 1977
- Submitted relicensing application in 2006 to the NRC

MURR Core Basic Reactor Parameters

MURR® is a pressurized, heterogeneous, reflected, open pool-type, which is light-water moderated and cooled

- Maximum power – **10 MW_{th}**
- Peak flux in center test hole – **6.0E14 n/cm^2-s**
- Core – **8 fuel assemblies (775 grams of U-235/assembly)**
- Excess reactivity control blades – **5 total: 4 BORAL® shim-safety, 1 SS regulating**
- **Primary Reflector - beryllium***
- Forced primary coolant flow rate – **3,750 gpm (237 lps)**
- Forced pool coolant flow rate – **1,200 gpm (76 lps)**
- Primary coolant temps – **120 °F (49 °C) inlet, 136 °F (58 °C) outlet**
- Primary coolant system pressure – **85 psia (586 kPa)**
- Pool coolant temps – **100 °F (38 °C) inlet, 106 °F (41 °C) outlet**
- Beamports – **three 4-inch (10 cm), three 6-inch (15 cm)**

Beryllium as a Primary Neutron Reflector at Research Reactors

Advantageous qualities of beryllium:

- Has one of the highest atom number densities (i.e., a relatively large scattering cross-section).
- A very small neutron absorption cross-section.
- Though not as efficient, also a neutron multiplier due to its small $^{9}Be\ (n_f, 2n)\ 2\ ^{4}He$ and $^{9}Be\ (\gamma, n)\ 2\ ^{4}He$ cross-sections which increases core excess reactivity.

Usage of beryllium as neutron reflector:

- ATR (INL)- 200MW
- HFIR (ORNL)- 100MW
- MURR (Missouri University) -10 MW

- Works well for high power density Research Reactors (e.g. MURR)

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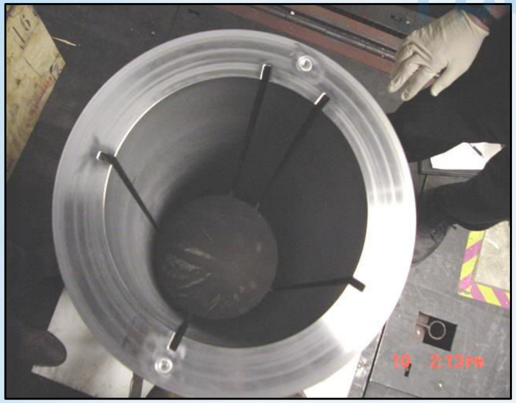
* The MURR Beryllium Reflector



- **Geometry**: cylindrical sleeve located around the outer reactor pressure vessel at the height that contains the reactor core
- **Material**: S-200FH grade
- **Height**: 37 inches (94 cm)
- **Outer diameter**: 19 inches (48.3 cm)
- **Sleeve thickness**: 2.71 inches (6.9 cm)

- **Present replacement schedule for MURR HEU core: 8 years of full-power operation or 26000 MWD at 10MW**
  - **Based on observed stress-fracture failure of beryllium in 1981**

- **Expected replacement schedule for proposed LEU-CD35 conversion core: ????**

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* Limits on the Beryllium Lifetime at Research Reactors

- Routine replacement of beryllium due to radiation induced stress-fracture failure:
  - Swelling stress from gas production

$n_f + {}^{9}Be \rightarrow {}^{6}He + {}^{4}He$	$\sigma_{n,\alpha} \approx 0.05$ barns
${}^{6}He \rightarrow {}^{6}Li + \beta^-$	$t_{1/2} = 0.8$ seconds
$n + {}^{6}Li \rightarrow {}^{4}He + {}^{3}H$	$\sigma \approx 838$ barns
${}^{3}H \rightarrow {}^{3}He + \beta^-$	$t_{1/2} = 12.5$ years
$n + {}^{3}He \rightarrow {}^{3}H + p$	$\sigma \approx 4900$ barns

  - Thermal stress from radiation (gamma) energy deposition

} Very limited studies and measurements available!

- Fuel conversion from HEU (UAl_x dispersion) to LEU (U-10Mo monolithic)
  - In accordance with the mission of the Global Threat Reduction Initiative (GTRI), the current capabilities and performance of research and test reactors must be maintained after conversion

} No previous studies available!

