Neutronic and Economic Assessment of Reusing HALEU Fuel Salt from a Long-Life Marine MSR

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1. Introduction

A lifetime-core marine molten salt reactor (MSR) requires a large initial fissile inventory because refueling and salt handling at sea are difficult. A fast-spectrum core may therefore use high-assay low-enriched uranium (HALEU) close to 20 wt% U-235. In this study, the reactor service life is 30 calendar years and the depletion target is 25 effective full-power years (EFPY), corresponding to an average equivalent full-power factor of 83.3%.

Reaching the marine reactor service-life limit does not mean that the circulating salt has exhausted its fissile value. Residual U-235 and bred plutonium may displace part of the fresh HALEU required by a land-based MSR, which is relevant because HALEU availability and front-end fuel-cycle cost remain deployment constraints [2-4]. The previous screening study identified this opportunity from the marine end-of-life (EOL) inventory but treated the BeO-reflected reuse core as future work.

The present update performs that second-stage Serpent depletion calculation. The 25-EFPY EOL salt is loaded into the same core geometry, the 49 MgO reflector cells are changed to BeO, and the reuse core is depleted for 20 additional EFPY. The resulting cycle length is then used to replace the full-life avoided-fuel-cost upper bound with a one-batch, 60-year life-average LCOE estimate.

2. Analysis Methodology

2.1 Two-stage depletion model

The marine reference system is a 100-MWth fast-spectrum MSR with NaCl-KCl-based fuel salt, 19.75 wt% initial U-235 enrichment, 21.423 t of uranium, a uniform temperature of 853 K, and an MgO reflector. Serpent 2.1.29 with ENDF/B-VIII.0 nuclear data was used [1]. Marine depletion was calculated at 5-EFPY intervals to 25 EFPY with all control drums at the maximum-reactivity OUT position.

For the reuse calculation, the isotope composition at 9,125 full-power days was transferred without cooling, fission-product removal, salt adjustment, or actinide loss. The geometry and 100-MWth power were retained, while all 49 MgO cells were replaced by 2.85-g/cm3 BeO at 853 K. Only the fuel was burnable; BeO and B4C were fixed. Four 5-EFPY depletion steps were calculated to 20 additional EFPY.

The reusable cycle was estimated as the point where maximum-reactivity k_eff reaches 1.0. Linear interpolation was applied between the 15- and 20-EFPY results. This interpolation is suitable for economic screening, but a final cycle definition requires 0.5-1-EFPY steps near the crossing.

Table I: Two-stage Serpent calculation boundary

Parameter	Marine stage	Reuse stage
Operation	25 EFPY	0-20 EFPY
Reflector	MgO	49 cells BeO
Power / temperature	100 MWth / 853 K	100 MWth / 853 K
Fuel treatment	Depletion	Direct restart
Control / fixed materials	Drums OUT	Drums OUT / BeO+B4C fixed

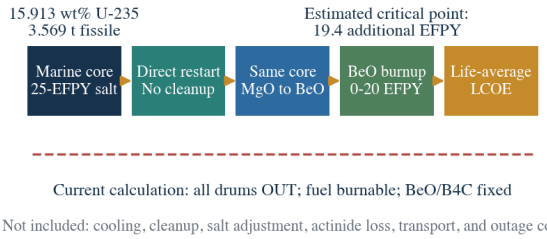


Fig. 1. Calculation boundary for marine-to-land reuse of the 25-EFPY EOL fuel salt.

2.2 Lifetime-average LCOE model

The land-MSR screening model follows the INL advanced-reactor cost structure [2]. The assumptions are OCC=6,000 $/kWe, plant life=60 years, capacity factor=93%, WACC=7.5%, construction duration=3.54 years, fixed O&M=117.77 $/kWe-yr, and variable O&M=2.16 $/MWh. The non-fuel LCOE is 80.33 $/MWh. Because the model is normalized in $/kWe and $/MWh, the 100-MWth Serpent power is not converted to an absolute MWe rating.

Fresh-fuel costs of 10.00, 19.45, 20.00, 26.00, and 30.00 $/MWh represent the INL base, NIA-adjusted, 2x HALEU, C3 proxy, and 3x HALEU cases [2-4]. One reused batch supplies a fraction f_reuse=t_reuse/(60 x 0.93) of lifetime generation. The life-average model is LCOE_reuse=80.33+(1-f_reuse)F_fresh+f_reuse C_reuse. Setting C_reuse=0 provides an upper bound before transport, cleanup, safeguards, losses, and outage costs are available.

