Revisions to the DOE Approved NAC-LWT Safety Analyses Report to Support Shipment of the CEUSP Materials

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ABSTRACT

Transportation of Consolidated Edison Uranium Solidification Project (CEUSP) material from Oak Ridge National Laboratory (ORNL) to the Nevada National Security Site (NNSS) represented several distinct challenges. Although the CEUSP material was qualified as low-level waste (LLW), it contained fissile U-233 and U-235, and hence the CEUSP material was managed as Special Nuclear Material (SNM). As the CEUSP material originated from a 1960s research and development test of thorium and uranium fuel, it also contained various impurities not typical of U-233 oxides. Since the CEUSP material started as 8,000 liters of liquid uranyl nitrate, cadmium and gadolinium were added to the solution to prevent criticality. By the mid-1980 with increased safety and security concerns, but no identified purpose for the CEUSP material, the material was solidified at high temperatures into more than 400 individual ceramic-like uranium oxide monoliths. Each uranium oxide monolith is bonded to the inside of a steel canister measuring about 8.9 cm (3.5 inches) in diameter by 61 cm (24 inches) long. After determining that downblending prior to disposal did not represent a viable option (i.e., shipping and disposal could occur in its current ceramic-like form), disposal was limited to the NNSS. An extensive safety analysis in packaging revision was initiated by NAC International to ensure the material could be safely transported.

INTRODUCTION

Purpose

This paper discusses vital additional technical analyses performed to support a revision to the United States Department of Energy approved NAC-LWT SARP to add the CEUSP material as approved content.

Background on CEUSP

LLW typically consists of containers of debris, trash, soil, equipment, tools, and personal protective clothing. The CEUSP material is LLW but only characterized as such by exemption. It contains radioisotopes of uranium from an R&D test of reactor fuel at the Consolidated Edison Indian Point-1 reactor in New York. The R&D finished in late 1968, with Nuclear Fuel Services of West Valley, then separating the uranium from certain other isotopes, fission products, and other constituents common to reactor fuel. The extracted liquid uranium (8,000 liters of uranyl nitrate) was then shipped to ORNL for storage, awaiting reuse. Cadmium and gadolinium were added to the liquid to prevent criticality. With a use was still not identified by the mid-1980s, for safety and security reasons, DOE solidified the 8,000 liters into 403 individual ceramic-like uranium oxide monoliths. Each monolith was bonded to the inside of a stainless-steel canister and contained just a few kilograms of uranium.

As early as 1997, the Defense Nuclear Facilities Safety Board expressed concerns about the continued storage of the CEUSP materials in Building 3019. In 2010, the board reiterated that it did not consider long-term storage of the CEUSP material in the aging building to be desirable. Meanwhile, in 2007, DOE-EM identified the continued storage in Building 3019 a significant burden on safety, safeguards, security, and finances. By 2014, with difficult to maintain its security systems because the storage building was about seven decades old, DOE changed its management strategy for the CEUSP material to disposal.

Although LLW, the CEUSP material was managed as Special Nuclear Material (SNM), requiring more stringent management controls for both material protection and physical security. Down blending before disposal was investigated but determined that direct disposal at NNSS represented the preferred option.

NAC-LWT Cask

The NAC-LWT cask is designed to meet the requirements of 10 CFR 71[1] and 49 CFR 173 [2] for transporting numerous radioactive materials from fuel assemblies, fuel elements, fuel rods, to waste. Figure 1 shows the cask.

Figure 1. NAC-LWT Cask

As part of the general NAC-LWT design concept, to assure that the cask contents are retained in a subcritical and safe configuration using different approved baskets. The baskets support the materials, both laterally and longitudinally. Since the CEUSP was not an approved content, NAC submitted revisions to the NAC LWT SARP to DOE for certification that included the CEUSP material. Figure 2 shows the U_3O_8 monolith bonded insider the stainless steel CEUSP can and overpacked in a CEUSP canister assembly.