The Importance and Purpose/Intent of Investigating Beryllium Lifetime Limits

* Beryllium reflectors are specifically designed and fabricated to provide a critical core and desired power/flux distributions
* Beryllium may be a part of the actual core structural component (HFIR, ATR) or can affect operation of other core component (MURR), such that failure can compromise normal operation
* Until now, the development of a systematic approach to study the beryllium performance and predict the total stress as a function of megawatt days, has been lacking
* **Specifically, the goal is to predict if there is a change in the stress vs. MWD curve, and performance, on conversion of MURR from 10MW HEU to 12MW LEU, using MCNP-coupled-ORIGEN depletion models**

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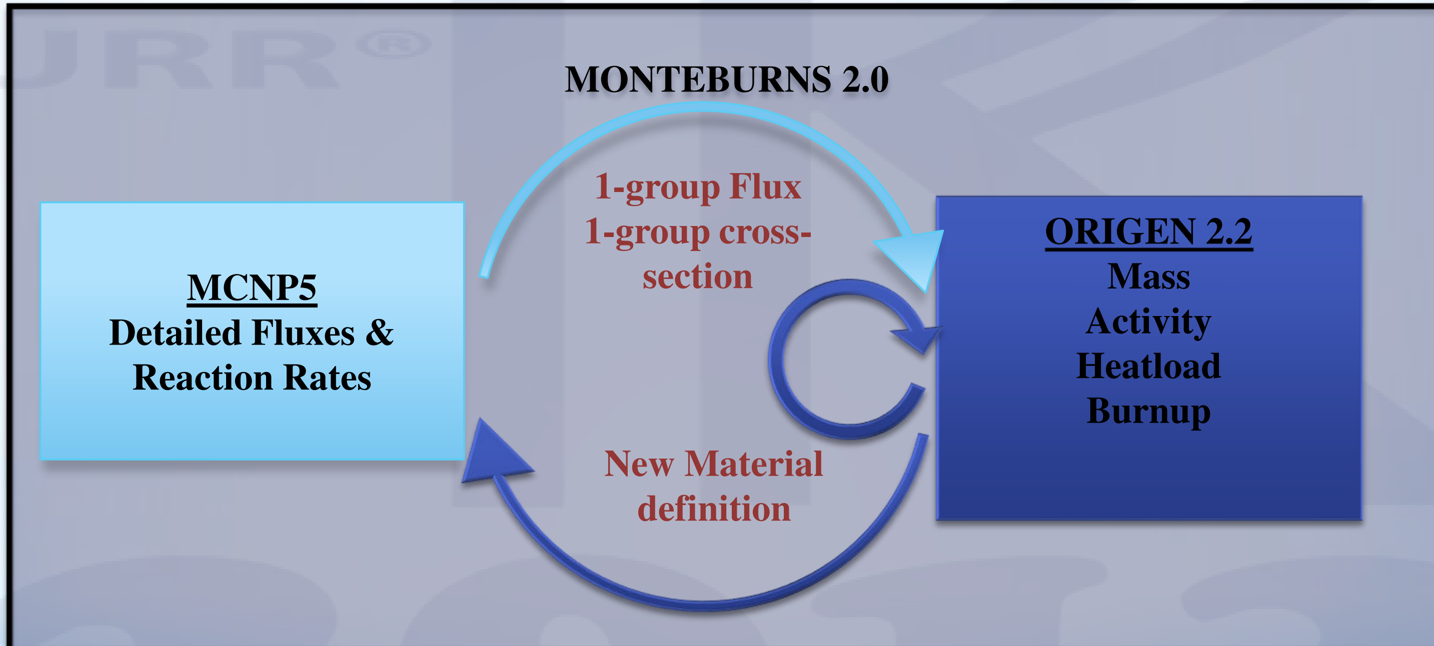
* Computational Methodology for Beryllium Depletion Models



