

Thermal, Fuel-Cycle, and Qualification Assessment of a Bare-BeO-Centered Annular UO₂ Fuel Rod with Cladding-Contacting Round Zr-Nb Spokes for a 140 MWe SMR

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1. Introduction

An annular UO₂ fuel rod with an unclad BeO center rod and round Zr-Nb spokes is considered for a 450 MWth / 140 MWe natural-circulation SMR. This skewer-type architecture is a research concept, not a qualified fuel design. The present assessment separates an analytical geometry effect, a conditional wire heat path, helium-pressure sensitivity, and unresolved mechanical requirements. “Qualification assessment” denotes identification of the necessary evidence, not completed qualification.

2. Architecture and Input Basis

The BeO member passes axially through the pellet bores. Two opposing radial wire arms at each pellet interface occupy shallow face grooves; their outer ends contact, but are not welded to, the cladding inner surface. Adjacent interfaces may be rotated by 90°. Centering and anti-rotation are intended functions only. End supports must carry pellet-stack loads without relying on an unbroken BeO column.

Table I: Nominal geometry and assigned inputs

Quantity	Value
Pellet OD / bore ID	8.192 / 2.640 mm
Bare BeO OD	2.590 mm
Cladding OD / wall	9.50 / 0.57 mm
Cladding ID	8.36 mm
Active length / pellet pitch	2.40 m / 10 mm
Interfaces / total arms	239 / 478
Wire diameter / arm length	0.300 / 2.885 mm
Wire k / nominal contact h	16 W/(m·K) / 10 ⁴ W/(m ² ·K)
Thermal benchmark q' / k _f	25 kW/m / 3 W/(m·K)
Fuel surface T _s / wire node T _c	400 / 350 °C

The bore and BeO diameters imply a 25 μm nominal radial clearance. The former dimensional targets, bore ±5 μm and BeO +0/-5 μm, imply 22.5–30 μm before ovality, straightness and surface defects. They are not demonstrated production tolerances. Assembly yield and chipping require measurement.

3. Component-Resolved Thermal Screening

3.1 Equal-power annular benchmark

Compare a solid pellet (A) with an annulus having an adiabatic bore (B), at equal linear power q', outer radius R, constant UO₂ conductivity k_f, and prescribed outer fuel-surface temperature T_s. The annulus therefore has higher volumetric heating, not equal volumetric heating. With bore radius a, define

$$\Delta T_{\text{solid}} = q' / (4\pi k_f), \quad f = (a/R)^2, \\ F = 1 + f \ln(f) / (1 - f). \quad (1)$$

$$\Delta T_{\text{ann}} = F \Delta T_{\text{solid}}. \quad (2)$$

For a = 1.320 mm and R = 4.096 mm, f = 0.1038551 and F = 0.7375349. The ideal maximum-to-surface temperature rise is reduced by 26.2465%. This is not a 26.25% reduction in absolute fuel temperature. The maximum is at the bore, not at the rod axis where no UO₂ exists.

The assigned Table I benchmark gives T_{max,A} = 1063.15 °C and T_{max,B} = 889.09 °C, a 174.05 K difference. The selected k_f = 3 W/(m·K) is illustrative; it is not a fitted irradiation-dependent property. Real conductivity and gap behavior require temperature-, burnup- and microstructure-dependent treatment [6].

3.2 BeO without a heat sink

Case C adds an unheated BeO center rod to B, but retains axial uniformity and no axial heat sink. A finite, source-free cylindrical center with zero axial heat removal has zero net radial heat flow at steady state. Thus C and B have the same UO₂ temperature in this model, irrespective of finite BeO conductivity. High conductivity alone does not create a heat sink.

The incremental BeO-only credit is therefore 0 K within this restricted benchmark, not zero in every physical condition. BeO nuclear heating, neutron-spectrum effects, axial spreading and transient heat capacity are excluded. A measured-conductivity, three-dimensional comparison is needed to isolate BeO–wire interactions; the present calculation does not supply that evidence.

