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Increasing Experiment Gamma Flux to Support Advanced Test Reactor Conversion

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Changing the World's Energy Future

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Increasing Experiment Gamma Flux to Support Advanced Test Reactor Conversion

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INTRODUCTION

The Advanced Test Reactor (ATR) is one of six remaining high performance research reactors in the United States scheduled to be converted from 93% high-enriched uranium (HEU) fuel to 19.75% low-enriched uranium (LEU) fuel as part of the Department of Energy (DOE), National Nuclear Security Administration (NNSA), Office of Material Management and Minimization (M3) reactor conversion efforts [1]. To ensure continued value to ATR users, it must be shown that available experiment environments maintain the same irradiation capabilities following conversion. One key aspect of these environments in the ATR is the relatively high energy gamma and neutron fluxes that play important roles in material and fuel testing in the pressurized water loops (PWLs). Therefore, it is required that the ratio of fast gammas to fast neutrons in the PWL experiment positions must not significantly decrease following reactor conversion. Gammas and neutrons with energies greater than 1 MeV are considered fast in this analysis.

The replacement LEU fuel is a U-Mo metal which is significantly denser than the existing UAl_x HEU fuel form. This increased density makes the LEU fuel an effective gamma shield and causes a significant reduction in the fast gamma fluxes at the ATR experiment positions. Therefore, a core modification must be made to ensure that the current fast gamma to neutron ratios in the ATR PWL experiment positions are achievable following conversion to LEU fuel. This abstract summarizes the density minimization approach taken to generate a potential core modification to increase the fast gamma to neutron ratio seen at PWL experiment positions to support ATR conversion.

Advanced Test Reactor Pressurized Water Loops

Six of the ATR's nine flux traps are equipped with PWLs [2]. The general layout of the ATR is shown in Figure 1 with the nine flux traps labeled based on their location in the core.

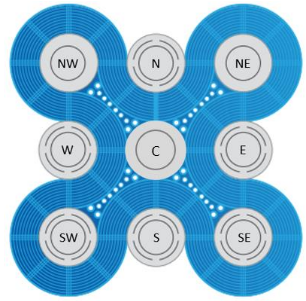

Fig. 1. General ATR Core Layout [3]

The PWLs utilize in-pile tubes that allow certain lobes to be operated at different temperatures, pressures, flow rates, and water chemistry conditions to test materials and fuels under the conditions expected in an operating pressurized water reactor [2]. Figure 2 shows an example of the standard in-pile tube geometry (labeled in bold) used in the ATR surrounded by other components in a standard flux trap.

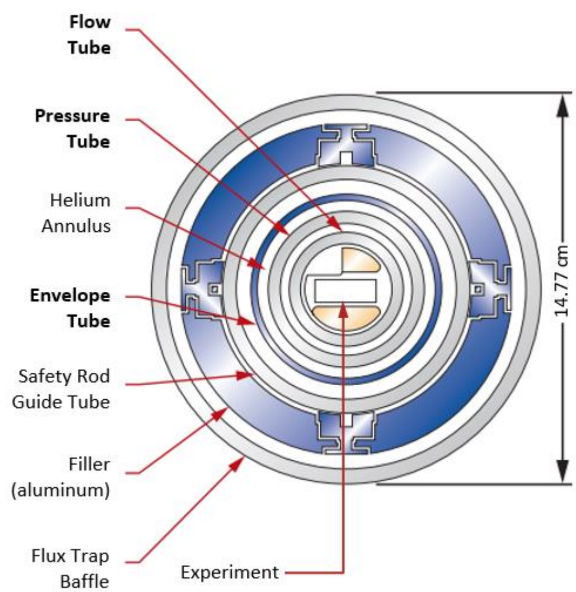

Fig. 2. In-Pile Tube Surrounding Pressurized Water Loop Experiment Position in a Standard Flux Trap [2]

The in-pile tube consists of three stainless steel tubes referred to as the envelope tube, the pressure tube, and the flow tube. The envelope tube and the pressure tube separate the helium annulus and pressurized loop water from the rest of the ATR. Therefore, they are considered reactor pressure boundaries and are required to be designed, analyzed, and manufactured according to the requirements for ASME Boiler and Pressure Vessel Code (BPVC) Section III Class 1 components. The flow tube separates the inlet and outlet pressurized water streams which are at similar pressures and therefore is not considered a reactor pressure boundary.

DENSITY MINIMIZATION APPROACH

The density minimization approach aims to increase fast gamma flux and therefore fast gamma to neutron ratio at the experiment by minimizing gamma attenuation on the path from the fuel to the experiment. This is accomplished by replacing highly dense stainless steel in-pile tube components with lower density metal alloy components.