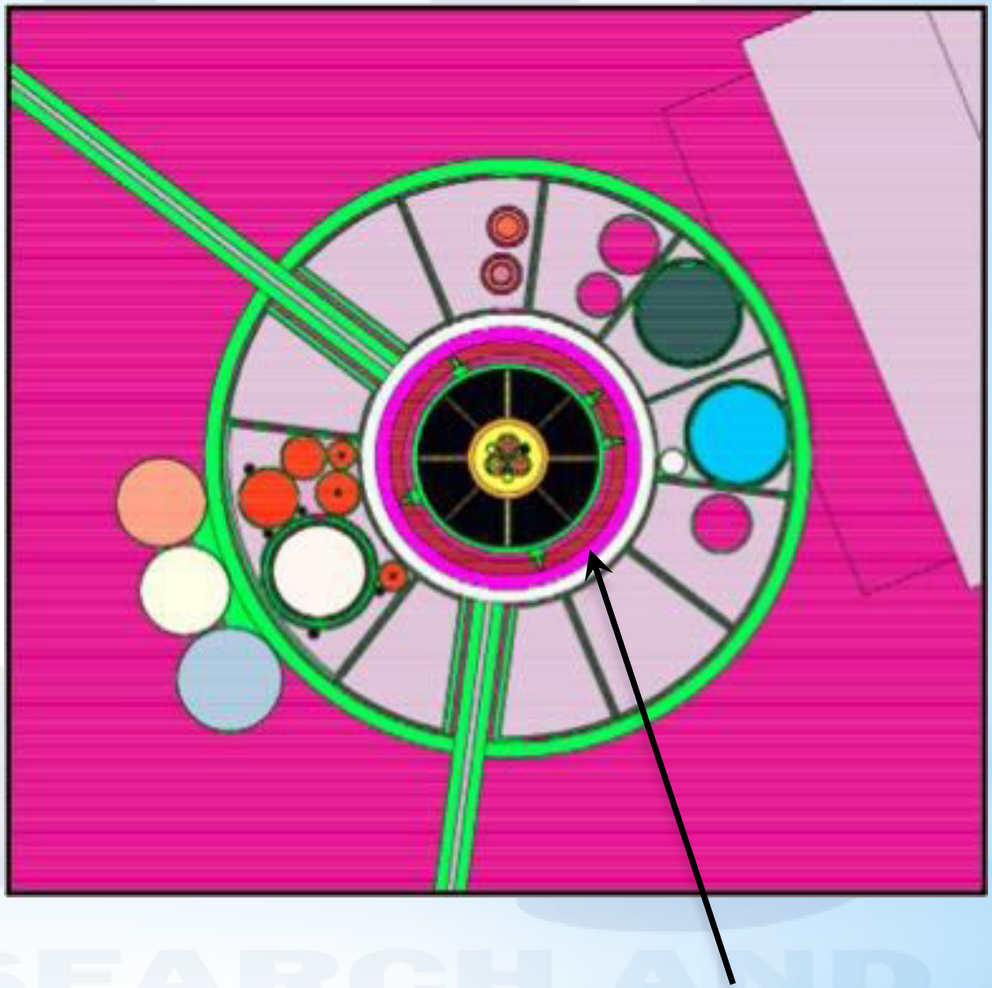
- MONTEBURNS 2.0 – Time-dependent, cyclic, stepwise, MCNP-coupled-ORIGEN nuclear burn-up code system (LANL)

* MCNP5 MURR Core HEU/LEU-CD35 Model

- MURR current HEU and proposed LEU-CD35 ex-core configuration is expected to have identical geometry

- **HEU core**:
  - Fuel matrix: UAl_x, 24-plate
  - Density = 3.7g/cc
  - Typical mixed-fuel core configuration: (640MWD) at 10MW
  - U mass per core = 6.2Kg

- **LEU-CD35 core**:
  - Fuel matrix: U-10Mo, 23-plate
  - Density = 15.7g/cc
  - Similar mixed-fuel core configuration: (765MWD) at 12 MW
  - U mass per core = 14.0Kg



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* Discretization of the Beryllium Reflector MCNP5 Model

Axial section 1

Axial section 2

Axial section 3
(peak flux zone)

Axial section 4

Axial section 5

Discretized Beryllium Sleeve

15 individual depletion zones (rings): 3 radial and 5 axial sections

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* Predicted Fast Flux Profile for MURR HEU Core Beryllium Reflector

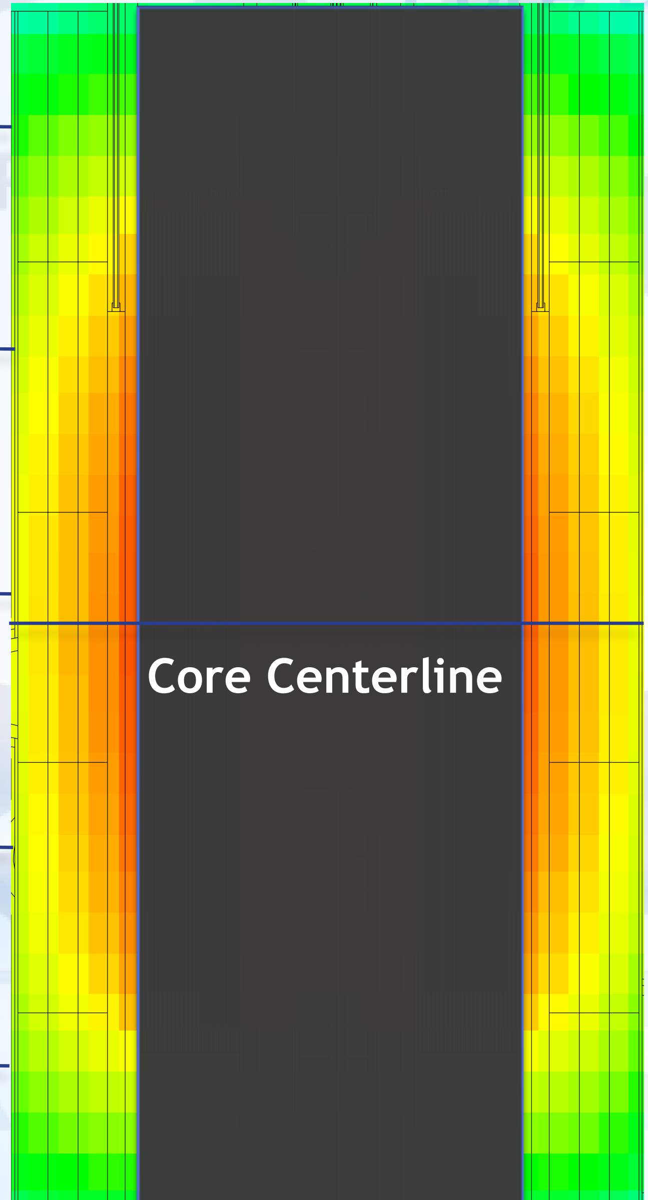
Axial section 1

Axial section 2

Axial section 3 (peak flux zone)