3.3 Reproducible spoke-network calculation

Case D connects the bore hot node to the prescribed cladding-contact node T_c through $N = 478$ identical arms. Each arm has area $A_w = \pi d_w^2/4 = 7.0686 \times 10^{-8} \text{ m}^2$ and length $L_w = (8.360 - 2.590)/2 = 2.885 \text{ mm}$. Two equal end contacts are assigned area A_w and conductance coefficient h . These areas and h are assumptions, not measured contact properties.

$$G = N / [L_w/(k_w A_w) + 2/(h A_w)],$$

$$Q_{\text{wire}} = G (T_{\text{hot}} - T_c). \quad (3)$$

With $h = 10^4 \text{ W/(m}^2\cdot\text{K)}$, $G = 0.088842 \text{ W/K}$. The former imposed 550 K difference gives 48.863 W/rod; removing both contact resistances gives 103.062 W/rod. These reproduce the earlier approximately 48.9 and 103.0 W values. They are network estimates, not measurements.

To calculate a temperature increment rather than only bypass power, spread the wire extraction uniformly along active length H and around the bore. Set $q_i = Q_{\text{wire}}/H$ and $q_v = q_i' / [\pi(R^2 - a^2)]$. With the same T_s as in A–C, the radial solution is

$$T(r) - T_s = q_v(R^2 - r^2)/(4k_f) - [q_v a^2/(2k_f) + q_i/(2\pi k_i)] \ln(R/r). \quad (4)$$

Setting $T_{\text{hot}} = T(a)$ closes the assigned network:

$$Q_{\text{wire}} = G [T_s - T_c + \Delta T_{\text{ann}}] / [1 + G \ln(R/a)/(2\pi k_f H)]. \quad (5)$$

$$r_{\text{max}}^2 = a^2 + q_i/(\pi q_v). \quad (6)$$

Equation (6) applies while $a \leq r_{\text{max}} \leq R$. The nominal case gives $Q_{\text{wire}} = 47.788 \text{ W}$ and $T_{\text{max}} = 887.90 \text{ }^\circ\text{C}$. The small change from 48.863 W follows from using the calculated hot-node temperature instead of an imposed 550 K difference. Only arithmetic, heat-balance and independent numerical-integration checks were performed.

3.4 Attribution and sensitivity

Table II: Paired thermal comparisons at Table I conditions

Case	T_{max} ($^\circ\text{C}$)	Incremental reduction (K)
A: solid UO_2	1063.15	Reference
B: annular UO_2	889.09	174.05 vs. A
C: B + BeO, no sink	889.09	0.00 vs. B
D: C + nominal wires	887.90	1.19 vs. C

Thus the demonstrated analytical contribution is primarily annular geometry. The added wire-path effect is approximately 1.19 K only in the specified smeared model. It is not a demonstrated increment attributable to the actual BeO conductivity. The combined A-to-D difference is 175.25 K.

Table III: Assigned contact-conductance sensitivity

h $\text{W/(m}^2\cdot\text{K)}$	Q_{wire} (W/rod)	Extra drop vs. C (K)
0 (disconnected)	0.00	0.00
10^3	8.35	0.21
10^4	47.79	1.19
10^5	90.55	2.26
∞ (no contact loss)	100.55	2.51

The benchmark rod power is $q'H = 60 \text{ kW}$; nominal bypass is 0.07965% of that power. It redirects existing heat to the cladding and does not increase total fuel-rod heat-removal capacity. The earlier 0.098% used a separate 50 kW denominator and must not be mixed with this 60 kW case.

Case D assumes no additional UO_2 -to-hot-node gap or BeO spreading resistance beyond the stated network. It neglects wire-side heat pickup, discrete interface cooling, local contact heat flux and circumferential hot spots. The ∞ row is a limiting case of this network only, not a validated upper bound for the actual three-dimensional rod.

A disconnected network returns the ideal temperature field to C; that does not establish safe behavior of broken wires or BeO. Fragment relocation, cladding damage, gas-path blockage and altered geometry are outside this calculation. No DNBR, accident-tolerance, irradiation or licensing credit is assigned.

