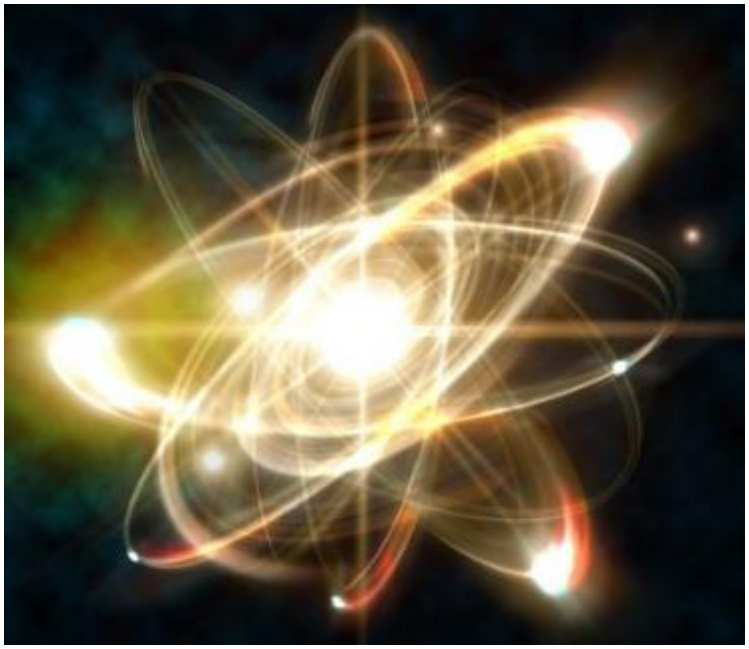
Global Nuclear Fuel

GNF-A SCALE Applications in Support of Advanced Fuel Cycle

2023 SCALE Users' Group Workshop
Wednesday–Friday, April 26–28, 2023
Oak Ridge National Laboratory (hybrid meeting)



SCALE Open Mic Session
[9:50 am – 12:00 pm]

Lon E. Paulson
April 27, 2023

SCALE Users Group Workshop
Hybrid Technical Session
ORNL Building 5100, Room 128

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Agenda

- Intro
- SCALE Validation [6.1.3, 6.2.4]
- Feedstock Transport
- LEU+ Fuel Fabrication
- HALEU U-Metal Fabrication
- Product Transport
- Conclusions

Team Players

- GNF-A Principal CSE – Dr. David Eghbali
- GNF-A Sr. CSE – Dr. Jim Banfield
- GNF-A Sr. CSE – Josh Thomas
- GNF-A Sr. CSE – Ethan Reisker
- GNF-A CSE – Ryan Priest

- Sr. CSE – Dr. Qi Ao (BGS subcontractor)
- Sr. CSE – Steve Painter (BGS subcontractor)
- Sr. CSE – Sandi Larson (BGS subcontractor)
- Sr. CSE – Bill Newmyer (BGS subcontractor)

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Introduction

Recent GNF-A efforts to expand scope include HALEU fuel fabrication.

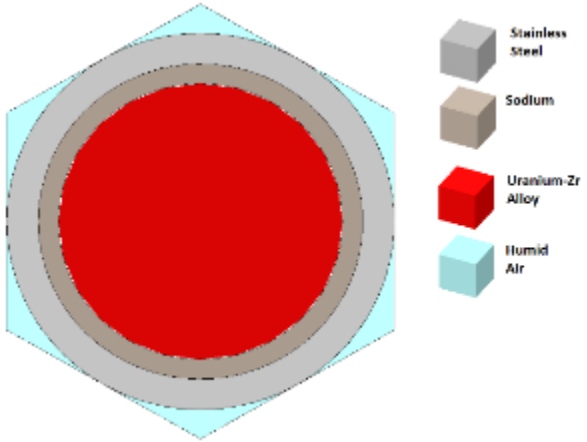
Higher enrichments are necessary to support the advanced fuel cycle

SNM-1097 License Amendment Pre-Application Meeting LEU+ Fuel Fabrication

USNRC

Rockville, MD

May 3, 2022



SNM-1097 Fuel Facility License Natrium HALEU Fuel Fabrication Design & NRC Licensing Update

June 2022

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Why Higher Assay LEU?

LEU+ HALEU (Up to 8%) - LWRs

- Existing BWRs/PWRs utilizing Accident Tolerant Fuel (ATF) designs such as IronClad (FeCrAl cladding) or ARMOR coated zircaloy cladding types require higher enrichments to permit higher exposure (up to ~80k MWD/MTU). Anticipated near term peak assay needs are <8 wt. % ^{235}U.

- The value to reactor utility is potentially high, LEU+ may permit optimization fuel cycle economics. Less fuel required with longer fuel cycle may improve fuel economics for existing fleet of LWRs.

- LEU+ may position PWRs to achieve a desired goal of ~24-month fuel cycle.

- Higher exposures and longer cycles *could* theoretically generate less SNF.

HALEU (up to 20%) – SFR Fuel

- Advanced reactors and novel SMR designs utilizing Sodium Fast Reactor (SFR) technology require metallic uranium fuel with assays up to ~20 wt. % U235.

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SCALE6.1 Validation (6.1.3, LEU+)

- ENDF/B-VII continuous energy (CE) cross section libraries used to support a variety of AOAs (7 total)
- USL And Bias + Bias Uncertainty Determined for Independent Parameter **H/^{235}U, or EALF**
- The MATLAB computer code, USLSA* is used for the statistical analysis of criticality safety code validation.

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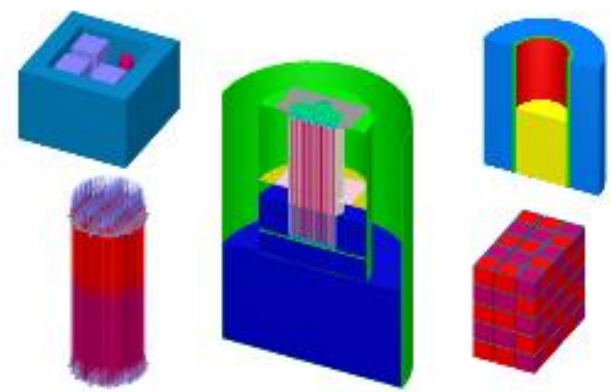
SCALE6.1/KENO-VI Monte Carlo Code Validation Report (Rev. 4.2)



AOA-1: LEU Homogeneous Systems
(≤ 10.0 wt.% U235)

AOA-3: LEU Heterogenous Compounds w/o Absorbers
(≤ 10.0 wt.% U235)

- SNM-1097 License Amendment is premised on AOA-1, AOA-3 [SNM-1097, Chapter 5, Tables 5.1 and 5.2]
- Due to lack of benchmark experiments with neutron absorber (Cd, Gd) for the region of interest ≤ 10 wt.% U-235; the SCALE/TSUNAMI code was applied to the existing benchmarks ≤ 5 wt. % U-235 to assess similarity between 5% and 8% enriched systems [e.g., USL ≤ (1 + bias – bias uncertainty) – MoS – **AOA$_m$**] for AOA-4 and AOA-7, respectively.