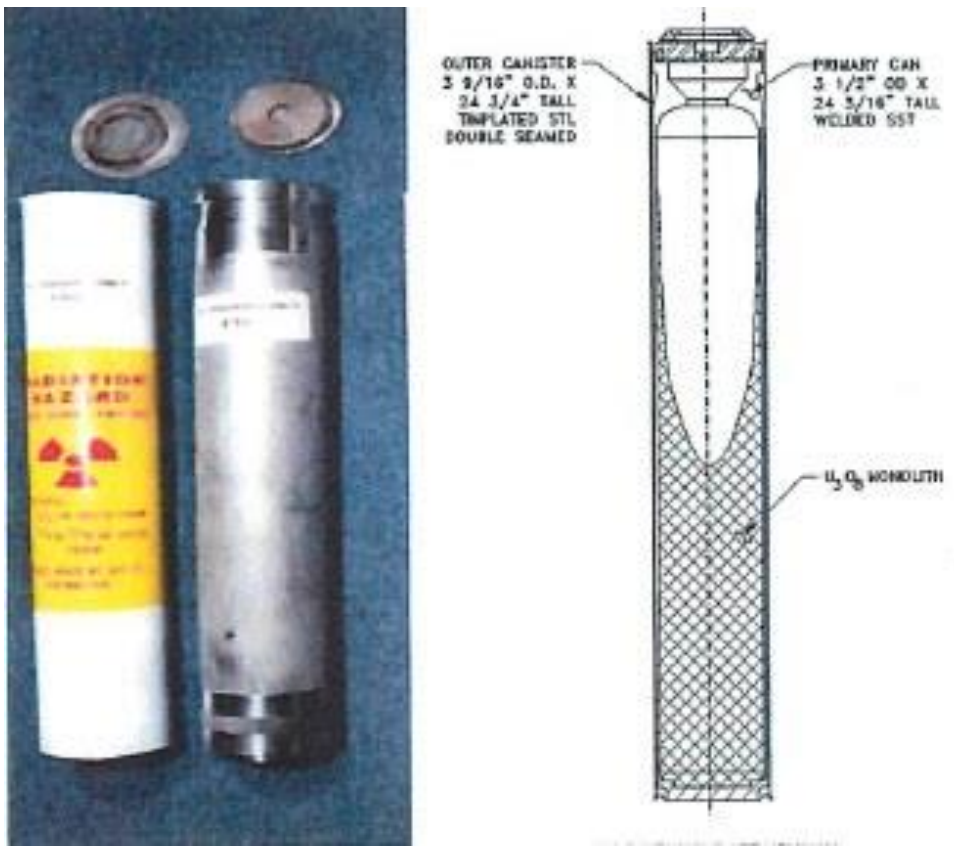

Figure 2. Double Canister Filled with Bonded CEUSP Waste

The primary can is welded stainless steel. The CEUSP canister assembly (shown in white below), which is a tin-plated steel thin shell over-pack (typically crimped closed with a tin-plated lid).

Configuration

Up to seven CEUSP canister assemblies fit in in a CEUSP sleeve. If fewer than seven canister assemblies are placed into a CEUSP sleeve, canister spacers are used to limit the movement of the canister assembly. The CEUSP sleeve is formed from stainless steel pipe with a welded base disk and a threaded lid. Up to three CEUSP sleeves are loaded into a CEUSP basket assembly. The CEUSP basket is a weldment fabricated from Type 304 stainless steel. The principal components of the weldment are three 5.56-inch diameter pipes and twelve 13.27-inch diameter disks. The disk arrangement maintains the separation of the pipes and provides a close fit with the 13.375-inch inside diameter of the NAC-LWT cask. The basket includes a wiper, which limits the dispersal of gross particulate material from the sleeve assemblies into the NAC-LWT cask cavity.

The basket assembly and sleeve assembly are designed for ease of handling, loading, and unloading operations with the NAC-LWT cask design. The application with the shipment of CEUSP generated U_3O_8 monoliths stored in CEUSP canisters, in the sleeve inside the CEUSP basket required a configuration change. The CEUSP basket assembly and sleeve were designed, analyzed, fabricated, inspection, and accepted per ASME Section III, Subsection NG.

KEY ADDITIONAL TECHNICAL EVALUATIONS

Structural

Structural evaluation of the NAC-LWT CEUSP basket and sleeve assemblies for NCT and HAC; as well as an evaluation of the sleeve assembly for handling and unloading conditions were performed. The basket assembly and sleeve assembly were analyzed for end- drop and side-drop conditions using classical hand calculations. The stresses from the end-drop and side-drop analyses are compared to the allowable stress criteria listed in Table 1, while the stresses from the handling and unloading condition analyses are compared to the applicable allowable criteria in Table 2.

