SHIELDING EVALUATION OF THE ENSA ENUN 32P CASK FOR ZONAL LOADING

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This paper presents the shielding evaluation of the ENUN 32P transport/storage cask which allows zonal loading of the spent fuel contents subject to the dose rate limits for transportation. Zonal loading allows the loading of high burnup/shorter cooled spent fuel in the interior of the cask basket. Energy dependent zonal dose rate responses are computed for normal and accident cask transport configurations by MCNP Monte Carlo. The cask exterior total dose rate is computed by multiplying the energy dependent zonal responses by energy dependent zonal sources terms and summing the results. Fuel burnup and cooling time loading curves for each zone are specified which satisfy transport dose rate requirements for the ENUN 32P cask.

I. INTRODUCTION

This paper presents the shielding evaluations of the ENSA ENUN 32P (ENUN 32P) for zonal loading. Zonal loading is a cask loading scheme that allows higher burnup and/or shorter cooling time discharged fuel to be loaded in the interior and lower burnup and/or longer cooled fuel in the exterior. The advantage of this scheme is greater flexibility in handling fuel of higher burnup and shorter cooling time than would be allowed assuming all fuel is at the same discharge burnup.

The ENUN 32P is a metal storage/transport cask that can accommodate 32 PWR type spent fuel assemblies. The ENUN 32P cask comprises a solid steel cask body enclosed by inner and outer lids. The body is SA-350 low alloy carbon steel. The side of the body is surrounded by solid neutron shielding. The cask cavity contains an egg crate type basket which holds the 32 spent fuel assemblies, either Westinghouse 17x17 or KWU 16x16 spent fuel assemblies. The basket is held in place with aluminum rails which also transfer decay heat from the basket to the body.

In this evaluation, twelve fuel assemblies with up to 1.35 kW of decay heat are allowed in Zone 2 (Figure 1), the interior zone, and the allowable burnup and cooling time is determined for the exterior twenty fuel assemblies to meet the transport dose rate limits. The transport dose rate limits are specified for Normal Conditions of Transport in SSR-6 Section 573 and 10 CFR 71.47 and for Hypothetical Accident Conditions in SSR-6 Section 671 and 10 CFR 71.51 [1,2].

II. METHODOLOGY

The shielding methodology for the ENUN 32P cask comprises the following tasks:

1. Determination of radiation source terms and decay heat as a function of fuel assembly initial enrichment and discharge burnup.
2. Shielding evaluations of the cask as a function of discharge burnup and cooling time under normal conditions of transport and hypothetical accident conditions.
3. Determination of the burnup and cooling time combinations which satisfy the decay heat load limit for Zone 2, and the burnup and cooling time combinations which satisfy the transport regulatory dose rate limits for Zone 1 in combination with Zone 2.

The radiation source terms of the spent fuel as a function of fuel burnup and cooling time are computed with the SAS2H sequence of the SCALE4.4a code system [3,4]. Shielding evaluations are performed with the MCNP5 Monte Carlo code [5]. Dose rate responses are computed on an energy group basis for each zone in the zonal configuration. The total gamma or neutron dose rate from each zone for any burnup and cooling time combination is computed by multiplying the energy dependent dose rate responses by the energy spectrum at a particular burnup and cooling time and then summing.