In-Pile Tube Primary Replacement Materials

Grade 9 Titanium Alloy is a suitable replacement material for stainless steel due to its low density, high strength, and its acceptance by the ASME BPVC. The allowable stresses given for Section III Class I pressure vessels by the ASME BPVC for grade 9 titanium alloy are higher than those given for stainless steel at equivalent temperatures, so grade 9 titanium alloy tubes are expected to withstand the stresses seen by the stainless steel in-pile tube. However, grade 9 titanium alloy has a maximum allowable metal temperature of 325°C while the existing stainless steel has a maximum allowable temperature of 450°C. Table I provides a comparison of relevant properties between the existing stainless steel and grade 9 titanium alloy.

TABLE I. Replacement Material Comparison Table [4]

Material (Temperature)	Design Stress Intensity[a]	Density
Stainless Steel (450°C)	125 MPa	8,030 kg/m^3
Stainless Steel (325°C)	132 MPa	8,030 kg/m^3
Grade 9 Titanium Alloy (325°C)	138 MPa	4,480 kg/m^3

In addition to its high strength and low density, titanium also has a large radiative capture cross section compared to stainless steel which consists primarily of iron. Radiative capture in the in-pile tube creates gammas which help to increase the gamma flux seen by the experiment, but it also decreases the neutron flux at the experiment. To balance the effect of titanium's large radiative capture cross section while further reducing average IPT density, aluminum alloy (which is low density and has a relatively small capture cross section) can be used in the flow tube.

Minimized Density In-Pile Tube Design Concepts

The lower currently allowable temperature for grade 9 titanium alloy necessitates two potential minimized density in-pile tube design concepts. The in-pile tube design concepts used to analyze gamma flux effects are shown in Figure 3.

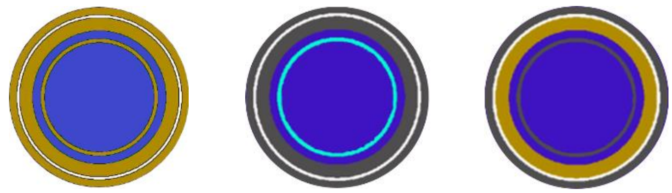

Fig. 3. Potential in-pile tube design concept models with stainless steel (brown), titanium alloy (gray), and aluminum alloy (light blue) tube components.

The Maximized Gamma Concept uses grade 9 titanium alloy in the envelope tube and the pressure tube while using aluminum alloy in the flow tube. Use of aluminum alloy in the flow tube is permissible as the flow tube is not considered a pressure vessel. The use of grade 9 titanium alloy in the pressure tube (which is limiting for in-pile tube metal temperatures) would likely require a decrease in the maximum allowable PWL experimentation temperatures to conform to the current ASME BPVC requirements. Implementation of this concept would require that either the allowable temperature for grade 9 titanium alloy can be increased or that decreasing the allowable operation temperature of PWL experiments will not significantly impact ATR value to users.

The ASME BPVC Compliant Concept uses grade 9 titanium alloy in the envelope tube and flow tube while using stainless steel in the pressure tube. Using stainless steel in the pressure tube eliminates the potential need to further limit the operation temperature of PWL experiments as the flow tube is not required to conform to ASME BPVC requirements and the envelope tube is not expected to reach temperatures above 325°C. The envelope tube is thermally insulated from the pressure tube by the helium annulus and is in contact with the lower temperature primary reactor coolant.

Fast Gamma to Neutron Ratio Comparative Analysis

MC21 [5] was used to solve coupled neutron/gamma calculations[b] for an as-run HEU cycle model using the standard in-pile tube and three comparative LEU models. The LEU models use the standard in-pile tube, the Maximized Gamma Concept in-pile tube, or the ASME BPVC Compliant Concept in-pile tube to house PWL experiments. The LEU fueled models use fuel elements with comparable simulated burnups to the fuel elements in the HEU model and operate at similar overall powers.

Fast gamma to neutron ratios are calculated for each model based on outputs from a tally covering a PWL experiment position (shown inside the flow tube in Figure 2). This tally is used to calculate both integrated neutron and gamma fluxes over the entire axial length of the PWL experiment position and includes an energy filter to separate fast particles from those at lower energies. Fast gamma to neutron ratios for each LEU model are compared to the fast gamma to neutron ratio for the HEU standard model using Equation 1 to draw conclusions about the efficacy of each design concept.

$$(\gamma/n)_{diff} = \frac{(\gamma/n)_{LEU} - (\gamma/n)_{HEU}}{(\gamma/n)_{HEU}} \times 100\% \qquad (1)$$

RESULTS

Fast gamma to neutron ratio comparisons between each LEU model and the standard HEU model are given in Table II. Scoping analyses support that fast gamma to neutron ratio comparisons between HEU and LEU at the PWL experiment position examined are generally most limiting during the middle of the ATR operating cycle than at the beginning or end of cycle. The comparisons reported in Table II are made on day 29 of the 58 day ATR cycle for this reason.