Table 1. Allowable Stress Values Used in End and Side Drop Analyses

CONDITION	STRESS CRITERIA
NCT	$P_m \leq 1.0\ S_m$* $P_m + P_b \leq 1.5\ S_m$ $\sigma_{bearing} < 1.0\ S_y$ $\tau \leq 0.6\ S_y$*
HAC	$P_m < 0.7\ S_m$* $P_m + P_b < 1.0\ S_m$ $\sigma_{bearing} < 1.0\ S_u$ $\tau < 0.42\ S_y$*

Note:
* Conservative and complies with ASME Boiler and Pressure Vessel Code, Section III, NG, 2004

Table 2. Allowable Stress Values Used in Handling and Unloading Analyses

EQUIPMENT	STRESS CRITERIA
Structural components not including slings and rigging accessories	Minimum design factor of 3 based on the yield strength of the material. Sleeve assembly is required to support three times the maximum loaded weight without exceeding material yield strength and five times its maximum loaded weight without exceeding materials ultimate strength [11].
Wire rope sling assembly	Design factor for wire-rope slings shall be a minimum of 5:1 based upon strength.
Rotation of canister sleeve assembly from vertical to horizontal	Minimum design factor of 3 based on the yield strength of the material. Canister sleeve assembly is required to be self-rotated from vertical to horizontal without exceeding the material yield strength.

Note: Criteria from Reference 11 unless otherwise noted

The bounding acceleration for the NCT LWT 1-ft end drop is 25 G [1]. The bounding acceleration for the NCT-LWT HAC 30-foot end drop is 61 G [1]. Table 3 lists the NCT evaluations performed, while Table 4 lists the HAC evaluations conducted.

Table 3. Drop Evaluations Performed for NCT

1-FT DROP	SLEEVE	BASKET	SPACER
SIDE	Stress • bending • bearing	Stress • bending • basket bearing on cask	Stress • bending
END	Stress • compressive • buckling stress • lid compressive Thread evaluations • lid external • pipe internal	Stress • tensile/compressive • buckling • middle/top weld stress from disks to tube • bottom weld stress from disk to tube	Stress • compressive • bending • buckling

Table 4. Drop Evaluations Performed for HAC

30-FT DROP	SLEEVE	BASKET	SPACER
SIDE	Stress • bending	Stress • bending • basket bearing on cask	Stress • bending
END	Stress • compressive • bearing • buckling • lid compressive Thread evaluations • lid external • pipe internal	Stress • tensile/compressive • buckling • middle/top weld stress from disks to tube • bottom weld stress from disk to tube	Stress • compressive • bearing • bending • buckling
TOP-END		Stress • tensile/compressive • buckling • middle/top weld stress - disk to tube • bottom weld stress - disk to tube	

NCT analyses show that all basket-bearing stresses during a side drop are much less than the material yield strength. Column analyses demonstrate that each basket assembly is self-supporting during an end drop. Therefore, it was concluded the CEUSP basket design and sleeves had enough structural integrity for adequate service during NCT and HAC conditions. The CEUSP basket and sleeves are structurally suitable for NCT and HAC. The minimum margin of safety for transport conditions was +0.73 and occurred for the accident top-end drop condition. Also, the sleeve was determined to be structurally adequate for handling and unloading conditions, with the minimum factor of safety being 3.15 when the sleeve assembly was lifted vertically.

Thermal

A new thermal analysis was performed for the CEUSP material loaded in the NAC LWT cask under NCT conditions. A two-dimensional finite element model for CEUSP material packed in the NAC-LWT cask was developed and used to perform steady-state thermal analysis under NCT [9]. The model consists of a 2-D 90-degree cross-section of the CEUSP assembly and basket, as well as the contents inside the cask inner shell. The CEUSP material was modeled as a concentrated cylinder in the center of the basket assembly with the material. Heat loads were calculated from the Source Term and Shielding Analysis [12]. As a result, a total heat load of 35 Watts for the whole cask was used in the analysis [9]. The heat load was applied to the center area of the model that has the equivalent area to the area of the three tubes. This method is conservative as it concentrates the heat in the center, resulting in higher temperatures. The maximum cask inner shell temperature of 215°F (for MTR Fuel with a heat load of 1.26kW with ISO container [1], was applied to the outer surface of the model as the boundary condition for the evaluation, which corresponds to the inner surface of the cask inner shell.

Thermal conductivities of air were used for both the inner part of the model and for the outer part of the model in the circumferential direction and the cask axial direction. Effective thermal conductivities in the radial direction of the outer part of the model are computed based on the thickness of the stainless-steel disks. Thermal conductivities of stainless steel from Reference 1 was factored by two resulting in a value of 0.02329 (=0.04658/2). Half of the factor is conservatively used, which is the ratio of the disk thickness (>1.0 inch, over the basket length (171.75 inches. The thermal effect of the base disk (0.5 in. thick) and top disks (6 inches thick) was conservatively neglected. Thermal conductance of the air between disks in the radial direction for the outer part was also conservatively ignored.