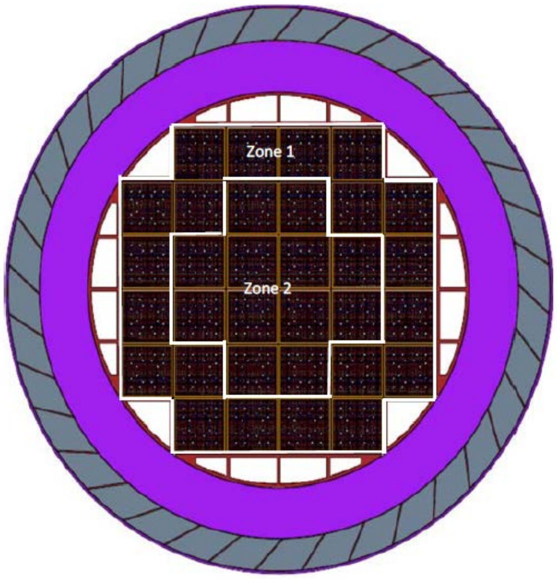

Figure 1 – ENUN 32P Zonal Loading Arrangement

II.A. Zonal Source Terms

The design basis source terms for zonal loading are based on 1) the maximum allowable decay heat load per assembly as determined by the cask thermal evaluations and 2) the maximum allowable decay heat load from fuel which satisfies the constraints of the cask shielding evaluations. By surrounding the 12 interior fuel assemblies of up to 1.35 kW fuel with up to 1.0 kW exterior fuel, the self-shielding of the exterior fuel with lower heat load/source terms should satisfy regulatory dose rate limits.

It is important to note that, while fuel assembly source terms correlate directly with decay heat, the behavior of individual components, i.e. fuel gamma, fuel neutron and activated hardware gamma exhibit non-linear behavior with burnup and cooling time. Thus, fuel at the same decay heat, but a different burnup and cooling time, will yield different dose rates, and parametric evaluations of the various burnup and cooling time combinations must be performed to demonstrate compliance with dose rate regulatory limits. In this evaluation, the burnup and cooling time (and associated heat load) in the Zone 1 fuel is varied until the dose rates are in compliance with regulatory requirements.

The source terms of the spent fuel in the ENUN 32P cask are computed using the SAS2H sequence of the SCALE4.4a code system [3,4]. Source terms databases of decay heat, neutron emission and gamma emission were created by performing SAS2H calculations spanning the burnup range from 15,000 to 70,000 MWd/MtU burnup and from 3 to 100 years cooling time. For the purposes of this evaluation, data up to 65,000 MWd/MtU burnup and up to 26.0 years cooling time is utilized.

Design basis source terms for the Zone 2 fuel assemblies are determined by plotting the decay heat versus cooling time for various discharge burnups, and then determining the corresponding cooling time which yields 1.35 kW per assembly. This is shown in Figure 2 for KWU 16x16 fuel and in Figure 3 for Westinghouse 17x17 fuel, and the results are given in Table 1 and Table 2.

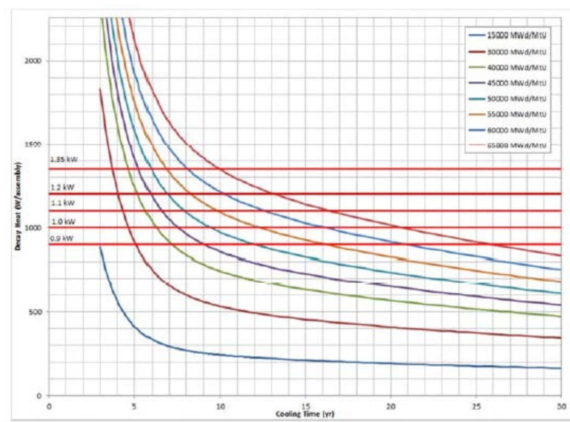

Figure 2 - Design Basis KWU 16x16 Fuel Assembly Decay Heat Characteristics

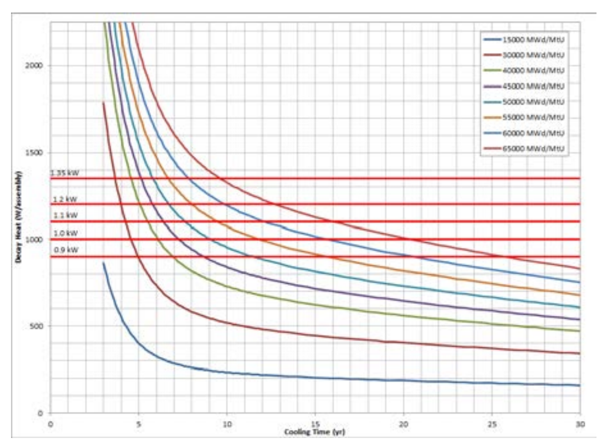

Figure 3 - Design Basis Westinghouse 17x17 Fuel Assembly Decay Heat Characteristics

Table 1 - Burnup and Cooling Time to Produce 1.35 kW per KWU 16x16 Assembly

Burnup (MWd/MtU)	Cooling Time (yr)
15000[1]	3.0
30000	3.8
40000	4.7
45000	5.3
50000	6.0
55000	6.9
60000	8.1
65000	10.0

