

Heat-Load-Normalized Thermal Screening and Pool-Capacity Planning for BeO-Centered Spent Fuel from a 140 MWe SMR

Se Yup Lee*

KONEC (Korea Nuclear Engineering Ltd), Seoul, Republic of Korea

*Corresponding author: edgelee@naver.com

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1. Introduction

Improved internal fuel conduction is not evidence of reduced radioactive decay power or earlier eligibility for dry storage. This study therefore treats the absence of a demonstrated transfer-time benefit as the main finding, rather than extrapolating an operating-temperature improvement to multi-year storage. It examines BeO-centered annular fuel for a conceptual 450 MWth / 140 MWe SMR using imposed heat loads, an explicit resistance model, and a discrete pool-inventory calculation.

Storage decisions require distinct thermal, fuel-condition, criticality, shielding and confinement assessments [1,4–6]. No depletion, criticality or cask-temperature calculation is claimed here. The contribution is the reproducible application of heat-load normalization and transfer-delay accounting to the stated fuel concept, not a new decay-heat correlation or a demonstration of fuel qualification.

2. Heat-Load-Normalized Model

2.1 Declared assumptions and comparison basis

The geometry follows the companion fuel-concept manuscript [7]. Table 1 reproduces the inputs needed here; they are conceptual design assumptions, not qualified irradiated-fuel data. The burnup and enrichment identify the intended fuel but do not determine its decay heat in this study.

Table 1. Design assumptions and sensitivity inputs.

Quantity	Value / status
Core / discharged batch	69 / 23 assemblies
Rods per assembly / active length	236 / 2.40 m
Core uranium / discharge burnup	17.029 tU / 50.40 GWd/tU
Initial ²³⁵ U enrichment	5.00 wt. %
Pellet / bore / BeO diameters	8.192 / 2.640 / 2.590 mm
Reference UO ₂ conductivity, k	2.2 W/(m·K); assumed
Gap coefficient, h _g	20, 100, 500 W/(m ² ·K)
Effective bridge, G	0, 0.10, 0.20 W/K; assumed

For a batch heat Q_b in kW, the representative rod heat q in W is

$$q = 1000FQ_b / (23 \times 236). \quad (1)$$

$F = 1$ gives the uniform average; $F = 2$ is a local peaking sensitivity, not a licensed bound or a multiplier for every rod simultaneously. All heat is assigned to rods. Hardware heating, gamma-energy redistribution and axial peaking are not resolved. The solid and annular rods are compared at equal q and identical external boundary conditions, not equal uranium mass or irradiation history.

2.2 Conduction and effective bridge network

For uniform volumetric heating q''' , constant k , an adiabatic bore of radius a , and a fixed outer surface of radius R , integrating the radial heat equation gives $T(r) - T(R) = q'''[R^2 - r^2 + 2a^2 \ln(r/R)]/(4k)$. Evaluating at $r = a$ and dividing by $q = \pi(R^2 - a^2)Lq'''$ yields

$$f = (a/R)^2, \quad \psi = 1 + f \ln(f)/(1 - f), \quad (2)$$

$$R_{r,s} = 1/(4\pi kL), \quad R_{r,a} = \psi R_{r,s}.$$

Here $a = 1.320$ mm, $R = 4.096$ mm and $L = 2.40$ m. Thus $f = 0.103855$, $\psi = 0.737535$, $R_{r,s} = 0.0150715$ K/W and $R_{r,a} = 0.0111158$ K/W. The no-bridge annular result is a geometry effect; it is not a measured BeO-conductivity benefit.

$$R_g = 1/(h_g \pi D_p L), \quad (3)$$

$$R_s = R_{r,s} + R_g, \quad R_a = R_{r,a} + R_g.$$

An optional lumped bridge G connects the hot-fuel node to the cladding node in parallel with the entire annular fuel-plus-gap path. It is not added only across the gap. Its positive values in Table 1 are independent sensitivity parameters, not measured or reconstructed spoke conductances. $G = 0$ assigns no bridge credit.

$$R_{a,G} = R_a/(1 + GR_a), \quad (4)$$

$$S_T = R_s - R_{a,G}, \quad \Delta T_{\text{fuel}} = qS_T.$$

S_T is the heat-load-normalized temperature reduction. For $G = 0$, $S_T = 0.00395574$ K/W at every h_g . For $G > 0$, this is an effective-node model, not a resolved prediction of pellet, BeO and discrete spoke temperatures. Contact state, irradiation damage and temperature-dependent properties require separate characterization.

2.3 Internal temperature versus cladding temperature

Let R_{ext} represent the common path from the cladding node to the heat sink. Steady-state energy balance gives

$$T_{\text{clad}} - T_{\infty} = qR_{\text{ext}}. \quad (5)$$

Changing only internal G changes the fuel-node temperature but not Eq. (5). This statement applies to the fixed-source lumped model, not to three-dimensional

cask hot spots. Neither a cask peak cladding temperature (PCT) nor a PCT safety margin follows from ΔT_{fuel} .

