

Performance-Based Solidification Architecture, Waste-Generation Screening, and Source-Term Traceability for Spent Ion-Exchange Resin and Radioactive Sludge from a 140 MWe SMR

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Abstract – Solidification of anticipated Sump sludge and spent ion-exchange resin from a 140 MWe SMR is assessed using stream-specific process variables and existing test evidence. Sump-sludge cementation is supported by two reported mixture endpoints and 24 core measurements; recalculated mean strengths are 8.01 and 10.28 MPa. For resin polymer solidification, the disclosed base-to-hardener mass ratio is 100:25, with a stated range of 100:(24–28), and resin-labelled thermal, water-exposure and irradiation test results are presented separately. Source-reported results, author recalculations and SMR planning assumptions are distinguished. The assessment links anticipated waste characteristics, applicable solidification conditions, performance verification and drum-level source-term records, while identifying the remaining information needed for plant-specific application.

Keywords: 140 MWe SMR; Sump sludge; spent ion-exchange resin; cementation; polymer solidification; process variables

1. Introduction

The present 140 MWe SMR concept considers two waste streams for solidification: Sump sludge collected during plant operation and maintenance, and spent ion-exchange resin discharged from water-cleanup service. The proposed reference routes are cementation for Sump sludge and polymer solidification for spent resin. The streams retain separate characterization, process-control and package records [1].

The objective is to establish what the available process variables and tests support for these anticipated wastes. The Sump sections of the sludge process-control-program (PCP) development report and the resin-labelled entries of the polymer test records form the performance basis [2–5]. The study is not a new experiment on waste generated by an operating SMR. Its contribution is the explicit connection between waste type, numerical process variables, test evidence and the records needed to apply that evidence to a future package.

2. Anticipated Wastes and Assessment Basis

Spent-resin generation in the project basis is screened at 1.0 m³/y, obtained from 4.0 m³ installed resin divided by an assumed four-year average service life [1]. This is a planning assumption, not a measured operating rate. The source does not establish a separate annual Sump inventory. Sump solidification requirements are therefore expressed per unit mass of the report-defined feed, rather than assigning an unsupported generation rate.

The sludge source is the April 20, 2026 Rev.4 report [2]. Polymer product guidance, resin certificate TAU-000934 and the resin subset of report 2009-TBU-00346 are identified separately [3–5]. Unrecorded specimen conditions are not inferred from product guidance.

$$\bar{x} = \sum x_i/n; s^2 = \sum (x_i - \bar{x})^2/(n - 1); RSD = s/\bar{x} \quad (1)$$

Equation (1) gives the labelled author recalculations; s describes specimen scatter. Source-reported summaries remain separate. Appendix A lists the 24 Sump-core and 18 resin-specimen values used.

3. Cementation of Anticipated Sump Sludge

3.1 Process variables and feed-mass basis

The PCP report selected upper and lower Sump-sludge quantity endpoints by considering workability and strength. Table 1 reproduces its final Table 3-1. W denotes tabulated water and SA the formulated solidification agent; W/SA is not automatically a water-to-neat-cement ratio [2].

Table 1. Reported Sump-sludge mixture endpoints [2].

Endpoint	W/SA	Sludge wt. %	SA wt. %	Water wt. %
SU	0.92	24.2	39.5	36.3
SL	0.84	19.8	43.6	36.6

SU/SL: upper/lower sludge quantity, not upper/lower strength. Mass fractions use the report's sludge–SA–water basis. Original reported rounding is retained.

Calculated from these fractions, 100 kg of report-defined Sump feed corresponds to 163.2 kg SA and 150.0 kg tabulated water at SU, or 220.2 kg SA and 184.8 kg water at SL. These are mixture-charge calculations, not measured annual waste generation or cured-product yields. Actual feed moisture must be reconciled with the PCP basis. Because sludge loading and W/SA change together, the two endpoints do not isolate a single-variable causal effect or prove every intermediate formulation.

3.2 Strength, conditioning and leachability evidence

The report provides 12 core measurements per endpoint, taken at four labelled locations and three heights. Table 2 recalculates their individual MPa entries by Eq. (1); these spatial samples are not 12 independent production batches. The source describes 28-day-cured drums, but exact compression age is not reconstructed from its differing sampling/testing dates [2].

Table 2. Recalculated Sump-core statistics (MPa) [2].

Group	n	Mean	s	Min.	RSD
SU	12	8.01	0.63	7.04	0.0790
SL	12	10.28	0.63	9.65	0.0616

Source: individual entries in Tables 2-270–2-271; no values excluded. These are author recalculations, not a transcription of the source summary statistics.