Table 2 - Burnup and Cooling Time to Produce 1.35 kW per Westinghouse 17x17 Assembly

Burnup (MWd/MtU)	Cooling Time (yr)
15000	3.0
30000	3.7
40000	4.6
45000	5.2
50000	5.8
55000	6.7
60000	7.9
65000	9.7

II.B. Shielding Evaluations

MCNP5, release 1.40 [5], Monte Carlo transport is used to determine the dose rates. The ENDF/B-VI neutron cross section library, ENDF60, and the ENDF/B-VI Release 8 Photo-atomic Data gamma cross section library, MCPLIB04 are utilized in the transport computations.

The ENUN 32P shielding evaluation involves estimating the dose rate from four source terms:

1. Fuel gamma emission
2. Fuel neutron emission
3. Activated hardware gamma (^{60}Co) emission
4. N-Gamma emission

In addition, for each source term above, efficient calculation of dose rates on the exterior surface requires biasing in the radial and axial directions. In the situation of a cylindrical transport cask, the analysis involves at a minimum:

1. Radial biasing
2. Top axial biasing
3. Bottom axial biasing

Each biasing scheme is a numerical iteration involving multiple MCNP5 runs to optimize the figure of merit for a particular surface tally of interest. Mesh based weight windows variance reduction is implemented to improve tally statistics and figure of merit. A cylindrical weight windows mesh is superimposed over the geometry, and the tally on either the side, top or bottom surface of the cask is selected for figure of merit optimization.

For licensing a transport cask, shielding evaluations have to be performed for the cask configuration under:

1. Normal Conditions of Transport (NCT)
2. Hypothetical Accident Conditions (HAC)

For the NCT, the configuration includes the top and bottom impact limiters attached to the cask and intact neutron shielding. The X-Y and X-Z plots of the NCT MCNP model are shown in Figure 4 and Figure 5, respectively. For the HAC, it is conservatively assumed that the impact limiters are lost, even though they are designed to remain attached. This is a conservative assumption since their exact geometry is unknown and may be very deformed due to the 9 meter drop conditions. Also for the HAC, it is assumed that the neutron shielding material is completely lost due to the fire conditions; even though the material is fire resistant and a significant amount will remain. An X-Z plot of the HAC model is shown in Figure 6.

Tally surfaces are defined in the model on the surface of the cask, the personnel barrier and 2 meters from the edge of the transport vehicle for the NCT and at 1 meter from the surface for the HAC. These tally surfaces are segmented with horizontal planes for the side surfaces and cylinders for the top and bottom surfaces. ANSI/ANS-6.1.1-1977 [6] neutron and gamma flux-to-dose conversion factors are applied to the tallies.

Energy dependent dose rate tally responses from the Zone 1 and 2 of the basket are computed for each bias direction and each cask NCT and HAC configuration. The total dose rate for the two zones given fuel loading burnup and cooling time combination is calculated by post processing the MCNP calculated energy dependent dose responses (mrem/h/(particle-s-energy bin)), spectra, and total particle emission from the source term database files.

[1] 15,000 MWd/MtU burnup set to a minimum of 3 years discharge cooling.

The energy dependent dose rate for each tally segment is calculated as follows:

$$DR(E) = R(E) * EP(E) * S_T$$

Where,

DR(E) = Energy dependent dose rate (mrem/h)
R(E) = Energy dependent MCNP calculated response function (mrem/h/particle/s)
EP(E) = Energy dependent emission probability from source term database
S_t = Total source particle emission (particles/s/zone)

The source particle emission contributions from each zone are calculated based on the number of assemblies (12 or 20) in each zone.

The total dose rate from each source term component for each tally segment is the sum of the energy dependent dose rate responses over all energy bins.

$$DR = \sum_{1}^{n} DR(E)$$

Where,

DR = Total dose rate (mrem/h)
DR(E) = Energy dependent dose rate (mrem/h)
n = Number of energy bins

The total standard deviation is calculated by the square root of the sum of the squares because only simple addition is used for calculating total dose rates.

$$SD_t = \sqrt{{sd_1}^2 + {sd_2}^2 + {sd_3}^2 \ldots}$$

where sd_1 is the standard deviation from energy group 1, etc. Each component of the dose rate from fuel gamma, fuel hardware, fuel neutron and n-gamma is computed from each zone. The Zone 1 and 2 dose rate contributions are then added together to get the total dose rate for the cask.