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*Ao, Q., "USLSA – A Statistical Tool for Criticality Analysis Code Validation," Trans. Am. Nucl. Soc., **96**, 271-173 (2007).

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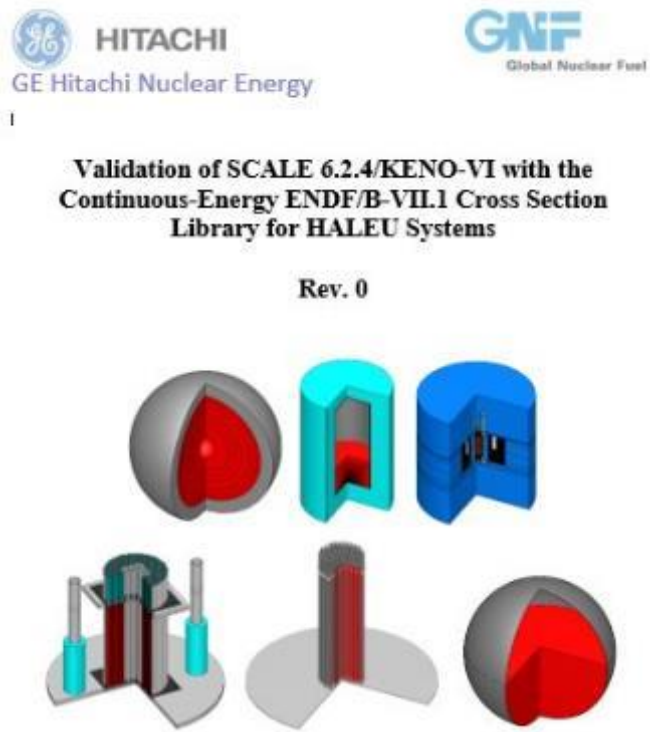
SCALE6.2 Validation (6.2.4, HALUE)

- ENDF/B-VII.1 continuous energy (CE) cross section libraries used to support a variety of AOAs (2 total)
- USL And Bias + Bias Uncertainty Determined for Independent Parameter **H/^{235}U, or EALF**
- A statistical analysis tool in EXCEL with the addition of an open-source statistics package – the Real Statistics Resource Pack (XRealStats), USLSA, was developed for criticality safety code validation (a total of six (6) normality tests performed)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Validation of SCALE 6.2.4/KENO-VI with the Continuous-Energy ENDF/B-VII.1 Cross Section Library for HALEU Systems

Rev. 0

AOA-1: HALEU Homogeneous Systems (≤ 37.76 wt.% U235)

AOA-2: HALEU Heterogenous Compounds (≤ 20.91 wt.% U235)

For both AoAs: SSNPL is the only applicable non-trending statistical method to determine a valid USL

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LEU+ Feedstock Transport

- **UX-30 Overpack** – Type B Fissile Package containing the 30B cylinder
- **30B Cylinder** – Contains minimum 99.5 % UF_6 at maximum net weight 2,277 kg UF_6 (currently limited to 5 wt. % enrichment with a stated Criticality Safety Index [CSI] of 5.0)

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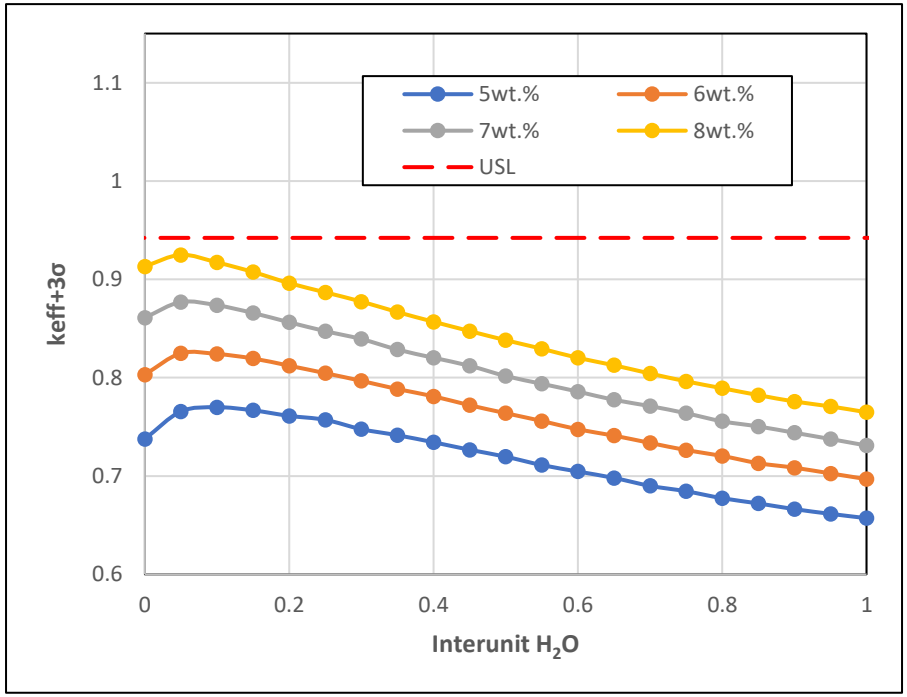
LEU+ Feedstock Transport I



CSI=0.0: At 8.0 wt.% ^{235}U, an infinite 3D array of Model 30B UF_6 cylinders* is demonstrated to remain subcritical independent of interunit water moderation using a **more detailed ellipsoidal ends model construct**.

*Banfield, J., Paulson, L., UF_6 Cylinder Handling, Storage, and Transport at 8% Enrichment, NCSD 2022 Topical, Anaheim, CA, June 2022