The lowest core value is 7.04 MPa. Conditioning results give a different perspective: the lowest Sump thermal-cycle specimen is 580 psi, and its three-specimen group mean is 620 psi [2, Table 2-206]. Both exceed the report's 500 psi screen, but they do not provide the same margin as the unconditioned cores. An observed strength ratio is not a production tolerance bound.

Table 3. Source-reported Sump performance results [2].

Property / test	SU	SL
28-d laboratory mean (psi)	1,010	1,424
Post-thermal-cycle mean (psi)	620	1,323
Post-irradiation mean (psi)	919	1,330
90-d immersed-core mean (psi)	1,000	1,560
Co leachability index	12.7	12.7
Cs leachability index	6.5–6.6	6.7–6.8
Sr leachability index	9.1	9.2
Reported full-form free liquid (mL)	0	0

Summary basis: Tables 3-2, 3-3, 3-4, 3-9, 3-12 and 3-14. Strength entries are reported group means, not individual minima; index entries summarize reported central values. The report labels strength in psig; it is treated here as compressive stress in psi (500 psi $\approx$ 3.45 MPa).

Sump leaching used artificial seawater and three specimens per endpoint [2, §2.7.2(c)]. The lowest Cs entry is 6.5 ± 0.1 ; the source defines this interval as $\pm 3s_m$, where s_m is the estimated standard error. Its central value exceeds the report's index screen of 6 by 0.5 index units. The irradiation summary records 10^9 rad and mass changes of -23.2% – -21.6% for SU/SL. These observations are retained alongside strength; meeting a strength screen alone does not establish unchanged material condition [2].

4. Polymer Solidification of Spent Resin

4.1 Disclosed resin-relevant process variables

For moisture-containing waste such as ion-exchange resin, the product sheet recommends a KOP-1000 base:KOH-2000 hardener mass ratio of 100:25, with a stated range of 100:(24–28). This is a ratio between binder components, not resin-to-binder loading. The stated usable time after mixing is 1.5–2 h at 25 °C. Table 4 presents the associated temperature-dependent product guidance [3].

Table 4. Supplier-stated polymer properties [3].

Temperature (°C)	10	25	40
Cure time (h)	15 ± 1	13 ± 1	10 ± 1
Base viscosity (P)	70–100	12–22	2.1–7.1
Hardener viscosity (P)	0.2–0.6	0.05–0.37	0.05–0.3

P: poise. Polymer and ambient temperatures are the listed values. The source distinguishes a 10–40 °C usable range from a 15–40 °C recommended curing environment. Its $\pm$ values are reproduced as product guidance, not recalculated confidence intervals.

These variables make the stated preparation conditions inspectable without assigning them retrospectively to specimens whose manufacturing record is unavailable. The supplied records do not establish the tested resin loading, a numerical feed-moisture limit or peak reaction temperature. Those quantities remain to be matched to the actual SMR resin before a batch recipe is finalized.

4.2 Resin-labelled test results

The resin strength certificate cites KS F 2481:2004; the thermal/water-exposure report cites KS F 2481:2009 [4,5]. Thermal testing used 30 cycles between -30 and $+60$ °C, with 10 °C/h ramps and 1 h holds. Water exposure used deionized water for 90 days (2,160 h), followed by five days of room-temperature air drying before compression. The report lists replacement times of 2, 7, 24, 48, 96, 456, 1,128 and 2,160 h [5].

Table 5. Recalculated resin-specimen strengths (MPa).

Test / group	n	Mean $\pm$ s
Thermal / before	3	31.07 ± 1.72
Thermal / after	3	36.87 ± 0.15
90-d immersion	3	31.19 ± 0.17
90-d leaching exposure	3	27.29 ± 0.83
Irradiation / before	3	22.70 ± 0.97
Irradiation / after	3	29.78 ± 0.84

Source: [4] for irradiation-labelled groups; [5] for thermal and water-exposure groups. Separate destructive-test specimens were used; before/after rows are not paired retests. All 18 values appear in Table A2.

After thermal cycling, the resin mean is 36.87 MPa; after immersion and leaching exposure it is 31.19 and 27.29 MPa, respectively. The latter is lower, and the report also relates the exposure results to changes in specimen appearance [5]. No matched unexposed baseline is assigned to the water-exposure groups. Reported K/Mg entries of 0.0 mg/L, without detection limits, do not establish zero release or a radionuclide leachability index.