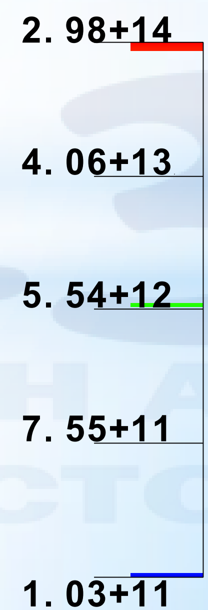
Axial section 4

Axial section 5



Current beryllium Peak Fast Flux (> 0.1MeV) = 9.40 x 10^{13} n•cm^{-2}s^{-1}

MURR LEU-CD35 Core (> 0.1MeV) fast flux =1.01 x 10^{14} n•cm^{-2}s^{-1}



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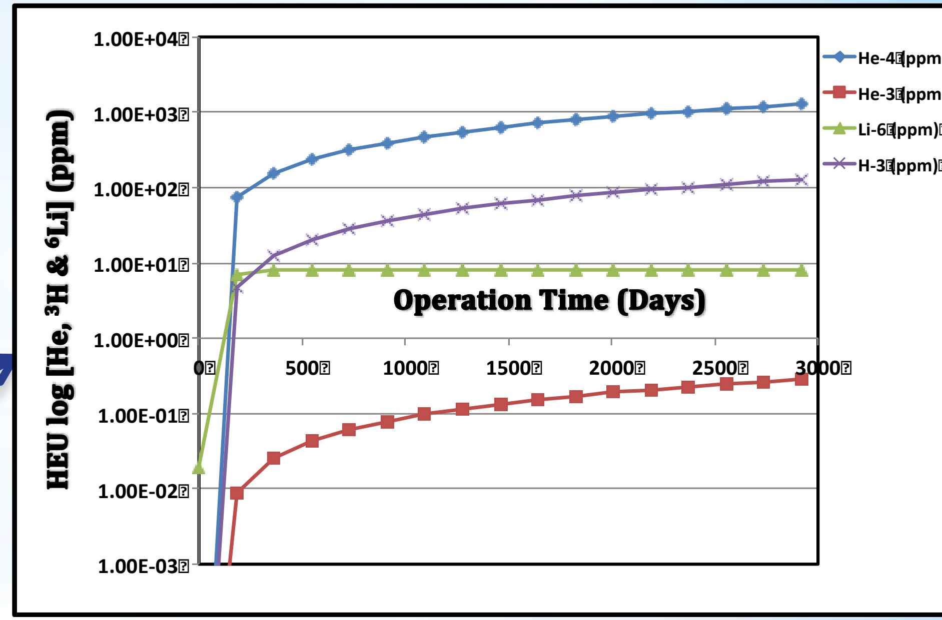
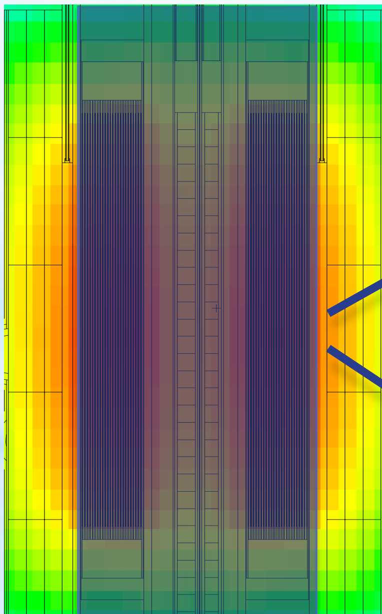
Gas Production Predictions from Models

Predicted Peak ^4He, ^3He, ^6Li and ^3H concentration in beryllium after 8 years of full-power **LEU** operation