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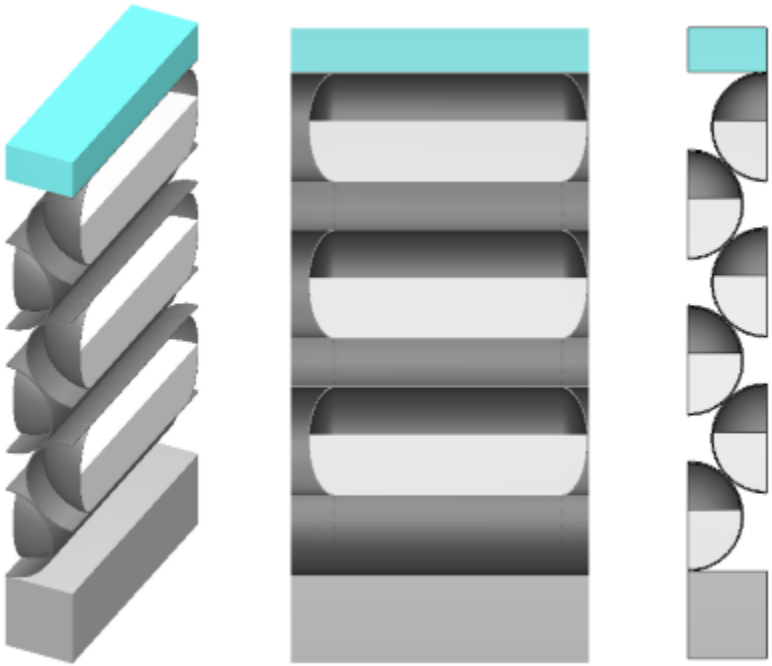
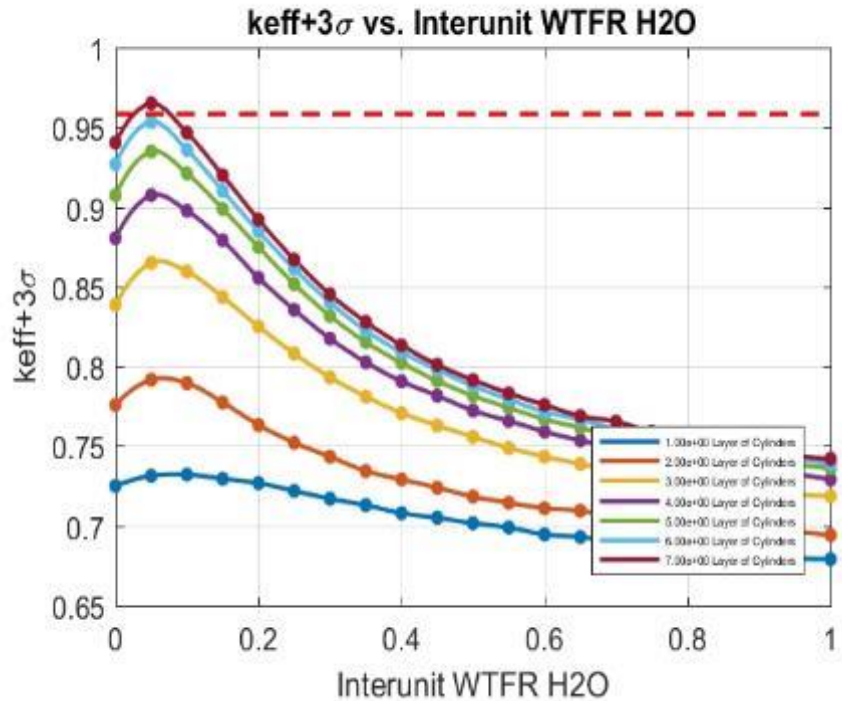
LEU+ Feedstock Transport II





CSI = 0.0: A horizontally infinite planar array of up to 6-layers of Model 30B cylinders containing the maximum allowable net weight 2277 kg UF_6 can be demonstrated to remain subcritical at 10.0 wt.%

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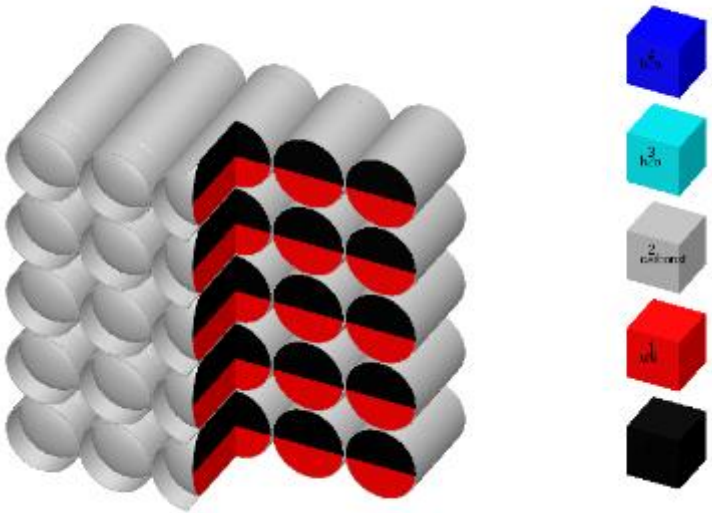
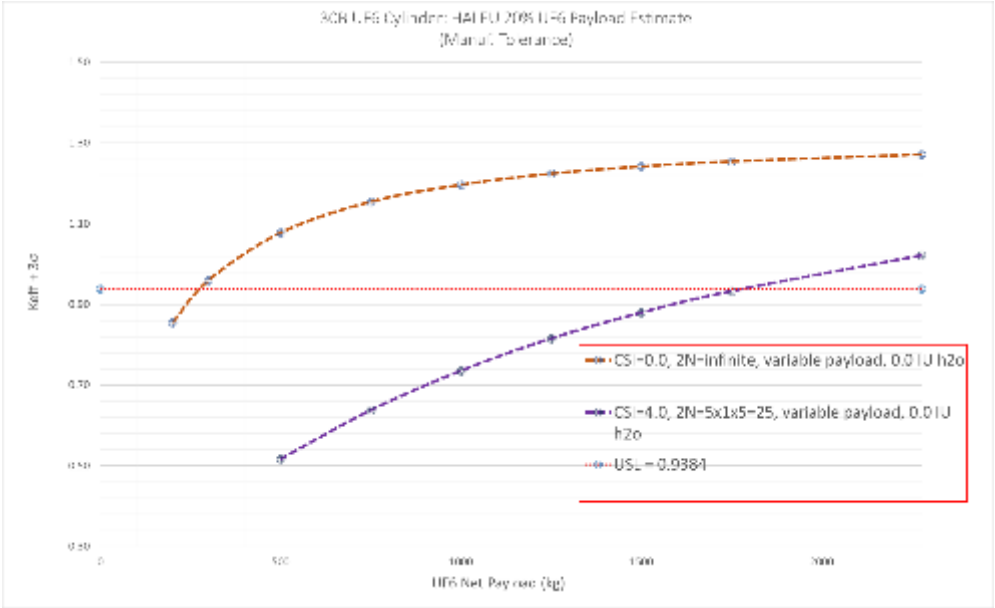
LEU+ Feedstock Transport III





CSI = 4.0: A finite 5x1x5 close packed array of Model 30B UF6 cylinders (2N = 25) containing the maximum allowable net weight ~1700 kg UF_6 can be demonstrated to remain subcritical at 20.0 wt.%