The total heat load of 35 watts was distributed over seven modules. Based on Reference 13, the CEUSP material occupies about 500/0 of the space inside the cylinder. The length of 10 inches was conservatively used to compute the heat generation rate, though the cavity length of the tube for each module is more than 20 inches.

The maximum calculated temperature from the thermal model was 315°F and was well below the allowable fuel temperature of 752°F under NCT [1].

SHIELDING

The U_3O_8 fissile material was assayed in 1968. Source terms for the CEUSP material were calculated using ORIGEN with a conservative decay period of only 40 years. The uranium composition, as recorded in 1968, is shown in Table 5.

Table 5. Pre-Decay Uranium Isotopic Composition

Uranium Nuclide	Mass U (g)	U3O8 (g)
232	0.4	4735
233	306.9	363.1
234	44.1	52.1
235	2422.9	2862.8
236	177.4	209.5
238	215.4	254.0
Total	3167.1	3742.0

For shielding, the content was modeled within the CEUSP can in two configurations. The first configuration was an "as poured" monolith in the CEUSP can, while the second was a shift of the CEUSP material to the top of the can. The model used a U_3O_8 density of 2.2 g/cm^3. This density is consistent with a radiograph which showed the can to be approximately 50% filled. The model assumed the maximum fissile uranium loading. Non-radiological impurities in the source material were not modeled but could add up to 1920.3 g to the maximum CEUSP canister weight [1].

The NCT-LWT thermal model was constructed using stainless steel and lead. Neutron shielding was provided by the water/glycol mixture filling the neutron shield tank. The material description for the water/glycol mixture was taken from the one-dimensional shielding analysis for the LWT, with the solution having a density of 0.9669 g/cm^3. Consistent with the default SCALE Standard Composition Library, the following densities were also employed: stainless steel at 7.94 g/cm^3, lead at 11.344 g/cm^3, and aluminum at 2.7 g/cm^3.

Table 6 summarizes the calculated maximum external dose rates for the NAC-LWT with CEUSP material under both NCT and HAC. Based on the calculated dose rates, the NAC-LWT with CEUSP material may be shipped as non-exclusive use.

Table 6. Summary Table of Maximum External Radiation Dose Rates

CONDITION	LOCATION	DOSE RATE [MREM/HR]	LIMIT [MREM/HR]
NCT	Side Surface of Cask	7.95	200
	Side 1m (Transport Index)	1.12	10
HAC	Side 1m	2.46	1000

For the NAC-LWT loaded with 21 CEUSP canisters, the calculated dose rates met the requirements of 10 CFR 71.47 and 10 CFR 71.51. The NAC-LWT with CEUSP material was assigned a Transport Index for shielding of 1.2 (TI = 1.2) based on the requirement of 10 CFR 71.4. As shown in Table 6, the maximum dose rate at 1 meter from the NAC-LWT in NCT was calculated as 1.12 mrem/hr.

CRITICALITY

Criticality evaluations were also performed for both NCT and HAC conditions. The Criticality Safety Index (CSI) for the CEUSP payload was set to 100. The NCT cask array criticality model, which applies a dry cask interior infinite cask array, represents a low reactivity configuration and is bounded by the HAC single cask model. As the single cask "array" fully water reflected is identical the 10 CFR 71.55 (e) configuration, so no new cases were required to be calculated for the 10 CFR 71.59(a)(2) evaluation. The following conditions were used for determining the bounding for the maximum reactivity configuration:

- Fissile material free volume flooded (i.e., a mixture of moderator and fissile material)
- Fissile material dispersed through can
- Preferential flooding
    - Canister and sleeve flooded
    - Cask interior dry
    - Cask fully water reflected

- Components shifted toward the center of the basket
- Tolerances applied
    - o Maximum outer can diameter
    - o Maximum sleeve outer diameter

The maximum reactivity for the CEUSP canisters in the NAC-LWT (keff+2 sigma) was determined to be 0.9110. Table 7 summarizes the maximum reactivity and CSI.

Table 7. Summary Table of Maximum Reactivity and CSI

GEOMETRY	KEFF	SIGMA	KEFF+2 SIGMA	# CASKS	CSI
NCT per 10 CFR 71.55(b)	0.9091	0.0009	0.9109	1	N/A
HAC per 10 CFR 71.55(e)	0.9092	0.0009	0.9110	1	N/A
NCT-Array per 10 CFR 71.59(a.1)	0.2154	0.0006	0.2166	Infinite	0
HAC- Array per 10 CFR 71.59(a.2)	0.9092	0.0009	0.9110	1	100

The model of the NAC-LWT was completed by modeling the CEUSP canister and stacking seven CEUSP canisters into the sleeve assembly, with three sleeves placed into the basket assembly. Material definitions employed in the MCNP model were primarily extracted from the SCALE material library, with the remaining material descriptions either calculated or obtained from reference calculations.