TABLE II. LEU Models Middle of Cycle Fast Gamma to Neutron Ratio Comparison to HEU Model

In-Pile Tube Design	γ/n Percent Difference at PWL Experiment[c]
Standard Stainless Steel Design	-12.4% ± 0.2%
Maximized Gamma Concept	+1.4% ± 0.3%
ASME BPVC Compliant Concpet	-5.2% ± 0.2%

As shown in Table II, the PWL experiment fast gamma to neutron ratio decreases significantly when the standard in-pile tube design is used and fuel is modeled as LEU. This decrease was expected due to increased gamma shielding by the denser LEU fuel as compared to HEU fuel.

The Maximized Gamma Concept results show that it is feasible to achieve a PWL experiment fast gamma to neutron ratio during LEU fueled operation comparable to that seen during HEU fueled operation by using lower density materials in the in-pile tube. The combination of the grade 9 titanium alloy envelope tube and pressure tube with the aluminum alloy flow tube increases the fast gamma to neutron ratio by minimizing gamma attenuation while maintaining a comparable radiative capture effect to the standard stainless steel in-pile tube design.

The ASME BPVC Compliant Concept results show that the fast gamma to neutron ratio seen by PWL experiments during LEU operation can be substantially increased without the potential need to decrease allowable experiment operating temperatures. Use of grade 9 titanium alloy in the envelope tube and flow tube of this concept help to increase gamma flux relative the standard in-pile tube while use of stainless steel in the pressure tube maintains ASME BPVC compliance up to currently allowable operating conditions. The ASME BPVC Compliant Concept provides a potential alternative to the Maximized Gamma Concept that would significantly reduce the negative effect LEU fuel use has on PWL experiment fast gamma to neutron ratio.

CONCLUSIONS

Maintaining currently available experiment environments in research reactors is of paramount importance to ensuring continued value to users following reactor conversion. Results from the density minimization approach show that it is feasible to recoup gamma flux losses caused by the high density LEU fuel by minimizing the density of components between the fuel and the experiment. The work presented in this document was completed to support conversion of the ATR, but the use of grade 9 titanium alloy and the density minimization approach can be applied to other current and future reactors with gamma flux requirements.

Future work relating to this project will include structurally qualifying these low density pressure vessel designs, potential research and testing on irradiation behavior of titanium alloys, and further refining coupled neutron and photon transport calculation methodologies. Much like the density minimization approach, the future work required by this project will provide significant value not only to the ATR conversion project, but also to the nuclear industry as a whole.

NOMENCLATURE

$(\gamma/n)_{diff}$ = percent difference in fast gamma to neutron ratio between the LEU and HEU models
$(\gamma/n)_{LEU}$ = LEU model fast gamma to neutron ratio
$(\gamma/n)_{HEU}$ = HEU model fast gamma to neutron ratio

ENDNOTES

[a] These represent unirradiated allowable stress values for seamless pipe product forms in the ASME BPVC [4].
[b] Coupled neutron/gamma calculations include gammas from fission, inelastic scattering, and radiative capture to support feasibility analysis for the potential in-pile tube replacement design concepts. Gamma contributions from decay of fission products and decay of activated core internals are not

included at this stage of analysis, and the use of MC21 [5] to calculate gamma to neutron ratios at ATR experiment positions has not yet been validated against experimental data. Scoping studies suggest the effect of gamma sources not considered at this stage of analysis on fast gamma to neutron ratio will not significantly impact the conclusions drawn from this work.

[c] Uncertainties reported in Table II reflect the Monte-Carlo uncertainties calculated from MC21 outputs [5]. These values do not capture uncertainties from fission product and activated material decay gammas.

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1. Idaho National Laboratory, *Advanced Test Reactor (ATR) Conversion to Low Enriched Uranium (LEU) Fuel*, Document ID. INL/CON-17-42010, Revision 0.

2. Idaho National Laboratory, *Advanced Test Reactor User Guide*.

3. Idaho National Laboratory, *Advanced Test Reactor*, Document ID. 20-50442, Revision 3.

4. *2021 ASME Boiler and Pressure Vessel Code*, American Society of Mechanical Engineers, 2021, Section II, Part D.

5. D. P. Griesheimer, D. F. Gill, B. R. Nease, T. M. Sutton, M. H. Stedry, P. S. Dobreff, D. C. Carpenter, T. H. Trumbull, E. Caro, H. Joo, and D. L. Millman, MC21 v.6.0 – A continuous-energy Monte Carlo particle transport code with integrated reactor feedback capabilities, Annals of Nuclear Energy 82 (2015) 29-40.