3. Results and Discussion

3.1 Marine-core EOL condition

The marine maximum-reactivity k_eff decreased from 1.08836 +/- 0.00011 at BOC to 1.00621 +/-

0.00014 at 25 EFPY, and burnup reached 42.59 GWd/tHM. The EOL uranium contained 15.913 wt% U-235. U-235 inventory was 3,195.0 kg, Pu-239 inventory was 372.8 kg, and the defined fissile inventory (U-233+U-235+Pu-239+Pu-241) was 3,569.2 kg, or 84.4% of its initial value.

3.2 BeO reuse-core depletion

The BeO reuse model started at k_eff=1.05898 +/- 0.00012. The corresponding MgO marine EOL result was 1.00621, giving a model-to-model difference of Delta k=0.05277, or approximately 4,952 pcm. This difference is not a pure BeO reflector worth because B4C was redefined as a fresh, fixed material in the reuse input. A controlled MgO/BeO comparison with identical B4C composition and burnability is still required.

Reuse-core k_eff decreased to 1.05039, 1.03476, 1.01671, and 0.99791 after 5, 10, 15, and 20 additional EFPY, respectively. Linear interpolation gives a critical point of 19.4 EFPY. At a 93% capacity factor, this equals about 20.9 calendar years and 17.0 TWhth at 100 MWth. The defined fissile inventory decreased from 3,569.2 to 3,009.7 kg, while U-235 decreased to 2,483.7 kg and Pu-239 increased to 520.3 kg.

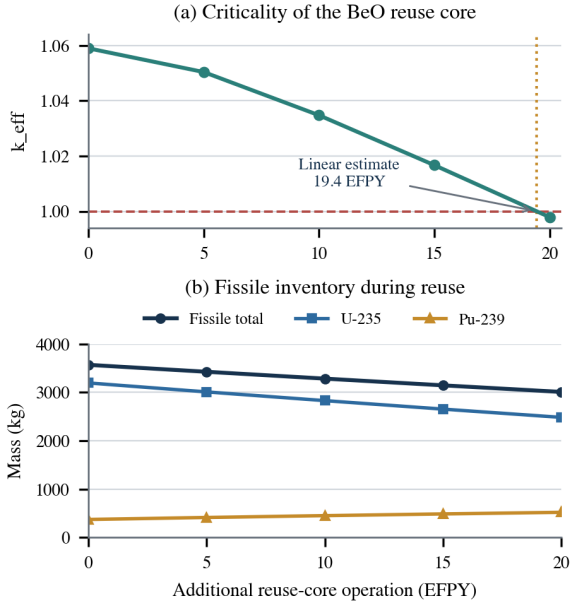


Fig. 2. Criticality and fissile inventory during additional operation of the BeO reuse core.

Table II: BeO reuse-core depletion results

Add. EFPY	k_eff	U-235 wt%	Fissile kg
0	1.05898 +/- 0.00012	15.913	3,569.2
5	1.05039 +/- 0.00013	15.174	3,425.8
10	1.03476 +/- 0.00012	14.441	3,284.4
15	1.01671 +/- 0.00013	13.715	3,145.6
20	0.99791 +/- 0.00012	12.996	3,009.7

3.3 Lifetime-average economic effect

A 60-year land plant operating at 93% capacity factor accumulates 55.8 EFPY. Therefore, one 19.4-EFPY reused batch supplies approximately 34.8% of lifetime generation, rather than the 100% assumed in the earlier full-life upper bound. With C_reuse=0, the resulting life-average LCOE reductions are 3.48, 6.78, 6.97, 9.06, and 10.45 $/MWh across the five fuel-price cases. These values correspond to 3.9-9.5% of fresh-fuel LCOE.

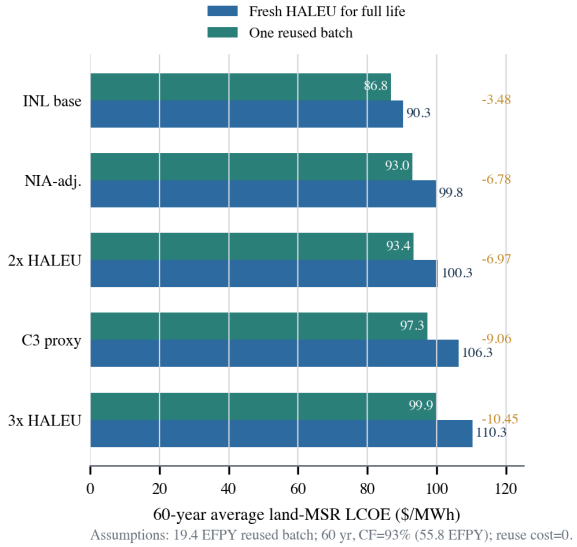


Fig. 3. Life-average land-MSR LCOE with one 19.4-EFPY reused batch; reuse cost is set to zero.