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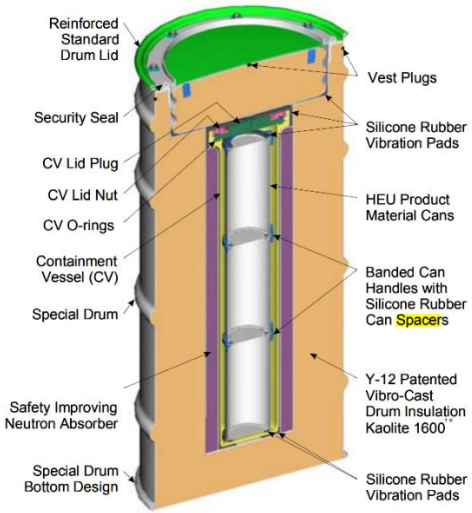
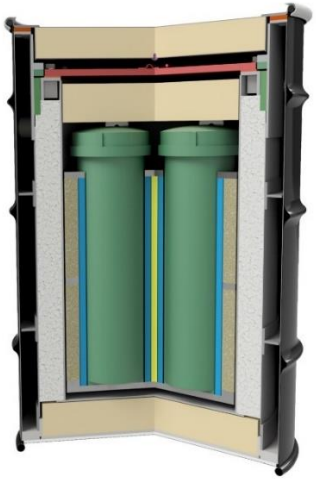
HALEU Feedstock Transport



ES-3100



Versa-Pac Model VP-55 MkII

Candidate transport containers under evaluation: u-metal payload at 20.0 wt.%

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LEU+ Fuel Fabrication

- Existing GNF-A fuel fabrication facility *rebaselined* to 8.0 wt. % U235.
- 45 nodal analyses completed using SCALE 6.1.3 – significant workload over 3 years.
- CSA effort divided into three separate phases of work. Each phase was categorized as HIGH, MEDIUM, LOW depending on and perceived impact to plant.
- Some key impact area(s) included: liquid radwaste treatment system, pellet storage cabinets, and HF recovery pollute tank – physical modifications required.
- SNM-1097 License Amendment Request (LAR) complete with ISA Summary was submitted to USNRC June 24, 2022.

UNITED STATES
NUCLEAR REGULATORY COMMISSION
WASHINGTON, D.C. 20555-0001

November 2, 2022

SUBJECT: ACCEPTANCE OF GLOBAL NUCLEAR FUEL – AMERICAS, LLC, LICENSE AMENDMENT REQUEST FOR 8 WEIGHT PERCENT URANIUM-235 (ENTERPRISE PROJECT IDENTIFICATION NUMBER L-2022-LLA-0065)

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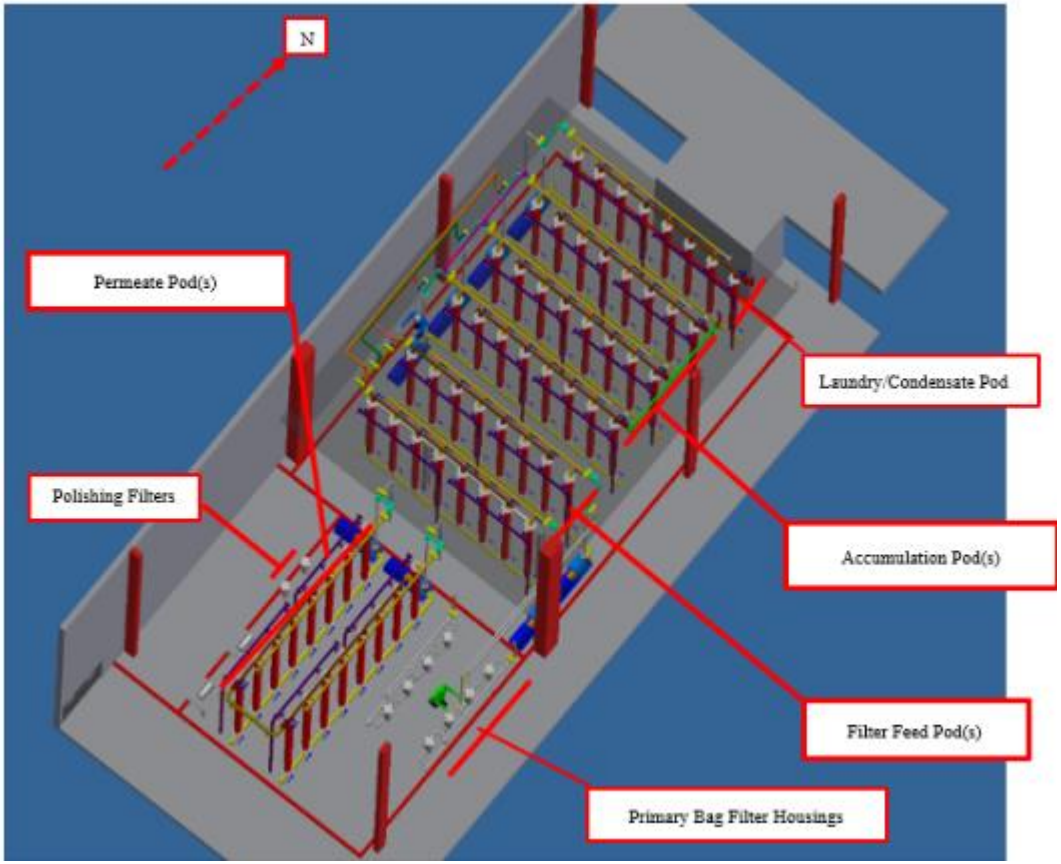
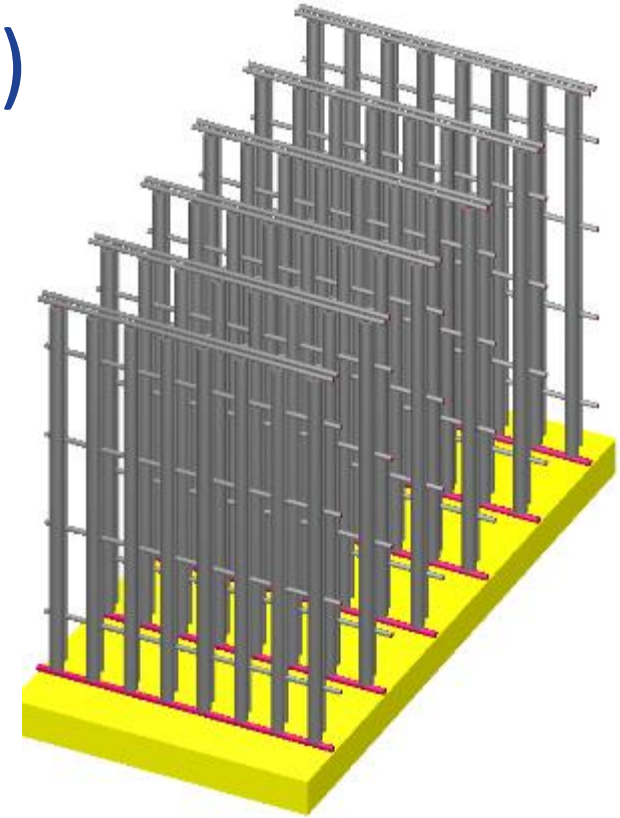
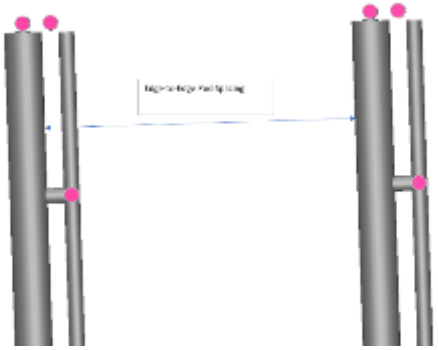
LEU+ Fuel Fabrication (example)