National Nuclear Security Administration (NNSA)

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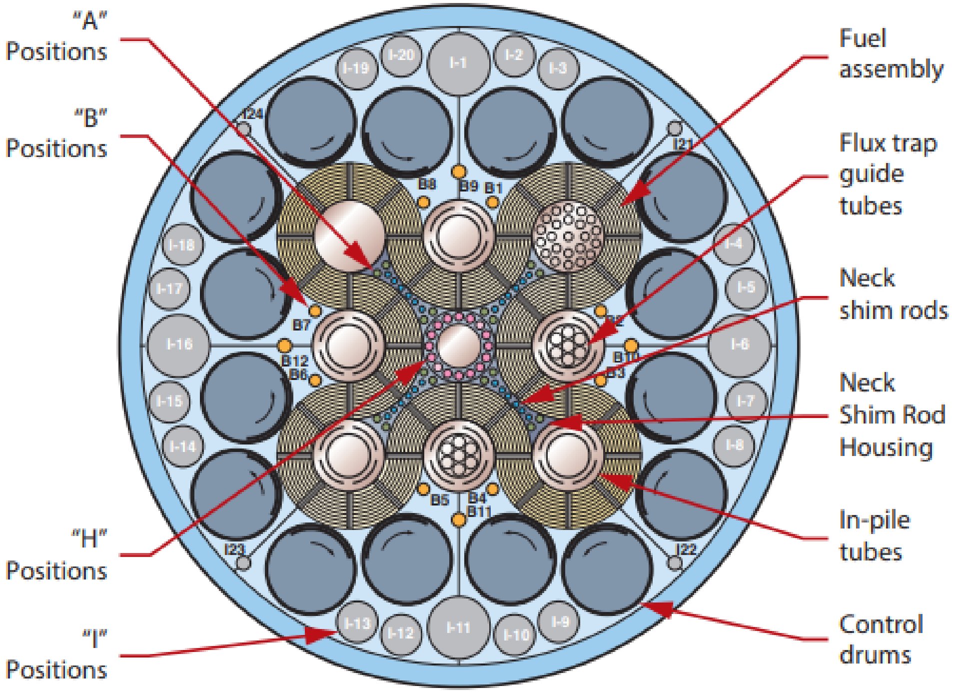
Advance Test Reactor (ATR) Conversion to Low Enriched Uranium (LEU)

- One of six remaining high performance research reactors in the US scheduled to be converted to LEU fuel

- Must meet certain requirements following conversion to ensure continued value to ATR users:
  - Gamma to neutron ratio at energies >1 MeV must be within -0%/+10% of current values
  - Fast to thermal neutron ratio must be within ±5% of current values



Source: Advanced Test Reactor User Guide

LEU to HEU Comparison with Existing Core Design

- The high density of LEU fuel relative to HEU fuel reduces gamma flux at the experiment position
- Increased parasitic absorption of thermal neutrons by U-238 in LEU fuel results in a harder neutron spectrum

MC21 Calculation Comparisons to HEU	
γ/n_f %Difference (-0%/+10%)	**n_f/n_t %Difference (±5%)**
-13.3%	+6.2%
Less Gammas	**Harder Spectrum**

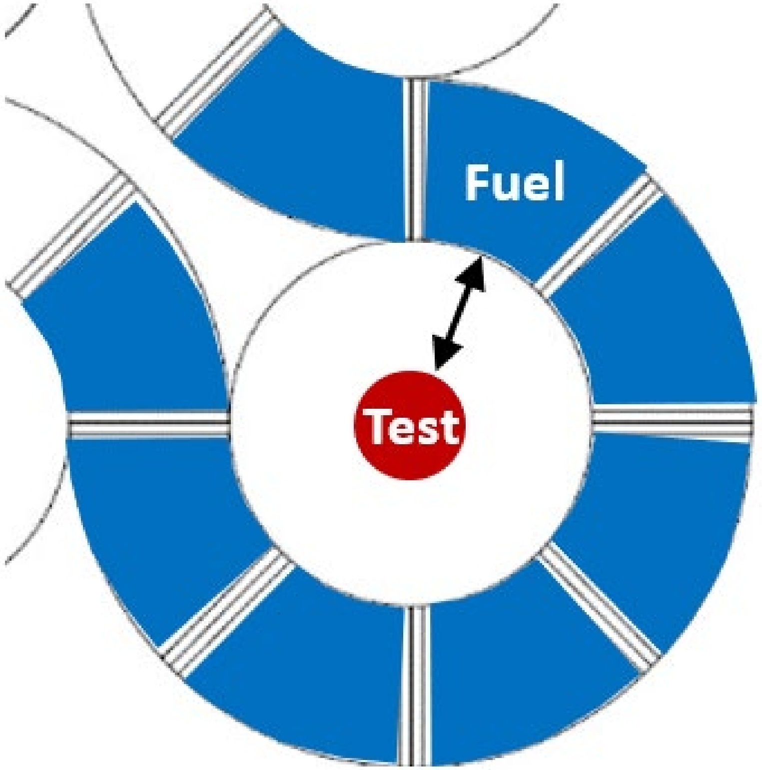
LEU Fuel to HEU Fuel Comparison Table			
Fuel Type	**Enrichment**	**Fuel Form**	**Approximate Density**
HEU	93%	UAl_x Dispersion	3.8 g/cm^3
LEU	19.75%	U-Mo Metal	16.9 g/cm^3

