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Signed by Esmaili, Hossein on 03/22/21

SUBJECT: HIGH-ASSAY-LOW-ENRICHED-URANIUM IMPACT ON STORAGE AND TRANSPORTATION CRITICALITY

This deliverable is provided in accordance with the following User Needs (UN) that drive application focused research:

Table 1: User Need Drivers

#	UN	UN Title	ADAMS ML#
1	NRR-2019-009	Regulatory Research Supporting Licensing of Burnup and Enrichment Extensions in Near-Term Accident Tolerant Fuel (ATF)	ML19171A205
2	NMSS-2020-005	Regulatory Research Supporting Licensing of Increased Enrichment (IE) and High Burnup (HBU) LWR Fuels	ML20062A944

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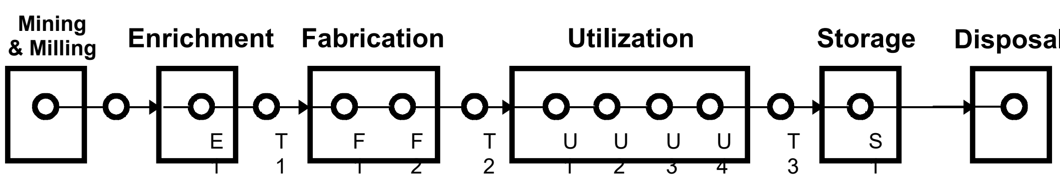
These UNs cover application, along with associated development and assessment efforts, intended to further equip staff to review industry approaches that use High-Assay-Low-Enriched (HALEU)/Increased-Enrichment (IE) fuel for High Burnup (HBU) and Accident Tolerant Fuel (ATF) concepts. In practice, the UNs are intended to perform the following functions:

1. Enhance NRC staff competency in the expected behavior and impacts of these concepts
2. Provide training to NRC staff in approaches to performing independent reviews including the development of baseline approaches for the evaluation of these concepts
3. Extend existing computational tools, data, developing validation basis, and uncertainty analysis to support efficient reviews

The neutronics effort are focused on a reference and delta approach making use of decades of Light Water Reactor (LWR) experience and existing computer codes. The reference is the fuel cycle that is driven by the current zirconium encapsulated 5 wt. % enriched uranium designs with maximum assembly average burnup of about 60 GWd/MTU. The delta will be the variations of HALEU/HBU and ATF concepts.

The neutronics activities may be understood holistically by looking at the existing fuel cycle, as characterized in Figure 1 below. The work performed in this report supports understanding of how fuel is staged in the "E" step, transport in the T1 step, staged in the "F" step, transport in the T2 step, and staged in the "U" step.



E1 – UF_6 enrichment
T1 – transportation of UF_6/UO_2(powder) to fuel fabrication facility
F1 – fabrication of UO_2 fuel pellets
F2 – fabrication of LWR fuel assemblies
T2 – transportation of fresh fuel assemblies to the plant
U1 – fresh fuel staging and loading
U2 – power production
U3 – spent fuel pool/shuffle operations
U4 – on-site dry cask storage
T3 – transportation of spent fuel to off-site storage
S1 – off-site storage

Figure 1: Light Water Reactor UO_2 Fuel Cycle Representation

To make the problem tractable the effort is broken into several phases where each phase informs the next. Phase 1 covered activities up until March 2021 and performed applications and development activities. Three applications-related deliverables are to be provided, covering: 1) criticality impacts in storage and transport environments, 2) neutronics impacts from the existing fleet moving towards HALEU/HBU for existing systems, and 3) impacts from ATF concepts. These three applications reports may be considered as scoping studies used to refine the activities in the following phases.