4. BeO Selection and Failure Envelope

4.1 Selection rationale and fracture

BeO is retained as a candidate because it combines a hydrogen-free solid moderator with high intrinsic unirradiated thermal conductivity [1]. The bare arrangement avoids a separate central metal sleeve and its additional material/interface; this geometric simplification is not proof of a net performance advantage. The 26.25% annular benchmark does not justify BeO selection by itself. Annular-only and sleeved-center alternatives remain necessary comparators; no overall material ranking is established.

Irradiation experiments and mechanistic studies document conductivity degradation, dimensional change and cracking in BeO [2,3]. Therefore continuity of the center rod is not credited as a safety-significant structural support. Qualification must address thermal-gradient fracture, swelling, fragment migration, eccentricity, UO_2/BeO /wire compatibility and loss of gas communication. Pellet/end-support load paths and fragment retention remain to be demonstrated. Segmentation or a containment sleeve would be separately evaluated design changes, not features already incorporated.

4.2 Helium generation, retention and pressure

Distinguish generated helium from helium released into the communicating rod free volume. Let Y be generated He atoms per million initial Be atoms, f_{rel} the release fraction, m_{BeO} the BeO mass, and M_{BeO} its molar mass. An ideal-gas pressure normalization is

$$\begin{aligned} n_{\text{He,gas}} &= (m_{\text{BeO}}/M_{\text{BeO}}) Y \times 10^{-6} f_{\text{rel}}, \\ \Delta p_{\text{He}} &= n_{\text{He,gas}} R_g T_g / V_{\text{free}}. \end{aligned} \quad (7)$$

For assigned density 3.00 g/cm^3 , diameter 2.590 mm and $H = 2.40 \text{ m}$, $m_{\text{BeO}} = 37.933 \text{ g}$. Taking $M_{\text{BeO}} = 25.0112 \text{ g/mol}$, $T_g = 600 \text{ K}$ and $V_{\text{free}} = 10 \text{ cm}^3$ gives $\Delta p_{\text{He}} = 0.7566 (Y/1000) f_{\text{rel}} \text{ MPa}$. At complete release, $Y = 100, 1000$ and 10000 give $0.0757, 0.7566$ and 7.566 MPa , respectively. These Y values are sensitivity inputs, not predicted irradiation yields.

Retained helium can contribute to material degradation even when its gas-pressure contribution is zero. Actual pressure requires spectrum/fluence-dependent production, release kinetics, initial fill gas, fission gas, evolving free volume and temperature. No rod-pressure margin or adequate plenum volume is established here.

5. Wire Contact and Irradiation Risks

The wire-cladding interface introduces a failure mechanism absent from the annular-only benchmark. Differential expansion of the hotter wire, fuel relocation, BeO swelling, cladding creep and irradiation growth can alter interference and contact force. A common Zr-Nb alloy designation does not establish common performance for a drawn wire and a cladding tube with different texture, processing and temperature histories.

For an initial mechanical screen, let $\delta(t)$ be net normal interference after all component displacements and initial clearances, and k_{eff} the effective local contact-system stiffness. Then

$$F_n(t) = k_{\text{eff}}(t) \max[\delta(t), 0]. \quad (8)$$

This equation defines the required coupling; it is not a calculated stress result. Contact curvature, actual contact area, friction, elastoplastic response, wire bending and creep must be resolved to obtain local cladding stress and strain. F_n divided by nominal wire area would only be an assumed average pressure, not a peak contact stress.

Non-welded sliding ends may reduce axial restraint but do not eliminate normal force, frictional work or fretting. External grid-to-rod experiments demonstrate sensitivity to loading and environment [4]; their water-side wear coefficients cannot be transferred directly to a wire rubbing inside a helium/fission-gas-filled rod. Representative internal-contact tests are necessary.