The dose rate computations are performed for the worst case Zone 2 source terms, but varying the cooling time for the Zone 1 source terms at given burnup until an acceptable cooling time for Zone 1 is achieved. This must satisfy dose rate requirements for NCT or HAC conditions. Typically, the NCT condition of 0.1 mSv/h at 2 meters from the edge of the transport vehicle is the bounding condition.

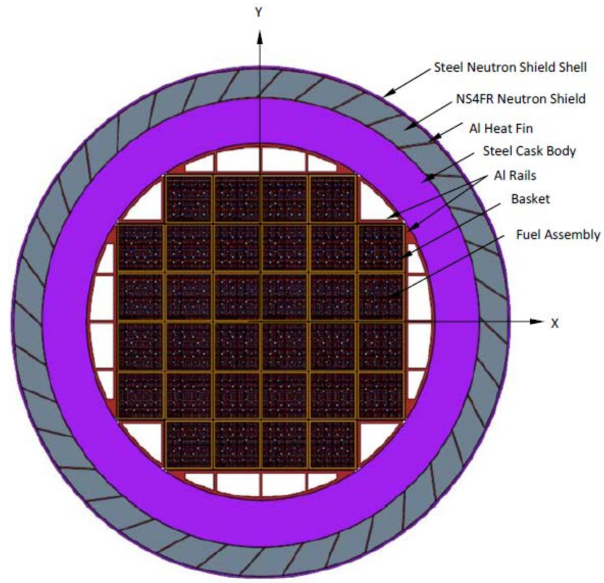

Figure 4 - X-Y VISED Plot of ENUN 32P NCT MCNP5 Model

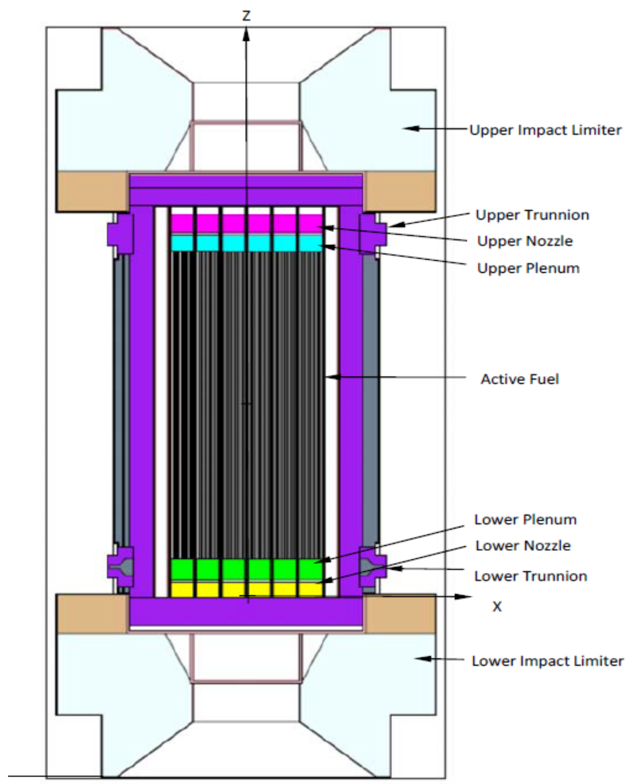

Figure 5 - X-Z VISED Plot of ENUN 32P NCT MCNP5 Model

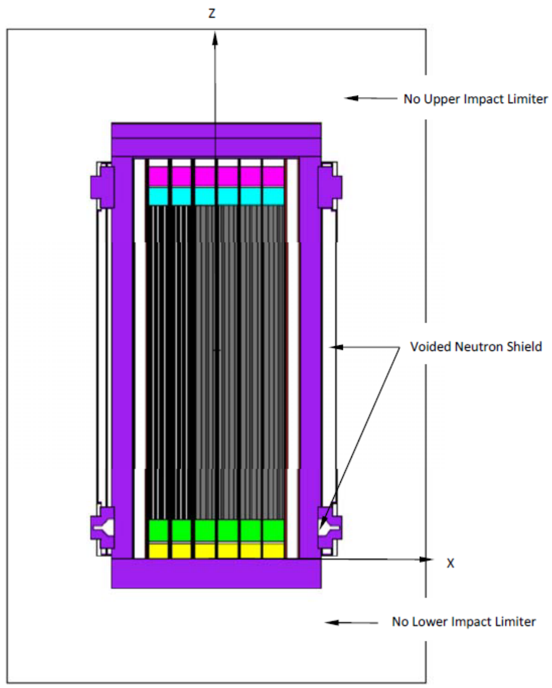

Figure 6 - X-Z VISED Plot of ENUN 32P HAC MCNP5 Model

III. RESULTS AND DISCUSSION

For zonal loading, a Zone 2 burnup cooling time loading curve is established which limits the Zone 2 heat load to a maximum of 1.35 kW per assembly (See Figure 7 for KWU fuel and Figure 8 for Westinghouse 17x17). The most limiting case for Zone 2 is the situation where 65,000 MWd/MtU burnup and 1.35 kW decay heat is loaded (10 year cooled fuel for KWU and 9.7 year cooled fuel for Westinghouse 17x17). This condition will have the highest neutron source term possible for Zone 2. Thus, in the evaluations that follow, the Zone 2 source term characteristics are set to the maximum burnup/cooling time value, and Zone 1 is varied in burnup and cooling time until acceptable dose rates are achieved for the limit