This memorandum covers the first of these applications driven studies and is focused on criticality impacts in both storage and transport of HALEU materials in several packages. The enclosed and publicly available report (ML21040A518)

Addresses:

- UN #1, Task 4.2 “Update SCALE with new materials and conduct verification & validation and code assessment,”
- UN #2, Back-End Task 3.h “Compare reactivity from baseline (5%) up to 19.75% and assess changes to criticality safety validation basis and benchmark applicability”

Completes:

- UN #2, Front-End Task 2.a “Assess enrichment facility, uranium hexafluoride feed material transportation and conversion/deconversion criticality validation (benchmark, ck @5% up to 19.75%), as practically possible using existing package designs.”
- UN #2, Front-End Task 2.b “Assess HALEU fuel fabrication facility/transportation/storage criticality validation (benchmark, ck @5% up to 19.75%), as practically possible using existing package designs.”

Summary of Analysis

The primary focus of this work is to provide the technical staff with an understanding of how existing transportation packages perform when loaded with HALEU LWR fuel materials, and the impacts to storage configurations at fabrication, enrichment, and utilization facilities. This work also provides insights as to if transportation limitations may be required to address the increase in reactivity due to increased enrichment and whether sufficient applicable benchmark criticality experiments can be identified for computer code validation.

Seven (7) fuel forms are considered along with their representative transportation package (ML21040A518). The key figure of merit considered is the system’s multiplication factor, k_{eff}, which is used to determine the system’s subcriticality margin. Assessments were made for a number of scenarios for optimum moderation and varying geometric configurations. Package designs were taken from publicly available information, from their respective Certificates of Compliance, and the resulting computer models used to support this work were made publicly available. Table 2 summarizes the transportation package and fuel forms analyzed in the study.

Table 2: Package and Fuel Form Description

Fuel Form	Package Type
Uranium Hexafluoride (UF_6) (solid)	DN-30 (overpack for ANSI N14.1 30B cylinder)
Boiling Water Reactor (BWR) fuel assembly (FA)	TN-B1
BWR fuel pins	Traveller
Pressurized Water Reactor (PWR) fuel pins and assembly	Traveller
Uranium metal	Versa-Pac
Tri-structural Isotropic (TRISO)	Versa-Pac
Uranium Dioxide (UO_2) pellets and powder	CHT-OP-TU

Evaluations were performed with the SCALE computer code, which has been supported by the NRC since the late 1970s. The primary SCALE sequences used in this work are KENO-VI, TSUNAMI-3D and TSUNAMI-IP, with nuclear data based the standard ENDF/B-VII.1 library. KENO-VI is the primary Monte-Carlo methodology used by staff in predicting system k_{eff}. The TSUNAMI-3D code is used to develop system k_{eff} sensitivity to both energy and isotopic reactions, and TSUNAMI-IP is used to combine system sensitivity data and nuclear data uncertainty to produce a correlation coefficient, the "c_k" value. The c_k value provides a quantitative assessment of how similar the application is to the benchmark experiment, and typically a c_k of >0.9 is desired.
Benchmark data used in this work is found in the International Criticality Safety Benchmark Evaluation Project (ICSBEP) Handbook, from which a subset of 1,584 critical experiments were selected.
The fuel forms and transportation packages, identified in Table 2, were then parametrized and tabulated in Table 3: Description of Package Configurations for K_{eff} and Validation Basis. Table 3: Description of Package Configurations for K_{eff} and Validation Basis presents the enrichment and package array size configuration that the was evaluated in this study. The results of this comparison are found in Appendix A of the report (ML21040A518).