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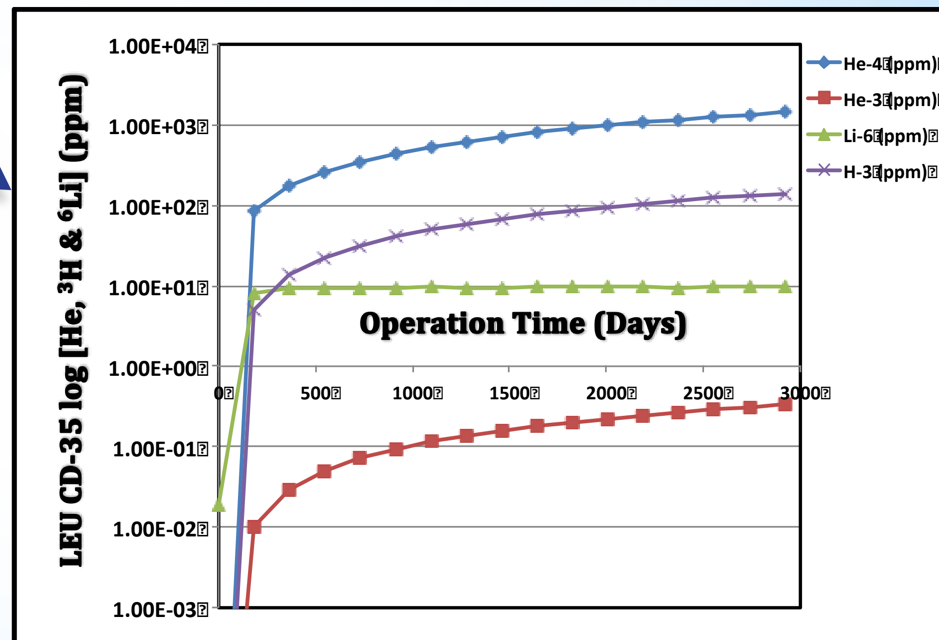
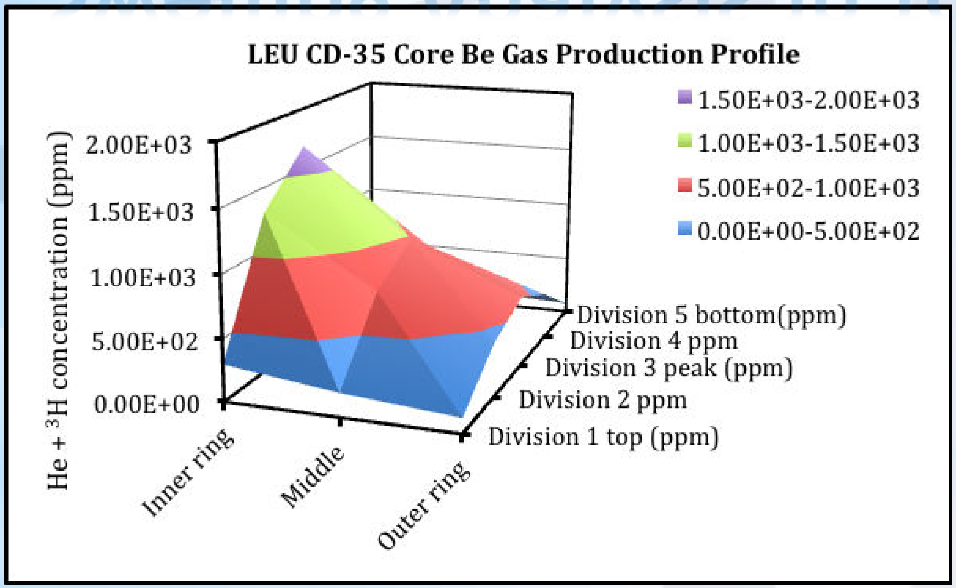


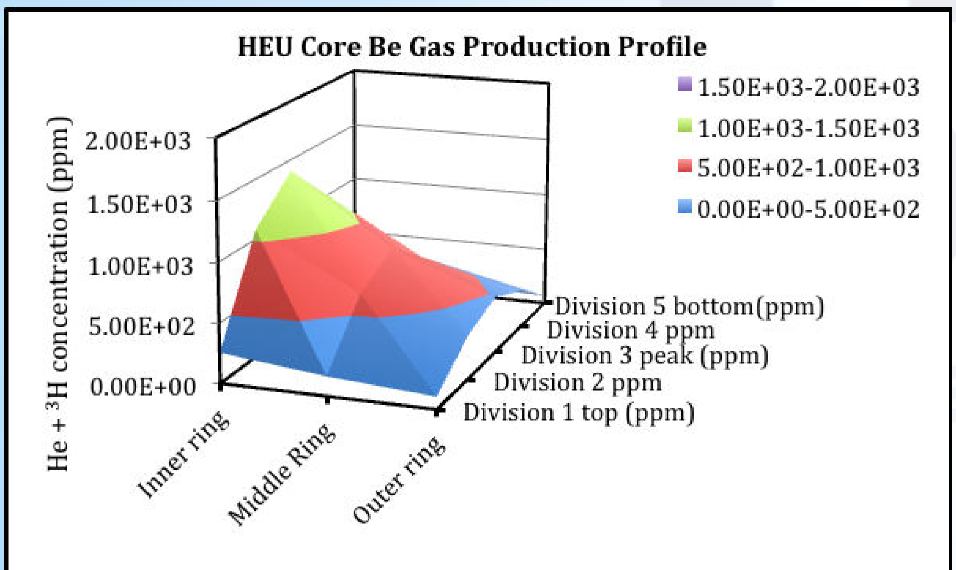
~11% larger gas + ^6Li production in beryllium from LEU-CD35 Core