The maximum reactivity for the CEUSP canisters in the NAC-LWT was determined using the most reactive configuration. The most reactive configuration was found through a moderator density study (including preferential flooding), component shift study, can and basket component tolerance study, and fuel geometry perturbation study. The most reactive configuration was applied to the NCT and HAC conditions.

Upper safety limits were established in separate bias calculations. The CEUSP containers contain both highly enriched U-235 and U-233. The bias calculation for intermediate and highly enriched fuel (IEU and HEU) resulted in an upper subcritical limit (USL) of 0.9171 (minimum USL based on a correlation to the average neutron lethargy causing fission). The bias calculation for material containing U-233 resulted in an upper subcritical limit of 0.9303 (minimum USL based on a correlation to the average neutron lethargy causing fission) [6]. The minimum of the two USLs, 0.9171 were employed. The bias calculations included the ZAID libraries.

CEUSP fissile material and can/canister design input was taken from the CEUSP design input. The U_3O_8 content was documented to occupy approximately 50% of the can cavity. The tolerances for the can OD was provided as ±0.030 inches. In addition to U3O8, the can also had additional content. During the creation of the U_3O_8 monolith, Cd and Gd oxides were mixed into the material. Table 8 shows the mass limits used for absorbers (about (0.05 wt%) and other minor metallic impurities, which were reported as being 13.79 wt% of the overall content. The material was defined as "assumed to be carbon," which for a dry lattice presents a conservative element (neutron moderator) at carbon density.

Table 8. Mass Ratios for CEUSP Material Contents

ELEMENT	RATIO TO URANIUM CONTENT	OXIDE DENSITY (g/cm^3)
U	1	--
Cd (in CdO)	0.150	8.15
Gd (in Gd2O3)	0.176	7.14

All sleeve assembly materials are type 304 stainless steel. The tolerances provided for the specified pipe are -0.03 inches, +0.00 inches for the sleeve thickness and -1/32 inches, +1/16 inches for the sleeve outer diameter (OD). The basket assembly accommodates three sleeve assemblies, packaging a total of 21 CEUSP canisters. All basket assembly materials are type 304 stainless steel. The tolerances for the specified pipe are -0.032 inches, +0.00 inches for the pipe thickness

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The full density moderator was water at standard temperature and pressure (0.9982 g/cm^3). With a radioactive material payload producing thermal decay heat, this value represents a reasonable upper bound on density. Fissile material and structural materials were assumed to be at 293°K. Based on the fact that maximum reactivity is achieved in a moderated system, small temperature changes, not exceeding liquid moderator maximum temperatures will not affect system reactivity due to limited temperature cross-section broadening at these low temperatures. The NAC-LWT neutron shield was modeled as an ethyl-glycol/water mixture without boron because omission of boron increases cask-to-cask interaction in a cask array and is therefore conservative. An upper impact limiter density (0.4997 g/cc) was used for both upper and lower impact limiters. Cask exterior material composition, especially for neutron transparent materials such as the aluminum impact limiter, does not have any significant effect on system performance. The upper top disk was modeled identical to the two lower top disks because the upper top disk has an OD of 13.19 inches compared to the lower top disk OD of 13.27 inches. The wiper was not included in the model, because the additional material at the top of the basket assembly would not affect system reactivity.

The fissile material characteristics were modeled to provide a bounding fissile material description for the criticality evaluation. The U_3O_8 monolith geometry within the CEUSP canisters was modeled as a cylinder with an ellipsoid surface forming the top. The dimensions of the ellipsoid minor and major axes were assumed. The height of the ellipsoid center was then calculated using the assumed axes and fissile material volume derived from the modeled fissile material density and mass. The assumed geometry for the U_3O_8 monolith was evaluated for the maximum reactivity configuration. The meniscus/ellipsoid geometry was only used in the configuration where the CEUSP material occupies 50% of the can volume. Various configurations beyond the nominal meniscus/ellipsoid were modeled as simple cylinders.

In summary, a criticality evaluation for the CEUSP canisters in the NAC-LWT was performed. The transport package was determined compliant with 10 CFR 71.59 and 10 CFR 71.55. With a maximum reactivity of 0.9110, the package was subcritical. The evaluation consisted of a moderator density study, component shift study, can and basket component tolerance study, and fuel geometry perturbation study. The transport package was designated to have a CSI of 100.

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