Methods for Tuning Experiment Conditions

- Decrease mass on the path from the fuel to the experiment
  - Minimize the attenuation of gammas

- Take advantage of neutron interactions with certain materials
  - Increase >1 MeV gamma production
  - Absorb thermal neutrons

- Increase neutron moderation
  - Decrease fast neutron flux
  - Increase thermal neutron flux



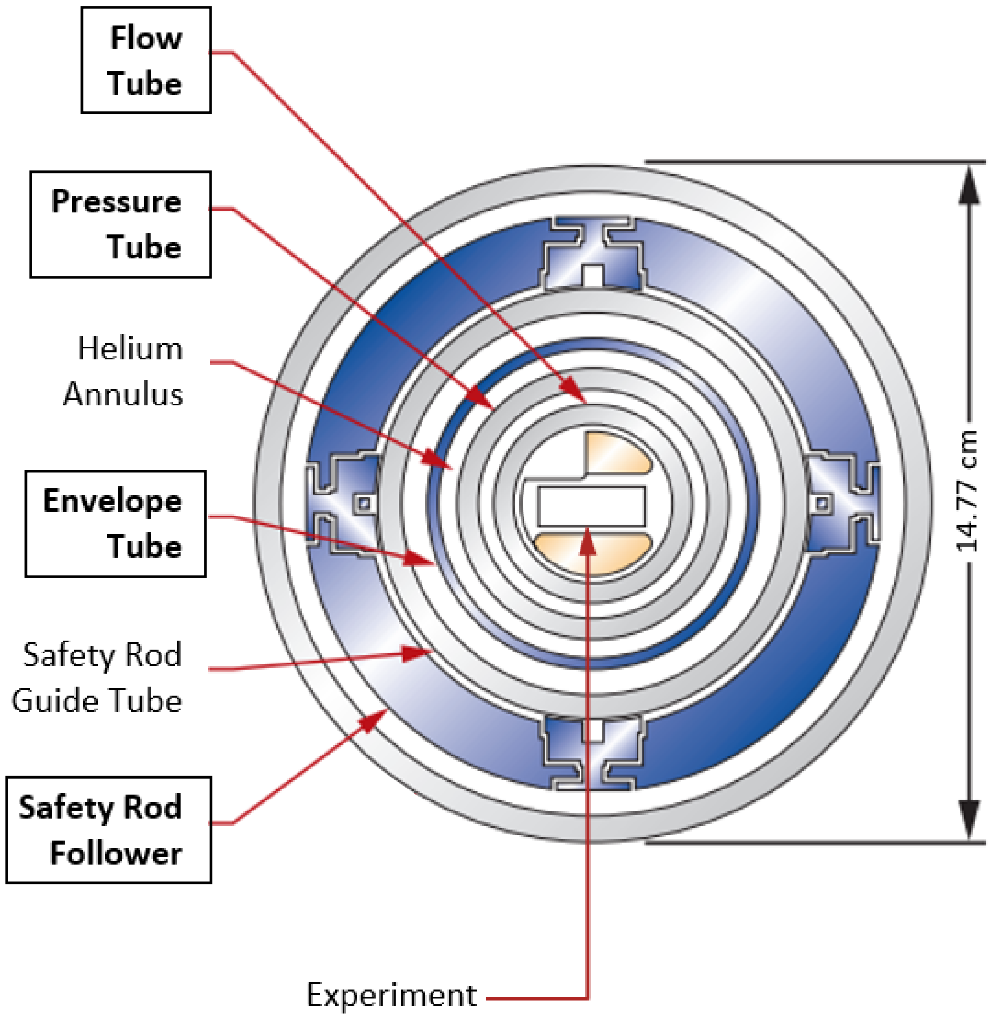
ATR Lobe

Opportunities for ATR Flux Trap Modification

- Replacement of highly dense stainless steel in the standard in-pile tube (flow, pressure, and envelope tubes)

- Thinning of the safety rod follower
  - From the Safety Control Rod and Flux Trap Fillers Design Manual (1963):

The metal-to-water ratio of the flux trap fillers is varied by replacing the fillers with other fillers of a different thickness, or material, or by omitting the fillers (one set of fillers and one set of stop plates only are provided under the original contract). The safety rod assembly is designed to allow exchange of flux trap fillers and absorber plates without removing the safety rod or the experiment test loop from the reactor.