Beryllium Gas Production Profiles for Swelling Analysis in for HEU and LEU Core



Total Gas production in beryllium for LEU Core at 8 yrs

Core: HEU Helium + tritium concentration at 8 yrs					
	Division 1 top (ppm)	Division 2 ppm	Division 3 peak (ppm)	Division 4 ppm	Division 5 bottom(ppm)
Inner ring	2.79E+02	1.20E+03	1.56E+03	1.02E+03	1.60E+02
Middle Ring	1.78E+02	6.95E+02	9.09E+02	6.39E+02	1.32E+02
Outer ring	1.13E+02	4.07E+02	5.33E+02	3.52E+02	7.03E+01



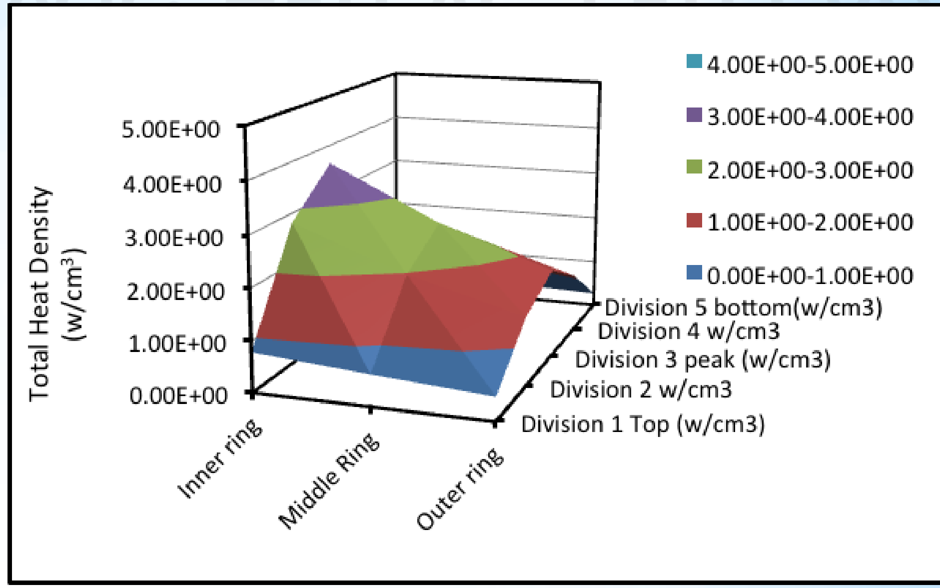
Total gas production in beryllium for HEU core at 8 yrs

Core: HEU Helium + tritium concentration at 8 yrs					
	Division 1 top (ppm)	Division 2 ppm	Division 3 peak (ppm)	Division 4 ppm	Division 5 bottom(ppm)
Inner ring	2.57E+02	1.08E+03	1.40E+03	9.23E+02	1.51E+02
Middle Ring	1.64E+02	6.27E+02	8.14E+02	5.41E+02	1.00E+02
Outer ring	1.04E+02	3.66E+02	4.80E+02	3.20E+02	6.90E+01

* Total Heating Profiles in Beryllium for Thermal Stress Analysis: HEU Vs. LEU Core

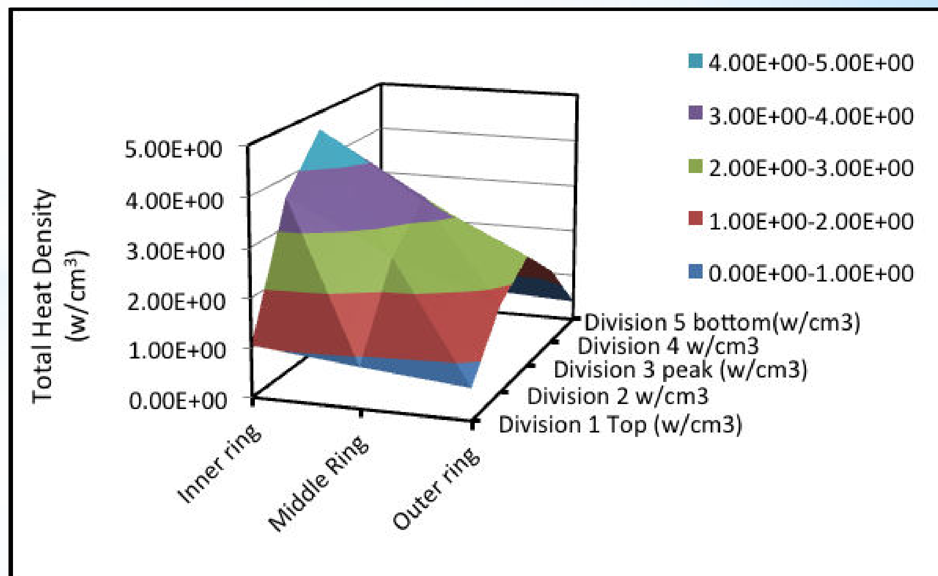
Total heating rate in beryllium for LEU Core