High-temperature and irradiation assessments must cover creep, stress relaxation, irradiation growth, loss of ductility, cyclic plasticity, fatigue and possible wire separation. Irradiation may also harden an alloy; a blanket assumption of strength loss is inappropriate. The wire hot end can approach the fuel-bore temperature, so coolant or cladding temperature cannot be used for the entire wire. Thermal conductivity assumptions in Section 3 provide no mechanical-strength qualification [6].

The proposed design requirements are bounded contact force over life, no unacceptable cladding indentation or wear, retained broken-wire/BeO fragments, preserved gas communication, and acceptable consequences of loss of centering. Groove capture alone has not demonstrated these requirements. A compliant terminal geometry or larger contact pad is only a candidate mitigation until its contact, neutronic and manufacturing effects are assessed.

No new contact finite-element analysis, creep-life calculation, vibration test or irradiation test is reported. Accordingly, the earlier wording that treated centering, vibration restraint and anti-rotation as demonstrated benefits has been replaced by intended-function language. The concept cannot be judged mechanically acceptable from its small bypass power.

6. Fuel-Cycle Accounting and Qualification

6.1 Geometry is not neutronic cycle closure

The nominal BeO area fraction is $(2.590/8.192)^2 = 9.99585\%$; the bore-only UO_2 displacement is $(2.640/8.192)^2 = 10.38551\%$. The former 10.4779% included a groove correction whose detailed volume was not specified; that combined value is not used as an independently established result. The 2.590 mm diameter is a constrained nominal choice, not a demonstrated neutronic optimum.

Retain 17.029 tU as an inherited inventory input, not a new mass measurement. For 69 assemblies, 23 assemblies per reload, 95% capacity factor and a 365-day year, the equilibrium equal-batch bookkeeping is

$$\begin{aligned} E_{\text{cycle}} &= 0.450 \times 0.95 \times 365 \times (\tau/12) \text{ GWd}, \\ B_{\text{dis}} &= n_{\text{batch}} E_{\text{cycle}} / 17.029. \end{aligned} \quad (9)$$

At $\tau = 22$ months and $n_{\text{batch}} = 3$, $E_{\text{cycle}} = 286.069$ GWd and $B_{\text{dis}} = 50.397$ GWd/tU. A four-batch, 16.5-month scenario has the same nominal discharge exposure. Neither proves that 5.00 wt.% enrichment sustains the cycle. Lattice/full-core depletion, leakage, power shape, shutdown margin and thermal limits remain necessary. The previous inferred critical-enrichment and cost-saving results are not retained.

6.2 Evidence required before design credit

Table IV: Uncompleted qualification gates

Gate	Required evidence / decision
Manufacture	Bore/rod straightness, groove dimensions, assembly yield and BeO contamination control.
Thermal/contact	Measured contact conductance and 3-D temperature fields; bound irradiation degradation.
Mechanical	Contact-force evolution, cladding wear/strain and retained fragments under cycling and vibration.
Irradiation	Spectrum-specific He release, swelling, wire creep and post-irradiation examination.
Integrated fuel	Validated coupled fuel performance, core depletion and lead-test qualification.

NUREG-2246 provides a useful technical framework connecting manufacturing parameters, performance envelopes, tests and evaluation models [5]. It is cited as a qualification framework, not as a finding of Korean regulatory compliance. Numerical acceptance limits must be justified for the final materials, irradiation history and plant; no generic stress or wear limit is invented here.

7. Conclusions

At equal linear power and prescribed fuel-surface temperature, the ideal annular geometry reduces the peak-to-surface rise by 26.2465%. In the source-free, axially uniform benchmark, BeO without a heat sink adds no steady radial cooling. The nominal wire network reproduces 48.863 W at an imposed 550 K difference and gives 47.788 W and an additional 1.19 K peak reduction when coupled to the stated smeared model.

These calculations separate supported analytical results from design intentions. They do not establish an actual irradiated BeO conductivity benefit, mechanical integrity, pressure margin, neutronic cycle length or economic saving. BeO and wire risks are retained explicitly rather than dismissed by the temperature benchmark. The concept remains a candidate for a staged qualification program, with final acceptability dependent on the uncompleted evidence in Table IV.

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