- Liquid Radwaste System – pipe tank array (floorplan model construct, e-e spacing):







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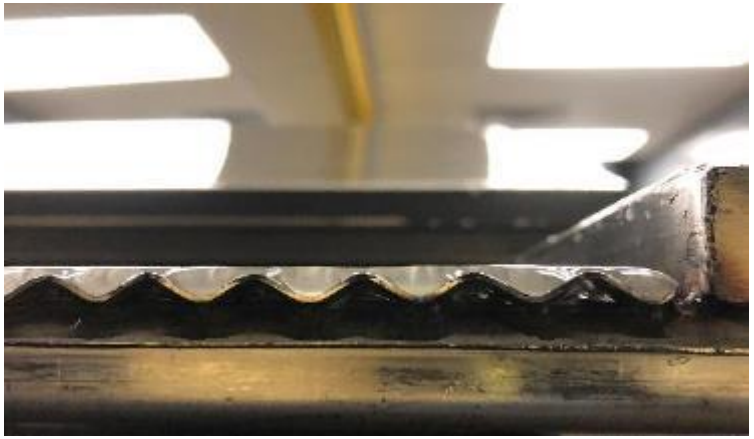
LEU+ Fuel Fabrication (example)

- Pellet storage cabinets – empirical water spray test(s)



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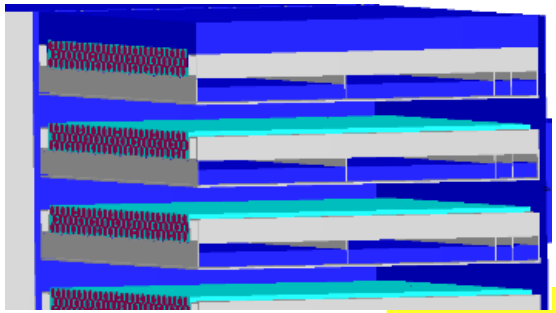
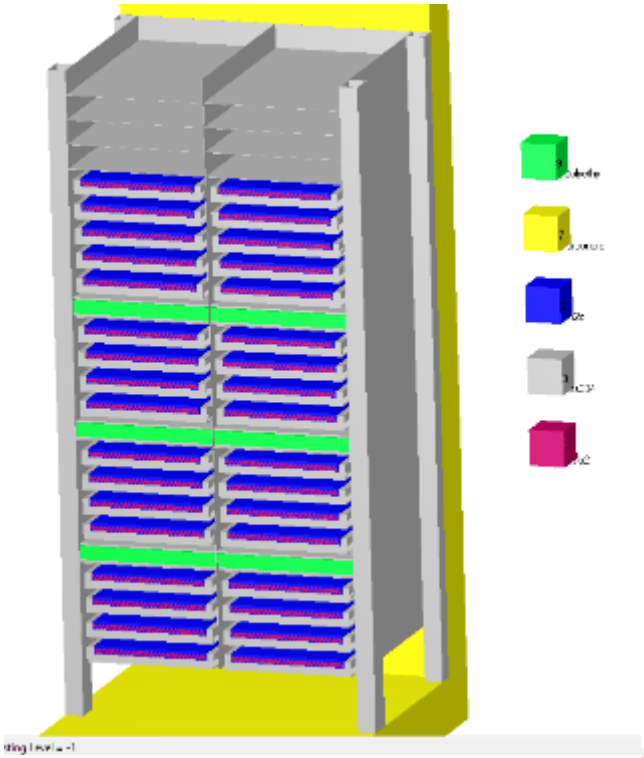
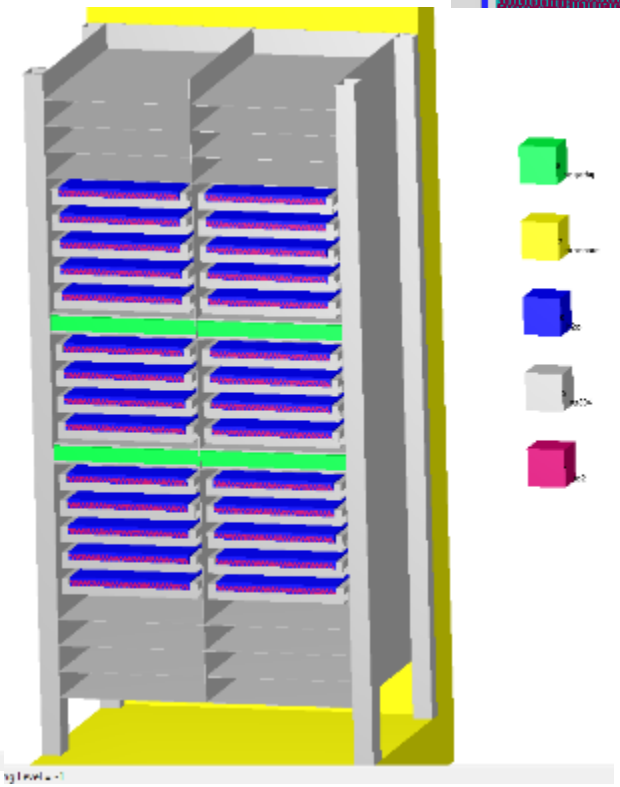
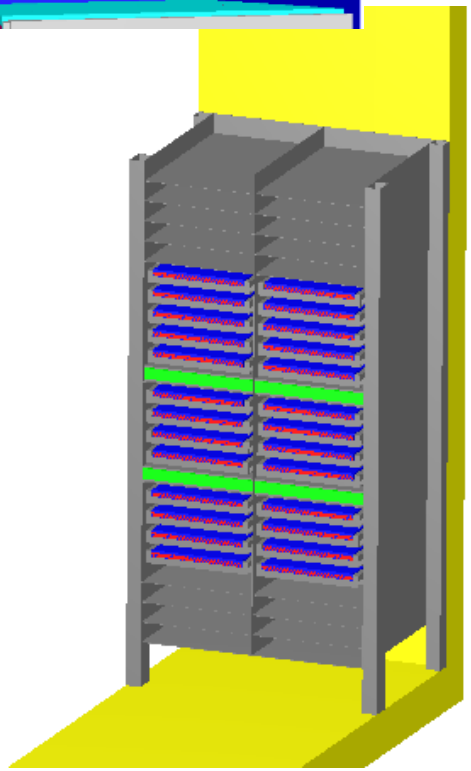
LEU+ Fuel Fabrication (example)