at 2 meters from the edge of the railcar. The evaluations conservatively set the acceptable dose rate at 2 meters from the edge of the transport vehicle to 0.09 mSv/h (9 mrem/h) to allow for various methodology and mechanical uncertainties in comparison to the regulatory limit of 0.10 mSv/h.

Given the source terms in Zone 2 for up to 1.35 kW of decay heat, the allowable burnup and cooling time for Zone 1 is shown in Figure 9 for KWU 16x16 fuel and Figure 10 for Westinghouse 17x17 fuel. Fuel with discharge burnups of 45,000 to 55,000 MWd/MtU require between 10 and 13 years of cooling time for KWU fuel and between 8 and 12 years of cooling time for Westinghouse 17x17 in order to be placed in Zone 1.

The typical split in Zone 1 and Zone 2 contributions to exterior dose rates is shown in Table 3 for the maximum dose rate at two meters from the edge of the transport vehicle. In this case, Zone 2 has 12 fuel assemblies at 65,000 MWd/MtU burnup, 9.7 years cooling and Zone 1 has 20 assemblies at 50,000 MWd/MtU burnup, 9.1 years cooling. The table shows that ~83% of the total dose rate is from the Zone 1 fuel. Also, the interior fuel and hardware gamma contribution is almost entirely self-shielded by the exterior fuel, but ~30% of the n-gamma and neutron dose comes from the interior.

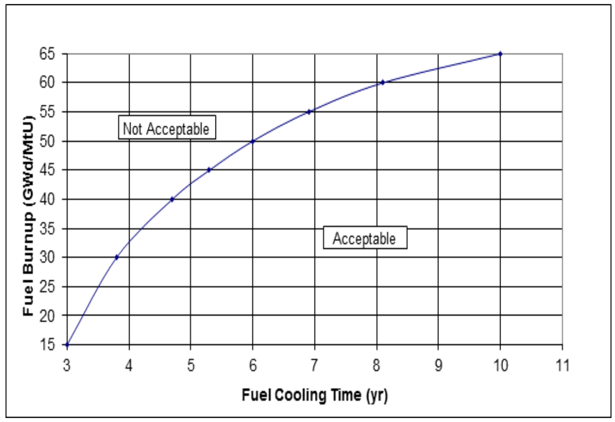

Figure 7 - ENUN 32P Burnup and Cooling Time Loading Curve for Zonal Loading - Zone 2 – KWU