3. Conditional Results and Pool Planning

3.1 Heat-load-normalized thermal sensitivity

At $Q_b = 40$ kW and $F = 1$, $q = 7.3692$ W. Table 2 can be rescaled by $FQ_b/40$ without assigning a cooling age. The conductance grid is not a confidence interval or an irradiated-fuel bound.

Table 2. Conditional fuel-node reduction at 40 kW, $F = 1$.

h_g W/(m ² ·K)	G W/K	S_T K/W	ΔT_{fuel} K
20	0.00	0.003956	0.029
20	0.10	0.066190	0.488
20	0.20	0.119651	0.882
100	0.00	0.003956	0.029
100	0.10	0.006898	0.051
100	0.20	0.009742	0.072
500	0.00	0.003956	0.029
500	0.10	0.004144	0.031
500	0.20	0.004331	0.032

The largest value within this grid is 0.882 K, increasing to 1.763 K for $F = 2$. With no bridge credit, the reduction is 0.029 K. These are conditional results, not the former one-year or five-year predictions. As G tends to infinity, Eq. (4) instead permits a 6.076 K limiting reduction at $h_g = 20$ W/(m²·K), $Q_b = 40$ kW and $F = 1$. Consequently, a universal sub-kelvin bound is not asserted. Even that idealized limit supplies no reduction in total decay power or Eq. (5).

3.2 Heat-acceptance envelopes without cooling-age claims

One discharged batch contains $17.029(23/69) = 5.67633$ tU. Table 3 converts hypothetical total heat budgets into average assembly, rod and mass-normalized limits. These are arithmetic acceptance envelopes, not ratings of a selected or certified cask.

Table 3. Hypothetical total-heat acceptance envelopes.

Total kW	Average kW/assembly	Average W/rod	Specific W/kgU
20	0.870	3.685	3.523
25	1.087	4.606	4.404
40	1.739	7.369	7.047

Assembly-by-assembly and basket-zone limits remain necessary; a compliant average is not sufficient. A future validated source calculation must establish an upper heat estimate $Q_{\text{upper}}(t)$, including method bias and applicable uncertainties [2,3]. The thermal-only crossing is then defined, but not evaluated here, by

$$t_Q = \inf \{t : Q_{\text{upper}}(t) \leq Q_{\text{limit}}\}. \quad (6)$$

No 15% multiplier, burnup-proportional source reduction, or age-dependent heat table is used. $Q_{\text{upper}}(t)$ is not supplied by this paper. Equation (6) cannot establish an operating permission, even after a source model becomes available.

3.3 Batch inventory and transfer delay

Assume a 23-assembly discharge every $\tau = 22$ months, a hypothetical cooling requirement t_c , and an additional transfer delay δ . Maintain 69 empty full-core-offload positions and six inspection/damaged-fuel positions in addition to the accumulated spent fuel. With removal before a coincident new discharge,

$$n_b = \lceil (t_c + \delta)/22 \rceil, \quad (7)$$

$$N_{\text{pool}} = 69 + 6 + 23n_b.$$

Table 4. Inventory scenarios; no transfer eligibility implied.

t_c months	δ months	Batches	Spent assemblies	Total positions
36	0	2	46	121
36	12	3	69	144
60	0	3	69	144
60	12	4	92	167

Thus the 36-month scenario requires 121, not 120, positions when all six special positions are retained. The reduction from 144 to 121 is 23 positions (16.0%), before rack-module and layout constraints. A 12-month delay removes this reduction or increases the 60-month case to 167 positions. The respective delay allowances before another batch accumulates are 8 and 6 months, subject to the stated event ordering.

At an exact multiple of 22 months, a discharge preceding removal temporarily adds one batch. The 36- and 60-month cases are planning assumptions only; neither is established as a qualified cooling period. Pool heat-removal capacity, shielding depth, structural design and rack criticality are not derived from a position count.

4. Qualification Boundary and Conclusions

4.1 Evidence required before a transfer decision

An acceptable source model must treat the actual enrichment, irradiation history, spectrum and material configuration, including BeO, with applicable validation and uncertainty evidence [2,3]. No existing LWR validation is assumed automatically applicable to this fuel. Unborated-pool and flooded-cask criticality, optimum moderation, absorber degradation and misloading remain unresolved. No k_{eff} or subcriticality margin is reported.

Cask-specific thermal performance, drying transients, confinement, shielding and accident behavior must also be established [4]. High-burnup cladding behavior depends on temperature, rod pressure and material condition [5]. The U.S. cask-content requirements distinguish cooling time, heat load, enrichment, burnup

and fuel condition [6]. These references provide technical context, not a determination of Korean licensing compliance. Internal fuel cooling cannot substitute for any of these independent demonstrations.

4.2 Conclusions

The imposed-heat calculation is self-contained and does not depend on an unidentified decay-heat table or unpublished rated spoke conductance. Within the declared grid, the largest 40 kW, uniform-average fuel-node reduction is 0.882 K, with no cladding-temperature or transfer-time credit. The discrete inventory calculation requires 121 or 144 positions for the 36- or 60-month no-delay scenarios, and shows why transfer delays must be included. These conditional results support planning and identify limits of thermal arguments; they do not establish safe storage or earlier dry transfer.

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