- Pellet storage cabinets – poly slot design modification option(s), optimal interunit H2O









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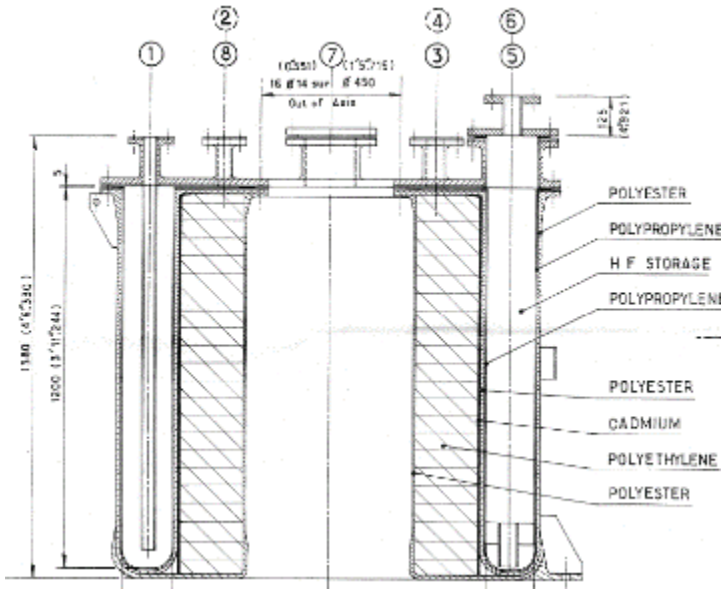
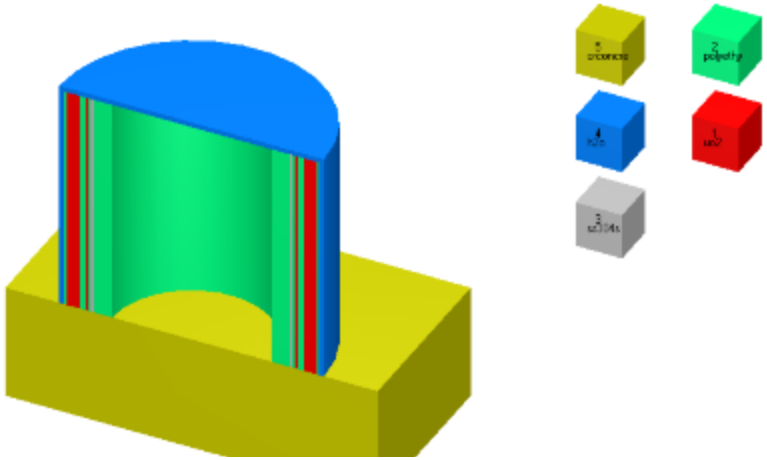
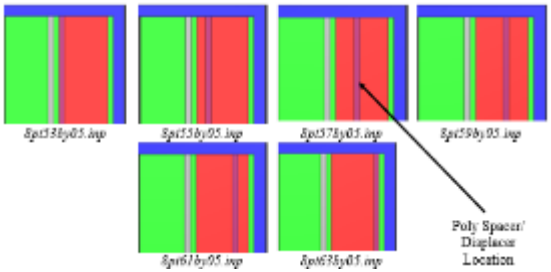
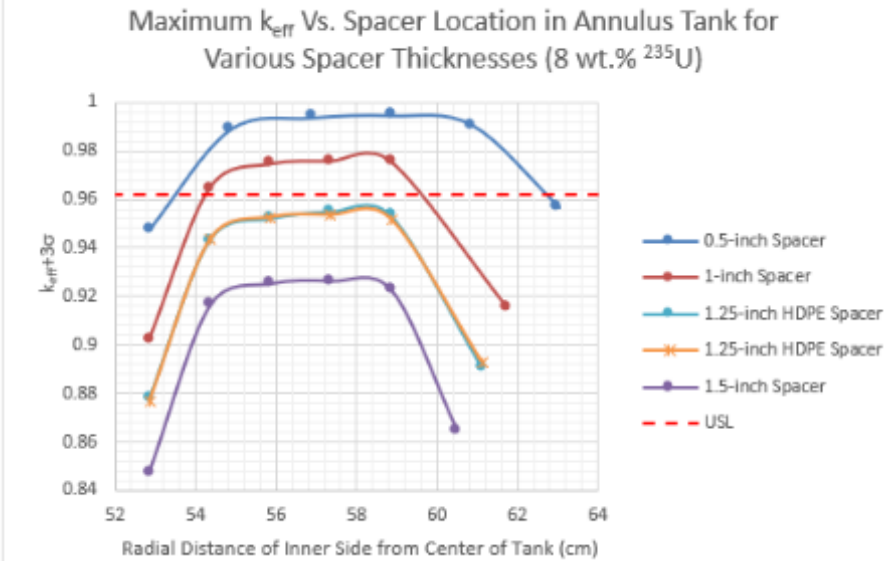
LEU+ Fuel Fabrication (example)

- HF pollute tank – annulus modification









When a spacer/displacer of 0.5-inches, or thicker, is inserted next to the inner or outer wall, then the new 8% annular geometry is also subcritical