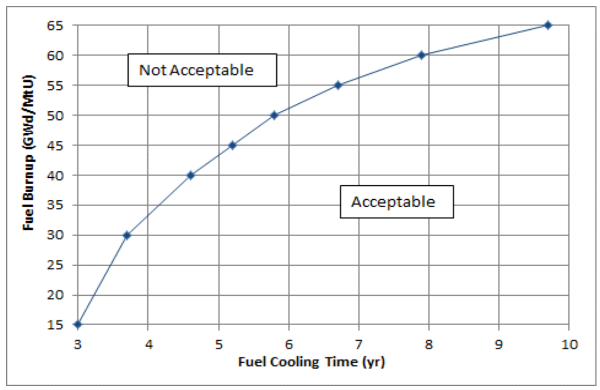

Figure 8 - ENUN 32P Burnup and Cooling Time Loading Curve for Zonal Loading - Zone 2 – Westinghouse 17x17

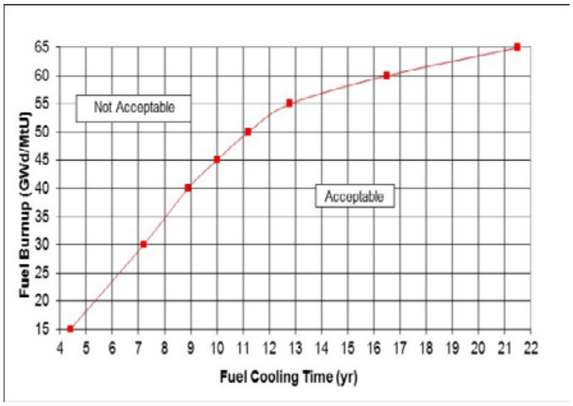

Figure 9 - ENUN 32P Burnup and Cooling Time Loading Curve for Zonal Loading - Zone 1 - KWU

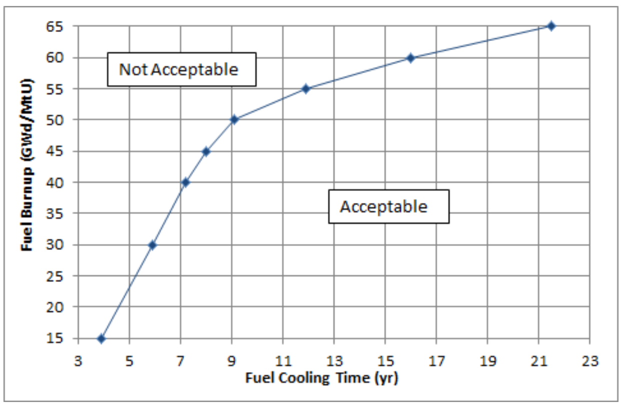

Figure 10 - ENUN 32P Burnup and Cooling Time Loading Curve for Zonal Loading - Zone 1 – Westinghouse 17x17

Table 3 – Maximum Dose Rate at 2 Meters from Edge of Transport Vehicle

	Fuel Gamma	N-Gamma	Hardware Gamma	Fuel Neutron	Total
Zone 2	0.0002	0.0053	0.0006	0.0093	0.0153
Zone 1	0.0375	0.0101	0.0072	0.0179	0.0727
Total	0.0377	0.0154	0.0078	0.0272	0.0880

IV. CONCLUSIONS

A zonal loading scheme was developed for the ENUN-32P allowing up to a maximum of 1.35 kW per assembly in the interior shielded by lower burnup or longer cooled fuel on the exterior of the basket. A generic shielding analysis methodology was employed which utilized MCNP computed energy dependent dose rate tally responses from the interior and exterior zones of the basket. The total dose rate under NCT or HAC for the two zones given any fuel burnup and cooling time combination was calculated by post processing the calculated energy dependent dose responses, source term spectra, and total particle emission. Comparison of the total dose rate with the regulatory limits defined an acceptable loading curve for the exterior zone.

REFERENCES

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2. 10 CFR 71, Packaging and Transport of Radioactive Materials.
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5. "MCNP/MCNPX Monte Carlo N-Particle Transport Code System Including MCNP5 1.40 and MCNPX 2.5.0 and Data Libraries," RSICC Code Package CCC-730, January 2006.
6. ANSI/ANS 6.1.1-1977, Neutron and Gamma Flux-To-Dose Conversion Factors.