Source: Advanced Test Reactor User Guide

Grade 9 Titanium Alloy (Ti-3Al-2.5V) use in the In-Pile Tube (Flow Tube)

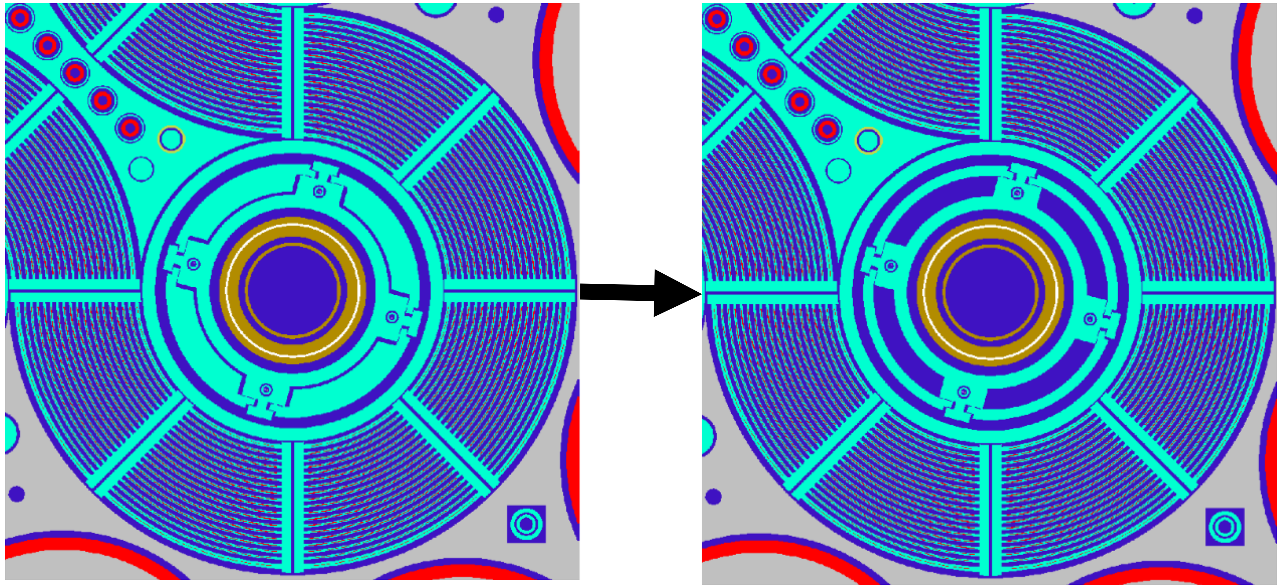
- Lower density than stainless steel
  - Minimizes gamma attenuation
- Approved for use in ASME Section III Class 1 pressure vessels up to 600°F
  - Appropriate for envelope or flow tube use
- Larger thermal neutron capture cross section than stainless steel
  - Increases high energy gamma production from radiative capture
  - Decreases thermal neutron flux

Material Comparison		
Material	**Density**	**Thermal Neutron Capture Cross Section**
Stainless Steel (Fe-56)	8.00 g/cm^3	2.59 b
Titanium Alloy (Ti-48)	4.48 g/cm^3	8.32 b

MC21 Calculation Comparisons to HEU		
In-Pile Tube Design	**γ/n_f %Difference (-0%/+10%)**	**n_f/n_t %Difference (±5%)**
Standard	-13.3%	+6.2%
Ti Alloy Flow Tube	-3.4%	+15.1%
	More Gammas	Less Thermal Neutrons

Thinning of the Safety Rod Followers

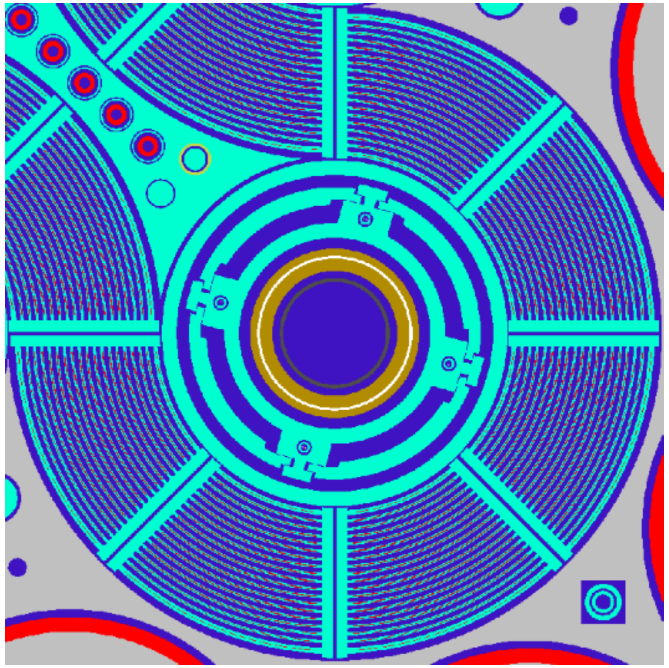
- Effectively replaces aluminum in the flux trap with water
  - Increases neutron moderation
  - Minimizes gamma attenuation