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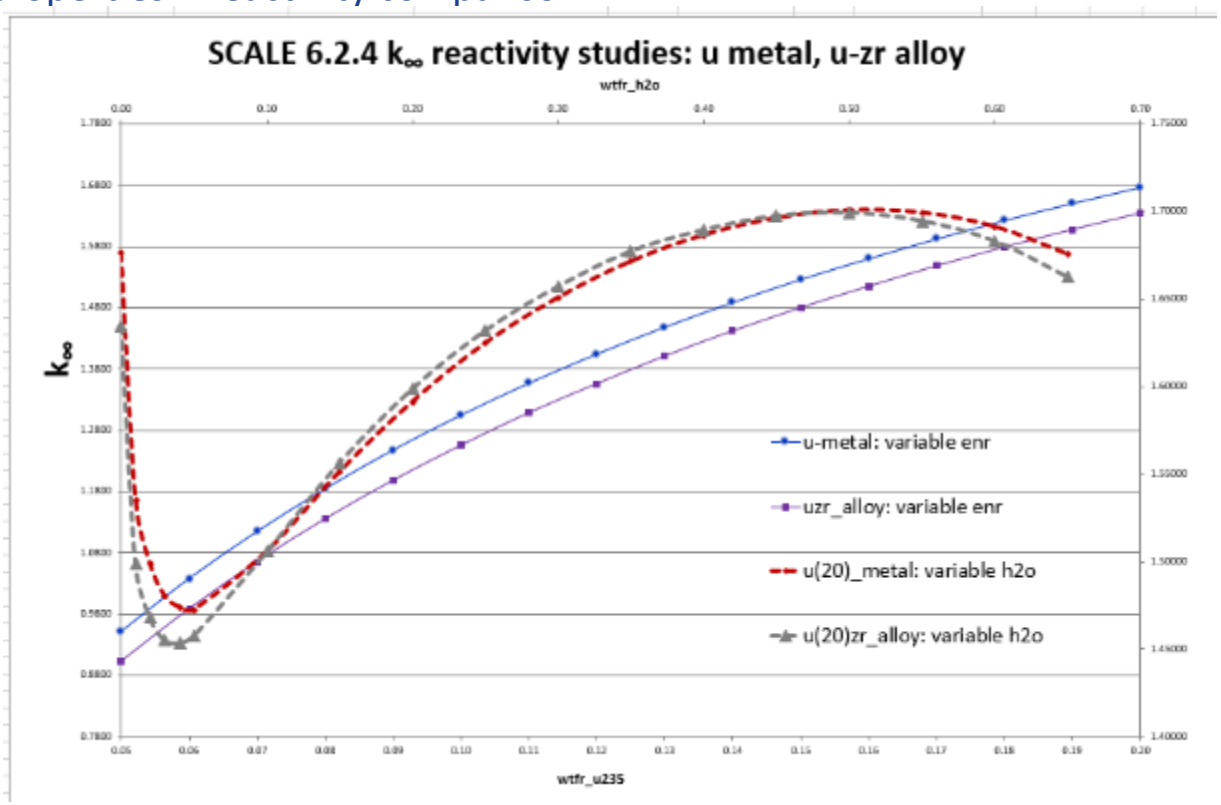
HALEU U-Metal Fuel Fabrication

- Material properties – reactivity comparison



Case Set	Compound	Density (g/cc)	k_{inf}	% delta_k/k
u, dry metal	u(5)	19.05	0.95104	0.0
	u(8)	19.05	1.18404	24.5
	u(10)	19.05	1.30421	37.1
	u(20)	19.05	1.67623	76.3

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HALEU U-Metal Fuel Fabrication

- Uranium Metal vs. Uranium Alloy Subcritical Limits at 20.0 wt.% ^{235}U

Geometry	Parameter	Mixture	Reflector	Subcritical Limit		
				U Metal	U-10Zr Alloy	Unit
Sphere	Mass	Homogeneous	1" Water	5.55	5.54	kg U
Hemisphere	Mass	Homogeneous	Top:1" Water Bottom:24" Concrete	5.85	5.93	kg U
Sphere	Volume	Homogeneous	1" Water	12.08	12.60	liter
Infinite Cylinder	Diameter	Homogeneous	1" Water	7.78	7.88	inch
Infinite Slab	Thickness	Homogeneous	1" Water	3.92	3.99	inch
Infinite Slab	Thickness	Homogeneous	Top:1" Water Bottom:24" Concrete	2.55	2.62	inch
Infinite System	Concentration	Homogeneous	N/A	58.33	58.29	gU/l
Sphere	Mass	Heterogeneous Fuel:1 mm dia.	1" Water	6.20	5.96	kg U
Sphere	Mass	Heterogeneous Fuel:3 mm dia.	1" Water	8.72	7.88	kg U
Sphere	Mass	Heterogeneous Fuel:5.415 mm dia.	1" Water	12.09	10.44	kg U
Hemisphere	Mass	Heterogeneous Fuel:1 mm dia.	Top:1" Water Bottom:24" Concrete	6.60	6.38	kg U
Hemisphere	Mass	Heterogeneous Fuel:3 mm dia.	Top:1" Water Bottom:24" Concrete	9.14	8.27	kg U
Hemisphere	Mass	Heterogeneous Fuel:5.415 mm dia.	Top:1" Water Bottom:24" Concrete	12.71	10.95	kg U
Sphere	Volume	Heterogeneous Fuel:0.254 - 6.35 mm rad.	1" Water	10.70	11.41	liter
Infinite Slab	Thickness	Heterogeneous Fuel:0.5 - 7 mm dia.	1" Water	3.72	3.83	inch
Infinite Slab	Thickness	Heterogeneous Fuel:0.5 - 7 mm dia.	Top:1" Water Bottom:24" Concrete	2.41	2.50	inch

Subset of a subcritical limits shown (USL=0.9584) for *defined* reflector, particle size range - optimal moderation conditions…

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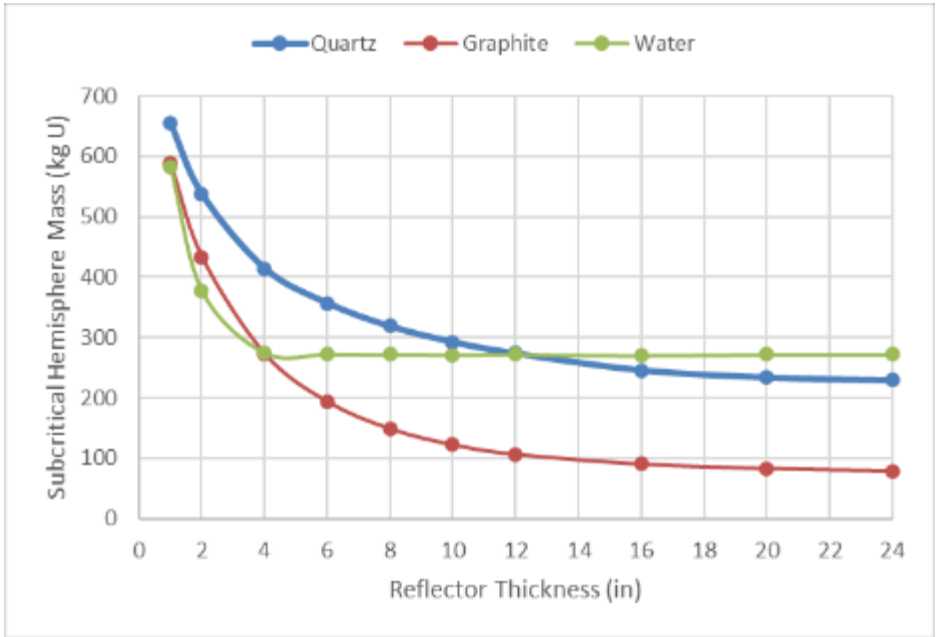
HALEU U-Metal Fuel Fabrication

- Uranium Metal at 20.0 wt.% ^{235}U



<u>Dry</u> uranium metal hemisphere mass limits shown (USL=0.9584) *as function of reflector media / thickness….*