	Core:LEU (CD35) Total Gamma Energy Deposition				
	Division 1 Top (w/cm^3)	Division 2 w/cm^3	Division 3 peak (w/cm^3)	Division 4 w/cm^3	Division 5 bottom (w/cm^3)
Inner ring	7.87E-01	2.82E+00	3.63E+00	2.32E+00	4.19E-01
Middle Ring	6.17E-01	1.98E+00	2.56E+00	1.66E+00	3.40E-01
Outer ring	4.66E-01	1.37E+00	1.77E+00	1.17E+00	2.64E-01



Total heating rate in beryllium for HEU Core

	Core: HEU Total Gamma Energy Deposition				
	Division 1 Top (w/cm^3)	Division 2 w/cm^3	Division 3 peak (w/cm^3)	Division 4 w/cm^3	Division 5 bottom (w/cm^3)
Inner ring	1.06E+00	3.62E+00	4.65E+00	3.05E+00	6.19E-01
Middle Ring	8.40E-01	2.56E+00	3.31E+00	2.62E+00	5.07E-01
Outer ring	6.47E-01	1.79E+00	2.32E+00	1.55E+00	4.09E-01



* Preliminary Estimation of LEU-CD35 Beryllium Lifetime at MURR

- **Internuclear Company calculated a maximum thermal stress of 16,690psi as compared to the assumed beryllium's yield stress of 27,000psi for HEU at 10MW**
  - **Gas swelling stress HEU = beryllium yield stress - maximum thermal stress (10,310 psi)**
  - **Thermal stress proportional heating difference between surfaces. Ratio between HEU and LEU-CD35 implies LEU-CD35 at 12MW thermal stress is reduced to 13,320 psi**
  - **Consequently, LEU-CD35 at 12MW swelling stress is increased to 13,680 psi**
- **Using a conversion factor of 10.25psi/ppm and the LEU-CD35 gas production rate of 139ppm/yr, lifetime for beryllium extended from 8 years to 9.6 years**

Caveats:

- **Assumes that the beryllium yield stress is constant (i.e., unaffected during operation**
- **The swelling behavior as a function of megawatts is not well known for beryllium**
- **No measurements to benchmark model predictions**

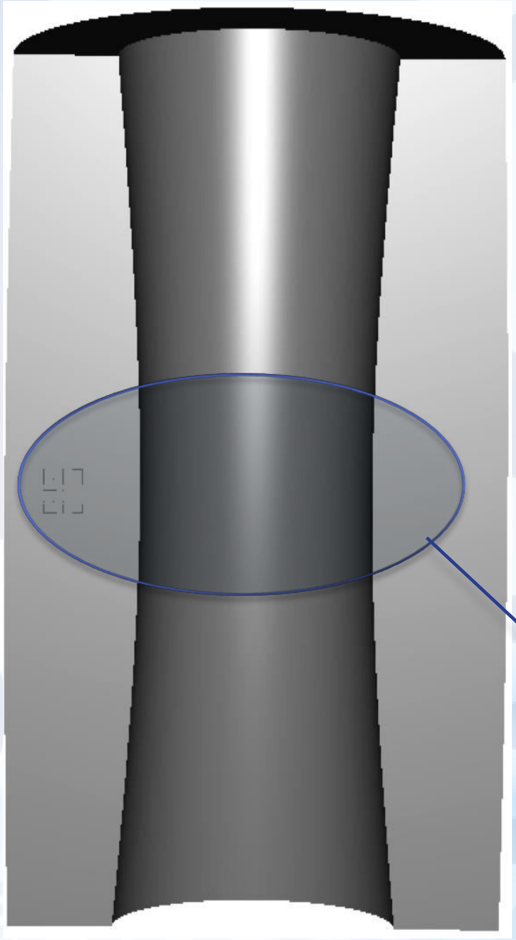
Collaboration with HFIR and ATR for more analysis of data on beryllium

Performance Degradation in Beryllium HEU and LEU Core: Excess Reactivity Loss

Core Excess Reactivity loss is due to:

- Buildup of the neutron poisons ^{6}Li and ^{3}He
  - absorption cross-sections = ~900 and 4900 barns
  - ^{6}Li reaches equilibrium value in ~1 year
  - ^{3}He constant increase with MWDs; small concentration <1ppm at 26000 MWD

- Swelling due to steady helium + tritium buildup decreases the beryllium macroscopic scattering cross-section