MC21 Calculation Comparisons to HEU		
Safety Rod Follower Thickness	**γ/n_f %Difference (-0%/+10%)**	**n_f/n_t %Difference (±5%)**
0.5405 inches (Standard)	-13.3%	+6.2%
0.1975 inches	-0.7%	-7.1%
	Less Fast Neutrons	**More Neutron Thermalization**

Combined Flux Trap Modification

- Gamma to neutron ratio (-0%/+10%) and fast to thermal neutron ratio (±5%) requirements can both be met by replacing the flow tube and thinning the safety rod follower.



MC21 Calculation Comparisons to HEU			
In-Pile Tube Design	**Safety Rod Follower Thickness**	**γ/n_f %Difference (-0%/+10%)**	**n_f/n_t %Difference (±5%)**
Standard	0.5405 inches (Standard)	-13.3%	+6.2%
Titanium Alloy Flow Tube	0.2975 inches	+6.7%	+3.5%
		Significant Increase	Minor Decrease

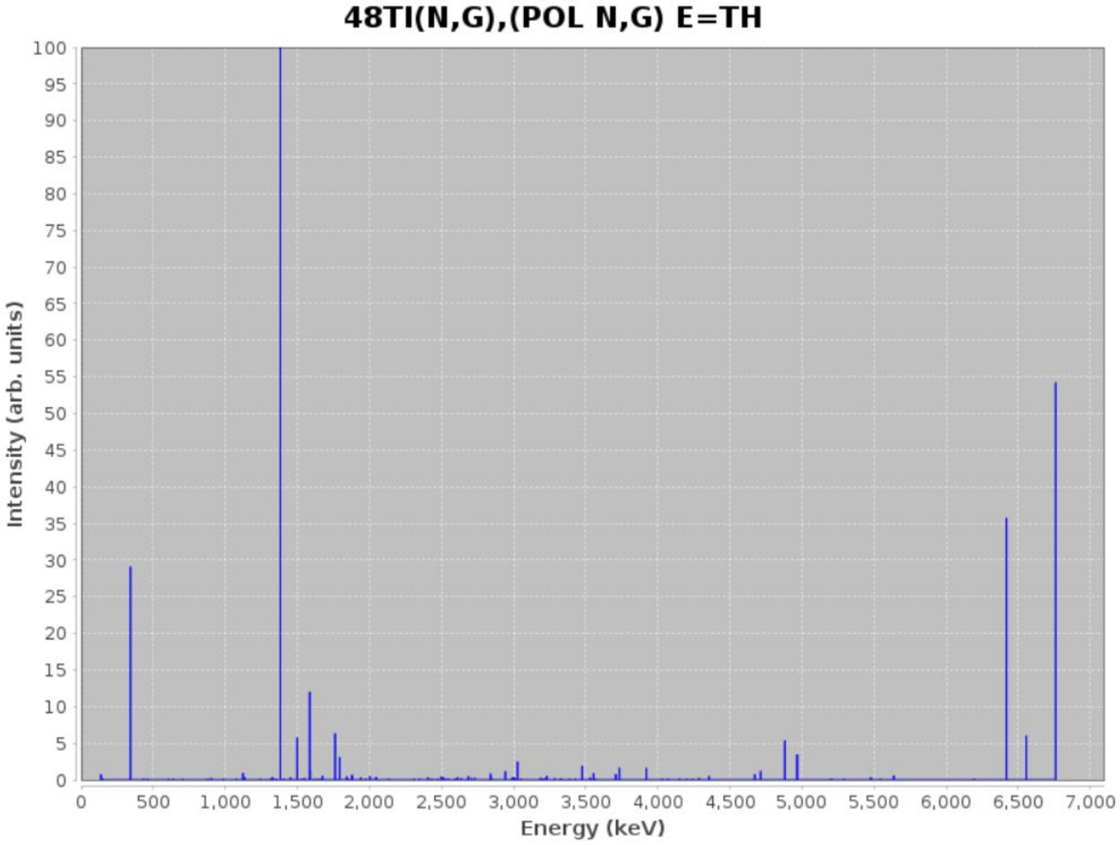
Key Takeaways

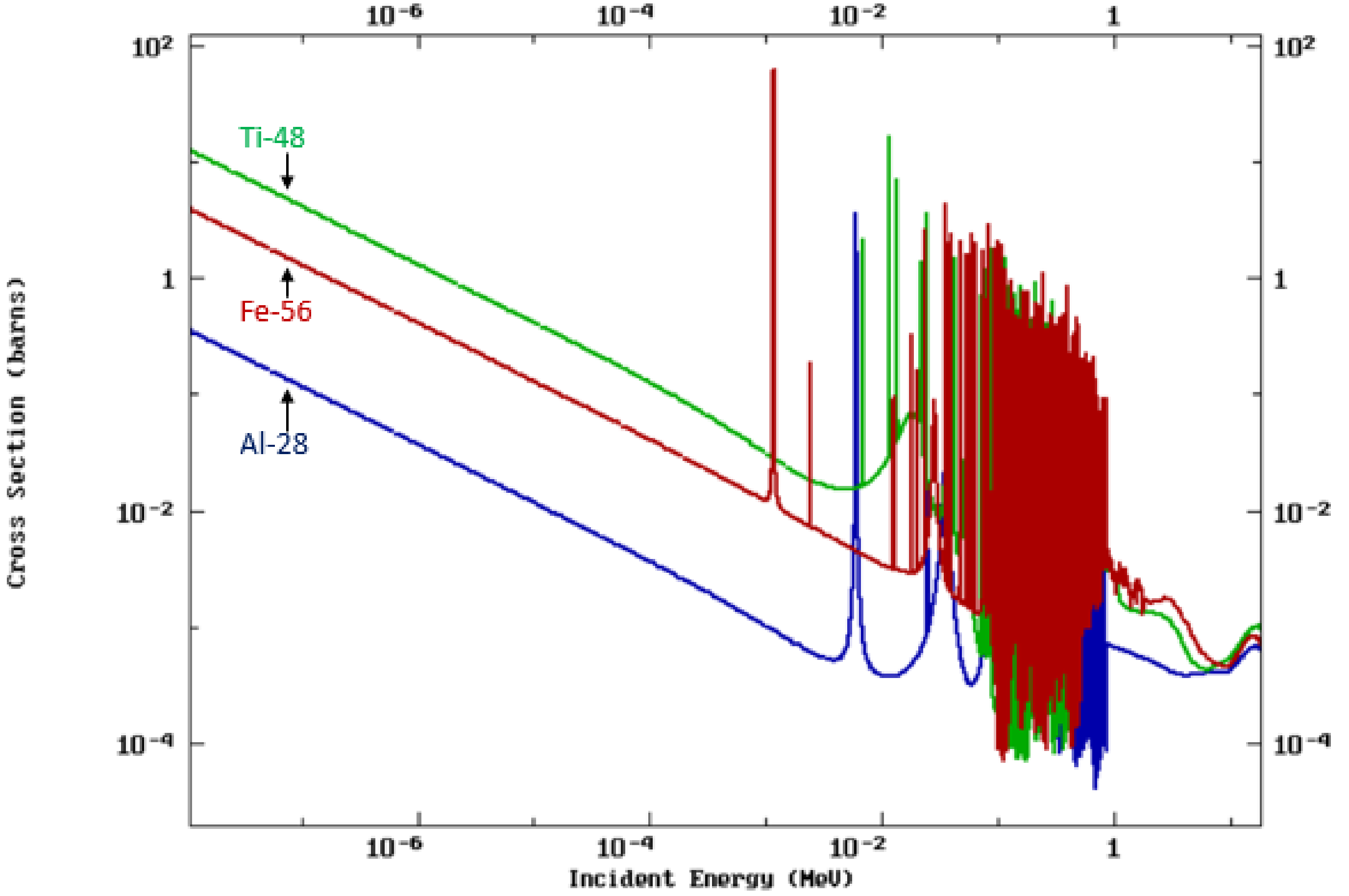
- It is feasible to meet both the gamma to neutron ratio and fast to thermal neutron ratio requirements for LEU fuel use by modifying flux trap components.
- The core internals modification design approach used in this project can inform transitions to LEU in other existing or future reactors with similar requirements.

Questions/Discussion

Supplemental Slides

Thermal Neutron Capture Data





Structural Feasibility Scoping

- Mechanical stresses are not expected to increase due to material change.
- Thermal stresses will likely change, but they are not expected to impact feasibility.

Stainless Steel 348 and Grade 9 Titanium Alloy Strength Comparison

Material	Design Stress Intensity (S_m)[1]	Ultimate Tensile Strength (S_u)	Faulted Condition Allowable Stress (S_a)	Maximum Metal Temperature Currently Allowed by ASME Code
Stainless Steel Grade 348	19.3 ksi	59.1 ksi	41.4 ksi	800°F
Titanium Alloy Grade 9	20.1 ksi	60.3 ksi	42.2 ksi	600°F

Note:

1. Stresses reported in this table assume a 600°F metal temperature for both materials.