Reflector Material	Reflector Thickness (inches)									
	1	2	4	6	8	10	12	16	20	24
	Maximum Subcritical Mass Limits (kg U)									
Graphite	588.1	433.2	273.1	193.7	148.8	122.3	106.5	90.3	82.9	79.1
Quartz	654.4	537.6	414.7	357.1	318.8	292.7	273.8	245.9	233.9	228.9
Water	582.1	377.2	274.7	272.6	272.2	271.5	271.8	270.0	271.8	271.8

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HALEU U-Metal Fuel Fabrication

- The uranium metal fuel fabrication is premised on INL EBR-II process experience (ca. 1965). Metallic fuel has an important historical significance in the development of nuclear reactors and continues to be relevant to the progression of advanced test and power reactors. About 30 years ago, the Experimental Breeder Reactor-II (EBR-II) was the last reactor in the U.S. to utilize a full core of metal driver fuel.
    - Description And Proposed Operation Of The Fuel Cycle Facility For The Second Experimental Breeder Reactor (EBR-II) [ANL-6605]
    - Fabricating Fuel for the Versatile Test Reactor [INL/RPT-22-63555-Rev002]
- In the interest of time/export control considerations, the metallic UZr alloy fuel fabrication process will need to be covered at a later date…

EXPORT CONTROLLED INFORMATION
Contains technology subject to U.S. export controls governed by the Export Administration Regulations (15 CFR Part 730 et seq.) and/or the Department of Energy regulations (10 CFR Part 810). Diversion contrary to U.S. law is prohibited.

LEU+ (8%) Product BWR Fuel Transport

UNITED STATES
NUCLEAR REGULATORY COMMISSION
WASHINGTON, D.C. 20555-0001

April 10, 2023

SUBJECT: AMENDMENT REQUEST FOR THE MODEL NO. RAJ-II PACKAGE

- SCALE 6.1.3 & KENO-VI are used; no package or hardware modifications.
- Expand authorized contents to include 8 wt.% ^{235}U enrichments for 10x10 lattice and rods.
- Criticality Safety Index (CSI) adjustment needed for increased ^{235}U enrichment.
- RAJ-II SAR (rev. 11) under active NRC review.
- Model No. RAJ-II, USA/9309/B(U)F-96

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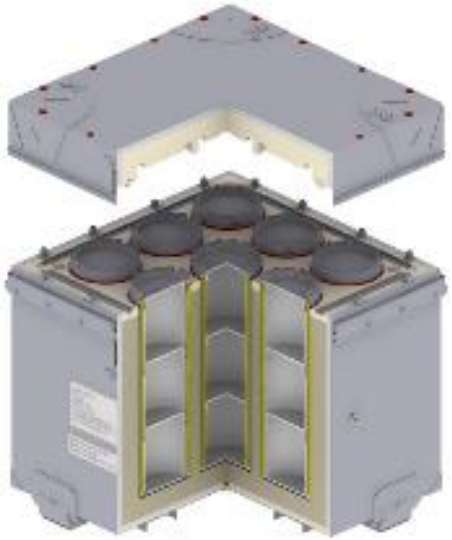
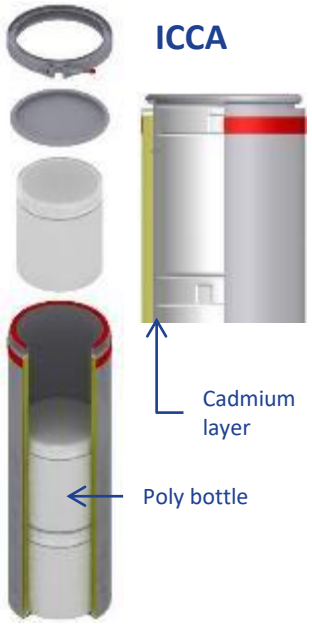
LEU+ (8%) Product UO2 Powder, Scrap U Transport





- SCALE 6.1.3 & KENO-VI are used; no package or hardware modifications.
- Expand authorized contents to include 8 wt.% ^{235}U enrichments for homogeneous/heterogeneous uranic material form(s)*.
- Criticality Safety Index (CSI) adjustment anticipated for increased ^{235}U enrichment.
- SAR (rev. 8) – in active development.
- Model No. NPC, USA/9294/AF-96

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*Paulson, L.E., "K-Infinite Comparison of Uranium Compounds," Trans. Am. Nucl. Soc., **121**, 937-940 (2019).

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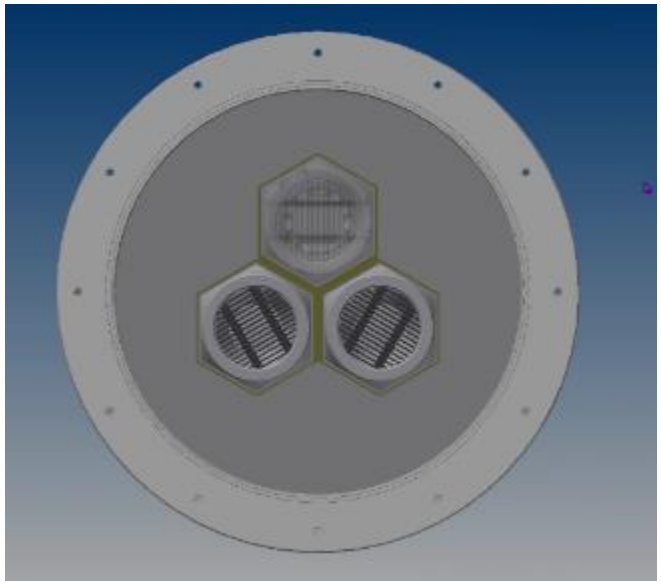
HALEU (20%) Product U-Metal Lattice Transport

- Under conceptual design development, TBD



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Global Nuclear Fuel

Conclusions

- Both SCALE6.1 and 6.2 release versions have been used in CSA process applications in support of advanced fuel cycle needs at GNF-A.

- LEU+: SCALE6.1/KENO-VI: Efforts to rebaseline the deconversion, fabrication, and balance of plant operations have been completed. This culminated a ~ 3-year effort. This work modernized and streamlined the nuclear criticality safety licensing basis used to support our ISA program [IROFS].

- HALUE: SCALE6.2/KENO-VI: Efforts to establish and document the required nodal analyses used to support the planned U-metal fuel fabrication facility is currently underway.

- LEU+/HALEU: SCALE6.1/KENO-VI is also used in support of safety analysis reports for licensed Type A or Type B fissile nuclear package designs and Chapter 6 criticality safety demonstrations and CSI determination.

- Additional SCALE analytic methodologies *not discussed* include TSUNAMI, ORIGEN, MONACO, MAVRIC).

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