The irradiation-labelled resin groups have means of 22.70 and 29.78 MPa [4]. Their ratio of 1.312 is a comparison of group means, not proof of radiation strengthening. A unique link between these strength specimens and an irradiation-dose record is not established in the supplied packet; no dose-specific qualification is claimed. These results concern the reported resin specimens only, not a general qualification of polymer waste forms.

5. Application to the 140 MWe SMR

The two routes require different input checks. For Sump sludge, the batch record must define the feed-solids/moisture basis, W/SA, sludge fraction and representative strength, leachability and free-liquid results. For spent resin, it must define the resin identity and moisture state, actual resin loading, base/hardener masses, temperature and curing record. The Sump recipe fractions and polymer binder-component ratio are not interchangeable loading measures.

The proposed acceptance logic is: characterize the anticipated waste; check correspondence with the relevant source formulation and test basis; confirm representative batch performance; and retain a traceable package record. A mismatch requires further evaluation rather than automatic use of the historical test result. Physical separation and distinct batch identities are retained without combining the two waste streams.

$$A_{i,d}(t_r) = \sum_b A_{i,b}(t_{s,b}) f_{i,b \rightarrow d} \exp[-\lambda_i(t_r - t_{s,b})] \quad (2)$$

Equation (2) expresses the proposed drum record: $A_{i,b}$ is the measured activity of nuclide i in source batch b at time $t_{s,b}$; $f_{i,b \rightarrow d}$ is its characterized fraction allocated to drum d ; and t_r is the common reference time. Allocation to other packages or separated liquid is accounted for separately. Volume alone does not determine activity. This form assumes no significant parent-to-daughter ingrowth; otherwise a decay-chain calculation is needed.

For a labelled arithmetic example, 1.00×10^8 Bq, a drum-allocation fraction of 0.40 and a decay factor of 0.90 give 3.60×10^7 Bq. These are illustrative inputs, not a predicted SMR source term. Each record links generation origin/time, sample and analysis, recipe revision, cure/test results, radionuclide inventory and reference time. Analytical uncertainty and unresolved allocations remain visible.

6. Conclusions

For the anticipated Sump sludge and spent ion-exchange resin of a 140 MWe SMR, the available evidence supports distinct reference solidification routes and a waste-specific verification approach. Sump endpoints at W/SA = 0.84 and 0.92 provide numerical mixture definitions, core-strength distributions and conditioning/leachability evidence. For resin, a stated 100:25 base/hardener ratio, temperature-dependent cure guidance and resin-specific specimen results replace a wholly undisclosed process description. The raw-data appendix permits independent statistical checking.

The conclusion is limited to the stated waste types and evidence: historical tests guide process selection but do not alone qualify future SMR waste. Plant-specific feed characterization, applicable batch conditions, representative performance tests and drum-level source-term traceability complete the proposed route to package-acceptance review.

REFERENCES

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Appendix A. Data for Independent Recalculation

Tables A1–A2 reproduce only the selected Sump and resin measurements. Their values, not assumed observations, are the basis of Tables 2 and 5. Source-reported summaries in Table 3 remain a separate evidence set.

Table A1. Individual Sump-core strengths (MPa) [2].

Location / height	SU	SL
A / upper	7.69	10.10
A / middle	8.59	9.69
A / lower	9.00	10.50
B / upper	7.87	9.65
B / middle	8.63	11.10
B / lower	7.04	9.97
C / upper	8.31	9.84
C / middle	7.46	9.80
C / lower	8.73	10.50
D / upper	7.53	10.10
D / middle	7.93	10.30
D / lower	7.31	11.80

Source: Tables 2-270–2-271, pp. 205–206. The SL individual values give 10.279 MPa; this is an explicit recalculation rather than use of the source’s inconsistent mean cell.

Table A2. Individual resin strengths (MPa) [4,5].

Test / group	1	2	3
Thermal / before	29.10	31.80	32.30
Thermal / after	36.70	37.00	36.90
90-d immersion	31.14	31.05	31.38
90-d leaching exposure	26.34	27.68	27.86
Irradiation / before	23.26	21.58	23.26
Irradiation / after	30.63	28.96	29.76

Source packet: thermal p. 47; immersion/leaching p. 59; irradiation p. 24. Values in N/cm² are converted to MPa by $\times 0.01$; N/mm² already equals MPa. Specimen numbering is local to each group.

Check: SU has $\Sigma x_i = 96.09$ MPa and $n = 12$, giving $\bar{x} = 8.0075$ MPa, $s = 0.63256$ MPa and $RSD = 0.07900$. For resin immersion, $(31.14 + 31.05 + 31.38)/3 = 31.19$ MPa. Recalculated s is sample scatter; it is not an uncertainty estimate for future batches.