The earlier 10-30 $/MWh reduction remains a theoretical full-life upper bound only if enough sequential marine batches are available to cover all 55.8 EFPY. For a single recovered batch, the cycle-limited result is the appropriate screening metric. Any positive C_reuse further reduces the benefit; break-even requires the levelized reuse cost, including lost generation, to remain below the displaced fresh-fuel cost.

3.4 Limitations and required verification

The present calculation uses 5-EFPY time steps, maximum-reactivity control drums, fixed BeO/B4C, and direct restart of the uncooled, uncleaned EOL isotope vector. It does not include temperature coefficients, power peaking, salt-density feedback, structural activation, decay heat, source terms, corrosion products, or process losses. The 15-20-EFPY interval should be refined before assigning a design cycle.

A decision-grade assessment must compare MgO and BeO with identical material treatment, model realistic control trajectories, and evaluate uncleaned, partially cleaned, and target-cleaned salt vectors. Cooling, licensed transport, cleanup, safeguards, waste management, salt make-up, refueling outage, and actinide loss must be levelized over the electricity actually produced [5].

3.5 Interpretation and deployment implications

The initial reactivity increase in the reuse model is technically useful because it converts residual isotopic value into additional cycle length, but it should not be interpreted as a recommendation to maximize reflector efficiency without constraint. A land core must retain shutdown margin, acceptable temperature coefficients, controllable power distribution, and sufficient protection against uncertainty. The BeO configuration

should therefore be optimized together with control-drum worth and fuel-salt feedback rather than selected from k_eff alone.

The one-batch calculation also clarifies the fleet-level boundary of the economic claim. A 60-year land reactor at 93% capacity factor requires 55.8 EFPY, which is equivalent to approximately 2.87 reuse batches of 19.4 EFPY. In practice, three comparable marine EOL batches, or a mixture of reused and fresh fuel campaigns, would be required to approach full-life fuel displacement. The timing of marine retirements, cooling periods, transport campaigns, and land-reactor outages must therefore be coordinated; otherwise, a nominally valuable salt inventory may not be available when the land plant requires it.

For nonzero reuse cost, the life-average reduction can be written as f_reuse(F_fresh-C_reuse). With f_reuse=0.348, every 1 $/MWh added to the levelized reuse cost reduces the land-plant benefit by about 0.35 $/MWh. For example, a reuse cost of 8 $/MWh lowers the INL-base benefit from 3.48 to about 0.70 $/MWh, while the 3x-HALEU benefit decreases from 10.45 to about 7.67 $/MWh. This relationship provides a direct cost target for transport and cleanup studies and shows why high HALEU prices improve, but do not guarantee, the economic case.

3.6 Reporting basis and uncertainty

The Serpent model reports thermal power, whereas the economic model is normalized by electric capacity and electric generation. The calculated 17.0 TWhth should therefore not be inserted directly into an electric LCOE denominator. A coupled plant model must specify thermal efficiency, auxiliary loads, heat rejection, and any cogeneration duty before reporting MWh of saleable electricity. The present analysis avoids this inconsistency by using the EFPY fraction of a normalized 60-year LCOE model.

Residual fissile mass and U-235 assay are also not direct measures of recoverable energy. Their economic value depends on neutron spectrum, leakage, fission-product absorption, breeding, control strategy, and the discharge criterion of the land core. The depletion calculation provides a first estimate of usable cycle length, while the inventory values support material-accountancy and process-loss studies. Both sets of outputs are required because a cleanup process can improve neutron economy while simultaneously losing valuable actinides.

Future reporting should propagate at least three uncertainty groups: Monte Carlo statistics and nuclear data, operational uncertainty such as temperature and control history, and fuel-cycle uncertainty such as cleanup efficiency, actinide loss, and outage duration. Scenario ranges should be reported for both reuse EFPY and C_reuse. This will prevent the interpolated 19.4 EFPY and zero-cost LCOE reduction from being interpreted as deterministic design or project values.

4. Conclusions

A 25-EFPY marine MgO-MSR retained 15.913 wt% U-235 and 3.569 t of defined fissile inventory. When this EOL salt was directly loaded into the same geometry with 49 BeO reflector cells, maximum-reactivity k_eff decreased from 1.05898 to 0.99791 over 20 additional EFPY. Linear interpolation indicates approximately 19.4 EFPY of reusable operation.

One reused batch can supply about 34.8% of the 55.8-EFPY output of a 60-year land MSR at 93% capacity factor. Under OCC=6,000 $/kWe and zero reuse cost, the life-average LCOE reduction is 3.48-10.45 $/MWh, or 3.9-9.5%, rather than the 10-30 $/MWh full-life upper bound. The result supports continued marine-to-land fuel-reuse assessment while showing that cycle length, cleanup losses, and reuse logistics must be included before an economic claim is finalized.

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