Exaggeration of MURR beryllium swelling

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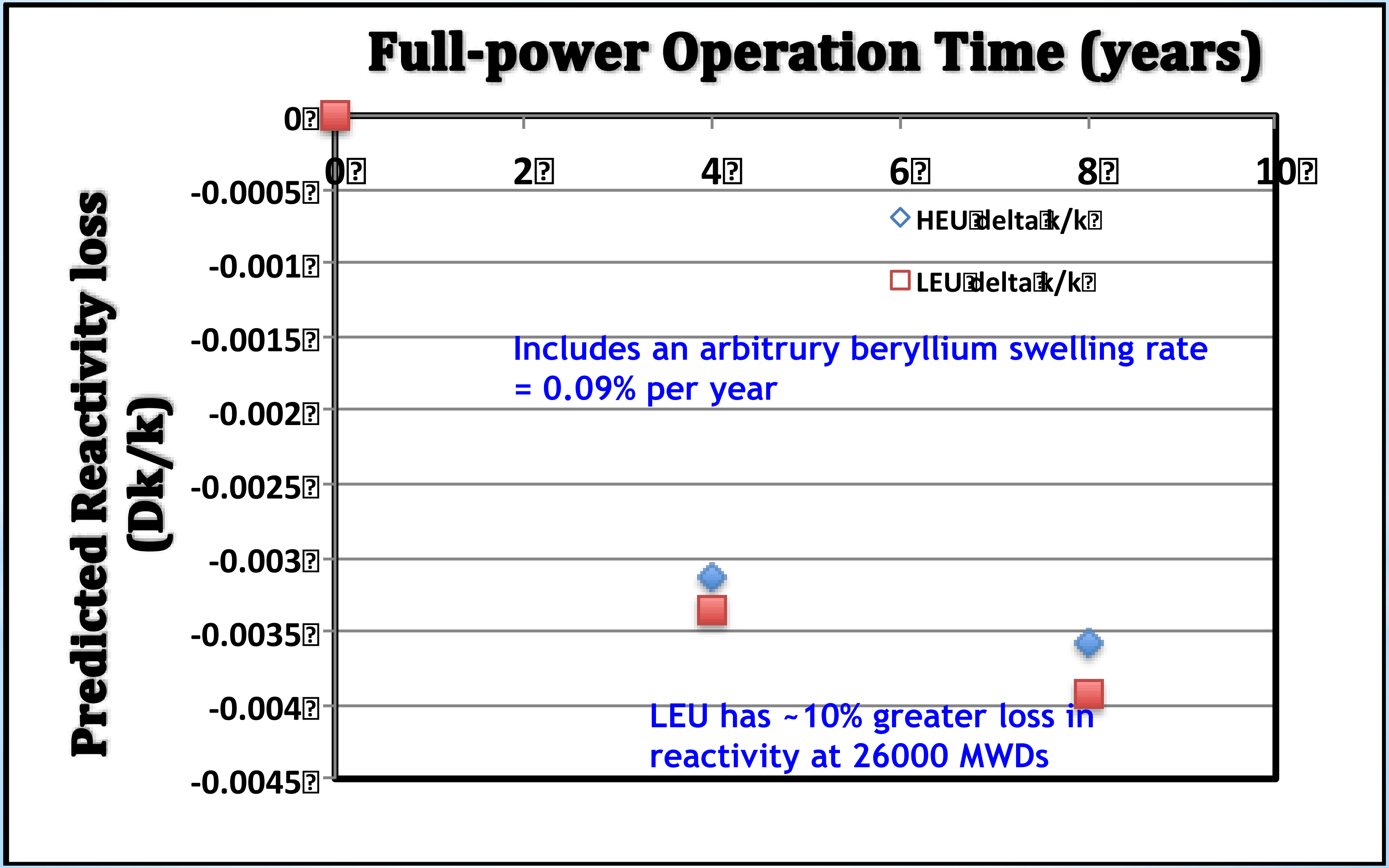
* Excess Reactivity Loss Vs. Time Curve for HEU vs. LEU-CD35



* Summary and Future Works

- MCNP-coupled ORIGEN depletion simulations were used to predict the gas production and heating profiles in beryllium neutron reflector to study stress increase that can lead to fracture failure for the HEU and LEU-CD35 MURR core configuration.

- It is shown that for the HEU core, there is more energy deposited and less gas produced in the beryllium which may correspond to greater thermal stress and lower swelling stress, as compared to the LEU core.

- Preliminary estimation for MURR's beryllium shows a 1½ years increase in beryllium lifetime using the LEU-CD35 core as compared to the HEU core.

- Neutron poison buildup and swelling appears to be responsible an increase lost (~10%) of excess reactivity in LEU-CD35 Core at 8 years of operation.

- Increasing the data based for the impact of irradiating beryllium at research reactors is planned for future works:
  - Benchmarking measurements are being done for the MURR beryllium
  - Analyzing beryllium irradiation data from HFIR and ATR

* Thank you

Questions ?

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