Table 3: Description of Package Configurations for K_{eff} and Validation Basis

Package #	Fuel Cycle Step	Package Description	Enrichment (wt% ^{235}U)	Package Array	Type
1	T2, U1	Traveller fuel assembly (17x17)	5.0	Infinite	PWR FA
2	T2, U1	Traveller fuel assembly	8.0	1	PWR FA
3	T2, U1	Traveller fuel assembly, 54 IFBA/FA	8.0	Infinite	PWR FA
4	--	Traveller rod pipe	5.0	Infinite	Pins
5	--	Traveller rod pipe	10.0	Infinite	Pins
6	T1	CHT-OP-TU UO2 powder	5.0	48	Powder
7	T1	CHT-OP-TU UO2 powder	8.0	18	Powder
8	T1, F1	CHT-OP-TU UO2 pellet	6.9	18	Pellets
9	T1, F1	CHT-OP-TU UO2 pellet	16.5	48	Pellets
10	T2, U1	TN-B1 BWR FA (11x11, 13 Gd rods/FA)	5.0	100	BWR FA
11	T2, U1	TN-B1 BWR FA (11x11, 13 Gd rods/FA)	6.7	36	BWR FA
12	T2, U1	TN-B1 BWR FA (11x11, 24 Gd rods/FA)	8.0	100	BWR FA
13	E1, T1	DX-30 UF6 in 30B (mod exclusion)	5.0	Infinite	UF6
14	E1, T1	DX-30 UF6 in 30B (mod exclusion)	6.7	6	UF6
15	E1, T1	DX-30 UF6 in 30B (optimum exclusion)	12.5	1	UF6

Several conclusions and insights are provided [ML21045A518]:

- Several options are available to maintain sufficient subcriticality margins to offset the increased reactivity due to increased enrichment, such as reducing transportation array sizes, reducing fissile mass, crediting neutron poisons & absorbers and performing additional safety analysis.

- Due to the incremental change of HALEU, no new neutronics phenomena are expected that would warrant a Phenomena Identification and Ranking Table exercise.

Traveller Package

- When the rod pipe container configuration is utilized, the Traveller package can support the transportation of PWR and BWR UO_2 fuel rods up to 10 wt. % ^{235}U.
- Subcriticality margin was found to be relatively insensitive to package array size due to the use of Boral plates and polyethylene moderator blocks.
- The Traveller standard version supports the transportation of 5.5 to 6.5 wt. % ^{235}U (assembly average) PWR fuel assemblies for some fuel designs through a combination of transportation array size modifications and use of best estimate type analyses.
- Maximum enrichment can be increased by crediting minimum integral poisons in the fuel assembly, similar to the TN-B1 BWR assembly package.
- Numerous critical experiment candidates are available for validation of 5 to 8 wt. % 235U Traveller models.

CHT-OP-TU Package

- The CHT-OP-TU package can support the transportation of UO_2 powder up to 18 wt. % ^{235}U and up to 16.5 wt. % ^{235}U for UO_2 pellets through a combination of oxide vessel diameter and package array size.
- Numerous critical experiment candidates are available for validation of up to 16.5 wt. % ^{235}U.

Versa-Pac Package

- The Versa-Pac package is currently licensed to transport uranium materials enriched up to 100 wt. % ^{235}U, no additional evaluation was performed.

TN-B1 Package

- The TN-B1 package can support transportation of BWR fuel assemblies up to 10 wt. % ^{235}U (assembly average) using a combination of package array size and gadolinia rod credit.
- Subcritical margin is highly sensitive to package array size in the un-poisoned configuration.
- Numerous critical experiment candidates were identified for validation of 5 to 8 wt. % ^{235}U.

DN-30 Package

- The DN-30 package can support transportation of UF_6 up to 9.5 wt. % ^{235}U by reducing transportation array size from unlimited (at 5 wt. % ^{235}U) to 2 packages (at 9.5 wt.% ^{235}U). These results are based on retaining the 10 CFR 71.55(b) exemption from the assumption of water leakage into the containment system. Because the limiting accident conditions do not include water in-leakage, the neutron energy spectrum of the DN-30 is harder than other evaluated packages.
- Only a few critical experiments were identified with a similarity index (c_k) of 0.8 or higher. Phase 2 of the work will investigate validation penalty assessments.

This work was performed in partnership with Kevin Heller (NRR), John Wise (NMSS), and Andrew Barto (NMSS).

Enclosure:

1. Assessment of Existing Transportation Packages for Use with HALEU, ADAMS ML: ML21040A518
2. Input Files, ADAMS ML: ML21040A517

HIGH-ASSAY-LOW-ENRICHED-URANIUM IMPACT ON STORAGE AND TRANSPORTATION CRITICALITY DATE March 22, 2021

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